



ANDRILL
McMurdo Ice Shelf Project
Science Integration Workshop
PROGRAM AND ABSTRACTS

10-13th February, 2009
 Victoria University of Wellington
 Wellington, New Zealand



ANDRILL Contribution 12

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Cover photos by Tamsin Falconer and Colleen Clarke/Gavin Dunbar

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS	4
INTRODUCTION	5
PROGRAM.....	6
General Information	6
The Venue	6
Refreshments.....	6
Social Events.....	6
Event Locations Map	7
Science Program	8
Field Trips.....	9
ABSTRACTS.....	11
Magnetic granulometry results from the AND-1B core, ANDRILL McMurdo Ice Shelf Project, Antarctica	
Brachfeld, S., and Pinzon, J.	12
Sedimentation rates for the lower portion of the MIS core, especially the volcanic-rich turbidite interval of LSU 5	
Browne, G., and Bland, K.	13
Water depth estimates using the volatile content of volcanic glass from lithostratigraphic units 1 and 2 of the AND-1B drill core	
Cameron, B., Wright, M., and Krans, S.....	14
Characterization of bacterial biomass in marine sediments beneath the Ross Ice Sheet, Antarctica by structural and $\delta^{13}\text{C}$ analyses of phospholipids	
Carr, S., Glossner, A., Dunbar, R., Vogel, S., Brandes, J., Wakeham, S., Naish, T., Powell, R., and Mandernack, K.....	15
Southern Ocean response to glacial-interglacial cycles – Insights from the SW Pacific and ANDRILL 001	
Carter, L., McCave, N., McKay, R., and Hall, I.....	16
Application of quantitative biostratigraphic modeling to the AND-1B drill core record: Local chronology and regional correlation	
Cody, R., Crampton, J., Levy, R., Naish, T., Wilson, G., and Harwood, D.....	17
Paleoenvironmental characteristics and depositional processes recorded in diamictites from AND-1B	
Cowan, E.....	18
Oceanic and atmospheric forcing of Antarctic ice sheet variability through the Plio-Pleistocene	
DeConto, R., Pollard, D., and Seth, A.	19
<i>Neogloboquadrina pachyderma</i> Mg/Ca-based sea surface temperature estimates associated with the retreat of the Ross Ice Shelf at 1.07 Ma	
Dunbar, G., Baker, J., and Naish, T.....	21
Miocene subaqueous volcanoclastic deposit in the AND-1B core, ANDRILL McMurdo Ice Shelf Project, Antarctica	
Di Roberto, A., Pompilio, M., and Wilch, T.....	22
ANDRILL – Drilling from an Ice Shelf platform – Past achievements and future ideas [#]	
Falconer, T., Pyne, A., Cowie, J., Huey, D., Leitch, J., Mitchell, M., and Webster, B... 23	
Initial Marine Palynology results from ANDRILL AND-1B	
Hannah, M.	24
A new technique for estimating erosion through comparison of tectonic subsidence and eustasy: Example from the ANDRILL-1B core	
Hayden, T., Kominz, M., Magens, D., Niessen, F., and Naish, T.	25
Dolomite highlights glacial to interglacial transitions in Ross Sea deposits, Antarctica	
Helling, D., Kuhn, G., von Eynatten, H., Vogel, S., Rugi, F., Castellano, E., Marino, F., Udisti, R., and Aghib, F.	26

Provenance analysis of Ross Embayment Basin deposits as evidence for Antarctic ice sheets growth	
Helling, D., Kuhn, G., von Eynatten, H., and Talarico, F.	28
Integrated seismic and core analysis of Pliocene-Pleistocene Late Cenozoic glacial-marine cycles (AND-1B), McMurdo Ice Shelf, Antarctica	
Henrys, S., Hansraj, D., Naish, T., and the ANDRILL MIS Science Team	29
Milankovitch-scale variations in the MIS AND-1B core wet bulk density log	
Hinnov, L., Mogens, D., Niessen, F., Naish, T., and Powell, R.	30
ANDRILL borehole AND-1B: Well log analysis of lithofacies and glacial-marine cycles	
Jackowski, C., Williams, T., Powell, R., Jarrard, R., Morin, R., Talarico, F., Niessen, F., and Kuhn, G.	31
Paleocurrents in the Ross Sea: Magnetic fabrics of Plio-Pleistocene samples from the AND-1B core, ANDRILL McMurdo Ice Shelf Project	
Joseph, L., Boschi, V., Ohneiser, C., Wilson, G., and the ANDRILL MIS Science Team	32
Fragmentation patterns in the diatom genus <i>Rouxia</i> and their potential for identifying latent depositional hiatuses in the early Pliocene diatomite of the AND-1B core	
Konfirst, M., Scherer, R., Winter, D., Sjunneskog, C., Warnock, J., Kuhn, G., Niessen, F., Helling, D., and Mogens, D.	34
Mineralogy of Neogene mudrocks from ANDRILL AND-1B: Provenance signal dominates sediment composition beneath the McMurdo Ice Shelf	
Krissek, L.	35
Proxies for warmer climate periods at the Antarctic Margin (AND-1B core): The XRF spectral silver (Ag) peak used as a new tool for biogenic opal quantification	
Kuhn, G., Helling, D., von Eynatten, H., Niessen, F., and Mogens, D.	36
The volcanic record of the upper 600 m of the ANDRILL AND-1 drill cores: Evidence of ice-free conditions and local volcanic activity over the past 6 million years	
Kyle, P., and Dunbar, N.	37
A chronostratigraphic framework for Neogene drill cores from McMurdo Sound, Antarctica and application to paleoclimatic and tectonic studies	
Levy, R., Cody, R., Crampton, J., Fielding, C., Harwood, D., Henrys, S., McKay, R., Riesselman, C., Scherer, R., Sjunneskog, C., Wilson, G., and Winter, D.	39
The high-resolution physical properties record of the AND-1B sediment core: Signature archive for both environmental changes and depositional mechanisms	
Mogens, D., and Niessen, F.	40
Pleistocene fluctuations of the Antarctic Ice Sheet in the Ross Embayment	
McKay, R., Naish, T., and Powell, R.	42
Syntectonic fluid flux during rift deformation: Record from the MIS core, Victoria Land Basin, Antarctica	
Millan, C., Wilson, T., and Paulsen, T.	43
Heat flow from the AND-1B borehole, ANDRILL McMurdo Ice Shelf Project, Antarctica	
Morin, R., Williams, T., Henrys, S., Mogens, D., Niessen, F., and Hansraj, D.	44
Obliquity-paced Pliocene West Antarctic Ice Sheet oscillations	
Naish, T., Powell, R., Levy, R., DeConto, R., Pollard, D., and the ANDRILL MIS Science Team	45
Natural fractures of the AND-1B core, McMurdo Ice Shelf Project, Antarctica	
Paulsen, T., Wilson, T., Läufer, A., Millan, C., and Jarrard, R.	46
Modeling West Antarctic Ice Sheet growth and retreat through the last 5 million years	
Pollard, D., and DeConto, R.	47
Alteration history in volcanoclastic deposits of AND-1B core: Inferences on syn- and post-depositional processes	
Pompilio, M., and Di Roberto, A.	48
Terrestrial palynomorphs from AND-1B	
Raine, I.	49

Radiation of a late-Pliocene <i>Fragilariopsis</i> fauna on the Antarctic continental shelf	
Riesselman, C., Sjunneskog, C., Winter, D., Scherer, R., and Dunbar, R.	50
⁴⁰ Ar/ ³⁹ Ar chronology of volcanic events in the AND-1B drill core – Implications for age models and glacial history of the Ross Embayment	
Ross, J., McIntosh, W., and Dunbar, N.	52
Pleistocene WAIS and RIS history from diatoms of AND-1B and 53 associated records	
Scherer, R., Sjunneskog, C., and Winter, D.	53
A diatom record of a stepwise late Pliocene (2.9-2.0 Ma) cooling from the AND-1B record	
Sjunneskog, C., Winter, D., and Scherer, R.	54
Foraminiferal fauna from MIS-1: Progress report	
Strong, P.	56
Provenance signatures of the Antarctic ice sheets in the Ross Embayment during the Late Cenozoic: The ANDRILL core AND-1B record	
Talarico, F., McKay, R., Powell, R., Sandroni, S., and Naish, T.	57
Mineral and chemical composition of volcanic clasts from the Cenozoic McMurdo Group in the AND-1B (MIS) core below 680 m	
Viereck-Goette, L.	58
Calcareous nannofossil evidence for Marine Isotope Stage 31 (1 Ma) in the AND-1B core, ANDRILL McMurdo Ice Shelf Project, Antarctica	
Villa, G., Persico, D., Wise, S., and Gadaleta, A.	59
Isotopic composition of autogenic carbonate - Records of glacial-interglacial interaction in the McMurdo Sound	
Vogel, S., Helling, D., Kuhn, G., and Brown, R.	60
Overview on isotopic and elemental composition of porewater derived from the ANDRILL MIS main core AND-001 B	
Vogel, S., Tulaczyk, S., Anderson, L., Andreasen, D., Mandernack, K., Dunbar, R., Newton, R., and Bottrell, S.	61
Downhole logs of natural gamma radiation and magnetic susceptibility and their relation to lithostratigraphy in AND-1B	
Williams, T., Morin, R., Jackolski, C., Jarrard, R., Henrys, S., Niessen, F., Magens, D., Pompilio, M., Di Roberto, A., Kuhn, G., and Powell, R.	62
Dating Antarctic climatic and tectonic events of the Neogene – Age models from the ANDRILL 1B and 2A cores	
Wilson, G., Levy, R., Acton, G., Naish, T., Harwood, D., Florindo, F., Powell, R., and the ANDRILL MIS and SMS Science Teams	63
Contemporary stress data from induced fractures in the AND-1B sedimentary rock core, McMurdo Ice Shelf, Antarctica	
Wilson, T., Paulsen, T., Jarrard, R., Läufer, A., Millan, C., and Schmitt, D.	64
Diatom-based correlation of early to mid-Pliocene drill cores from the southwestern Ross Sea, Antarctica	
Winter, D., Sjunneskog, C., Scherer, R., Maffioli, P., and Harwood, D.	65

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Last but not least, we would like to acknowledge the ANDRILL MIS Science Integration Workshop organizing committee of Tim Naish, Ross Powell, Richard Levy, Michelle Dow, Steve Fischbein, Mary-Ellen Reeves, and Tamsin Falconer, without whom the workshop would not have been possible. In particular, Michelle Dow was instrumental in organising everything on the ground in Wellington, Mary-Ellen Reeves coordinated US participation and Steve Fischbein collated the abstracts for this volume.

INTRODUCTION

The ANDRILL McMurdo Ice Shelf Project Science Integration Workshop is the culmination of many years of work that involved planning, proposal writing, drill rig development and construction, drilling operations and scientific investigation. The Project has involved a team of well over 100 people including research scientists, students, technicians, engineers, project/program managers, drillers, science educators and media personnel. The AND-1B core was recovered between October and December, 2006. During this time over 50 members of the MIS Project Science Team worked in Antarctica at the Drill Site and Crary Science and Engineering Center at McMurdo Station to conduct initial studies on the core. Results of this work were published in Naish et al., (2007). A workshop was held at the Antarctic Marine Geology Research Facility at Florida State University in May 2007. This workshop provided an opportunity to bring the whole Science Team (on and off-ice participants) together to share initial results and further sample the core. Since this time, Science Team Members have continued their work to further develop a robust set of discipline-focussed data and interpretations. A large portion of the results of these on-going research efforts have been submitted to various journals and will be published soon.

The MIS Project Science Integration Workshop is the last formal activity of the Project and ends the official Science Documentation Phase. The workshop's main objective is to bring the Science Team together to share data, provide an update on the current state of discipline-based research, and develop collaborative multidisciplinary teams to address key questions arising from analysis of the core. To facilitate this objective, day one of the workshop comprises overview presentations that aim to highlight key science results and focus ongoing workshop discussion on key science questions/issues/papers. Each presentation session is designed to include interaction and 'audience participation' and will guide the direction of the workshop. Break-out sessions are scheduled during the remaining three days of the workshop and will allow participants to work on data integration and development of manuscripts. In addition to break-out sessions individual data sets and specific results of the MIS Project science documentation phase will be presented via poster presentations made during thematic sessions hosted each afternoon. These data sets will become the focus of group discussion and collaboration.

Although the formal part of the ANDRILL MIS Project has ended we recognize that scientific collaboration will continue. The core provides a wealth of information regarding the climatic and tectonic evolution of the Ross Sea region and much has yet to be learned. The Co-Chief Scientists will continue to follow ongoing research activities and will likely convene sessions at future scientific meetings with a goal to continue to foster and coordinate research efforts on the spectacular AND-1B core.

Tim Naish and Ross Powell, Co-Chief Scientists
Richard Levy, Staff Scientist

McMurdo Sound Portfolio Science Implementation Committee: Gary Wilson (Chair), NZ; Fabio Florindo, Italy; David Harwood, USA; Gerhard Kuhn, Germany; Frank Niessen, Germany; Franco Talarico, Italy.

PROGRAM

GENERAL INFORMATION

Welcome to the ANDRILL McMurdo Ice Shelf Project Science Integration Workshop 2009. The conference commences with an Icebreaker on Monday 9th February, 2009. The scientific sessions run from Tuesday 10th February until Friday 13th February. Two post-conference field trips complete the program on Saturday 14th February.

THE VENUE

The workshop is hosted by Victoria University of Wellington, Cotton Building, Gate 6, Kelburn Parade, Kelburn, Wellington, New Zealand.

The talks on day one will be held in the Cotton Building Lecture Theatre (COLT122) on the Ground/1st Floor. Each talk will be either 15 or 20 minutes duration and will present an overview/summary of key results in the context of significant local and global scientific questions and identify how the new results may contribute to an evolving understanding. The key goal for these presentations is to stimulate discussion on how to move forward with collaborative teams and multidisciplinary, integrated datasets.

The poster sessions will be held on the 2nd Floor of the Cotton Building in both CO216 and CO217. Posters will be grouped into themes and time has been allocated for a brief (5 mins per poster) formal presentation of individual posters. Thematic topics and schedule will be discussed and finalized on day one of the workshop. Posters will be put-up in the appropriate room on day one and will be on display for the duration of the workshop. Announcements will be made each day outlining details regarding the thematic emphasis for the day and a schedule for relevant poster presentations will be provided at this time.

Allocation of break-out rooms for the different themes will also be announced at the beginning of day two. The break-out rooms are all located within the Cotton Building. All workshop attendees should meet in the Lecture Theatre (COLT122) at 8:30am each day.

REFRESHMENTS

Morning tea, lunch, and afternoon tea will be served each day in CO217 on the 2nd floor of the Cotton Building.

SOCIAL EVENTS

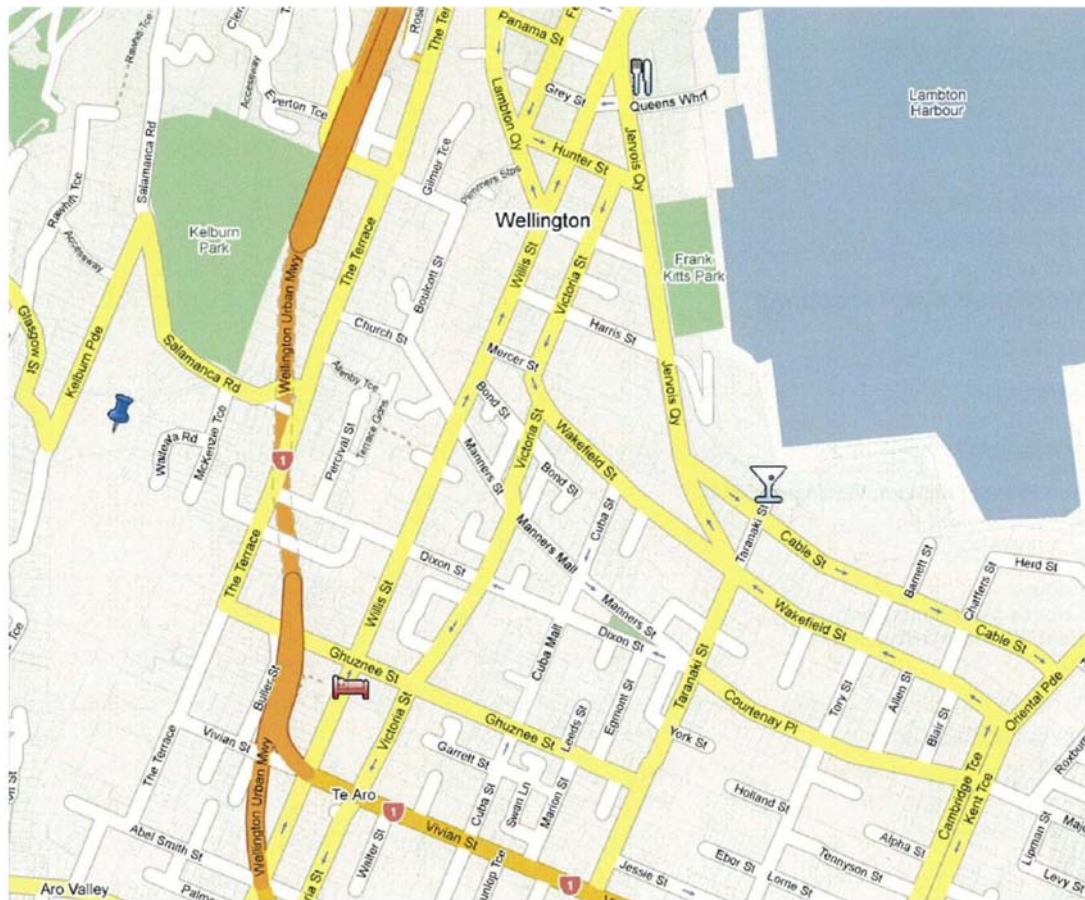
Icebreaker:

The Workshop Icebreaker (Welcome Event) will be held on Monday 9th from 6:00-7:30pm at Mac's Brewery Bar & Restaurant (upstairs), Wellington waterfront, corner of Cable and Taranaki Streets. Some complimentary drinks will be provided, after which a cash bar will be available.

Workshop Dinner:

The Workshop Dinner will be held on Thursday 12th from 7:00pm at Dockside Restaurant (upstairs), Queens Wharf. The dinner will comprise a set menu with the option of chicken, lamb, fish or vegetarian. You will be asked for your preference on the night. Some complimentary drinks will be provided, after which a cash bar will be available.

EVENT LOCATIONS MAP



[Victoria University Of Wellington](#)

Cotton Building,
Gate 6, Kelburn Parade, Kelburn, Wellington 6012
(04) 472 1000



[Cumberland House](#)

Cumberland House (Accommodation)
235 Willis Street, Te Aro, Wellington 6011
(04) 802 1300



[Mac's Brewery Bar & Restaurant](#)

4 Taranaki Street
Wellington, Wellington 6011
(04) 381 2282



[Dockside Restaurant & Bar](#)

Queens Wharf
Wellington, (Jervois Quay), 6001
(04) 499 9900

SCIENCE PROGRAM

There are 14 presentations on day one of the workshop and three poster sessions spread over days two and three as outlined in the program schedule below:

Monday 9th February

0900 1700 McMurdo Sound-ANDRILL Science Implementation Committee (M-ASIC) Meeting
1800 1930 *Icebreaker (Welcome Event): Mac's Brewery Restaurant & Bar*

Tuesday 10th February

0830 0900 Workshop Opening (COLT122)
0830 0840 Welcome & house-keeping (Tim Naish, Ross Powell, Richard Levy)
0840 0850 Official opening (PVC of the Faculty of Science, Prof. David Bibby)
0850 0900 Goals of the workshop (Tim Naish, Ross Powell, Richard Levy)
0900 1030 Chronostratigraphy and Regional Correlations (Chair: Richard Levy-COLT122)
0900 0920 Richard Levy: Age model for the Plio-Pleistocene section (20 mins)
0920 0940 Gary Wilson: Age model for the Miocene section (20 mins)
0940 1000 Richard Levy: Correlation with local/regional drill cores (20 mins)
1000 1030 Discussion: Priorities for future refinement of the chronostratigraphy (30 mins)
1030 1100 *Morning Tea*
1100 1230 Glacial and Climate History (Chair: Ross Powell-COLT122)
1100 1115 Ross Powell: Stratigraphic overview (15 mins)
1115 1130 Tim Naish: Miocene and Pliocene (15 mins)
1130 1145 Robert McKay: Pleistocene (15 mins)
1145 1200 Linda Hinnov: Applications of cyclostratigraphy (15 mins)
1200 1230 Discussion: Prioritise future multidisciplinary research (30 mins)
1230 1300 *Lunch*
1300 1430 Tectonic History and Basin Evolution (Chair: Terry Wilson-COLT122)
1300 1320 Stuart Henrys: Regional seismic stratigraphic correlations (20 mins)
1320 1340 Terry Wilson: Tectonic implications (20 mins)
1340 1400 Massimo Pompilio/Phil Kyle: Volcanic implications (30 mins)
1400 1430 Discussion: Prioritise future multidisciplinary research (20 mins)
1430 1500 *Afternoon Tea*
1500 1650 Global Connections (Chair: Rob Dunbar-COLT122)
1500 1520 Lionel Carter: Paleooceanographic implications (20 mins)
1520 1540 Rob DeConto/David Pollard: Modeling and ice volume (20 mins)
1540 1600 Rob DeConto/Reed Scherer: Orbital controls on Antarctic ice volume (20 mins)
1600 1620 Tim Naish: Early Pliocene warmth (20 mins)
1620 1650 Discussion: Prioritise future contributions (30 mins)

Wednesday 11th February

0830 0930 Develop plan for break-out paper writing groups (COLT122)
0930 1030 Break-out group time
1030 1100 *Morning Tea*
1100 1230 Break-out group time
1230 1330 *Lunch*
1330 1500 Break-out group time
1500 1530 *Afternoon Tea*
1530 1730 Poster Session 1 - Chronostratigraphy and Environments 1

Thursday 12th February

0830	0900	Group discussions/presentations (COLT122)
0900	1030	Break-out group time
1030	1100	<i>Morning Tea</i>
1100	1230	Break-out group time
1230	1330	<i>Lunch</i>
1330	1500	Poster Session 2 - Environments (modern and paleo), glacial and climate history
1500	1530	<i>Afternoon Tea</i>
1630	1730	Poster Session 3 - Volcanism, Tectonism and Basin Evolution and Operations
1900	late	<i>Workshop Dinner: Dockside Restaurant</i>

Friday 13th February

0830	1030	Group discussions/presentations (COLT122)
1030	1100	<i>Morning Tea</i>
1100	1230	Break-out group time
1230	1330	<i>Lunch</i>
1330	1500	Open-plan discussions
1500	1530	<i>Afternoon Tea</i>
1630	1700	Workshop Closing

Saturday 14th February

0800	1900	Field Trips
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FIELD TRIPS

Both field trips depart from outside the Cotton Building 24 hr entrance, Gate 6, Kelburn Parade on Saturday 14th February. Workshop participants who have registered for a field trip should assemble outside this entrance by 7:50am, the buses will depart at 8:00am and return before 8:00pm. Fieldtrip guides will be distributed on the day and lunch will be provided.

Southern Wairarapa:

Guides: Cliff Atkins, Peter Barrett, and Sam Nowland (Victoria University of Wellington) and Richard Levy (GNS Science).

We will visit a Plio-Pleistocene section in southern Wairarapa that incorporates a transition from deep marine to marginal marine environments and preserves several glacio-eustatic sea-level cycles. The trip includes a barbeque lunch and a visit to Ata Rangi one of the fine Martinborough vineyards which produce some of New Zealand's best wine.

Make sure you bring two pairs of shoes (sneakers and water shoes [sandals]) as we will be hiking through streams. Sun screen, a sun hat, and drink bottle are essential and bug spray is highly recommended.

Wanganui Basin: Plio-Pleistocene Record of Sea Level Change:

Guides: Tim Naish, Gavin Dunbar (Victoria University of Wellington)

A trip to view several outcrops of the Pliocene-Pleistocene shallow-marine sedimentary record of glacio-eustatic sea-level change recorded in Wanganui Basin. Specifically we will view evidence of facies development and sea-level change during glacial-interglacial cycles spanning MIS31-27 and MIS15-11 in coastal outcrops North of Wanganui City. A picnic lunch will be provided.

ABSTRACTS

(in alphabetical order, by lead author)

Bibliographic reference:

Author, A.B., 2009. Title of abstract. In Dow, M., Fischbein, S., Levy, R., Naish, T., Powell, R. *ANDRILL McMurdo Ice Shelf Project Science Integration Workshop - Program and Abstracts*. 10-13th February, 2009. Victoria University of Wellington. ANDRILL Contribution 12. Wellington, New Zealand, 65 pp.

Magnetic granulometry results from the AND-1B core, ANDRILL McMurdo Ice Shelf Project, Antarctica

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We present new rock magnetic data from the upper 900 m of ANDRILL McMurdo Ice Shelf Project core AND-1B. Discrete samples were collected every 1-4 m and analyzed for magnetic hysteresis parameters, induced remnances, and temperature-dependent order-disorder transitions. The magnetic mineral assemblage in diamictite, coarse clastic units, mudstone, and diatomite units is characterized by pseudo-single-domain and multidomain particles. S-ratio values are near to one. Volcaniclastic units are characterized by finer pseudo-single-domain particles. SIRM/ χ values are between 5-30 kA/m, indicating the presence of iron sulfides throughout the core. Diamictite, clastic units, and mudstones display Curie temperatures consistent with magnetite. Volcaniclastic units display multiple Curie temperatures in the range of 360-380 C, 400-500 C, and 550-580 C indicative of iron sulfides, titanium-rich titanomagnetite, and titanium-poor titanomagnetite, respectively. Work in progress includes disaggregating and sieving selected samples at 45-500 μ m and extracting the iron oxide grains for analysis via reflected light and electron microscopy. Detailed characterization of the magnetic mineral assemblage can aid in tracing of sediment provenance and past ice flow directions.

Sedimentation rates for the lower portion of the MIS core, especially the volcanic-rich turbidite interval of LSU 5

Greg Browne* and Kyle Bland

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In contrast to the upper portion of the MIS core (AND-1B), less information has been available for the interval from 586.45 mbsl to TD (LSUs 5.1 to 8.1) due largely to the mineralisation and absence of biogenic material for dating. Age constraints are provided only by disparate radiometric ages through this lower portion of the core. We have attempted to better constrain sedimentation rates for the lower portion of the core (from LSU 5.1) including, the volcanic-rich sedimentary package between 586.45 mbsl and 759.32 mbsl (LSU 5.1 to 5.4) using an indirect geohistory approach. The later interval is dominated by turbiditic volcanic sandstones, with a radiometric age of 6.48 ± 0.13 Ma from phonolitic lava in LSU 5.2 (646.49 to 649.3 mbsf). The complete 173 m thick interval of study represents a significant depositional phase at the MIS site.

The age-based sedimentation model that we develop from our geohistory approach is based on the age model of Wilson et al. (2007), and takes into account known or assumed periods of non-deposition at unconformities. This gives a basis for comparison with the remainder of the core. For the turbidite interval of interest, we have taken these sedimentation rates and compared them to published data from modern and ancient turbidite sandstone successions, mostly out of the petroleum literature. Rates of sedimentation are highly variable, and are determined by a number of factors – water depth, depositional setting on a submarine fan system (suprafan channels, distal versus proximal lobes), sediment supply, and subsidence rate. In deep water basins with abundant sediment supply, typical sedimentation rates are 40-60 cm/1000 yrs, but range upward to 900 cm/1000 yrs. We suggest similarly large sedimentation rates for this interval in the AND-1B core, controlled largely by abundant sediment supply from the proximal (White Island) volcanic source areas as well as subsidence.

Wilson, G., Levy, R., Browne, G., Cody, R., Dunbar, N., Lorindo, F., Henrys, S., Graham, I., McIntosh, W., McKay, R., Naish, T., Ohneiser, C., Powell, R., Ross, J., Sagnotti, L., Scherer, R., Sjunneskog, C., Strong, C.P., Taviani, M., Winter, D., and the ANDRILL MIS Science Team, 2007. Preliminary integrated chronostratigraphy of the AND-1B core, ANDRILL McMurdo Ice Shelf Project, Antarctica. *Terra Antartica* 14: 297-316.

Water depth estimates using the volatile content of volcanic glass from lithostratigraphic units 1 and 2 of the AND-1B drill core

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Volatile contents of volcanic glass from the ocean floor and subglacial environments can help determine water depth or ice thickness, respectively, owing to the pressure-dependence of volatile solubility in magma. The higher the pressure (i.e. the greater the water depth or ice thickness), the greater the volatiles dissolved in the magma. The existence of volcanic glass in the AND-1B drill core erupted subaqueously or even subglacially affords the possibility of constraining water depth by measuring the volatile content of the glass. Water depth is a critical variable required for the ANDRILL climate models. Three samples of volcanic sediment from Lithostratigraphic Unit (LSU) 1 at ~25 m depth in the AND-1B core were acquired in November 2006. The samples were fresh-looking basanitic/phonotephritic glassy sands. The glass and tachylite was very blocky suggesting a near-source subaquatic eruption origin rather than a subaerial eruptive process. The vesiculated nature of the glass indicates eruption into shallow water. Additionally, eleven volcanic sands were obtained from LSU 2 between 92 and 145 m depth. The black and well sorted sands from subunit 2.4 were likely derived from subaerial Hawaiian/Strombolian type eruptions. The graded bedding exposed in this subunit may result from fallout of tephra through the water column.

The glassy samples were examined under a binocular microscope to pick about 100 mg of the freshest glass for measurement of H₂O and hydrogen isotopic composition at the Stable Isotope Laboratory at Southern Methodist University. The H₂O content will be measured by manometry and the D/H ratio by mass spectrometry. Small chips of fresh glass were also picked in order to make doubly polished glass wafers for volatile analysis by Fourier Transform Infrared (FTIR) microspectrometry at the University of Wisconsin-Milwaukee. H₂O contents calculated from FTIR spectra depend on absorbance, density of the glass, and thickness of the glass wafer. Thickness of the wafer was initially measured using a digital micrometer. Error estimates using the digital micrometer are approximately $\pm 3\mu\text{m}$. More recently, H₂O content measurements have adopted wafer thickness determinations using interference fringes on spectra collected in reflectance mode on the FTIR. The three samples from LSU 1 were measured to have between 0.70 and 0.77 wt% H₂O by FTIR. No carbonate peaks were observed in the FTIR spectra indicating the glass contained less than the detection limit of ~30 ppm CO₂. On-ice participants interpret the volcanic glass in the black sands from the core as a product of subaqueous eruptions. Assuming a SiO₂ content of 47 wt% for the glass and a temperature of 1000°C, the mean H₂O content of 0.75 wt% for LSU 1 glass yields a saturation pressure of 580 bars. An eruption pressure of 580 bars translates into a water depth of 580 m assuming 0 ppm CO₂ in the glass. The water depth calculation depends significantly on the CO₂ content, however small. A CO₂ concentration of 10 ppm in the same glass results in a water depth estimate of 698 m, whereas 20 ppm CO₂ indicates a water depth of 818 m. Future studies should concentrate on manometric measurements of CO₂ concentration to allow better estimates of water depth of eruption. The water depth estimates using the measured volatile contents critically relies on the preservation of primary concentrations. Consequently, two approaches have been undertaken to distinguish between magmatic and secondary H₂O contents in the volcanic glass. Step-heating hydrogen isotopic measurements and H₂O maps of glassy clasts using synchrotron FTIR can help determine the true magmatic H₂O content.

Characterization of bacterial biomass in marine sediments beneath the Ross Ice Sheet, Antarctica by structural and $\delta^{13}\text{C}$ analyses of phospholipids

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As concerns regarding climate change increase, so does the importance of understanding the biogeochemical cycling of elements such as carbon. In the marine sediments of the Ross Sea, Antarctica, the bacterial community plays a significant role in the decomposition, mineralization and recycling of organic and inorganic carbon. Estimates of the active bacterial biomass living as deep as 155 cm below sea floor of the Ross Sea, Antarctica were calculated using phospholipid fatty acid (PLFA) concentrations and by Acridine Orange direct cell counts (AODC). The PLFA-based and AODC biomass estimates were then compared to evaluate each method's ability to accurately estimate viable microbial populations. This comparison shows a linear correlation, indicating good agreement between both methods for determining cell biomass. Structural analysis of the PLFAs can identify changes in the microbial composition with sediment depth. Identification of the PLFAs i15:0, a15:0 and i17:0 throughout the 155 cm of sediment suggest the presence of sulfate reducing bacteria. The $\delta^{13}\text{C}$ values of PLFAs ($\delta^{13}\text{C}_{\text{PLFA}}$) will also be determined which reflect the $\delta^{13}\text{C}$ of the source carbon, as well as the isotopic fractionation associated with carbon assimilation and lipid synthetic pathways. The $\delta^{13}\text{C}_{\text{PLFA}}$ will then be compared to the pore water and sedimentary organic and inorganic carbon concentrations and $\delta^{13}\text{C}$ values water in order to assess the changes in microbial metabolic pathways as a function of sediment depth and changing redox conditions. Pore water DIC $\delta^{13}\text{C}$ values fluctuated between -2.52‰ to -3.72‰ while corresponding $\delta^{13}\text{C}$ values for sedimentary organic carbon (OC) varied from -26.25‰ to -23.12‰ in the surface and 155 cm pore waters, respectively, with an isotopic shift of > 2‰ occurring within the top 10 cm of sediment. These changes in $\delta^{13}\text{C}$ values reflect bacterial carbon mineralization occurring in the sediments and will likely track changes in $\delta^{13}\text{C}_{\text{PLFA}}$ values. Integrated analysis of $\delta^{13}\text{C}_{\text{dic}}$, $\delta^{13}\text{C}_{\text{oc}}$ and $\delta^{13}\text{C}_{\text{PLFA}}$ values can provide a more comprehensive picture of microbial carbon cycling in deep sea sediments.

Southern Ocean response to glacial-interglacial cycles – Insights from the SW Pacific and ANDRILL 001

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Benthic $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotopes from 10 sediment cores off eastern New Zealand yield an insight into the structure and behaviour of water masses over recent glacial-interglacial (G-I) cycles. The cores are located mainly on North Chatham Rise where the Pacific Deep Western Boundary Current – the largest single inflow of the global thermohaline circulation – enters the Pacific Ocean carrying with it major water masses that are either generated or modified around Antarctica. The isotopic profiles for the Holocene were verified against the structure of modern water masses. When applied to earlier climatic cycles, the profiles reveal that [i] Lower Circumpolar Deep Water, [ii] Upper Circumpolar Deep Water/North Pacific Deep Water and [iii] Antarctic Intermediate Water retained their basic structure with no major change in the depths of water mass boundaries over G-I periods. Furthermore, sortable silt size data suggest that the strength of the deep Pacific inflow, while variable, appears to have remained constant on average, although there may be a G-I modulated overprint of the Antarctic Circumpolar Current (ACC) at ODP site 1123.

Some of the lowest Last Glacial Maximum values of benthic $\delta^{13}\text{C}$ in the world ocean (-1.03‰ based on *Cibicidoides wüllerstorfi*) occur in the SW Pacific gateway at $\sim 2200\text{ m}$ depth. Comparable values have been recorded in the Atlantic sector of the Southern Ocean, whereas those from the rest of the Pacific are distinctly higher confirming that the Southern Ocean was the source for the $\delta^{13}\text{C}$ depleted/nutrient-enriched water in the gateway. $\delta^{18}\text{O}$ data are compatible with a glacial, cold deep-water mass of high salinity, but lower nutrient content deeper than $\sim 3500\text{ m}$. This contrasts with the South Atlantic where low $\delta^{13}\text{C}$ /high nutrient water extends right to the ocean floor. The deeper reaches of the ACC are not homogeneous around the Southern Ocean with the Kerguelen Plateau and Macquarie-Balleny Ridges forming barriers to the eastward spread of the deepest, low $\delta^{13}\text{C}$ water out of the South Atlantic in glacial periods. These barriers, combined with an inferred high density of bottom waters due to salinity, restricted inter-basin exchange thus creating three domains dominated by bottom waters from the Weddell Sea, Adélie Coast and Ross Sea, respectively. We suggest that the Ross Sea was the main source of deep water entering the SW Pacific below $\sim 3500\text{ m}$.

That lack of evidence for a major reorganisation of the SW Pacific ocean over recent G-I cycles is consistent with the retention of a substantial Ross Ice Shelf – a prime control on deep water formation - over similar and longer time scales as revealed by the AND-1B core. What then happened to the SW Pacific inflow during Marine Isotope Stage (MIS) 31 and other warm periods when the ice shelf had either substantially or fully receded? In the absence of isotopic data for the water masses outlined above, we can only speculate on the basis of a few measurements. $\delta^{13}\text{C}$ from ODP 1123 located at 3290 m water depth within lower Circumpolar Deep Water, has MIS 31 values similar to the Holocene, although $\delta^{13}\text{C}$ for the glacials MIS 32 and 30 is more negative than the LGM suggesting a higher input from the Atlantic sector of the Southern Ocean. For waters deeper than ODP 1123, potential impacts of MIS 31 on deep and bottom water production are discussed.

Application of quantitative biostratigraphic modeling to the AND-1B drill core record: Local chronology and regional correlation

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New quantitative biostratigraphic techniques support the correlation of sparse, incomplete, and reworking-prone Plio-Pleistocene records of Ross Sea fossil diatom flora with the more extensively documented but potentially diachronous offshore history of species' first and last appearances (FAs and LAs). The approach uses a comprehensive regional database of DVDP, CIROS and IODP microfossil records and computer-automated Constrained Optimization (CONOP) routines to (a) find the multidimensional line of correlation (LOC) that best fits local observations, and (b) map out confidence intervals based on the full range of equally parsimonious composite FA/LA sequences and local range-end adjustments.

Integrated quantitative chronostratigraphy for the AND-1B drill hole was developed iteratively: initial CONOP correlation was based on preliminary on-ice observations of fossil diatom highest and lowest occurrences (HOs and LOs). The model LOC was subsequently updated as off-ice sampling and analysis of AND-1B sediments yielded additional biostratigraphic marker events and revised HO/LO horizons, Ar/Ar ages for volcanic material, improved magnetostratigraphic constraints for this section. The current version integrates the local ranges of 28 diatom taxa, 5 dated ashes, and independently constrained ages of 6 paleomagnetic events from AND-1B.

By varying the constraints and weights used to optimize the correlation of local taxon ranges, three alternative models were constructed that effectively test different hypotheses regarding the degree to which local records reflect geographic diachroneity, reworking and stratigraphic mixing, and other failures of preservation, collection, and observation. Alternative age models for the upper 600 m of AND-1B differ by no more than 0.18 myr, on average, regardless of underlying assumptions. CONOP results corroborate almost all the on-ice magnetozone age interpretations, but identify a previously unrecognized major disconformity (~800 kyr hiatus) near 440 mbsf.

Large discrepancies between observed and expected HO/LO horizons reveal significant diachronism in the timing of a few species' FAs and LAs on the shelf vs. offshore. In other cases, positions of HOs and LOs that were predicted by the quantitative analysis were subsequently validated by collection of additional microfossil count data that documented occurrences of the taxon near the stratigraphic limits predicted by regional correlations. Quantitative biostratigraphic analysis of this type could potentially be useful in guiding more intensive, supplementary off-ice or post-cruise sampling and investigation.

In spite of drastic augmentation and progressive refinement of the original AND-1B input dataset, successive iterations of the output LOC retain the same fundamental structure/shape with only relatively minor, fine-scale differences. This remarkable stability indicates that quantitative biostratigraphic analysis is capable of constructing robust and reliable regional correlation schemes and local section chronologies, even where microfossil data are rough/qualitative or low-resolution, include some errors or low-quality content, or lack independent age control.

Paleoenvironmental characteristics and depositional processes recorded in diamictites from AND-1B

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Diamictites can be deposited by differing processes under a range of paleoenvironmental conditions including subglacial deposition, rainout from beneath an iceshelf, iceberg rafting, and debris flows, each representing variable ice conditions. This project focuses on a nested set of samples collected at overlapping scales of observation to interpret diamictite depositional processes and paleoenvironmental conditions through time. Four intervals were chosen for detailed study, each with at least one glacial surface of erosion (GSE) within the cycle and with diamictites interpreted to have been deposited under conditions from subpolar to polar. These intervals include 38-48 mbsf and 56-68 mbsf (in Motif 1), 201-212 mbsf (in Motif 2a) and 1050-1063 mbsf (in Motif 3). Data used for detailed sedimentological analyses include cm-scale core logging based on x-radiographs of the archive halves in addition to the original core description, bulk samples, and 25 oriented 45 x 70 mm thin sections of diamictites for micromorphology analysis. In addition, quartz sand grain microtextures from 33 samples from varying depths within AND-1B were imaged with a scanning electron microscope (SEM) to document the extent of glacial transport, weathering, and fluvial activity recorded within the population of grains examined.

Analysis of the sand size fraction in bulk samples from AND-1B has shown an abundance of aggregate grains (up to 80% of the sand fraction within a sample), termed till pellets following terminology used by sedimentologists in the Ross Sea. These cohesive grains are dominated by a clay matrix but have inclusions of mineral grains or lithic fragments that range in size from coarse silt up to 1 mm in diameter. The occurrence of these grains is associated with massive diamictites interpreted to have been deposited subglacially. These aggregates are not present in stratified diamictite facies interpreted to have been deposited by iceberg rafting. An understanding of the processes of till pellet formation may lead to recognition of depositional processes of diamictite during glacial periods.

Oceanic and atmospheric forcing of Antarctic ice sheet variability through the Plio-Pleistocene

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The numerical modeling effort associated with ANDRILL is using a hierarchy of models to explore the climatic and glacial evolution of Antarctica on orbital and longer (Cenozoic) timescales. Modeling work over the past several years has concentrated on the development of a combined ice sheet-shelf model, the adaptation of a Regional Climate Model (RCM) to the Antarctic region, GCM-ice sheet coupling, and the development of asynchronous coupling techniques allowing long time-continuous climate-ice sheet simulations on orbital and longer timescales.

To complement recent findings by the ANDRILL MIS Project, recent simulations have concentrated on the Plio-Pleistocene, and in particular on Marine Isotope Stage 31 (~1.07 Ma); a super-interglacial interval when the Ross Embayment appears to have been ice-free and the West Antarctic Ice Sheet (WAIS) was partially or completely collapsed. Here, we show results from GCM, RCM, and ice sheet-shelf models exploring the range of potential surface mass balance forcing and oceanic sub-ice melt in response to orbital forcing and changing Plio-Pleistocene greenhouse gas concentrations.

Our climate model results generally reinforce the conclusions of prior 5-myrr ice sheet-shelf simulations (Pollard and DeConto, in press) using simple parameterized climate forcing to drive the ice model (derived from deep-sea oxygen isotope records and austral summer insolation), and point to the overriding importance of sub-ice melt to Ross Ice Shelf and WAIS variability on these timescales. In the long 5-myrr ice sheet-shelf simulations, the model does a good job reproducing ice volume and grounding line locations from the Last Glacial Maximum (LGM) to present and at Marine Isotope Stage 31. However, the model simulates several Pleistocene “super-interglacials” and WAIS collapses that are not clearly seen in the AND-1B sediment record. This suggests that either the climatic forcing applied to the model is inappropriate for some parts of the Plio-Pleistocene and/or the AND-1B record is missing several WAIS collapses and readvances, particularly over the last ~1 million years. Several of the smallest simulated Antarctic ice volumes (most extreme Pleistocene WAIS collapses) do not occur at times when WAIS collapse has been implied indirectly from sea level records (e.g., MIS 5 and 11), hinting at the possibility of anti-phased ice volume contributions from Antarctica and the Northern Hemisphere (e.g., Raymo et al., 2006), during some (but not all) intervals with high eccentricity orbits.

New GCM and RCM simulations show that the potential for significant surface melt over West Antarctica or the margins of the East Antarctic Ice Sheet is minimal, even during the warmest austral summer orbits and/or at levels of CO₂ (~400 ppmv) presumed to have existed during the warmth of the early-middle Pliocene. Again, this suggests that during this interval, Antarctic ice volume variability has been driven mostly by changes in sub-ice oceanic melt, rather than from warm surface air temperatures. While the potential for melt on the flanks of terrestrial ice sheets appears to be limited, any surface melt on ice shelves during the most extreme warm summer orbits and/or at times with elevated atmospheric CO₂ would have an additive effect to thinning caused by oceanic melting from below. Subsequent consequences for grounded ice

via the loss of ice shelf buttressing could be an important factor, however this surface melt/retreat mechanism has yet to be fully explored.

The clear importance of marginal ocean temperatures and sub-ice melt in Plio-Pleistocene WAIS variations highlights the need for more explicit, high-resolution ocean modeling of West Antarctic embayments as well as the need for more robust proxy estimates of ice-proximal surface and benthic ocean temperatures.

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***Neogloboquadrina pachyderma* Mg/Ca-based sea surface temperature estimates associated with the retreat of the Ross Ice Shelf at 1.07 Ma**

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Recent computer modeling studies suggest sea surface temperature plays an important role in the mass balance of the Ross Ice Shelf (RIS) by influencing the rate of basal melting that occurs underneath it. Modeling also suggests that the presence or absence of the ice shelf affects the stability of the feeder ice sheets, in this case the West Antarctic Ice Sheet (WAIS) which is considered inherently unstable because most of it is grounded below sea level and contains 4-6 m sea level equivalent of ice.

The Cape Roberts Project (CRP-1) and ANDRILL (AND-1B) drill cores from southern McMurdo Sound suggest that Marine Isotope Stage (MIS) 31 at 1.07 Ma is significant because it marks the youngest unequivocal evidence of greatly reduced ice cover at both sites, suggesting substantial retreat of the RIS occurred then. Sediment deposited after MIS 31 is represented only by lithofacies characteristic of sub-glacial environments, indicating a critical environmental threshold had been crossed enabling the RIS to form and persist.

Using laser ablation ICPMS we have estimated sea surface temperatures (SSTs) during MIS 31 by measuring Mg/Ca, a proxy for SST, in well preserved shells of the planktonic foraminifera *Neogloboquadrina pachyderma* from the CRP-1 drill core. These SST measurements are calibrated against Mg/Ca in modern *N. pachyderma* from the Ross Sea and Southern Ocean which have measured SSTs ranging from -1.2°C to 14°C. Initial measurements on *N. pachyderma* from the AND-1B core show they contain significant amounts of a Mn-Mg contaminant from an as yet unidentified source which will need to be removed, or corrected for, before they can be confidently used for SST reconstruction.

Miocene subaqueous volcanoclastic deposit in the AND-1B core, ANDRILL McMurdo Ice Shelf Project, Antarctica

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During its first season of drilling (29 October and 26 December 2006) from the McMurdo Ice Shelf (MIS) the ANDRILL program recovered a 1285 m-long core (MIS AND-1B drill core) that represents the longest and most complete geological record from the Antarctic continental margin. The core is a succession of cyclic glacial-marine sediment with interbedded thick volcanic deposits. During the on-ice sedimentologic description and lithostratigraphic subdivision of the AND-1B core eight main lithostratigraphic units (LSU) and 25 subunits, based on lithological abundances were recognized. Among the eight, LSU 5 (between 588 and 759.30 mbsf), represents the thickest and most continuous volcanic sequence among the whole core. A detailed characterization of the LSU 5 sequence was further performed by means of microscope and SEM-EDS analysis on about one hundred thin sections; 30 selected sections were probed by means of EPMA and LA-ICP-MS to determine composition of glass shards, minerals and alteration phases.

Results indicate that the sequence comprises two main sub-sequences that are distinguishable by sediment composition, texture, and alteration style. The first sub-sequence (759.30 mbsf to ~714.80 mbsf) is composed of an almost monothematic sequence of stacked volcanic rich turbidites that are interpreted to have been deposited through epiclastic processes. The second sub-sequence spans between 714.80 and 588 mbsf and is mainly comprised of cm to m thick lapilli tuff, tuff breccia beds and volcanoclastic diamictites; a 3-m thick lava flow also occurs. Almost the whole second sub-sequence is attributed to primary volcanic submarine processes originating close to a volcanic system with long lasting (<Ma?) activity and likely records recurring cycles of submarine explosive activity to submarine lava flows. High eruption rates, shallow depths, and high volatile contents suggest submarine fire fountaining or subaqueous pyroclastic jets (from which eruption fed density currents may evolve), while lower eruption rates, greater depths, and lower volatile content may have produced lava flows and associated diamictites.

This new dataset throws light onto the reconstruction of the nature, age, frequency and persistence of volcanic activity in the McMurdo Sound-Ross Island area and helps to understand volcano-glacio-sedimentary processes including interactions of ice-sheets/ice-shelves with volcanic structures in McMurdo Sound-Ross Island area.

ANDRILL – Drilling from an Ice Shelf platform – Past achievements and future ideas[#]

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[#]This poster was presented at SCAR 2008

In 2006/07 in McMurdo Sound, Antarctica, the ANDRILL drill rig successfully cored to 1285 mbsf with 98% recovery, from an 82-m thick ice shelf platform overlying 850 m of water. The drilling system was developed with a mix of minerals coring technology and innovative custom-built components.

Technological challenges overcome at the McMurdo Ice Shelf (MIS) site included: the development of a hot water drill that utilised seawater heated to 90°C; the maintenance of a sea riser access hole through the ice shelf for up to three months; a lateral platform movement rate of 100 m/year due to ice shelf flow; and vertical tidal movement of up to 1.7 m.

Future proposed drill sites include locations with significantly thicker shelf ice, and lateral movement rates of 750 m/year and higher. In developing drilling strategies for these locations, the major challenge will be determining how to achieve target depths within allowable operational limits of sea riser and casing bending. Options under investigation include sea floor re-entry, accelerated drilling and multiple holes.

Here we present an overview of the MIS drilling operation and technological challenges to be faced by future Antarctic ice shelf-based stratigraphic drilling projects.

Initial Marine Palynology results from ANDRILL AND-1B

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ANDRILL AND-1B was drilled on the McMurdo Ice shelf near Scott Base and McMurdo Station during the austral summer of 2006-07. Almost 1300 m of nearly continuous core was recovered from beneath 85 m of ice and 943 m of seawater. The glacial-marine and volcanic sediments recovered are a record of climate and ice sheet variability over the past about 13 million years. Repeated stacking of facies are interpreted as representing up to 60 cycles of ice sheet advance and retreat.

Diatoms were the most common fossils recovered, they were abundant in the upper about 600 m – but rare to absent below this level. The upper part of the core contained intervals of diatomite, reflecting warm periods with no ice input into the basin and high levels of primary productivity. Other microfossils (foraminifera, calcareous nannofossils, were present sporadically through the core.

The palynomorph content of samples at about twenty meter spacing through the entire core have been examined. Most samples contained palynomorphs, often in reasonable numbers. Lower numbers were recorded in diamictite intervals and samples from intervals dominated by volcanic debris yielded very low numbers or were entirely absent. Terrestrial palynomorphs were scattered throughout the section and are not considered further here.

Reworked dinocysts from the well established Eocene/Earliest Oligocene Trans Antarctic Flora (TAF) were recovered, almost exclusively, from two intervals 60.42 – 145.46 mbsf and 759.30 – 1143.65 mbsf. This very restricted distribution may reflect significant changes in source.

Three abundance peaks in numbers dinocysts that are not part of the (TAF) have been identified. The youngest is between 201.25 and 224.38 mbsf older peaks are in single samples from 759.3 and 983.15 mbsf. These dinocyst species are most likely to be in situ because they do not coincide with levels of increased reworking as marked by the TAF, but they are coincident with elevated numbers of foraminiferal linings which are so delicate they are unlikely to be reworked.

The presence of *Eatonicysta* (?) in the youngest interval presents a problem, as the genus has not previously been reported from above the Eocene nor from the Antarctic region. The identification of *Cryodinium* in the upper two peaks may represent the first occurrence of this genus in sediments older than the recent. The identification of this in situ flora raises some significant questions;

- There are many peaks in overall marine palynomorph numbers in the section but the dinocyst floras are restricted to only a few – why are the dinocyst floras not more common?
- Each interval containing a significant number of in situ dinocysts yields a different assemblage – does this reflect some longer term climate change?

A new technique for estimating erosion through comparison of tectonic subsidence and eustasy: Example from the ANDRILL-1B core

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We present a novel technique for estimating maximum erosion in the mixed diamict and shelfal environment of the Ross Sea in Antarctica over the past 5 million years. This technique utilizes backstripping to model the tectonic subsidence observed within the AND-1B core. We assign the lower frequency signals to tectonic processes, and remove that signal from the tectonic subsidence results. The remaining signals are higher frequency glacial/interglacial changes, and are combined with the $\delta^{18}\text{O}$ record of sea level change from Miller et al. (2005), as correlated by Naish et al. (in review) for the AND-1B core. We use this comparison of expected sea level change from $\delta^{18}\text{O}$ and the modeled tectonic subsidence to estimate the maximum amount of erosion. When the tectonic subsidence calculated from observed sediment thickness was greater than the accommodation space generated by the change in sea level then a water-depth change was required. In most cases sediment thickness was considerably less than that required to fill the space generated by the change in sea level. The maximum amount of erosion was calculated by assuming that the accommodation space generated by the sea level change was completely filled by sediments. The resulting extreme sedimentation rates were limited by observed sedimentation rates in the core, particularly in the Diatomite units of lithostratigraphic unit 4.1, and the first diamict occurrence representing deposition since last glacial maximum. The results of this model are discussed within a framework of assumptions, limitations and insights gained from this technique.

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Dolomite highlights glacial to interglacial transitions in Ross Sea deposits, Antarctica

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The retreat phases of Antarctic ice mass fluctuations during the Plio-Pleistocene were characterized by large-scale environmental changes at the continental margin. Increased meltwater runoff was mixed with seawater and created conditions for a huge variety of chemical reactions. The precipitates of these reactions, recorded within the sedimentary deposits, are reliable tools for reconstructing specific paleoenvironmental changes. Discrete horizons with high dolomite and calcite content (up to ~20 and ~30% respectively) were detected in the AND-1B core from the ANDRILL McMurdo Sound Project. We measured the split core in the field during the austral summer 2006/2007 with a non-destructive AVAATECH XRF-Core Scanner. Chemical analyses were carried out on discrete samples and the mineral composition was examined using X-ray diffraction measurements.

Dolomite and other iron bearing carbonates were mainly detected in the upper 500 mbsf and the carbonate phase, calcite, was primary present in samples in the lower part of the core (below 500 mbsf). Whereas calcite can be linked to late diagenetic features, like healed fractures, dolomite and the other carbonate phases are indicators for specific depositional environments and early diagenesis.

At specific depths high dolomite, siderite and ankerite values were found within the glacial to interglacial transition zones (98.28, 127.47, 162.71, 182.10, 205.29, 224.58, 292.15 425.61, 426.67, 437.11, 449.27, 460.77 and 571.43 mbsf). Our hypothesis states that dolomite, siderite and ankerite formation in the transition zones is possible under cold glacialmarine conditions. Meltwater runoff with high amounts of dissolved HCO_3^- in contact with Mg^+ and Ca^+ rich seawater at the grounding line region or in the sub-ice hydrological system could provide the necessary physicochemical conditions. The different carbonate phases represent varying 'microenvironments' during ice retreat.

In this environment, dolomite was precipitated in the pore water system, where sub-ice freshwater was mixed with seawater (Dorag model; Badiozamani, 1973) during glacial to interglacial transitions. The reducing conditions for building up carbonate phases like ankerite, siderite and dolomite could have originated from the microenvironments in the pore spaces of the diamictites, which contained a mixing zone of sub-ice freshwater and seawater and were overlain by organic rich diatomaceous sediments early in an interglacial. The degradation of the organic material may have caused reducing conditions in the underlain diamictites. The carbonate concretions can potentially be linked to the following depositional environments:

- (i) Ankerite with dolomite formed by early diagenesis could be an indicator for a more aerobic and freshwater influenced depositional 'microenvironment'.
- (ii) In the layers where siderite was formed, mainly dysaerobic to anaerobic environments led to iron-reducing conditions.

(iii) Whenever dolomite was precipitated, the 'microenvironment' possibly could have been a sulfate reduction one with a contribution from sulfate-reducing bacteria.

These different 'microenvironments' could represent different types of glacial to interglacial transition zones. How these environments occurred and what the transition scenarios look like needs further research.

In conclusion, most of the dolomite formations in the AND-1B core can be related to shelf ice retreats and (bio?) geochemical processes at or close to the sediment surface. They are not late diagenetic features.

Badiazamani, K., 1973. The diagenetic dolomitization model - application to Middle Ordovician of Wisconsin. *Journal of Sedimentary Petrology* 43: 965-984.

Provenance analysis of Ross Embayment Basin deposits as evidence for Antarctic ice sheets growth

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Bulk chemical sediment compositions from the South Victoria Land glaciomarine sediments can provide significant constraints on the reconstruction of sediment provenance models in the McMurdo Sound in Late Cenozoic time. High-resolution (~1 ka) geochemical data were obtained with a non-destructive AVAATECH XRF Core Scanner (XRF-CS) on the 1285-m-long ANDRILL McMurdo Ice Shelf Project (MIS) sediment core AND-1B. This data set is complemented by high-precision chemical analyses (XRF, ICP-OES) on discrete samples.

The data indicate that diamictites at the drill site are largely dominated by local sources, mainly the McMurdo Volcanic Group. However, during the Mio-Pliocene transition as well as during the Late Pliocene and the Late Pleistocene a shift occurred in source material, from local to Transantarctic Mountain (TAM) sources. The composition of TAM clasts and the related geochemical clusters are consistent with a supply of TAM debris from the Byrd Glacier-Darwin Glacier areas in an early stage (Mid-Late Miocene), and from the Mulock Glacier-Skelton Glacier region in a later stage (Early Miocene to Early Pleistocene). Expansions of the ice flow lines of these outlet-glaciers into the McMurdo Sound is consistent with glaciological reconstructions for the Last Glacial Maximum and interpreted as the result of the dynamic behavior (waxing and waning) of the West Antarctic Ice Sheet (WAIS) and East Antarctic Ice Sheet. Consequently the relative contributions of diamictite sub-clusters within the core provide a reliable tool to evaluate climate variability in the Ross Embayment, and they can also be used as a sensitive indicator of WAIS influence on provenance and dispersal of sediments in the Ross Embayment.

Integrated seismic and core analysis of Pliocene-Pleistocene Late Cenozoic glacimarine cycles (AND-1B), McMurdo Ice Shelf, Antarctica

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Surface seismic reflection data collected on the McMurdo Ice shelf are integrated with a regionally extensive McMurdo Sound seismic network and correlated with the AND-1B drill hole. Three regional Pliocene-recent unconformity-bounded sequences, or seismic units, are mapped across the seismic grid. The sequences are separated by three sub-seafloor seismic surfaces (Ri to Rk), recognised as regionally extensive unconformities marked by either stratal truncation below or onlap above.

Ri is marked above by onlap of low-amplitude reflections at the base of a c. 90 m-thick seismically opaque interval onto high-amplitude reflections of the underlying unit. This surface corresponds to the base of prograding clinoforms north of Ross Island, and locally marks the base of flexure associated with Ross Island volcanic loading. In AND-1B Ri correlates with the boundary between the ~100 m-thick, low-density, low-velocity Early Pliocene diatomite interval (LSU 4.1), and diamictites of LSU 4.2. Diatom assemblages bracket this surface to between 4.5 Ma and 5.0 Ma.

Rj is characterised by truncation of underlying moderate-amplitude reflections and onlap by overlying reflections at the base of a c. 150 m-thick unit of strongly alternating high and low-amplitude reflections. Rj separates strata above that are younger than c. 3.0 Ma and below greater than c. 3.3 Ma.

Rk is characterised by stratal onlap above and marks the top of the cyclic diatomite-diamictite LSU 3. The stratigraphic interval above Rk comprises Late Pliocene–Early Pleistocene diamictite/volcanic mudstone and sandstone cycles of LSU 2, passing up into the Middle–Late Pleistocene, diamictite dominated sedimentary cycles of LSU 1. The age of this reflector is well constrained to older than 1.67 Ma and younger than c. 2.1 Ma.

In addition to the three major surfaces, up to 10, high-frequency, alternating high and low-amplitude minor seismic reflectors are identified with the major sequences and mapped in our seismic data. These surfaces correlate to a number of the 26 recognised high resolution glacial-interglacial cycles evident in the AND-1B core and interpreted to be the result of fluctuations in the marine-based grounding lines of the West Antarctic Ice Sheet (WAIS), and imply a dynamic nature in the Western Ross Sea during the Late Cenozoic. This seismic signature of stacked alternating high and low-amplitude reflectors bounded by major unconformities may be a hallmark of Pliocene-Pleistocene glacimarine deposits in the Ross Sea.

Milankovitch-scale variations in the MIS AND-1B core wet bulk density log

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A major goal of the ANDRILL Program is to study the response of the Antarctic ice sheet to global Milankovitch forcing from the perspective of the Antarctic margin sediment record. The recovery of the MIS AND-1B Core and establishment of a detailed chronostratigraphy now makes possible a quantitative assessment of Milankovitch variations recorded by glacio-marine sedimentation at the MIS drill site.

AND-1B Core sedimentology and chronostratigraphy of the upper 600 meters indicates a sediment record covering the past 5 million years with numerous unconformities of variable severity. The five most severe unconformities were identified through a combination of high-resolution magnetostratigraphy and biostratigraphy, and indicate time gaps that are on the order of 0.5 to 1 million years. Other less severe disruptions of unknown duration are indicated by some 30 other glacial surfaces of erosion (GSE's). The GSE's, together with detailed facies analysis, have been interpreted to represent periodic advances of the ice sheet into the Ross Embayment at approximately 40,000 year intervals.

The strategy of this study is to perform time-series analysis on the sediment record preserved between major unconformities, using the high-resolution wet bulk density (WBD) log as a paleoclimate proxy. Intervals of focus are from 438.61 m to 282 m (Pliocene) and from 85 m to 55 m (Late Pleistocene). The first objective is to examine Milankovitch-scale variability in these intervals, and to compare WBD variations with the theoretical Milankovitch parameters. The second objective is, through application of complex signal analysis, to verify and estimate missing time represented by individual GSE's. Preliminary results indicate that substantial precession scale variability occurs together with obliquity variation through both study intervals. Eccentricity variation is also present. The precession-scale variations, however, do not always match the predicted precession parameter, possibly due to erosion and/or other processes. These results serve to improve the high-resolution chronostratigraphy of the AND-1B Core, and contribute to understanding the Milankovitch forcing of the Antarctic ice sheet.

ANDRILL borehole AND-1B: Well log analysis of lithofacies and glacimarine cycles

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During the 2006-2007 austral summer, the Antarctic geological drilling program ANDRILL recovered cores of sedimentary rock from a 1285-m-deep borehole below the McMurdo Ice Shelf. Well logging instruments were deployed to a depth of 1017 mbsf after core recovery. This study focuses on two intervals of the AND-1B borehole: upper HQ (238-343 mbsf; Pliocene) and NQ (698-1017 mbsf; upper Miocene), which were logged with natural gamma ray, induction resistivity and magnetic susceptibility tools. To understand how the well logs fit into a more complete physical properties data set, we performed factor and cluster analyses on a suite of well logs and core logs in the upper HQ and NQ intervals. In both intervals, factor analysis groups resistivity and core P-velocity into a factor that we interpret as being inversely proportional to porosity. It also groups natural gamma and potassium (from the XRF core scanner) into a factor that we interpret as a particle-size or lithology index. An additional factor in the NQ interval, influenced by clast number and magnetic susceptibility, distinguishes subglacial diamictites from other lithofacies. The factors in each interval (2 in HQ, 3 in NQ) are used as input to cluster analysis. The results are log data objectively organized into clusters, or electrofacies. We compare these electrofacies to the lithofacies, well logs and unconformity-bounded glacimarine cycles of AND-1B.

Patterns in the glacimarine cycles are observed in the well logs and electrofacies. In the NQ glacimarine sediments, an electrofacies pattern is produced between subglacial diamictites at the bottom of each sequence and the glacial retreat facies above. Subglacial diamictites have higher values for the additional NQ factor, corresponding to clast number and magnetic susceptibility, than the muds and sands that form the retreat facies. Differences in the porosity factor are not observed in any electrofacies pattern in the NQ interval, but subtle patterns in the resistivity well log are observed. Subglacial diamictites have greater resistivities than most retreat facies. In the HQ interval, there is only one glacimarine cycle that resembles those in the NQ interval, and most of the interval is subglacial or ice-proximal diamictite. There are only two and a half cycles in the HQ interval, but they contain an incipient electrofacies pattern. In the lower two cycles, the potassium/gamma factor is low at the bottom and high toward the top, and porosity, as indicated by the porosity factor, is low at the bottom and high toward the top. Throughout most of the HQ interval, potassium/gamma correlates with porosity. Two exceptions are the lower half of the top cycle, in which resistivity increases toward the top, and the two diatomite beds at the top of the two lower cycles, in which potassium/gamma is low and porosity is very high.

Paleocurrents in the Ross Sea: Magnetic fabrics of Plio-Pleistocene samples from the AND-1B core, ANDRILL McMurdo Ice Shelf Project

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The ANDRILL McMurdo Ice Shelf (MIS) Project successfully recovered 1,285 m of core from below the Ross Ice Shelf, an area known for significant bottom water formation, providing an opportunity to investigate near-ice and open water Plio-Pleistocene paleocurrents that may have affected global circulation. Initial characterization of the core established the presence of eleven recurring lithofacies, or characteristic depositional environments (Krissek et al., 2007). Those lithofacies that represent depositional environments in front of the grounding line of the ice shelf may provide information about paleocurrent energies present beneath, or in absence of, the ice shelf at the MIS site. Previous studies have indicated the utility of magnetic fabrics (i.e. P') to obtain information on the relative velocity of the depositional environment when analyzing paramagnetic sediment samples; application to a sequence of varying and lithified lithologies is more complicated but offers the potential to derive relative current information within an individual lithofacies (rather than between lithofacies). Analysis of Lithofacies 6v, interpreted by the on-ice sedimentologists to be primarily upward fining turbidite deposits with a significant volcanic component, allowed for testing of the methodology; strong grain alignments would be expected with turbidity current deposits as turbidity currents are among the fastest currents within the ocean basins.

Approximately 240 paleomagnetic samples were obtained from AND-1B, focusing on Lithofacies 1a, 1b, 2, 3, 3v, and 6v which had been interpreted by on-ice sedimentologists to have been deposited in open water or beneath an ice shelf. Samples were analyzed initially for anisotropy of magnetic susceptibility (AMS) on a KLY-4S KappaBridge at Ursinus College, demagnetized at the University of Otago, and subsequently analyzed again for AMS at a combination of the two laboratories. Interlaboratory comparisons of the KappaBridges at both labs were completed (both pre- and post-demagnetization) and the results were found to be comparable. Additionally, the demagnetization seemed to result in minimal variation of the magnetic fabric (P') or the corrected bulk magnetic susceptibility values (MS), indicating that drilling and transportation processes had only minimally affected the AMS of the samples, if at all.

As predicted, the P' values of interpreted turbidity current deposits of Lithofacies 6v extended higher, indicating greater grain alignment, than any of the other lithofacies sampled (~1.02-1.50). The MS of these samples fell in the middle range (mostly between 5×10^{-4} and 5×10^{-3} SI). The correlation between MS and grain alignment (P') for these samples appears to be very weak; a plot of MS versus P' has an r^2 value of 0.053 for all Lithofacies 6v samples and 0.136 with the outliers removed, indicating that for these samples, it is not a high MS that allows a stronger grain alignment, but is likely the actual grain alignment itself. Further mineralogical analysis may reveal how much this effect is dominated by the specific mineralogy versus the grain orientation resulting from a strong turbidity current (or both). The diatomites (Lithofacies 1a and 1b), representing open water deposition, with varying hemipelagic or fallen iceberg debris inputs, had very low bulk MS (ranging from $\sim 2 \times 10^{-5}$ to 3×10^{-3} SI) and relatively low P' values (~1.01-1.11) that varied somewhat within the repeated analysis of a single sample while the standard deviation from the average of repeated P' measurements on a single sample was greater than for other lithofacies that had higher MS values. As well, when plotted on a stereonet, the orientation of the axes of the magnetic fabric ellipsoids for Lithofacies 1 often varied within repeated runs of a single sample, indicating that the orientation of the magnetic fabric was not clearly determined. Continued work may indicate if the AMS signal is reliable

enough to be used for these samples. Lithofacies 2 and 3(v) were characterized as mudstones likely derived from hemipelagic sedimentation possibly proximal to or distal from grounded ice; these paramagnetic-rich samples (bulk MS values $\sim 2 \times 10^{-4}$ to 9×10^{-3} SI and P' values ~ 1.01 to 1.16) likely afford the greatest opportunity to derive paleocurrent information over time and will be used for downcore interpretations.

Krissek, L., Browne, G., Carter, L., Cowan, E., Dunbar, G., McKay, R., Naish, T., Powell, R., Reed, J., Wilch, T., and the ANDRILL-MIS Science Team, 2007. Sedimentology and Stratigraphy of the AND-1B Core, ANDRILL McMurdo Ice Shelf Project, Antarctica. *Terra Antarctica* 14(3): 185-222.

Fragmentation patterns in the diatom genus *Rouxia* and their potential for identifying latent depositional hiatuses in the early Pliocene diatomite of the AND-1B core

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Diatom genera have traditionally been split into two primary groupings based upon the symmetry of the siliceous frustule. Diatoms symmetric about a point are classified as centrics, while those symmetric about a line are classified as pennates. This fundamental difference in shape has consequences for preservation in ice proximal settings, where an overriding ice sheet can create shearing in the upper meters of the sediment column. This leads to preferential breakage in pennate forms, and results in a higher ratio of undamaged centric to pennate frustules (Scherer et al., 2004). Similarly, an ice sheet grounded over highly porous diatomite results in significant diatom fragmentation resulting from normal load compaction.

The diatom genus *Rouxia* is a pennate form with a relatively wide raphe, making it particularly susceptible to breakage during ice advance and retreat, and offering the opportunity to evaluate ice advance stages in sedimentary units where glacial erosion may have removed upper depositional units.

In the AND-1B core, a long interval of nearly pure diatomite was recovered from 382.98-459.24 mbsf. Construction of an age model during this interval has relied primarily on age ranges provided by presence or absence of key diatom species. However, questions still remain as to the continuity of deposition. In this study, samples were collected at an average of 50-cm spacing for the length of the long diatom unit as well as for 20 m of the silica-rich diamictite unit directly overlaying the diatomite. Fragments of specimens from the genus *Rouxia* were counted and classified into categories based on the size of the fragment in relation to total frustule length. These data were then used to develop a quantitative index, which was examined for changes in fragmentation through time.

Preliminary data are presented that indicate increased fragmentation at the top of the section under study, which we interpret to indicate evidence for increased glacial shearing. Below this (401.11-373.61 mbsf), fragmentation levels remain virtually constant, which is taken to indicate a relatively long interval of continuous deposition and evenly distributed effects of normal load compaction. A sharp increase in the fragmentation index at 401.35 mbsf is interpreted as evidence for a depositional hiatus and corresponds to a peak in abundance of the silicoflagellate genus *Distephanus*. More sporadic fragmentation occurs below 401.35 mbsf. Future work will include comparing these results to sediment texture and physical properties of the core.

Scherer, R.P., Sjunneskog, C.M., Iverson, N.R., Hooyer, T.S., 2004. Assessing subglacial processes from diatom fragmentation patterns. *Geology* 32(7): 557-560.

Mineralogy of Neogene mudrocks from ANDRILL AND-1B: Provenance signal dominates sediment composition beneath the McMurdo Ice Shelf

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The goal of the ANDRILL McMurdo Ice Shelf (MIS) Project is to define the Late Neogene tectonic, volcanic, paleoclimatic, and paleoenvironmental histories of the northwestern sector of the Ross Ice Shelf. To achieve this goal, a 1284.87 m-long drill core (AND-1B) was recovered from beneath the present-day MIS during October – December 2006. The core contains a range of lithologies, including diamictites, sandstones and mudstones (some clast-bearing), diatomites, volcanic ash/tuff, and one lava flow.

Because the mineralogy of fine-grained terrigenous sediments can provide valuable data about both sediment provenance and terrestrial weathering conditions, samples from fine-grained terrigenous intervals of AND-1B are being analyzed by x-ray diffractometry (XRD) of pressed powders. Data presently are available for 26 samples, and define large-scale compositional patterns through AND-1B.

In scans of unglycolated pressed powders, the most abundant phases generally are quartz and feldspar. The quartz/feldspar ratio, estimated from the relative intensities of their largest XRD peaks, is low in Lithostratigraphic Unit 1 (LSU 1), intermediate in LSUs 2, 3, 4, and 8, and high but variable in LSU 6. These ratios are consistent with the relative importance of older mafic volcanic vs. more silicic “basement” sources identified for each LSU from sandstone and clast analyses. Analcime dominates the one sample from LSU 5, reflecting alteration of its contemporaneously erupted volcanic component. Calcite or dolomite is present in six samples in varying abundance, reflecting the heterogeneity of carbonate cementation observed during visual core description.

In scans of glycolated pressed powders, the relative abundance of illite generally follows the pattern of the quartz/feldspar ratio, whereas the relative abundance of expandable clays (“smectites”) follows the abundance of the “contemporaneous” volcanic component identified in smear slides.

These compositional patterns are controlled by sediment provenance – older volcanics vs. “basement” vs. contemporaneous volcanics. The complete data set ultimately will provide significant compositional detail within each LSU, and may reveal variations linked to changes in terrestrial weathering conditions.

Proxies for warmer climate periods at the Antarctic Margin (AND-1B core): The XRF spectral silver (Ag) peak used as a new tool for biogenic opal quantification

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Quantification of biogenic opal in marine sediments is a time consuming job, but the results could indicate periods of higher bioproductivity and warmer conditions than today at the Antarctic margin. Within the international Antarctic Geological Drilling Program (ANDRILL), core AND-1B was drilled and recovered a 1285 m sequence from a flexural moat basin filled with glaci-marine, terrigenous, volcanic and biogenic sediments below the McMurdo Ice Shelf. Our main goal is to study the variability and the stability of the Ross Ice Shelf from Miocene to Recent. The melting and collapse of large Antarctic ice shelves may cause a significant sea level rise because of accelerated inland ice glacier surges into the ocean.

Biogenic opal content in sediments can be deduced indirectly from grain density measurements on single samples, or faster and more continuous by gamma ray attenuation measurements on the core, with subsequent wet bulk and grain density calculations. Spectral color reflectance (b^* value, CIELAB color space) measurements on the split core surface can also be a fast tool for opal content quantification. Of course, they all have disadvantages in comparison to direct measurement on samples using X-ray diffraction or geochemical leaching methods.

Some major and minor chemical elements were measured directly on split core surfaces with a non-destructive X-Ray Fluorescence Core Scanner method (XRF-CS, AVAATECH) in the field. Quantitative geochemical analyses like determination of total inorganic and organic carbon (TOC), biogenic opal as well as major and minor elements were done on core samples. We found a strong positive correlation between the counts per second of the XRF-CS Ag peak area and the biogenic opal content of the samples ($r=0.81$) not only in the AND-1B core but in others as well from the Antarctic margin. In literature, it is noted that diatoms could accumulate Ag in sediments, so at first we were pleased to find this Ag enrichment with our tool. But further geochemical analyses revealed that measuring these low Ag concentrations and their variability ($< 2\text{ ppm}$) is not possible or at least problematic with the XRF-CS. The detector of the XRF-CS has an Ag collimator, possibly acting as an amplifier on perhaps higher induced X-ray emissions in opal rich sediments within the Ag energy spectrum range. This might have nothing to do with Ag concentration itself, however, we are still studying the physics behind this measurement phenomenon. Nevertheless, this Ag peak can be used as a proxy for biogenic opal concentrations. It is negatively correlated to Fe and Ti and variability downcore has a high signal to noise ratio. Combining the opal calculations from fast measurements of the Ag peak (opal-Ag), the grain density (opal-GD), and the b^* value (opal- b^*) we yielded a new multi-parameter proxy (opal-MP) for a high-resolution record of biogenic opal concentration in the upper 600m of the core (spacing: about 2cm or 300y). This opal-MP proxy correlates very well with measured opal leaching data ($r=0.88$, $n=481$). The biogenic opal concentrations in combination with other high-resolution data will be used as a cyclostratigraphic approach to understand paleoenvironmental and climate changes. Periods with much higher accumulation of biogenic opal than today were detected in the core indicating a retreat and perhaps a total decay of the Ross Ice Shelf.

**The volcanic record of the upper 600 m of the ANDRILL AND-1 drill cores:
Evidence of ice-free conditions and local volcanic activity over the
past 6 million years**

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The upper 600 m of the ANDRILL McMurdo Ice Shelf (MIS) AND-1 drill cores contain numerous volcanic-rich intervals. These intervals provide samples for radiometric dating and give insights into the location and nature of volcanic activity in McMurdo Sound. The occurrence and nature of the volcanic layers also has implications to ice local conditions, sediment provenance and magmatic evolution. We examined the volcanic material in over 80 core samples by electron microprobe to characterize their morphology, mineralogy and chemical compositions. Volcanic glass was examined in samples from the upper 185 m and the 430 to 600 m intervals of the core.

Volcanic materials in the core consist of reworked volcanogenic sediments, volcanic clasts and reworked or primary pyroclastic materials. Pyroclastic materials consist of volcanic glass fragments and shards, pumice and cinders. The glass shards are vesicular with low crystal contents and often have delicate bubble-wall textures. Many such layers are well-sorted and show no evidence of reworking. These are interpreted as primary pyroclastic fall deposits which have settled through the water column which resulted in deposition of graded beds. Angular and blocky glass occurs in the sediment cores and this is likely reworked materials, but may, where chemically uniform, be derived from hyaloclastite subaqueous eruptions. Some volcanic-rich parts of the cores are characterized by rounded volcanic fragments of heterogeneous compositions and morphology. These layers may contain some fragments that appear pyroclastic and others that are more characteristic of lava flows and represent reworked material erupted from multiple volcanic events.

The identification of primary pyroclastic deposits based on morphology is reinforced using microprobe analyses of chemical compositions of individual glass shards and fragments. Primary deposits typically have uniform glass compositions and are likely to be derived from individual volcanic events and have not been significantly reworked. The compositions of the homogeneous layers tend to be basanitic, although examples of phonotephrite, trachyte and phonolite are also present in the core. In contrast, some volcanic-rich horizons are heterogeneous and contain glass shards ranging from basanite to trachyte and phonolite suggesting that reworking has occurred. Several layers in the 420-500 m depth range have bimodal populations of basanite and trachyandesite perhaps from reworking from two distinct sources.

Interpretation of the morphology of glass shards and their uniform chemical compositions as primary pyroclastic deposits implies open-water conditions at the site at the time of volcanic deposition. A thick primary ash (tephra) fall interval from 134 to 146 m depth is a chemically homogeneous basanite and was likely deposited over a short interval of days or weeks during a time when there was open water in McMurdo Sound. Primary and slightly reworked pyroclastic deposits at 427-459 m and more commonly at 577-584 m depth correspond with long intervals of open water conditions inferred from other core properties (Naish et al., in review).

Hut Point Peninsula has a known eruptive history extending from 0.4 to over 1.6 Ma. Its close proximity to the MIS drill site makes it a likely source for many of the volcanic intervals examined in the upper 160 m of drill core. The thick tephra at 134-146 m is dated at ~ 1.67 Ma (Ross et al., 2007) and we suggest it correlates with the early eruptive phase of the polygenetic

Crater Hill eruptive center. Surprisingly there is no record in the MIS drill core of eruptions of the 1.2 Ma phonolitic Observation Hill or other younger subaerially erupted volcanic vents on Hut Point Peninsula. There is a paradox in that subglacial eruptions are absent from Hut Point Peninsula showing ice has not covered the area for extended periods whereas the drill core record shows extensive periods of ice cover in McMurdo Sound. Also difficult to reconcile is the lack of tephra from the many known subaerial Hut Point Peninsula eruptions which implies ice cover which would have hindered or precluded tephra deposition into the adjacent McMurdo Sound. There is limited evidence for volcanic detritus and some pyroclastic material which matches the subaerial eruptive sequence seen in the Dry Valley Drilling Project drill hole 3 which was drilled on Hut Point Peninsula. In the upper 20 m of the AND-1 core a clast and reworked phonolitic glass identical to that found at the Erebus volcanic center was likely transported during the Last Glacial Maximum by ice that travelled around the north tip of Ross Island and moved south into McMurdo Sound. No pyroclastic fall tephra from Erebus volcano has been identified. The eruptive center for “trachytic” pumice found at ~85 m depth and dated at 1.014 Ma (Ross et al., 2007) is unknown but could be from Mount Terror.

Naish, T., et al. Obliquity-paced, Pliocene West Antarctic Ice Sheet oscillations. *Nature* (in review).

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A chronostratigraphic framework for Neogene drill cores from McMurdo Sound, Antarctica and application to paleoclimatic and tectonic studies

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New age and correlation models for Late Neogene drill cores from the McMurdo Sound Region (AND-1B, CIROS-2, DVDP-10 and -11) were developed using constrained optimisation (CONOP), a computer assisted quantitative biostratigraphic technique. These models are used to establish ties between lithostratigraphic units and disconformities in the cores and provide a mechanism to evaluate the regional signature of climatic variability and tectonic events during the Plio-Pleistocene. The models help focus on key events (including warm periods) and episodes of increased basin subsidence. In addition, these high-precision models provide a means to examine glacial-interglacial signatures preserved in isochronous stratigraphic intervals at different locations in the basin, thus allowing the evaluation of regional responses of the East and West Antarctic ice sheets to climatic changes.

Several regional seismic reflectors were mapped throughout the southern portion of the Victoria Land Basin (VLB) and are tied to the McMurdo Sound drill cores. In this report we focus on a major sequence boundary (red reflector) at the base of a prominent interval of clinoform sets. The age of the red reflector is 4.7-4.3 Ma based on a tie to AND-1B, located in the central VLB. Although the surface cannot be tied directly to coastal cores (CIROS-2, and DVDP-10 and 11) our correlation models provide a framework to examine the lithostratigraphic signature of the sediments that likely encase the sequence boundary at these sites. For example, a transition from marine to terrestrial sediments is preserved in DVDP-10. This transition occurred between 4.8-4.3 Ma and indicates that the red reflector is associated with relative sea-level fall resulting from ice-sheet growth and/or local tectonic uplift. Correlative sediments preserved in AND-1B indicate regional climatic warmth, which suggests that the red reflector is more likely related to a tectonic event. Furthermore, the onset of sediment accumulation at CIROS-2 post-dates 4.5 Ma, suggesting that local subsidence and creation of accommodation space began at this time.

In addition to age constraint on regional seismic reflectors, correlation models for the AND-1B and CIROS-2 cores provide an opportunity to examine sedimentation patterns across a coastal-offshore transect. Current models produce results that indicate an 'alternating' pattern of accumulation at each site. Intervals of increased sediment accumulation at the CIROS-2 site are often tied to condensed intervals at AND-1B and vice versa. These accumulation patterns may reflect glacial-interglacial dynamics, tectonic episodes, or combinations of both influences. Ongoing integrated studies will focus on producing models to further examine and explain these observations.

The high-resolution physical properties record of the AND-1B sediment core: Signature archive for both environmental changes and depositional mechanisms

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The physical properties record of the more than 1200-m-long sediment core AND-1B, drilled beneath the McMurdo Ice Shelf near Ross Island (Antarctica) in austral summer 2006/07, represents an excellent parameter set characterized by the highest data resolution so far for this core (spacing of data points: 1-4 cm). This allows for core studies with respect to various research questions, which is not given through other proxies. In this sense, whole-core near-continuous logging of the acoustic velocity (V_p), wet-bulk-density (WBD) and magnetic susceptibility (MS), performed at the drill site laboratory by means of a Multi-Sensor Core Logger (MSCL, GEOTEK), offers the potential not only for qualitative core descriptions supporting general lithological changes as their numerical expression, but also for pursuing in-depth approaches, e.g. with regard to small-scale environmental variations.

Three main sub-projects have been followed so far in terms of analysis of this data set: (1) the development of a WBD-grain density-based algorithm for calculating refined porosities, (2) the lithology-differentiated examination of compaction gradients reflected in down-core porosities as a promising tool for quantifying ice sheet dynamics, and (3) detailed studies of diatomites with respect to small-amplitude variations in WBD and MS, indicating global and/or regional climate and/or environmental changes on sub-orbital timescales.

In sub-project (1), an empirically based mathematical function was derived from the relationship between grain density (GD) values of about 1,200 discrete samples, determined through pycnometer measurements, and MSCL-WBD mean values of the respective sample interval. This approach is based on the fact that both WBD and GD show a general increase of values with depth with similar local deviations from the down-core trend related to dominant lithology. GD values range from 2.15 g/ccm in diatomites to 2.9 g/ccm in volcanic sandstones. Also in WBD, being a function of (i) the degree of compaction seen as reduced porosities with depth from about 55% in the top part to about 25% at the bottom, (ii) the clast content with clasts being almost absent in diatomite deposits and (iii) the individual GD, the minimum of 1.4 g/ccm is found in the diatomites, whereas the maximum in terms of lithological characterization is related to diamictites from the lower part of the core. Based on the GD-WBD algorithm, individual, high-resolution grain densities were calculated for each WBD data point. Resulting fractional porosities differ by up to 15% from porosity data that are calculated in conventional manner using assumed constant grain densities of e.g. 2.7 g/ccm.

The new porosity data set represents the input data for consolidation studies as performed in sub-project (2). Overall, porosities decrease with depth as a result of increasing overburden pressure through successive sediment loading. Removing the general trend, significant deviations in porosity residuals are clearly seen in the upper 600 m as response to lithological variations reflecting major environmental changes (diatomites representing open ocean conditions, diamictites deposited beneath an ice sheet/ice shelf). Nevertheless, in order to examine porosity trends unbiased by lithological changes, a lithology-separated approach is chosen for compaction analysis. For the two end-member lithologies, diatomites and diamictites, this points to different control mechanisms on the actual parameter value. For the latter we find an overconsolidation signature indicating the presence of a grounded ice sheet, which is most pronounced in Pleistocene diamictites from the upper 150 m. In contrast to that, finding porosities in the diatomites of still almost 80% at almost 600 m suggests that lithology-attributed properties cause this abnormal porosity behavior.

In the WBD and MS signature of deposits of warm intervals there is, however, environmental/climate information preserved which is the focus of sub-project (3). Synchronous small-amplitude variations in both parameters superimposed on Milankovich cycles and generally related to relative changes in sediment composition (dominance of terrigenous vs. biogenic input), support the occurrence of subtle changes in the depositional system, driven by a yet unidentified forcing. According to the age model, these oscillations are in the order of 200-2000 yrs/cycle.

Further analysis is planned e.g. on Vp-porosity relationships to identify clusters of certain sediment properties such as cemented intervals. Integrating results from the different sub-projects will finally allow for a comprehensive reconstruction of past environmental changes in response to global climate changes.

Pleistocene fluctuations of the Antarctic Ice Sheet in the Ross Embayment

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Past fluctuations of the marine-based Antarctic Ice Sheet in the Ross Embayment are reconstructed for the Pleistocene by developing a model for the glacimarine depositional sequences documented from the ANDRILL McMurdo Ice Shelf project drill core AND-1B. This model reveals glacial to interglacial fluctuations of the AIS in the Western Ross Embayment responding at orbital frequencies. Chronology is constrained by an age model based on $^{40}\text{Ar}/^{39}\text{Ar}$ dating of volcanic ashes and magnetostratigraphy. The glacimarine sequences in AND-1B appear to correlate one-to-one with cycles in the benthic $\delta^{18}\text{O}$ record for the past ~ 0.8 Myr (Marine Isotope Stages 20-2). Five sequences between ~ 1.7 and 1.0 Myr can also be matched with specific intervals in the $\delta^{18}\text{O}$ record, and indicate oscillations of the AIS grounding line operating at a 40-kyr frequency. This record provides new insight into the response of the AIS in the Ross Embayment across the Mid-Pleistocene Transition. Prior to 1.0 Myr, glacimarine sequences have 40-kyr duration, whereas subsequently 100-kyr glacimarine cycles can be clearly recognised in the core. During this “100-kyr world”, subglacial to grounding-zone sedimentation dominates at the AND-1B site, with thin intervals of ice-shelf deposition during interglacials also preserved in the AND-1B sedimentary record. An unconformity in AND-1B that spans most (~ 200 kyr) of the Mid-Pleistocene Transition is inferred to represent large scale expansion of AIS in the Ross Embayment at ~ 0.8 Myr. Prior to the Mid-Pleistocene Transition, interglacial periods are characterised by open-water conditions with high abundances of volcanoclastic deposits and occasional diatomaceous sediments, indicating that the marine based ice sheet was more dynamic during this interval.

Syntectonic fluid flux during rift deformation: Record from the MIS core, Victoria Land Basin, Antarctica

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The McMurdo Ice Shelf project recovered *c.* 1285 m of Neogene sedimentary core from the Victoria Land rift basin in Antarctica. The core contains approximately 1475 structures macroscopically logged as faults, veins, and clastic dikes. Veins, mainly calcite, constitute at least 625 of this population and include at least 12 vein types, many of them showing multiple generations of calcite fill. Microstructural analysis of core structures is focused on the role of fluids in deformation, as well as the structural control on fluid pathways during lithification, compaction and diagenesis in this unique glaciated rift basin setting.

Initial results show that calcite veins from 1-15 mm thick are associated with discrete faults; many have dip-slip slickenfibers and calcite fills voids along pull-aparts, indicating veins formed during fault displacement. Intricately branching webs of hairline veins form planar arrays around thicker veins with typical conjugate geometries suggesting that these vein complexes represent fault zones. The diffuse, pervasive nature of the veining suggests that tensile strength of the rocks was low and fluid pressures were high. Opening-mode veins are common, are filled by calcite fibers and sparry calcite that grew normal to vein walls, and show multiple episodes of opening and fill. Tightly folded, vertical veins of calcite fibers perpendicular to the vein walls are ubiquitous in the core and indicate the host sediment was cohesive enough to support fracture, but was not fully lithified, and accommodated vein buckling during compaction. Vertical fibrous calcite veins occur as pressure shadows on the margins of pebbles, documenting formation during vertical loading and compaction. Multiple generations of vein material track kinematic changes as indicated by fault-parallel slickenfibers overprinted by opening-mode calcite fibers. Calcite vein generations as well as vein cross-cutting relations document the relative chronology of deformation and fluid flux.

The abundant and pervasive nature of calcite veins in the MIS core reveals a spatial and temporal continuum in the history of deformation in the Victoria Land rift basin, and implies abundant fluids and high pore fluid pressures were clearly important throughout the progressive deformation history of the basin, with rift-related structures exerting a fundamental control on dewatering of the rift basin strata.

Heat flow from the AND-1B borehole, ANDRILL McMurdo Ice Shelf Project, Antarctica

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During the austral summer of 2006-2007, the Antarctic Drilling Program (ANDRILL) successfully drilled a borehole, AND-1B, beneath the McMurdo Ice Shelf to a total depth of 1285 meters below the seafloor (mbsf), with 98 percent sediment core recovery for detailed study of climate and ice-sheet history. Several complementary geophysical logs were also collected in this borehole to a depth of approximately 1000 mbsf for a variety of scientific analyses. Among these downhole measurements were three temperature logs recorded over a span of five days after a 60-day period of drilling and circulation had ceased. These temperature profiles generally display a gradual and systematic return to equilibrium geothermal conditions, interspersed with several marked anomalies indicating fluid exchange between the borehole and the surrounding formation, and locating distinct zones where mud circulation was lost during drilling activities. A logarithmic decay method (Horner plot) was used to extrapolate the three temperature records to infinite recovery time in order to arrive at an estimate of the undisturbed temperature gradient from the seafloor down to 640 mbsf. Below this depth, the temperature logs are too disrupted by the effects of drilling and mud circulation to offer reliable estimates of equilibrium temperature. The average temperature gradient across this upper 640-m section of the borehole is determined to be 76.7 K/km. Representative values of thermal conductivity are computed from mixing models using core descriptions and direct measurements of density/porosity obtained on core. Relatively high porosities in the range of 50 percent are reflected in relatively low thermal conductivities averaging 1.5 W/mK. These estimates yield a corresponding heat flow value of 115 mW/m² for this site. This value of heat flow is comparatively high for the region and may be due to the borehole's proximity to several volcanic centers of the Erebus Volcanic Province and its associated crustal thermal anomaly.

Obliquity-paced Pliocene West Antarctic Ice Sheet oscillations

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Thirty years after the first deep-sea oxygen isotope records confirmed Milankovitch's orbital hypothesis of the ice ages, fundamental questions remain over the response of Antarctica's ice sheets to cycles in Earth's orbital geometry. Furthermore, an understanding of the behaviour of the marine-based, West Antarctic Ice Sheet (WAIS) during "warmer-than-present" Early Pliocene Epoch (~5-3 million years ago) is needed in the context of future global warming. Here we present a marine glacial record from the upper 600 m of a sediment core (AND-1B) recovered from beneath the northwest part of the Ross Ice Shelf by the ANDRILL Program. Well-dated, cyclic variations in the core link ice sheet extent to cycles in insolation controlled by the ~40,000 year period of Earth's axial tilt (obliquity) during the Pliocene. Our data provide the first direct evidence for orbitally-induced oscillations in the WAIS, which periodically collapsed resulting in a switch from grounded ice, or ice shelves, to open waters in the Ross Embayment when planetary temperatures were up to ~3°C warmer than today and atmospheric $p\text{CO}_2$ as high as ~400 ppm. The evidence is consistent with a new ice sheet-ice shelf model that simulates fluctuations in Antarctic ice volume of up to +8 m equivalent sea level, in response to ocean-induced melting paced by obliquity. During interglacial times, diatomaceous sediments indicate high surface water productivity, minimal summer sea ice and air temperatures above freezing, suggesting an additional influence of surface melt under conditions of elevated CO_2 .

Natural fractures of the AND-1B core, McMurdo Ice Shelf Project, Antarctica

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We have examined the McMurdo Ice Shelf (MIS) AND-1B core for natural fractures (e.g., faults and veins) in order to establish the deformation history of the strata cored at the MIS drill site. We logged over 4300 fractures of all types in the AND-1B core. Of these 4300 fractures, we identified 1475 natural fractures (i.e., pre-existing fractures in the rock that were intersected by coring) based on their geometry and characteristics, such as truncation/offset of bedding, mineralization or brecciation. The density of these fractures reached up to c. 6 fractures/meter, and averaged ~1.1 fractures/meter over the entire AND-1B core. Kinematic indicators document dominant normal faulting, although reverse faults are also present. Vein types include slickenfiber veins along faults, opening-mode fibrous veins, pressure shadows on clast margins, and complex microvein webs within fault zones.

Natural fractures are present in the highest core that we were able to log (i.e., not retrieved in plastic liners), with conjugate faults occurring at 42.35 mbsf. There is a zone of high fracture density between c. 125-300 mbsf, within an interval currently estimated to range in age between approximately 1 and 3 Ma. Natural fractures are consistently present through the core below c. 450 mbsf, the estimated depth of the 'B-clino' seismic reflector. This is consistent with the presence of seismically-detectable faults below this horizon. The presence of sedimentary intrusions and the abundance of veining documents high fluid pressures during deformation. The sedimentary intrusions and steep veins folded by compaction indicate that deformation occurred prior to complete lithification of the strata, suggesting deformation was approximately coeval with deposition. The large population of natural fractures, occurring in core strata from Miocene to Pleistocene in age, indicates that deformation has affected this sector of the basin throughout deposition of the strata.

Efforts are currently under way to reorientate the core and core-based measurements using the red scribe line 'in situ' orientation derived from BHTV analysis and drilling-induced fracture orientation analysis. After the core fractures have been reorientated, comparison of their trends with seismically-mapped faults will help determine if the deformation is related to evolution of the Terror Rift, which seems likely given the dominance of normal faults in the core. This analysis, together with detailed correlation of the depth distribution of deformed intervals of the core with respect to episodes of glacial advance and retreat documented from the core strata, will help discriminate glaciotectonic and tectonic deformation.

Modeling West Antarctic Ice Sheet growth and retreat through the last 5 million years

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The West Antarctic Ice Sheet, grounded mostly below sea level and fringed by floating ice shelves, is considered to be vulnerable to future anthropogenic warming. However, projections of its future behavior are hampered by limited understanding of past variations and the main forcing mechanisms. Here a combined ice sheet-shelf model with imposed grounding-line fluxes following Schoof (2007) is used to simulate Antarctic variations over the last 5 million years. We argue that oceanic melting below ice shelves is an important long-term forcing, controlled mainly by far-field influences that can be correlated with deep-sea-core $\delta^{18}\text{O}$ records. Model West Antarctic configurations range between full glacial extents with grounding lines near the continental shelf break, intermediate states similar to modern, and brief collapses to isolated ice caps on small West Antarctic islands. Transitions between these states can be relatively rapid, taking one to several thousand years. Several aspects of our simulation agree with a sediment record recently recovered beneath the Ross Ice Shelf by ANDRILL (MIS AND-1B core), including a long-term trend from more frequently collapsed to more glaciated states, and brief but dramatic collapses at Marine Isotope Stage 31 (~1 Ma) and other super-interglacials. Higher-resolution nested simulations over the Ross Embayment resolve Siple Coast ice streams, Transantarctic outlet glaciers, and details of shelf flow. Correlations between modeled local conditions near the AND-1B core site and the overall West Antarctic state are examined, along with implications for the AND-1B lithologic record.

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Alteration history in volcanoclastic deposits of AND-1B core: Inferences on sin- and post-depositional processes

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Volcanoclastic rocks in the core below 591.85 mbsf show a progressive and pervasive alteration leading to a complete textural, mineralogical and chemical transformation. Detailed textural and compositional analyses indicate close relationships between depth of burial, style of alteration of volcanic sediments, original texture of the deposits and composition of intergranular material.

EPM analysis was performed on glass shards, pumices, and scoriaceous fragments. This analysis reveals, via application of the “alteration box plot” proposed by Large et al. (2001), that hydrothermal and/or diagenetic alteration has occurred.

Hydrothermal alteration is more effective for small sized clasts that are easily replaced by palagonite even where traces of unaltered glass are present in the coarser fraction. Palagonitization of glass is widely accompanied by glass hydration (grain fracturing), precipitation of carbonate, chlorite and clay minerals rinds in cavities and vesicles. Hydrothermal alteration is also evidenced by a progressive transformation of volcanic glass into palagonite and/or smectite with consistent leaching of SiO_2 , Al_2O_3 , K_2O , Na_2O , CaO and increase of MgO and FeO together with water content, while TiO_2 remains almost stable.

Diagenetic alteration, consists of a progressive transformation of hydrothermally altered clasts, mineral phases, and eventual clay matrix into zeolite (analcime). The replacement is gradual and increases with the depth of burial. Alteration first involves clay matrix (and smallest volcanic fragments dispersed in the matrix) and then proceeds with the formation of analcime pseudomorphs on glass shards. Diagenetically altered samples mainly belong to reworked and laminated sands of the sequence between 759.30 and 714.80 mbsf. However diagenetic alteration is not limited to the deepest part of the core but is also distributed in patches through intervals dominated by hydrothermal alteration as a result of special and local thermal conditions.

The current data set allows us to discriminate and evaluate effects of sin- (e.g. eruption styles, environment, climate) and post- depositional processes (e.g. burial, diagenesis, hydrothermal fluids, tectonics).

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Terrestrial palynomorphs from AND-1B

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During drilling, a total of 242 samples for palynological analysis were collected from AND-1 push core SS011, AND-1A, and in AND-1B at c. 5-6 m intervals below 24.88 mbsf. For a general reconnaissance of the core, 65 samples at c. 20 m intervals through the whole section were initially prepared from this set; later, the complete set of samples down to 580 m has been prepared. Most samples have yielded marine and terrestrial palynomorphs, but often the concentration is very low, of the order of a few specimens per gram of rock.

Analysis of samples is still underway. Observations so far include:

- Permian/Triassic spores and pollen are found throughout the core, obviously recycled from Beacon Supergroup. There is a great range in degree of thermal alteration of this material, indicating provenance from a wide area, including possibly from beyond the Trans-Antarctic Mountains (because thermal alteration in the TMA is usually high). This Beacon material is found both in diatomites and diamictites, indicating transport in suspended load particles as well as in ice-rafted clasts.
- A few specimens suggest a possible Late Cretaceous, ?Campanian source: *Peninsulapollis* spp. and cf. *Forcipites sabulosus*. Some podocarp pollen could also be of Mesozoic age, but discrimination is difficult because most taxa are very long-ranging.
- Cenozoic and possible Cenozoic miospores are also found throughout, but are less abundant. Like the Beacon material, a range in degree of thermal alteration is evident, judged from both transmitted light and autofluorescence colours. The most abundant taxa are species of *Nothofagidites* and saccate podocarp pollen. Species characteristic of the latest Oligocene to Middle Miocene in the CIROS-1, Cape Roberts, and AND-2A cores, such as "*Tricolpites* sp.A" and *Belgisporis* sp. have so far not been observed.

The relatively low numbers of Cenozoic pollen, the absence of a clear correspondence of Cenozoic pollen abundance with diatomite facies, the range in degree of thermal alteration, and the lack of known Neogene-restricted taxa suggests that much of it is redeposited from Paleogene strata.

Radiation of a late-Pliocene *Fragilariopsis* fauna on the Antarctic continental shelf

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The marine sediment core collected by the ANDRILL Program from beneath the McMurdo Ice Shelf (MIS; AND-1B) represents the longest, most complete record to date of late Neogene climatic evolution proximal to the Antarctic continent. Multiple extensive, well-preserved diatomaceous intervals distributed throughout the upper six hundred meters of the core provide a unique perspective on the transition from the mid-Pliocene climatic optimum into modern cold-polar conditions. Here we focus on the late Pliocene diatom units (DU) IX-IV, between 292 and 150 mbsf, which record the radiation of a remarkably diverse complex of *Fragilariopsis* morphologies that are previously undescribed from Antarctic sediments (Scherer et al., 2007).

The AND-1B *Fragilariopsis* complex dominates the diatom assemblage in the lower late Pliocene units, comprising up to 45% of the community at the base of the lowermost DU IX (~3.3 Ma). Consequently, ongoing assemblage-based biostratigraphic refinement and paleoenvironmental interpretations have required that this complex be resolved into a species framework. Although the *Fragilariopsis* complex is complicated by the presence of rare and gradational forms, three morphologies are adequately abundant and distinctive to be described as new species. These new species, *F. bohatyi*, *F. robusta*, and *F. laqueus*, have affinities to the Miocene and Pliocene *Fragilariopsis* flora described by Gersonde (1991) from Maud Rise in the Weddell Sea and to the extant species *F. ritscheri*, and *F. obliquecostata*, allowing us to identify likely evolutionary lineages.

Fragilariopsis bohatyi is very abundant from DU IX-VI and persists in lower abundances through DU IV. Larger and more coarsely structured than the open-ocean species from which it likely evolved, *F. bohatyi* alone accounts for nearly 40% of the entire diatom assemblage in samples immediately above its first occurrence (FO) in AND-1B. In counts from which *Chaetoceros* spores are excluded, *F. bohatyi* makes up more than 40% of the assemblage throughout most of DU IX and up to 62% of the assemblage in the sample of first occurrence. This remarkably rapid radiation suggests that the AND-1B *Fragilariopsis* species complex evolved in response to the development of newly ideal environmental conditions for growth, likely associated with the initiation of Pliocene cooling. Because of its initial abundance, persistence through the late Pliocene, and distinct morphology, *F. bohatyi* is used to designate a late Pliocene biostratigraphic zone in the new Antarctic continental shelf and near-shore zonal scheme proposed by Winter et al. (in review) for AND-1B. This species is named in honor of S. Bohaty.

Fragilariopsis robusta and *Fragilariopsis laqueus* are also present throughout the late Pliocene of AND-1B, although their abundance patterns differ significantly. *F. robusta*, whose name reflects an overall coarseness of silicification, is extremely rare (<0.5%) in the lower portion of the record and increases in abundance up-core, replacing *F. bohatyi* as the dominant member of the complex in DU V and IV (~2.0 Ma). This species is likely ancestral to the extant cold-

water-dwelling *F. obliquecostata*; given the paucity of extant species in the AND-1B late Pliocene diatom assemblage, this evolutionary relationship may represent a unique opportunity for paleoenvironmental interpretation. By contrast, peak abundance of *F. laqueus* never exceeds 1% of the assemblage. This species, whose fine valve structure and extensively branched costae inspire a name derived from the Latin for “lace”, is distinct from *F. bohatyi* in the older portion of the record, although the two species become increasingly difficult to distinguish as *F. bohatyi* gradually becomes shorter and more inflated up-core. Ultimately, the quality of the AND-1B record and the richness and persistence of the *Fragilariopsis* complex should provide a valuable correlation tool for late Pliocene records recovered from around the continent.

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$^{40}\text{Ar}/^{39}\text{Ar}$ chronology of volcanic events in the AND-1B drill core – Implications for age models and glacial history of the Ross Embayment

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$^{40}\text{Ar}/^{39}\text{Ar}$ dating of a suite of volcanic clasts and tephra, collected throughout the AND-1B drill core, significantly aids the development of an age-depth model. High precision dates determined for a variety of volcanic materials provide pinning points for constraining the chronostratigraphy of the drill core. The volcanic samples we have dated include 1) felsic and basaltic tephra, 2) interior of a ~3-m-thick intermediate lava flow and 3) felsic and basaltic volcanic clasts. Two felsic tephra, two basaltic tephra and the intermediate lava flow yield precise and accurate depositional ages, whereas the volcanic clasts provide maximum depositional ages. The ages for the seven stratigraphic intervals dated are 1) 17.17-17.18 mbsf, basaltic clast (maximum depositional age 0.310 ± 0.039 Ma, all errors quoted at 2σ), 2) 52.80-52.82 mbsf, three basaltic clasts (maximum depositional age 0.726 ± 0.052 Ma), 3) 85.27-85.87 mbsf felsic tephra (1.014 ± 0.004 Ma), 4) ~112-145 mbsf sequence of basaltic tephra (1.633 ± 0.057 to 1.67 ± 0.05 Ma), 5) 480.97-481.96 mbsf pumice-rich mudstone (4.800 ± 0.076 Ma), 6) 646.30-649.34 mbsf intermediate lava flow (6.48 ± 0.13 Ma), and 7) ~1280 mbsf, three volcanic clasts (maximum depositional age 13.57 ± 0.13 Ma).

Incremental heating analyses of glass from the basaltic tephra display a reproducible saddle-shaped spectrum with discordant apparent ages. Two out of twenty-one basaltic glass analyses yield a statistically defined plateau in the saddle region of the spectrum and a precise inverse isochron age. The other 19 analyses yield discordant apparent ages for all steps and statistically unconstrained isochron ages. Recoil effects, excess ^{40}Ar , and xenocrystic contamination are possible explanations for the observed discordance. Understanding of the $^{40}\text{Ar}/^{39}\text{Ar}$ age-spectra from basaltic glass analyses, is important because 1) glass shards represent a abundant volcanic phase preserved in the drill core and 2) they have the potential ($\text{K}_2\text{O} = \sim 1\text{-}3\%$) to yield precise and accurate ages for the upper ~650 m of the drill core.

Volcanic clasts provide the best means of constraining the age of the drill core at depths >650 mbsf. Electron microprobe characterization of numerous volcanic intervals below ~650 mbsf indicates high degrees of alteration in the felsic and basaltic tephra, whereas the volcanic clasts show little to no alteration. The paucity of fresh tephra at depths greater than ~650 mbsf requires age constraints for the lower ~650 m of drill core to rely on dating populations of volcanic clasts. Although volcanic clasts do not provide accurate time-stratigraphic pinning points they do yield accurate maximum depositional ages and are important for provenance studies.

Pleistocene WAIS and RIS history from diatoms of AND-1B and associated records

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One of the primary goals of the ANDRILL-MIS project was to determine the Pleistocene history of the West Antarctic Ice Sheet. Specifically discussed in the proposal and in the drilling prospectus was whether the WAIS “collapsed” during late Pleistocene “superinterglacials” MIS-5e (120 ka ago) and MIS-11 (400 ka ago).

Interglacials that culminated in Ross Ice Shelf retreat should be characterized by marine diatom deposition in the Ross Embayment. Previously, Pleistocene age diatoms have been recognized in glacial sediments recovered from beneath the grounded portion of the WAIS (Scherer et al., 1998). These diatoms were interpreted as reflecting open marine deposition following WAIS collapse, with an inferred age of MIS-11, based on distal records of climate. AND-1B may provide a new perspective on this interpretation.

Drilling at Cape Roberts revealed a warmer than present interval identified as MIS-31 (1.07 Ma ago) and the AND-1B record strongly corroborated those findings. MIS-31 in the AND-1B record (Diatom Unit II) indicates an interval of open marine conditions with high primary productivity and very limited sea-ice. MIS-31 was characterized by very high insolation early in the interglacial, at 1.08 Ma. CRP-1 and ODP Site 1090 contain evidence of extreme warmth with WAIS retreat in phase with precession-amplified insolation (Scherer et al., 2008). The interval of highest southern insolation coincides with growth of Mt. Erebus and, specifically, the eruptive phase of Hut Point Peninsula, resulting in disturbance and dilution of the stratigraphic record of AND-1B. The MIS-31 record of pelagic deposition preserved in AND-1B represents the latter half of the interglacial, with lower insolation, and includes local-sourced IRD.

The Late Pleistocene record of AND-1B is the most controversial and poorly dated interval in the upper 600m of the AND-1B core. There is an absence of hard dates from between the Brunhes-Matuyama boundary to the top of continuous coring at ca. 29 mbsf. Only thin, unfossiliferous mudstone units separate thick diamictites, most interpreted as basal till. Questions will be explored related to whether these reflect an absence of late Pleistocene retreat of the RIS during interglacials MIS-11 through MIS-5e or an incomplete stratigraphic record.

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A diatom record of a stepwise late Pliocene (2.9-2.0 Ma) cooling from the AND-1B record

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The AND-1B core from beneath the McMurdo Sound Ice Shelf recovered a late Pliocene interglacial diatom record of an extent that has not been recovered before, allowing insight into a largely unknown climatic interval. The late Pliocene (2.9-2.0 Ma) is contained in four diatomaceous intervals, DU-VII to DU-IV. Diatom assemblages comprise a large proportion (average 65%) of extinct species which limits the utility of the modern diatom assemblage data as an analogue. To evaluate the paleoenvironmental record the late Pliocene diatom assemblages were compared to 1) the modern diatom habitats (sea-ice, cold open ocean, and sub-Antarctic) and 2) to a compilation of diatom species and abundance data across the oceanic fronts through mid Pliocene to Present based on ODP records.

Each of the diatomaceous intervals has different diatom assemblages that are associated with environmental and climate change based on reduction in number of warm water associated species and their abundances towards the younger units, and a successive introduction of an extinct assemblage associated with the paleo-Polar Front and more southerly water masses. The modern open ocean assemblage is constant through the record with only ca 7% present, and does not provide any significant environmental information. The modern sea ice assemblage is only represented by 10-15% total; *F. curta*, the dominant sea ice species in the Southern Ocean, is only represented by 3-6%. This low abundance indicates that the modern sea ice dominated environment was not established by 2.0 Ma, winter sea ice was present but summer sea ice was sparse.

DU-VII (2.9 Ma, isotope stage G17) is interpreted as a relatively warm period. The sub-Antarctic assemblage is represented by only two modern species, *Shionodiscus tetraoestrupii* (30%) and *Stellarima stellaris* (2%). Such an abbreviated assemblage suggests that true sub-Antarctic conditions never reached the continental shelf during this time. Extinct species present that are predominantly found in sediment north of the Polar Front support higher than present SST, as does the low abundance of the sea ice assemblage and the random occurrence of *F. curta*. This assemblage is closely related to the one recorded in the mid-Pliocene. In the transition to DU-VI (2.62-2.58 Ma, isotope stage G1) abundant extinct species associated with the paleo-Polar Front, *A. karstenii*, *R. antarctica* and *T. vulnifica*, suggest somewhat colder conditions and possibly a freshening of the water column, also supported by the presence of *Chrysophyte* cysts. The warm water assemblage from DU-VII remains but in reduced abundance indicating continued warmer than present conditions. The warm water assemblage is drastically reduced in DU-V (<2.58 Ma) and replaced by an assemblage dominated by extinct species *R. antarctica* and *F. robusta* proposed to be related to pack ice. The continued low abundance of sea-ice species indicates that the present ice-shelf and sea-ice conditions are not yet established. The sea-ice assemblage increase slightly in DU-IV (>1.9 Ma), a cooling trend within this unit is inferred by the appearance of modern sea-ice species *Actinocyclus actinocylus* and *F. obliquecostata* at the top. New to the assemblage is *S. tetraoestrupii* var. *remerii*, an extinct species that is most commonly documented in sediment cores north of the Polar Front which gives an indication of still warmer-than-present SST. The DU-IV assemblage, is also identified at DSDP site 274 off the Adelie Land coast, in the Northern

Basin, Ross Sea and at ODP Site 742 in Prydz Bay, East Antarctica indicating a continental wide event at ca. 2 Ma.

The mid Pliocene, ca. 3 Ma, is well recognized as the last period of global warmth with elevated sea level and SST and often referred to as model for future warming. The extent of this warmth on the Antarctic continental shelf was largely unknown prior to AND-1B. We have compared the diatom records of the warm mid-Pliocene with near continuous deposition through several glacial cycles to the punctuated but still warmer than present late Pliocene record. This illustrates the range and pace of climate change in the coastal Antarctica, which based on diatom evidence also from sites on the East Antarctic coast, experienced a dynamic glacial margin. We also compare the diatom derived data with recent models of Antarctic sea-ice and glacial dynamics.

Foraminiferal fauna from MIS-1: Progress report

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Off-ice studies of the MIS-1 foraminiferal fauna have focused upon three objectives: 1) processing and examining unstudied samples collected during drilling; 2) providing specimens for geochemical studies (Ca-Mg paleotemperature and Sr dating); and 3) faunal taxonomic study.

The entire well section, from 1.82 to 1283.52 mbsf, has been studied at a characterisation level, and a total of 192 samples have been examined to date. All on-ice samples down to 700 mbsf, about 100 m below the onset of pronounced diagenesis, have now been processed and the foraminifers extracted for detailed study. The typical sample interval through the upper well section is about 5 m. Foraminifers, most often represented by only a few specimens, occur in 94 of the 167 samples in this suite. Below 700 m, foraminifers occur in low numbers in 15 of the 24 samples examined at a typical interval of about 25 m. There are 55 additional, unprocessed, samples from the lower section of MIS-1, but at present their study is on hold for practical considerations.

Foraminiferal calcite is often used for geochemical analyses, and all samples were processed using deionised water, then air-dried at room temperature for possible geochemical work. Suites of 5-50 *Neogloboquadrina pachyderma* individuals, recovered from 20 levels between 27 to 370 mbsf, have been provided for Ca-Mg paleotemperature studies, using laser ablation, at Victoria University, Wellington. An early attempt to use foraminiferal calcite for Sr dating gave encouraging results in the upper section of MIS-1, but was abandoned because of difficulty obtaining enough specimens for adequate samples below c. 600 mbsf. Easily dated volcanogenic minerals were also recovered, post-drilling, from deeper levels in MIS-1, alleviating the need for Sr dating.

Taxonomic study includes review and revision, as required, of the species identifications and working names used on-ice, and also identification of species recovered from newly processed samples. At present, the known fauna comprises 67 species, including 13 agglutinated, 4 planktic, and 50 calcareous benthic foraminiferal taxa.

Preliminary results and observations include:

- Calcareous faunas are the dominant type, with planktics, mainly *Neogloboquadrina pachyderma*, present in c. 40% of all assemblages. This suggests mainly open water environments, often with good connection to oceanic circulation.
- Agglutinated foraminifers typically are absent to sparse, but prolific, monospecific, *Bathysiphon* assemblages occur in volcanic sands and silts at c. 140 mbsf.
- Diatomites and foraminifers are almost mutually exclusive, however, rare, but very well preserved, foraminifers were sometimes recovered, suggesting that the general absence of foraminifers is due to the unfavourable environment, rather than to post-depositional solution.
- Sandy mudstones and sandy biosiliceous mudstones tend to produce the most abundant assemblages, typically with good preservation.

Provenance signatures of the Antarctic ice sheets in the Ross Embayment during the Late Cenozoic: The ANDRILL core AND-1B record

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Petrological investigations of the sand fraction and of granule- to cobble-sized clasts in the Miocene-Pleistocene sedimentary cycles of the AND-1B drill core at the NW edge of the Ross Ice Shelf (McMurdo Sound) highlight significant downcore modal and compositional variations. These variations provide: (i) direct information about potential source regions during both glacial maxima and minima; and (ii) evidence of an evolving provenance, documented by long-term and short-term shifts in compositional patterns.

The provenance of glacially transported material (as both subglacial till and ice rafted debris) is identified in the region between Ross Island and the Skelton-Mulock glaciers area (South Victoria Land) (Pleistocene and Plio-Miocene section) and in the Darwin Glacier catchment (Miocene section). Provenance changes can be discussed for their implications on ice dynamic models, with results that are consistent with glaciological reconstructions for the Last Glacial Maximum and numerical ice sheet models.

The identified compositional changes reflect variations in ice volume and ice sheet thermal regimes, acting in concert with paleogeographic changes related to the local volcanic activity during the glacial evolution recorded over the past ~ 13 my in the western Ross Embayment.

Mineral and chemical composition of volcanic clasts from the Cenozoic McMurdo Group in the AND-1B (MIS) core below 680 m

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At the workshop in Tallahassee we took the responsibility as off-site scientists for the petrography and geochemistry of volcanic clasts in the MIS core below 680 m. We asked for about 160 samples that we selected from the archive half using the Corelyzer images. However, sampling the working half resulted in about $\frac{1}{4}$ of samples containing no volcanic clast, $\frac{1}{4}$ containing just minor relicts of clasts too small for thin section preparation and chemical analyses as well. It seems as if the clasts selected often were not large enough to extend far enough into the working half.

We studied thin sections of 68 samples, about $\frac{1}{2}$ of which were identified to be clasts of fine grained meta-sediments, meta-plutonics, and Jurassic dolerite. From the other half of the thin sections $\frac{2}{3}$ represented McMurdo volcanic lithics and $\frac{1}{3}$ samples from volcanoclastic sediments from intervalls above 760 m and below 1220 m. The volcanic samples represent two distinct differentiation lineages: (1) dense aphyric to plagioclase phyric mildly alkaline rocks of the alkali-basalt – trachybasalt - trachyte lineage and (2) olivine – clinopyroxene-phyric lava fragments of the more alkaline basanite-tephrite-phonolite lava lineage. While the former is most abundant below 1100 m the latter is restricted to depths above 1014 m.

Plagioclase in the alkali-/trachybasalts is generally little too unaltered and exhibits primary An-contents of An₄₀₋₇₅. The olivine phenocrysts are usually completely replaced, while unaltered xenocrystic fragments from ultramafic xenoliths occur at about 900 m depth. The clinopyroxenes are characterized as augites with variable Ti-component. Oxides are rare as phenocrysts but are abundant as minerals in the matrix dominated by fresh plagioclase laths. Kaersutite is rare and occurs as phenocryst together with Ti-augite in a clast at 932 m in the core, while neither Arfvedsonite nor Acmite were identified. The secondary mineral assemblage clearly dominated by calcite being associated by smectite and leucoxene as well as less often smectite-chlorite mixed minerals or rarely chlorite.

Calcareous nannofossil evidence for Marine Isotope Stage 31 (1 Ma) in the AND-1B core, ANDRILL McMurdo Ice Shelf Project, Antarctica

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Preliminary on-ice analysis of the smear slides of the MIS AND-1B drill core showed calcareous microfossils (dinoflagellates, calciosponge spicula and small foraminifera) occurring with variable concentrations. Subsequent shore-based analyses of 100 samples from 86-96 mbsf revealed for the first time the presence of Pleistocene coccolithophorids at these high southern latitudes (77°S), including: *Coccolithus pelagicus*, small *Gephyrocapsa*, *Reticulofenestra asanoi*, *Pseudoemiliania lacunosa*, *Dictyococites productus*, *Reticulofenestra* sp., *Reticulofenestra minutula*, *Thoracosphaera* spp. The presence of several Tertiary reworked species and rare Cretaceous reworked taxa are interpreted in terms of provenance. As the lower temperature limit for living calcareous nannoplankton is about 2.5°C, the presence of nannofossils from 86 to 96 mbsf, though rare, is an indication of ice-free and sea surface temperatures warmer than today, in the Ross Sea. An ⁴⁰Ar/³⁹Ar age of 1.014 ± 0.004 Ma on pumice at 85.50 mbsf confirms the age assignment given by diatom biostratigraphy (1.07 Ma) for this interval. Accordingly, the short normal magnetozone between 84.97 and 91.13 mbsf is correlated with the Jaramillo Subchron (C1r.1n) (Wilson et al., 2007).

The presence of nannofossil in the biogenic interglacial sediments is consistent with warm episode of surface waters and open marine conditions during the Jaramillo subchron, at ~1 Ma, which corresponds with superinterglacial Marine isotope stage (MIS) 31 (Naish et al., 2007). Climate proxies from other studies from the Southern Ocean at ODP Site 1165 (Villa et al., 2008), at ODP Site 1094 (Scherer et al., 2008), and from the Antarctic margin, in a shelly carbonate sequence at Cape Roberts 1 (Villa and Wise, 1998; Scherer et al., 2008), also support the idea of a warming event during this time, suggesting that it was extended around the Antarctic Continent. This in turn implies a total or partial collapse of McMurdo Ice Shelf and a concurrent shift or temporary dissipation of the Polar Front (Antarctic Convergence) and Antarctic Divergence that currently serve as barriers to the influx of calcareous nannofossils to the margins of Antarctica. The warm interval during the Jaramillo Subchron shows that these areas were more climatically dynamic than previously thought and brings into questions the notion that the EAIS has remained in a stable polar condition since the late Neogene. The warm surface water event reported here is especially significant given its proximal position to the Antarctic ice sheet.

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Isotopic composition of autogenic carbonate - Records of glacial-interglacial interaction in the McMurdo Sound

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Carbonates are long known to contain paleo-climatic and paleo-environmental records. A very specific form of autogenic carbonates form beneath glaciers, bearing the very extreme and distinct isotopic signature of glacial meltwater. Mixing of even small amounts of very light subglacial carbonate with marine carbonate influences the isotopic composition of carbonates in bulk sediment. Measurements of isotopic composition of bulk sediment in a previously or currently glaciated setting therefore provide useful information about glacial-interglacial processes and the waxing and waning of ice sheets, in this case the West Antarctic Ice Sheet across the McMurdo Sound.

The isotopic composition of carbonate in bulk sediment from the AND-1B core is currently analyzed. Initial results indicate a relationship between high TIC and carbon and oxygen isotope anomalies. The heaviest measured $\delta^{18}\text{O}$ (+3.33 ‰ PDB), indicating a marine influence, was found in a glacial diamictite while the lightest $\delta^{18}\text{O}$ (- 19.49 ‰ PDB) was found in a diatomite. While on first sight this is contradictory at a closer look this inverse relationship provides valuable insight into glacial processes across the ice sheet grounding zone. The diatomite for example was fractured indicating the infiltration of glacial meltwater during a glacial period into the open marine deposit. The heavy diamictite sequences likely represents a sequence of glacial sediment which was deposited in front of the glacier by melting of a sediment laden basal ice layer, trapping marine sub ice shelf cavity water in this processes. Further detailed work at higher resolution (1 m sample intervals) is currently under way to further elucidate glacial-interglacial processes and ice-ocean interaction across ice sheet grounding zones.

Overview on isotopic and elemental composition of porewater derived from the ANDRILL MIS main core AND-001 B

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The isotopic and elemental composition of interstitial water in sediment contains information on diagenetic processes. During the 2006/07 Antarctic field season a 1285 m deep drill core (AND-1B) was recovered from the sea floor of the McMurdo Sound. Using a titanium pore water squeezer (based on Ocean Drilling Program design) it was possible to extract 28 pore water samples down to a depth of 1076 m. Major cation and anion concentrations were measured on-ice and sub samples for off-ice isotopic composition of dissolved inorganic carbon, sulfate and $\delta^{18}\text{O}$ and δD on the porewater itself were prepared.

Most notable is the increase in concentrations of all major cations and selected chloride and bromide in the top few hundred meters of the core. The concentration in most major cation and anions exhibit two peaks, one occurring in the top 100 to 200 m and the later one occurring between a depth of 400 and 600 m. Below 600 m, concentrations of most elements decrease, while sodium and chloride return to values close to seawater. Concentrations of fluoride and strontium increase with depth showing values two to three times that of initial seawater concentrations in the deepest sample at 1076 mbsf. A sulfate peak between 450 and 500 mbsf may result from anaerobic microbial mediated pyrite oxidation.

In the upper 400 m dissolved inorganic carbon isotopes becoming lighter with depth bottoming at -17.30 ‰ PDB at 375 mbsf either indicating the increase in microbial mediated carbon or increase of carbon derived from thermally derived methane. A spike of heavier carbon isotope values (-7.99 ‰ PDB at 649.50 mbsf vs. -13.64 and -13.32 ‰ PDB sample above and below) coincides with a fracture zone where circulation was lost during drilling. Around 1000 mbsf the carbon isotopes become heavier again, possibly indicating a return to marine derived sea water. This is similar to the isotopic composition of the porewater. $\delta^{18}\text{O}$ decrease from oceanic values of -0.2 ‰ SMOW at the water sediment interface to -9.29 ‰ SMOW at a depth of 39.32 mbsf (first AND-1B sample) indicating the influence of glacial meltwater. With depth the glacial meltwater influences decreases and $\delta^{18}\text{O}$ values near marine values towards the bottom of the core (-1.26 ‰ SMOW at a depth of 936.68 mbsf).

Several factors contribute to this behavior. During deposition of these sediments glaciers had been expanding and retreating across the McMurdo site. With depth sediment is being compressed and pore water expelled rising towards the sea floor. Within the sediment diagenetic and microbial processes influence porewater composition. In addition the McMurdo Sound is a volcanic active area and volcanic processes are leaving an imprint on the pore water geochemistry. Further work is underway and has still to be done to carefully identify individual processes.

Downhole logs of natural gamma radiation and magnetic susceptibility and their relation to lithostratigraphy in AND-1B

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The ANDRILL McMurdo Ice Shelf (MIS) project drilled 1285 m of sediment representing the last 14 million years of glacial history. Downhole geophysical logs were acquired to a depth of 1018 m, and are complementary to data acquired from the core itself. We describe here the natural gamma radiation and magnetic susceptibility logs, and their application to understanding lithological and paleoenvironmental change at ANDRILL McMurdo Ice Shelf Hole AND-1B.

Prior to interpretation, a 1.6% depth correction was applied to the depth values of the downhole logs to bring them in line with the core depths, natural gamma radiation logs were stacked and corrected for signal attenuation through the drill pipe, and magnetic susceptibility logs were corrected for drift. Natural gamma radiation logs cover the whole interval from the sea floor to 1018 m; magnetic susceptibility and other logs covered the open-hole intervals between 692-1018 and 237-342 m.

Natural gamma radiation is produced by radioactive isotopes of potassium, uranium, and thorium, which are contained in K-feldspars, clay minerals, heavy minerals, etc. The gamma log reflects both the mineralogy of the source rocks and dilution of the K, U, and Th-bearing minerals by non-radioactive material such as diatoms. Magnetic susceptibility is primarily controlled by the amount of magnetite in the sediment, and, similarly, reflects both the magnetite content of the source rocks and dilution by non-magnetic minerals. In addition, magnetite dissolution can also be an important process in silica-rich pore waters.

The downhole logs show a clear correspondence to lithology. The natural gamma radiation logs have high values in the sub-glacial diamict facies and drop to low values in the open-water diatomite facies. Similarly, high magnetic susceptibility indicates the high terrigenous input in the diamict. In addition to showing broad-scale sedimentary patterns, these logs can also be used to give information on subtle lithological trends and features that are difficult to quantify from visual inspection of the core itself, for example the varying terrigenous content of diatomites. Magnetic susceptibility is especially interesting in the volcanoclastic interval between 700-760 m, where the log displays high amplitude repetitive peaks, which probably mark eruptive volcanic cycles.

Cluster analysis and factor analysis of the downhole logs add a further dimension, bringing out features that are less apparent in any one log taken singly (see related abstract by Jackolski et al.). Overall, downhole logs provide a valuable contribution to understanding the lithological record at the McMurdo Ice Shelf.

Dating Antarctic climatic and tectonic events of the Neogene – Age models from the ANDRILL 1B and 2A cores

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A network of seismic surveys in McMurdo Sound provides an image of the tectonic, glacial, and sea-level controls on accumulation of Cenozoic strata in the West Antarctic Rift. Integration with previously recovered drill cores revealed a younger Neogene succession, which was the target of drilling from floating ice platforms under the ANDRILL program in the austral summers of 2006 and 2007. Continuously recovered core from the AND-1B and 2A drill holes provides key paleoenvironmental data regarding climatic variation and ice volume fluctuation of the Antarctic Ice Sheets through the Neogene. Chronostratigraphic data available from the drill cores includes diatom and nannofossil biostratigraphy, magnetic polarity stratigraphy, ⁴⁰Ar/³⁹Ar ages on numerous ashes from the McMurdo Volcanic Complex, and strontium dates on carbonate material. Integration and optimization of the currently available data provides a robust age model for the Plio- Pleistocene (upper 600 m) of the AND-1B drill core and the middle and lower Miocene (224-1139 m) interval of the AND-2A drill core. The Plio-Pleistocene record is punctuated by multiple hiatuses that correlate with climate (ice sheet and sea level fluctuations) events and account for approximately half of the time spanned by the record. Despite these hiatuses, the distribution of chronostratigraphic data still enable the identification of orbital influence in remaining strata. The lower 600 m of the AND-1B extends well down into the Miocene as constrained by a ⁴⁰Ar/³⁹Ar age of approximately 13.8 Ma towards the base of the core. The upper 300 m interval of the AND-2A core contains punctuated middle Miocene to Pliocene succession with hiatuses accounting for more than two thirds of the time spanned by the record. The ~800-m thick lower Miocene interval of the AND-2B core is nearly continuous and enables new constraints on regional tectonic and climatic events of the West Antarctic Rift sedimentary succession.

Contemporary stress data from induced fractures in the AND-1B sedimentary rock core, McMurdo Ice Shelf, Antarctica

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Fractures that form during drilling (i.e. in the rock around the drill bit), coring (i.e. on entry or in the core barrel), or subsequent handling of the core are classified as “induced” fractures. Sedimentary rock core recovered from beneath the McMurdo Ice Shelf, located within the Neogene Terror Rift superimposed on the Victoria Land Basin, contains abundant drilling-induced core fractures that have been well characterized due to the superb core recovery. Steep petal-centerline and low-angle core-edge fractures in drill core were produced from shallow depths to over 1300 m below the seafloor. A population of 410 steeply-dipping, petal, petal-centreline and core-edge induced fractures is present, reaching a maximum density of 5 fractures/m but with an average of 0.33 fractures/m over the entire length of core. Subhorizontal induced extension fractures are also abundant.

Petal, petal-centreline, and core-edge fractures consist of steeply-dipping, typically curvilinear, extension fractures that propagate in the formation below the drill bit and then are partially captured in the core as drilling proceeds. Petal-centreline fractures and core-edge fractures occurred most commonly at or near the top of core runs, but also were present mid-run and, more rarely, near the base of runs. Petal, petal-centreline, and core-edge fractures are most abundant in mudstones, which commonly were more difficult to drill and were associated with higher pump pressures during drilling and are uncommon in the diatomites and diamictite lithologies. Fractographic features, including arrest lines and fine hackle plumes, demonstrate propagation of these fractures inward and downward along the core axis. We are using drilling data on pump pressure, weight-on-bit, and drilling mud densities, to determine the pressure/stress conditions that produced the induced fractures. The orientation of these fracture planes parallels the maximum horizontal stress in the crust and is perpendicular to the minimum horizontal stress. Preliminary analyses of tensile fractures in borehole walls identified in BHTV imagery indicate an east-west orientation of the maximum horizontal stress direction. Reorientation of core to in situ coordinates is ongoing; once completed we will test this result based on the strikes of the steep drilling-induced fracture set.

Subhorizontal induced tensile fractures form when the core is broken off at the end of a run, when the rock is released from load upon entering the core barrel (known as ‘disc’ fractures), during flexing of the core splits during transport, or due to handling during core processing. Surface fractographic features on all these subhorizontal fractures demonstrate opening of the fractures due to tension. Hackle plume structures were common on these fractures in some core lithologies. The trend of the long axis of oriented hackle plume will also provide a test of the direction of the maximum horizontal stress. Unusual arrays of conchoidal arrest lines, marking pauses in fracture propagation, were common in fine-grained lithologies in the core. The development of the different types of induced fractures in the same intervals of core and/or borehole walls provides constraints on the *in situ* stress regime. Based on the integrated information from drilling data and induced fractures in core and borehole walls, we are obtaining constraints on both stress regime and stress orientation at the McMurdo Ice Shelf site which, when combined with regional stress data, will allow us to evaluate upper crustal stresses associated with intraplate rifting and flexure due to the volcanic load of Ross Island.

Diatom-based correlation of early to mid-Pliocene drill cores from the southwestern Ross Sea, Antarctica

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The marine diatomites in AND-1B have greatly enhanced our understanding of the coastal Antarctic environment for the Pliocene and early Pleistocene of southern Victoria Land Basin and provide important new chronostratigraphic control for paleoenvironmental changes also noted in three near-shore drill cores; DVDP-10 and DVDP-11 in Taylor Valley and CIROS-2 from the seaward edge of Ferrar Fjord. These three cores contain a fragmented nearshore Plio-Pleistocene marine record from the western McMurdo Sound area.

The refined continental-shelf biostratigraphy developed from AND-1B provides a framework for regional correlation in order to better understand the timing and character of large paleoenvironmental changes in the western Ross Sea that involve both the West and East Antarctic Ice Sheets. Multivariate analysis and traditional biostratigraphic approaches enable the correlation and comparison of coeval intervals in these drill cores. A composite stratigraphic sequence from these four cores suggests the early Pliocene Ross Sea experienced extended intervals of minimal sea-ice cover and high diatom production and deposition. This new information provides important constraints on Antarctic paleoclimate and ice-sheet history during an important interval when global climate was warmer than today. The history preserved in these four drill cores, together with the near-shore diatom zonation for the Ross Sea based on AND-1B (IGC July 2008, Oslo, Norway) and the ecological variability preserved in diatom assemblages from the contiguous ~60 m of diatomite from 376-439 mbsf (SCAR June 2008, St. Petersburg, Russia), will be important tools to guide and test future ice-sheet and climate models.