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Using new tools to explore undiscovered country: Understanding the stratigraphic and tectonic history of greenhouse to icehouse worlds of offshore New Harbor, Ross Sea, Antarctica

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Summary The Offshore New Harbor Project will investigate the stratigraphic and tectonic history of westernmost Southern McMurdo Sound. This will be used to address two widely recognized but unresolved issues regarding Antarctica's history: 1) the mid-Paleogene cryospheric development on Antarctica; and 2) the abrupt climate shift across the Eocene/Oligocene transition. The first step for this project is to collect the requisite seismic and gravity data for identifying future drilling targets for the ANDRILL Program. ANDRILL is a multinational program, with the aim to recover stratigraphic intervals for interpreting Antarctica's climate and glacial history over the past 50 million years. Offshore New Harbor is an ideal locale to tackle these questions because existing data suggest substantial strata deposited during Eocene time, across the Eocene/Oligocene boundary, and into the "mid" Oligocene are preserved updip of current seismic profiles and borehole locations.

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Introduction

The climatic, cryospheric, and tectonic history of Antarctica are important links for understanding global changes that have shaped Earth's past. Our understanding of Antarctica's cryosphere suggests dramatic changes occurred during the Cenozoic; evolving from a warm mainly ice-free continent, to a transitional state of expanding and contracting polythermal ice sheets to extreme polar conditions, such as observed today. These paradigms have been shaped mainly from distal records, such as from deep-sea isotopic and lower latitude shallow marine stratigraphic records. In comparison, far fewer records from the Antarctic continent and adjacent shelf exist to provide direct confirmation of these changes, a problem that has led to numerous conflicting interpretations of the cryospheric evolution. This includes the timing of the first significant ice sheets in Antarctica, with estimates ranging from late Eocene (~37 Ma) based on isotopic records (e.g. Zachos et al., 2001), to no later than the late early Eocene (~51 Ma) based on stratigraphic evidence (Miller et al., 1998; Pekar et al., 2005). Additionally, the size of the initial ice sheets is still unresolved, with estimates of maximum ice volume ranging from ~ 50% (e.g. Zachos et al., 2001) to 125-150% (Lear et al., 2004; Pekar and Christie-Blick, in press) to 150-200% (Coxall et al., 2005) of the present day East Antarctic Ice Sheet (EAIS). Additionally, another debate concerns the apparent decoupling between distal deep-sea records (e.g., δ^{18}O records) and Antarctic records and pCO$_2$ estimates in the Oligocene and Miocene (Pagani et al., 2005; Pekar and Christie-Blick, in press).

In contrast, proximal records obtained from outcrops, cores, and seismic profiles have provided a consistent picture of Antarctic climate change although these records thus far, are fragmented and sparse. These studies indicate a gradual cooling of the continent from warm to cool temperate conditions in the Eocene (Barrett, 1989; Cape Roberts Science Team, 1998, 1999, 2000; Naish et al., 2001; Raine and Askin, 2001). This cooling trend culminated with tundra-like conditions occurring during glacial minima based on stratigraphic records (Naish et al., 2001) and grounded ice extending beyond the present-day coastlines during glacial maxima in the Prydz Bay region by the early Oligocene and in the Ross Sea by the late Oligocene based on seismic records (Cooper et al., 1991; Sorlien et al., 2007).

However, critical pieces of Antarctica's history remain unknown owing to a lack of high quality geophysical and sedimentary data. These include: the Eocene, a time dubbed the Greenhouse World; the Eocene/Oligocene boundary, considered among the most important climatic transitions of the Cenozoic, and "mid" Oligocene, an interval when the ice sheet may have been larger than today (Lear et al., 2004; Pekar and Christie-Blick, in press). The stratigraphic archives preserved in offshore New Harbor may contain these missing stratigraphic intervals, which could provide a better understanding of the climatic and tectonic history of Antarctica. These archives include middle Eocene and early and "mid" Oligocene strata, presumably located updip of the CIROS-1 borehole. Fault and flexure-related subsidence associated with rifting has provided the requisite accommodation for thick sedimentary wedges to accumulate since the Eocene. The Offshore New Harbor Project proposes to first image and then recover these sediments in offshore New Harbor, which will provide a greater understanding in resolving conflicting hypotheses regarding the early ice-volume history in Antarctica.

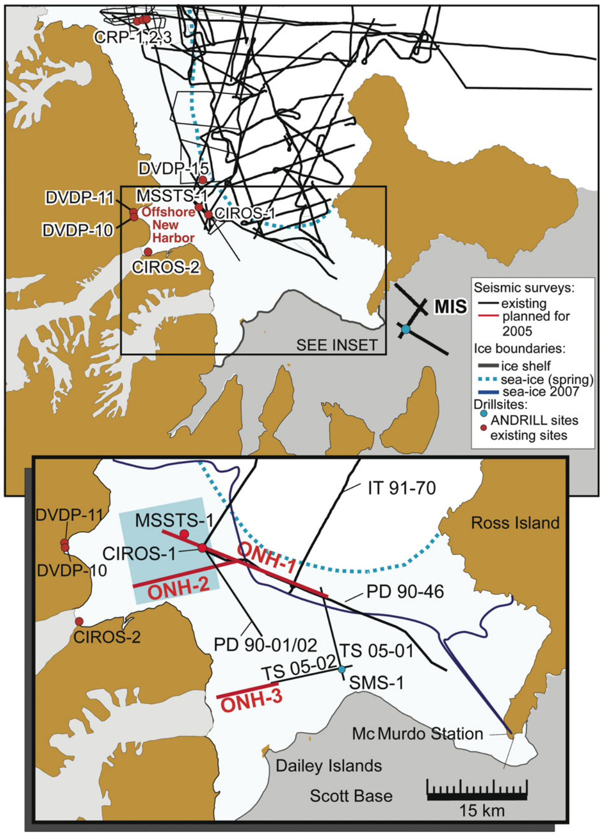

Figure 1. The stratigraphic architecture of sediment fill of the western Victoria Land Basin in McMurdo Sound is known from an array of existing single and multichannel marine seismic data shown in black lines (Anderson and Bartek, 1992; Brancolini et al., 1995; Melhuish et al., 1995; Hamilton et al., 2001; Wilson et al., 2004; Horgan et al., 2005). Offshore New Harbor area is labeled in red. In the inset are the proposed sea-ice MCS lines for offshore New Harbor shown in thick red lines (ONH-1, ONH-2, and ONH-3). Also shown is the proposed gravity grid for ONH shown as a light blue shaded box. The ANDRILL sites for the McMurdo Ice Shelf (MIS, 2006) and Southern McMurdo Sound (SMS, 2007) projects as well as SMS sea-ice seismic lines (ATS-05-01 and ATS-05-02, 2005) are shown.

Objectives: Imaging and sampling stratigraphic and tectonic holy grails in Antarctica

New Harbor is located on the western side of the McMurdo Sound in the Ross Sea (Fig. 1) and is where tectonic subsidence has permitted the preservation of thick sedimentary successions that have not been sampled elsewhere in this region (Fig. 2). This project proposes to first image and then afterwards core these strata with the following objectives.

1) **Greenhouse worlds –** With the exception of upper Eocene strata obtained in CIROS-1, no cores containing Eocene strata have been recovered in the Ross Sea (Fig. 2), although middle and late Eocene marine fossilliferous rocks are present locally, as indicated by the McMurdo Erratics (Harwood and Levy, 2000).

a) Test two hypotheses that concern the age of the oldest sediment in the ONH area. One idea is that the base of the CIROS-1 drillhole is close to basement rock (Hambrey, 1989), while another suggests that a considerable thickness of sediment exists below CIROS-1 (Davy and Alder, 1989). Resolving this stratigraphic question will provide constraints on initial rifting in this area.

b) We propose that older sediments were preserved in ONH, because upper Eocene strata at CIROS-1 dip basinward at ~20˚; therefore we expect older strata to exist immediately updip of CIROS-1.

c) Test two stratigraphic/tectonic models for the McMurdo Sound area: one suggests the VLB rifting commenced with the TAM uplift at c. 55 Ma while a second model suggests that rifting began ~34 Ma.

2) **The Eocene-Oligocene boundary and "mid" Oligocene (~29-24 Ma) –** These intervals also have never been unequivocally recovered in the Ross Sea (Fig. 2). Although grounded ice may have produced unconformities across this region during both of these time intervals, another hypothesis suggests that these stratigraphic targets are located updip of CIROS-1.

3) **Bedrock -** An important goal is to sample bedrock in the New Harbor area as there is little known about the underlying bedrock and structural history in this area.

4) **The TransAntarctic Mountain Border Fault -** The TAM Border Fault is among the most significant structures in the western Ross Sea and has never been seismically imaged clearly. Complex faulting structures between the TAM and Victoria Land Basin (VLB) are suggested by limited gravity data (G. Wilson, pers. comm., 2005). We expect to be able to constrain the tectonic history of Offshore New Harbor by implementing the now well-tested and innovative techniques developed for over sea-ice seismic acquisition.

Geophysical surveys for offshore New Harbor

Previous seismic studies in the New Harbor area

Previous marine seismic data collected in the McMurdo Sound region have been limited to mainly single channel (e.g., Anderson and Bartek, 1992), which limited penetration owing to not being able to process out the

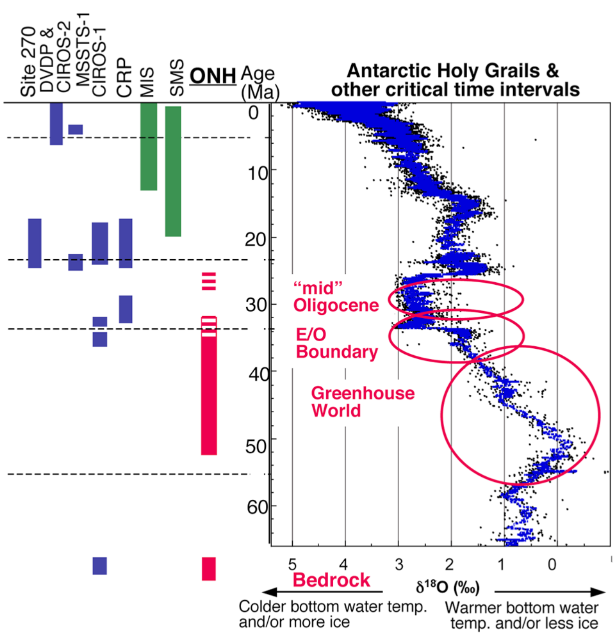

Figure 2. Boreholes from the Ross Sea. Previous cores studies are in blue (Barrett, 1989; CRP, 1998; 1999; 2000;), and recently drilled and proposed ANDRILL boreholes (MIS, 2006 and SMS, 2007) are green. On the right is the Zachos et al. (2001) isotopic composite, with time intervals circled to show stratigraphic intervals not yet sampled from boreholes in the Ross Sea. The ONH Project proposes to image and then sample sedimentary archives from these Antarctic "Holy Grails". Thick dark red lines are targets with a high likelihood of recovery, while lighter red lines are sediments from time intervals that are less certain of recovery.

seafloor multiple. Additionally, MCS seismic data extend up to where the sea ice broke out during each survey, therefore the western objectives (e.g., updip of CIROS-1 and MSST-1 sites) were not reached. Since access by research ship to the ONH area is rare due to the annual fast ice that persists in this area (Fig. 1), sea-ice seismic surveys have been conducted (e.g. Bannister and Naish, 2002). However, their results found that no sub-seafloor reflections could be resolved using existing seismic techniques. To this end, a new over-ice seismic survey method was developed and the implemented for the Southern McMurdo Sound (SMS) seismic field season conducted during October-November, 2005. A Generator-Injector (GI) air gun was used as the seismic source, which minimized the source bubble effects that had previously plagued other over-sea-ice experiments. (Betterly et al., in press) Additionally, the GI gun allowed the stacking of data at each shot location, thereby increasing the signal-to-noise ratio. A 60-channel seismic snowstreamer consisting of vertically oriented gimbaled geophones with 25-m takeout spacing was employed that permitted rapid data collection (average about 2 km/ day). Members of the 2005 SMS survey are refining these methods for the proposed Offshore New Harbor Seismic Survey.

Proposed seismic and gravity survey for offshore New Harbor

A survey is being planned for acquiring MCS and gravity data during the austral spring of 2008, with the purpose of further refining a drilling strategy for this area (Fig. 1). The seismic study consists of three seismic dip profiles, with the primary aim of each line being to identify site locations to sample Greenhouse World sedimentary archives older than what was recovered at CIROS-1. Because of the complex structural nature of this area, ages of the oldest strata may differ among the sub-basins, therefore the strategy is to image different parts of this area to maximize efforts in finding the optimal location to drill.

Seismic line ONH-1 will evaluate potential drilling targets in the direction of Taylor Valley. It will extend up-dip of MSSTS-1, and extend eastward, tying into CIROS-1, MSSTS-1 and MCS ATS-05-01 line, which will provide continuous seismic coverage from MSSTS-1 drillhole to marine seismic data that extends into the Ross Sea as well into the MCS seismic data collected in 2005. This will tie these borehole data to MCS data, providing the first opportunity to correlate the deeper reflectors to the older strata sampled in these boreholes. Seismic line ONH-2 will begin one km eastward of ONH-1 and continue up-dip in the direction of Ferrar Valley to evaluate the stratigraphy and tectonic structures of this area for the first time. Seismic line ONH-3 will tie into ATS-05-2 and extend 9 km up-dip evaluating potential targets up-dip of the SMS borehole. All three seismic lines are expected to cross the TAM fault, providing constraints on its location and geometry and will image the basement reflectors for determining the structural geometry of the ONH and Blue Glacier areas.

Gravity survey

This project will also undertake a detailed gravity survey of the offshore New Harbor region. The gravity survey will be undertaken to define the intersecting N-S and E-W fault block system beneath New Harbor and to determine the nature of block tilt and the distribution of sediment between the sea floor and basement blocks. A 0.5 - 1 km grid spacing is proposed for the survey over the ~250 km^2 area of New Harbor and the ~150 km^2 immediately seaward of the southern Victoria Land coastline offshore from New Harbor.

Summary

The Offshore New Harbor Project aims to collect the requisite seismic, gravity and sedimentary cores to evaluate the climatic and tectonic history of the western Ross sea area during the mid Paleogene. Although the proposed drilling locations will ultimately be modified once the seismic and gravity surveys are completed, we expect that the drillsite will be located either up-dip of CIROS-1 or up-dip of the proposed SMS-1 drillsite, with its location being sufficiently up-dip of the CIROS-1 (or SMS-1) site as to minimize overlap of strata between the two sites.

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