Terra Antartica
2007, **14**(3), 317-327

Synthesis of the Initial Scientific Results of the MIS Project (AND-1B Core), Victoria Land Basin, Antarctica

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Abstract - The ANDRILL Program successfully recovered a 1285 m-long succession of cyclic glacimarine sediment with interbedded volcanic deposits in its first season of drilling from the McMurdo Ice Shelf (MIS). The MIS AND-1B drill core represents the longest and most complete (98% recovery) geological record from the Antarctic continental margin to date, and will provide a key reference record of climate and ice-sheet variability through the Late Cenozoic. Here we present a synopsis of this Initial Science Report with emphasis on the potential of the record for improving our knowledge of Antarctica's influence on global climate.

INTRODUCTION

The aim of the MIS Project was to obtain a continuous sediment core through *c.* 1200 metres (m) of Neogene (*c.* 0–10 Ma) glacial, glacimarine, volcanic, and biogenic sediment that has accumulated in the Windless Bight region of the McMurdo Ice Shelf. 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 flowing 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; Fielding et al. in press).

Between the 29 October and 26 December 2006 a single 1284.87 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), but employed 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 shelf and to keep the riser free during drilling operations.

CHRONOSTRATIGRAPHY

The available age data allow a relatively well-constrained age model to be constructed for the upper 700 m of the AND-1B drill core (Wilson et al., Preliminary Integrated Chronostratigraphy, this volume). Available diatom biostratigraphic constraints (Scherer et al. this volume) and $^{40}Ar/^{39}Ar$ ages (Wilson et al., Preliminary Integrated Chronostratigraphy, this volume) allow a unique correlation of ~70% of the AND-1B magnetic polarity stratigraphy (Wilson et al., Palaeomagnetism of the AND-1B Core, this volume) with the geomagnetic polarity time scale (GPTS; Ogg & Smith 2004). Unique correlation is not possible in several coarse diamictite intervals with closely spaced glacial erosion surfaces and sparse microflora. The age model indicates relatively rapid (up to 1 m/k.y.) and continuous accumulation of intervening finer-grained diatomaceous intervals punctuated by several half- to million-year hiatuses, representing more than half of the last 7 m.y. of the AND-1B record.

THE PLEISTOCENE RECORD
(0–150 metres below seafloor [mbsf])

A significant hiatus (1.7–2.4 m.y.) coincident with the Rk seismic reflector separates an overlying Pleistocene succession dominated by diamictite from an underlying Pliocene succession of alternating diamictites and diatomites. The hiatus coincides with a closely spaced pair of glacial erosion surfaces identified at 150.23 and 150.73 mbsf and represents about 0.7 m.y. Two $^{40}Ar/^{39}Ar$ ages on basaltic tephra constrain the interval between 112 and 136 mbsf to the lowermost Pleistocene and indicate relatively rapid accumulation (*c.* 5 m/k.y.). A series of glacial surfaces of erosion between 93 and 109.42 mbsf account for much of the early Pleistocene (Chron C1r.3r) followed by a less rapidly accumulated interval of normal polarity between 80.03 and 84.97 mbsf, which immediately overlies the felsic tephra (1.014 ± 0.004 Ma at 85.53-85.85 mbsf) and is correlated with ChronC1r.1n (Jaramillo). Accumulation rates of the diamictite interval above 72.84 mbsf are 0.5 m/k.y. or less, but poor recovery in the upper 30 m and sparse age data in the upper 50 m at present prevent any better constraint on the upper Pleistocene.

THE LATE PLIOCENE RECORD *(150–c. 350 mbsf)*

Between 150 m and *c.* 350 mbsf, correlation of the AND-1B magnetic polarity record with the GPTS is constrained by several first and last occurrences of diatom species as well as diatom assemblage zones generally represented by diatomite intervals punctuated by diamictite intervals with poorly represented diatom flora. Although the combined diatom flora suggests that this interval of the core correlates with the mostly normal Chron C2An (Gauss), the AND-1B polarity record is dominated by reversed polarity and represented by an R-N-R polarity pattern. The intervals between 150 and 210.56 mbsf and at about 300 mbsf are relatively well constrained and correlated with the Chron C2An.1n/Chron C2r.2r (Gauss/Matuyama) boundary and Chron C2An.2r (Mammoth), respectively. While unambiguous correlation is not possible for the rest of the upper Pliocene interval of the core, an average accumulation rate of 0.2 m/k.y. with Milankovitch order cyclicity in diatomite/diamictite alternations is indicated. The Rj seismic reflector (*c.* 3 Ma) appears to correlate with a lithologically distinct diamictite–diatomite transition marked by an erosion surface at ~285 mbsf.

THE EARLY PLIOCENE RECORD *(c. 350–c. 620mbsf)*

A succession of disconformities between 346.03 and 375.85mbsf contain the boundary between Early and Late Pliocene with a 0.5–1 m.y. hiatus distributed on one or more of the glacial surfaces of erosion. Diatom flora constrains a unique correlation of the interval between 350 and 620 mbsf with Chrons C3n.1n (Cochiti) to C3n.r (one of the short reversed subchrons within the Gilbert) of the GPTS. An average accumulation rate of 0.5 m/k.y. is indicated for both the mostly diatomaceous intervals as well as the alternating diatomite/diamictite intervals. The exception is the lower part of diatomaceous lithostratigraphic unit 4.1, where a much slower accumulation rate (~0.1 m/k.y.) is indicated. This interval corresponds with seismic reflection horizon Ri.

THE MIOCENE RECORD *(Deeper than c. 620mbsf)*

Below *c.* 620 mbsf, an $^{40}Ar/^{39}Ar$ age (6.48 ± 0.13 Ma) on the basaltic lava flow at 648.37-648.43 mbsf indicates a Late Miocene age for this interval of the core and a correlation with Chron C3A is implied. A *c.* 1 m.y. hiatus is distributed among several disconformities between 615 and 635 mbsf. At the time of this writing, the only chronostratigraphic data available below 700 mbsf include three $^{40}Ar/^{39}Ar$ ages (13.82 ± 0.09 Ma; 13.85 ± 0.18 Ma and 13.57 ± 0.13 Ma) on volcanic clasts from near 1280 mbsf providing a maximum depositional age for the base of the AND-1B drill core.

STRATIGRAPHIC ARCHITECTURE

The 1 284.87 m-long, AND-1B drill core provides the first long high-resolution, Late Cenozoic, record from nearshore glacimarine settings for Antarctica (Fig. 1). It also provides the first rock-core record ever recovered from under a major ice shelf. Details of the lithostratigraphic subdivision, facies analysis, and sequence stratigraphy are presented in Krissek et al. (this volume).

GLACIAL-INTERGLACIAL CYCLOSTRATIGRAPHY

At the time of writing, 60 unconformity-bounded glacimarine sedimentary cycles, of probable Milankovitch-duration have been identified, representing repetitive advances and retreats of an ice sheet across the vicinity of the drill site during the Late Neogene. Bounding unconformities, *glacial surfaces of erosion* (GSEs), are typically sharp and planar and mark dislocations between enclosing facies. Immediately subjacent facies display a range of intraformational deformation, including physical mixing of lithologies, clastic intrusions, faulting, and soft-sediment deformation. Superjacent facies are typically coarse grained, such as diamictites and conglomerates, and are interpreted as subglacial tillites or near grounding-line glacimarine deposits. In many cycles, the facies succession reflects retreat of the grounding line through ice shelf into open-ocean environments at the interglacial minimum, followed by ice readvance characterised by progressively more glacially dominated facies in the upper parts culminating in a GSE at the glacial maximum. This stratigraphic motif is similar to that described for Cape Roberts cores from older successions in the same area (Fielding et al. 2000; Naish et al. 2001). However, this succession is deeper water, reflecting no influence of sea-level changes, and displays many similarities to the glacially dominated model developed by Powell & Cooper (2002).

MAJOR CHRONOSTRATIGRAPHIC INTERVALS AND THEIR CYCLIC CHARACTER

Here we summarise the overall AND-1B cored succession by subdividing it into six chronostratigraphic intervals on the basis of characteristic facies cycles, and their glacial and climatic signatures. These intervals are punctuated by two major volcanic

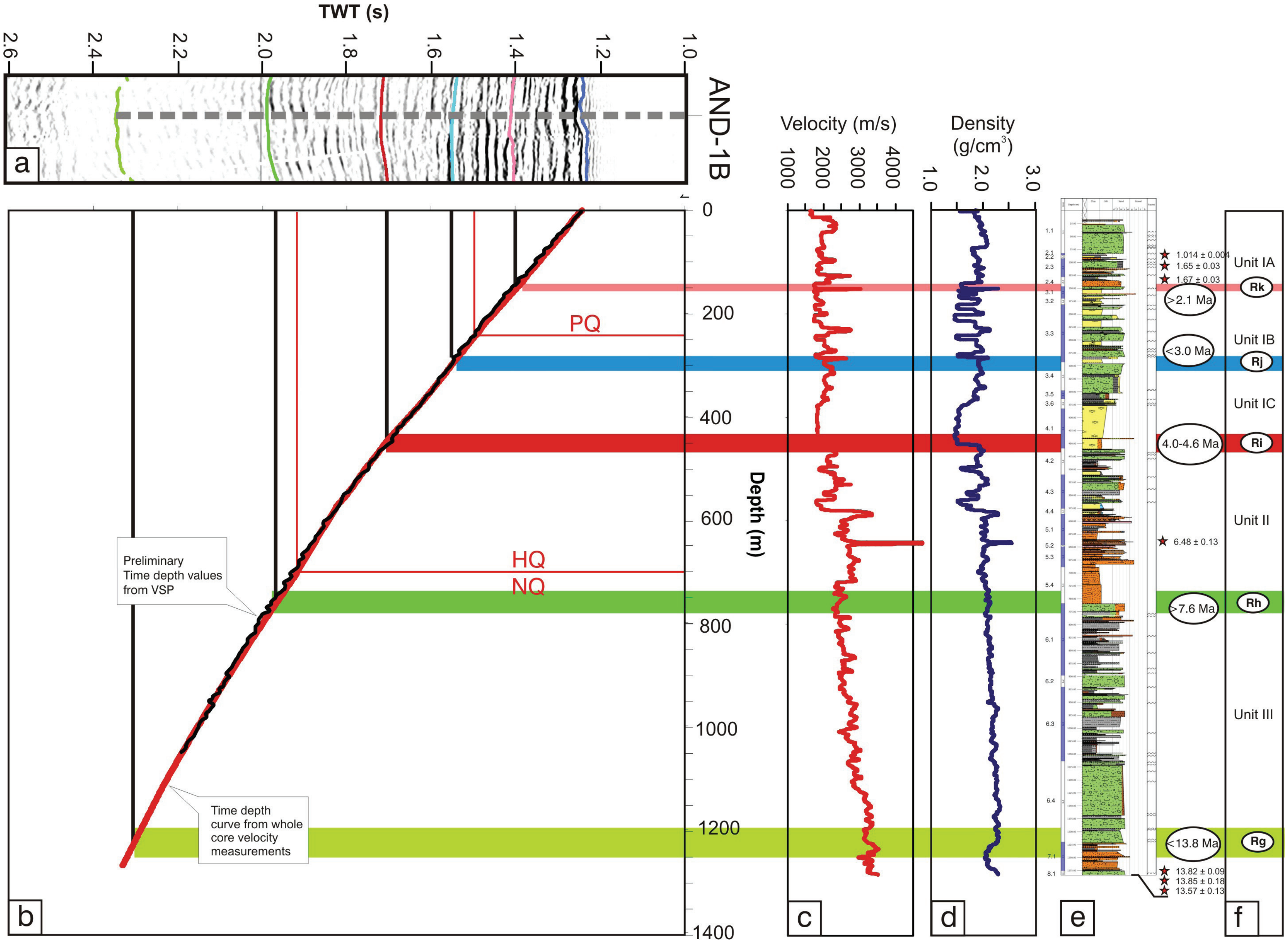

Fig. 2 – Integrated plot. We have used the whole-core velocity (c) to derive a time-depth conversion curve (b) together with vertical seismic profile (VSP) arrival times to map seismic reflection profile from MIS-1 (a) to depth and correlate with core lithologies and lithostratigraphic units (e). Seismic boundaries are identified by letter (Fig. 3). Seismic stratigraphic units identified in (f) are from the MIS Scientific Logistics Implementation Plan (SLIP; Naish et al. 2006) and have been mapped regionally (Fielding et al. in press).

episodes, and a *c.* 90 m-thick interval diatomite. The chronostratigraphic units discussed below broadly conform to the lithostratigraphic units (LSUs) outlined in Krissek et al. (this volume), but not in all cases. Below we have used lithologic-time relationships in a more sequence-stratigraphic approach to subdivide the 13 m.y. stratigraphic record. The broad subdivisions are based on characteristic lithological features representing distinctive climatic, glacial, volcanic, or tectonic influences.

(1) Late Miocene volcanic sandstone (1275.24–1220.15 mbsf), LSU 7.
(2) Late Miocene diamictite-dominated sedimentary cycles (1220.15–1069.2 mbsf), LSU 6.4
(3) Late Miocene, diamictite/mudstone and sandstone sedimentary cycles (1069.2–759.32 mbsf), LSU 6.1–6.3.
(4) Late Miocene–Early Pliocene? lapilli tuff, lava flow, and volcanic sandstone and mudstone (759.32–586.45 mbsf), LSU 5.
(5) Early Pliocene diamictite/diatomite sedimentary cycles (586.45–459.24 mbsf), LSU 4.2-4.4.
(6) Early Pliocene diatomite (459.24–382.98 mbsf), LSU 4.1
(7) Late Pliocene diamictite/diatomite sedimentary cycles (586.45–146.79 mbsf), LSU 3.
(8) Late Pliocene-Early Pleistocene diamictite/volcanic mudstone and sandstone cycles (146.79–82.72 mbsf), LSU 2.
(9) Middle-Late Pleistocene, diamictite-dominated sedimentary cycles (82.72–0 mbsf), LSU 1

LATE-MIOCENE DIAMICTITE-DOMINATED CYCLES OF LSU 6.4 *(1220.15–1 069.2 mbsf)*

This interval is dominated by massive diamictite with mudstone interbeds. Cyclicity is highlighted by generally thin stratified mudstone intervals representing alternation between tillites and glacimarine deposits. Overall the greater than 150 m-thick interval is characterised by massive diamictites containing medium to high-grade metamorphic basement clasts known from the Byrd Glacier region (Pompilio et al. this volume). At this stage we have been conservative in our recognition of grounding-line fluctuations used to identify the sedimentary cycles. More detailed study is likely to highlight smaller-scale more subtle fluctuations in the grounding line represented by amalgamations of alternating sharp-based massive and stratified diamictites. The high proportion of subglacial and pro-grounding-line environments represented by these cycles, together with the occurrence of granitoid and metamorphic rocks known from the Byrd Glacier region implies long-term existence of a grounded Ross Ice Sheet and ice streaming from the southern Transantarctic Mountains. Once a magnetostratigraphy is developed for this section of the core together with a new $^{40}Ar/^{39}Ar$ ages, further sedimentological and petrographic work should provide an important history of Antarctic Ice Sheet behaviour during the 'big' Late Miocene, Mi-glaciations (*e.g.* Miller et al. 1991; Zachos et al. 2001; Miller et al. 2005).

LATE MIOCENE, DIAMICTITE/MUDSTONE-SANDSTONE SEDIMENTARY CYCLES OF LSU 6.1–6.3

(1069.2–759.32 mbsf)

This section is characterised by cycles of subglacial and grounding-line diamictites that pass upwards into a glacimarine retreat succession of redeposited conglomerate, sandstone, and mudstone. These units are overlain by a more distal hemipelagic terrigenous mudstone with outsized clasts and lonestones. The retreat facies succession is then followed by a proglacial advance assemblage in which clast abundance increases together with the occurrence of submarine outwash facies, which then passes up to the glacial surface of erosion. Compared to the underlying interval of diamictite-dominated cycles, this unit represents periods of significant retreat of the ice sheet when there was open ocean at the drill site, possibly associated with a relatively warmer climate and a warmer style of glaciation, as indicated by abundant meltwater deposits.

LATE MIOCENE-EARLY PLIOCENE VOLCANIC SANDSTONE AND MUDSTONE OF LSU 5

(759.32–586.45 mbsf)

This interval is dominated by subaqueously redeposited volcanic sediments, many with near-primary volcanic characteristics. The volcaniclastic sediments are organised into sediment gravity-flow deposits (mostly proximal turbidites), indicating a nearby active volcanic centre, delivering primary volcanic material into a deep basin (several hundred metres water depth). A series of fining-upward altered and degraded pumice lapilli tuffs occur at 623 mbsf, 603 mbsf and 590 mbsf, and a pure fine volcanic glass sand occurs at 577 mbsf. All of these have been targeted for argon geochronology. A plagioclase Hawaiite lava with chilled margins and 'baked sediments' under its lower contact interrupts the volcanic sediment gravity flows between 646.49 and 649.30 mbsf, and has been dated by $^{40}Ar/^{39}Ar$ at 6.38 Ma. The source of this lava and the redeposited volcanic units is thought to be nearby given the freshness of the glass and angular nature of the clasts forming breccias. The unit is virtually devoid of outsized clasts or any other features indicative of iceberg rafting and/or grounding-line proximity, suggesting that much of the 120 m-thick interval was deposited rapidly within open water. At this stage we consider this volcanic interval to represent a single eruptive sequence with very high rates of accumulation during a single orbital-scale interglacial.

EARLY PLIOCENE DIAMICTITE/DIATOMITE SEDIMENTARY CYCLES OF LSU 4.2–4.4

(586.45-–59.24 mbsf)

In general these cycles can be summarised as comprising, in ascending stratigraphic order: (1) a sharp-based massive diamictite with variable amounts of volcanic glass (subglacial to grounding zone) passing up into, (2) stratified diamictite, sandstone, and mudstone with dispersed clasts (grounding-line to distal glacimarine) followed by, (3) stratified diatomite (open ocean) which in turn often passes up into glacimarine mudstone and sandstone with dispersed clasts (perhaps an indication of an approaching grounding line). The interval spanning the base of the diamictite and the underlying glacimarine lithologies is often physically intermixed and displays deformation associated with glacial overriding and shearing, but interestingly, appears to represent little significant erosion by the advance. These cycles show a dramatic change from hemipelagic open-water sedimentation to open-water biogenic sediments–diatomite at interglacial minima.

EARLY PLIOCENE DIATOMITE OF LSU 4.1
(459.24–382.98 mbsf)

Diamictites are absent between 376 and 460 mbsf with the interval being represented by an impressive *c.* 90 m-thick diatomite, indicating an extended period of high-productivity open water over the site. This unit is of Early Pliocene age (*c.* 4 Ma), and may span a number of glacial-interglacial cycles indicating disappearance of a major sector of the ice shelf/ice sheet. Further research is planned in order to constrain the contemporaneous climate, and will involve examination of the terrestrial microfossils and estimation of sea-surface temperatures from geochemical and biological proxies. We note this diatomite corresponds to a period of Antarctic warming and hypothesised loss of a significant part of the East Antarctic Ice Sheet (EAIS; *e.g.* Webb & Harwood, 1991), but at this stage we cannot constrain the ice volume changes of the more distal contemporaneous ice sheets. The lower 10 m of the diatomite displays a progressively higher terrigenous mud component together with an increased intensity of outsized clasts and centimetre- to decimetre-thick gravity-flow deposits, before passing downwards into a clast-rich to clast-poor muddy-diamictite at 460 mbsf.

LATE PLIOCENE DIAMICTITE/DIATOMITE SEDIMENTARY CYCLES OF LSU 3
(382.98–146.79 mbsf)

Within this interval the core is strongly cyclic in nature, and is characterised by 12 glacial-interglacial cycles that typically comprise a sharp-based lower interval in the upper few metres that passes upwards into a c. 5 to 10 m-thick unit of biosiliceous ooze and/or biosiliceous-bearing mudstone (diatomite). The lower parts of diamictites and the upper few metres of diatomites are glacially sheared and deformed. The transitions from diamictite (glacial and glacimarine) to diatomite (open ocean) are dramatic, in many cases occurring over less than a metre thickness of core. Below we discuss these abrupt deglacial facies transitions in terms of rapid-retreat of an ice sheet, or even collapse of an ice shelf. Our preliminary age model implies that the 12 cycles accumulated in less than 1 m.y., implying a Milankovitch orbital-control, on large-scale fluctuations of the Ross Ice Sheet/West Antarctic Ice Sheet (WAIS). This interval is intriguing and will be the focus of further work as we evaluate its significance in terms of the global climatic deterioration coincident with the development of large ice sheets on the northern hemisphere continents (*e.g.* Shackleton et al. 1984; Maslin et al. 1999).

LATE PLIOCENE-EARLY PLEISTOCENE DIAMICTITE/VOLCANIC MUDSTONE-SANDSTONE CYCLES OF LSU 2
(146.79–82.72 mbsf)

This interval displays lithologic alternations between ice-proximal facies and open-water volcaniclastic facies. A GSE at 150.90 mbsf, is correlated with the Rk-pink reflector and spans as much as 0.7 m.y. between 2.4 and 1.7 Ma. Above this, the interval from 146.79 to 134.48 mbsf represents another glacial-interglacial cycle, which above the diamictite is almost entirely made up of redeposited, volcanic (basaltic) sandstone. The sandstone is organised into a series of normally graded turbidites The interval from 134.48 to 120 mbsf is characterised by an open water assemblage of interstratified mudstone and volcanic sandstone that lies stratigraphically above, weakly stratified diamictite alternating with sparsely fossiliferous claystone and mudstone, more typical of grounding-line and iceberg-zone systems. A muddy-sandy volcanic breccia displaying near-primary volcanic material occurs at 117 m, and has yielded a preliminary age $^{40}Ar/^{39}Ar$ age of ~1.6 Ma on basaltic volcanic glass. The interval from 116 to 112 mbsf is dominated by volcanic sandstone (for more detail, see Pompilio et al. this volume).

The stratigraphy is complex between the GSE at 109.7 mbsf and the GSE at 82.72 mbsf. A dramatic change upwards into massive diamictite from 109.7 to 97.2 mbsf indicates the return of the ice sheet to the proximity of the drill site. Our preliminary age model suggests that between GSE at 109.7 mbsf, and at least 3 superjacent GSEs in the overlying interval of amalgamated diamictite, up to *c.* 0.4 m.y. is missing from between 1.5 and 1.1 Ma. From 97.2 to 92.5 mbsf diamictite and volcanic sandstone pass downward into interstratified bioturbated volcanic sandstone and mudstone. The interval from 92.5 to 86.6 mbsf contains the youngest biosiliceous-bearing sediments in the AND-1B core. The presence of numerous volcaniclastic units and biosiliceous sediments in this interval indicate an extended period of open-water conditions with no sea ice, beyond the calving line. An immediately overlying, fining-upwards lapilli tuff between 85.86 and 85.27mbsf has yielded a high-precision $^{40}Ar/^{39}Ar$ age on sanidine phenocrysts of 1.01 Ma within a short normal polarity interval interpreted as the Jaramillo Subchron. Thus, the underlying biosiliceous interglacial sediments are tentatively correlated with warming during the 'super-interglacial' associated with Marine Isotope Stage 31. This interval will be the focus of a future concentrated effort to establish a wide range of climate proxies to better characterise the impact of this warm period on ice-sheet behaviour.

MIDDLE-LATE PLEISTOCENE, DIAMICTITE-DOMINATED SEDIMENTARY CYCLES OF LSU 1
(82.72–0mbsf)

Between 83 and 27 mbsf there are marked repetitions in lithologies that characterise at least eight, approximately 15 to 10 m-thick cycles dominated by diamictite with thinner intervals of bioturbated, but more stratified claystone and siltstone, volcanic sandstone, and muddy conglomerate. In a similar fashion to the Late Miocene diamictite-dominated cycles, the high proportion of subglacial and grounding-line proximal deposits, together with the occurrence of granitoid and metamorphic rocks known from the Byrd glacier region (Pompilio et al. this volume) implies existence of a grounded Ross Ice Sheet in the Middle and Late Pleistocene.

The implied presence of a cold grounded ice sheet for much of this time is intriguing as it also corresponds to a period of Earth's history dominated by 80–120 k.y. fluctuations in large northern hemisphere ice sheets. Further work will focus on: (1) how this ice sheet responded to the Late Pleistocene interglacials, which in Antarctic ice core records indicated polar temperatures warmer than today (*e.g.* Petit et al. 1998; EPICA Community Members 2004), and (2) the role of orbital forcing on Antarctic Ice Sheets (*e.g.* Huybers & Wunsch 2005; Raymo et al. 2006) in regulating Pleistocene climate.

RELATIONSHIP TO REGIONAL SEISMIC STRATIGRAPHY

Prior to drilling, five distinctive reflectors marking regional stratal discontinuities had been mapped through a grid of seismic data in the vicinity of the drill site (HPP and MIS lines, Naish et al. 2006), and linked to marine seismic reflection data and reflector nomenclature in McMurdo Sound (Fielding et al. in press). An integrated plot is shown in figure 2. We have used the whole-core velocity measurements and vertical seismic profile (VSP) first arrival travel-time picks (Moran et al. this volume; Niessen et al. this volume) to derive time-depth conversion curves to map the seismic reflection section to depth. In figure 3 and below we summarise the correlations of the regional seismic stratigraphy with the AND-1B drill core.

1. Rg (Surface C, bilious green reflector): This regionally extensive discontinuity is characterised by truncation of underlying locally hummocky and lobate, continuous, high-amplitude reflections, and by regional onlap of moderate to high amplitude reflections above. Surface C is correlated with top of a *c.* 60 m-thick interval Late Miocene volcanic sandstone (LSU 7), and the base of a 150 m-thick, high-velocity (3000 ms^{-1}) interval of diamictite cycles (LSU 6.4). $^{40}Ar/^{39}Ar$ dates on ashes beneath Rg (Wilson et al., 'Preliminary Integrated Chronostratigraphy', this volume) indicate that this discontinuity is less than 13.8 Ma.
2. Rh (Surface B, dark green): This regionally extensive discontinuity is characterised by truncation of underlying discontinuous to continuous, moderate-amplitude reflections, and regional onlap of high-amplitude reflections above. It is correlated with the base of a *c.* 180 m-thick interval of Late Miocene to Early Pliocene(?), pyrite-cemented, high-velocity volcanic sandstone and mudstone (LSU 5). Regionally the green reflector correlates with the base of volcanic bodies in the Victoria Land Basin north of Ross Island. It is correlated with the base of White Island volcano dated at *c.* 7.6 Ma (Alan Cooper, University of Otago, personal communication/unpublished data).
3. Ri (Surface A2/B-clino, red reflector): This regionally extensive reflector is marked above by onlap of low-amplitude reflections at the base of a *c.* 90 m-thick seismicallyopaque interval onto high-amplitude reflections of the underlying unit. Surface A corresponds to the base of prograding clinoforms north of Ross Island, and locally marks the base of flexure associated with Ross Island volcanic loading (Horgan et al. 2005). In AND-1B Surface A2 correlates with the boundary between the ~100 m-thick, low-density, low-velocity (1700 ms^{-1}), Early Pliocene diatomite interval (LSU 4.1), and the subjacent higher-velocity (<2500 ms^{-1}) diamictites of LSU 4.2. Diatom assemblages bracket this surface to between 4.5 Ma and 5.0 Ma. Regionally this reflector has been projected into the area of Cenozoic Investigations in the Western Ross Sea (CIROS)-1 and McMurdo Sound Sediment and Tectonic Studies (MSSTS)-1, where it can be correlated to the litho- and biostratigraphy. In MSSTS-1, the red reflector correlates to about 20 mbsf in the core, close to a sample that contained Pliocene (4.6–4.0 Ma) microfossils and below which they were absent (Harwood et al. 2006).
4. Rj (Surface A1, turquoise reflector): This regionally extensive reflector is characterised by truncation of underlying moderate-amplitude reflections and onlap by overlying reflections at the base of a *c.* 150 m-thick unit of strongly alternating high- and low-amplitude reflections. These dramatic cycles in density and velocity reflect regular alternations between diatomite and diamictite in Late Pliocene, LSU 3. The turquoise reflector separates strata above that are younger than *c.* 3.0 Ma and below greater than *c.* 3.5 Ma. However, there is uncertainty about how much time is missing at this horizon. The turquoise reflector has been correlated into the Erebus Moat

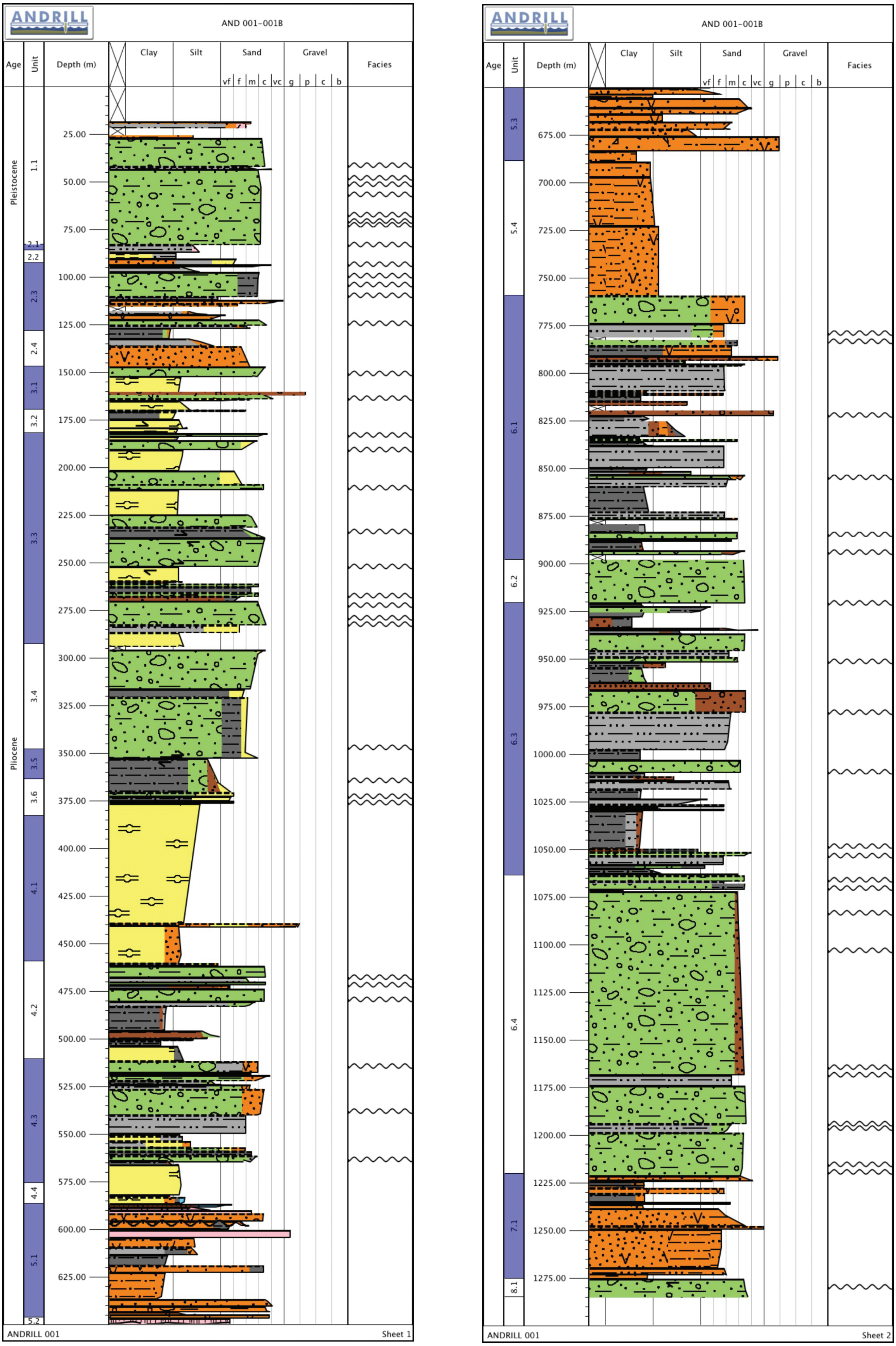

Fig. 2 – Lithostratigraphy and sequence stratigraphy of the AND-1B drill core. Blue and white units denote lithostratigraphic units (LSUs). Wavy lines denote glacial surface of erosion (GSEs). Orange = volcanic sandstone, mudstone; pink = primary volcanic deposits; green = diamictite; brown = conglomerate/breccia; grey = terrigenous siltstone and sandstone; yellow = biosiliceous-bearing, or diatomite.

Seismic Reflector ID	TWT (s)	Depth (mbsf)	2% Error in depth (± m)	SLIP		Comment
Rk	1.40	150	2.9988	Pink	Surface A0	Base of LSU 2.4 top of LSU 3.1
Rj	1.56	297	5.9388	Turquoise	Surface A1	Base of LSU 3.4 top of LSU 3.5 Top of thick diatomite layer
Ri	1.71	451	9.0216	Red (B-clino)	Surface A2	Base of LSU 4.1 top of LSU 4.2. Base of 100 m thick diatomite layer
Rh	1.97	757	15.1368	Dark Green	Surface B	Base of LSU 5.4 top of LSU 6.1 Base of thick volcanic unit
Rg	2.33	1223	24.4692	Bilious Green	Surface C	Base of LSU 6.4 top of LSU 7.1

Fig. 3 – Summary of correlation of the AND-1B drill core with the regional seismic reflection stratigraphy (Fielding et al. in press; Naish et al. 2006; Horgan et al. 2005). *LSU - Lithostratigraphical Sub-Unit ; *strongest and most persistent reflectors.*

area (Fielding et al. in press) where it represents the oldest horizon that is clearly influenced by flexural loading imposed by construction of the Ross Island volcanic edifices.

5. Rk (Surface A0, pink reflector): This regionally extensive reflector is characterised by stratal onlap above and marks the top of the cyclic diatomite-diamictite LSU 3. The stratigraphic interval above Surface A0 comprises Late Pliocene–Early Pleistocene diamictite/volcanic mudstone and sandstone cycles of LSU 2, passing up into the Middle–Late Pleistocene, diamictite-dominated sedimentary cycles of LSU 1. The age of this reflector is well constrained by $^{40}Ar/^{39}Ar$ dates (Wilson et al., 'Preliminary Integrated Chronostratigraphy', this volume) and diatom assemblages to older than 1.67 Ma and younger that *c.* 2.1 Ma.

Most of the major lithostratigraphic subdivisions correspond to seismic-stratigraphic surfaces and units identified prior to drilling. Since drilling, it has been possible to recognise a number of additional stratal surfaces and distinctive seismic intervals that correspond to glacial surfaces of erosion and lithostratigraphic subunits identified in the core. These correlations, together with those that will result from Southern McMurdo Sound drilling in late 2007 and with a refined chronostratigraphy, will be mapped into the regional McMurdo Sound seismic data set, and have the potential to provide a finely resolved stratigraphic architecture for the Neogene tectonic and climate history of the Victoria Land Basin.

SEDIMENTARY ENVIRONMENTS

As is evident from the cycle motifs identified in the sequence-stratigraphic interpretation, there are distinctive palaeoenvironments that have occurred during particular time intervals in the southern Victoria Land Basin as represented by the record from the MIS site. The youngest (above about 83 mbsf) and oldest (below about 1 083 mbsf) intervals represented by the AND-1B core appear to represent the coldest periods characterised by the dominance of a grounded ice sheet in the vicinity of Ross Island, whereas the intervening stratigraphic interval shows evidence of a relatively warmer climate characterised by a more variable ice sheet regularly oscillating across the region with subglacial, ice-shelf and open-ocean environments all represented. Though data remain preliminary, it is possible to make some important inferences about palaeoenvironments based on lithofacies, their successions, and other lines of evidence, especially the preliminary fossil (Scherer et al. this volume) and volcanic sedimentary data (Pompilio et al. this volume). Here we discuss broad palaeoclimatic changes on the order of millions of years with shorter-term environmental changes down to Milankovitch-scale superimposed. The most dramatic environmental fluctuations and marked sedimentary cyclicity occur within the warmer, middle intervals of the core.

The diamictite-dominated motif 1, which dominates the upper 83 m-thick Middle to Late-Pleistocene interval, and the interval below about 1 083 mbsf of Late Miocene age, is preliminarily interpreted as representing the coldest climates analogous to the last glacial maximum (LGM) and modern conditions. These periods are characterised by the presence of a large ice sheet because deposits comprise primarily diamictite facies with erosional surfaces below and only thin intervals of stratified and/or current-sorted sediments between, as is true for most deposits of the modern ice-sheet system. These intervals show little sign of major meltwater discharges from the ice sheet and much of the ice movement was likely to have been via deformation of subglacial till by large, massive ice sheets. The vertical facies successions from diamictite into stratified glacimarine deposits have many features described in Quaternary continental-shelf deposits including subglacial and lift-off glacimarine facies (*cf.* Domack & Harris 1998) from near the ice-shelf grounding line. Open-marine facies (*e.g.* facies 1 and 2) are rare in these cycles and have probably been truncated by subglacial erosion during subsequent glacial advances. However, the diamictites lack diatom fragments that are common in the most recent Ross Sea diamictons (Scherer et al. this volume), and this characteristic is taken to indicate that interglacial deposits rich in diatoms were absent and thus were unable to be eroded and incorporated into the tillites during an ice-sheet readvance.

Notwithstanding the rarity of non-diamictite facies, intervals of amalgamated diamictites and some cryptic facies assemblages, the cycle architecture is generally well defined within the thick, diamictite-dominated intervals, characterised by regular alternations between sharp-based coarse-grained grounding-line facies (9, 10, 11), and fine-grained more oceanic facies (2, 3, 4). The combined lines of evidence described above are used to infer that the ice sheet never retreated substantially from the site to allow significant marine accumulations, nor did it have significant subglacial meltwater discharge through conduits. We view the stratigraphic variability within diamictite-dominated intervals as reflecting the presence of a cold polar, grounded ice sheet with periodic retreats of its grounding line allowing glacimarine sedimentation in the vicinity of drill site during interglacial minima. With further work it should be possible to evaluate the cyclicity in the context of orbital climatic influences during times of large ice volume on Antarctica.

Cycle motifs 2 and 3 dominate about a 500 m-thick Pliocene (4.5 to 2.5 Ma) interval of the core from 83 to 587 mbsf, and is interpreted as representing dynamic ice sheets with substantial areal oscillations in grounding lines probably associated with large excursions in their volume during glacial-interglacial, advance-retreat cycles. We base this interpretation on the recognition of more than 30 repetitive cycles of sharp-based diamictite passing upwards, often abruptly, into diatomite or terrigenous glacimarine facies. The volume of diatomite at this MIS site, and the presence of submarine outwash grounding-line glacimarine strata are consistent with conditions of a warmer climate than today, with significantly higher rates of primary productivity and significant meltwater discharge from the grounding line. Locally the transitions from diamictite into diatomite are very sharp indicating stratal attenuation. As the core becomes better chronologically constrained, we hope we can correlate the cycles with orbital-scale climate proxy records (*e.g.* marine isotope records and ice core records), and be able to evaluate the rate of ice-sheet/ice-shelf response to contemporary atmospheric and oceanic climatic conditions. This may allow short-term (centurial- to millennial-scale) Antarctic ice sheet dynamics and thresholds to be understood within the context of ocean and atmospheric temperature sensitivity, especially for times that were significantly cooler or warmer than the present day.

While the ice sheets had retreated during the time that the environment was dominantly represented by diatomite, there are intervals when iceberg rafting was occurring and other intervals when it was absent. When present, iceberg-rafted debris (IBRD) indicates the ice sheet had retreated most likely to the coastline where outlet glaciers were still calving into the sea. During the intervals where IBRD is absent, the area must have been substantially warmer than today, because the ice sheets had retreated onto land and were not calving icebergs into the sea. We cannot tell directly what size the ice sheet was on land. However, further work developing sea-surface temperature proxies from Mg/Ca composition of planktic forams, and biological assemblage data, together with atmospheric temperature estimates from contemporaneous terrestrial microfossils (where evident) should help constrain computer-simulations of ice volume. Although analyses need to be completed, some of the stratified diatomite appears to have millimetre-scale laminae deposited during one monospecific blooming event. After more detailed studies are completed we may be able to constrain more precisely durations represented by these deposits to understand more fully the significance of the warm intervals.

In a number of instances within the core an intriguing phenomenon occurs, that is, the ice-sheet-advance facies are preserved below diamictite interpreted as subglacial till. This is taken to represent either that deep water at the site helped protect the deposits from significant erosion by the ice sheet during its advanced stage and/or, perhaps more significantly, the advance was short lived and the ice had too little time to cause major erosion. In some of these intervals the subglacial sediment has been deformed or intermixed with underlying lithologies immediately below the glacial erosion surface. Soft-sediment folding, fractures, and rotated blocks are common, and are attributed to sub-ice deformation and/or ice pushing related to ensuing ice advance.

IMPLICATIONS FOR ANTARCTIC GLACIAL AND CLIMATE HISTORY

This AND-1B core record from the MIS Project has the potential to contribute significant new knowledge on the dynamics of the WAIS and Ross Ice Shelf/Sheet system, as well as contributing to understanding the behaviour of the EAIS during the Late Cenozoic. The evolving chronology will allow certain intervals of the core to be correlated with proxy climate records (*e.g.* ice and marine isotope records) and the sensitivity of the ice sheet to a range of past global climate changes to be evaluated. The significant results thus far are that the Ross Ice Sheet (fed by both east and west Antarctic ice) has undergone considerable changes during the Late Cenozoic. A relatively stable, large, cold polar ice sheet dominated the region in the early Late Miocene, between 13 and 10 Ma, that became more dynamic in the Late Miocene (19 to 7 Ma), with significant subglacial stream discharges in the late Miocene–Pliocene (5 to 2.5 Ma), and periods of significant retreat, when the region experienced highly productive, warmer oceanic conditions (*e.g. c.* 4 Ma and 1.1 Ma). From the Middle Pleistocene to Recent, the ice sheet is characterised by a change back to more stable cold polar conditions. Our preliminary analysis of the more than 25 Pliocene sedimentary cycles indicates significant glacial-interglacial variability, with regular oscillations between subglacial/ice proximal and open-ocean ice distal environments, including extended periods of interglacial warmth when the ice was not calving into the ocean, and global temperatures may have been up to 3°C higher. Our environmental reconstructions, to date, imply changes in ice sheet volume that must have contributed significantly to eustasy and ocean circulation.

Cold-climate Early Miocene and Pleistocene subglacial till-dominated intervals, which comprise clasts originating in the southern TAM, imply that the WAIS was large and feeding significant volumes of ice into the Ross Embayment. That grounded ice from the big outlet glaciers of the southern TAM (*e.g.* Byrd) was reaching McMurdo Sound during these times requires an expanded WAIS. Without the buttressing influence of westward-flowing ice from the WAIS, the TAM outlet glaciers are more likely to have flowed toward the east away from the mountains without the ice making it farther north, simply as a consequence of insufficient ice volume from the more stable EAIS. Present-day flow lines show that ice from Byrd Glacier flows well east of McMurdo Sound. Consequently, times of ice-shelf/ice-sheet absence in the McMurdo Sound region also record an absence of ice supply from West Antarctica. Significant work is planned in the near future to further understand and constrain ice-sheet dynamics, especially during periods of hypothesised global warmth that will provide useful analogues for constraining the behaviour of Antarctic ice sheets in the context of future climate change. To achieve this, we will integrate our core data, such as quantitative biological and geochemical climate proxies, with the new generation of ice sheet and climate models.

Acknowledgements - The ANDRILL project is a multinational collaboration between the Antarctic programmes of Germany, Italy, New Zealand and the United States. Antarctica New Zealand is the project operator and developed the drilling system in collaboration with Alex Pyne at Victoria University of Wellington and Webster Drilling and Enterprises Ltd. Antarctica New Zealand supported the drilling team at Scott Base; Raytheon Polar Services Corporation supported the science team at McMurdo Station and the Crary Science and Engineering Laboratory. The ANDRILL Science Management Office at the University of Nebraska-Lincoln provided science planning and operational support. Scientific studies are jointly supported by the US National Science Foundation, NZ Foundation for Research, Science and Technology and the Royal Society of NZ Marsden Fund, the Italian Antarctic Research Programme, the German Research Foundation (DFG) and the Alfred Wegener Institute Polar and Marine Research.

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TERRA ANTARTICA
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TERRA ANTARTICA

Università di Siena
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Direttore Responsabile:
Maurizio Boldrini

Direttore Scientifico:
Carlo Alberto Ricci

Autorizzazione del Tribunale di Siena n. 633
del 18 Luglio 1996