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A Record of Antarctic Climate and Ice Sheet History Recovered

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Antarctica's late Cenozoic (the past ~15 million years) climate history is poorly known from direct evidence, owing to its remoteness, an extensive sea ice apron, and an ice sheet cover over the region for the past 34 million years. Consequently, knowledge about the role of Antarctica's ice sheets in global sea level and climate has relied heavily upon interpretations of oxygen isotope records from deep-sea cores. Whereas these isotopic records have revolutionized our understanding of climate-ice-ocean interactions, questions still remain about the specific role of Antarctic ice sheets in global climate. Such questions can be addressed from geological records at the marine margin of the ice sheets, recovered by drilling from floating ice platforms [e.g., *Davey et al.*, 2001; *Harwood et al.*, 2006; *Barrett,* 2007].

During the austral summer of 2006–2007, a new Antarctic geological drilling program (ANDRILL) successfully recovered a 1285-meter-long record of climate and ice sheet variability spanning the past 13 million years from beneath the McMurdo Ice Shelf (Figure 1). The cores contain sedimentary rocks deposited by the ice sheets grounded in the sea, and they provide the best direct evidence to date of past Antarctic ice sheet and climate fluctuations for this period of Earth's history.

The new geological evidence is being used to provide direct physical calibration for deep-sea isotope records, low-latitude continental margin sea level records, and numerical climate and ice sheet models, especially for times of past global warmth. Such analogs are becoming increasingly important because of the difficulties in predicting the dynamic response of ice sheets to global warming [*Vaughan and Athern,* 2007]. In this article we summarize the initial results of the ANDRILL program's first drilling project from the McMurdo Ice Shelf (MIS) site [*Naish et al.,* 2007a, 2007b], with an emphasis on the potential of the record for improving our knowledge of Antarctica's influence on, and response to, global climate change.

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The Role of Antarctic Ice Sheets in Late Cenozoic Climate

The deep-ocean isotope record indicates a profound cooling about 14 million years ago, which is interpreted as an expansion of the East Antarctic Ice Sheet (EAIS) to perhaps its present-day extent and the development of ice on West Antarctica (the West Antarctic Ice Sheet, or WAIS) [*Zachos et al.,* 2001]. A number of lines of evidence, including geomorphic studies from the Transantarctic Mountains [*Sugden et al.,* 1993], suggest that the EAIS has been more or less stable for the past 14 million years. Notwithstanding this, oxygen isotope records indicate moderate oscillations of global ice volume capable of producing sea level fluctuations of up to 25 meters above present [*Kennett and Hodell,* 1993], prior to the development of Northern Hemisphere ice sheets about 3 million years ago [e.g., *Raymo*, 1994]. These ice volume changes are thought to have involved an ice cap on Greenland, the marine-based WAIS, and, at times, the margins of the EAIS.

A more dynamic view of the late Cenozoic EAIS has been proposed from a number of on-land geological studies that provide evidence for marine incursions into the continental periphery during the Pliocene (5–2 million years ago) [*Harwood et al.*, 2000]. The occurrence of marine diatom-bearing tills in a number of locations high in the Transantarctic Mountains led *Webb et al.* [1984] to propose that the diatomaceous sediments must have been deposited within interior seas subsequently to be glacially eroded and transported to their present-day sites. This concept, known as the "Webb-Harwood" hypothesis, requires a significant deglaciation of East Antarctica. Although uncertainty remains over the scale of Antarctic ice sheet dynamism, the early and middle Pliocene (5–3 million years ago) is generally regarded as a time of global warmth [e.g., *Crowley,* 1996] and an important window into Earth's future climate in the context of anthropogenic global warming [*Intergovernmental Panel on Climate Change*, 2007].

The McMurdo Ice Shelf Project

The MIS drill site was situated on an 85-meter-thick section of the Ross Ice Shelf close to where the shelf's calving line has been stabilized to Ross Island for the past 9000 radiocarbon years [*McKay et al.,* 2007]. The cored strata were recovered through about 850 meters of water, from a moat-like sedimentary basin that surrounds Ross Island. This basin was created by a local loading of the crust from the basaltic volcanoes that make up Ross Island, within the Victoria Land Basin (VLB), a region of late Cenozoic crustal extension of the West Antarctic Rift System.

A custom-built sea riser system embedded into the seafloor was used for drilling; this enabled soft-sediment coring of the upper sediments and continuous wireline diamond-bit coring through rock (Figure 1). A hot-water drill and a reaming tool fitted around the sea riser were used to make an access hole through the ice shelf and to keep the sea riser free from effects of tidal motion. The AND-1B hole was drilled in 60 days with 98% core recovery, reaching a depth of 1284.87 meters below the seafloor and making it the deepest geological drill hole in the Antarctic region.

The strata accumulated about 100 kilometers seaward off the Victoria Land coastline in the western Ross Sea in deep water (200–1000 meters) as part of a laterally extensive seaward-thickening wedge. This geometry is evident in strike and dip seismic profiles [*Horgan et al.,* 2005; *Fielding et al.*, 2007]. The diverse range of rock types recovered includes diamictites (poorly sorted deposits associated with glacial processes), sandstones and mudstones, diatomites (siliceous microfossil deposits), volcanic ash, and one lava flow (Figure 1). The rocks were interpreted in terms of lithofacies associations—sediments representing specific environments of deposition, which included open marine diatomites, mudstones and turbidites deposited during interglacials, ice-proximal massive and stratified diamictites, and conglomerates and sandstones representing glacial periods. During glacial periods, the ice sheet had a

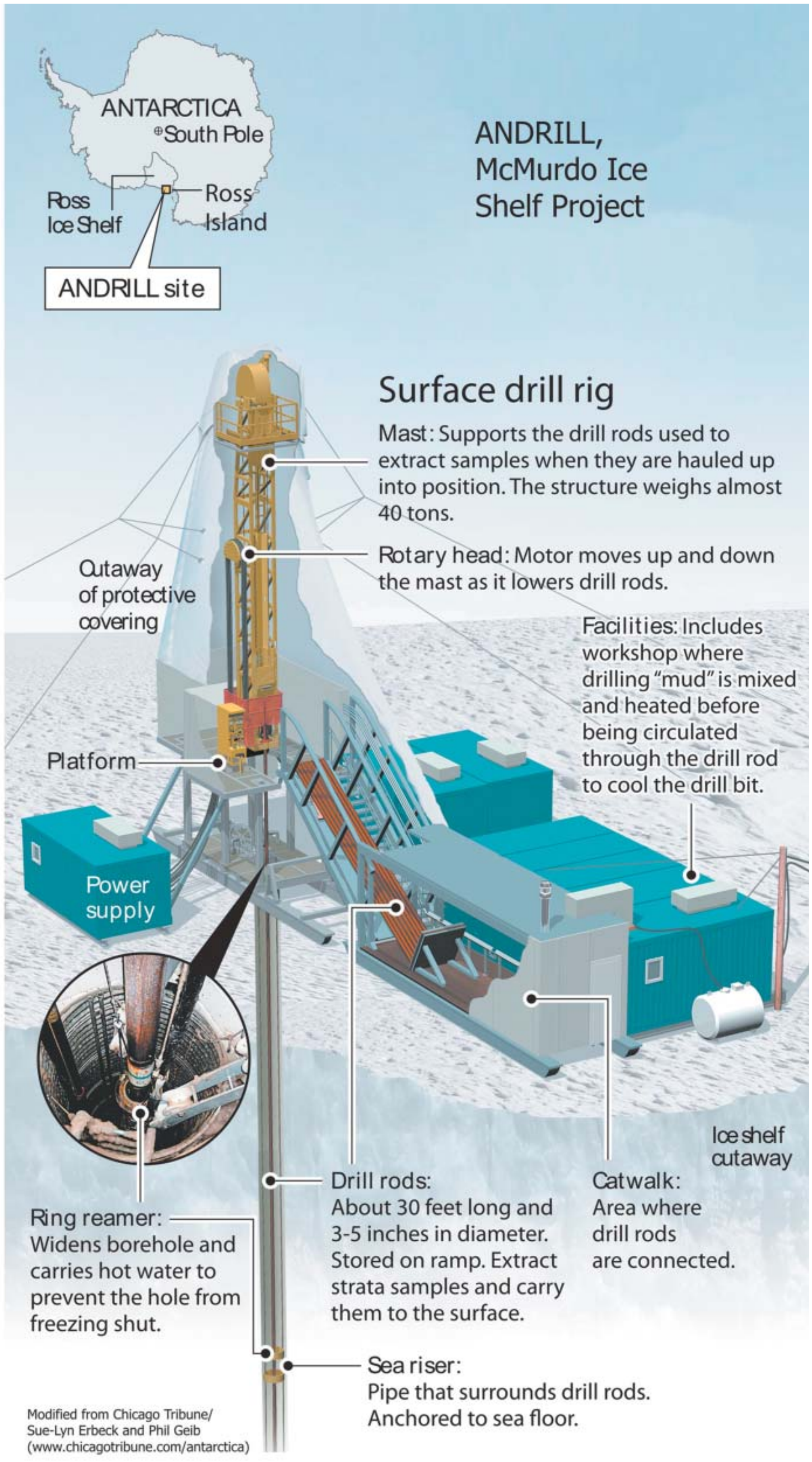

Fig. 1. Schematic view of the McMurdo Ice Shelf drilling operation (credit: Chicago Tribune*).*

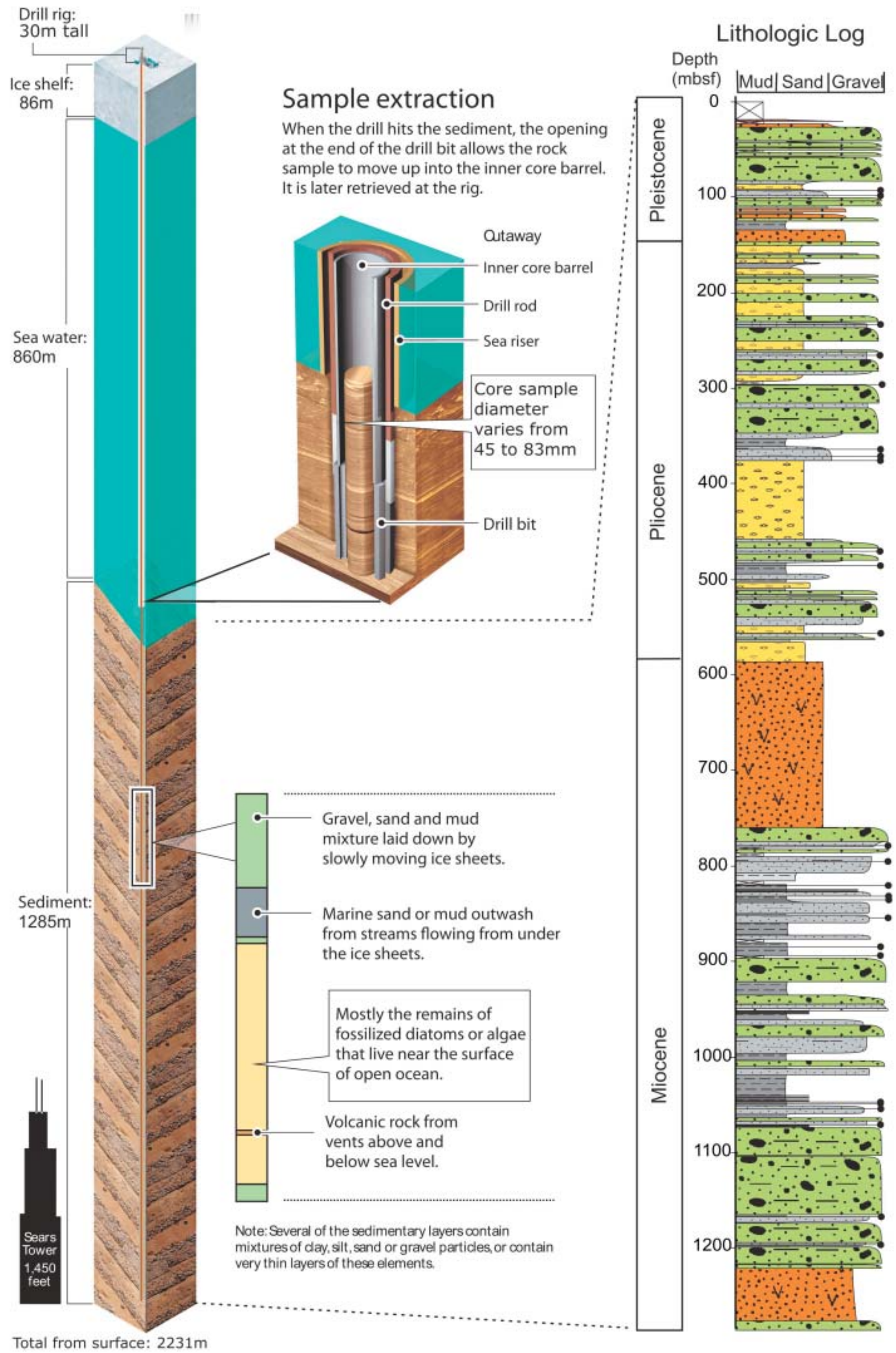

Fig. 2. The stratigraphic log of the drill core shows cyclic variations in rock types representing regular advances (diamictites, green) and retreats (diatomite, yellow; marine mudstone, gray) of the ice sheet in the western Ross Sea during the past 13.5 million years. Volcanic deposits originated from local basaltic vents (orange). For details of the stratigraphy and chronology, see Naish et al. *[2007a].*

laterally extensive marine terminus located hundreds of kilometers north of the drill site into the Ross Sea. During interglacials the drill site either was covered by an ice shelf (similar to present day) or lay in open water at times when the ice sheet had retreated onto the continent, with local deposition of marine diatoms, terrigenous mud, and occasional debris from icebergs.

Glacial-Interglacial Cycles

More than 60 oscillations of ice sheet advance and retreat are preserved in the AND-1B record. Each cycle begins with a glacial erosion surface created by the sole of the advancing ice sheet on the seabed. Above this, coarse-grained, ice-proximal sediments pass upward into a sequence reflecting retreat of the grounding line, sometimes with rapid transitions into an open-ocean environment during interglacial times. These retreat sequences may then pass back into ice readvance deposits before being overridden by the ice sheet, creating another glacial erosion surface.

Till composition indicates that the depositing ice originated from large outlet glaciers in the southern Transantarctic Mountains (TAM), especially the Byrd and Skelton glaciers. Glaciological reconstructions [*Denton and Hughes,* 2002] require a significant ice volume from WAIS to force the flow lines of the southern outlet glaciers into the McMurdo region during glacial periods, and also to maintain an ice shelf during ensuing interglacial retreats. Thus, we view the sedimentary cycles primarily as responses to the expansion and contraction of WAIS in concert with fluctuations in the flow of TAM outlet glaciers.

Chronology

A preliminary age model for the upper 700 meters of drill core constructed from diatom biostratigraphy and radiometric ages on volcanic material allows a unique correlation between about 70% of the magnetic polarity stratigraphy and the Geomagnetic Polarity Time Scale. The age model provides several well-constrained intervals displaying relatively rapid (<1 meter per 1000 years) and continuous accumulation of sediment punctuated by several 0.5- to 1-million-year stratal hiatuses representing more than half of the past 7 million years. Thus, the AND-1B record provides several highly resolved "windows" into the late Cenozoic development of the Antarctic ice sheets. Strata below about 620 meters below seafloor (bsf) are late Miocene in age (5–13 million years ago). Currently, the chronostratigraphic data available for this interval include three radiometric ages on volcanic clasts from near 1280 meters bsf, constraining the age for the base of the AND-1B drill core to about 13.5 million years. Work continues to improve the age control on the lower part of the cored interval.

Implications for Late Cenozoic Antarctic Climate

The glacimarine sedimentary cycles reflect orbitally influenced, glacial-interglacial oscillations of the ice sheets during four different phases of late Cenozoic climate evolution.

1. A colder period of polar ice sheets dominated the early-late Miocene, about 13.5–10 million years ago, consistent with a period of cooling in the oxygen isotope record. During this time the cycles are composed almost entirely of glacial diamictite (most interpreted as subglacial tillites), with minor interstratified glacimarine mudstones from interglacial times.
2. A relatively warm period of subpolar ice sheets is implied by increased submarine outwash deposits during the latest Miocene, about 9–6 million years ago. Open-water, ice distal conditions occur during interglacials, with ice grounded at the site during glacial maxima implying important changes in ice sheet volume.
3. The Pliocene period (5–2 million years ago) is characterized by a dynamic ice margin with interglacials displaying spectacular pelagic diatomite, implying high phytoplankton productivity in locally open water. An interval of diatomite more than 80 meters thick between 370 and 460 meters bsf represents an extended period of open water in the Ross Embayment and high phytoplankton productivity. Abrupt transitions between subglacial/ice-proximal diamictites and open marine diatomites occur in the late Pliocene (~2.6–2.2 million years ago); the transitions appear to be paleo-environmentally significant in terms of glacial-climate interactions, and they are receiving ongoing analysis.
4. A return to cold polar glaciation dominated by extensive ice sheets during the past 800,000 years is represented in the upper 83 meters of core. Thin units of sandstone, mudstone, and volcaniclastic sediment occur in the upper parts of the cycles, and these units may represent ice shelf or calving-line proximal interglacial conditions, much like the present-day setting of the drill site

Preliminary environmental reconstructions imply changes in Antarctic ice volume that have contributed significantly to eustasy and ocean circulation. The focus now is to integrate the geological evidence for ice variability and the proxies for sea surface and terrestrial temperatures with ice sheet and global climate models to quantify the magnitude of, and to better understand the nature of, Antarctic ice volume changes during these past times of global warmth.

The MIS project is the first of a two-project international collaboration involving over 100 scientists from the United States, New Zealand, Italy, and Germany. The collaboration is funded jointly by the Antarctic programs and science funding agencies from each of the nations (U.S. National Science Foundation's Office of Polar Programs, New Zealand Foundation of Research Science and Technology, Royal Society of New Zealand, National Antarctic Research Program of Italy, and the Alfred Wegener Institute of Polar and Marine Research, which coordinates German polar research).

ANDRILL's management structure has two parts: a science implementation committee for developing and overseeing project science priorities, and an operations management group for developing and implementing logistics operations. A science management office is based at the University of Nebraska at Lincoln. The New Zealand Antarctic Program (Antarctica New Zealand) is providing operational management for the program. During the present austral summer (October–December 2007), ANDRILL has just successfully completed its second drilling project in southern McMurdo Sound with more than 1000 meters of core. The southern McMurdo Sound cores overlap with, and are older in age than, those of the MIS project, and these new cores extend the ice sheet and climate record back to 20 million years.

ANDRILL planning documents, background information, and education and outreach resources are available at the Web site: http://www.andrill.org.

Acknowledgments

The authors wish to acknowledge that the initial results of the MIS project summarized in this article reflect the collective efforts of the MIS Science Team. The names and affiliations of team members can be found at the Web site: http://www.andrill.org/support/references/appendixc.html.

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Digital Library for Computational Seismology

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Computational methodologies play an increasingly important role in Earth sciences. However, Earth science curricula in general often do not equip scientists with the necessary background in mathematical and computational aspects of the rapidly expanding field of simulation technology.

This lack of preparation applies in particular to the field of computational seismology. Despite the fact that the same numerical methodologies (e.g., finite differences, finite/spectral elements) are used in various domains (e.g., exploration seismics, volcanology, global seismology, earthquake physics), there often has been little interaction and exchange of experiences among researchers working in these different domains.

Since 2004, the European-funded Marie Curie Research Training Network has brought together 14 institutions (universities and research centers) and several associated partners (exploration industry, seismic data and computing centers, and non-European universities) in a project to carry out research in computational seismology. The Seismic Wave Propagation and Imaging in Complex Media: A European Network (SPICE) Consortium aims to integrate institutions with specializations in physical, mathematical, geological, and computational aspects of wave propagation. The goal is to develop, verify, and apply computational tools for wave propagation and imaging problems on all scales.

The project scope was reported by *Igel* [2004] and the SPICE Team. This brief report outlines recent achievements and describes tools and material available to the community.

One of the key deliverables of the project is an open, Internet-based digital library comprising a wide range of seismological codes (wave and rupture simulation, analytical solutions, processing, visualization, and so forth), training materials, and benchmarking exercises in the field of wave and rupture propagation modeling. The library could be of interest to scientists and students working in the field of numerical wave and rupture modeling. It can be accessed at the Web site: http://www.spice-rtn.org. Although the project draws to an end in December 2007, the library will remain in operation after that date.

Software and Training Materials

The software library was initiated in 2005, and several algorithms are now available to the scientific community. The library's goal is to provide codes and tools that may be useful for researchers who are starting out in the field or observational seismologists who are interested in using the simulation techniques. In addition to the library's sophisticated, parallelized, three-dimensional wave propagation algorithms based on finite differences, finite (spectral) elements, or the pseudospectral methods for local, regional, and global models, there are also simple training codes that can help with getting started with a particular method or that can be used in tutorials.

The library also contains "classical" techniques such as ray approaches, and the reflectivity and normal mode methods. Strong attention also is paid to the provision of analytical solutions (Lamb's problem, source at bimaterial interface, and so forth) that can be used to test numerical solutions and that are often difficult to obtain.

Each available code is supplemented by a manual and one or more examples. The codes are classified in many categories according to, for example, solution type (numerical, quasi-analytical, and analytical) and code level (production code, research, and training). The classification can in turn be used to filter the entries and therefore to provide quick orientation among the codes.

The library is an open platform so that anyone can participate and submit a code. For example, an author can submit a code to the software library under any license (e.g., GNU general public license). Then the author can benefit from other users who would be interested in that particular code, providing software bug reports, and/or helping with the code development. Regarding the latter, the library also can be used as a version control system because it keeps track of all previous versions.

The network has organized four open research and training workshops with lecture series and computer practicals. Most of the key presentations by invited lecturers are published in the library, including several audio-video lectures. The library also includes two books (with pdf versions available) developed in connection with the SPICE research and training workshops [*Brokesova*, 2006; *Moczo et al.*, 2004]. The library's training material covers a broad range of seismological topics, such as basics in wave propagation and rupture modeling, theory, applications of seismic inversions, and recent issues in volcano seismology.

Benchmarking Exercises

The library provides three benchmarks related to global tomography, wave-propagation code validation, and source imaging. In the global tomography benchmark [*Qin et al.*, 2006], a synthetic data set for testing global tomographic methods is provided. This global-scale benchmark data set comprises complete full-waveform seismograms synthesized with the spectral element method for a three-dimensional model of the mantle that is realistic and that contains complexities on various spatial scales and different types of heterogeneities in velocity, anisotropy, attenuation, and density.

In addition, the benchmark data set takes into account topography, ellipticity, Earth's rotation, self-gravity, and ocean thickness. Each participant can download the benchmarking synthetic seismograms and test the performance of his or her tomography code.

Within the wave-propagation code validation benchmark, an interactive Web interface has been developed, offering a simple way to compare numerical, analytical, and/