

## Summary

The aim of the ANDRILL McMurdo Ice Shelf (MIS) Project was to obtain a continuous sediment core through approximately c. 1 200 metres (m) of Neogene (c. 0 to 10 Ma) glacial, terrigenous, volcanic, and biogenic sediment that has accumulated in the Windless Bight region under 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 c. 10 k.y. and is nourished by ice sourced from East Antarctic Ice Sheet (EAIS) outlet glaciers in the southern Transantarctic Mountains (TAM). The MIS drill site was situated c. 10 kilometres (km) east of Hut Point Peninsula (77.8894417°-S, 167.0893282°-E) above a flexural moat basin 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. Between 29 October and 26 December 2006 a single 1 284.87 m-deep drill core (ANDRILL [AND]-1B) was recovered (98% core recovery) from the bathymetric and depocentral axis of the moat in 917 m of water from an 82 m-thick ice-shelf platform. The drilling technology utilised 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 the ice shelf and to keep the riser free during drilling operations.

Prior to rotary coring a range of soft-sediment coring tools were deployed to recover the sediment-water interface and the upper few metres of strata, whose integrity may have been compromised by embedment of the sea-riser for drilling of the AND-1A/1B holes. These coring options included (1) a sediment gravity corer deployed through the ice-shelf hole, and (2) a push corer deployed through the sea riser suspended a few metres above the seabed. Within the AND-1A hole (during an initial attempt at sea-riser embedment) an extended-nose corer was advanced in front of the sea riser with limited success. The hydraulic piston corer was not deployed as a consequence of the firmness of the Last Glacial Maximum (LGM) diamicton and the occurrence of oversized clasts, which could damage the drill string and compromise the deeper coring options. Successive attempts at gravity and push coring recovered 12 cores up to a maximum of 1.56 metres below sea-floor (mbsf). The longest core was dedicated to sampling for microbial life and pore-water geochemical studies, which were expected to show the greatest gradients in the upper few metres of the sediment column. All cores sampled Holocene sub-ice-shelf sediments above the LGM diamicton, and displayed a similar stratigraphy to a previously obtained site-survey core, 250 m to the southeast, with an unconsolidated diamicton passing upwards into muddy sub-ice-shelf facies. The sediment cores record the retreat of the grounding line through the region at about 10 ka and a transition from grounding line proximal, through sub-ice shelf to calving-line proximal environments.

A range of whole-core physical properties including wet bulk density, P-wave velocity, and magnetic susceptibility were determined on site. A comprehensive set of downhole measurements were also collected consisting of caliper, temperature, fluid conductivity, induction resistivity, magnetic susceptibility, natural gamma activity, acoustic televiewer, borehole deviation, and dipmeter. In addition, two standard vertical seismic profiles (VSP) and one walk-away VSP were obtained. Although the total depth of the hole is 1284.87 mbsf, the depth range for *in situ* measurements was limited by the length of the wireline (1018 mbsf) and by the nullification of some geophysical logs due to the presence of steel casing. A depth correction was derived to account for systematic discrepancies in depth between downhole measurements and cores; consequently, log responses can be directly compared to core properties. The resulting downhole data when integrated with core physical-properties data will contribute to studies of lithologic cyclicity and climate, diagenesis heat flux and fluid flow, and structure and stress.

Over 4300 fractures of all types were logged in the AND-1B drill core. A population of 410 steeply dipping, petal, petal-centreline, and core-edge-induced fractures is present, reaching a maximum density of 5 fractures/metre. Subhorizontal induced extension fractures are also abundant. There are 1475 natural fractures in the core, including faults, brecciated zones, veins, and sedimentary intrusions. Kinematic indicators document dominant normal faulting, although reverse faults are also present. Vein types include slickenfiber veins along faults, opening-mode fibrous veins, pressure shadows on clast margins, and complex microvein webs within fault zones. The natural fractures occur in strata ranging in age from Miocene to Pleistocene.

The core contains a range of lithologies, including siliciclastic and volcanic diamictites, sandstones, and mudstones; diatomites; and volcanic ash/tuff and one lava flow. The succession has been subdivided into eight lithostratigraphic units and 25 subunits, based on lithological abundances.

Eleven lithofacies have been recognised, ranging from open-marine diatomites and mudstones to turbidites to ice-proximal massive and stratified diamictites. Carbonate and pyrite are the dominant secondary phases in the core. The pyrite overprint is especially notable in volcanic sediments below c. 400 mbsf, where it often obscures stratification and sediment texture.

More than 60 unconformity-bounded glacial-marine 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 Cenozoic. 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 glacial-marine deposits. In many cycles, the facies succession reflects retreat of the grounding line through ice shelf into open-ocean environments at the interglacial maximum, followed by ice readvance characterised by progressively more glacially facies (in the upper parts) culminating in a GSE.

We recognise three types of facies-cycle 'motif', which correspond to glacial-interglacial variability during climatically distinct periods of the Late Cenozoic:

- (1) Cold polar climate and ice sheet (Late Miocene, c. 13 to 10 Ma and Pleistocene, c. 1 to 0 Ma). The sequence motif is dominated by diamictite and is interpreted as a glacial advance-retreat cycle that represents a dominance of sub-glacial environments with the most distal facies representing calving line-proximal settings.
- (2) Relatively warmer climate, subpolar ice sheets, and interglacials dominated by pelagic diatomites (Pliocene, c. 5 to 2 Ma). The sequence motif begins with a basal diamictite overlying a GSE, and grades upward through ice retreat facies to more distal glacial-marine deposits, and finally into open-water diatomites. The upper half of this motif contains a similar set of facies, but stacked to record ice advance and culminating in a stratified diamictite that is deformed immediately below the overlying GSE.
- (3) Warmer climate, polythermal ice with interglacials dominated by hemipelagites (Early—Late Miocene, c. 9 to 6 Ma). The third sequence motif is similar to the second motif, except that diatomite is absent and the upper portion of the cycle is dominated by mudstones. In addition, the upper portion of the motif, which is interpreted to record ice advance, tends to be either absent, truncated or thinned.

A >80 m-thick Early Pliocene interval of diatomite shows no apparent glacial cyclicity and represents an extended period of ice-free conditions indicative of a reduced West Antarctic Ice Sheet (WAIS). The WAIS appears not to have responded to at least one, and probably more Milankovitch cold periods. In contrast, spectacular Late Pliocene (c. 2.6 to 2.2 Ma) glacial-interglacial cycles characterised by abrupt alternations between subglacial/ice-proximal facies and open-marine diatomites imply significant WAIS dynamism, and contribution to global ice-volume changes coeval with the initiation of Northern Hemisphere glaciations. A c. 4 m-thick interval of diatomaceous mudstone in the Middle Pleistocene also represents warm-interglacial ice-free conditions. Intriguingly, the last 1 m.y. is dominated by glacial deposits interrupted by periodic and apparently small-scale retreats of the grounding line.

Fossils provide key data sets for the interpretation of the AND-1B core. Calcareous plankton and benthos provide the basis for palaeoenvironmental interpretations of both surface and bottom waters. Calcareous fossils are rare throughout, but occurrences noted are significant. Some calcareous fossils provide potential for age control via  $^{86}\text{Sr}/^{87}\text{Sr}$ , and palaeoenvironmental information may come from Mg/Ca ratios as well as oxygen and carbon isotopes. Organic-walled microfossils provide an index of reworking and transport, as well as the identification of a possible *in situ* Pliocene assemblage of previously unknown marine palynomorphs. Diatoms are abundant in the core, with diatom-rich sediments constituting nearly half of the upper 600 m of core, subdivided into 13 diatomaceous units, ranging in thickness from under 1 m to nearly 100 m. Diatoms provide biostratigraphic age control, but calibration to the Southern Ocean zonation is limited by ecologic exclusion of many taxa and previously undocumented diachrony among other taxa. A new, high-resolution diatom biostratigraphy for the Antarctic continental shelf is now under development. Diatoms provide the basis for numerous palaeoenvironmental applications, including providing a proxy for palaeotemperature and palaeo-sea ice, as well as palaeoproductivity.

Volcanic deposits include: (1) phonolitic pumice layer at c. 85 mbsf, which is not correlated with any known event onshore; (2) a black well-sorted volcanic sand succession (132.83 to 146.79 mbsf) interpreted as being derived mainly from subaerial Hawaiian/Strombolian eruptions; (3) a thick volcanic succession in the middle part of the core with an interbedded submarine lava flow. The flow may be derived from a nearby vent less than 3 km away on the seafloor, based on average length

of lava flows with similar composition; and (4) deeply altered tuffs and minor sandstone below 1220 mbsf. Diagenesis and intense alteration at depths >600 mbsf, hamper the interpretation of magma evolution and provenance.

Chronostratigraphic data available for the preliminary age model for the upper 700 m for the AND-1B drill core include diatom biostratigraphy, magnetostratigraphy,  $^{40}\text{Ar}/^{39}\text{Ar}$  ages on volcanic material,  $^{87}\text{Sr}/^{86}\text{Sr}$  ages on calcareous fossil material, and surfaces of erosion identified from physical appearance and facies relationships recognized in the AND-1B drill core. The available age data allow a relatively well-constrained age model to be constructed for the upper 700m of the drill core. Available diatom biostratigraphic constraints and  $^{40}\text{Ar}/^{39}\text{Ar}$  ages allow a unique correlation of c. 70% of the AND-1B magnetic polarity stratigraphy with the Geomagnetic Polarity Time Scale (GPTS). Unique correlation is not possible in several coarse diamictite intervals with closely spaced glacial surfaces of erosion and sparse microflora. However, the age model indicates relatively rapid (up to 1 m/k.y.) and continuous accumulation of intervening finer grained diatomaceous intervals punctuated by several 0.5 to 1 m.y. long hiatuses representing more than half of the last 7 m.y. in the AND-1B record. The mid-late Pleistocene is represented by superimposed diamictite units separated from upper Pliocene alternating diamictites and diatomites by a c. 1 m.y.-long hiatus coincident with a regionally correlated seismic reflection surface. A c. 80 m-thick diatomite represents a significant portion of the early Pliocene record in the AND-1B drill core. Strata below c. 620 mbsf are late Miocene in age; however, biostratigraphic constraints are absent below 586 mbsf and correlation with the GPTS is relatively unconstrained. At the time of writing, the only chronostratigraphic data available below 700 mbsf include three  $^{40}\text{Ar}/^{39}\text{Ar}$  ages on volcanic clasts from near 1 280 mbsf affording a maximum depositional age of 13.57 Ma for the base of the AND-1B drill core.

Prior to drilling, five distinctive, regional seismic reflectors marking regional stratal discontinuities had been mapped through a grid of seismic data in the vicinity of the MIS drill site, and linked to marine seismic reflection data and reflector nomenclature in McMurdo Sound. We have used the whole-core velocity measurements and VSP first arrival travel-time picks to derive time-depth conversion for AND-1B, and to map the seismic reflection section to depth. Our velocity model prior to drilling, which was based in interval velocities calculated from the multichannel seismic reflection site surveys, proved remarkably close to the seismic-well correlation.

The 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 Neogene. New chronological data will allow certain intervals of the core to be correlated with other proxy climate records such as ice and marine isotope records. Furthermore, the record will allow us to test the sensitivity of the Antarctic Ice Sheet to a range of past global climate changes.

The significant results thus far are that the Ross Ice Sheet has undergone significant cyclic variations in extent and timing during the Late Neogene. A relatively colder and more persistent ice sheet dominated the Ross Embayment in the early Late Miocene between 13 and 10 Ma, becoming more dynamic in the Late Miocene (c. 9 to 7 Ma), with significant water discharge via subglacial conduits in the latest Miocene-Early Pliocene (5 to 2.5 Ma). This period also saw times when the Ross Embayment was relatively ice-free, with highly productive, warmer oceanic conditions (e.g. at c. 4 Ma and 1.1 Ma). From Middle Pleistocene to Recent, the ice sheet is characterised by a change back to more stable, colder ice sheet 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. Our environmental reconstructions to date imply changes in ice-sheet volume that must have contributed significantly to eustasy and ocean circulation.

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