ANDRILL MCMURDO ICE SHELF PROJECT

SCIENTIFIC PROSPECTUS

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ANDRILL McMurdo Ice Shelf Project Scientific Prospectus

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1. SUMMARY

Response of Antarctic ice sheets to projected greenhouse warming of up to 5.8°C by the end of the century is not known. Models on which predictions are based need to be constrained by geological data of the ancient ice sheets during times when Earth is known to have been warmer than today. The marine-based West Antarctic Ice Sheet (WAIS) and its fringing ice shelves are hypothesized (Clark *et al.*, 2002; Weaver *et al.*, 2003; Stocker, 2003) and documented (Scherer *et al.*, 1998) to have collapsed during past "super-interglacial" warm extremes when global sea-level was more than 5m higher than today. Recent collapse of small ice shelves along the Antarctic Peninsula (Doake and Vaughn, 1991; Skvarca, 1993; Rott *et al.*, 1996; Vaughn and Doake, 1996; Doake *et al.*, 1998; Rott *et al.*, 1998; Skvarca *et al.*, 1999; Rott *et al.*, 2002) highlights the vulnerability of these glacial components to global warming. The Ross Ice Shelf appears to represent one of the most vulnerable elements of the WAIS system. Future demise of the RIS, on timescales of decades to centuries, may well provide an important precursor to eventual WAIS collapse.

The key aim of this research project is to determine past ice shelf responses to climate forcing, including variability at a range of timescales. To achieve this aim the ANtarctic Geological DRILLing Program (ANDRILL) will drill a stratigraphic hole from a platform located on the northwest corner of the Ross Ice Shelf - the McMurdo Ice Shelf (MIS) sector, east of Hut Point Peninsula, Ross Island. Drilling will be undertaken in the austral summer of 2006-2007. The primary target for the MIS site is a 1200m-thick body of Plio-Pleistocene glacimarine, terrigenous, volcanic, and biogenic sediment that has accumulated in the Windless Bight region of a flexural moat basin surrounding Ross Island (Harwood *et al.*, 2003). A single ~1000m-deep drill core will be recovered from the bathymetric and depocentral axis of the moat in approximately 900m of water. The drilling technology will utilize a sea-riser system in a similar fashion to the Cape Roberts Project (CRP), but will employ a combination of hydraulic piston coring (in upper soft sediments) and continuous wireline diamond-bit coring. Innovative new technology, in the form of a hot-water drill and over-reamer, will be used to make an access hole through ~ 200m of ice and to keep the riser free during drilling operations.

This prospectus outlines the background and scientific rationale for the McMurdo Ice Shelf (MIS) Project and presents specific scientific questions to be addressed. It provides a basis for prospective research participants to assess the merits of the MIS Project, and to make their applications to participate in the ANDRILL Program.

2. THE ANDRILL PROGRAM: BACKGROUND AND OVERVIEW

ANDRILL is a multinational program with objectives to recover stratigraphic intervals for use in interpreting Antarctica's climatic, glacial and tectonic history over the past 50 my, at various scales of age resolution (1 to 100,000 years). The key motivation for ANDRILL stems from a lack of knowledge of the complex role the Antarctic cryosphere (ice sheets, ice shelves and sea-ice) plays in the global climate system. Understanding the history of ice volume variation and associated physical changes in the Antarctic region is critical for assessing the interaction of ice sheets with other elements of the Earth System, such as ocean, atmosphere, lithosphere and biosphere. Accurate assessment of the scale and rapidity of changes affecting large ice masses is of vital importance because ice-volume variations: (1) lead to changing global sea-levels, (2) affect Earth's albedo, (3) control the latitudinal gradient of the southern hemisphere and thus heat transport via atmospheric and oceanic circulation, and (4) influence the distribution of ice shelves and seasonal sea-ice, which are commonly attributed to forming cold-bottom waters that drive global ocean circulation. General circulation models indicate that polar regions are the most sensitive to climate warming (and cooling), thus the projected global rise in mean temperature of 1.4-5.8°C by the end of the century (IPCC; Houghton *et al.*, 2001) is likely to be even greater in the Antarctic, with a significant impact on the Antarctic cryosphere.

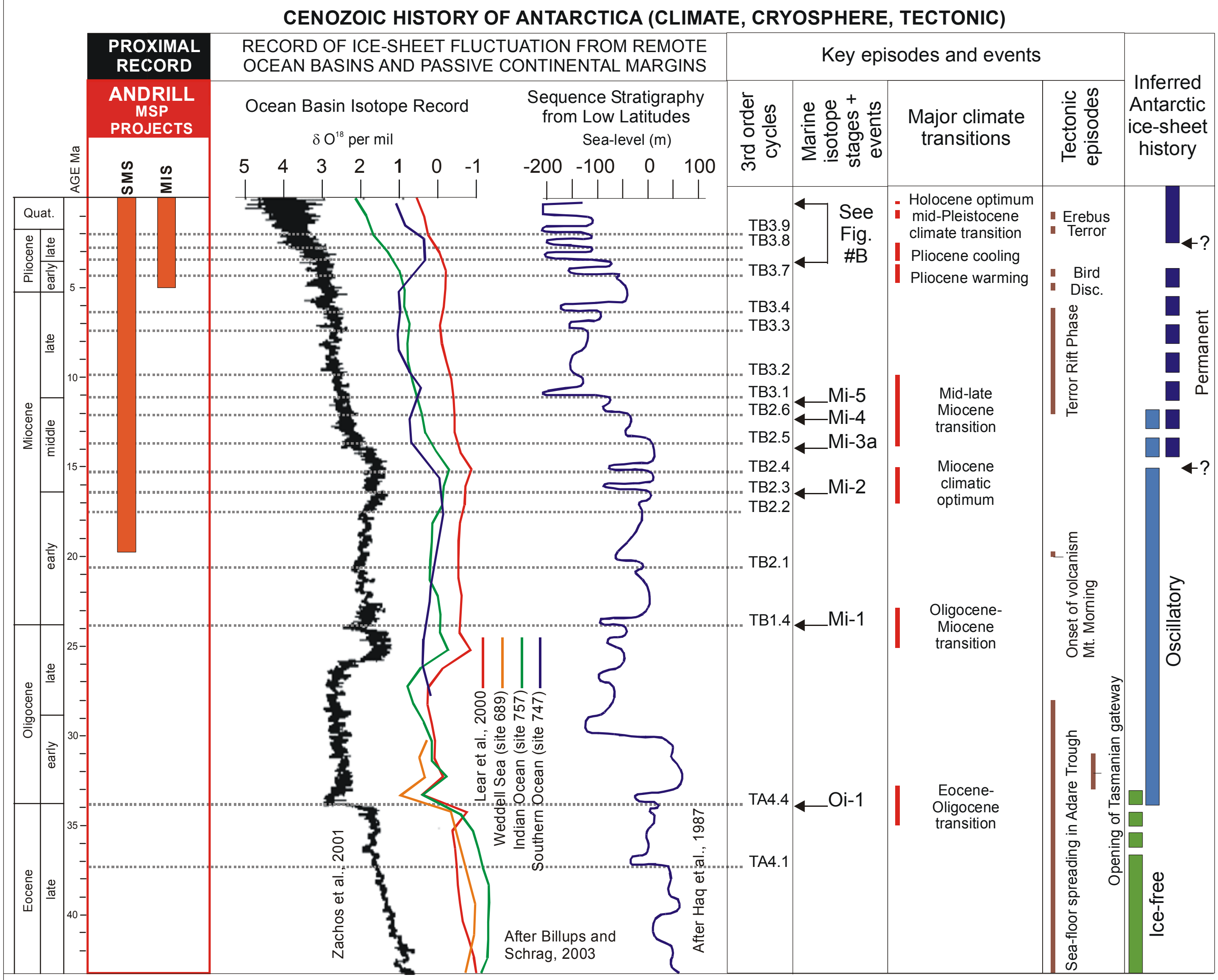

Figure 1. Each ANDRILL McMurdo Sound Project aims to recover stratigraphic intervals that preserve an Antarctic margin record of episodes and events of regional and global importance. These new data will provide direct calibration points for Antarctic cryospheric behaviour and resulting glacio-eustasy that is currently interpreted from remote ocean basins and from passive continental margins (ANDRILL International Science Proposal, 2003).

The ANDRILL Program recognizes that efforts to understand the role of Antarctic drivers on global climate variability require a fundamental knowledge of Antarctic cryospheric evolution, not only in recent times, but also for earlier periods when global temperature and atmospheric pCO_2 were similar to levels that might be reached by the end of this century. Due to a lack of Cenozoic strata exposed on land and a limited number of drill cores on the continental margin of Antarctica, our understanding of Antarctica's climate history relies heavily on inferences from low latitude climate-proxy records, such as deep-sea oxygen isotope records and sequence stratigraphic interpretations of non-glaciated passive margins (Fig. 1). Although a number of high-quality sedimentary archives that record past ice sheet behavior have become available recently from the CRP (e.g. Naish *et al.*, 2001; Wilson *et al.*, 2004) and from Ocean Drilling Program (ODP) legs 178 (e.g. Domack *et al.*, 2001) and 188 (e.g. Grutzner *et al.*, 2003), they remain too few in number to allow a comprehensive understanding of Antarctica's influence on global climate.

2.1 The McMurdo Sound Portfolio of stratigraphic drilling objectives

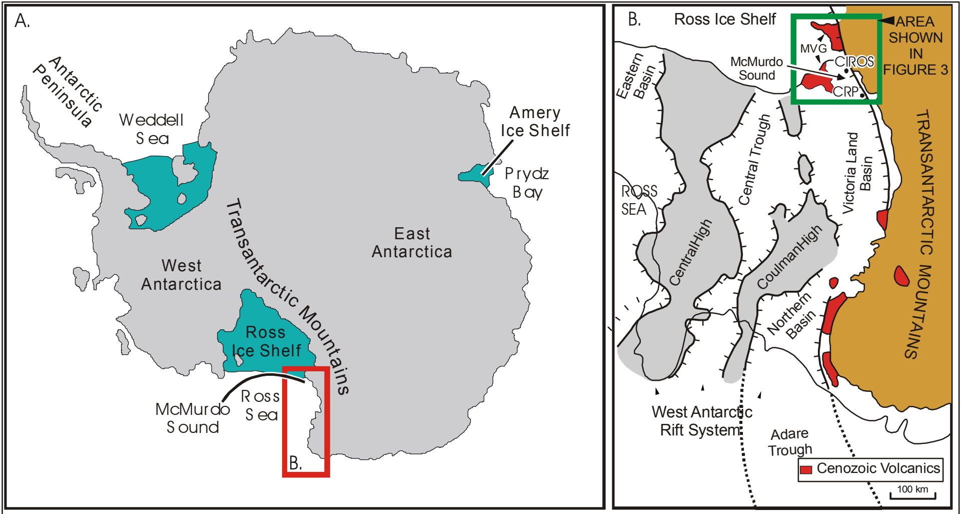

Figure 2. General location of the McMurdo Sound in western Ross Sea adjacent to the northwestern corner of the Ross Ice Shelf and the Transantarctic Mountains. Inset (B) shows the regional tectonic setting and area enlarged in Fig. 3 (ANDRILL International Science Proposal, 2003).

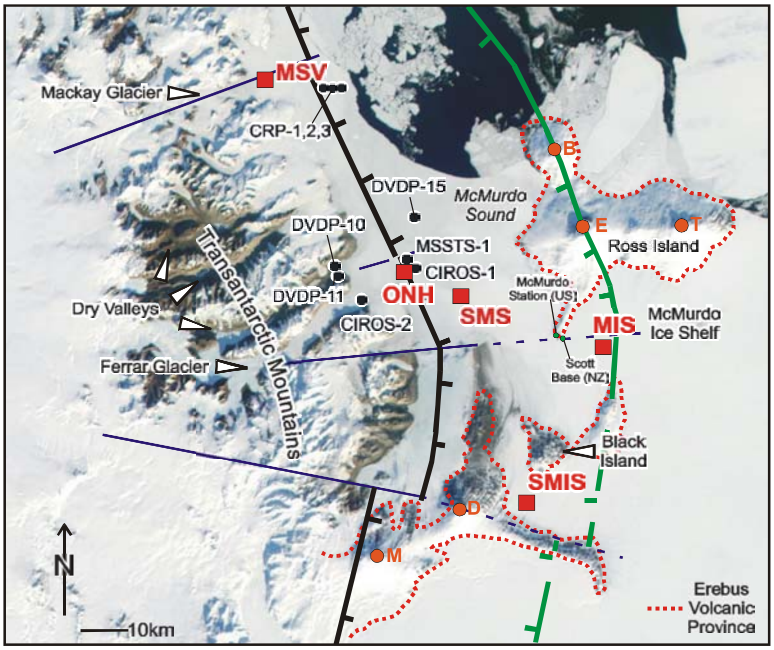

Figure 3. Location of key geographical and tectonic features in southern McMurdo Sound. Dotted coastline outlines the extent of the Erebus Volcanic Province (Kyle and Cole, 1974), while the volcanic centres of Erebus (E), Terror (T), Bird (B), Discovery (D), and Morning (M) are annotated. Drillsites proposed by the ANDRILL Program are also shown. Offshore New Harbour (ONH), Southern McMurdo Ice Shelf (SMIS), Southern McMurdo Sound (SMS), Mackay Sea Valley (MSV) and McMurdo Ice Shelf (MIS). MIS and SMS are scheduled for drilling in 2006-2007 and 2007-2008 austral summers, respectively. Also shown are the locations of previous stratigraphic drill holes in McMurdo Sound (ANDRILL International Science Proposal, 2003). NASA MODIS image I.D.: Antarctica.A2001353.1445.250m.

ANDRILL proposes to focus its initial efforts on the McMurdo Sound region, because it has a reasonably well-understood stratigraphic and tectonic framework, and is situated at a critical juncture between components of the West Antarctic Rift System, including the Victoria Land Basin (VLB), the Transantarctic Mountains (TAM) and the Erebus Volcanic Province (Figs. 2 & 3). Fault and flexure-related subsidence associated with rifting and volcanic loading has provided Early Cenozoic to Recent stratigraphic accommodation space adjacent to the rising TAM (Fig. 4). The combination of a high sediment supply from TAM and the accommodation provided by tectonic subsidence of the VLB has allowed the region to act as a "high-fidelity sedimentary tape recorder" for the past 50 my, helping preserve the contained sediments from the erosive effects of glacial advances that often remove ice-proximal records. McMurdo Sound is one of a limited number of locations that have been influenced by three significant components of the Antarctic cryospheric system: East Antarctic Ice Sheet (EAIS), Ross Ice Shelf (RIS)/WAIS, and Ross Embayment sea-ice.

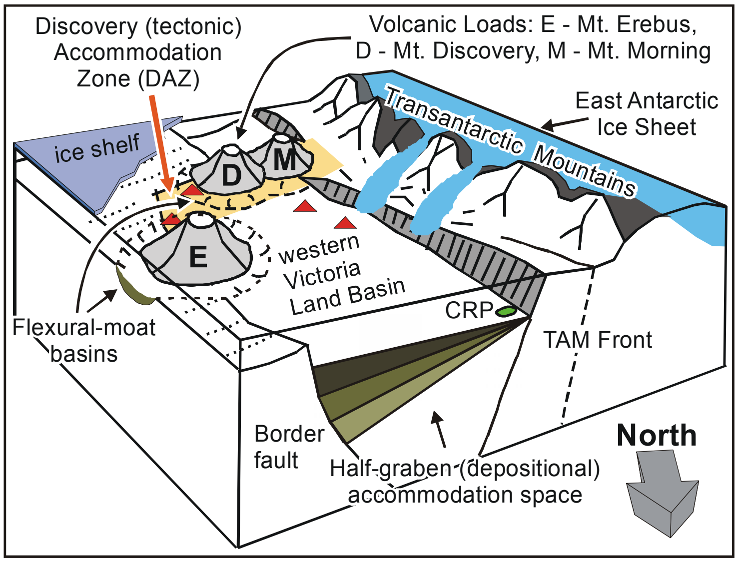

Figure 4. Schematic stratigraphic and structural cartoon of the Victoria Land Basin (VLB) shows development of accommodation space within a half graben, tilted to the west and bounded by a major down-to-the-west border fault system that controls the stratigraphic architecture of the basin-fill, which dips and thickens to the west. The Discovery Accommodation Zone (DAZ) is a transverse element where the rift-flank steps westward ~100 km (Wilson, 1999). Localized accommodation space is superimposed on the rift basin where Neogene volcanoes of the Erebus Volcanic Province have progressively depressed the crusts forming flexural-moat basins. The depositional accommodation space provided by the rift and flexural moat basins provides an unparalleled opportunity to recover stratigraphic records with high-resolution chronology provided by the dating of volcanic detritus integrated with biostratigraphic and magneto-stratigraphic techniques (ANDRILL International Science Proposal, 2003).

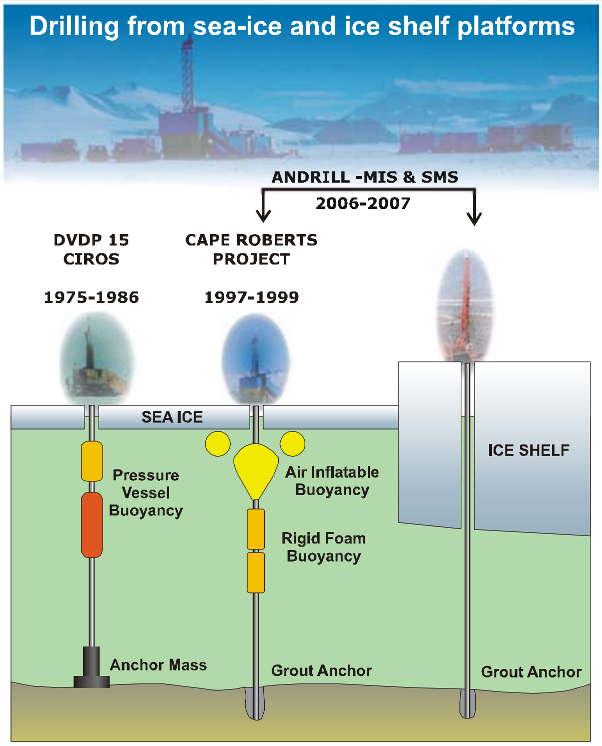

Figure 5. The ANDRILL Programme must address unique logistical and drilling requirements to achieve its science goals. New drilling tools have been developed (drill rig, coring tools, and riser system) from proven drilling technology that was employed during the Cape Roberts Project (ANDRILL International Science Proposal, 2003).

Moreover, the McMurdo Sound region has the best-understood sedimentary record from the Antarctic margin due to acquisition over the past 30 years of integrated seismic and drill-core data. These data greatly improve our ability to select drill sites with the greatest potential for achieving ANDRILL science goals (outlined in the ANDRILL International Science Proposal, 2003)

A new drilling system is currently being built for the ANDRILL Program that represents a significant technological evolution from the highly successful CRP drill system (Fig. 5). The drilling system will have the capacity to operate on both shore-fast-ice and ice shelf platforms and to recover continuous long stratigraphic records (up to 1200m) from water depths of up to 1000m.

Two projects within the McMurdo Sound Portfolio have been supported by the national science funding agencies and Antarctic Programs of the U.S.A., New Zealand, Italy, and Germany. The first Project, which is the subject of this prospectus, will be drilled from the MIS during the 2006-2007 austral field season. Drilling from a shore-fast sea-ice platform in Southern McMurdo Sound (SMS) is scheduled for the following field season in 2007-2008 (see SMS Scientific Prospectus, http://andrill.org).

3. MCMURDO ICE SHELF PROJECT

3.1 Introduction

Ice shelves, large floating bodies of ice fed by ice sheets, are extremely sensitive early indicators of climate changes affecting ocean and atmospheric temperatures. Warming around the Antarctic Peninsula over the last 50 years has led to catastrophic collapse of its fringing ice shelves, most notably the Larsen Ice Shelf collapse of March 2002 (e.g. Doake and Vaughn, 1991; Skvarca, 1993; Vaughn and Doake, 1996; Rott *et al.*, 1996; Doake *et al.*, 1998; Rott *et al.*, 1998; Skvarca *et al.*, 1999; Rott *et al.*, 2002). Future stability of the RIS, the world's largest ice shelf system, which is coupled to the behavior of the WAIS, is of wide interest in the context of current global warming projections (IPCC) (Houghton *et al.*, 2001). Despite calving of a 40km-wide strip of ice from its northern margin in 2000, the RIS is currently considered to be stable. However, recent glaciological evidence indicates that the RIS is becoming increasingly undernourished with at least one of its ice stream feeders from West Antarctica stagnating and at least one other slowing down (Joughin and Tulaczyk., 2002). Rapid fluctuations in the flow velocity of ice streams near the WAIS grounding line are being observed (Joughin *et al.*, 2002; Bindschadler *et al.*, 2003; Bougamont *et al.*, 2003), and suggest that over timescales of decades to centuries ice shelves may represent the most vulnerable element of the WAIS-RIS system, and that their collapse may come rapidly (MacAyeal; 1992). Their demise will provide an important precursor to eventual collapse of the West Antarctic Ice Sheet.

Collapse of the RIS could affect climate, WAIS ice sheet extent, and sea level in a number of ways: Firstly, a large-scale discharge of melt-water, coupled with a reduction in ice shelf area, could slow down the production of salty bottom water around Antarctica. Such an effect could significantly alter the global thermohaline ocean circulation system, which has been suggested to have caused abrupt climate changes of global extent in a decade or less (Clark *et al.*, 2002; Weaver *et al.*, 2003; Stocker, 2003). Secondly, Earth's albedo (the fraction of incident solar radiation reflected) will change as 560,000km^2 of permanent ice cover is replaced with shallow ocean, consequently amplifying regional warming (ice-albedo feedback). Lastly, the exchange of heat and water vapour between the ocean and the atmosphere could lead to accelerated loss and eventual collapse of the marine-based WAIS in as little time as just a few centuries, raising sea level by 5 to 6m (e.g. Alley and Bindschadler, 2001).

Of particular concern is that the fundamental behavior of the RIS is poorly understood and models on which predictions are based need to be constrained by new data (Bentley, 2004; Huybrechts 2004), including those gathered from records of the ancient RIS during times when Earth was known to be warmer than it is today. For example, sectoral collapses of WAIS-RIS are thought to have occurred both 125,000 and 400,000 years ago during "super-interglacial" warm periods (Marine Isotope Stage 5e and 11) (Scherer *et al.*, 1998; EPICA Community Members, 2004), when sea-level may have been 5-20m higher than today (Neuman and Hearty, 1996).

In the austral summer of 2006/07 the ANDRILL Program will drill at a site on the MIS on the northwestern corner of the RIS where it is pinned to Ross Island (Fig. 6). The site is situated in 900m of water. Drilling aims to recover a continuous 1000m-long sediment core from a sedimentary basin formed by the progressive emplacement of the Ross Island volcanic complex on the crust during the last 5 my. New multi-channel seismic reflection data reveal a well-stratified, regionally extensive sedimentary succession of at least 1.2km below the sea-floor in the deepest part of the depression (Horgan *et al.*, 2005) (Figs. 7 & 8A,B). We anticipate recovering a relatively complete sequence as phases of volcanic-loading of the crust are likely to have periodically over-deepened the basin (Stern *et al.*, 1991; Wilson *et al.*, 2003), providing a mechanism to accumulate and preserve a sedimentary, fill below the sole of WAIS during its past expansions.

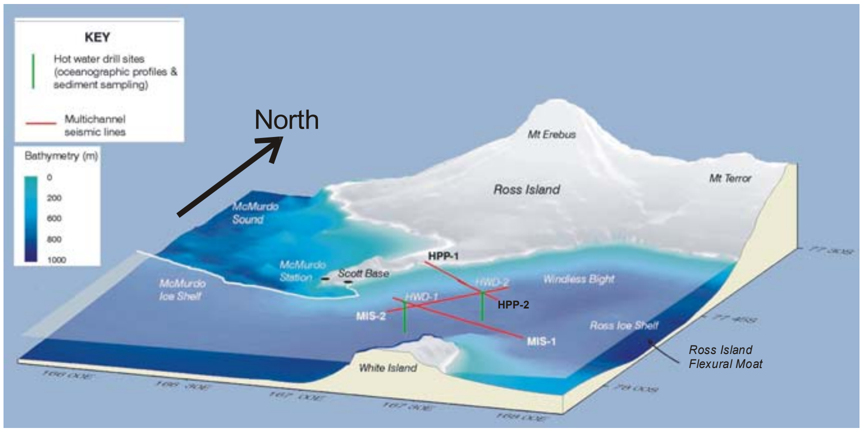

Figure 6. Bathymetry of the Ross Island flexural moat within the vicinity of the proposed ANDRILL MIS drillsite (at HWD-1) (after Horgan *et al.*, 2005). The locations of over-ice shelf seismic reflection lines (HPP-1, HPP-2, MIS-1, and MIS-2) and hot-water drilling and seafloor sampling sites (HWD-1 and HWD-2) are shown (Horgan *et al.*, 2005).

Radiometric age determinations on volcanic rocks from Ross Island (Wright and Kyle, 1990a and b; Kyle, 1990a, Esser *et al.,* 2004; Tauxe *et al*., 2004) date the timing of crustal loading by the volcanic pile and allows us to infer that the sediments preserved in the basin have accumulated over the past 5my. The MIS Project will recover the first long stratigraphic record from beneath a major ice-shelf system. Analysis of the environmental proxies contained within the cored sediments will significantly advance our knowledge of ice shelf behaviour during past climatic optima and in a future warmer world.

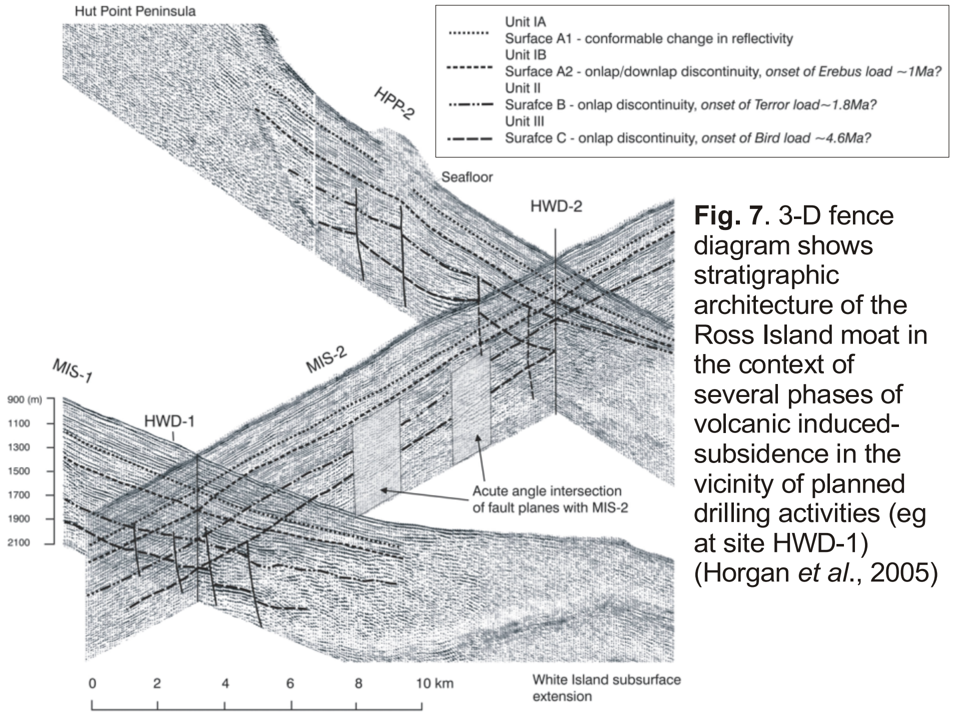

Fig. 7. 3-D fence diagram shows stratigraphic architecture of the Ross Island moat in the context of several phases of volcanic induced-subsidence in the vicinity of planned drilling activities (eg at site HWD-1) (Horgan *et al*., 2005)

3.2 Regional Tectonic and Stratigraphic Setting

Ross Island lies at the southern end of the Victoria Land Basin (VLB), a structural half-graben, approximately 350km-long, hinged on its western side at the Transantarctic Mountain front (Wilson, 1999). Major rifting in the VLB has occurred since the latest Eocene, perhaps having been initiated in the Cretaceous, and has accommodated up to 10km of sediment (Cooper and Davey, 1985; Brancolini *et al.*, 1995). Late Cenozoic extension in the VLB is associated with alkalic igneous intrusions (e.g. Beaufort Island and Ross Island) and led to the development of the Terror Rift (Cooper *et al.*, 1987).

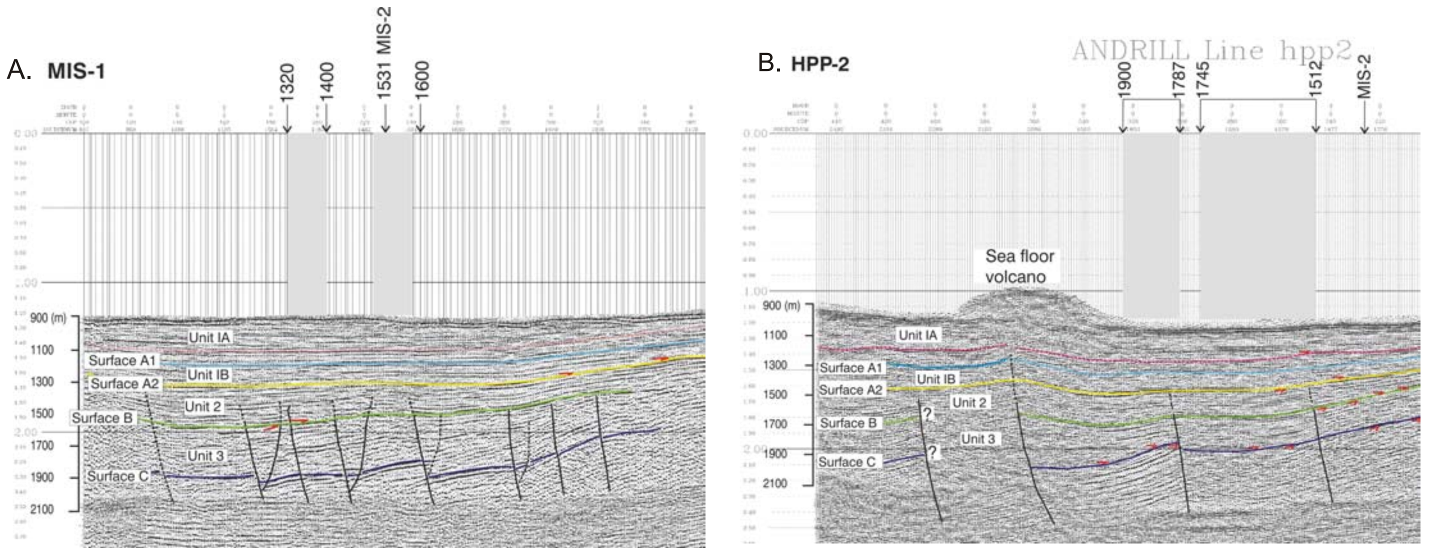

Figure 8. Processed and interpreted multi-channel seismic reflection profiles of the Ross Island flexural moat-fill, in Windless Bight east of Hut Point Peninsula (Fig. 6). All lines are oriented with east to the right. (A) MIS-1 line. (B) HPP-1, HPP-2 line. Shaded regions show possible sites for the MIS ANDRILL drill site. A location on MIS-1 line near the MIS-2 intersection is currently favoured (Naish, unpublished data).

Ross Island volcanic complex lies at the southern end of the Terror Rift (McGinnis *et al.*, 1985) and is considered to be associated with the latest phase of rifting. The complex comprises the central cone of Mt Erebus which is surrounded by Mt Bird, Mt Terror and Hut Point Peninsula each separated by ~ 120º. The radial distribution likely results from crustal doming and associated radial fracturing, due to mantle upwelling as a plume or hotspot (Kyle *et al*., 1992). Loading of the crust by the Ross Island volcanic pile has produced as much as 1.8km net subsidence beneath Ross Island and the development of an enclosing moat (Stern *et al.*, 1991). Local accommodation space created by the subsidence is superimposed on the regional pattern of accommodation space created by rifting (Fig. 4).

While Cretaceous and Paleogene strata are predicted to occur within the axis of the VLB (e.g. Davey and Brancolini *et al.*, 1995), to date, latest Eocene sediments are the oldest post-Paleozoic strata actually recovered by stratigraphic drilling. The

Eocene strata occur at the western margin of the basin and unconformably overlie Devonian sediments of the Taylor Group (Davey *et al.*, 2001). Since the latest Eocene, sedimentation along the western margin of the VLB has evidently kept pace with or exceeded the rate of subsidence resulting in the development of a 1.5 to 2km-thick sediment wedge, which thickens seaward.

The wedge comprises glacimarine conglomerates, diamicts, and sandstones with interbedded mudstones of nearshore and shelf affinity (Barrett, 1989; Cape Roberts Science Team, 2000). Numerous unconformities occur within the Oligocene and lower Miocene strata recovered in CIROS-1 and CRP drillcores (Fig. 3). A number of these unconformities have been correlated with sub-horizontal erosion surfaces in regional seismic lines (Henrys *et al.*, 2000; Fielding *et al.*, 2001), implying widespread grounding of an extensive ice terminus on the continental shelf during glacial periods. Coastal glacier behavior has been linked to mass changes in the interior East Antarctic Ice Sheet, which feeds through outlet glaciers in the TAM.

Interglacial-glacial periods during the Oligocene – lower Miocene are recorded by sedimentary sequences displaying vertical cyclical facies successions of ice retreat and re-advance (Powell *et al.*, 2001) in association with relative bathymetric deepening and shallowing, respectively (Naish *et al.*, 2001b). The frequency of oscillation in ice extent, which controls the finer-scale stratigraphic architecture of the basin-fill, corresponds to Milankovitch orbital forcing as inferred from global oxygen isotope records (Naish *et al.,* 2001a). The lack of long and continuous Plio-Pleistocene glacimarine drill core records in western VLB is probably due to sediment bypass across the western margin, and/or lack of accommodation, and/or erosion of these younger strata during periodic glacial expansions of the WAIS and grounding of the RIS over the last 5my. However, marine seismic data (Bartek *et al.*, 1991, 1996; Wilson *et al.*, 2004, unpublished data NBP-0401), and new seismic data presented here, suggest such records do exist farther east in the VLB and within the flexural moats associated with Plio-Pleistocene volcanic centers.

3.3 Site Survey and a Stratigraphic Interpretation of Target Interval

3.3.1 Seismic Stratigraphy

Ross Island volcanic complex began forming with the emplacement of the basaltic shield volcanoes of Mt Bird and Mt Terror between c. 4.6 and 1.3 Ma (Wright and Kyle, 1990a, b). However, the most significant development of the complex has occurred over the last 1my during an eruptive phase that produced the 3794m-high composite vent of Mt Erebus (Moore and Kyle, 1990; Esser *et al.*, 2004). Loading of the lithosphere at the southern end of the Terror Rift by the Ross Island volcanic pile has progressively depressed the crust resulting in a sub-circular flexural moat around the periphery of the Island.

Multi-channel seismic reflection data collected from the MIS sector of the RIS reveal the stratigraphic architecture of the moat-fill on the south eastern side of Ross Island (Bannister, 1993; Melluish *et al.*, 1995; Bannister and Naish, 2002; Horgan *et al.*, 2005). The moat region has accommodated a well-stratified, regionally extensive sedimentary succession of at least 1.2km below the sea-floor in the deepest part of the depression. Three seismic stratigraphic units are identified that generally thicken and dip towards Ross Island and are bounded by angular (onlap) unconformities (Horgan *et al.*, 2005). These units are deposited in accommodation space inferred to have been created during discrete phases of volcanic load-induced subsidence (Figs. 7 & 8):

1. Unit III. Moderate- to low-amplitude discontinuous reflectors that are dislocated and tilted by normal faulting and interpreted to represent coarse-grained glacigenic and fine-grained marine sediments with likely intercalated volcanic ash.
2. Unit II. Moderate- to high-amplitude continuous reflectors that onlap Unit III and are interpreted to represent coarse-grained glacigenic and fine-grained marine sediments with likely intercalated volcanic ash.
3. Unit I. Relatively continuous low-amplitude to seismically-opaque reflectors (Unit IB), onlap Unit II and grade upwards into moderate- to high-amplitude reflectors below the sea floor (Unit IA).

3.3.2 Seismic stratigraphic interpretation and age relationships: A prognosis for ANDRILL drilling

The geometry of the three seismic units described above has been interpreted in terms of inferred accommodation space generated by progressive emplacement of over 4600 km^3 of Ross Island volcanic centers (Esser *et al.*, 2004) on the crust in southern Terror rift (Horgan *et al.*, 2005). The chronology of the eruptive history of Ross Island (Kyle, 1990b; Esser *et al.*, 2004) (Fig. 9) indicates several phases of volcanism and associated load-induced subsidence within the adjacent flexural moat: Mt Bird loading between 4.6-3.8 Ma (Wright and Kyle, 1990a) and this was followed by a hiatus of over 1 million years. There was then continuous loading due to emplacement of Mt Terror from 1.7-1.3 Ma (Wright and Kyle, 1990b), Hut Point Peninsula from 1.6 till 0.33 Ma (Kyle, 1981, 1990a; Tauxe *et al.*, 2004) and Mt Erebus between 1.3 Ma and present day (Esser *et al.,* 2004).

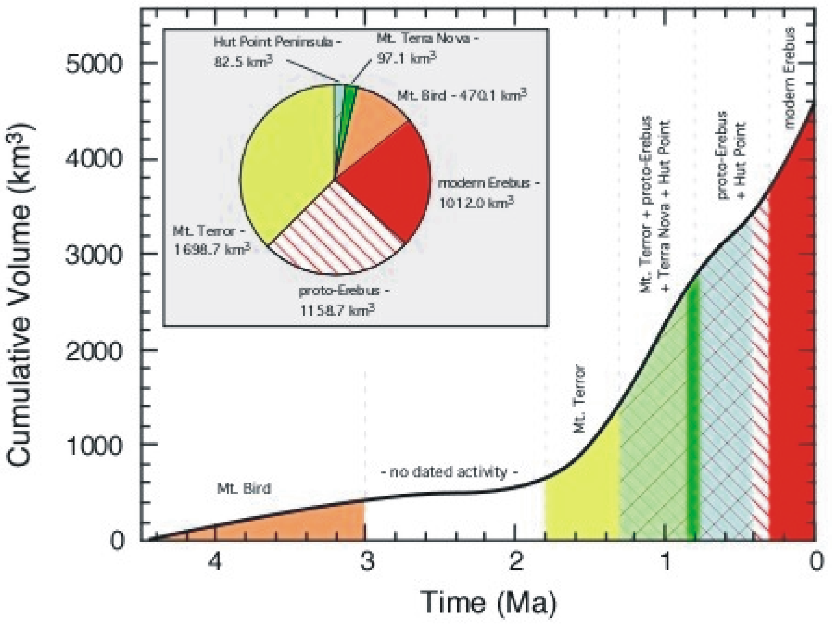

Figure 9. Plot showing the growth of Ross Island based on radiometric age determinations and estimated volumes of the various volcanic centers (Esser et al., 2004).

Flexural modeling of the lithosphere in response to these loads being emplaced at their respective times is being carried out presently and will be presented in a future paper (Wilson *et al.*, in prep). Initial results are consistent with the accommodation-space implied from the seismic stratigraphic architecture of the moat-fill presented in this prospectus (also see Wilson *et al.*, 2003).

Probable lithofacies are inferred from the nature of seismic reflectivity, lateral continuity of the reflectors, and internal geometry of the seismic units, all considered within the context of the probable depositional setting. In general, seismically-opaque or low-amplitude units are interpreted as predominantly fine-grained lithologies (e.g. mudstone and volcanic ash). Intervals of moderate to high-amplitude reflectivity are interpreted as coarse-grained or alternating coarse- and fine-grained lithologies (e.g. diamictite, conglomerate, sandstone, and/or coarse volcanic deposits). The stratigraphic interpretation and prognosis presented here is for a single drill site located near the intersection of lines MIS-1 and MIS-2 (Figs. 7 & 10).

Unit III, which comprises up to 350m of moderately reflective strata deformed by normal faulting, is interpreted as alternating coarse- (diamictite, conglomerate, lapilli and sandstone) and fine-grained (pelagic mud and ash) lithologies deposited in a flexural moat basin during Mt Bird loading (4.6-3.8 Ma). Local truncation of subjacent strata near normal fault blocks at the top of Unit III is intriguing. It may represent significant bathymetric shallowing and erosion by currents and/or grounding of ice on structural highs prior to the emplacement of the Mt Terror load. Subsequent onlap of the strata at the beginning of deposition of Unit II implies rapid regional subsidence and reorientation of the seafloor perhaps in association with the beginning of Mt Terror volcanism (1.7-1.3 Ma).

Unit II, which comprises up to 300m of relatively continuous moderately to highly reflective strata, is interpreted as infilling of the Mt Terror flexural moat with alternating coarse- (diamictite, conglomerate, lapilli and sandstone) and fine-grained (pelagic mud and ash) lithologies, that progressively fine-upwards.

Unit I, which comprises up to 400m of relatively continuous strata that display increasing reflectivity upward, is interpreted to represent progressive infilling of the Mt Erebus flexural moat from seismically opaque fine-grained sediments (pelagic mud and ash) to highly reflective coarse-grained deposits (diamictite, conglomerate, lapilli and sandstone) with intervening fine-grained (pelagic mud and ash) lithologies. Onlap of strata at the beginning of deposition of Unit I is interpreted as rapid regional subsidence and reorientation of the seafloor coincident with the onset of significant volcanic activity from Mt Erebus (< 1.3 Ma). The predominance of seismically-opaque facies within the lower 150m (Unit IB) is consistent with initial rapid subsidence and bathymetric deepening, prior to infilling and shoaling to more proximal coarse-grained glacimarine facies in the upper 250m (Unit 1A).

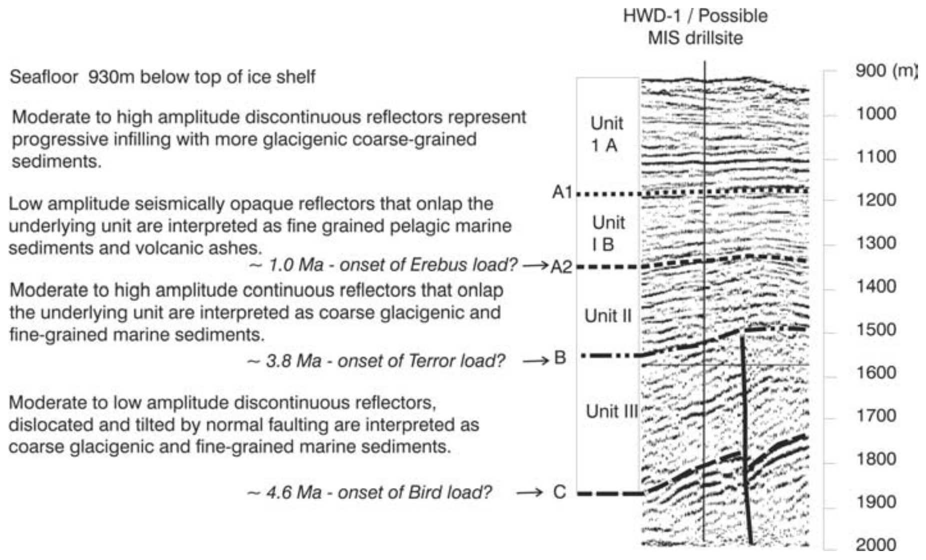

Figure 10. Summary interpretation and stratigraphic prognosis of the moat-fill succession in the vicinity of the proposed drillsite near HWD-1 (near the intersection of the MIS-1 and MIS-2 lines) (Horgan et al., 2005).

The close vicinity of the MIS drill site to Ross Island and nearby White Island to the south ensures that volcanic sediments should dominate in the core. Subtle differences occur in the compositions between volcanic material from Mt Erebus compared to Bird, Terror and Hut Point, which radially surround Erebus (Kyle, 1990b). Erebus lavas define the Erebus lineage (Kyle *et al.*, 1992) and are more evolved in composition and have olivine throughout the magmatic fractionation series. Lavas in the three areas surrounding Erebus are characterized by Dry Valley Drilling Project (DVDP) lineage lavas (Kyle, 1981), which usually contain kaersutite in the more evolved lavas. Volcanic eruptions usually produce, almost instantaneously, significant volumes of fragmented material (pyroclasts), which are easily transported. With Hut Point Peninsula being the closest landmass to the MIS drill site, eruptions at Hut Point should cause episodic rapid influxes of volcaniclastic material. Evidence of subglacial eruptions are rare on Ross Island suggesting that ice cover was not extensive for long periods of time, so one can also expect deposition of fall tephra from the more explosive phonolitic vents on Ross Island.

3.3.3 Faulting and Deformation

High-angle, north-south trending faults, aligned with the structural grain of the Terror Rift, offset horizontal to sub-horizontal strata below 1.7s two-way travel time (TWT) (about 1600m), with normal throws of up to 100ms TWT (about 90m) in lines MIS-2 and HPP-2 (Figs. 7 & 8). These faults do not offset strata above seismic Unit III; however, they do appear to mildly deform sub-horizontal reflections in the base of seismic Unit II (see below). The strike of the eastern most faults in line MIS-2 (Fig. 3), are inferred to intersect line MIS-2 at a very acute angle, which may explain the loss of coherency below seismic Unit II in the line. The cessation of normal faulting within Unit II may represent a change in local stress regime, as the concentric pattern of crustal flexure is progressively superimposed on the pre-existing regional pattern of extension within the Terror Rift.

3.3.4 Bathymetry

Bathymetry appears to deepen away from Ross Island to a maximum water depth of 1.2s TWT (950m) about 7km east of Hut Point Peninsula along the HPP-1/HPP-2 composite line (Figs. 6 & 7). Farther eastward along this line the moat begins to shallow to a depth of 810m. South and farther to the east a pronounced bathymetric shallowing from 950 to 400m occurs along the MIS-1 line as it passes over the northern sub-seafloor extension of deformation associated with White Island volcanic center, and then progressively deepens beyond this to 700m. We note that all bathymetric conversions from TWT to meters require assumptions concerning ice shelf thickness and the velocity characteristics of the ice shelf and water column.

3.3.5 Oceanography

In 2002 (Barrett *et al.*, 2004), oceanographic measurements were obtained from beneath the MIS at hotwater drill sites HWD-1 and HWD-2 near Windless Bight (see Figs. 6, 7, and 11). Water column measurements from the two locations show that the net current direction is to the east from McMurdo Sound through to the RIS (Fig. 11), with speeds averaging 5 to 7cm/sec but at times reaching 17cm/sec. Flow measurements obtained at a third, shallower location at the ice shelf edge near Scott Base, were in the same net direction but were faster – up to 60cm/sec.

Water column profiles beneath HWD-1 and 2 also encountered waters with extremely low temperatures and high densities. Salinity and temperature measurements are similar to those recorded 25 years ago at the first ever hole drilled through the RIS some 400km south of the MIS site at J9 (Jacobs *et al.*, 1979). These sub-ice shelf water masses, which comprise Deep Ice Shelf Waters (DISW) and High Salinity Shelf Waters (HSSW) are some of the coldest and densest in the world. Modification of Circumpolar Deep Water (CDW) by Ross Sea Shelf Water helps drive the global thermohaline conveyor system, although the magnitude and significance of Ross Sea Shelf Water on CDW composition is not well constrained (see summary by Jacobs, 2004).

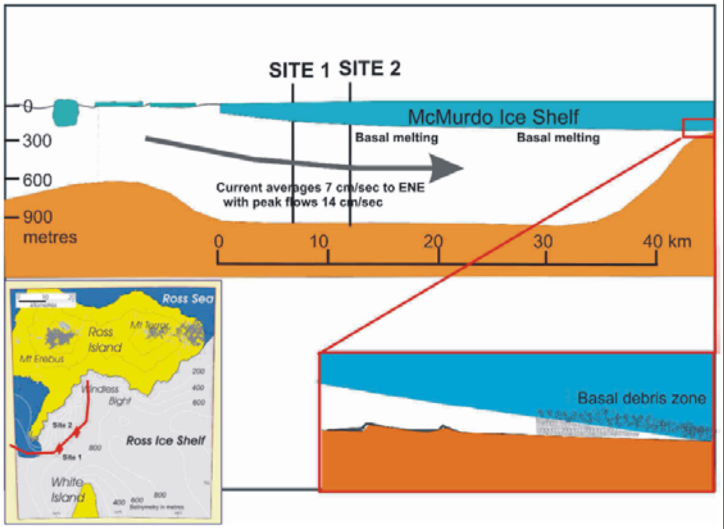

Figure 11. Schematic cross-section from the calving line of the McMurdo Ice Shelf at the southern end of Hut Point Peninsula through HWD sites 1 and 2 northwards beneath Windless Bight. Note that proximity of the calving line and current speeds allow transportation open water biogenic detritus and terrigenous sediments to the seabed near the core sites (Barrett *et al*., 2004).

3.3.6 Seafloor and Shallow Sub-Seafloor Stratigraphy

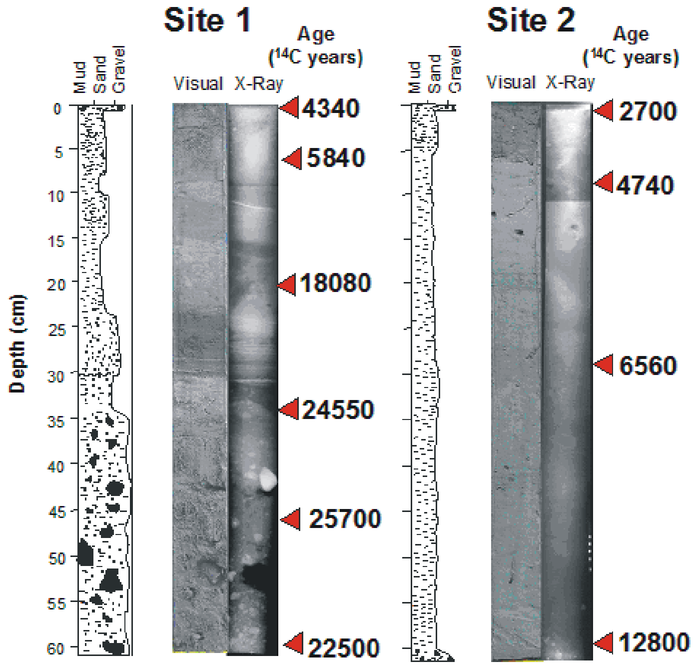

Figure 12. Stratigraphy and chronology of short sediment cores recovered from HWD sites 1 & 2 (Barrett *et al*., 2004)

A high-amplitude seafloor arrival is observed in all profiles with the exception of the western end of the HPP-1 line, where the profile runs up onto Hut Point Peninsula. In 2002, shallow sediment cores (up to 80cm-long) were acquired from the seafloor near the intersections of both MIS-1 and HPP-2 with MIS-2 (Barrett *et al.*, 2004; Fig. 12). The two sites, respectively, located 5 and 12km east of the shelf edge near Scott Base, were covered by ice 70 and 143m-thick, and lay at water depths of 926m and 923m.

Seafloor samples at both sites comprise soft mud, diatoms, foraminifera and micro-molluscs (Barrett *et al.*, 2004). Diatom taxa recovered at the sites usually live in open marine waters and are inferred to have been carried under the ice shelf by currents (Fig. 11). Recovery of the foraminifera and micro-mollusc assemblages was unexpected as (1) these assemblages are typically found locally at shallower depths and (2) we had assumed that the cold and deep corrosive (from carbonate under-saturation) waters would inhibit carbonate preservation. A transition from fine-grained sediment to a loosely consolidated diamicton occurs at ~ 30 cm in the core recovered at the HWD-1 site. The diamicton is interpreted to have been deposited beneath floating ice at a location proximal to the grounding line of the WAIS as it last retreated through the MIS area after having occupied most of the Ross Sea during the last glacial maximum (Licht *et al.*, 1996; Conway *et al.*, 1999; Domack *et al.*, 1999; Hall and Denton, 2000a, b.; Fig. 12). Shear strength measurements from the diamicton indicate that the sites were too deep to have been over-compacted or eroded by grounded ice. This observation, together with the variable nature of the sediment recovered in the cores, supports our conjecture that the planned 1000m-deep hole will recover a relatively complete and sensitive record of Ross Ice Shelf history for the past 5my.

3.4 Towards a Glacial-Interglacial Depositional Model

The aim of the sub-seabed coring was to test and develop a depositional model for sedimentation in the Ross Island flexural moat below the ice shelf during the Last Glacial Maximum (LGM) and the Pleistocene-Holocene deglacial transition. The model presented here is based on data from the two cores described above and is compared with previously published models that were (a) developed from direct study of a modern system (Powell *et al.*, 1996; Dawber and Powell, 1998) and (b) inferred from the record of Holocene glacial retreat in Ross Sea sediments (Domack and Harris, 1998; Domack *et al.*, 1999; Fig. 13). The last glacial-interglacial transition is well–constrained in these latter studies by radiocarbon chronologies, and should provide a basis for interpreting older Pleistocene glacial-interglacial sequences to be recovered in the ANDRILL MIS drilling.

Domack *et al.*, (1999) describe a "typical" glacial to open-marine vertical succession of facies based on studies of a number of sediment cores from Western Ross Sea that includes in ascending stratigraphic order: (1) over-consolidated massive, mud-rich diamictons of subglacial affinity, (2) a granulated sandy, muddy gravel facies associated with the lift-off zone, (3) well-sorted, very fine sand interpreted as sub-ice shelf near the grounding-line, which passes upwards into (4) a siliceous mud representing deposition in an open marine environment. In some cases a sandy volcaniclastic facies marks the transition from sub-ice-shelf to open marine conditions and the passage of the calving line.

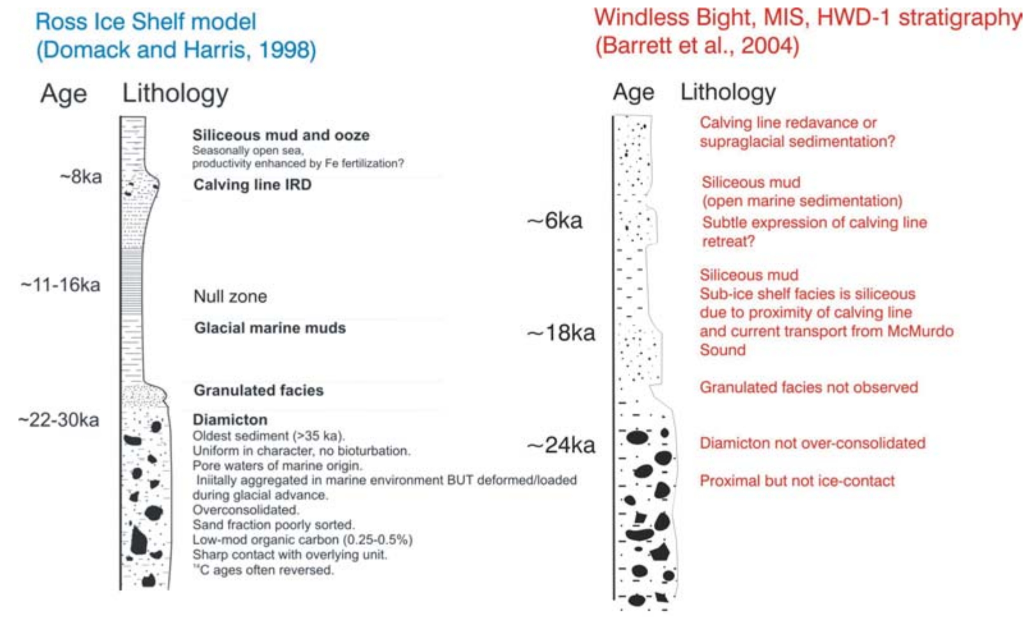

Figure 13. Depositional models developed for the Pleistocene-Holocene glacial-interglacial transition in Ross Sea (Domack and Harris, 1998; Domack *et al.*, 1999) and beneath the McMurdo Ice Shelf in the Ross Island flexural moat.

The deglacial facies succession from the Ross Island flexural moat below the McMurdo Ice Shelf differs in three important ways from Domack *et al.*'s model; first, the last glacial diamicton is not over-consolidated, and appears more like the glacimarine diamicton accumulating by sub-ice-shelf rainout near the grounding line of modern Mackay Glacier (Powell *et al*, 1996). The normal consolidation of the diamicton indicates that the WAIS-RIS did not ground in the over-deepened moat regions during the LGM. Secondly, in a similar way to the modern Mackay Glacier (cf. Powell *et al.*, 1996), the granulated "lift-off zone" facies is absent, but a well-sorted sand above the diamicton may indicate proximity to the grounding line. Thirdly, sub-ice-shelf mud facies comprise siliceous open-marine biogenic components owing to the proximity of the drill sites to the calving line and strong currents sweeping northwards up the moat from McMurdo Sound. The sweeping-in of biogenic material under the floating ice is similar to that occurring beneath the modern Mackay Glacier Tongue (Dawber and Powell, 1998). Sandy mud facies near the top of the core at HWD-1 site may reflect subtle fluctuations in the position of the calving line during the Holocene.

On the basis of the depositional models outlined above, it should be possible to reconstruct fluctuations in ice shelf extent for the MIS area using predictable sedimentological and biogenic criteria. These criteria represent a range of states including full glacial (grounded and floating) ice sheet, present day interglacial ice shelf with proximal calving line, and ice-free "super-interglacial" open marine conditions (Fig. 14).

3.5 Chronostratigraphy

Regular contributions of volcaniclastic sediments and tephra to the moat-fill succession over the last 5my from the Erebus Volcanic Complex will greatly aid the development of a high-resolution chronostratigraphy. We anticipate being able to develop an age model for the cored record based on radiometric dating of tephra (e.g. fission track and Ar/Ar), biostratigraphy (primarily diatom, but other microfossil groups such as marine palynomorphs, foraminifera and radiolaria may be useful), paleomagnetic, stratigraphy, and cyclostratigraphy. Other potentially useful tools will be strontium isotope dating of calcareous macrofossils (depending on preservation) and radiocarbon dating of the organic components for the uppermost part of the core.

Such a chronology will be critical if millennial-scale variations in ice shelf processes are to be compared with more distal atmospheric ice core (e.g. EPICA) and oceanic deep marine records.

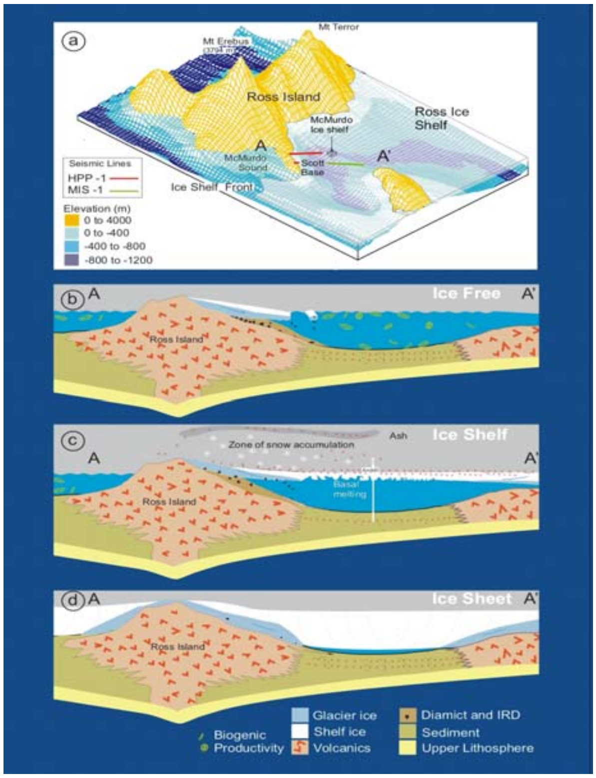

Figure 14. Schematic representation of the ANDRILL-MIS drillsite under (B) ice-free "super-interglacial" open marine conditions (e.g. MIS 11), (C) present day conditions with the calving line pinned by Ross Island, and (D) full glacial conditions (e.g. LGM) (G. Dunbar, unpublished data).

4. SCIENTIFIC OBJECTIVES

4.1 Overview

Cycles in oxygen isotope records from deep-sea sediment cores spanning the last 3my (Fig. 15), have been taken to indicate global sea-level fluctuations of up to 120m which have occurred primarily as a consequence of orbital control (40 and 100ky) on high-latitude Northern Hemisphere temperature and ice volume. Although increased ice mass on Antarctica is thought to account for about 20% of the observed oxygen isotope signal at the LGM (18ka), behavior of the inherently unstable, marine-based WAIS and its ice shelves in response to Quaternary glacial-interglacial climate variability remains poorly understood. Concern over the future integrity of the WAIS, and recognition that changes to the more vulnerable RIS will provide precursory warning signals, necessitates a better understanding of the fundamental

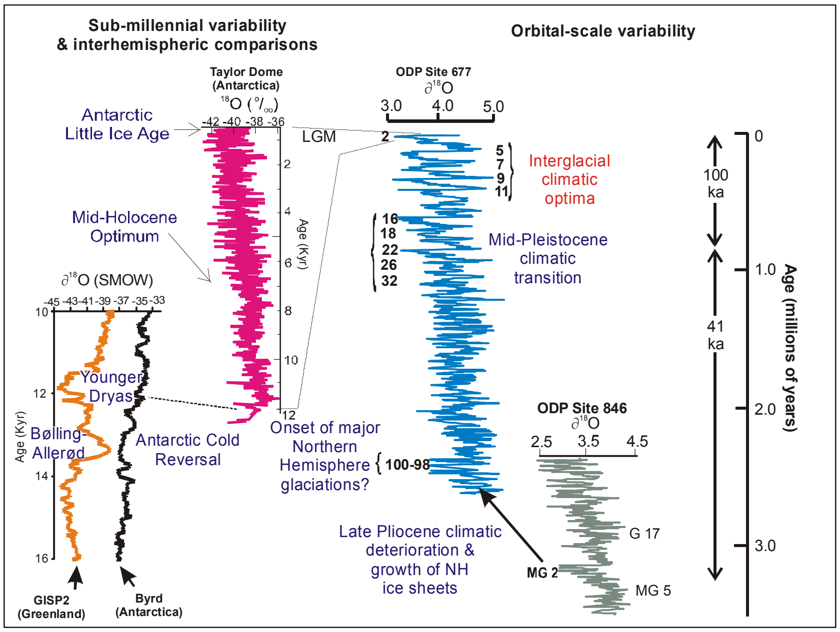

Figure 15. Global proxy records of climate variability at orbital and sub-millennial scale for the past 3.5 my. The MIS Project will provide proximal cryospheric paleoenvironmental data on these timescales.

behavior of the RIS during past glacial-interglacial climatic extremes.

Moreover, at orbital and millennial time-scales, the trigger for Northern Hemisphere climate change may well lie in the south, and likely includes variations in Antarctic melt-water discharge (Clark *et al.*, 2002; Weaver *et al.*, 2003) and Southern Ocean surface warming (Stocker, 2003). Prior attempts to constrain the rate, magnitude and timing of ice-shelf/ice-sheet advance and retreat in western Ross Sea have been hampered by lack of long, high-resolution sediment core records that are relatively continuous. Moreover, the resolution of seismic data has been too low to resolve facies and sequences on the scale of sediment core records, thus restricting accurate regional mapping of ice margin behavior. Although, some previous shallow core studies have contributed to an understanding of the retreat from the last maximum extent of the WAIS system in the Ross Sea (Domack and Harris, 1998; Domack *et al.*, 1999), a coring program is yet to reach back to interglacial warm climate extremes such as MIS 11 (about 400ka).

4.2 Key Climatic Questions to be Addressed

The MIS project will contribute to our understanding of the behavior of the RIS as a dynamic element of the global climate system. We are motivated by the question…

> ***"How will the Ross Ice Shelf behave as global average temperatures continue to rise over the next few centuries?"***

Are the atmosphere and ocean systems coupled to the RIS and the WAIS such that climatic warming is likely to trigger (or have past climatic changes have already triggered) widespread break-up and collapse of the ice shelf? Attempts to predict the future behavior of the ice shelf requires development of models that have been tested with geological data which provide insight into past environmental conditions. Therefore, a specific goal of this project is to…

> ***"Determine ice shelf response to climate forcing, including previous ice shelf collapse, over the past 5my at a range of temporal scales (10^2-10^4 years)."(Fig. 15)***

Water masses in the Ross and Weddell Sea's comprise some of the coldest and densest in the world and are important contributors to Antarctic Bottom Water (AABW) that helps drive the global thermohaline conveyor system. AABW and associated CDW decouple from the Antarctic Circumpolar Current to enter the Pacific Ocean via the Earth's largest abyssal current, which flows along the eastern margin of New Zealand (e.g. Carter *et al.*, 2004; Fig. 16). Modeling studies imply that melt-water released during periods of retreat or collapse of the WAIS reduces the density of southern deep-water masses. Less dense southern water masses can potentially strengthen thermohaline circulation and cause the North Atlantic to warm (Weaver *et al.*, 2003, Stocker, 2003). The concept of a Southern Ocean "flywheel" in global ocean

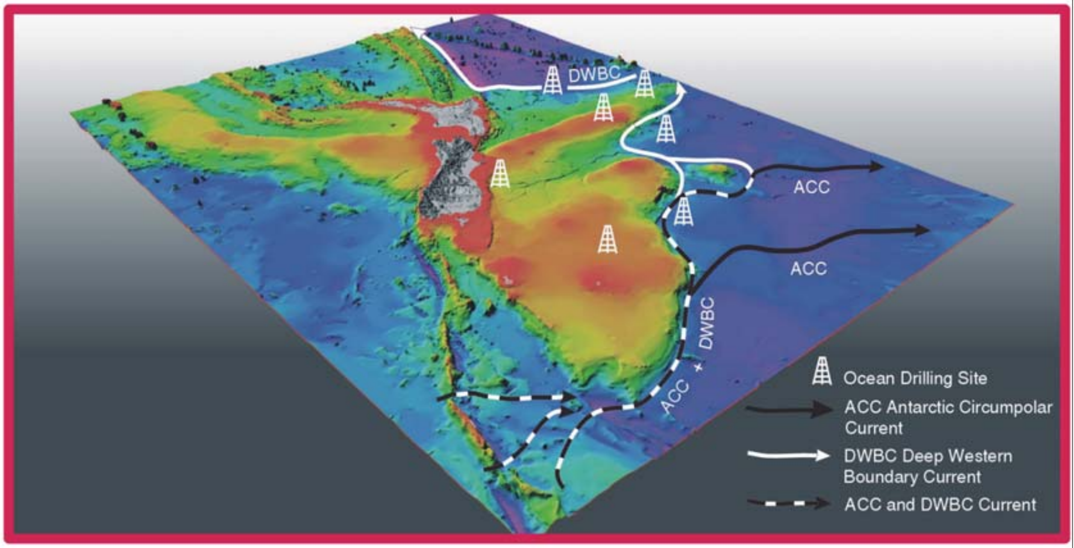

Figure 16. Inflow of Circumpolar Deep Water (CDW) along the eastern edge of the New Zealand continental margin where it decouples from the Antarctic Circumpolar Current (ACC) at 55 S and continues its passage into the Pacific Basin as the Deep Western Boundary Current (DWBC) (Carter *et al*., 2004). The DWBC carries 60 % of cold deep water to the global ocean conveyor. High-quality sedimentary records of the Plio-Pleistocene history of deep Pacific inflow are available from ODP Leg 181 drilling through sediment drifts along eastern New Zealand (e.g. *Hall et al*., 2001). These records, which imply glacial-interglacial variations in the production of Antarctic Bottom Water AABW, will be correlated with proximal records of RIS variability from ANDRILL MIS drilling.

circulation and climate involving Antarctic ice-wasting and associated melt-water discharge will be tested by this project. Therefore, another high-level goal is to…

> ***"Relate RIS variability to thermohaline circulation as expressed by variations in abyssal Pacific inflow along eastern New Zealand to the Pacific Ocean, and compare the phasing of these histories with northern hemisphere records"***

The objectives of this project will be achieved by investigating well-located Plio-Pleistocene sedimentary records from beneath the northwest corner of the Ross Ice Shelf, east of Ross Island, that will enable high-quality drill hole and core data to be linked to detailed regional stratal geometry from seismic reflection surveys and ultimately correlated downstream with lower-latitude and Northern Hemisphere sedimentary records.

Specific climatic and tectonic objectives are to determine the:

1. Timing of RIS-WAIS development relative to major ice expansion of northern hemisphere ice sheets about 3.0 to 2.5 Ma.
2. Nature of grounding- and calving-line variability during both the last glacial cycle and Plio-Pleistocene climate cycles.
3. Behavior of the RIS during past interglacial warm climatic optima (e.g. MIS 5e, 11, 31), and interstadial warm periods.
4. Sedimentological and biological evidence for RIS collapse and melt-water discharge.
5. Effect of RIS collapse on the global thermohaline ocean conveyor.
6. Phase relationships between RIS collapse and Northern Hemisphere climatic events.
7. History of the Ross Island Volcanic Complex and relationship between rift-related and "hot-spot" volcanism.
8. Flexural response of the local continental lithosphere to volcanic and sediment loading.
9. Nature of Plio-Pleistocene basin formation and deformation in the area.
10. Temporal relationships between volcanism, ice volume, relative sea-level and glacio-eustasy.

5. THE SCIENCE TEAM

An interdisciplinary team of international researchers will employ cutting edge approaches to address the fundamental scientific questions and achieve the key scientific objectives of the ANDRILL's MIS Project. We anticipate that 27 members of the Science Team will work on-ice in Antarctic during core recovery. Other members of the MIS Project Science Team will work at their home institutions and receive samples and information about on-ice results on a regular basis. Disciplines and numbers of scientists and technicians required for the on-ice component are summarized in Table 1 below. It is anticipated that an equal number of scientists may be working off-ice at their home institutions. Both the on-ice and off-ice teams would meet at the Core Characterization Workshop several months after the completion of drilling to review the new results, examine the core and select sample intervals for future studies. The composition of the off-ice

DISCIPLINE / POSITION'S AVAILABLE		DISCIPLINE / POSITION'S AVAILABLE	
Phys Props - Whole core	1	**Petrography (volcanic)**	1
Phys Props - Whole core (T)	2	Thin-section technican (T)	1
Phys Props - downhole	2	**Micropaleontology - Diatoms**	3
Phys Props - downhole (T)	1	Paleontology Technician (T)	1
Seismic Stratigraphy/VSP	1	**Micropaleontology - Foraminifera**	1
Fracture Studies	2	**Macropaleontology**	1
Fracture studies technician (T)	2	**Paleomagnetism**	2
Sedimentology (log)	2	Paleomag samplers (T)	2
Sedimentology (facies/seq.)	2	**Clastology**	2
Sedimentology (smear-slide analyses)	2	**Split Core - XRF**	1
Petrography (sedimentary and general)	1	XRF scanner technician (T)	2
-	-	Science Educators	6

Table 1. List of required on-ice science disciplines and positions available

science team is unknown at this time, pending receipt of applications and description of proposed science activities. It is anticipated that the off-ice team will include a team of geochemists, paleomagnetists, palynologists, paleontologists and other disciplines.

We invite all scientists who are eligible and interested to apply (note that eligibility requires that the nation in which you currently work is contributing to the logistical and operations costs of the MIS Project). We particularly encourage individuals who can offer new and innovative approaches to Antarctic stratigraphic research. Please contact Dr. Tim Naish (Co-Chief Scientist – New Zealand), Dr. Ross Powell (Co-Chief Scientist – U.S.) or the ANDRILL Science Management Office for more information.

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