Late Quaternary circulation changes and sedimentation in Disko Bugt and adjacent fjords, central West Greenland

Antoon Kuijpers, Jerry M. Lloyd, Jørn B. Jensen, Rudolf Endler, Matthias Moros, Laura A. Park, Bernd Schulz, Karin Gutfelt Jensen and Troels Laier

Several important outlets for meltwater and iceberg discharge occur along the margin of the Greenland Inland Ice. One of these is Disko Bugt in central West Greenland (Fig. 1). Large-scale exchange processes between the deep ocean and atmosphere are highly sensitive with regard to meltwater fluxes and global climate change. The Greenland Sea and Labrador Sea (see Fig. 1) with adjacent waters are the only regions in the Northern Hemisphere where deep-water formation occurs. New evidence shows that this process appears to be highly variable (e.g. Sy *et al.* 1997). Thus, meltwater production and iceberg calving from the Inland Ice margin of West Greenland may play a crucial role in controlling deep-water formation, notably in the Labrador Sea.

In order to examine the sensitivity of the Inland Ice margin to climate change, the UK Natural Environment Research Council (NERC) has since 1998 supported a project coordinated by Durham University. The project has included both land-based studies focusing on post-glacial sea-level rise and the regional ice sheet history since the last glaciation as well as offshore investigations. While the Institute of Geography, University of Copenhagen, is a project partner for the onshore investigations, the Geological Survey of Denmark and Greenland (GEUS) has contributed with marine geological work and expertise. In summer 1999 a 10-day cruise was carried out with the R/V *Porsild* from the Arctic Station in Qeqertarsuaq/Godhavn. During this cruise short sediment cores and surface sediment were collected, and hydrographic measurements were also made (Lloyd *et al.* 1999). With financial support from the Danish Natural Science Research Council, a further cruise was carried out by the R/V *Dana* from 3 to 6 August 2000. The objective was to collect longer piston cores for the study of late Quaternary palaeo-oceanographic changes in the Disko Bugt area, in particular with respect to meltwater and iceberg fluxes from the Inland Ice. In addition, relevant high-resolution shallow seismic information was to be obtained. On this occasion, a 12 m piston coring system newly acquired by GEUS was successfully operated from R/V *Dana* for the first time.

In this article the main results from the R/V *Dana* cruise are reported, as well as some of the previous findings from the 1999 cruise with R/V *Porsild*. In addition, some of the preliminary results from post-cruise laboratory work are referred to, amongst others that by the Baltic Sea Research Institute in Warnemünde, Germany.

Regional setting and previous work

Water depth in the western and eastern part of Disko Bugt is generally between 200 m and 400 m. This area has a generally very rugged sea floor, with frequent outcrops of Palaeogene rocks, hummocky glacial deposits, and widespread evidence of iceberg scouring (Brett & Zarudzki 1979). An up to 990 m deep valley (Egedesminde Dyb, see Fig. 1) extends across Disko Bugt from the area between Kronprinsen Ejland and Hunde Ejland to the shelf edge further to the south-west, where a fan system is found (Zarudzki 1980). Very little is known about the late Quaternary palaeo-oceanographic development of the area. During the last glaciation a major outlet glacier from the Inland Ice probably covered large parts of Disko Bugt (Ingólfsson *et al.* 1990; Bennike *et al.* 1994). Holocene sedimentary and hydrographic conditions in fjords at the west coast of Disko have recently been described by Gilbert *et al.* (1998) and Øhlenschlæger (2000). The latter demonstrated a climate warming at the beginning of the medieval period at around A.D. 1020. Hydrographic measurements in Disko Bugt show that relatively low (< 34‰) salinities prevail in the upper *c.* 150 m of the water column (Lloyd *et al.* 1999). A much thicker low-salinity surface layer due to meltwater discharge is found in the fjords around Disko Bugt (Fig. 2) .

As raised beaches and archaeological sites of palaeo-Eskimo cultures are abundant around Disko Bugt, these

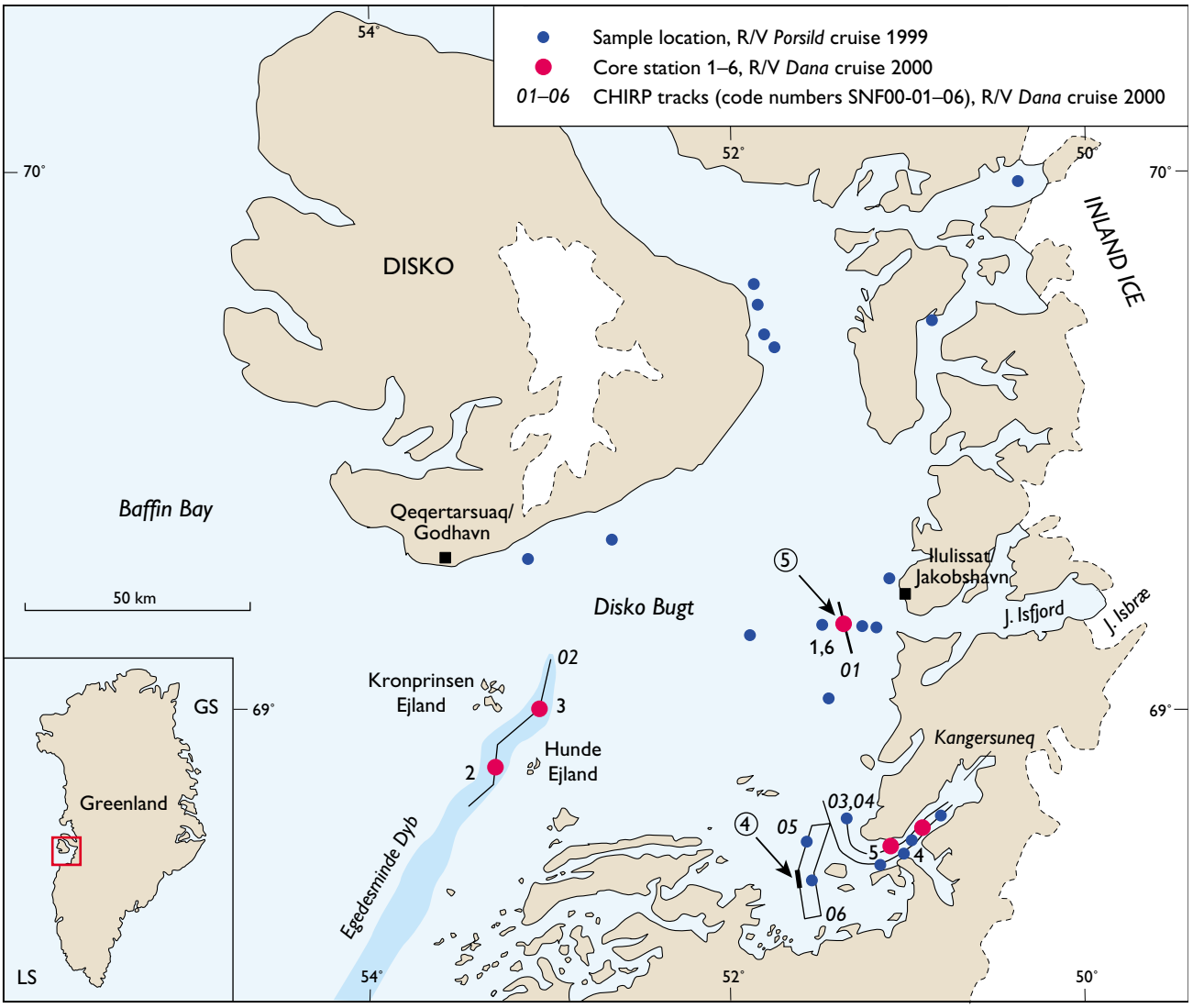

Fig. 1. Location of the sediment coring stations and CHIRP sub-bottom profiling tracks in Disko Bugt 1999 and 2000. The tracks SNF00-01–SNF00-06 have been abbreviated to 01, 02, etc. The coring stations 1 to 6 (DA00–0 code omitted) are indicated by **large red dots**, while smaller, unlabelled **dark blue dots** show the position of the hydrographic and sediment sampling stations occupied during the cruise with R/V *Porsild* in 1999. Coring stations 4 and 5 are located in the fjord Kangersuneq, where hydrographic measurements and other work were carried out in 1999 (see Fig. 2). ***J. Isfjord***: Jakobshavn Isfjord; ***J. Isbræ***: Jakobshavn Isbræ; **GS**: Greenland Sea; **LS**: Labrador Sea. The **labelled arrows** indicate: (**4**) the location of the CHIRP record illustrated in Fig. 4; and (**5**) the position of the piston core DA00-06 of which GEOTEK logging profiles are shown in Fig. 5.

onshore areas have been the subject of a large number of studies dealing with relative sea-level changes and glacio-isostatic adjustment. Moreover, Jakobshavn Isbræ, which is the fastest moving tidally controlled glacier in the world (Clarke & Echelmeyer 1996), has been the subject of numerous studies dealing with ice margin fluctuations since the last glaciation. It is generally believed that the ice sheet retreated from the shelf in two stages (Funder & Hansen 1996). After a first rapid retreat, the later deglaciation stage was much slower to reach its maximum position inland, i.e. > 15 km behind the present margin, in mid-Holocene times (Weidick *et al.* 1990). At the beginning of the Neoglaciation, around 4000 B.P., the Inland Ice readvanced, and at the end of the Little Ice Age (LIA) Jakobshavn Isbræ attained its maximum extension with a frontal position about 25 km west of its present margin (Weidick 1992). Regional sea-level changes, possibly related to a crustal response to Neoglaciation, have been reported by Rasch & Jensen (1997) and Long *et al.*

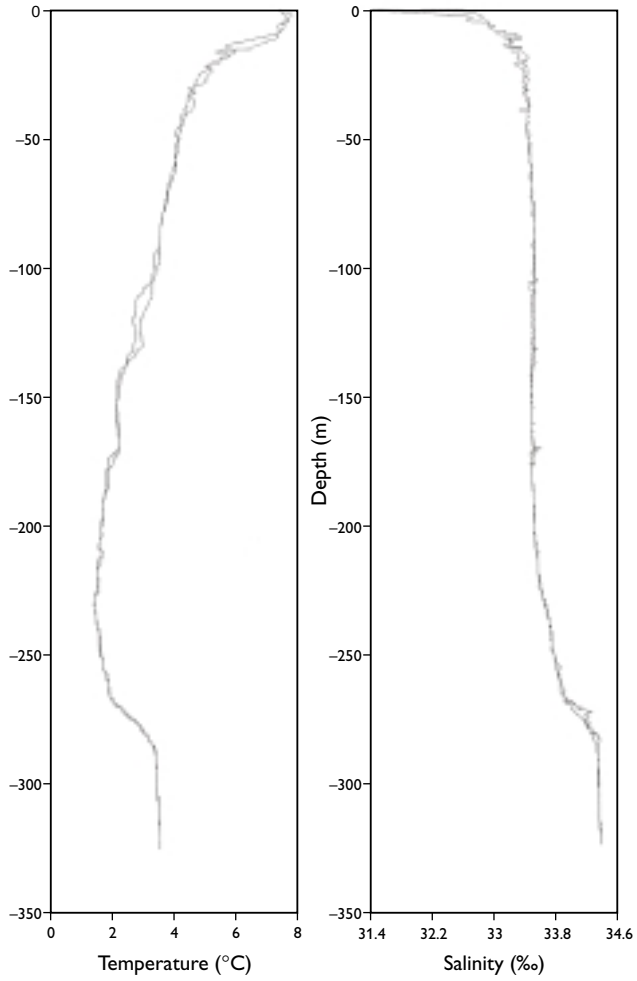

Fig. 2. *CTD* (conductivity/temperature/depth) profile illustrating temperature and salinity (conductivity) in the fjord Kangersuneq near the site of the cores DA00-04 and -05. The profiles show the presence of a thick (*c*. 275 m) low-salinity meltwater layer overlying saline bottom waters from Disko Bugt. Each diagram displays two profiles showing minor, fine-scale differences in temperature and salinity measured by the probe on its way to and from the bottom.

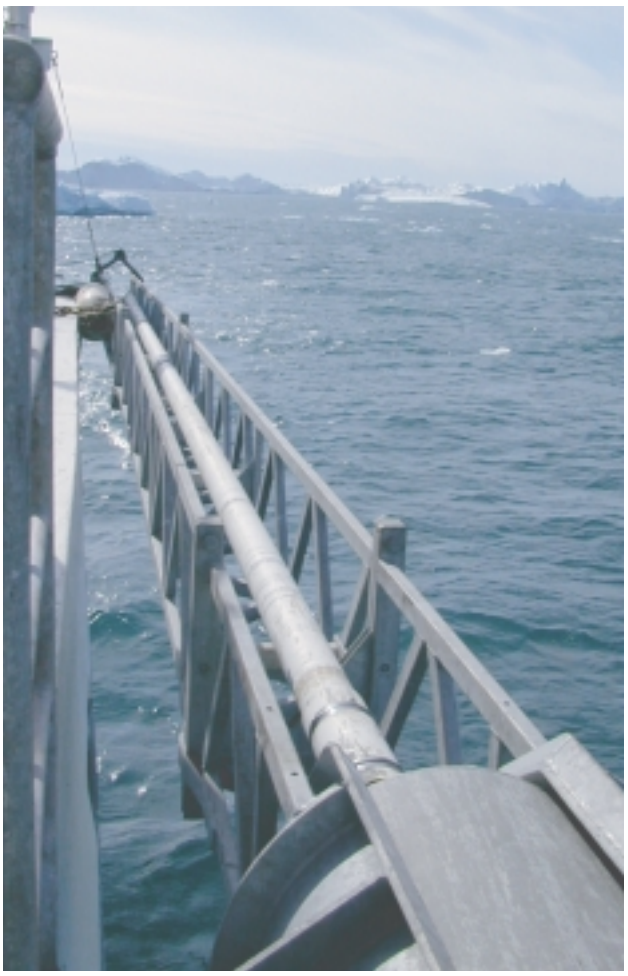

Fig. 3. The outboard cradle on R/V *Dana* with the 12 m piston corer, near the coring site off Jakobshavn Isfjord. Photo: John Boserup.

(1999). Studies on the south-east coast of Disko have demonstrated 3–4 transgressional stages within the past 2500 years, with the latest having occurred around the 14th–15th and 16th–17th centuries (Rasch & Nielsen 1995).

Work at sea – R/V *Dana*

With ice-sheet dynamics and their relationship to ocean climate as underlying rationale, the present study primarily focuses on the eastern part of Disko Bugt. Prior to the 1999 *Porsild* cruise, archive seismic data from the Westmar Project (Brett & Zarudzki 1979) had been studied for selecting potential (shallow) coring sites. From this pre-cruise archive study it appeared that relatively large accumulation areas of late glacial and Holocene sediments are mainly found in the easternmost part of Disko Bugt. One exception to this is the north-easterly extension of the Egedesminde Dyb in western Disko Bugt (Fig. 1). The archive seismic data indicate the presence of a > 200 ms TWT (Two-Way Travel Time) thick infill of presumed glaciomarine and younger sediments in the channel. Additional seabed data acquired with R/V *Porsild* in 1999 in the area off Jakobshavn Isfjord had yielded further evidence of a large sediment sheet or fan west and north of the mouth of this fjord. Preliminary results of accelerated mass-spectrometry (AMS) ^{14}C datings of the short cores from this location (J.M.L., unpublished data) indicate a clear decrease of the sedimentation

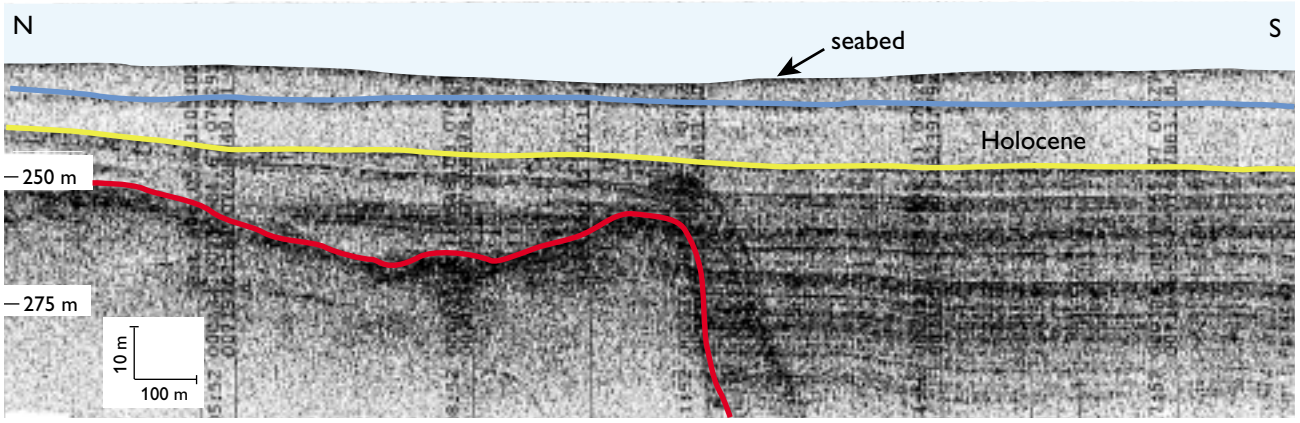

Fig. 4. CHIRP record from south-eastern Disko Bugt showing the northern, marginal zone of a large sedimentary basin, with an upper unit of presumed Holocene age divided into two parts by a reflector (**blue line**), overlying a thick, acoustically laminated sequence of late Pleistocene to early Holocene age. The top of the latter sequence is indicated by the **yellow line**, while the **red line** shows the top of the moraine. The location on line 05 is indicated by an arrow (**4**) in Fig. 1.

rates in a direction away from the mouth of the fjord. During the same cruise in south-easternmost Disko Bugt and adjacent fjord system, indications of a large depositional fan and basin had been found.

During the cruise of R/V *Dana* in 2000, first priority was given to collection of a long core from the immediate vicinity of the ice margin at the mouth of Jakobshavn Isfjord (Fig. 3) in order to obtain a sedimentary record of the history of Jakobshavn Isbræ. The ice conditions in August 2000 were, however, less favourable than in 1999, and consequently the coring site (Fig. 1, station 1/6) had to be located somewhat further away from the mouth of the fjord. (Note that the station codes 1 to 6 on Fig. 1 refer to the full core numbers DA00-01 to DA00-06.) For coring, a newly acquired 12 m piston corer with an inner liner diameter of 9.8 cm was used. The corer (total weight nearly 2 tons) was deployed with the help of a cradle along the port side of the vessel (Fig. 3), and coring was carried out using the port side trawl winch and its (20 mm) steel cable. For surface sediment sampling a Jonasson box-corer developed at Gothenburg University, Sweden, was used. In total five stations were occupied (Fig. 1) and the piston cores collected had lengths ranging from 8.90 to 11.20 m. Due to the presence of coarse ice-rafted debris causing coring failure at the first attempt, the station off Jakobshavn Isfjord had to be occupied twice (station 1/6). Intensive degassing with sediment blowing out from the corer during retrieval demonstrated the presence of large amounts of shallow gas in sediments from the deep-water stations 2 and 3 located in Egedesminde Dyb.

In addition to coring, shallow seismic sub-bottom information was obtained with a Datasonics CHIRP (2–10 kHz) acoustic profiling system. The 38 kHz (Simrad) hull-mounted echo sounder of R/V *Dana* was used for analogue bathymetric recording. The CHIRP sub-bottom profiling tracks were run in all areas where cores were taken (Fig. 1), and in addition in the south-easternmost part of Disko Bugt. The CHIRP data from the latter area indicate the presence of a large sedimentary basin and provide acoustic evidence of marked changes in late Quaternary depositional conditions (Fig. 4). The Holocene, assumed to be acoustically characterised by the uppermost, transparent unit shown on the CHIRP record, also yields evidence of a change in the sedimentary regime. This is concluded from the presence of a distinct reflector which divides the transparent unit into two parts. Moreover, in the adjacent area to the north, faulting in late Quaternary sediments indicates neotectonic activity possibly related to glacio-isostatic adjustment of the area.

Post-cruise core studies and preliminary results

Prior to opening of the cores, all core sections were logged using either a Bartington MS2 device for measuring magnetic susceptibility (cores DA00-02, -04), or the GEOTEK multi-sensor core-logger of the Baltic Sea Research Institute in Warnemünde, Germany. The latter instrument produces core logs for magnetic susceptibility (MS), GRAPE (gamma ray attenuation porosity

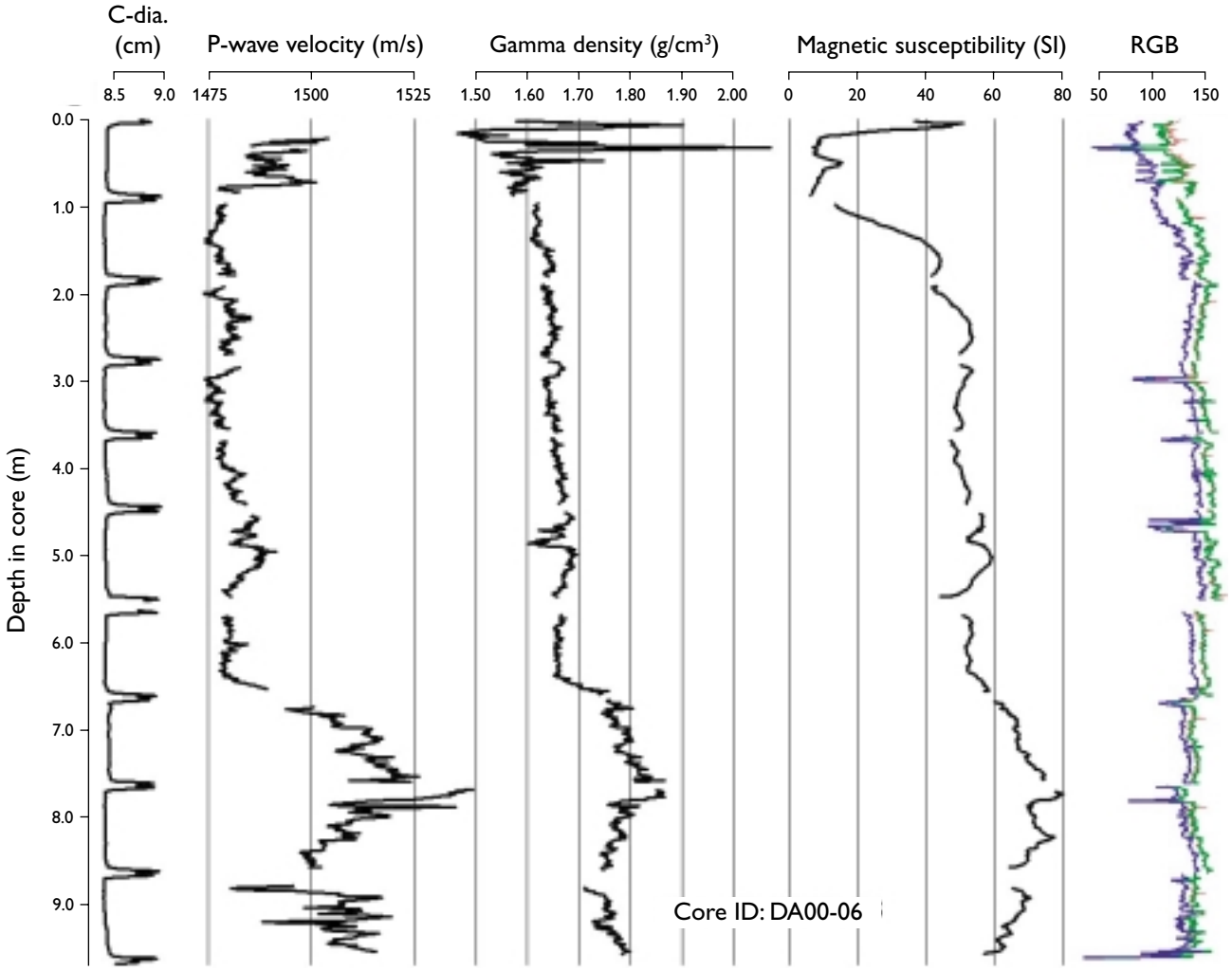

Fig. 5. GEOTEK logs for core DA00-06 taken off Jakobshavn Isfjord. Location is shown by arrow (**5**) in Fig. 1. The figure shows the down-core variation of P-wave velocity, GRAPE gamma-ray density, magnetic susceptibility and the **RGB** (Red/Green/Blue) colour scanning data. **C-dia**: Core diameter.

evaluator) density, P-wave velocity, and the RGB (Red/Green/Blue) digital colour scale. The GEOTEK results for core DA00-06 are illustrated in Fig. 5. After logging, the cores were opened, visually inspected, and described. Subsampling was carried out for AMS ^{14}C dating, magnetic and mineralogical analyses, grain-size determination, and micropalaeontological studies including foraminifera (Durham University, UK), diatoms and dinoflagellates. Using the surface sediment samples from the 1999 R/V *Porsild* cruise, a reference base for palaeo-oceanographic reconstruction based on the actual microflora and fauna is about to be completed.

The core data shown in Fig. 5 provide evidence for two major changes in the sedimentary environment off Jakobshavn Isfjord. These occur at around 1.0 m depth, and more gradually between 6.5 m and 7.0 m core depth. From visual inspection of the core, only the distinct change at around 1.0 m depth is obvious. At this depth a transition is seen from more mottled and bioturbated (light) olive-grey sandy mud with coarse ice-rafted debris (gravel, pebbles) at the top of the core to mainly homogeneous grey mud with some silt and very fine sand below, notably without coarse ice-rafted debris. This lithological change can be interpreted to reflect the transition from mainly open water conditions during summer to a subglacial situation with a floating glacier over the site. Moreover, we assume that the latter conditions were characterised by a virtual absence of warmer, saline (Baffin Bay) bottom water (see Fig. 2), resulting in very low bottom melting rates and conse-

quently almost no ice-rafting. This hypothesis will be tested by foraminiferal (L.A.P.) and diatom analyses currently being undertaken. The deeper level, more gradual change is illustrated by higher MS, density and P-wave velocity, and can probably be related to a general slight increase of grain size and/or different mineral input. This is tentatively attributed to the stronger influence of Jakobshavn Isbræ on near-bottom sediment transport and deposition, as would be expected with increased glacier thickness at an early deglaciation stage.

The two cores DA00-04 and -05 taken in the fjord Kangersuneq in south-easternmost Disko Bugt (Fig. 1) demonstrate a marked difference in sedimentation rates between the two sites. This is not unexpected, as echo sounder profiling during the earlier R/V *Porsild* cruise in 1999 had revealed the presence of two sedimentary basins at different water depths, separated by an interpreted moraine ridge. The lithology of the easternmost core DA00-04 suggests sedimentation rates that are markedly lower than those found in core DA00-05. This conclusion is based on a change at mid-core depth in core DA00-04 which shows a transition from bioturbated (light) olive-grey silty mud to homogeneous, mainly grey silty mud with occasional sand stringers. The latter lithology is concluded to be indicative of a subglacial or proximal ice-margin environment with low bottom melting rates, as coarse ice-rafted material is virtually absent. The core DA00-05 contains bioturbated sediment throughout the core, and its sediment is comparable with the sediment type of the upper part of core DA00-04. This suggests a depositional environment with continuous advection of well-ventilated (saline) bottom water from Disko Bugt (Baffin Bay) and the absence of a permanent ice cover.

The lithologies of the cores DA00-02 and -03 taken from Egedesminde Dyb show a non-oxic sub-bottom environment below an oxidised, 2–3 cm thick surface layer. This is in contrast to observations in the other cores, in which sediments appear to be oxic. The sediments retrieved from Egedesminde Dyb are mottled and burrowed silty clays. Noteworthy are 2–4 cm thick, rhythmically alternating lighter and darker coloured intervals particularly seen in the lower part of the cores. As noted above, a very high gas content was observed in the cores. Due to gas expansion during retrieval, the sediment column of core DA00-03 was disrupted and it shows large, up to 0.5 m long, void intervals. Otherwise, the sedimentary structures appear intact, and no disturbance due to the piston coring process was observed. Intact sedimentary structures suggest that gas hydrates are not likely to occur in the sediments cored; if present these would have caused disturbance of the internal sediment bedding.

Prior to opening of core DA00-02, pore water and gas were sampled from the core with a syringe, and large intact sediment samples were taken for pore water and solid phase organic matter analyses. The analysis of the syringe gas sample shows the presence of shallow gas with an elevated (22.2%) methane content, and only traces (*c*. 1 ppm) of propane and pentane. The measured pore water chlorinity values deviate only little from that of normal marine sediment pore water, which confirms that significant volumes of gas hydrates are unlikely to occur at the surface or in shallow sub-seabed sediments of Egedesminde Dyb. Formation of significant amounts of gas hydrates alter pore-water chlorinity, as the water fixed in hydrates is less saline. Thus, the shallow gas may be formed either *in situ* from the accumulation of marine organic matter, or may originate from seepage from depths where conditions within the relatively thick (> 200 ms TWT) post-glacial sedimentary sequence may have been particularly favourable for gas formation. The results meanwhile obtained for the solid phase organic matter content of core DA00-02, which show organic carbon contents of about 2%, clearly point to *in situ* formation as a likely source of the gas.

Concluding remarks

It can be concluded that several cores collected during the R/V *Dana* cruise in 2000 have the potential to provide high-resolution records of Holocene palaeo-oceanographic changes in Disko Bugt (cores DA00-02, -03, -05). Moreover, core DA00-05 collected in the fjord Kangersuneq may also yield information on terrestrial environmental changes, as for example variations in freshwater discharge. In addition, diagenesis related to the formation of shallow gas is a specific issue which can be studied in cores from Egedesminde Dyb. Preliminary geochemical analyses suggest a mainly *in situ* origin of the gas found in the shallow sub-seabed sediments of this area. This finding does not, however, exclude the possible presence of gas hydrates at greater sub-seabed depth.

The cores DA00-04 and DA00-06 both display a sedimentary record which appears to provide important information on the deglaciation history of the Inland Ice of West Greenland.

The shallow seismic data obtained during the R/V *Dana* cruise, as well as the echo sounding and shal-

low-core data from the 1999 R/V *Porsild* cruise, have shown that future collection of long piston cores at several other sites could further contribute to better understanding of the postglacial development of the area.

Acknowledgements

We acknowledge the Danish Natural Science Research Council who financed the project with R/V *Dana*. The participation of Durham University was financed through the (UK) National Environmental Research Council (NERC). We very much appreciate the excellent collaboration of Peter Østrin, Master of R/V *Dana*, and his crew. During this cruise a basic introduction to piston-corer handling was given by Jack Schilling of the Netherlands Institute for Sea Research (NIOZ), Texel. Successful coring would not have been possible without his expertise and skill, and was carried out together with John Boserup and the deck crew of R/V *Dana*. Egon Hansen is thanked for his contribution in acquiring shallow seismic data.

References

Bennike, O., Hansen, K.B., Knudsen, K.L., Penney, D.N. & Rasmussen, K.L. 1994: Quaternary marine stratigraphy and geochronology in central West Greenland. Boreas **23**, 194–215

Brett, C.P. & Zarudzki, E.F.K. 1979: Project Westmar. A shallow marine geophysical survey on the West Greenland continental shelf. Rapport Grønlands Geologiske Undersøgelse **87**, 27 pp.

Clarke, T.S. & Echelmeyer, K. 1996: Seismic reflection evidence for a deep subglacial trough beneath Jakobshavn Isbrae, West Greenland. Journal of Glaciology **141**(42), 219–232.

Funder, S. & Hansen, L. 1996: The Greenland ice sheet – a model for its culmination and decay during and after the last glacial maximum. Bulletin of the Geological Society of Denmark **42**, 137–152.

Gilbert, R., Nielsen, N., Desloges, J. & Rasch, M. 1998: Contrasting glaciomarine environments of two Arctic fjords on Disko, West Greenland. Marine Geology **147**, 63–83.

Ingólfsson, O., Frich, P., Funder, S. & Humlum, O. 1990: Paleoclimatic implications of an early Holocene glacier advance on Disko Island, West Greenland. Boreas **19**, 297–311.

Lloyd, J.M., Kuijpers, A. & Hansen, E. 1999: Marine geological investigations in Disko Bugt as part of the UK NERC ARCICE project Late Quaternary Ice Sheet Dynamics in West Greenland. Cruise Report R/V *Porsild*, 19–30 August 1999, 15 pp. Durham, UK: Durham University.

Long, A.J., Roberts, D.H. & Wright, M. 1999: Isolation basin stratigraphy and Holocene relative sea-level change on Arveprinsen Ejland, Disko Bugt, West Greenland. Journal of Quaternary Science **14,** 323–345.

Øhlenschlæger, R. 2000: Recente foraminiferers fordeling og Sen-Holocæne klimavariationer fra fjordsystemer i det centrale Vestgrønland, 87 pp. Unpublished cand. scient. thesis, Geologisk Institut, Aarhus Universitet, Danmark.

Rasch, M. & Jensen, J.F. 1997: Ancient Eskimo dwelling sites and Holocene relative sea-level changes in southern Disko Bugt, central West Greenland. Polar Research **16**(2), 101–115.

Rasch, M. & Nielsen, N. 1995: Coastal morpho-stratigraphy and Holocene relative sea level changes at Tuapaat, southeastern Disko Island, central West Greenland. Polar Research **14**(3), 277–289.

Sy, A., Rhein, M., Lazier, J.R.N., Koltermann, K., Meincke, J., Putzka, A. & Bersch, M. 1997: Surprisingly rapid spreading of newly formed intermediate waters across the North Atlantic Ocean. Nature **386**, 675–679.

Weidick, A. 1992: Jakobshavn Isbræ area during the climatic optimum. Rapport Grønlands Geologiske Undersøgelse **155**, 67–72.

Weidick, A., Oerter, H., Reeh, N., Thomsen, H.H. & Thorning, L. 1990: The recession of the Inland Ice margin during the Holocene climatic optimum in the Jakobshavn Isfjord area of West Greenland. Palaeogeography, Palaeoclimatology, Palaeoecology **82**, 389–399.

Zarudzki, E.F.K. 1980: Interpretation of shallow seismic profiles over the continental shelf in West Greenland between latitudes 64° and 69°30´N. Rapport Grønlands Geologiske Undersøgelse **100**, 58–61.

Authors' addresses

A.K., J.B.J., K.G.J. & T.L., *Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen NV, Denmark.* E-mail: *aku@geus.dk*

J.M.L. & L.A.P., *Department of Geography, Durham University, Science Laboratories, South Road, Durham DH1 3LE, UK.*

R.E., M.M. & B.S., *Institute for Baltic Sea Research, Seestrasse 15, D-18119 Warnemünde, Germany.*