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Background to the ANDRILL McMurdo Ice Shelf Project (Antarctica) and Initial Science Volume

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INTRODUCTION TO THE VOLUME

The aim of the McMurdo Ice Shelf (MIS) Project was to obtain a continuous sediment core through approximately ~1 200 metres (m) of Neogene (~0-10 Ma) glacimarine, terrigenous, volcanic, and biogenic sediment that has accumulated in the Windless Bight region of the McMurdo Ice Shelf (Fig. 1). The present-day MIS forms the northwest part of Ross Ice Shelf where it has been pinned by Ross Island for the last ~10 k.y., and is nourished by ice sourced from East Antarctic Ice Sheet (EAIS) outlet glaciers in the southern Transantarctic Mountains (TAM). The drill site was situated above a flexural moat basin adjacent to Ross Island that formed in response to Quaternary volcanic loading of the crust by Ross Island, superimposed on more regional subsidence associated with Neogene extension of the Terror Rift (Horgan et al. 2005; Naish et al. 2006; Fig. 2).

Between 29 October and 26 December 2006 a single 1 285 m-deep, drill core (AND-1B) was recovered from the bathymetric and depocentral axis of the moat in 943 m of water from an ice-shelf platform. The drilling technology employed a sea-riser system in a similar fashion to the Cape Roberts Project (CRP), as well as a combination of soft sediment 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, was used to make an access hole through 85 m of ice and to keep the riser free during drilling operations.

The MIS Project has two key scientific objectives:

- Provide new knowledge on the Late Neogene behaviour and variability of the Ross Ice Shelf/Ice Sheet (RIS) and the West Antarctic Ice Sheet

Fig. 1 – Location of key geographical, geological and tectonic features in Southern McMurdo Sound. Volcanic centres of the Erebus Volcanic Province include Mt Erebus (E), Mt Terror (T), Mt Bird (B), White Island (W), Black island (B), Mt Discovery (D), Mt Morning (M) and Minna Bluff (MB). Location of cross-section A-A (Fig. 4) is shown. Boundary faults of the southern extension of Terror Rift are also shown. Together with the location of the MIS (AND-1B) drill site and the location of the proposed drill site for the Southern McMurdo Sound (SMS) Project to be drilled in late 2007.
(WAIS), and their influence on global climate, sea level, and ocean circulation.

- Provide new knowledge on the Neogene tectonic evolution of the West Antarctic Rift System (WAR), Transantarctic Mountains (TAM), and associated volcanism.

A key outcome of the project will be to provide age control for, and determine the environmental significance of, seismic reflectors that have been mapped regionally within the Victoria Land Basin (VLB) (Henrys et al. this volume; Fielding et al. in press; Wilson et al. in press) in order to assess the regional impact of global climatic and local tectonic events. A second key outcome of the project will be to use palaeoclimatic proxies and boundary conditions to help constrain numerical global climate and dynamical ice sheet models. The specific climatic, environmental, and tectonic aims and objectives of the MIS Project are outlined in the Scientific Logistics Implementation Plan for the ANDRILL McMurdo Ice Shelf Project (SLIP; Naish et al. 2006).

This volume presents the initial science results of the AND-1B drill-hole and drill core, and associated short soft-sediment cores recovered as part of the MIS Project. The first iteration of this volume was compiled on ice as part of the Web-based MIS Project On-Ice Report. It has subsequently been expanded to include the results of continuing multidisciplinary core-characterisation activities conducted off-ice, prior to a core workshop held at Florida State University, Antarctic Marine Geology Research Facility, 1–4 May 2006. In this section we provide contextual background on the geological and environmental setting, site surveys, and stratigraphic prognosis prior to drilling. This is followed in Falconer et al. (this volume) by an operational overview of the environmental conditions that affected drilling, the drilling operation itself, the curation and management of the core and the science operations both at the drill site and at Crary Laboratory. The rest of the volume provides the initial scientific characterisation of the drill core set out under major discipline areas. Finally, we offer some initial syntheses and areas of further investigation.

**TECTONIC AND GEOLOGICAL SETTING**

Ross Island lies at the southern end of the Victoria Land Basin (VLB), a structural half-graben, approximately 350 km long, hinged on its western side at the Transantarctic Mountain (TAM) front (Fig. 2). Major rifting in the VLB has occurred since the latest Eocene, perhaps having been initiated in the Cretaceous, and has accommodated up to 10 km of sediment (e.g. Cooper & Davey, 1985). Late Cenozoic extension in the VLB is associated with alkalic igneous intrusions and extrusive volcanisms (e.g. Beaufort Island and Ross Island) and has led to the development of the Terror Rift (Cooper et al. 1987).

Ross Island itself is likely associated with the latest phase of rifting. The complex comprises the central cone of Mount (Mt) Erebus which is surrounded by Mt Bird, Mt Terror and Hut Point Peninsula each separated by ~120°. The radial distribution has been interpreted to represent 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 km 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 Late Cenozoic rifting (Figs. 3 & 4).

Originally described by Cooper et al. (1987), the Terror Rift is located within the VLB, in the western Ross Sea. It comprises two parts, the Discovery Graben and the Lee Arch. Faults reach the seafloor within the Terror Rift, indicating that the rift represents the youngest episode of faulting within the Western Antarctic Rift System (WARS). Cooper et al. (1987) proposed a ‘magmatically intruded Lee Arch’ along
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the eastern margin of the Terror Rift. New seismic lines from the Drygalski Ice Tongue, in the north, to south of Ross Island show that the ‘arch’ is a structural feature not associated with magmatic intrusion or doming (Henrys et al. in press; Fielding et al. in press). North and south of Ross Island, the arch has been extensively intruded by Late Cenozoic volcanic rocks that obscure the structural geometry. The arch can be projected southward where it forms eastern uplifted margin of a half graben that has accommodated up to 3 km of Neogene sediment beneath Windless Bight. Here, the load-induced subsidence caused by Ross Island has contributed significantly to the generation of accommodation space, especially during the last ~ 2 Ma.

Cretaceous and Palaeogene sediments are predicted to occur within the axis of the VLB (e.g., Davey & Brancolini, 1995). However, to date latest Eocene sediments are the oldest post-Palaeozoic 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 2 km-thick sediment wedge that thickens seaward to approximately 7 km underneath Ross Island (Fig. 4). On its western margin the wedge comprises glacimarine conglomerates, diamicts, and

Fig. 3 – Schematic stratigraphic and structural cartoon of the Victoria Land Basin (VLB) shows development of accommodation space within a half graben, tilted to the east 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 east. The Discovery Accommodation Zone (DAZ) is a transverse element where the rift-flank steps westward ~100km (Wilson 1999). Localised accommodation space is superimposed on the rift basin where Neogene volcanoes of the Erebus Volcanic Province have progressively depressed the crust 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 magnetostratigraphic techniques (figure from T. Wilson, unpublished data).

Fig. 4 – Schematic structural-stratigraphic cross-section across the VLB shows the stratigraphic context of the MIS and SMS drill sites with respect to previous drilling in Southern McMurdo Sound. The cross-section is compiled from interpreted seismic reflection data, previous drill core data (Barrett 1986; 1989) and models for the evolution of the VLB (Cooper et al. 1987; Fielding et al. 2005; Wilson et al. in press).
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 Cenozoic Investigations in the Western Ross Sea (CIROS)-1 and CRP drill cores (Fig. 4). A number of these unconformities have been correlated with subhorizontal 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 behaviour 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. 2001; Dunbar et al. in press). 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. 2001). The lack of long and continuous Plio-Pleistocene glaciomarine drill-core records in the western VLB is probably the result of sediment bypass across the western margin, due to the 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 5 m.y. However, marine seismic data (Bartek and Anderson 1991; Bartek et al. 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 depocentral axis of the Terror Rift where flexural moats have formed in association with Plio-Pleistocene volcanic centres. Younger Neogene strata have been extensively mapped in Southern McMurdo Sound from the Drygalski Ice Tongue south to Ross Island. These strata show a thickening and eastward-dipping succession that extends under Ross Island in the vicinity of the MIS Project drill site (Fielding et al. in press; Henrys et al. in press).

**SEISMIC STRATIGRAPHY**

Multichannel seismic reflection data collected from the MIS sector of the RIS reveal the stratigraphic architecture of the moat-fill on the southeastern side of Ross Island (Bannister 1993; Melluish et al. 1995; Bannister & Naish 2002; Horgan et al. 2003; Horgan et al. 2005; Henrys et al. 2006; Naish et al. 2006; Henrys et al. in press) (Figs. 5 & 6). The moat region has accommodated a well-stratified, regionally extensive sedimentary succession of 1.8 km below the seafloor in the deepest part of the depression (Fig. 7). 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; Naish et al. 2006). These units are deposited in accommodation space inferred to have been created during phases...
of volcanic load-induced subsidence superimposed on basin-scale transtensional subsidence associated with development of the Terror Rift (Figs. 7 & 8):

- 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.

- 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.

- Unit I. Relatively continuous low-amplitude to seismically opaque reflectors (Unit IC) onlap Unit II and grade upwards into moderate- to high-amplitude reflectors below the seafloor (Units IB and IA). Units IB and IA are separated by Surface A0 which locally truncates Unit IB and is characterised by onlap above.

Figure 9 shows the pattern of N–S normal faulting and major structural lineations within the Terror Rift. The location of lines used to construct two west-to-east seismic cross-sections (Fig. 4) is shown on this map. These cross-sections reveal an eastward-dipping and -thickening package of strata dislocated by N–S-trending high-angle normal faults and bounded in the east by an N–S line of intruded volcanic bodies, the southernmost body forming the edifice of White Island (Fig. 7). The volcanism is coeval with Late Miocene/Early Pliocene to recent extension in the Terror Rift and appears to be associated with a major west-dipping normal fault forming the eastern margin of a half graben that can be traced from Minna Bluff (Henrys et al. 2006) to Drygalski Ice Tongue (Hall et al. 2005). A gravity survey acquired along the MIS 5 seismic line shows a positive water-adjusted free-air anomaly east of the graben over the volcanics, which may also be indicative of a shallow basement horst block.

**SEISMIC STRATIGRAPHIC INTERPRETATION AND AGE RELATIONSHIPS PRIOR TO 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 4,600 km$^3$ of Ross Island volcanic centres (Esser et al. 2004) on the crust in southern Terror Rift (Horgan et al. 2005) in combination with basin-scale subsidence associated with Neogene transtensional normal faulting and subsequent thermal relaxation (Wilson et al. in press; Fielding et al. in press). The chronology of the eruptive history of Ross Island (Kyle 1990b; Esser et al. 2004; Alan Cooper unpublished data) indicates several phases of volcanism and potentially associated load-induced subsidence within the adjacent flexural moat; Mt Bird loading between 4.6 and 3.8 Ma (Wright & Kyle 1990a) was followed by a hiatus of over 1 m.y. There was then continuous loading due to emplacement of Mt Terror from 1.7 to 1.3 Ma (Wright & Kyle, 1990b), Hut Point Peninsula from 1.6 to 0.33 Ma (Kyle 1981, 1990a; Tauxe et al. 2004) and Mt Erebus between 1.3 Ma and present day (Esser et al. 2004). White Island volcanism appears to have begun as early as 7 Ma. A wedge-shaped unit interpreted as volcanic deposits can be traced from the flanks of White Island along the MIS 1 line towards the MIS drill site where they overlie Surface B (dark green reflector).

Flexural modelling 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. 2003). Initial results are consistent with the accommodation space implied from the seismic stratigraphic architecture of the moat fill for Unit I. Recent compilations (Fielding et al. in press; Henrys et al. in press) of the seismic stratigraphy of Southern McMurdo Sound incorporating a grid of new multichannel marine data (Wilson et al. 2004) reveal a clear relationship...
between volcanism and sedimentation in Terror Rift. Between Ross Island and the Drygalski Ice Tongue, volcanic bodies consistently overlie the dark green reflector and their inferred deposits are intercalated with strata of seismic units I and II. On this basis we infer an age of \( \sim 5-7 \) Ma for the surface (Fig. 10). Thus, Units I and II are of probable Plio-Pleistocene age, and their accommodation space was provided through a combination of progressive crustal flexure from volcanic loading, especially in Unit I, superimposed on basin-scale extension, which is likely to have been more influential on the geometry of Unit II. The red reflector, b-clino, (Fig. 10) has also been mapped regionally west and north of Ross Island where it marks the base of westward-thickening and dipping strata of the Terror Rift. Tentative correlation of this horizon with an unconformity immediately below an interval of Pliocene mudstone in the drill core from McMurdo Sound Sediment and Tectonics Studies (MSST) implies an age for Unit I of \( \sim 4 \) Ma.
The deepest unconformity to be targeted by the MIS drilling was the so-called 'bilious green' reflector (Surface C). The age of this reflector can only be speculated. It lies stratigraphically between the beige reflector (Fielding et al. in press) dated at 17 Ma in CRP 2/2A and the dark green reflector (5 - 7 Ma). If the unconformity, which is characterised by stratal truncation below and by onlap above, is climatic in origin it may correspond to one of the major Late Miocene glaciations (Mi-4-7; Miller et al. 1991). Fielding et al. (in press) also associate this surface with renewed rifting in the VLB.

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,
Fig. 10 – Seismic velocity to depth conversion and interval velocity analysis at the MIS Project drill site. A stratigraphic prognosis is inferred on the basis of limited age information and lithofacies interpretation of the seismic characteristics.
seismically opaque or low-amplitude units are interpreted as predominantly fine-grained lithologies (e.g. mudstone, ooze, 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). A stratigraphic prognosis was presented in the MIS SLIP (Naish et al. 2006) for the drill site (Fig. 10).

Unit III, which comprises up to 350 m of moderately reflective strata deformed by normal faulting, is interpreted as alternating coarse-grained (diamictite, conglomerate, lapilli, and sandstone) and fine-grained (pelagic mud and ash) lithologies with a thick lower velocity interval of probable mudstone between 1000 and 800 metres below seafloor (mbf; Fig. 10) that has been accommodated by rifting. Local truncation of subjacent strata near normal fault blocks at the top of Unit III is intriguing. It may represent erosion by currents and/or grounding of ice on structural highs prior to the emplacement of volcanic loads on the crust. 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 alkalic volcanism in the region.

Unit II, which comprises relatively continuous moderately to highly reflective strata up to 300 m-thick, is interpreted as infilling the Terror Rift and possibly the accommodation space associated with the early development of the flexural moat, by alternating coarse-grained (diamictite, conglomerate, lapilli, and sandstone) and fine-grained (pelagic mud and ash) lithologies that progressively fine-upward.

Unit I, which comprises up to 400 m of relatively continuous strata that display increasing reflectivity upward, is interpreted to represent progressive infilling of the Ross Island flexural moat from seismically opaque fine-grained sediments (pelagic mud, ooze, and/or ash) to highly reflective coarse-grained deposits (diamictite, conglomerate, lapilli, and sandstone) with intervening fine-grained (pelagic mud, ooze, and/or ash) lithologies.

**VOLCANISM**

The close vicinity of the MIS Project drill site to Ross Island, nearby White Island to the south, and numerous subsurface volcanic features interpreted from aeromagnetics (Wilson et al. in press) suggested that volcanic sediments should be well represented in the core. Subtle differences occur in the compositions between volcanic material from Mt Erebus compared to Mt Bird, Mt Terror, and Hut Point, which radially surround Mt Erebus (Kyle 1990b). Mt Erebus lavas define the Erebus lineage (Kyle et al. 1992) and are more evolved in composition and have olivine throughout the migmatic fractionation series. Lavas in the three areas surrounding Mt Erebus are characterised 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) that are easily transported. With Hut Point Peninsula being the closest subaerially exposed landmass to the MIS Project 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, so deposition of fall tephra from the more explosive phonolitic vents on Ross Island was also anticipated.

Numerous small volcanic cones occur on the seafloor under the McMurdo Ice Shelf. Many of these have clear signatures in aeromagnetic data (Wilson et al. in press) and have been identified in seismic reflection data (Horgan et al. 2005). A buried volcanic edifice has been identified in the MIS-4 seismic line no more than 2 km south of the MIS drill site. This feature appears to overlie the dark green seismic reflectors and is interstratified within seismic Unit II. The volcanic feature may have erupted in a submarine environment and contributed material to the sedimentary succession.

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