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Pilot shallow drilling on the continental shelf, Dronning Maud Land, Antarctica

YNGVE KRISTOFFERSEN[1]*, KARI STRAND[2], TORE VORREN[3], DAVE HARWOOD[4] and PETER WEBB[5]

[1]*Institute of Solid Earth Physics, University of Bergen, N-5007 Bergen, Norway*
[2]*Thule Institute, University of Oulu, Finland*
[3]*Department of Geology, University of Tromsø, N-9037, Tromsø, Norway*
[4]*Department of Geology, University of Nebraska, Lincoln, NE 68588, USA*
[5]*Byrd Polar Research Center, Ohio State University, Columbus, OH 43210, USA*
**yngve.kristoffersen@ifjf.uib.no*

Abstract: A light, mining drill rig deployed from the stern of a research vessel has been used to carry out shallow drilling in 212 m water depth on the continental shelf in the eastern Weddell Sea. Penetration was 15 m below the seabed with 18% recovery in the 31 hours available for the experiment. The recovered glacigenic sediments are predominantly volcanic material of basaltic and andesitic composition with petrological characteristics and age similar to the continental flood basalts exposed in Vestfjella, about 130 km upstream from the drill site. The sediments include a reworked marine Miocene diatom flora. The material documents oscillations of the East Antarctic Ice Sheet over the past 30 ka. The lowermost diamicton probably represents a deformation till, and the grounding line retreated past the drill site 30 km from the shelf edge about 30 kyr BP. A readvance occurred during the Late Wisconsin Glacial Maximum. Assuming a reservoir correction of 1300 yr, marine conditions existed at the site between 10.1–7 kyr BP, and later at least between 2.8 and 2.5 kyr BP. The stratigraphy at the site has been disturbed by iceberg ploughing and/or contact between the ice shelf and the sea floor during local advances after 2.5 kyr BP.

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Key words: Antarctica, glacial sediments, grounding line positions, Mid-Weichselian, shallow drilling

Introduction

Scientific drilling on the continental slope (ODP Site 693, 2539 m water depth) in the eastern Weddell Sea has documented the dramatic transition to glacial conditions in the Neogene environment of East Antarctica (Barker & Kennett 1988). Gravity coring in water depths between 2000 m and 2800 m along the margin have provided details of the changes in sediment input during glacial and inter-glacial periods over the last 300 000 years (Grobe & Mackensen 1992). However, these locations are distal to the East Antarctic Ice Sheet (EAIS) in Dronning Maud Land and do not provide specific information on the position of the grounding line during the glacial cycles. This information is better defined in the ice-proximal geological record on the uppermost continental slope, or on the continental shelf in the topsets or palaeoslopes now exposed by erosion on the shelf.

Sediment sampling during the past two decades on the continental shelf, by conventional gravity-, piston- or vibro-corers, has typically penetrated up to 1 m into the overcompacted diamicton below Holocene mud (Anderson *et al.* 1980, Elverhøi 1981, Elverhøi & Roaldset 1983, Solheim & Kristoffersen 1985, Grobe 1986, Grobe & Mackensen 1992). We have attempted to sample the overcompacted sediments on the shelf by shallow drilling from the Finnish research vessel "*Aranda*", and were successful in reaching 15 m sub-bottom with about 18% recovery. The aims of the present paper are twofold:

1) To report on the feasibility of shallow drilling on the Antarctic continental shelf using a light drill rig deployed from a research vessel, and
2) to contribute to the understanding of the Holocene and Late Weichselian glacial history on the shelf off Dronning Maud Land.

Site survey and the physical environment

A 13 km wide swath across the continental shelf (Fig. 1) was surveyed in preparation for drilling using intermediate resolution (30–300 Hz) seismic reflection and chirp sonar (4 kHz) to obtain sub-bottom information, and sidescan sonar to image the bottom morphology (Winterhalter *et al.* 1997). A line spacing of 1200 m gave 100% sidescan coverage of the sea floor.

The continental shelf north of Kvitkuven ice rise is characterized by truncated foresets partly covered by younger moraine ridge complexes that are parallel to the shelf edge (Fig. 2). On the innermost shelf, we observed a *c.* 60 m thick unit of flat-lying sediments above an erosional unconformity. This unit is stratigraphically below reflector F, except for a possible top veneer of young sediments unresolved by the

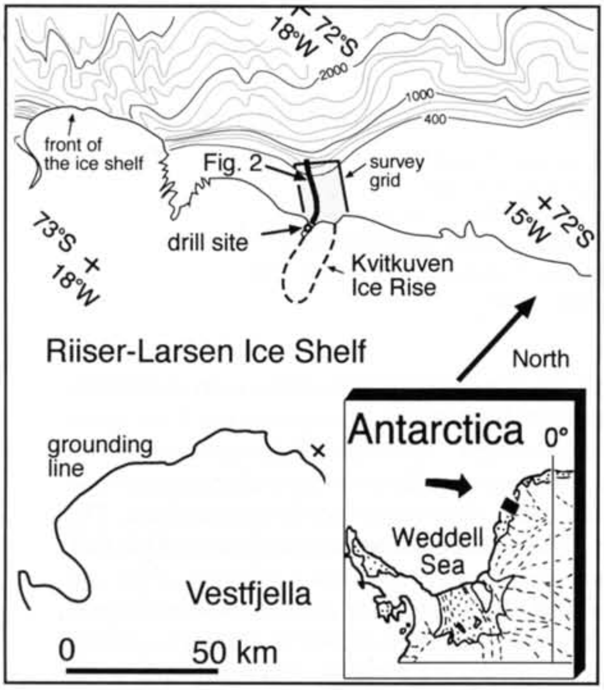

Fig. 1. Location of the survey area and site for shallow drilling. Seismic stratigraphic cross section (heavy line) shown in Fig. 2.

seismic reflection data. Reflector F marks the onset of vigorous shelf progradation to the north (Kristoffersen *et al.* 2000). The 20 km wide shelf area between the present grounding line and the drill site is underlain by a several kilometre thick wedge of sediments (Kristoffersen & Aalerud 1988). Based on the site survey information and the need to minimize ice risk, we chose a drill site location (72°30.94'S, 16°32.01'W) in a small re-entrant between Kvitkuven ice rise and the floating Riiser–Larsen Ice Shelf in 212 m water depth (Fig. 1). The sidescan sonar images in the vicinity of the drill site show long northtrending small ridges and grooves less than 20 m wide (B. Kjellin personal communication 1996), and no sub-bottom penetration was obtained in the chirp sonar record (M. Jakobson personal communication 1996).

Automatic Doppler current measurements at the site showed that tidal current velocities in the upper 40 m of the water column reach 50 cm s^{-1} (T. Perikovski personal communication 1996), whereas peak velocities in the lower half of the water column were less than 25 cm s^{-1}. Bottom current velocities were less than 15 cm s^{-1} at all times. Low present current velocities at the drill site are indicated by a rich fauna of sponges, sea anemones, sea urchins, holoturians and brittle stars as recorded by a video camera mounted on a remotely operated vehicle (B. Winterhalter personal communication 1996).

The drilling operation

Sea ice and icebergs efficiently attenuate wave motion and provide an environment with little vertical heave of the vessel. Ice does, on the other hand, represent a hazard to any marine activity where the vessel must maintain position. We tested the feasibility of shallow drilling on the continental shelf using a light mining rig deployed over the stern of a research vessel tied to the edge of sea ice frozen to the ice shelf in the bay. Regular thin-walled (56 mm inner diameter) steel drill rods (BWL) anchored to a 1.6 ton bottom frame were used as a riser, and the drill string consisted of rods (AWL) with an inner diameter of 45 mm yielding a core of 35 mm diameter. Two counterweights of *c.* 1 tonne provided riser tension and compensation for tidal motion (Fig. 3). The tide had an observed peak-to-peak amplitude of *c.* 2 m. Short period (seconds) motion of the vessel was of no concern even during intervals of more than 25 knots wind speed from the north into the bay.

The drill pipe touched bottom at 212.7 m below the sea surface. At 2.5 m below the seafloor (mbsf), circulation of light polymer mud was lost, and the core barrel was retrieved empty. Drilling proceeded another 0.7 m with a lower flow rate, but again the core barrel returned empty. Blocked circulation was a major problem and a number of strategies with different flow rates, rotation rates and core catchers were tried. Also, several times the core barrel did not seat properly behind the drill bit. In these cases, a pipe trip was necessary

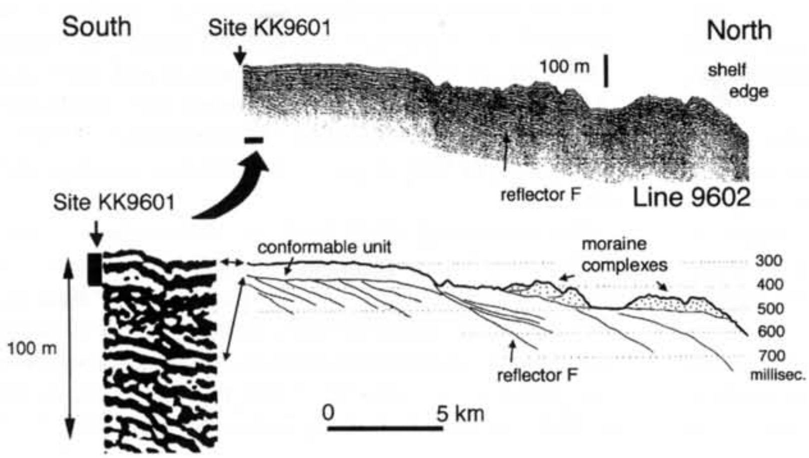

Fig. 2. Seismic section from the drill site to the shelf edge. Position of reflector F after Kristoffersen *et al.* (in press).Location of the profile is shown in Fig. 1.

to clear residual clayey sediments. At 5.0 mbsf circulation was lost again and the core barrel stuck. This time the first core, containing 2.4 m of medium sand to silty, clayey sand, was recovered. Subsequent recovery of sediments was limited to two intervals, 5 cm and 18 cm thick. Most encouraging was recovery of basalt boulders at 12.4 mbsf, 13.1 mbsf and 14.0 mbsf, respectively. The diameter of the largest boulder was 18 cm. Drilling was terminated at 15 mbsf when the fast ice where the vessel was docked cracked from tidal forces. In total, the drilling template was on the sea bed for about 31 h and the time spent at the site from the start of riser deployment to departure was 50 h.

Lithology and sediment geochemistry

The recovered sediments are grouped into four units (Fig. 4). The uppermost Unit I is represented by brown mud recovered from the drilling template, which penetrated *c.* 20 cm into the sea floor before settling on a more competent substratum. During drilling, no material was recovered in the upper 260 cm below the sea floor. Unit II (260–315 cm) consists of coarse sand and fine gravel with shell fragments, with an interval of silty sand with gravel (Fig. 5). The framework grains include monomineralic, subrounded quartz, plagioclase, potassium feldspar, and predominantly basaltic and andesitic to diabasic rock fragments (Fig. 6). The rock fragments also include a few sandstone and gneissic clasts. Unit III (315–420 cm) is a very dark greyish brown (2.5Y 3/2) muddy sand which is siltier in its upper part. Scattered clasts (up to

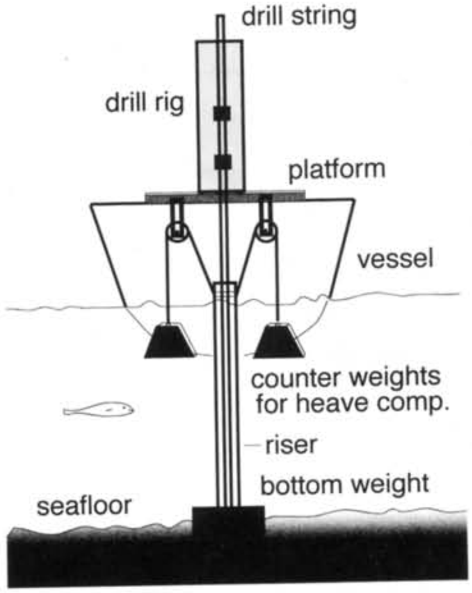

Fig. 3. Cartoon of drill rig and riser compensation.

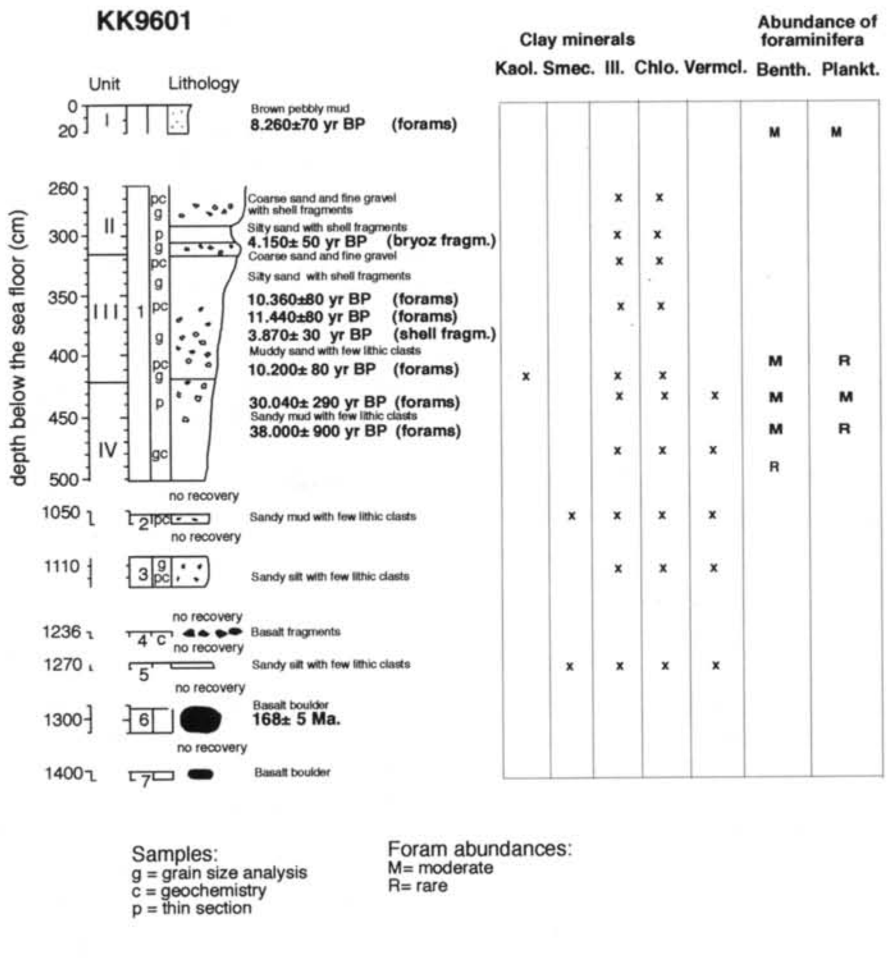

Fig. 4. Lithlogic log, distribution of clay minerals, foraminifera and results of age dating of the recovered sediments.

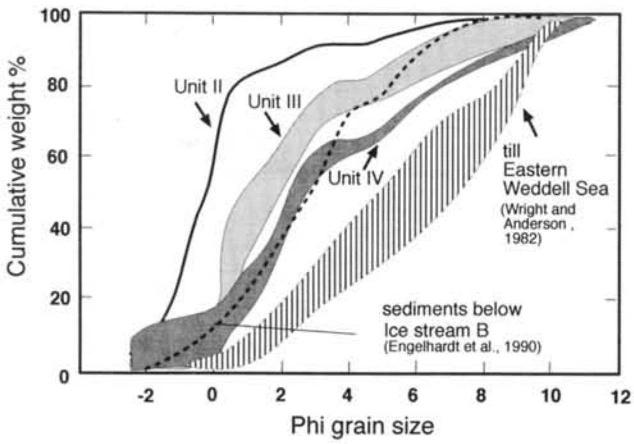

Fig. 5. Grain size distribution at selected intervals of the recovered sediments. Cross-hatched area indicates range of grain size distribution of sediments recovered by piston cores on the shelf (after Wright & Anderson 1982).

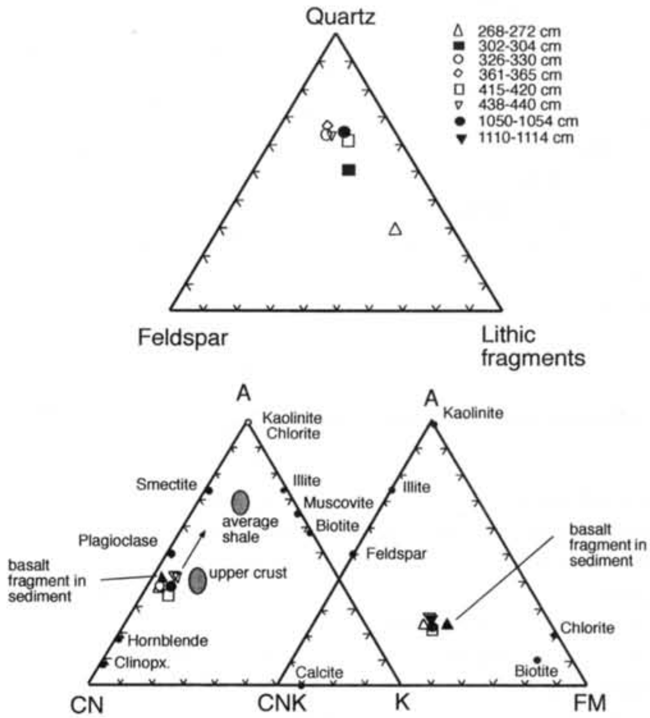

Fig. 6. Compositions of the sampled sediments plotted as molar proportions. A = Al_2O_3, CN = CaO* + Na_2O, K = K_2O, CNK = CaO* + Na_2O + K_2O, FM = FeO_{tot} + MgO. CaO* represents CaO associated with the silicate fraction of the sample. The arrow indicates the weathering trend of average rock types.

15 mm diameter) are most prevalent in the lower part of the unit. The underlying Unit IV (420–1405 cm) is a sandy mud with dispersed smaller clasts (< 5 mm). Typically fine to medium-sized quartz grains show subangular to angular shapes. The lowermost part of the unit contains relatively fresh basalt samples at three intervals (Fig. 4). Alteration of plagioclase to sericite and chloritized pyroxcenes indicates influence of hydrothermal processes.

Ten samples were prepared for analysis of clay mineralogy by X-ray diffraction using molybdenum radiation at angles from 2° to 30°. The samples were analysed air dried, after ethylene glycol treatment, and subsequently after heating to 400°C and 550°C. KCl-treatment of the bulk samples was performed to verify vermiculite occurrences. Illite and chlorite are present throughout the core with minor smectite containing mixed layers. However, the presence of pure smectite is uncertain except in cores 2 and 5 (Fig. 4). Kaolinite is present only at the base of Unit III. Kaolinite can not form under polar conditions, but is resistant and may be derived from older sediments (Ehrmann *et al.* 1992, Ehrmann 1998). Vermiculite is present in the sandy mud and silt below 4.2 mbsf (Unit IV). Vermiculite forms by hydration of primary mica and is present in Holocene and older soils in Antarctica (Ugolini & Jackson 1982, Claridge 1965).

Eight samples were analysed for major elements by XRF and for trace and rare earth elements (REE) by ICP mass spectrometer (Table I and Fig. 6). The Al_2O_3/TiO_2 ratios (6.6–7.2) are near constant throughout the core and represent a proxy indicator of unchanged sediment provenance. These ratios compare with values of 5.5–10 from the Jurassic lavas and dykes in Vestfjella (Hjelle & Winsnes 1972, Furnes & Mitchell 1978) and are significantly different from values (> 22) of basement gneisses in Heimefrontfjella (Juckes 1972) farther inland. The low and narrow range of values (48–54) of the chemical index of alteration (CIA) reflects the volcanic nature of the sediments as well as insignificant change in the intensity of weathering (Nesbitt & Young 1982), although values are < 50 in Unit III and consistently above 50 in the units below. Also, the trace element distributions show high concentrations of volcanic material with Rb/Sr values ranging from 0.14 to 0.24. Generally, sediments that contain volcanogenic material show Rb/Sr ratios below 1.0 whereas shelf sediments derived from continental source rocks have higher values. Both the trace and REE element distribution reflect volcanic source material, but the REE pattern also indicate that a significant contribution from acid plutonic and/or metamorphic rocks are present and documented by depletion from light REE (La) to heavy REE (Yb) typical for continental rocks.

Dating

Well preserved planktic and benthic foraminifera are present in Units I–III where up to 14 species can be identified in one sample. In Unit IV, the abundance is low at 500 cm and increases upward. The lower part of Unit IV (below 500 cm) is barren except for a few worn specimens of *Cibicides refulgens*, and no other carbonate fossils (macro- or micro) are present. All foraminifera assemblages in the core are

Table I. Geochemistry.

Sample	268–272	326–330	361–375	415–420	478–482	1050–1054	1107–1111	1236–1238
Na_2O%	3.02	2.77	2.83	2.58	2.57	2.77	2.56	2.16
MgO	4.76	4.17	3.90	3.46	4.06	4.76	4.22	6.31
Al_2O_3	12.2	10.9	10.4	9.67	11.5	11.6	11.2	13.9
SiO_2	53.6	56.6	57.9	58.4	59.5	57.3	59.7	48.8
P_2O_5	0.21	0.19	0.18	0.16	0.18	0.19	0.19	0.21
K_2O	1.29	1.41	1.51	1.57	1.66	1.49	1.56	0.72
CaO	7.73	6.96	6.40	5.98	5.72	6.66	5.80	9.10
TiO_2	1.75	1.61	1.57	1.46	1.58	1.58	1.65	1.93
Cr_2O_3	0.03	0.03	0.04	0.04	0.07	0.06	0.03	0.02
MnO	0.14	0.13	0.13	0.12	0.10	0.13	0.11	0.18
Fe_2O_3	10.6	10.8	11.0	11.2	9.15	9.98	9.31	13.9
LOI	3.35	3.80	4.25	5.35	3.75	3.15	2.70	1.00
Sum	98.8	99.5	100.2	100.1	100.0	99.8	99.1	98.3
Rb ppm	44	47	58	55	61	54	44	16
Sr	323	278	270	259	252	275	253	267
Y	35	27	28	26	33	30	28	29
Zr	261	372	239	250	265	347	249	126
Nb	17	11	13	13	13	53	29	8
Ba	357	365	345	365	363	368	394	236
La ppm	19.9	18.3	18.9	18.7	18.1	21.6	19.8	12.9
Ce	43.8	40.3	42.2	41.3	39.8	47.3	44.6	30.7
Nd	23.3	20.5	21.0	20.0	20.8	23.7	23.2	19.4
Sm	6.1	5.5	5.2	5.1	5.3	5.9	5.4	5.8
Eu	1.46	1.26	1.25	1.13	1.27	1.35	1.32	1.61
Gd	5.2	4.5	4.4	4.1	4.5	4.9	4.9	5.3
Dy	4.8	4.0	4.1	3.8	4.1	4.5	4.4	5.2
Er	2.6	2.3	2.1	2.0	2.4	2.4	2.3	2.6
Yb	2.3	2.1	2.1	2.0	2.1	2.4	2.2	2.3
CIA	50.3	49.5	49.2	48.8	53.6	51.5	53.0	53.7

CIA (chemical index of alteration) = $[Al_2O_3/(Al_2O_3 + CaO + Na_2O + K_2O)] \times 100$

Quaternary in age. Fossil debris includes sponge spicules echinoderm spines, bryozoans, gastropods, bivalves and ostracods. Unit III has low abundance of *Neoglobuquadrina pachyderma* (Ehrenberg) near the base.

Diatom valves throughout the core are broken and poorly preserved, and the floras are most likely all reworked and recycled. The presence of *Thalassiosira* spp. and *Fragilariopsis kerguelensis* (O'Meara) Hustedt can be recognized in units II and III. However, a different diatom flora is found in Unit IV. Although no taxa have been identified in the upper part of Unit III, some upper Miocene diatoms (*Thalassiosira oliverana* var. *sparsa* Harwood et Maruyama and *Denticulopsis simonsenii* Yanagisawa et Akiba) are consistently present but poorly preserved below 4.75 mbsf. Plio–Pleistocene taxa have not been recognized in this lower unit.

We obtained six radiocarbon dates by accelerator mass spectrometry (AMS) on tests of benthic foraminifera (*Cibicides refulgens*, Montfort) and two dates from macrofossil fragments (Table II and Fig. 4). Ages given are uncorrected for reservoir effects. The results indicate that Units I–III are of Holocene age and rest with a stratigraphic break on the underlying Unit IV (> 30 040 ± 290 yr BP). Dates of carbonate shell fragments give consistently young ages (3870 ± 30 and 4150 ± 50 yr BP) compared to the benthic microfossils (8260–11 440 yr BP).

Two fresh basalt samples from the largest boulder in Unit IV penetrated at 13.0 mbsf were dated by K–Ar to 168 ± 5 Ma. Basalts of the up to 900 m thick Vestfjella sequence exposed more than 80 km upstream (Fig. 1), yield a wide range of ages (170–230 Ma), but 180 Ma is considered a representative age

Table II. Results of radiocarbon dating.

Lab. number*	Weight (mg)	Depth in core (cm)	Dates ^{14}C yr BP (uncorrected)	Material
Beta-131899	74	20	8260 ± 70	benthic forams
KIA-483		314	4150 ± 50	shell fragments
Beta-131900	88	350–362	10 360 ± 80	benthic forams
KIA-484 fragment		386	3870 ± 30	bryozoa
Beta-131901	86	383–393	11 440 ± 80	benthic forams
Beta-127474	148	406–420	10 200 ± 80	benthic forams
Beta-127475	84	430–446	30 040 ± 290	benthic forams
AAR- 4764	51	450–490	37 750 ± 1200	benthic forams

*AAR = Aarhus University, Aarhus, Denmark
Beta = Beta Analytic Inc, Miami, Florida, USA
KIA = Leibniz Labor für Altersbestimmung und Isotopenforschung, Christian-Albrechts Universität, Kiel, Germany

(Peters *et al.* 1991). The basalt pile is cut by dykes dated at 160–170 Ma (Furnes & Mitchell 1978, Furnes *et al.* 1987, Brewer *et al.* 1996).

Discussion

Drilling an open hole in sandy sediments with no casing immediately raises the issue of contamination by debris falling in from the upper part of the hole. When circulation was lost, the drill string had to be retrieved and the hole wall was left unsupported. We attempted to clean the hole during re-entries by washing down to the previous total depth. Units II, III and upper part of Unit IV were recovered in a single core and sorting of the coarse sand (0.5 m thick) of Unit II (Fig. 4) may be partly due to winnowing during re-entry. The deeper Units III and IV show an age progression and poor sorting which argue for a representation of *in situ* stratigraphy not disturbed by drilling.

Units III and IV are diamictons of sandy mud with clasts, with Unit III being slightly better sorted than Unit IV (Fig. 5). Most of the finer grain-sizes are most likely reworked Pleistocene to upper Miocene? marine sediments, based on the content of broken and poorly preserved diatom tests. The coarse fraction is predominantly volcanic material of basaltic and andesitic composition. The mineralogy is similar to suites of largely volcanogenic clasts in surface sediments occurring north of 75°S, with the largest amount (> 90%) occurring north-east of 73°S where our drill site is located (Oskierski 1988, Anderson *et al.* 1991). The presence of kaolinite at the base of Unit III indicates temporary source contribution from eroded soils or older sediments. Unit III has abundances of benthic and planktic foraminifera comparable to those observed in the near surface sediments of Unit I (Fig. 4). Better sorting of Unit III with respect to the underlying Unit IV may be a result of gravity flows away from the grounding line or current winnowing.

Unit IV has a grain-size distribution that is broadly similar to sediments recovered from the base of ice stream B (Engelhardt *et al.* 1990) and also contains several basalt boulders over an interval more than 2.5 m thick, the largest boulder being 18 cm in diameter. No Quaternary microfossils are present in Unit IV below 500 cm and this part of the unit is considered to represent true subglacial deposit and possibly part of a deforming bed (Alley *et al.* 1989). The provenance of this diamicton includes Miocene? marine shelf sediments. The mineralogy reflects a terrigenous origin from Jurassic volcanics and denudation of the supracrustal rocks of the East Antarctic craton. The presence of vermiculite in Unit IV, as well as a more consistent upper Miocene diatom flora, suggests a shift in the sediment source area. In the upper 60 cm of the sandy mud in Unit IV, lithic clasts are evident and abundances of benthic and planktonic foraminifera gradually increase to levels comparable to Unit I (Fig. 4).

The lithologic change between Unit IV and overlying units is associated with a hiatus between Middle Weischselian ages of Unit IV and Holocene ages (8–11 kyr BP) in Units I–III. This include two dates around 4 kyr BP of shell and bryozoan fragments (Fig. 4). Several possibilities may be considered to explain the apparent age discordance within Units I–III between shell and benthic foraminifera. Firstly, the radiocarbon dates of foraminifera may include considerable amounts of reworked material. However, the relatively narrow range of ages (10–11 kyr BP) in Unit III is, however, surprising, and does suggest that sediment deposition took place at this time. Secondly, some of the radiocarbon dates may be influenced by an anomalously large reservoir effect. Radiocarbon dating of sea-water samples, living marine organisms and modern shell samples gives a range of anomalously old ages in the range 800–1500 yr BP, and may be caused by upwelling of ^{14}C-deficient deep water or by dilution of fresh meltwater from icebergs, iceshelves and glaciers (Omoto 1983, Gordon & Harkness 1992). In one instance an age of 2860 ± 125 yr BP was obtained from a sea water sample taken from 10 m depth about 4 km from the ice shelf (Omoto 1983). The issue of the magnitude of the reservoir correction remains problematic with the present location of the drill site in close proximity (< 500 m) to, or in the past below, an ice shelf. In this respect the apparent age of *c.* 8 kyr BP of the brown pebbly mud at the sea floor is intriguing.

Thirdly, sediments at the site may have been disturbed after 3.8 kyr BP by iceberg ploughing or a minor advance of grounded ice. The site is located in the middle of a 1 km wide and *c.* 4 km deep re-entrant between Kvitkuven ice rise and Riiser–Larsen Ice Shelf (Fig. 1). The thickness of the ice shelf measured by radio echo sounding (Orheim 1986) compared with observed bathymetry suggest that the water layer below the floating ice shelf is only a few tens of metres thick. A relatively small increase in ice flux could lead to interaction between the base of the ice shelf and the sea floor. The seafloor within the re-entrant, as seen in sidescan images, is characterized by subdued northtrending small ridges and grooves (B. Kjellin personal communication 1996) parallel to the direction of motion of the ice shelf, although the age of this morphology is unknown. Examples of local middle to late Holocene glacial readvances along the margin of the EAIS are known from the Law Dome ice margin over Windmill Island after *c.* 4000 yr BP (Goodwin 1996), from the Sørsdal Glacier in the Vestfold Hills after *c.* 700 yr BP (Fitzsimons & Colhoun 1995), and from Terra Nova Bay after *c.* 500 yr BP (Baroni & Orombelli 1994).

Holocene marine sediment cores from sites along the periphery of the EAIS off Wilkes Land and in Prydz Bay record periods of open marine conditions between 10.7 kyr BP and 7.3 kyr BP, and later renewed warming described from several areas around Antarctica, which peaked in a hypsithermal event between 4700 and 2000 yr BP (Domack *et al.* 1991, Ingólfson *et al.* 1998). Grounding line advance of ice tongues and ice shelves took place during the intervening period between 7 kyr and 4 kyr BP. Although, the recovered sediments at our drill site (Fig. 1) are only a partial representation of the stratigraphy, we note that the available radiocarbon dates indicate marine conditions at this locality on the Weddell Sea shelf during corresponding intervals (10.1–7 kyr BP and at 2.8–2.5 kyr BP) assuming a radiocarbon reservoir correction of 1300 yr (Gordon & Harkness 1992). Local advance(s) of grounded ice or iceberg ploughing after 2.5 kyr BP most likely disturbed the stratigraphy at Site KK9601.

Conclusions

1. Shallow drilling in 212 m water depth have been carried out using a tensioned riser of regular thin-walled mining drill pipe deployed from the stern of a research vessel. Drilling was completed to 15 mbsf with 18% recovery. Although penetration of predominantly coarse sediments without use of proper mud gave recovery problems, this experiment has demonstrated that it is possible to sample diamicton by inexpensive shallow drilling. Use of larger diameter drill pipe and heavy mud would probably enhance recovery.
2. The lithologies of the recovered material include predominantly erosion products from the Jurassic continental flood basalts farther inland with minor contributions from acid plutonic and/or metamorphic basement rocks. A reworked and poorly preserved marine Miocene diatom flora is present and all foraminifera assemblages in the core are Quaternary in age. Holocene sediments form a thin unit of brown pebbly mud at the sea floor overlying diamictons which in turn are resting with a temporal hiatus of 19 kyr on Late Weichselian sediments. The lower part of the Late Weichselian unit includes boulder size clast and contains no Quaternary microfossils. This part of the unit is considered to represent true subglacial sediments.
3. The grounding line retreated past the drill site about 30 kyr BP (uncorrected age) and the ice shelf advanced over the site during the LGM. If we assume a reservoir correction of 1300 yr, marine conditions existed at the site on the Weddell Sea continental shelf between 10.1–7 kyr BP and later at least between 2.8 and 2.5 kyr BP. Contact between the ice shelf and the sea floor from local advances and/or iceberg ploughing after 2.5 kyr BP have disturbed the stratigraphy.

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