Antarctic Ice Sheet dynamics through the Neogene from evidence in the ANDRILL–McMurdo Ice Shelf Project drillcore (AND-1B)

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Summary ANDRILL completed its first season in 2006-07 drilling AND-1B through the McMurdo Ice Shelf (MIS) to a depth of 1,285m below the sea floor, a record for Antarctic margin drilling, with 99% recovery. The alternating glacial-interglacial sediment packages interbedded with volcanics provide a uniquely detailed record of Antarctic glacial and climatic change through the Neogene. This paper summarizes the initial characterization of lithofacies and syndepositional structures relevant to understanding the regime and dynamics of past Antarctic ice sheets based on the ANDRILL-MIS Initial Report. Results suggest that the Antarctic Ice Sheet was relatively cold with little basal melting in the middle Miocene and Pleistocene times but under a more dynamic and warmer polythermal glacial regime in late Miocene and Pliocene times. More detailed research, including a modeling component, is planned in order to understand the dynamics under these different regimes.

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Introduction

The MIS section comprises nine lithostratigraphic units (Naish et al., this volume, Krissek et al., this volume), some volcanic-dominated, but most sedimentary. Here we focus on Miocene diamictite-dominated cycles from 1220 to 1069 mbsf, late Miocene diamictite-mudstone and sandstone cycles from 1069 to759mbsf, Pliocene diamictite-diatomite cycles from 586-147mbsf and middle-late Pleistocene diamictite-dominated cycles from 83-0mbsf, the first and last being of similar lithofacies. This subdivision of the succession is a consequence of distinctive paleoenvironments having occurred during particular time intervals in the southern Victoria Land Basin as represented by the record from the MIS site. Part of these distinctions is generated by the condition and dynamics of prior Antarctic ice sheets as they occupied, passed across or remained distant from the MIS site. The main data used in this initial general overview of ice sheet dynamics are the lithofacies assemblages and the syndepositional structures of the core, especially at contacts and transitions, and the deformational style of sediment below diamictites.

Relative to understanding past glacial regime from which general climatic inferences can also be made, the core can be simply broken down into four main packages, two of which are similar in character. The youngest (above about 83mbsf, Pleistocene) and oldest (below about 1083mbsf, Miocene) intervals represented by the AND-1B core appear to represent the coldest periods characterized by the dominance of a grounded, polar ice sheet in the vicinity of Ross Island, whereas the intervening stratigraphic interval shows evidence of a warmer climate characterized by a more variable polythermal (subpolar) ice sheet regularly oscillating across the region with subglacial, ice shelf, iceberg and open ocean environments all represented. The earliest phase of the warmer ice (late Miocene) is associated with significant meltwater discharging subglacially and its outwash mud dominates the glacimarine environment. The later phase of polythermal ice sheet conditions (Pliocene) has less terrestrial glacimarine mud and the interglacial periods are dominated by diatom production.

The glacial record

Ice sheet dynamics during Miocene diamictite-dominated cycles (1220.15-1069.20 mbsf)

Massive diamictites dominate this 150m-thick interval of core with short intervals of glacimarine sediment preserved between. Sharp-based massive and stratified diamictites commonly alternate but some erosional surfaces are difficult to detect because of amalgamations within the diamictites. The degree of subglacial deformation and deforming bed thickness is difficult to assess due to the massive internal structure of much of the record, although the stratified diamictites do exhibit some syndepositional deformation. The lack of glacimarine sediment is inferred to indicate much less subglacial meltwater than in younger deposits, assuming there was the same amount of accommodation at the site then as there was for the younger record. However, the amount of erosion and magnitude of glacial fluctuations is somewhat enigmatic because of the lack of significant advance and retreat glacimarine sediment packages in the section. With low channelized subglacial meltwater, 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 and Harris, 1998; McKay et al., in press) from near the ice shelf grounding line, although the latter is inconsistent in occurrence. Generally we take this style of dominant subglacial and proximal grounding-line environments to indicate a cold, polar ice sheet similar to that of today because of the similarity between the Modern and Pleistocene facies and motif style. We infer that the ice sheet was less dynamic over this earlier Miocene interval than for the late Miocene to Pliocene period discussed below.

The diamictites contain granitoid and medium to high-grade metamorphic basement clasts known from the Byrd Glacier region (Talarico et al., this volume). Although glacial recycling of clasts may be an issue, we take this to imply the long-term existence of a grounded ice sheet and ice streaming from the southern Transantarctic Mountains (TAM) from the East Antarctic Ice Sheet (EAIS) during this period. Modeling is to come, but currently we argue that ice coming from a southern TAM source requires the contemporaneous existence of an expanded West Antarctic Ice Sheet (WAIS) to provide the volume of ice required to build an ice sheet out into the Ross Sea and for it to be grounded at MIS.

Ice sheet dynamics during late Miocene diamictite-mudstone and sandstone cycles (1069.20-59.32mbsf)

Motif 3 characterizes this interval where cycles of ice contact and ice proximal diamictite 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, dropstones and lonestones. The retreat facies succession may be followed by glacimarine advance facies through which clast abundance increases together with the occurrence of proximal submarine outwash facies, which then passes up to a glacial erosion surface. These packages are dominated by a terrigenous mud component with few diatoms. This character together with a general lack of bioturbation may imply high sedimentation rates associated significant submarine outwash. The lack of diatomite here as compared to Motif 2 described below, perhaps may be diagenetic with the diatomites having been transformed to an opal C-T mudstone, but that needs further study. However, given the other associated sorted facies of rhythmically interlaminated mudstone and sandstone, interstratified mudstone and sandstone and conglomerate the ice sheets appear to have had similar regimes to those of the diatomite-dominated interval. Significant submarine outwash with likely high sediment accumulation rates and mud production lend support to many of the mudstones being terrigenous rather than diagenetic.

These characteristics show that the glacial environments were similar to those of the younger diatomite dominated intervals described below, but the interglacial periods were dominated by outwash muds rather than more open marine systems dominated by diatom productivity. Perhaps this implies grounding lines remained sufficiently close during interglacials that the site remained under relatively high turbidity within reach of significant turbid surface plumes from the ice sheet. The source for the ice feeding this succession is from a more northerly source than for older Miocene diamictites, now coming from the Mulock-Shackelton Glacier area (Talarico et al., this volume). Modeling is required to understand the change completely, however, we interpret this change in the origin of ice flow lines directed to the MIS site as being a smaller WAIS ice volume. A smaller ice volume from WAIS had less influence on deflecting the EAIS outlet glacier flow lines from the southern TAM. Consequently, the more southerly sourced ice from the Byrd Glacier area that is farther to the interior of a grounded Ross Ice Sheet than that from Mulock-Shackelton Glacier area, cannot be pushed far enough westward to force it over the MIS site by the smaller WAIS.

Compared to the underlying interval of diamictite-dominated cycles, this interval also represents significant retreats of the grounding line during periods of open ocean at the MIS site, associated with a warmer climate and a warmer glacial regime. The accommodation must have been significant to allow, at least locally, the preservation of glacimarine advance sections. Whether this also indicates either a very brief or aerially restricted (at least north of MIS) advance period to minimize subglacial erosion remains to be determined.

Ice sheet dynamics during Pliocene diamictite-diatomite cycles (586.45-146.79 mbsf)

The Pliocene is dominated by Motif 2 cycles typified by having a sharp-based massive diamictite (subglacial to grounding zone) below stratified diamictite, sandstone and mudstone with dispersed clasts (proximal glacimarine) that pass up to massive or stratified diatomite (open ocean), which may locally be followed by mudstone and sandstone with dispersed clasts (glacimarine advance facies). These cycles are interpreted as representing dynamic ice sheets with substantial lateral oscillations in groundling lines probably associated with large excursions in their volume during glacial-interglacial, advance-retreat cycles. The lower ten meters of the diatomite does include a higher outwash mud component, lonestones and gravity flow deposits indicating initially the grounding line was nearby and the ice sheet was quite stable for an initial period of time before retreating. The volume of diatomite at this MIS site and the presence of meltwater-dominated glacimarine facies are consistent with warmer climatic conditions than today with significantly higher rates of primary productivity and also significant meltwater discharges from groundling lines.

Locally, transitions from diamictite into diatomite are very sharp with major facies dislocations representing a dramatic change from hemipelagic iceberg-zone sedimentation to open-water biogenic sedimentation at the height of interglacials. These transitions are enlightening in that they appear to represent the relative speed of ice sheet retreat based on the thickness of transitional glacimarine sediment packages. In many cases the transitions occur over less than a meter of core. Although time involved in the transitions is unconstrained at present, we speculate that these transitions probably represent a rapid ice sheet retreat from the area, and in a number of cases, perhaps even a sector "collapse" of an ice shelf. On other occasions the transition is gradual and includes terrigenous grounding-line glacimarine sediments between the two dominant facies. That situation is taken to represent a more gradual ice sheet retreat.

Often the sections within and below the base of a diamictite interpreted as subglacial till is syndepositionally, physically intermixed in soft-sediment folds, fractures and rotated blocks, and are attributed to glacial overriding and sub-ice deformation, and/or pushing due to ensuing ice sheet advance. This deformation is locally quite pervasive below diamictites and appears to be synchronous throughout its thickness rather than having been deformed stepwise up core. Interestingly, these intervals often indicate only minor erosion occurred during ice sheet advance because re-advance glacimarine grounding-line deposits and significant thicknesses of diatomite are preserved. Consequently, these intervals are inferred to represent pervasive and subglacially extensive deformation during overriding with limited erosion, indicating that shear was transferred well below (<~10m) the sole of the ice sheet. It is also taken to show that either 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. Furthermore, unlike marine diamictites common in Ross Sea piston cores today, most AND-1B diamictites contain very few diatoms even in this diatomite-rich interval, although the significance of this has not yet been determine (Scherer et al., this volume).

A ~90m-thick diatomite within the Pliocene indicates an extended period of highly productive open water that may have lasted through a number of glacial-interglacial cycles. This implies a major sector of the Antarctic Ice Sheet was absent at least regionally, and did not expand in response to at least one Milankovitch cold period if not more.

When iceberg-rafted debris (IBRD) is present, it indicates the ice sheet had retreated most likely to the coastline where outlet glaciers were still calving icebergs into the Ross Sea and then they drifted over the site. If the ice shelf had remained, but was smaller, it is less likely the MIS site would have received IBRD from the southern TAM shoreline where a proportion of the clasts appear to originate, because most of the debris would have been melted out below the ice shelf and thus, icebergs would have been relatively free of debris. In addition, the amount of outwash mud reaching the site was minimal; also indicating the grounding line was distant from the site. There are also intervals with no iceberg-rafted debris when the area must have been substantially warmer than today, because the ice sheets in the Ross Sea sector must have 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 coupled climate-ice sheet simulations of ice volume.

Ice sheet dynamics during middle-late Pleistocene diamictite-dominated cycles (82.72-0 mbsf)

Between 27-83mbsf there are marked repetitions in lithologies dominated by diamictite with thinner intervals of bioturbated and stratified claystone and siltstone, volcanic sandstone and muddy conglomerate. In a similar fashion to the Miocene diamictite-dominated cycles lower in the core, the high proportion of subglacial and grounding-line proximal environments, together with the presence of granitoid and metamorphic rocks known from the Byrd glacier region, imply the existence of a grounded ice sheet in the Ross Sea, as has been discussed for the Miocene interval above.

Conclusion

This AND-1B core record from the MIS Project has the potential of significantly constraining the paleo-ice dynamics of the WAIS and Ross Ice Shelf/Sheet system, as well as contributing to understanding the behavior of the EAIS during the Neogene. The significant results thus far are that the Antarctic Ice Sheet has undergone considerable changes during the Neogene from a massive cold polar ice sheet in the earlier Miocene, through one that was warmer and had significant subglacial stream discharges in late Miocene-Pliocene, to return again to the colder ice sheets of Pleistocene and Holocene times. During colder ice sheet periods subglacial erosion appears to be important whereas the warmer ice sheet did not always erode significantly and instead slid on deforming subglacial sediment. Further facies analyses and modeling will be used to clearly define the important implications of these characteristics on ice sheet dynamics and response times to warming and cooling periods.

During warmer periods the ice sheet was dynamic with repeated glacial advances and retreats reflecting major changes in ice sheet volume that must have contributed significantly to eustasy and global ocean chemistry. There appear to be periods when the ice sheet was not calving into this sector of the Ross Sea indicating it had a much smaller volume than today. In contrast, we argue at this stage, that for intervals where we know the diamictite is a subglacial till and has clasts from the southern TAM, that the WAIS must have been large and feeding major ice volumes into the Ross Embayment. Grounded ice in the Ross Sea originating from the big outlet glaciers from the EAIS without the WAIS present are more likely to have flowed toward the east away from the mountains and formed local till to the south of our site without the ice making it farther north simply as a consequence of insufficient ice volume feeding it. These conditions would represent the core intervals where IBRD is being rafted to MIS from these southerly outlet glaciers. Additionally, during warmer late Miocene-Pliocene times the ice sheet was probably not as large as during the cold extremes of earlier Miocene and Pleistocene times inferred from flow line trajectories. To further understand and constrain ice sheet dynamics and the flow paths and perhaps size of the ice sheet, in future we will use core data, such as clast provenance, biological and geochemical proxies, combined with previously described terrestrial outcrop data and ice sheet modeling. Lastly, on occasion the ice sheet appears to have retreated quite rapidly and during other periods the retreat was slower; understanding these transitions is critical in terms of assessing the ice sheet response to past global warmings and thus, this topic also remains a focus of future studies.

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References

Domack, E.W., and P.T. Harris, (1998), A new depositional model for ice shelves, based upon sediment cores from the Ross Sea and the MacRobertson shelf, Antarctic, Annals Glaciology, 27, 281–284.
Krissek, L.A., et al., (this volume).
McKay, R.M., G.B. Dunbar, T.R. Naish, P.J. Barrett, L. Carter, and M. Harper, (in press), Retreat history of the Ross Ice Sheet (Shelf) since the Last Glacial Maximum from deep-basin sediment cores around Ross Island, submitted to, Palaeogeography, Palaeoclimatology, Palaeoecology.
Naish, T.R., R.D. Powell, R. Levy and the ANDRILL-MIS science team, (in prep.), Initial reports of the ANDRILL Program's, McMurdo Ice Shelf Project drillcores AND-1A and AND-1B, Antarctica, for Terra Antartica.
Naish, T.R. et al., (this volume).
Scherer, R. et al., (this volume).
Talarico, F. et al., (this volume).