Late Pleistocene to Holocene Strata from Soft-Sediment Coring at the AND-1B Site, ANDRILL McMurdo Ice Shelf Project, Antarctica

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Abstract - 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 was threatened by embedment of the sea riser for drilling of the ANDRILL (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 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 outsized clasts that 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 (McKay et al., in press), 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 about 10 000 years ago and a transition from grounding line proximal, through sub-ice-shelf to calving-line proximal environments.

INTRODUCTION

Before rotary drilling started a number of short cores were collected from the AND-1B site. These cores were to serve two main purposes: (1) The primary objective was to ensure the youngest glacial/climate record was recovered so that the McMurdo Ice Shelf (MIS) Project had as complete a geological record as possible through unlithified material in the upper ~30 m of sediment. (2) The supplementary purpose for recovery of the youngest record was to provide material 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.

Three different coring methods were employed to achieve these goals. First, after completion of the hot water drill hole through the ice shelf and prior to deployment of the sea riser, a small (~80 kg) gravity corer was used to recover the sediment-water interface and a few decimetres of sediment below the surface. Second, the sea riser was lowered to within a few metres of the seafloor, and the PQ drill string with a 1.6 m-long push corer was deployed through the riser. Last, following commencement of the primary AND-1A hole, an extended nose case sampler was used in advance of a rotating PQ drill bit to core to a depth where sediment became consolidated enough to cement the sea riser in place.

CORING OPERATIONS

Soft-sediment coring commenced on 16 October 2006 with the deployment of a gravity corer designed and built at the Alfred-Wegener-Institute (AWI) and fitted with either a 1.0 or 1.5 m-long plastic core barrel (Fig. 1). The corer was lowered to within 5 to 22 m above the seafloor. After waiting for the corer to stabilise for ~2 minutes, the winch was permitted to 'free-wheel', allowing the corer to build up momentum before penetrating the seafloor. Eight coring attempts were made, of which seven yielded a useable amount of material (Tab. 1). On recovery, cores were capped at the bottom and carried upright (with headspace water intact) into the drill site laboratory for microbial and pore water sampling, or drained and capped at the top for later analyses.

The push-core inner tube assembly was deployed on 25 October 2006 through the sea riser and PQ drill string which were lowered to within a few metres of the seafloor. The push corer assembly extends below the PQ drill bit and is 'pushed' into the sediment without rotation or use of drilling mud, at pressures up to 24 000 kilopascals (kPa). Using this technique, it was hoped the sediment-seawater interface would be recovered as well as allowing deeper penetration than was possible with the gravity corer. Four cores were collected in Ocean Drilling Program (ODP) liners (approximately HQ diameter) using this method, ranging in length from 0.33 to 1.56 m (Tab. 1). Once recovered, the cores were handled and processed in the same manner as gravity cores.

Coring in the AND–1A primary hole commenced on the 28 October 2006 with the extended nose case inner tube assembly (XNC). With this coring system

Fig. 1 – Gravity soft-sediment corer being deployed into the MIS hot-water drill hole.

the nose of the corer extends 0.13 centimetres (cm) beyond the rotating cutting bit, this time aided with KCI-based drilling mud. Penetration proceeded in advances of 3 m to match the core barrel length.

Tab. 1 - Details of McMurdo Ice Shelf soft-sediment cores.

AND-1	Type	Length (m)	Samples	Push pressure Start (kPa)	End (kPa)	Comments
001	GC	0.11	IW, BIO			Core sampled in whole round sections
002	GC	0.24	IW, BIO			Core sampled in whole round sections
003	GC	0.33				
004	GC	0.27	IW, BIO			Core sampled in whole round sections
005	GC	0.33				
006	GC	0.37	IW, BIO			Core sampled in whole round sections
007	GC	0.53				29 cm lost off bottom of core. Rhizon sampled.
008	GC	CC only				
009	PU	0.45		n.d.	n.d.	
010	PU	1.56	IW, BIO	6900	24100	Core sampled in whole round sections,
011	PU	0.54		10000*	22000*	
012	PU	0.33		n.d.	n.d.	
AND-001 001A		**Interval (mbsf)**				
001X	XNC	0.70 – 1.66				
001X	XNC	1.66 – 2.03				
001X	XNC	2.06 – 2.16				CC bagged
006X	PU	9.43 – 10.18				CC bagged 10.18-10.23m

*CC=core catcher; GC= gravity core; PU= push core; XNC = extended nose core;
IW = sampled for interstitial water; BIO = sampled for microbiology. *recorded in drillers log as 10 and 22 bar (1000 and 2200 kPa) respectively.

Tab. 2 - Shear strength measurements on McMurdo Ice Shelf project soft-sediment cores.

AND-1A	Depth (mbsf)	Measurement on spring dial	Approx. Shear Strength (kPa)	Comment
001XNC	1.57	14	23	
001XNC	1.94	44	73	Sediment dried and cracked during measurement
001XNC	10.11	10	17	

However, progressively deeper cores yielded only 23 % recovery with a total of 2.16 m of sediment retained between 0.70 and 10.18 mbsf. No sediment was recovered in runs two through five. Run six was completed with a push corer and recovered 0.8 m of sediment between 9.43 mbsf and the terminal depth of 10.23 mbsf. This material was split, imaged and logged as described in Krissek et al. this volume.

PHYSICAL PROPERTIES

UNDRAINED SHEAR STRENGTH

Undrained sediment shear strength was estimated using a Geotechnics hand-held, 19 millimetres (mm) diameter shear vane (Tab. 2). This instrument measures the torque required to shear the sediment along the vertical and horizontal edges of the vane which can be converted to shear strength (kPa) by empirically calibrating the instrument prior to use. The vane was inserted into the face of the split core until the blades were completely covered by sediment, and then rotated by hand until the sediment sheared. Note that it was impossible to insert the vane to the recommended depth (twice vane blade length) in order that it was well below the free surface, thus values given here underestimate the true shear strength of sediment. Shear strength values for unconsolidated sediment recovered from Windless Bight site survey cores (Niessen in Barrett et al. 2005) range between 0-20 kPa, with a maximum of 30 kPa, whereas Dowdeswell et al. (2004) report an abrupt (~20 centimetres below seafloor (cmbsf) core thickness) increase in shear strength from ~10 kPa to >60 kPa in subglacial diamicton deposited in Marguerite Bay. We do not consider these AND-1A results as absolute indicators of the degree of consolidation of the diamictons at this site, but they provide an indication of relative consolidation.

MULTISENSOR CORE LOGGER MEASUREMENTS

All soft-sediment cores were scanned for gamma density, p-wave velocity and magnetic susceptibility using a GEOTEK multisensor core logger (MSCL) before further processing and sampling. Exceptions to this are AND-1-007-GC (gravity core) and AND-1-008-GC, which were split and sampled prior to the installation of the MSCL. One core, designated for biological sampling only (010-PU [push core]) was measured prior to extrusion and whole-round sampling. Details of measurement procedures are given in Niessen et al. (this volume). Deviations from those procedures sometimes occurred due to the short core lengths and the requirements of subsequent analyses. The very

short cores AND-1-003-GC and AND-1-005-GC were analysed with 2 mm logging intervals, AND-009-PU to AND-1-011-PU with 1 cm intervals and AND-1-012-PU as well as AND-1A-001-XNC and AND-1A-006-XNC again with a logging interval of 0.5 cm. Wet bulk density was not measured on AND-1-010PU due to the risk of alteration of biological material by gamma radiation. For AND-1-009PU and AND-1-011PU the gamma attenuation was counted during 1 s per interval (instead of 10 s) to decrease the logging time prior to sampling. The level of radiation was increased by using a beam collimator of 5 mm instead of 2.5 mm in order to compensate for the low number of counts per second.

Results of these measurements (Figs. 2 & 3) show that the P-wave velocity (Vp) of the matrix is rather low (~1600 ms^{-1}) compared to Vp values at greater depths. Nevertheless, velocities as high as ~2200 ms^{-1} occur through clasts. In contrast to the low velocities encountered in these cores, their densities are relatively high with values around 1.8-1.9 g cm^{-3}. This may be related to some over-consolidation of the sediments induced by glacial grounding during the LGM. Clasts also can be identified by high density 'spikes'. Magnetic susceptibility values typically range from 100 to 300 (10^{-5} SI) and almost all cores show a slight increase in this parameter with depth.

Apart from the gravity cores 003-GC and 005-GC and the push core 012-PU, especially with regard to their magnetic susceptibility curve, no obvious correlation between the gravity and push cores and the two extended nose cores (AND-1A-001-XNC and AND-1A-006-XNC) can be identified from their physical properties. An explanation for this could be that the surface sediments may be disturbed in various ways by either natural (*e.g.* water current-sediment interaction, glacial erosion) or by drilling due to sea riser movement on the seafloor.

LITHOSTRATIGRAPHY AND SEDIMENTOLOGY

LITHOSTRATIGRAPHY

Split gravity and push cores were described by applying the same criteria as for the AND-1B drill core (see Krissek et al. this volume). In general, the lithostratigraphy is comparable to that documented from other LGM to Holocene cores in the Ross Sea (*e.g.* Domack et al. 1999) and, in particular, to that described from gravity cores collected from a nearby site survey location (HWD03-1; Barrett et al. 2005) and documented in McKay et al. (in press). The 'micro-stratigraphic' units encountered in these cores, from the seafloor down, are summarised in a composite
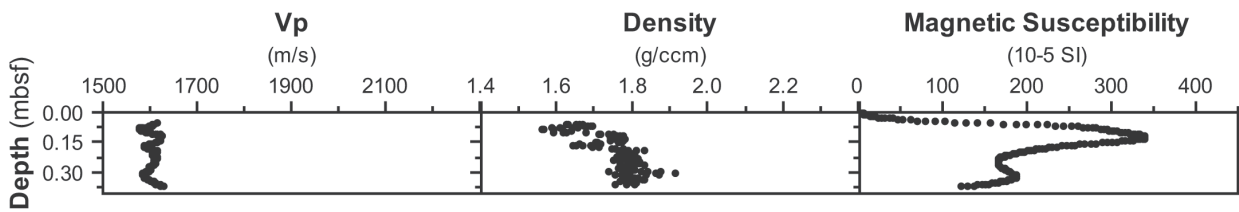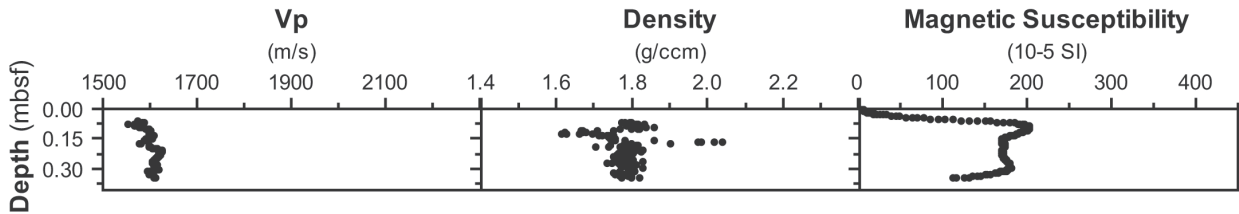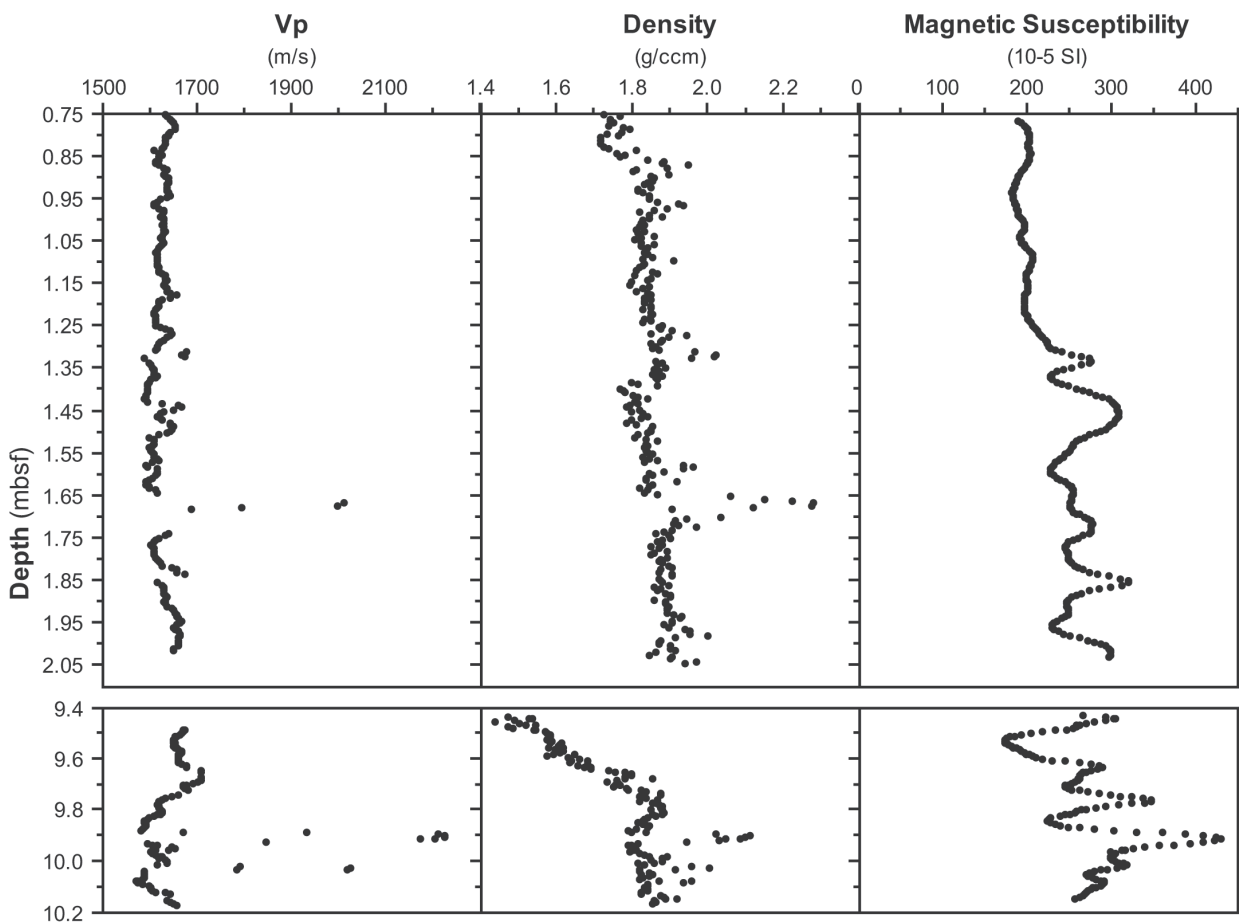
Fig. 2 – Log of velocity (Vp), density, and magnetic susceptibility of a) AND-1-003-GC, b) AND-1-005-GC, and c) AND-1-006-PU.

stratigraphic log (Fig. 4) and described below.

(A) Biosiliceous-bearing mud, ranging between 0.02 to 0.06 m-thick. With varying amounts of sand and gravel in the form of either (a) mud with abundant clasts; (b) clast-poor muddy diamicton; or (c) sandy muddy gravel. Clast composition is heterolithic and includes granule-sized mud aggregates, granitoids, sedimentary lithic fragments, and phonolite.

(B) Mud with minor to trace amounts of marine biosiliceous sediment commonly with well-rounded, granule-sized clasts of mudstone plus quartz and basalt, ranging in thickness from 0.00 to 0.28 m.

(C) A bed of volcanic, very fine sand with well-rounded rock and glassy fragments of mainly volcanic origin. The bed has a sharp, erosional base with weak grading of the sand, but possibly continuing
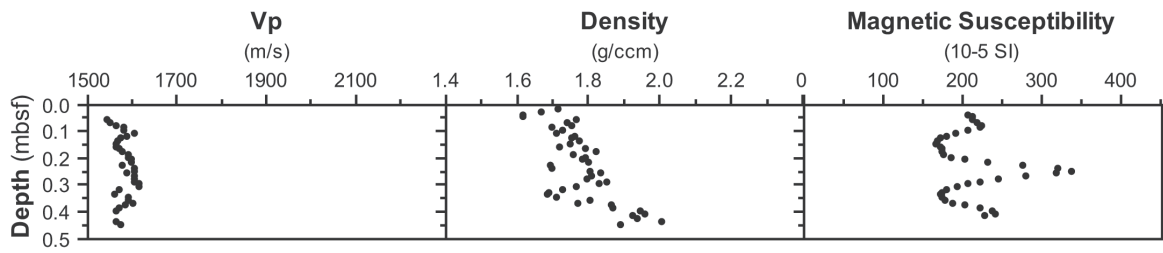
a. AND-1-009 PU
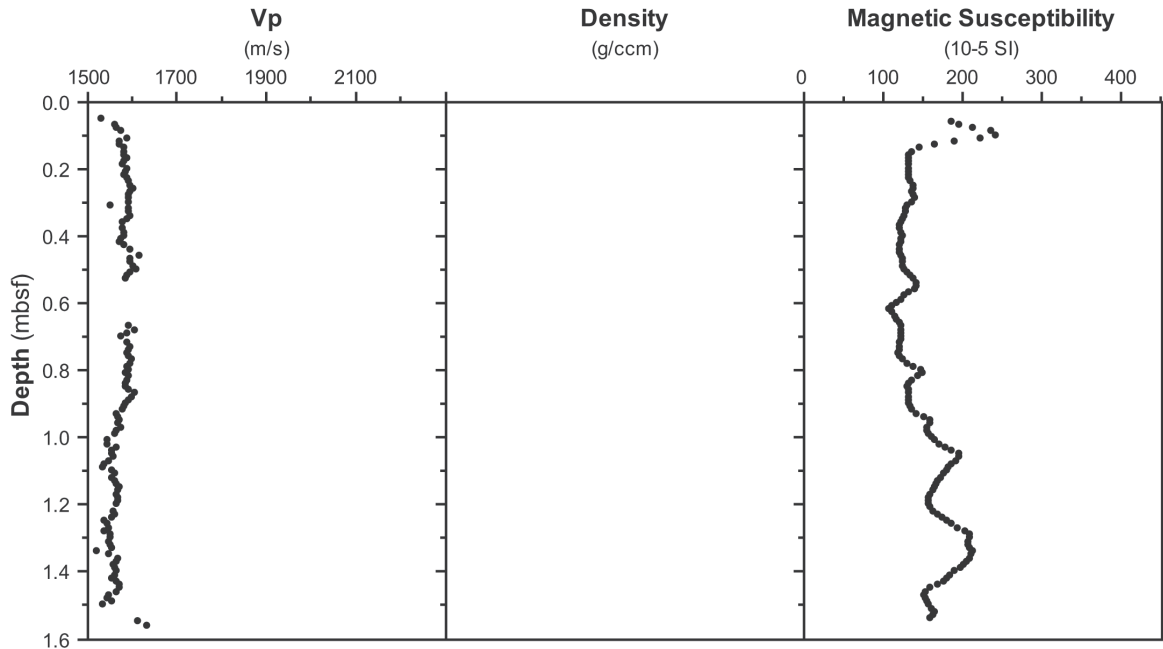
b. AND-1-010 PU
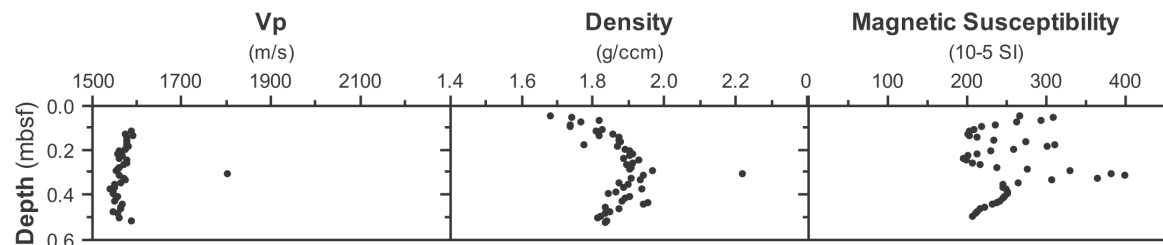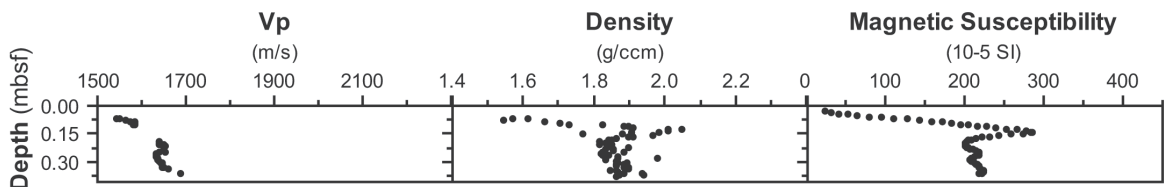
c. AND-1-011 PU

d. AND-1-012 PU

Fig. 3 – Log of velocity (Vp), density, and magnetic susceptibility for a) AND-1-009-PU, b) AND-1-010-PU, c) AND-1-011-PU, and d) AND-1-012-PU. Note density was not measured in 010 PU (see text).

into a 0.03 m-thick (maximum) layer of mud. The unit coarsens upward in one core (AND-009-PU) and ranges in thickness from 0.00 to 0.07 m.

(D) A 0.00 to 0.35 m-thick basal bed of mud with dispersed clasts is unconsolidated, but has varying degrees of stiffness. The clasts are up to 0.06 m in diameter and comprise mainly basic volcanics,

metasediments, and granitiods. Biosiliceous remains are absent, or when rarely present, are highly fragmented.

Gravity (GC) and push (PU) cores were collected without the use of drill fluids. Some disturbed sediment sections collected with the extended core barrel in the AND-1A core had drilling fluid (KCl) mixed with
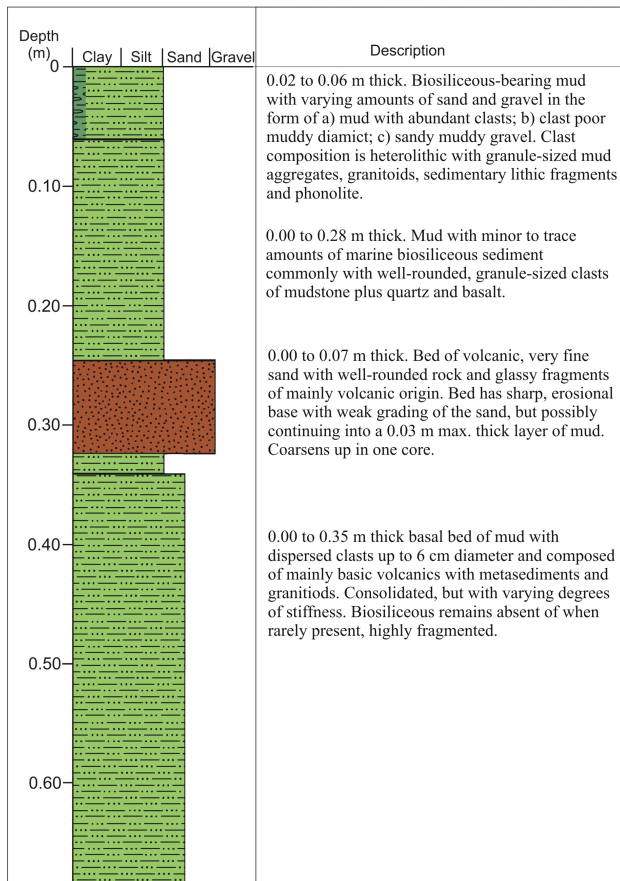
Fig. 4 – Composite lithostratigraphy of soft-sediment cores extracted at the MIS drill site.

sediment. The drill fluid was identified as isotropic rhombic crystals in smear slides and when present in high concentrations, it occurred as a gelatinous fluid in split core sections.

FACIES ANALYSIS

Unit 1D is interpreted as an ice-proximal glacimarine diamicton. Due to its lack of consolidation we associated this deposit with sub-ice-shelf grounding-line environments, and infer a downward transition into an over-consolidated till at about 1.5 mbsf, as shown in table 2 from the AND-1A core. Its sub-ice-shelf affinity is also supported by the presence of a wide range of different sized clasts in a very fine-grained matrix, an absence of bioturbation structures, and a paucity of biosiliceous remains (cf. Anderson et al. 1991; Domack et al. 1999).

The overlying Unit 1B contains trace amounts of whole marine diatom valves, which suggests a subtle transition away from the grounding line, with some sub-ice-shelf transport of the diatoms (Anderson et al. 1991). The presence of weakly packed, rounded mud granules is reminiscent of the granulated unit of Domack et al. (1999) who regard the unit to represent the lifting of an ice shelf from the seabed. Although not inferred in modern settings, they suggest that with lift-off, the ice shelf base melts to release soft till pellets together with dropstones having the same

lithologies as in the till. Pellets may round as they pass through the water column; however, rounding is more likely by ambient currents possibly enhanced by tidally forced pumping of the ice shelf. This mode of sedimentation was interrupted by the passage of a turbidity current that deposited the volcanic fine sand (Unit 1C). The sand is tentatively assigned to a single local volcanic source, which from the presence of common glassy clasts was relatively close, but detailed petrographic analysis has yet to be done. The occurrence of the turbidity current during the lift-off phase may be coincidental, or perhaps the lift-off process or related water movements triggered the current. Clearly basal melt out continued after this event as attested by the presence of dropstones and mud granules in the upper parts of the turbidite and the continuation of the overlying granular unit.

The abundance of marine diatoms, the muds of Unit 1A reflects an open connection with the ocean and the advection of phytoplankton beneath the ice shelf. The presence of dropstones of variable provenance (local volcanic centres and the Transantarctic Mountains; TAM) suggests that basal melting of the ice shelf has contributed to the seabed over the Holocene. However, other mechanisms such clast concentration through current-winnowing around local bathymetric highs may also play a role.

PETROLOGY AND PETROGRAPHY

CLAST PETROLOGY

All clasts, ranging in dimension from granule to pebble sized, were logged and counted on the basis of both lithology and size, following the same procedure adopted in CRP-2/2A (Cape Roberts Science Team, 1999). The clasts are predominantly volcanic rocks and granitoids, with minor metasedimentary rocks and rare sedimentary rocks (claystone) and dolerites (Tab. 3). Thin-section examination of selected pebbles indicates that volcanic clasts include both mafic and felsic types, the granitoids are mainly foliated biotite ±hornblende granites and the metasedimentary clasts are very fine-grained amphibole-bearing biotite metasandstones.

SAND PETROLOGY

Five representative lithologies from AND-1-007-GC were processed for grain-size analysis. The 63–500 μm sand fractions were set in an epoxy resin and thin sectioned. Modal analysis of this fraction was undertaken by a point count (300 grains) of mineral and lithic grains. Results shown in figure 5 are similar to a previous study of seafloor sediments from a nearby site (HWD03-1) at Windless Bight (Barrett et al. 2005; McKay et al. in press). The sample at 0.03 mbsf contains ~10% minerals inferred to have a TAM provenance, including rounded and angular quartz from the Beacon Supergroup and granites (among others). The samples at 0.09, 0.12, and 0.14 mbsf

Tab. 3 - Clast counts and lithologies for McMurdo Ice Shelf soft-sediment cores.

Core	Top	Bottom	Volcanic	Granitoid	Sedimentary	Metamorphic	Quartz	Dolerite	Intraclasti	Total No.Clasts
003GC	0.00	0.10			1					1
003GC	0.10	0.20	2							2
003GC	0.20	0.30	2	1						3
003GC	0.30	0.32								0
005GC	0.00	0.10	3							3
005GC	0.10	0.20	4							4
005GC	0.20	0.30	1							1
005GC	0.30	0.32								0
007GC	0.00	0.10								0
007GC	0.10	0.20								0
007GC	0.20	0.30	2							2
007GC	0.30	0.40	2							2
007GC	0.40	0.50	1							1
007GC	0.50	0.52								0
009PU	0.00	0.10	2	2						4
009PU	0.10	0.20	1	1						2
009PU	0.20	0.30	3							3
009PU	0.30	0.40								0
009PU	0.40	0.46								0
011PU	0.00	0.10	4	1						5
011PU	0.10	0.20	2							2
011PU	0.20	0.30	2							2
011PU	0.30	0.40	1	2						3
011PU	0.40	0.50	1	1						2
012PU	0.00	0.10	1	1						2
012PU	0.10	0.20	2	2						4
012PU	0.20	0.30								0
012PU	0.30	0.32								0
001XCN	0.70	0.80								0
001XCN	0.80	0.90			2					2
001XCN	0.90	1.00	1							1
001XCN	1.00	1.10								0
001XCN	1.10	1.20								0
001XCN	1.20	1.30								0
001XCN	1.30	1.40	2							2
001XCN	1.40	1.50	2							2
001XCN	1.50	1.60				1				1
001XCN	1.60	1.66						1		1
001XCN	1.66	1.76	1			1				2
001XCN	1.76	1.86	1	1						2
001XCN	1.86	1.96								0
001XCN	1.96	2.03	1							1
001XCN	2.06	2.16	1			1				2

are dominated by McMurdo Volcanic Group (MVG) grains, indicating a local sediment source originating by hemipelagic settling or sediment gravity flows. The volcanic sand between 0.10 and 0.17 mbsf is mostly composed of rounded and weathered volcanic lithics and glass. The bottom-most sample (mud with clasts) contains ~40% TAM grains, including quartz, microcline (granite), and sedimentary and doleritic lithics, and most likely requires a glaciogenic origin. Given the unconsolidated nature of this unit, it is likely that it was deposited by rainout from an ice shelf. The sand and mud units overlying the gravelly mud mostly consist of locally derived McMurdo Volcanic Group (MVG) sediment; however, the sample at 0.03 mbsf contains a distinct (~10%) TAM signal. Given the diverse lithologies recovered in other gravity cores during this study and lack of evidence for open water, the TAM signal is likely due to localised current reworking of older glaciogenic sediments exposed nearby, rather than rainout from an iceberg or ice shelf.

PALAEONTOLOGY

DIATOMS

The diatom record of GC and PU cores was analysed using smear slides made from residues from pore-water 'squeeze cakes' and trimmings taken prior to squeezing (for methods, see Scherer et al. this volume). The diatom abundance in GC and PU cores varies from abundant in the upper ~0.05 m, to rare with poor preservation or barren in the underlying diamicton. Diatom composition is dominated by sea-ice-related species with some contributions from both open-ocean and reworked species (Tab. 4). Variation in the diatom assemblages among cores is slight which may be expected within a limited geographical area. Overall the assemblage resembles that described from gravity cores collected during the MIS site surveys (Barrett et al. 2005).

The presence of a typical post-glacial well-preserved diatom flora carries evidence of diatoms being advected beneath the ice shelf. The diatom composition in surface sediment of the western and central Ross Sea is divided in four major assemblages with distinct geographical distribution (Cunningham & Leventer 1998). A meltwater stratification assemblage characterised by *Fragilariopsis curta*, up to 87% of the assemblage, is described along the coast north of Drygalski Ice Tongue. The coastal assemblage along the coast and north of Ross Island is characterised by *Thalassiosira antarctica* and *F. curta*. Farther west, towards the central Ross Sea an open-water assemblage characterised by *T. gracilis, F. obliquecostata,* and *Eucampia antarctica* dominates the assemblage. A heavily reworked, extinct assemblage characterises the surface sediment in the central Ross Sea. The assemblage encountered in the surface sediment recovered by GC and PU cores has similarities with both the coastal and open-water assemblages described by Cunningham and Leventer (1998), suggesting a local source for the advection rather than distant transport. The rather high proportion of open-water species is proposed to be related to the formation of a polynya where wind induced mixing, and ice breakup promotes a different assemblage from the coastal sea-ice melt areas.

FORAMINIFERA

Seafloor samples from two gravity cores (GCs) and five push cores (PUs) all contained rare foraminifers, and yielded a combined total of 22 specimens, including planktic, benthic, and agglutinated taxa. These samples and their palaeoenvironmental significance are summarised in table 5.
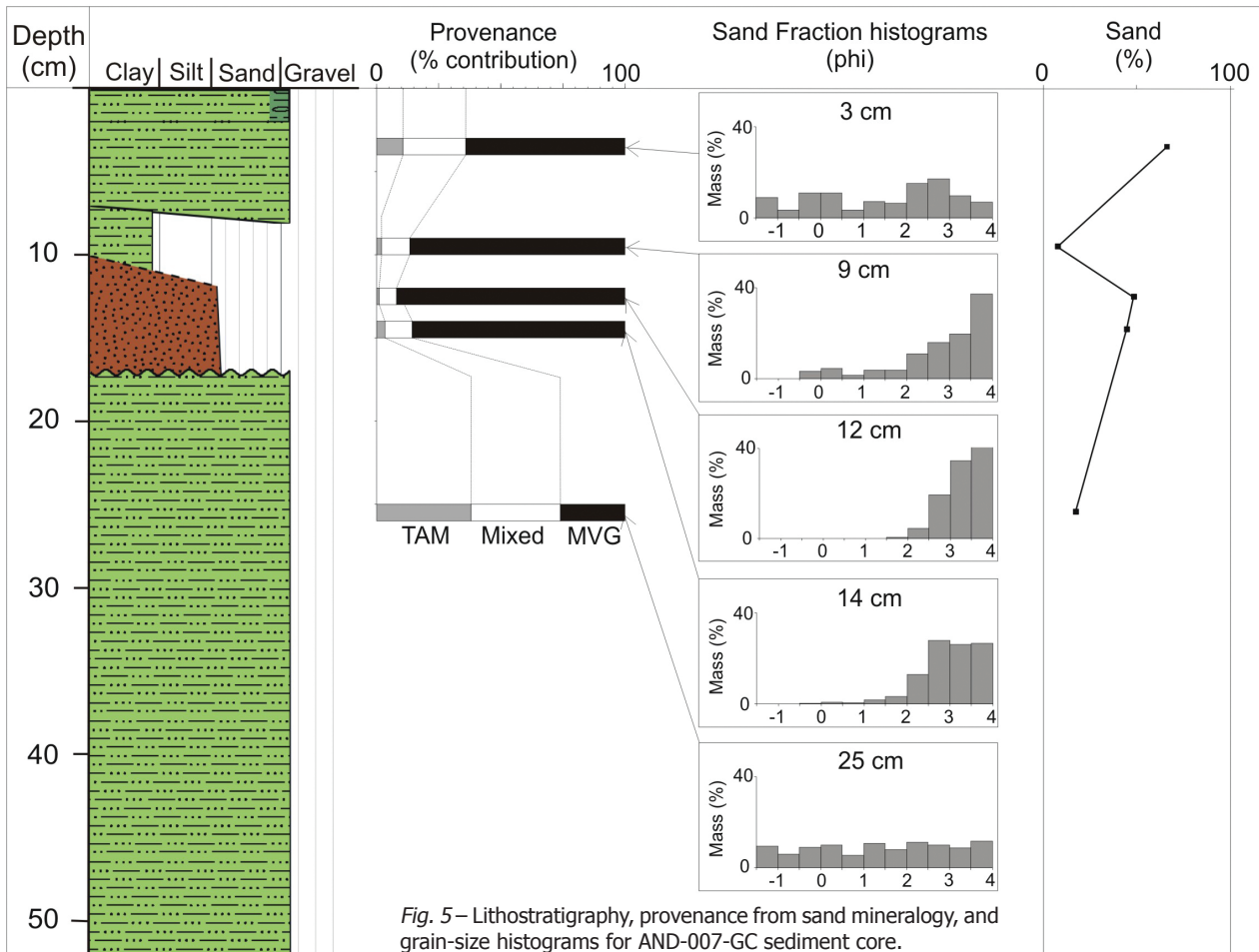
Fig. 5 – Lithostratigraphy, provenance from sand mineralogy, and grain-size histograms for AND-007-GC sediment core.

PALYNOMORPHS

Palynology is the study of the acid-insoluble remains of microscopic marine and terrestrial flora and fauna (palynomorphs). One sample from a push core (0.35–0.37 mbsf) and two samples from AND-1A (24.88–24.90 and 40.73 and 40.75 mbsf) have been processed and examined for palynomorphs. See Scherer et al. (this volume) for details of processing.

Although no sample was barren, the yield was extremely low, ranging from 0.36 grains per gram in the push core down to 0.08–0.09 in the other two samples. The flora is overwhelmingly marine; a single recycled taeniate bisaccate (Permian) grain comprises the entire terrestrial assemblage. The small marine assemblage is almost evenly split between reworked Eocene species and an assemblage that is probably *in situ* (see Scherer et al. this volume for details of the *in situ* assemblage).

MICROBIOLOGY

Sediment whole rounds were collected from gravity and push cores inside a sterile flow hood for microbiological analyses. A hole was cut in the centre of the table on which the flow hood rested. This hole matched the outer diameter of the sediment core liners in order that the cores could be extruded upward and vertically within the working space of the flow hood by using an extruder that was positioned beneath the table. This extruder has a threaded shaft, capped with a round surface on which one end of the core + liner rests, and a threaded 'nut'. The core is extruded at the top of the liner inside the flow hood when the nut is threaded downward along the shaft.

Before extruding the core for pore-water geochemistry and microbiological sampling, the excess seawater was drained off by poking a small hole, ~2–3 cm above the sediment-water interface, with a sterile 16-gauge syringe needle. Once the liner was punctured with the needle, some of the initial seawater was collected for chemical analysis and the remainder discarded. After draining most of the water, the core liner was then cut near the puncture hole with a core-cutting tool, and the remaining standing water above the sediment removed with a sterile syringe. These final steps of draining the water and cutting the liner were done directly in front of the sterile flow hood to minimise outside contamination.

After the core was cut, it was inserted through the hole of the sterile flow hood so that the bottom of the core rested on the working surface of the threaded shaft of the extruder that was positioned beneath the table. For the first core (AND-1-001-GC), the top 0–5 m was collected for microbiological analyses, and the following 5 cm below for pore-water geochemical analysis. This alternating sampling interval was used to collect samples from the entire core length for both microbiology and pore-water geochemistry (*e.g.* 0–5,

Tab. 4 - Diatom count and abundance estimate table for gravity (GC) and push (PU) cores recovered during the McMurdo Ice Shelf Project. The abundance is estimated from smear slide analyses, where X = presence, R = rare, F = few, and C = common occurrence per transect. On top of the graph is indicated preferred environment for the different species based on circum-Antarctic investigations (Crosta et al. 2005).

Sample metadata (per AND-1SS core sample):

AND-1SS Core	Sample depth	Abundance	Preservation	Total counted
001GC	0.04-0.08 t	A	G	270
003GC	0-0.01 s	A	G	539
003GC	0.03-0.04 s	A	G	322
003GC	0.06-0.07 s	A	G	235
005GC	0-0.01 s	A	M	580
005GC	0.04-0.05 s	F	P	185
005GC	0.2-0.21 s	X	G	30
006GC	0-0.05 t	F	P	180
007GC	0-0.01 s	A	M	445
007GC	0.03-0.04 s	C	M	335
007GC	0.17-0.18 s	R	P	70
007GC	0.33-0.34 s	X	M	10
009PU	0.01-0.02 s	C	P	550
009PU	0.03-0.04 st	X	P	64
009PU	0.06-0.07 s	X	P	30
009PU	0.15-0.16 s	X	P	10
009PU	0.3-0.31 s	X	P	30
009PU	0.42-0.43 s	X	P	10
011PU	0.02-0.03 s	C	M	540
012PU	0-0.01 s	C	M	316

Diatom count / abundance (species as rows; sample columns S1–S20 correspond to the rows in the metadata table above, top to bottom):

Species	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20
Achnanthes brevipes var angustata (Greville) Cleve				1																
Achnanthes groenlandica Grunow in Cleve et Grunow																			X	X
Actinocyclus actinochilus (Ehrenberg) Simonsen	3	3	3	2	X				X	X	X		X	1					R	9
Actinocyclus ingens Rattray	1			2									X	X						
Actinocyclus karstenii Van Heurck		1	1																	
Asteromphalus hookeri Ehrenberg				3															X	X
Asteromphalus parvulus Karsten	1	3	3		X				X	X			X						X	2
Chaetoceros spp.		2		2					R	R			F	5					R	7
Cocconeis costata Gregory									X	X									X	
Corethron criophilum Castracane				1					X	X										
Coscinodiscus spp.		1	1		X					X										
Dactyliozolen antarcticus Castracane		1	1																	
Denticulopsis maccollumii Simonsen								X												
Denticulopsis spp.	1																			
Ethmodiscus rex (Rattray) Wiseman & Hendey				1																
Eucampia antarctica flat													F							
Eucampia antarctica pointy													X						X	11
Eucampia antarctica var recta (Mangin) Fryxell & Prasad	12	43	11	18	F	X			X	F	R	X							F	25
Fragilariopsis angulata (O Meara) Hasle													X						R	9
Fragilariopsis curta (Van Heurck) Hustedt	77	61	110	56	F	R			X	R			F	17	X		X		F	41
Fragilariopsis cylindrus (Grunow in Cleve) Kieger	2	9	1						X	X			X						X	4
Fragilariopsis kerguelensis (O Meara) Hasle	2	9	3	6	R				X	X			X	1					X	1
Fragilariopsis matuyamae Gersonde et Bárcena	9	30	30	8	X				X	R	X	X								
Fragilariopsis obliquecostata (Van Heurck) Hasle	41	178	57	41	A	X			R	F	F		F	16					F	89
Fragilariopsis peragalli (Hasle) Cremer																				1
Fragilariopsis praeinterfrigidaria (McCollum) Gersonde et Bárcen				2																
Fragilariopsis rhombica (O Meara) Hustedt	9	9	5	1					X			X								
Fragilariopsis ritscheri Hustedt		10	1	2	X														X	3
Fragilariopsis separanda Hustedt	4	3	2	1	R	X				X			X							2
Fragilariopsis sublinearis (Van Heurck) Heiden	9	30	30	8	X	X			X	R	X	X								
Fragilariopsis vanheurckii (Peragallo) Hustedt	33	18	13	25	R	R			X										X	9
Lithodesmium reynoldsii Barron			1	1																
Nitzschia acidoclinata Lange-Bert																				
Nitzschia lecointei van Heurck	8			2																
Nitzschia lineata Hasle	1				X															
Nitzschia sp 17 of Schrader	1																			
Nitzschia spp.									X											
Odontella weissflogii (Janisch) Grunow		1	1						X				X							
Paralia sulcata (Ehrenberg) Cleve	2	1	1	1	X		X		X	X	X		X				X	X		
Porosira pseudodenticulata (Hustedt) Jousé, in Kozlova	3	2	2		X				X	X			X						X	
Proboscia alata Brightwell														1						
Proboscia inermis (Castracane) Jorden & Ligowski																				1
Rhizosolenia antennata f semispina Sundström								X												
Rhizosolenia polydactyla Castracane		1																		
Rhizosolenia spp.					X								X	X						
Stellarima microtrias (Ehrenberg) Hasle and Sims	8	35	12	4	F	X	X		X	R	X		R	1	X				F	10
Stephanopyxis spp ?		2																		
Stephanopyxis turris (Greville and Arnott) Ralfs, in Pritchard									X				X							
Synedropsis recta Hasle, Medlin et Syvertsen																			X	
Synedropsis spp.																				1
Thalassionema / Thalassiothrix spp		6	5	1					X	X										
Thalassiosira antarctica Comber	35	57	37	42	F	R			R	F	R									
Thalassiosira antarctica type 1 Comber													R	8	X		X		R	32
Thalassiosira antarctica type 2 Comber																				2
Thalassiosira fasciculata Harwood and Maruyama			1		X															
Thalassiosira frenguellii Kozlova													X							
Thalassiosira gracilis var expecta (Van Landingham) Fryxell & H														3						14
Thalassiosira gracilis var gracilis (Karsten) Hustedt	7	28	4	7	R				X	X	X		R						R	13
Thalassiosira inura Gersonde																			X	X
Thalassiosira lentiginosa (Janisch) Fryxell	4	11	9	4	R	X			R	X	X		R	1					X	14
Thalassiosira leptopus (Grunow) Hasle & Fryxell	1																			
Thalassiosira oliverana (O Meara) Sournia		6	4		R				X	X	X		R						R	5
Thalassiosira oliverana v sparsa Harwood and Maruyama								X												
Thalassiosira sp. 1	1	1	1		X					X										
Thalassiosira sp. 2													X							
Thalassiosira torokina Brady	1									X										
Thalassiosira tumida (Janisch) Hasle in Hasle et al	2	9	2	3	R	X			X	R	R		R	1					X	4
Thalassiothrix spp.													X	X						3
Trachyneis aspera (Ehrenberg) Cleve		1																		
Triceratium pileus Ehrenberg		2																		
Unknown Chrysophyte spp.													X	9					X	
Unknown Silicoflagel spp.		4	1		X	X														

Tab. 5 - Foraminifera from McMurdo Ice Shelf Project soft sediment cores.

Core	Depth (m)	Wgt (g)	Lithology	Faunal record	Interpreted paleoenvironment
006GC	0.20-0.25	51.9	siltstone, pebbly, grey	*Haplophragmoides* sp., *Oolina globosa*, *Neogloboquadrina pachyderma.* Total 5 specimens	Open water; fauna consistent with present-day depth.
006GC	0.30-0.35	49.2	siltstone, pebbly, grey	Only a single *Oolina globosa* found.	Indeterminate.
009PU	core catcher	47.89	clay, grey, sticky	*Recurvoides contortus, Sphaeroidina bulloides, Bulimina* sp., *Globocassidulina crassa, Ehrenbergina glabra, Neogloboquadrina pachyderma.* Total 9 specimens.	Open water, depth most likely >400 m.
010PU	core catcher	59.43	clay, grey, sticky	Single *Cibicides* sp. recovered.	Indeterminate.
011PU	0.42-0.45	16.42	clay, grey, sticky	Single specimens of *Oolina globosa* and *Neogloboquadrina pachyderma* recovered.	Open water; Genus *Oolina* found mid-shelf to deeper bathyal.
011PU	core catcher	85.54	clay, grey, sticky	Single specimens of *Sphaeroidina* cf. *bulloides* and *Anomalinoides* sp. recovered.	Probably mid-shelf or deeper.
012PU	core catcher	27.19	clay, grey, sticky	Single specimens of *Globocassidulina crassa, Fursenkoina schreibersiana.*	Probably mid-shelf or deeper.

10–15, 20–25 cm for microbiology and 5– 10, 15–20, 25–30 cm for pore-water geochemistry). However, in other cores this alternating sampling scheme was reversed, so that the second core was sampled at 0–5, 10–15 cm and so on, for pore-water geochemistry, and the intervening intervals for microbiology. All core sampling and subsampling for microbiology and pore-water geochemistry occurred inside the sterile flow hood.

From each 5 cm thick whole round designated for microbiology, subsamples were collected for the following: (a) cell counts, (b) DNA analysis, and (c) bacterial cell membrane phospholipids. Beginning with the sediment-water interface, and continuing downcore with each of the fresh sediment surfaces designated for microbiology, approximately 4–5 cc of sterile sediment was collected from the centre of the core by suction using a sterile 5 cc syringe that had its lower tip cut off. The entire length of the 5 cc syringe was pushed into the sediment; however, most sediment subsamples were limited to 4 cc rather than 5 cc. The 4 cc of sediment collected were further subdivided and ejected from the syringe sequentially as follows: (1) the first gram (corresponding to the bottom of the whole round) was placed into a sterile 20 millilitre (ml) serum vial which contained 10 ml of filter-sterilised (0.2 μm) seawater with 3.8% formaldehyde (final concentration, v/v) in order to fix the cells for subsequent counting by the acridine orange staining method. (2) The next 2 cc were ejected into a sterile "whirlpak" bag and immediately frozen for DNA analysis. (3) The final 1 cc (corresponding to the top of the whole round) was placed into another 20 ml serum vial for a replicate cell count as described in step number 1. The formaldehyde used in the serum vials for fixing the cells was previously filter sterilised (0.2 μm filtered) as previously described (Cragg et al. 2003). The serum vials designated for cell counts were crimp-sealed and immediately placed into a refrigerator (4°C) next to the sterile flow hood.

After the 4 cc of sediment was subsampled as described above, 5 cm of this whole round was then extruded and cut off with a pre-autoclaved spatula (or autoclaved metal butter knife) and placed into a pre-sterile whirlpak bag (11.2 cm diameter, minimum). These larger samples were collected for bacterial cell membrane phospholipid analysis. The bagged sample was then placed into a vacuum seal bag with two oxygen-scrubbing packets, immediately vacuum-sealed and subsequently frozen. Samples collected for DNA and phospholipids were kept frozen during storage and transported back to the Colorado School of Mines. The serum vials collected for cell counts were refrigerated during storage and transport.

After sampling a whole round for microbiological analysis, the subsequent underlying 5 cm of core was extruded into a clean 5 cm-long section of core liner. This whole round was collected for pore-water geochemical analysis by cutting with a sterile (pre-autoclaved) spatula in order to avoid any contamination. This whole round was immediately covered with cellophane wrap at both ends, subsequently capped at each end, placed into a Ziploc bag and refrigerated. Within 12 hours of collection, these whole round samples were squeezed for collecting pore waters for geochemical analyses.

The preliminary results of bacterial cell counts in the sediments at MIS (Fig. 6) are consistent with similar counts reported for deep marine sediments of the northwest Pacific by Cragg et al. (2003) and Mills et al. (2006). In general, there is good agreement between the estimated cell numbers over the top 10 cm of sediments at MIS and these other marine locations. However, there is a more rapid decline in cell numbers with depth at MIS, with cell numbers at >40 cm depth being approximately half that measured at these other locations. These differences seem reasonable given the relatively low concentrations of organic carbon at the MIS site. Future microbiological analyses will include quantification and identification
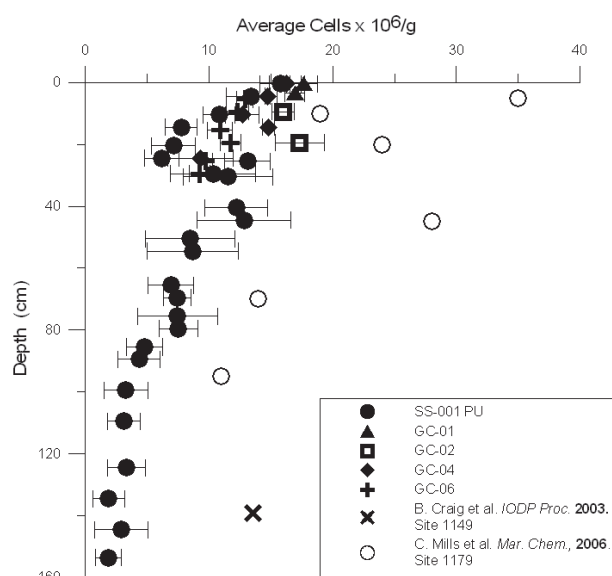
Fig. 6 – Cell counts with depth in the MIS soft-sediment cores.

of total bacterial phospholipid fatty acids (PLFAs) and archaebacterial phosphoether lipids (PELS) using GC-FID and GC-MS, respectively. Once these lipids have been measured, their $\delta^{13}C$ values will also be measured by gas chromatograph (GC) isotope ratio mass spectrometry. To further characterise the bacterial communities, DNA analyses using polymerase chain reaction (PCR), cloning, and restriction fragment length polymorphism sequencing techniques will be made.

PORE-WATER GEOCHEMISTRY

Pore-water was extracted from gravity core (GC) and push core (PU) sediment samples (see Tab. 1) using Rhizon samplers and an ODP-pore water squeezer (see Pompilio et al. this volume for details). The scientific party included Gavin Dunbar, Larry Krissek, Kevin Mandernack, Matt Olney, Chieh Peng, Ross Powell, and Stefan Vogel.

METHODS

Pore-water squeezing: Following the ODP protocols for pore-water squeezing, 5 cm-long whole rounds were collected in connection with the sediment sampling for microbiological work at the drill-site lab. After recovery of the soft-sediment cores from the drill hole, the cores were capped and transferred to the drill-site lab. In the drill-site lab the cores were extracted from the core liner into a laminar flow hood, and 5 cm sections for microbiological and pore-water work were taken in alternating sequence. After collection, sediment samples for pore-water sampling were sealed and capped immediately. Sediment samples were then transferred to the laboratory at McMurdo Station within hours.

In the laboratory, the outside of the sediment samples was cleaned by cutting away a rim of ~1 cm. The remaining clean inner core of the sample was then

transferred into the titanium squeezer. This procedure followed ODP pore-water extraction protocols as instructed by Chieh Peng (ODP technician; see Manheim & Sayles, 1974 for details on squeezer). The squeezer was transferred into a hydraulic press and a pressure of 20 000 to 30 000 pounds (lbs) was applied. After an initial consolidation phase with applied pressures of ~5000 lbs the pressure was manually increased in steps of 2 000 to 3 000 lbs. The maximum pressure was usually reached after about 1 to 1.5 hours. After passing through a Whatman no. 1 filter at the bottom of the squeezer all pore-water samples were collected with 50 ml plastic syringes. All syringes were acid cleaned with 10% HCl prior to use.

Rhizon sampling: On two cores AND-1-007-GC and AND-1-009-PU pore-water was also extracted using Rhizon samplers. Rhizon sampling was also used to extract pore-water from AND-1A at 9.95 mbsf. An attempt to obtain pore-water samples with the Rhizon setup from AND-1B at a depth of 20.55 mbsf yielded ~ 0.5 ml but was unsuccessful at 35.97 mbsf.

Rhizon sampling is a method to extract pore-water, which does not destroy the acquired sediment core and causes minimal disturbance, aside from dewatering the core material. The Rhizon sampler consists of a membrane filter, which is attached to tygon tubing, and inserted through a small hole in the core liner. The inserted sampler is then either attached to a syringe or a glass vacuum tube, and pore-water extracted using the suction created by the applied vacuum. Each Rhizon sampler was acid cleaned prior to use with 30 ml of 1% HCl and carefully rinsed with Milli-Q water. Rhizon samplers were purchased from www.rhizosphere.com, see www.eijkelkamp.com for product information.

ANALYTICAL MEASUREMENTS

Immediately after collection, pore-water samples were filter through a 0.2 μm nylon membrane filter into acid washed HDPE plastic vials. Aliquots for individual work were then dispensed into the appropriate sample vials for later on-ice and off-ice work, and when the sample quantity was sufficient, electrical conductivity, pH, and alkalinity were measured immediately. On-ice measurements included NH_4^+, Cl^- titration, and measurement of major cation and anion concentrations using ion-chromatography.

ACCURACY OF CHEMICAL ANALYSIS

The accuracy of the geochemical measurements is assessed using the electro-neutrality (EN [%]; Appelo & Postma, 1996, chapter 1.4.2) using the charge balance of the measured cations and anions.

$$EN\ [\%] = (Sum\ cations + Sum\ anions)\ /\ (Sum\ cations - Sum\ anions)\ x\ 100$$

With cations and anions being expressed in meq/l and the correct charge sign (cations positive,

Fig. 7 – Geochemistry of pore water in the MIS soft-sediment cores. (A) Cation concentration profiles (Na, K, Mg, NH4++, Li, Ca), (B) Anion concentration profiles (F, Cl, Br, SO4).

A
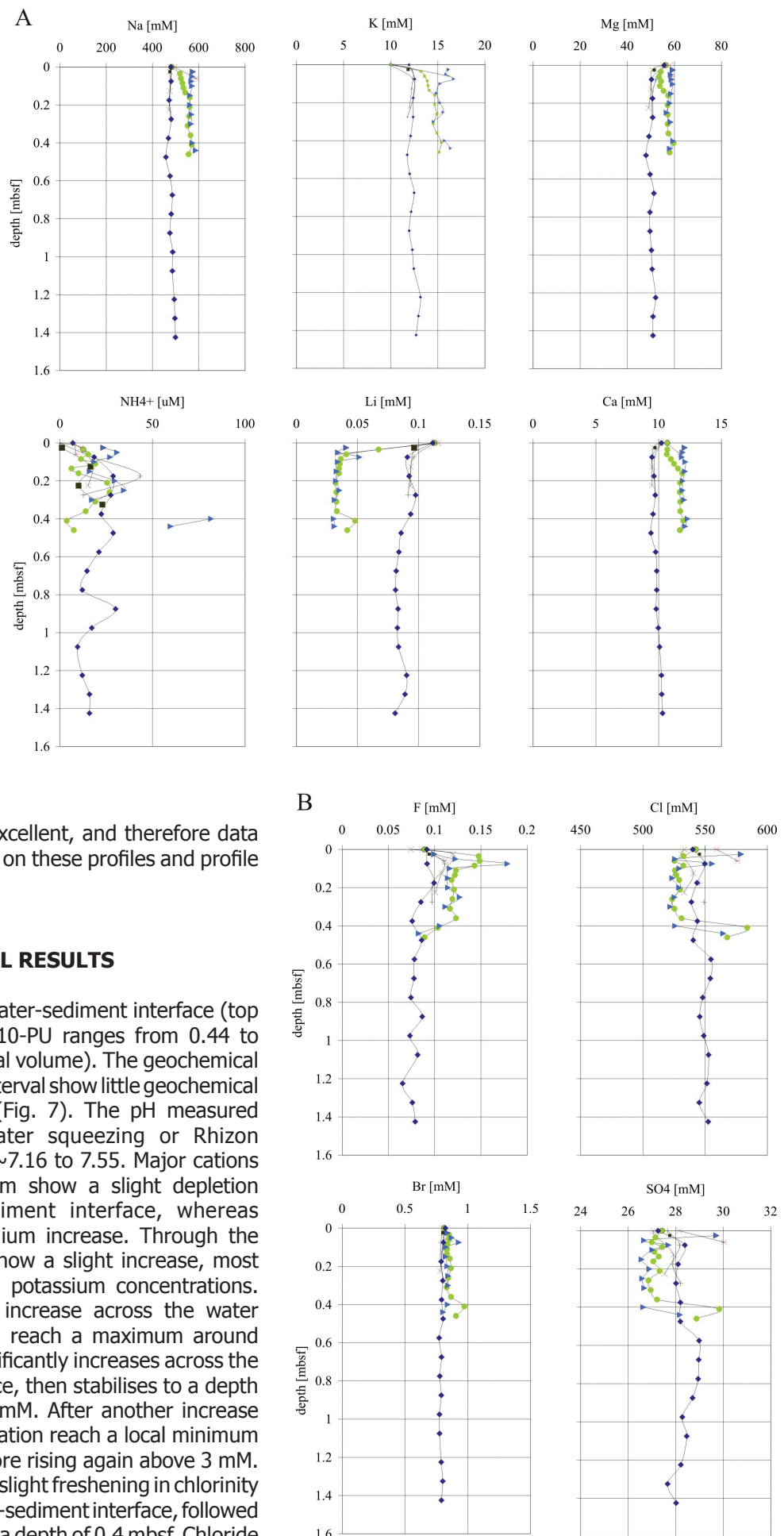
anions negative). The calculated electro-neutrality is good with an average of 0.75% and standard deviation of 1.00%. Electro-neutrality of samples from cores AND-1-007-GC, AND-1-009-PU, and sample AND-1-001/004/008-GC, however, averaged 8.81% with standard deviation of 1.95. Ion chromatography measurements were drift-corrected for individual runs. Overall these samples had a lower reproducibility. Reproducibility of the remaining samples is excellent, and therefore data interpretation will focus on these profiles and profile AND-1-010-PU.

INITIAL RESULTS

Porosity at the seawater-sediment interface (top 1.5 m) of core AND-010-PU ranges from 0.44 to 0.59 (volume water/total volume). The geochemical measurements in this interval show little geochemical variability with depth (Fig. 7). The pH measured directly after pore-water squeezing or Rhizon sampling ranges from ~7.16 to 7.55. Major cations magnesium and calcium show a slight depletion across the water-sediment interface, whereas potassium and ammonium increase. Through the top 1.5 m all cations show a slight increase, most visible for calcium and potassium concentrations. Sulfate concentrations increase across the water sediment interface and reach a maximum around 0.6 mbsf. Alkalinity significantly increases across the water-sediment interface, then stabilises to a depth of 35–40 cm at ~ 3.0 mM. After another increase to 3.3 mM the concentration reach a local minimum of 2.9 mM at ~1m, before rising again above 3 mM. This corresponds with a slight freshening in chlorinity (Fig. 7) across the water-sediment interface, followed by a general increase to a depth of 0.4 mbsf. Chloride

B

C

Cl titr. [mM]

initial pH

electrical conductivity [mS]
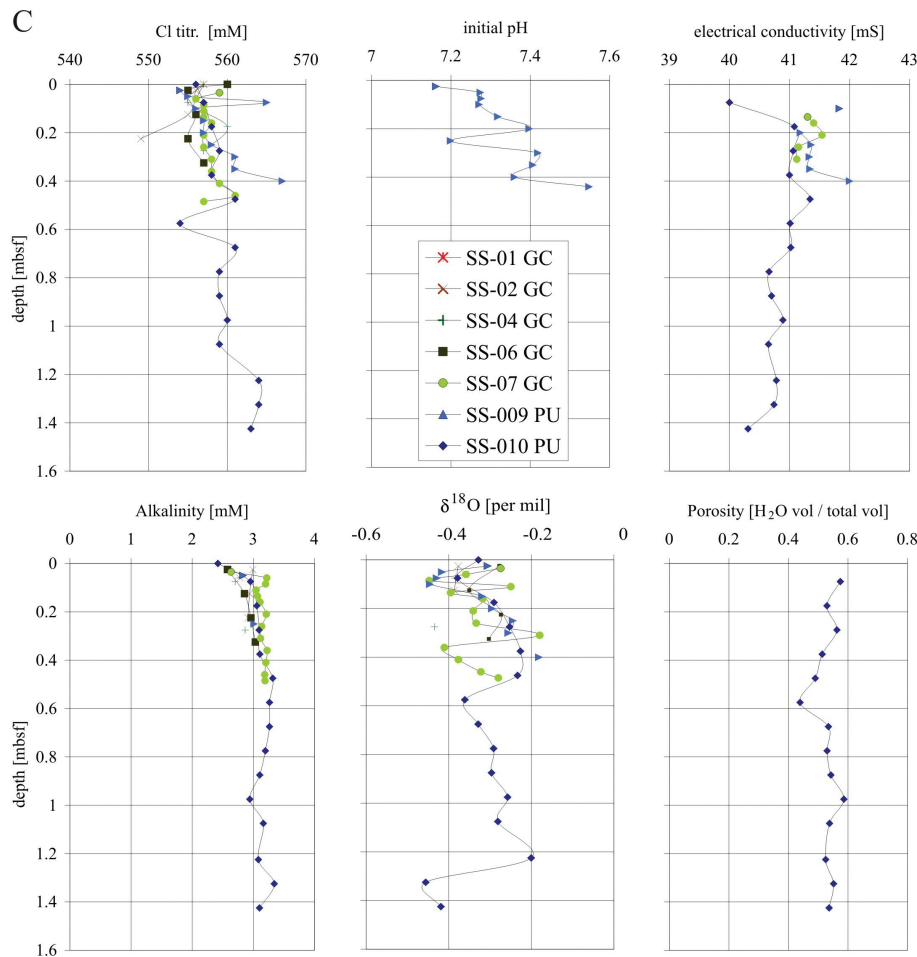
Fig. 7 - Continued. (C) Cl by silver nitrate titration, pH, electrical conductivity, alkalinity, δ¹⁸O, and porosity profile.

Legend:
- ✗ SS-01 GC
- ✗ SS-02 GC
- ✕ SS-04 GC
- ■ SS-06 GC
- ● SS-07 GC
- ▲ SS-009 PU
- ◆ SS-010 PU

Alkalinity [mM]

δ¹⁸O [per mil]

Porosity [H₂O vol / total vol]

was decided not to deploy the hydraulic piston corer, in order not to compromise the deeper hole.

Consequently, the stratigraphy of the recovered short cores was similar to the HWD03-1 site survey core, 250 m to the southwest. While we have not undertaken any radiocarbon dating thus far, we are confident in our interpretation and correlation of the composite stratigraphy of the MIS soft-sediment record (Fig. 4) with the previous radiocarbon dated site survey core (Fig. 8).

Some consistent features observed in both previous site survey and MIS soft-sediment cores include:

concentrations vary around 560 mM in the subsequent interval down to ~1.2 m followed by a stepwise increase to 564 mM. These changes correspond to three distinct intervals identifiable in the δ¹⁸O. The δ¹⁸O shows a freshening across the water sediment interface followed by an increase over the top ~40 cm. After a sudden drop this increase is repeated over the next 60 cm followed by another even larger drop at a depth of 130 cmbsf. The interpretation of this finding depends also on the diffusivity and estimated age and residence time of water in these top 1.5 m. The observed chlorinity and isotopic changes could represent changes in bottom water flux across the McMurdo Sound. In a sediment core taken during the site survey activity at a site 250 m to the northwest (McKay et al. in press), deposits of the LGM were identified at a depth of 0.3 mbsf. At least 60% faster sediment accumulation is estimated for core AND-010-PU.

1. Low sedimentation rates. While sedimentation rates are typically low in both sub-ice shelf records (<0.05 mm/y), the MIS record has ~60% higher rates during the Holocene, likely reflecting local changes in seabed topography and ocean circulation.

2. An unconsolidated mudstone with clasts/diamicton occurring in the lowermost unit represents grounding-line proximal, sub-ice-shelf deposition around 10–9 k.y. (¹⁴C yrs BP), when the grounding line is inferred to have passed southward across the region (McKay et al. in press).

3. A regionally correlatable volcanic turbidite sand interrupts the depositional sequence in all cores.

4. Above this, a terrigenous mud, sub-ice-shelf/lift-off facies, with rare intact diatoms and granules continues and passes upwards into a late Holocene biosiliceous mud with variable amounts of clasts.

The cored succession indicates the continuous presence of the Ross Ice Shelf during the Holocene, despite nearby ice core evidence for a mid-Holocene climatic optima 1°–2°C warmer than present (Steig et al. 1998).

CONCLUDING REMARKS

Recovery of soft-sediment cores during McMurdo Ice Shelf drilling operations was of limited success, with several good-quality records of Holocene sub-ice-shelf sedimentation. Unfortunately, the overconsolidated LGM-diamicton was not successfully penetrated using gravity and push-coring options. Given the strength of this unit and the occurrence of outsized clasts it
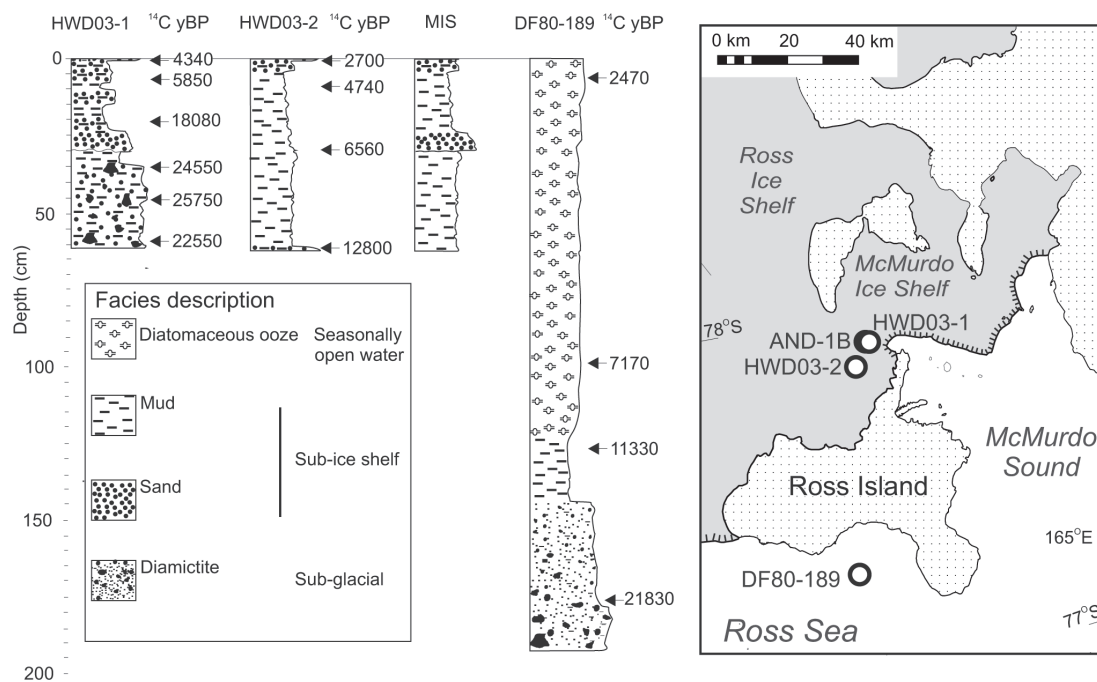
Fig. 8 – Core logs and lithological characteristics for selected cores from beneath the McMurdo Ice Shelf (HWD03-1, HWD03-2, MIS) and the north of Ross Island (DF80-189). The sub-ice shelf cores are dominated by diamict, sand, and mud facies, while the Lewis basin core contains a similar succession but is overlain by a 1.2m thick diatom ooze layer with IRD. The laminated vitric sand in HWD03-1 is interpreted as a sediment gravity flow (after McKay et al., in press).

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