Late Quaternary palaeo-oceanography of the Denmark Strait overflow pathway, South-East Greenland margin

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Direct interaction between the atmosphere and the deep ocean basins takes place today only in the Southern Ocean near the Antarctic continent and in the northern extremity of the North Atlantic Ocean, notably in the Norwegian–Greenland Sea and Labrador Sea. Cooling and evaporation cause surface waters in the latter region to become dense and sink. At depth, further mixing occurs with Arctic water masses from adjacent polar shelves. Export of these water masses from the Norwegian–Greenland Sea (Norwegian Sea Overflow Water) to the North Atlantic basin occurs via two major gateways, the Denmark Strait system and the Faeroe–Shetland Channel and Faeroe Bank Channel system (e.g. Dickson *et al.* 1990; Fig.1). Deep convection in the Labrador Sea produces intermediate waters (Labrador Sea Water), which spreads across the North Atlantic. Deep waters thus formed in the North Atlantic (North Atlantic Deep Water) constitute an essential component of a global 'conveyor' belt extending from the North Atlantic via the Southern and Indian Oceans to the Pacific. Water masses return as a (warm) surface water flow. In the North Atlantic this is the Gulf Stream and the relatively warm and saline North Atlantic Current.

Numerous palaeo-oceanographic studies have indicated that climatic changes in the North Atlantic region are closely related to changes in surface circulation and in the production of North Atlantic Deep Water. Abrupt shut-down of the ocean-overturning and subsequently of the conveyor belt is believed to represent a potential explanation for rapid climate deterioration at high

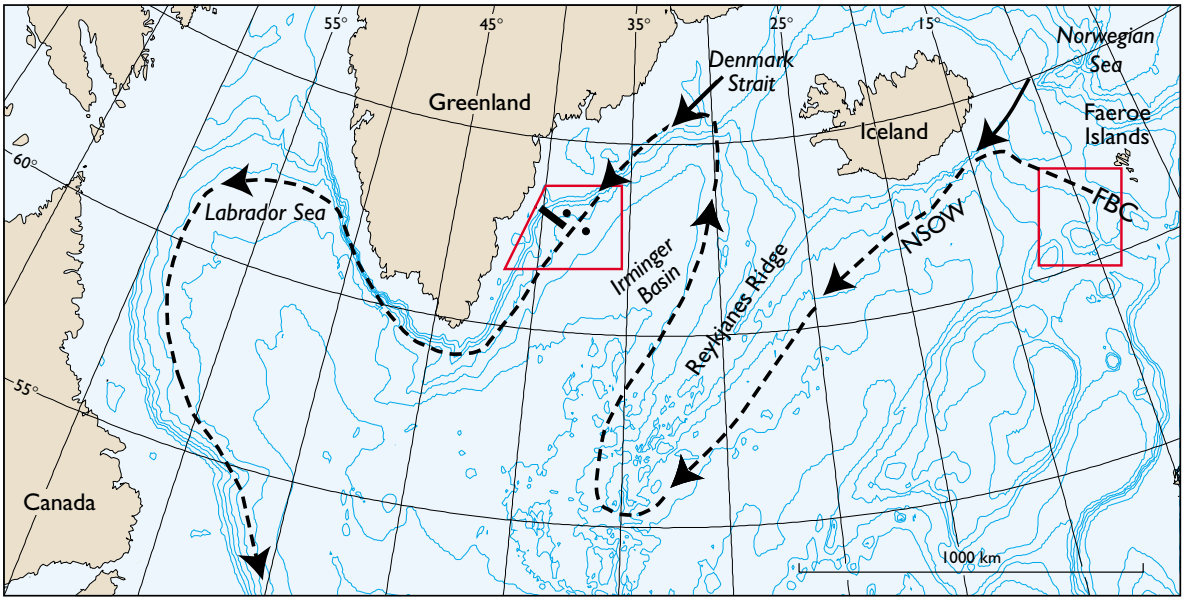

Fig. 1. North Atlantic deep water transport (Dickson *et al.* 1990) and locations of the 'overflow' study area (European North Atlantic Margin project) south-west of the Faeroe Islands, and the present study area off South-East Greenland with the ODP sites 918 and 919 (dots) and the side scan sonar track. A record of the sonar track is shown in Figure 2. NSOW: Norwegian Sea Overflow Water; FBC: Faeroe Bank Channel.

latitudes, such as those that caused the Quaternary ice ages. Here it should be noted, that significant changes in deep convection in Greenland waters have also recently occurred. While in the Greenland Sea deep water formation over the last decade has drastically decreased, a strong increase of deep convection has simultaneously been observed in the Labrador Sea (Sy *et al.* 1997).

Project concept

Within the European North Atlantic Margin project, which is part of the European MAST programme, the former Geological Survey of Denmark (now amalgamated into the Geological Survey of Denmark and Greenland – GEUS) in 1993 initiated palaeo-oceanographic studies of the flow pathway of the Norwegian Sea Overflow Water at the immediate outlet of the Faeroe–Shetland overflow gateway south-west of the Faeroe Islands. Late Quaternary palaeo-oceanographic studies had not previously been carried out in this particular area. Amongst other institutions, Amsterdam Free University has been involved in these studies. Significant changes in overflow intensity have been determined and related to major climate changes, which have occurred during the last 150 000 years (Kuijpers *et al.* 1998). The main aim of these studies has been to investigate the relationship between the fluctuations in the flow of the Norwegian Sea Overflow Water and the late Quaternary climate change. In order to complete the reconstruction of the export of deep waters from the Norwegian–Greenland Sea into the North Atlantic basin, the late Quaternary overflow history of the Denmark Strait pathway must also be taken into consideration.

In the summer of 1995 a project proposal was made together with the Free University in Amsterdam (S.R. Troelstra), which was submitted to the Netherlands Geosciences Foundation. The proposal focused on funding of a research cruise to the South-East Greenland continental margin with the main purpose of collecting piston cores from the sea bed for palaeo-oceanographic research. In addition, some seismic and acoustic work and hydrographic measurements were planned. Site selection for coring would be based mainly on the previously existing high resolution multichannel sleeve gun seismic grid from the nearby Ocean Drilling Program (ODP) drill area (e.g. Larsen *et al.* 1994). The proposal was granted in 1996, and after consideration of various other options, the Russian ice-classified research vessel *Professor Logachev* (St. Petersborg) was selected for the work. Simultaneously an agreement was made with the Danish Lithosphere Centre (DLC) to conduct part of the additional seismic work in collaboration with DLC onboard the Danish RV *Dana* (Hopper *et al.* 1998, this volume).

Work at sea – RV *Professor Logachev*

The research cruise with RV *Professor Logachev* was conducted between 16 August and 15 September 1997, with a port call in Reykjavik on 8 September. Mobilisation of various equipment was made in Aberdeen (14–16 August), while demobilisation was in Kiel (15–16 September). Weather conditions in the research area were favourable throughout the survey period, and during the work in coastal waters there were no major problems with ice. Participants were from various institutions in Canada, Denmark, England, Holland, Russia and Sweden. During the work the vessel proved to be an excellent platform for marine geological work, both for coring and (deep-tow) acoustic work. Most of the work was carried out in the immediate vicinity of the ODP drill sites 918 and 919 and the adjacent area to the south (Troelstra & Kuijpers 1997).

Seismic data acquisition, sub-bottom profiling, and sea floor imaging

Seismic data acquisition was done using a Tisey airgun source, a 350 m long 12-channel hydrophone streamer, and a digital recording system storing data on a (magneto-optical) disk. The signal frequency range was 20–250 Hz. Records from the slope and basin display three seismic sequences that could be tentatively correlated with the regional seismic stratigraphy proposed by Clausen (1997). While the seismic facies of the upper two sequences clearly indicate a dominance of downslope sedimentary processes and enhanced contour current activity, the seismic facies of the lowermost sequence indicates a relatively low-energy depositional environment. The lower unconformity marking this change is probably of (Mid) Miocene age. An example of a normal fault was observed, cutting the basaltic basement.

Sea bed characteristics and shallow sub-bottom structures were recorded, using a digital hull-mounted (25 transducers) sediment echosounder system (2–15 kHz). The sediment echosounder records showed strong reflectivity, and relatively little penetration in most parts of the study area.

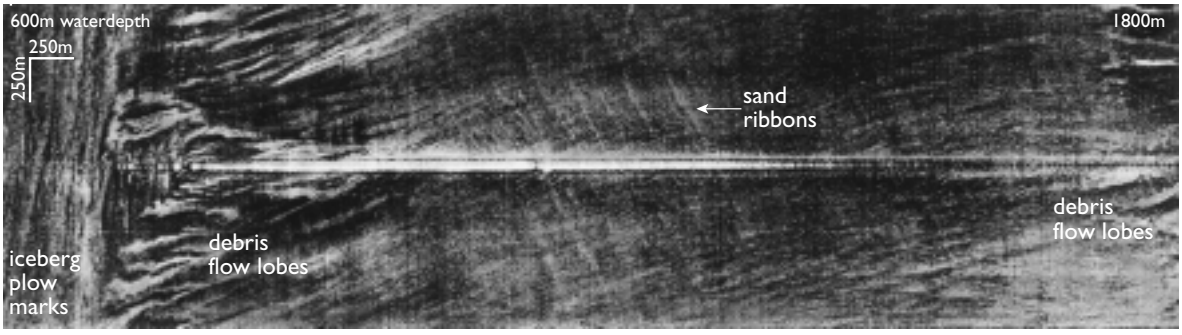

Fig. 2. Sonograph from the South-East Greenland margin, showing iceberg plow marks on the outer shelf (water depth 600 m), and mass and debris flow structures on the upper part and at the base of the continental slope, where water depth is 1700–1800 m. Longitudinal bed forms (narrow sand ribbons and streamers) of 'infinite' length indicate the high-velocity core of south-flowing Labrador Sea Water between 900 m and 1500 m water depth

Acoustically stratified sediments are mainly confined to the northern part of the surveyed continental rise and adjacent basin, where sub-bottom penetration generally was in the range of 10 to 25 ms.

Deep-tow side scan sonar profiling was carried out along six transects with an orientation approximately perpendicular to the continental slope, covering water depths ranging from about 500 m to more than 2000 m. For this purpose an Oretech 30 kHz dual channel (2 × 1000 m range) side scan sonar device with a 3–7 kHz sub-bottom profiler and underwater navigation facilities was deployed. The digital data acquisition unit and acoustic data processing software was developed by Polarexpedition, St. Petersborg, Russia. The side scan profiles provide highly informative records of the South-East Greenland continental margin setting, showing large current-parallel iceberg plow marks on the outer shelf, whereas on the slope, mass flow and debris flow features occur, locally cut off by (Holocene) sand streamers and narrow sand ribbons of 'infinite' (> 2000 m) length (Fig. 2). The distribution of these bed forms demonstrates that the strongest (southerly) bottom currents are confined to water depths between 900 and 1500 m, which corresponds to the Labrador Sea Water depth stratum shown by hydrographic measurements (Dickson & Brown 1994). The bed form type dealt with indicates the (episodic) occurrence of very strong currents (at least 0.8–0.9 m/s). This current speed is 2–3 times higher than found so far by hydrographers. Both mass flow deposits, erosional features and current-induced bed forms are also seen on the continental rise. The sub-bottom profiler and side scan sonar records from the central and northern basinal part of the study area reveal more regular sub-bottom reflectors and a smoother relief incised by a few turbidite channels, as already reported by Johnson *et al.* (1975).

Sediment coring

After initial site selection based on sleeve gun seismic information, final positioning when deploying the coring equipment was carried out with the help of information from the digital hull-mounted sediment echosounder system. This enabled release of the corer at the most favourable position, in particular in areas where strong variation of (sub)bottom characteristics occurred over short (50–150 m) distances, i.e. within the range of GPS navigational accuracy.

A total of nine box cores, eight piston cores and one gravity core were collected. The piston cores obtained in the area have a length of 7–9 m, while on transit from Aberdeen to Greenland a 10 m core was retrieved from a small basin on the eastern flank of the Reykjanes Ridge, south of Iceland. In addition, a giant video-grab was deployed off the Greenland margin, which showed a sea floor covered by large dropstones. The grab sample, 1–2 tons of sediment, contained a large variety of basaltic, granitic and sedimentary rocks, which will provide information on both the origin of the icebergs and the glacial fan sediments in the area.

Almost all sediment cores were logged onboard for their magnetic susceptibility signal, opened and described. Smear-slides were taken and analysed by microscope for lithogenic and biogenic components (diatoms, foraminifera, calcareous nannoplankton, dinoflagellates). The deep water (> 1800 m) cores consist mainly of (late) glacial turbidite sequences underlying a coarsening-upward Holocene top unit indicative

Fig. 3. View of RV *Professor Logachev* at rendezvous with RV *Dana* for transferring seismic information, 1 September 1997.

of increasing deep water circulation. Two cores taken from the outer shelf below the Polar Front Zone where cold surface waters of the south-flowing, ice-laden, East Greenland Current meet the relatively warm surface waters from the Irminger Basin, are of particular interest. Holocene fluctuations of this zone may thus be reconstructed, whereas basal glaciomarine sediments and a 4 m thick varved sediment unit are likely to provide information on the deglaciation history of the South-East Greenland margin.

Hydrographic measurements

Hydrographic measurements and sampling included temperature measurements, plankton net and water sampling for determination of the planktonic foraminiferal fauna and associated DNA research, analysis of stable isotopes (O/C), determination of the calcareous nannoplankton assemblages, and the collection of water samples for determination of the regional C-14 reservoir age. The location of the Polar Front Zone was accurately determined with the aid of temperature measurements, and water samples were collected accordingly.

Work at sea on RV *Dana*

After mobilisation, 17–20 August 1997, the RV *Dana* left Hirtshals, Denmark, on 20 August 1997, and arrived in the survey area off South-East Greenland on 27 August. The seismic lines planned to be recorded within the framework of the VU–GEUS palaeo-oceanographic project were run under favourable weather conditions in the period 27–31 August. Positioning of these lines was made over a large fan-like bathymetric structure extending into the basin near 62°N immediately south of the pre-existing ODP seismic grid. The following main part of the DLC survey was concentrated in areas further to the north, and after successful completion Reykjavik was reached on 23 September; the vessel then returned to Hirtshals (see cruise report RV *Dana;* DLC 1997).

The seismic system used included a cluster of four 40″ TI SG-I sleeve guns and a 96 channel, 594 m long hydrophone streamer. Storage of the digital data was on 3490E tapes. Real-time processing and display of the data is an essential component of the system. For high resolution seismic information, in particular on the uppermost sedimentary sequences, an Elics recording system was also used.

Prints of the seismic records collected during the VU–GEUS leg of the survey were transferred from RV *Dana* to RV *Professor Logachev* on 1 September using a line-firing rocket followed by ship-to-ship container transport (Fig. 3). The data exchange also included other material of crucial interest. This seismic information formed the basis for the selection of additional coring sites for RV *Prof. Logachev* in the southernmost part of the target area not covered by the pre-existing ODP seismic grid.

The large fan-like structure at 62°N, referred to above, to a large extent was found to comprise mass and debris

flow deposits with a considerable amount of coarse sediment. This is clearly indicated by the strong reflectivity on sonographs and a lack of acoustic penetration on the sub-bottom profiler records. A suitable site for piston coring was found only in the distal part of the fan. One further site was selected in a local basin on the outer shelf. In addition, a box core was taken from the level of Labrador Sea Water flow at intermediate depth on the continental slope; this showed a late glacial to Holocene (hemipelagic) sediment unit with a characteristic coarsening upward trend. This trend was found also in cores from the central and northern part of the target area. Further palaeo-oceanographic investigations of various biogenic components and associated stable isotopes together with acceleration mass spectrometry C-14 dating are expected to reveal more details of the circulation regime and timing of the major oceanographic events which occurred in this area during the late Quaternary climate change.

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