Late- and postglacial environments in the northern Barents Sea west of Franz Josef Land

LEONID POLYAK and ANDERS SOLHEIM

Polyak, L. & Solheim, A. 1994: Late- and postglacial environments in the northern Barents Sea west of Franz Josef Land. *Polar Research 13(2)*, 197–207.

A lithological and micropaleontological study of three sediment cores from the western Franz Josef Land area, two of them AMS ^{14}C dated, provides new data on the environmental evolution of the northern Barents Sea during and after the last deglaciation. Glacimarine conditions commenced in the deep Franz Victoria Trough by 13 kyr BP, and then presumably propagated into adjacent inter-island channels of Franz Josef Land. Pulses of Atlantic-derived water occurred during deglaciation and could have accelerated ice-sheet decay. Normal marine environments were established close to 10 kyr BP. Ameliorated conditions are recorded for the interval of approximately 9.5 to 5 kyr BP. After that, more severe environments existed probably associated with heavier sea-ice cover.

L. Polyak, VNII Okeangeologia, St. Petersburg, Russia; present address: Byrd Polar Research Center, The Ohio State University, Columbus, OH 43210, U.S.A.; A. Solheim, Norwegian Polar Institute, P.O. Box 5072, Majorstua, N-0301 Oslo, Norway.

Introduction

Despite extensive studies of the Barents Sea during the last two decades, there are major gaps in the understanding of the glacial and postglacial history of the region. The most widely studied areas are the western (e.g. Elverhøi et al. 1990; Sættem et al. 1992) and southern (Vorren et al. 1989; Gataullin et al. 1993) parts of the Barents Sea. Results from these areas show that most, if not all, of the Barents Sea was covered by an ice sheet during the last glaciation. There are indications of repeated glaciations through the Quaternary, which have eroded most of the Barents Sea shelf surface down to Mesozoic strata (Vorren et al. 1989; Sættem et al. 1992). However, the mode and timing of glaciation and deglaciation processes are still poorly understood.

The northeastern part of the Barents Sea, the least accessible due to ice conditions, is the least investigated. This area, including the Franz Josef Land archipelago (Fig. 1), could have been an important drainage basin for the Barents Sea Ice Sheet. Furthermore, the adjacent deep Franz Victoria Trough and Saint Anna Trough are the main gateways for the water and ice exchange between the Barents Sea and the Arctic Ocean.

Intensive investigations on Franz Josef Land were performed in the 1950s by Russian geologists, including studies of bottom sediments in the straits (Dibner et al. 1959). Sediment coring in the area surrounding the archipelago was pursued by VNII Okeangeologia in the 1970s, and the results were presented in technical reports (e.g. Kirillov et al. 1979). Foraminiferal investigation of selected cores was performed by Polyak (1982, 1985). However, these studies lack reliable chronostratigraphic framework.

We have chosen three sediment cores from the Okeangeologia collection for more detailed, AMS ^{14}C time-constrained lithological and foraminiferal examination. In combination with other recent research efforts in the same region (Lubinsky et al. 1994; Forman et al. in press; Lubinsky et al. unpubl.) these results will allow the reconstruction of deglacial and Holocene environments of the marine area around Franz Josef Land.

Physiographic features

Western Franz Josef Land encompasses two large islands, Alexandra and George Land, which are separated by Cambridge Strait (Fig. 1). The latter includes a silled basin with depth exceeding 500 m. The northern parts of the islands are presently ice-covered. West of the islands the large Franz Victoria Trough with depths of 500–600 m opens to the Arctic Ocean.

Franz Josef Land is composed of sedimentary

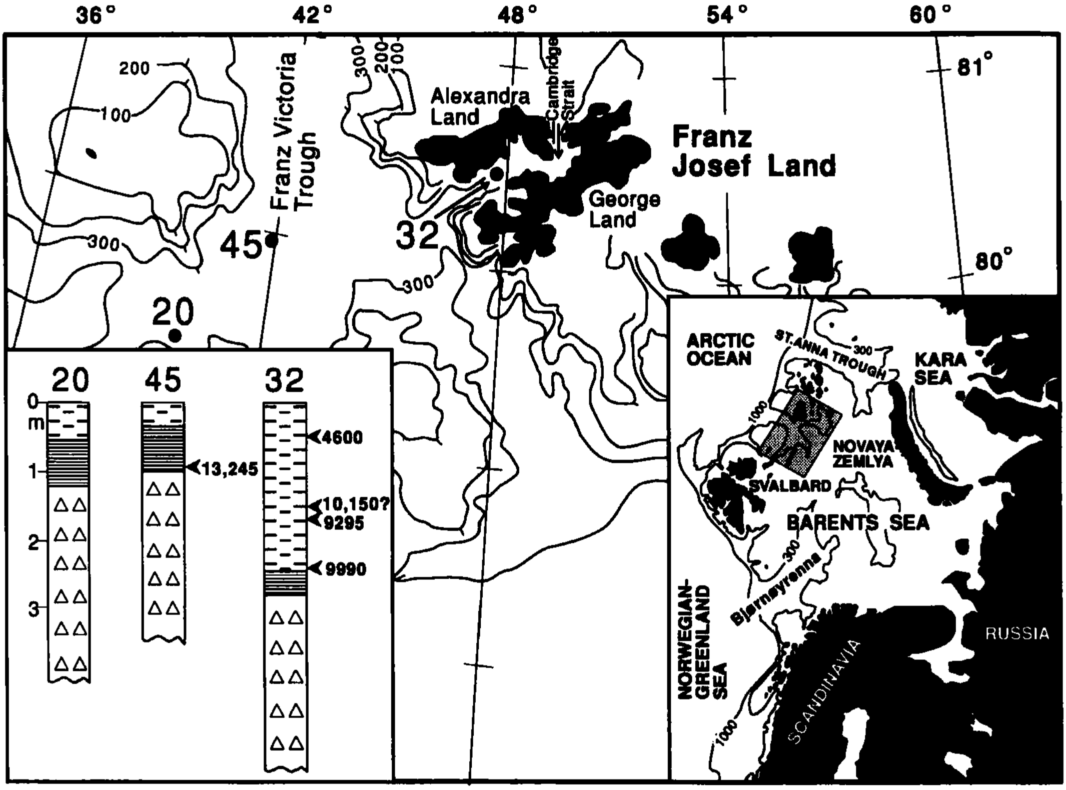

Fig. 1. Locations and stratigraphy of the investigated cores. The three main lithological units shown are olive grey bioturbated mud, grey laminated mud, and diamicton (from top to bottom). The positions of AMS ^{14}C dates are also indicated.

and igneous rocks mainly of Mesozoic age (Dibner 1957). The igneous component distinguishes the archipelago from the surrounding Barents Sea shelf.

The study area is located within the fluctuation zone of the pack-ice margin and is characterised by the multilayer hydrological structure of the Arctic Ocean (Gorshkov 1983; Treshnikov 1985). The upper layer of Arctic Water moves in a southwesterly direction and has low temperatures and salinities (mostly <0°C and <32.5%). In Franz Victoria Trough it is underlain by Atlantic-derived water, defined by oceanic salinity (>34.5%) and positive temperatures. This Atlantic Water moves from Fram Strait along the northern slope of the Arctic Eurasian shelf, and penetrates the marginal troughs. The core of Atlantic Water in Franz Victoria Trough lies at 200 to 400 m. It is possible that some portion of Atlantic Water also flows into the trough from the southwest. Below the Atlantic Layer, Franz Victoria Trough is filled with saline and cold Deep Arctic water which originates from the Norwegian–Greenland Sea, and dense "winter" water which cascades from the shelf along the marginal troughs (Midttun 1985). Atlantic Water typically does not penetrate the straits of Franz Josef Land and the water column consists of the surface Arctic Water and cold, saline Local Bottom Water (Matishov et al. 1992).

Materials and methods

The piston cores used in this study were collected by VNII Okeangeologia in 1977 (Stations 32 and 45) and 1979 (Station 20) from the hydrographical vessels IVAN KIREEV and PAVEL BASHMAKOV. Core 32 is from the deep silled basin in the Cambridge Strait. Cores 20 and 45 are from the southern part of Franz Victoria Trough (Table 1; Fig. 1). The core material was dried, stored, and

Table 1. Core locations.

Core No.	Area	Lat. N	Long. E	Depth (m)
32	Cambridge Str.	80°41.07′	47°43′	360
20	Franz Victoria Tr.	79°22.86′	39°43.24′	321
45	Franz Victoria Tr.	79°58.8′	41°56.9′	365

sampled several times over a period of fifteen years.

The results of previous lithological studies, including heavy mineral investigations were compiled by Kirillov et al. (1979). Additional sedimentological analyses of cores 32 and 45 were performed during this study at the Norwegian Polar Institute. The sampling covered the lower part of the core 45 section, and most of core 32. The grain size distribution was analysed by wet sieving of the >63 micron fractions, while the fine fractions were optically analysed in a Sedigraph. X-ray diffraction analyses (XRD) were carried out on the bulk <63 micron fraction and on the clay fraction. The analyses were undertaken on a Phillips PW1700 diffractometer with standard procedures of heating and ethyleneglycol treatment. Semi-quantitative calculations were done using a method described by Karlsson et al. (1978).

Previous foraminiferal investigation of the cores is described by Polyak (1982, 1985). Additional sampling of core 32 was undertaken in 1992. Samples were soaked, wet sieved (0.1 mm), and concentrated by inorganic heavy liquid (KJ + CdJ) with specific gravity 1.8 g/cm^3. In general, the number of calcareous microfossils in the 1992 samples is less than that of the previous studies, probably due to dissolution and/or disintegration during storage. This process does not seem to affect the percentage of foraminiferal species, allowing us to combine previous and recent results.

AMS ^{14}C dating (Fig. 1; Table 2) was performed at the Swedberg Laboratory, University of Uppsala, Sweden on four samples of calcareous foraminiferal tests from cores 32 and 45; an additional sample from core 32 was dated in the Lawrence Livermore Laboratory, U.S.A. The North Atlantic marine reservoir correction of 440 years (Mangerud & Gulliksen 1975) was subtracted from the laboratory-reported, ^{13}C-normalised age.

Results

Lithology

The studied cores have similar lithostratigraphies, and resemble cores described by Dibner et al. (1959). There are three main lithostratigraphic units (Fig. 1). The lower unit is composed of unstratified dark-grey stiff diamicton, identical to glacigenic diamictons described elsewhere from the Barents Sea (e.g. Elverhøi & Solheim 1983; Sættem et al. 1992; Gataullin et al. 1993). The middle unit consists mainly of light-grey soft laminated mud/clay. The lamination is caused by alternation of clayey and silty bands 1–20 mm

Table 2. AMS ^{14}C dates.

Core No.	Depth in core, cm	Material	Sample weight, mg	Age corr., 14-C years	Lab. ref. no.
32	38–41	mixed forams	5.30	4600 ± 100	TUa-180
32	172–174	I.norcrossi/helenae	9.10	9295 ± 110	TUa-181
32	244–248	mixed forams	4.00	9990 ± 95	TUa-182
45	91–97	mixed forams	4.65	13,245 ± 150	TUa-183
32	150–152	I.norcrossi/ helenae, N.labrador.	4.10	10,150 ± 70	CAMS-5561

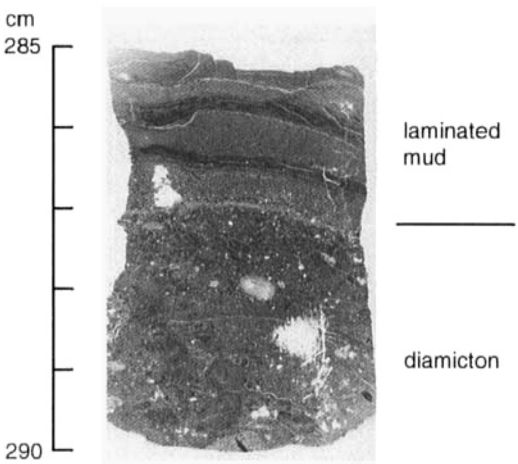

Fig. 2. Thin-section of the contact between diamicton and laminated mud in core 32.

thick. This type of lithofacies is characteristic of proximal glacimarine environments and results from rhythmical changes in the tidewater glacier melting regime and abscence of bioturbation (e.g. Elverhøi et al. 1983; Powell 1983; Mackiewich et al. 1984; Görlich 1986). A photo of a thin section (Fig. 2) shows a distinct contact between the diamicton and the laminated clay in the Cambridge Strait. The upper unit is olive-grey bioturbated mud, iron stained and somewhat sandy in its lower part. This type of sediment is typical for Holocene marine environments of the Barents Sea (Elverhøi & Solheim 1983; Spiridonov et al. 1992).

Both core 45 from the Franz Victoria Trough and core 32 from the Cambridge Strait show distinct changes in grain size distribution and clay mineralogy at the boundaries between diamicton, laminated clay and olive grey mud (Fig. 3). The diamicton appears homogeneous with little variation in grain size distribution. In both cores the sand and gravel contents drop to minimal values on transition from diamicton to deglacial sediments, increasing slightly in the overlying olive grey mud with a maximum in its lower part. The silt and clay contents, however, seem to show more diverse trends. In the Cambridge Strait the clay content increases to a maximum in the deglacial sediments before it drops to postglacial levels, which are roughly similar to those of the diamicton. The clay peak is accompanied by a silt low, while the overlying olive grey mud yields the highest silt content. In Franz Victoria Trough, on the other hand, the silt content increases in the laminated mud, while the clay content drops. There are no detailed analyses in the upper half of this unit, nor in the above postglacial part.

These lithostratigraphic changes are also reflected in the mineralogy (Fig. 3). In core 32, the transition from diamicton to laminated mud shows a decrease in smectite content followed by a sharp increase. The subsequent peak corresponds to the clay maximum in laminated mud, while the upper unit is marked by further increase in the smectite concentration. The chlorite content (based on the 14 Å peak only) also slightly rises through the laminated mud to the postglacial level. The remaining clay minerals have their highest contents in the diamicton and eventually drop to lower postglacial values. In the Franz Victoria Trough (core 45), smectite drops to zero at the transition from the diamicton to laminated mud, and chlorite appears to drop.

Heavy minerals of the fine sand fraction (Kirillov et al. 1979) are dominated by either pyroxenes or clastic, originally authigenic minerals (mainly pyrite). Pyroxenes, typical for the Franz Josef Land mineralogical province (Dibner 1957; Klenova 1960) have the highest concentrations in postglacial sediments of the Cambridge Strait and decrease both down-section and towards the Franz Victoria Trough. In contrast, pyrite and other "authigenic" minerals, characteristic of the Mesozoic sedimentary bedrock of the central and northwestern Barents Sea (Yashin et al. 1985; Elverhøi et al. 1988), have their maximum content in the Franz Victoria Trough diamicton.

Paleontology

The samples, particularly those from the upper lithological unit (olive-grey muds), generally contain rich assemblages of calcareous benthic foraminifers with smaller amounts of planktonic forms, and several ostracodes and molluscs (Figs. 4 and 5). Arenaceous foraminifers are practically absent, which is typical for subsurface sediments of the Arctic shelf and probably results from disintegration during early diagenesis (Østby & Nagy 1982; Spiridonov et al. 1992). Additional damage due to dry storage is highly probable.

The foraminiferal content in the diamicton is low, rarely exceeding 1–2/g of dry sediment. The

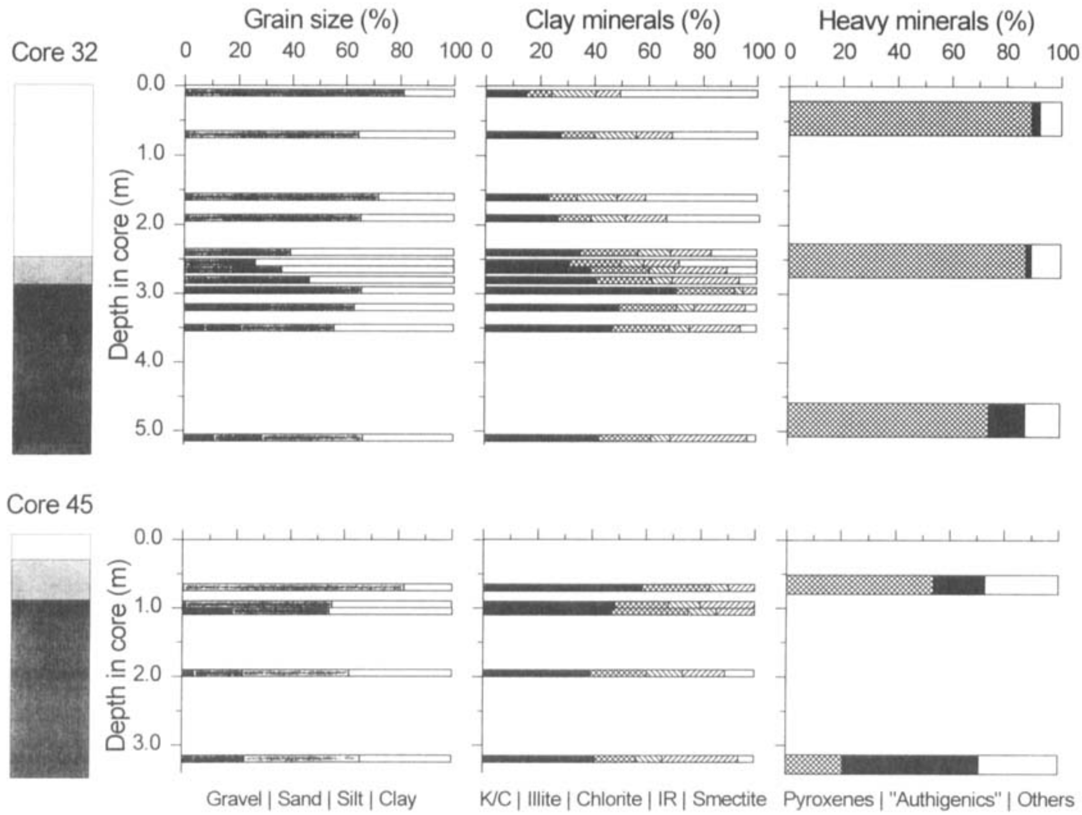

Fig. 3. Grain-size and mineralogical contents in cores 32 and 45. The lithological columns indicate homogenous mud, laminated mud, and diamicton (from top to bottom).

assemblage is dominated by the most common Quaternary Arctic species (see Faunal reference list, p. 207) *Elphidium excavatum* forma *clavatum* and *Cassidulina reniforme*, and includes "exotic" taxa of more warm-water and older faunas. The preservation varies, and some of the tests display signs of abrasion and recrystallisation. The same assemblage is recognized in glacigenic diamicts throughout the Barents Sea, and is considered to be reworked from older marine deposits (Hald & Vorren 1987; Hald et al. 1990; Spiridonov et al. 1992).

The laminated mud is practically unfossiliferous in the Cambridge Strait, but contains intervals with relatively high foraminiferal abundance (up to 65/g of dry sediment) in the Franz Victoria Trough. Most detailed study of the lower part of laminated mud in core 45 (Fig. 5) shows that these abundance spikes are separated by foraminiferal-barren intervals. The lowermost assemblage is dominated by *E. e. clavatum* and is followed by *C. reniforme* and/or *Cassidulina teretis* assemblages, the latter being sometimes associated with an increase in planktonic abundance.

The foraminiferal assemblages in the uppermost olive-grey mud are more diverse. In the Cambridge Strait basin (Fig. 4) they are mostly dominated by *Islandiella norcrossi/helenae* or *E. e. clavatum*. In the Franz Victoria Trough cores (Fig. 5) the dominant species is *C. reniforme*. In the middle part of all the sections there is a pronounced abundance maximum of *Melonis barleeanus*, and the tops are characterised by an increase in the *E. e. clavatum* content.

Age control

AMS ^{14}C dating was performed on well-preserved foraminiferal tests >150 μm picked from their abundance spikes, and supposed to be in situ.

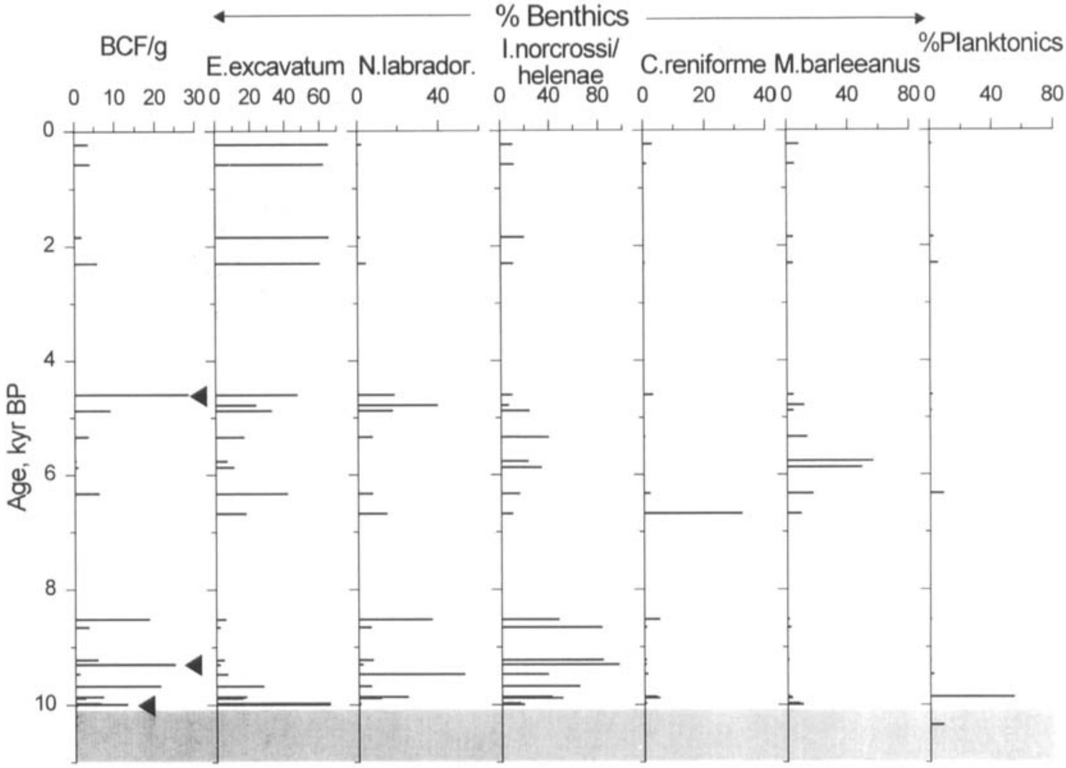

Fig. 4. Distribution of foraminifers in core 32 vs. age in ^{14}C years. The triangles indicate dated levels. BCF/g—number of benthic calcareous foraminifers per gram of dry sediment. The legend for lithology is explained in Fig. 3.

The three Uppsala dates of the postglacial olive-grey mud in core 32 form an orderly succession, while an additional date obtained later at the Livermore Laboratory gave an age 1 ka too old relative to the other dates. No signs of reworking to explain this 'old' date were found in that part of the core. Such a discrepancy cannot be understood without additional dating.

Available dates of gravity core tops from the eastern Barents Sea sediment basins have modern age (Polyak et al. in press; Forman pers. comm.), and we assume similar age for the top of core 32. Together with the three Uppsala dates this forms a basis of an age model for core 32, obtained by linear interpolation (Fig. 4).

Discussion

Deglaciation record

The date from the base of laminated mud in the Franz Victoria Trough (Core 45; Fig. 1) suggests that deglaciation of the trough occurred roughly at 13 kyr BP. A similar date was obtained from a Franz Victoria Trough core in deeper water to the north (Lubinski et al. unpubl.). The accumulation of laminated mud is likely to have been controlled by glacier melting. The small thickness of laminated mud and absence of apparent brown coloration indicate restricted meltwater influence, which is in contrast to the southeastern Barents Sea record (Polyak et al. in press). This implies fast deglaciation, probably due to a sea level controlled ice break-up and subsequent calving (Jones & Keigwin 1988; Elverhøi et al. 1990). At the same time, light oxygen isotope values in planktonic foraminifers from the Franz Victoria Trough laminated muds indicate reduced salinity of surface water due to local ice-sheet melting (Lubinski et al. unpubl.).

The mineral composition of the diamictons indicates glacial transportation of the eroded bed-

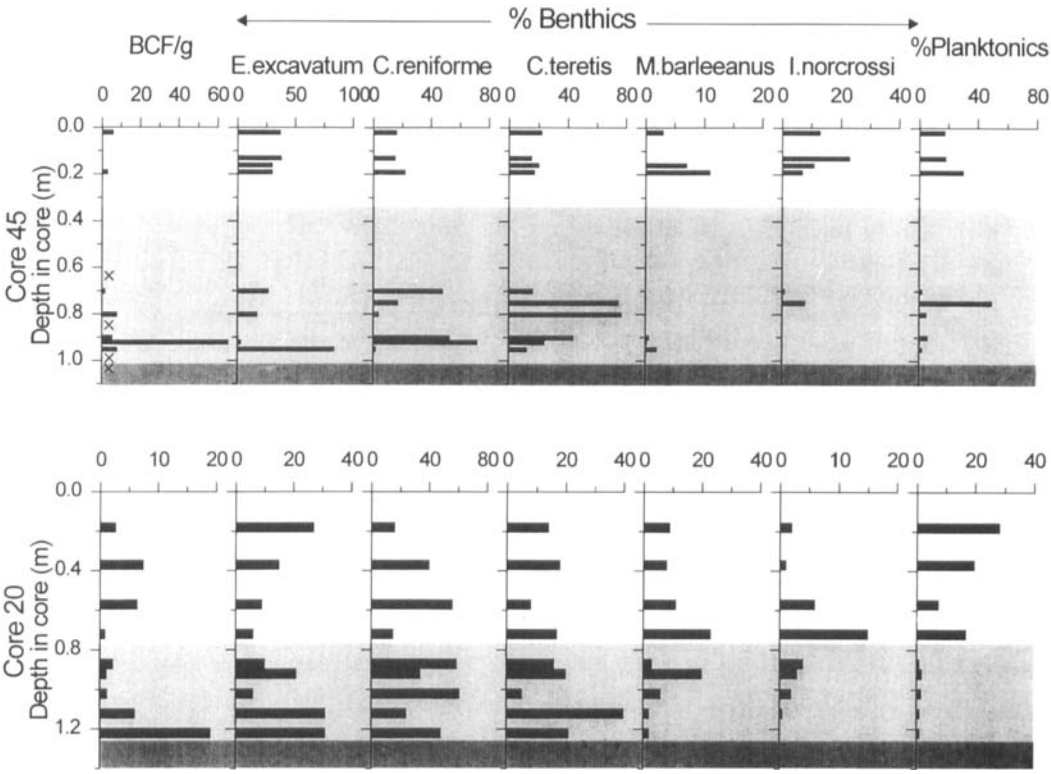

Fig. 5. Distribution of foraminifers in cores 20 and 45 vs. depth in core. The crosses indicate foraminiferal-barren intervals in core 45. The legend for lithology is explained in Fig. 3.

rock material from the northwestern Barents Sea to the Franz Victoria Trough and even to the Franz Josef Land straits. This suggests that the main center of glaciation in the northern Barents Sea was located west of Franz Josef Land, which is consistent with the glacioisostatic rebound pattern (Forman et al. in press). The transition to glacimarine and marine environments increased the role of Franz Josef Land as a minerogenic source for the northern Barents Sea; this is reflected in the high pyroxene concentrations.

The benthic foraminiferal assemblage from the bottom of laminated mud (Core 45) is characterized by low diversity and the strong dominance of *Elphidium excavatum* forma *clavatum*, which is common in glacimarine deposits proximal to a retreating glacier (Osterman 1982; Hald et al. 1993). Successive assemblages in laminated muds are mainly dominated by *Cassidulina reniforme*, a second most important species in glacimarine environments (Osterman 1982; Vilks et al. 1989; Steinsund et al. unpubl.). Foraminiferal spikes, with high contents of *Cassidulina teretis* and occasional planktonic foraminifers, suggest the periodic inflow of Atlantic-derived subsurface waters which could have promoted ice melting. Recent distribution of *C. teretis* and planktonics on the Eurasian Arctic shelf is confined to areas influenced by Atlantic-derived water (Khusid & Polyak 1989; Steinsund et al. unpubl.).

The transition from laminated clay to homogenous olive-gray mud in the Cambridge Strait reflects a major ice retreat within the island limits and is dated to approximately 10 kyr BP (Figs. 1 and 4). Assuming that the ice sheet break-up was bathymetrically controlled, we infer a similar time for the glacimarine-marine transition in the Franz Victoria Trough; this is confirmed with dates from the core to the north (Lubinski et al. unpubl.). Deglaciation of inter-island channels in central Franz Josef Land, as well as in eastern Svalbard, is estimated to take place roughly at the same time (Solheim 1991; Landvik et al. 1992; Forman et al. in press).

Postglacial environments

The early Holocene in the Cambridge Strait (Core 32) is characterized by relatively high sedimentation rates of 1 mm/yr, as found elsewhere in the eastern Barents Sea (Polyak et al. in press; Forman pers. comm.). A likely reason for this is residual glacier melting on the islands and/or redeposition of glacigenic material from the shallow areas due to glacioisostatic rebound (c.f. Elverhøi et al. 1989; Spiridonov et al. 1992). Upsection sedimentation rates decrease to 0.1 mm/yr. Such low values are typical for recent Barents Sea environments with the exception of areas, proximal to actively melting glaciers (Elverhøi et al. 1989; Polyak et al. 1994).

The high content of smectite in the postglacial mud of the Cambridge Strait is typical for Holocene sediments of the northern Barents Sea, in contrast to underlying glacial diamictons (Elverhøi et al. 1989). Its presence seems to be associated with the sediment transport by sea-ice from the Siberian shelf via the Arctic Ocean (Stein et al. 1994a).

The pioneering foraminiferal assemblage in the Cambridge Strait at 10 to 9.5 kyr BP is dominated by *Elphidium excavatum* forma *clavatum*. This species is known to be highly opportunistic, thriving in stressed environments such as low and fluctuating temperatures and salinities, high turbidity, and short-term productivity period (Mudie et al. 1984; Hald et al. 1993). The present distribution of *E. e. clavatum* in the Barents Sea is mainly connected with the Polar Water and appears to be associated with sea-ice cover (Khusid & Polyak 1989; Hald et al. 1993; Steinsund et al. unpubl.).

Early Holocene foraminiferal assemblages in Franz Victoria Trough (Core 20; Fig. 5) are mostly dominated by *Cassidulina reniforme*, a common species in distal glacimarine and coldwater marine soft-bottom environments (Osterman 1982; Mudie et al. 1984; Hald & Vorren 1987; Steinsund et al. unpubl.). Its prevalence in the early Holocene is typical for the Franz Josef Land surroundings (c.f. Lubinski et al. 1994), and is also reported elsewhere from northwestern and eastern areas of the Barents Sea (Østby & Nagy 1982; Spiridonov et al. 1992).

The interval of 8.5–9.5 kyr BP in the Cambridge Strait is characterised by the dominance of *Islandiella norcrossi/helenae* and *Nonion labradoricum*, which typically follow *E. e. clavatum* and *C. reniforme* assemblages in postglacial sequences and reflect ameliorated environmental conditions (Osterman 1982; Vilks et al. 1989; Spiridonov et al. 1992). These species presently are characteristic of areas with seasonal sea-ice cover and, consequently, high seasonal organic productivity (Steinsund et al. unpubl.). *N. labradoricum* is also known to be a deep infaunal species which feeds on buried organic matter (Corliss 1991), and is therefore potentially indicative of high-productive environments. The predominance of *I. norcrossi/helenae* and *N. labradoricum* coincides with the warmest Holocene sea-surface temperatures recorded for Svalbard (Salvigsen et al. 1992), probably marking a relatively warm and high-productive period for the Franz Josef Land area.

The above species are also abundant ca. 5–7 kyr BP in core 32, accompanied by the peak of *Melonis barleeanus*. The latter is typical for mid-Holocene sediments elsewhere in the northern and eastern Barents Sea at depths <200 m (Polyak 1982; Spiridonov et al. 1992). Highest concentrations of *M. barleeanus* are reported from fine-grained sediments, typically enriched with organic detritus (Corliss 1985, 1991; Korsun & Polyak 1989). Its recent distribution on the Arctic shelf is also somehow tied to Atlantic-derived water (Mudie et al. 1984; Khusid & Polyak 1989), although not necessarily to increased bottom temperatures (Steinsund et al. unpubl.). According to diatom data from the Norwegian-Greenland Sea, the strongest Atlantic inflow took place at 5–7.5 kyr BP (Koc & Jansen 1992). A light oxygen isotope spike obtained from planktonic foraminifers, probably reflecting the maximum warming in the upper water layers, is also observed around 7 kyr BP in the Franz Victoria Trough and further north in the Eurasian Basin of the Arctic Ocean (Stein et al. 1994b; Lubinski et al. unpubl.). These events correspond to the position of *M. barleeanus* abundance maximum, which might indicate the increase of Atlantic influence in the Arctic during the mid-Holocene climatic optimum.

Late Holocene assemblages (after ca. 5 kyr BP in Core 32) are dominated by *E. e. clavatum*, which is a regional pattern for the northeastern Barents Sea and probably marks the climatic deterioration and expansion of the Polar Water with perennial sea-ice in late Holocene (Spiridonov et al. 1992; Lubinski et al. 1994). Relatively high contents of *C. teretis* and planktonics in the Franz Victoria Trough at this time indicate the advection of the Atlantic-derived water as well. Thus, we suggest that at approximately 5 kyr BP the recent pattern of circulation with the Polar Water at the surface and the Atlantic Layer below was established in the northern Barents Sea.

Conclusions

The deglaciation of the western Franz Josef Land area commenced at approximately 13 kyr BP in the Franz Victoria Trough and was completed by 10 kyr BP with the establishment of normal marine environments. Inflows of Atlantic-derived subsurface water into the Franz Victoria Trough likely occurred during deglaciation.

The main minerogenic supply for the study area during the glaciation must have been from the northwestern Barents Sea, presumably due to sub-glacial erosion. Glacimarine and marine sediments yield larger amount of the local Franz Josef Land mineral component. Another important sediment source in the Holocene seems to be associated with the sea-ice transport from the Siberian shelf through the Arctic Ocean.

The foraminiferal record indicates that the most favourable marine conditions took place at 9.5–5 kyr BP, with the strongest Atlantic influence about 5–7 kyr BP. In the late Holocene, after 5 kyr BP, climatic environments deteriorated and the recent oceanographic pattern was developed in the northern Barents Sea.

Acknowledgements. – This study is part of a collaborative research between Norsk Polarinstitutt and VNII Okeangeologia. Sediment cores were collected by O.V. Kirillov and N.A. Pashukova. The Norwegian Research Council for Science and Humanities (NAVF) is acknowledged for financial support under project 440-93/041. The CAMS-5561 ^{14}C date was supported by S.L. Forman from NSF award DPP-9001471. D. Lubinski kindly revised the early version of the manuscript. Anders Elverhøi helped interpreting XRD data. Two anonymous reviewers provided constructive critical comments. The editor was most helpful in improving the manuscript. To all these persons and institutions we offer our sincere thanks. This is Byrd Polar Research Center Contribution No. 949.

References

Corliss, B. H. 1985: Microhabitats of benthic foraminifera within deep-sea sediments. *Nature 314*, 435–438.

Corliss, B. H. 1991: Morphology and microhabitat preferences of benthic foraminifera from the northwest Atlantic Ocean. *Mar. Micropaleontol. 17*, 195–236.

Dibner, V. D. 1957: Geological structure of Franz Josef Land. *Trudy NIIGA 81* (in Russian).

Dibner, V. D., Kordikov, A. A. & Razin, V. K. 1959: First results of the study of bottom deposits in the Franz Josef Land area. *Informacionnyj Sbornik NIIGA 15*, 43–51 (in Russian).

Elverhøi, A. & Solheim, A. 1983: The Barents Sea ice sheet—a sedimentological discussion. *Polar Res. 1*, 23–42.

Elverhøi, A., Lønne, Ø. & Seland, R. 1983: Glaciomarine sedimentation in a modern fjord environment, Spitsbergen. *Polar Res. 1*, 127–149.

Elverhøi, A., Antonsen, P., Flood, S. B., Solheim, A. & Vullstad, A. A. 1988: The physical environment, western Barents Sea, 1:1,500,000: Shallow bedrock geology. *Norsk Polarinst. Skr. 179 D*. 40 pp.

Elverhøi, A., Pfirman, S. L., Solheim, A. & Larssen, B. 1989: Glaciomarine sedimentation in epicontinental seas exemplified by the northern Barents Sea. *Mar. Geol. 85*, 225–250.

Elverhøi, A., Nyland-Berg, M., Russwurm, L. & Solheim, A. 1990: Late Weichselian ice recession in the central Barents Sea. Pp. 289–307 in Bleil, U. & Thiede, J. (eds.): *Geological history of the Polar Oceans: Arctic versus Antarctic*. Kluwer Academic Publishers, Dordrecht.

Feyling-Hanssen, R. W. 1972: The foraminifera *Elphidium excavatum* (Terquem) and its variant forms. *Micropaleontol. 18*, 337–354.

Feyling-Hanssen, R. W. & Buzas, M. A. 1976: Emendation of *Cassidulina* and *Islandiella helenae* new species. *J. Foraminiferal Res. 6*, 154–158.

Feyling-Hanssen, R. W., Jørgensen, J. A., Knudsen, K. L. & Andersen, A. L. 1971: Late Quaternary Foraminifera from Vendsyssel, Denmark and Sandnes, Norway. *Bull. Geol. Soc. Denmark 21*, 67–317.

Forman, S. L., Lubinski, D., Miller, G. H., Matishov, G., Snyder, J., Myslivets, V. & Korsun, S. in press: Post-glacial emergence and distribution of Late Weichselian ice sheet loads in the northern Barents and Kara Seas, Russia. *Geology*.

Gataullin, V. N., Polyak, L. V., Epstein, O. G. & Romanyuk, B. F. 1993: Glacigenic deposits of the Central Deep: A key to the Late Quaternary evolution of the eastern Barents Sea. *Boreas 22*, 47–58.

Gorshkov, S. G. (ed.) 1983: *World Ocean Atlas, vol. 3, Arctic Ocean*. Pergamon Press, Oxford. 184 pp.

Görlich, K. 1986: Glacimarine sedimentation of muds in Hornsund fjord, Spitsbergen. *Ann. Soc. Geol. Polonica 56*, 433–477.

Hald, M. & Vorren, T. O. 1987: Foraminiferal stratigraphy and environment of late Weichselian deposits on the continental shelf off Troms, northern Norway. *Mar. Micropaleontol. 12*, 129–160.

Hald, M., Sættem, J. & Nesse, E. 1990: Middle and Late Weichselian stratigraphy in shallow drillings from the southwestern Barents Sea: Foraminiferal, amino acid and radiocarbon evidence. *Norsk Geol. Tidsskrift 70*, 241–257.

Hald, M., Steinsund, P. I., Dokken, T., Korsun, S., Polyak, L. & Aspeli, R. 1993: Recent and Late Quaternary distribution of *Elphidium excavatum* f. *clavata* in Arctic seas. *Cushman Foundation Sp. Publ. 32*, 141–153.

Jones, G. & Keigwin, L. 1988: Evidence from Fram Strait (78°N) for early deglaciation. *Nature 336*, 56–59.

Karlsson, W., Vollset, J., Bjørlykke, K. & Jørgensen, P. 1978:

Changes in mineralogical composition of Tertiary clays from North Sea wells. *Developments in Sedimentology, 27*, 281–289.

Khusid, T. A. & Polyak, L. V. 1989: Biogeography of benthic foraminifers in the Arctic Ocean. Pp. 42–50 in Barash, M. S. (ed.): *Neogenovaya i chetvertichnaya paleookeanologiya po mikropaleontologicheskim dannym* (Neogene and Quaternary paleoceanology based on micropaleontological data). Nauka, Moscow (in Russian).

Kirillov, O. V., Kuleshova, O. N. & Rozhdestvenskaya, I. I. 1979: Rezul'taty poputnyh morskih geologo-geomorfologicheskih issledovanij na shel'fe arkticheskih morej (Results of marine geological and geomorphological studies on the Arctic continental shelf). Technical report, NPO Sevmorgeologia, Leningrad. 259 pp. (in Russian).

Klenova, M. V. 1960: *Geologiya Barentseva morya* (Geology of the Barents Sea). Izdatel'stvo Akademii Nauk SSSR, Moscow. 367 pp. (in Russian).

Koc Karpuz, N., and Jansen, E. 1992, A high-resolution diatom record of the last deglaciation from the SE Norwegian Sea: Documentation of rapid climatic changes: *Paleoceanography* 7, 499–520.

Korsun, S. A. & Polyak, L. V. 1989: Distribution of benthic foraminiferal morphogroups in the Barents Sea. *Oceanology (USSR) 29*, 838–844.

Landvik, J. Y., Hansen, A., Kelly, M., Salvigsen, O., Slettemark. Ø. & Stubdrup, O. P. 1992: The last deglaciation and glacimarine/marine sedimentation on Barentsøya and Edgeøya, eastern Svalbard. *LUNDQUA Report 35*, 61–83.

Loeblich, A. R. & Tappan, H. 1953: Studies of Arctic Foraminifera. *Smithsonian Misc. Collection 121*, 150 pp.

Lubinski, D., Korsun, S., Forman, S., Miller, G., and Matishov, G. 1994: Was there a Holocene marine optimum in Franz Josef Land, northeastern Barents Sea? 24th Arctic Workshop Abstracts, Boulder, p. 52–54.

Mackensen, A. & Hald, M. 1988: *Cassidulina teretis* Tappan and *C. laevigata* d'Orbigny: Their modern and late Quaternary distribution in northern seas. *J. Foraminiferal Res. 18*, 16–24.

Mackiewicz, N. E., Powell, R. D., Carlson, P. R. & Molnia, B. F. 1984: Interlaminated ice-proximal glacimarine sediments in Muir Inlet, Alaska. *Mar. Geol. 57*, 113–147.

Mangerud, J. & Gulliksen, S. 1975: Apparent radiocarbon age of recent marine shells from Norway, Spitsbergen and Arctic Canada. *Quatern. Res. 5*, 263–273.

Matishov, G. G., Matishov, D. G., & Shaban, A. Y. 1992: *Novye dannye o roli zhelobov v biookeanologii shel'fa Zemli Franza-Iosifa i Novoj Zemli* (New data on the role of troughs in the bio-oceanology of the Franz Josef Land and Novaya Zemlya shelves). Preprint, Russian Academy of Sciences, Kola Science Center, Apatity. 46 pp. (in Russian).

Midttun, L. 1985: Formation of dense bottom water in the Barents Sea. *Deep-Sea Res. 32*, 1233–1241.

Mudie, P. J., Keen, C. E., Hardy, I. A. & Vilks, G. 1984: Multivariate analysis and quantitative paleoecology of benthic foraminifera in surface and Late Quaternary shelf sediments, northern Canada. *Mar. Micropaleontol. 8*, 283–313.

Østby, K. L. & Nagy, J. 1982: Foraminiferal distribution in the western Barents Sea, Recent and Quaternary. *Polar Res. 1*, 53–87.

Osterman, L. E. 1982: Late Quaternary history of Southern Baffin Island, Canada: A study of foraminifera and sediments from Frobisher Bay. University of Colorado, Boulder, Ph.D. Dissertation. 380 pp.

Polyak, L. V. 1982: The downcore distribution of foraminifers in the sediments of marginal troughs of the Barents and Kara Seas. Pp. 19–26 in Zarkhidze, V. S. (ed.): *Stratigrafiya i paleogeografiya pozdnego kajnozoya Arktiki* (Stratigraphy and paleogeography of the Late Cenozoic in the Arctic). Sevmorgeologia, Leningrad (in Russian).

Polyak, L. V. 1985: Foraminifers of bottom sediments of the Barents and Kara Sea and their stratigraphic significance. Unpubl. dissertation, Leningrad (in Russian).

Polyak, L. V., Lehman, S. J., Gataullin, V. & Jull, A. J. T. in press: Two-step deglaciation of the southwestern Barents Sea. *Geology*.

Powell, R. D. 1983: Glacial-marine sedimentation processes and lithofacies of temperate tidewater glaciers, Glacier Bay, Alaska. Pp. 185–232 in Molnia, B. F. (ed.): *Glacial-marine sedimentation*. Plenum Press, New York.

Sættem, J., Poole, D. A. R., Ellingsen, K. L. & Sejrup, H. P. 1992: Glacial geology of outer Bjørnøyrenna, southwestern Barents Sea. *Mar. Geol. 103*, 15–51.

Salvigsen, O., Forman, S. L. & Miller, G. H. 1992: Thermophilous molluscs on Svalbard during the Holocene and their paleoclimatic implications. *Polar Res. 11*, 1–10.

Sejrup, H. P. & Guilbault, J. P. 1980: *Cassidulina reniforme* and *C. obtusa* (Foraminifera), taxonomy, distribution, and ecology. *Sarsia 65*, 79–85.

Solheim, A. 1991: The depositional environment of surging sub-polar tidewater glaciers. *Norsk Polarinst. Skr. 194*, 97 pp.

Spiridonov, M. A., Rybalko, A. Ye. & Polyak, L. V. 1992: Late Quaternary stratigraphy and paleogeography of the eastern Barents Sea off central Novaya Zemlya. Pp. 47–68 in Spiridonov, M. A. & Rybalko, A. Y. (eds.): *Osadochnyj pokrov glyacial'nogo shel'fa severo-zapadnyh morej Rossii* (Sedimentary cover of glaciated shelf, North-Western seas of Russia). VSEGEI, St. Petersburg (in Russian).

Stein, R., Grobe H. & Washner, M. 1994a: Organic carbon, carbonate, and clay mineral distributions in eastern central Arctic Ocean surface sediments. *Mar. Geol. 119*, 269–285.

Stein, R., Nam, S.-I., Schubert, C., Vogt, C., Fütterer, D. & Heinemeier, J. 1994b: The last deglaciation event in the eastern central Arctic Ocean. *Science 264*, 692–696.

Steinsund, P. I., Polyak, L., Hald, M., Mikhailov, V. & Korsund, S. in press: Recent distribution of calcareous benthic foraminifera in the Barent and Kara Seas. *J. Foraminiferal Res.*

Treshnikov, A. F. (ed.) 1985: *Atlas of the Arctic*. Moscow. 204 pp.

Vilks, G., MacLean, B., Deonarine, B., Currie, C. G. & Moran, K. 1989: Late Quaternary paleoceanography and sedimentary environments in Hudson Strait. *Geogr. physique Quatern. 43*, 161–178.

Vorren, T. O., Hald, M. & Thomsen, E. 1984: Quaternary sediments and environments on the continental shelf off northern Norway. *Mar. Geol. 57*, 229–257.

Vorren, T. O., Lebesbye, E., Andreassen, K. & Larsen, K.-B. 1989: Glacigenic sediments on a passive continental margin as exemplified by the Barents Sea. *Mar. Geol. 85*, 251–272.

Yashin, D. S., Mel'nitsky, V. Ye. & Kirillov, O. V. 1985: Structure and composition of bottom deposits of the Barents Sea. Pp. 101–115 in: *Geologicheskoe stroenie Barentsevo-Karskogo shel'fa* (Geological structure of the Barents and Kara Sea shelf). Sevmorgeologia, Leningrad (in Russian).

Faunal reference list

Cassidulina reniforme Nørvang

Cassidulina crassa d'Orbigny. Feyling-Hanssen et al., 1971, pl. 7, figs. 18, 19; Østby and Nagy, 1982, pl. 3, fig. 13.
Cassidulina reniforme Nørvang: Sejrup and Guilbault, 1980, fig. 2F–K.

Cassidulina teretis Tappan

Cassidulina laevigata d'Orbigny: Østby and Nagy, 1982, pl. 3, fig. 18.
Cassidulina teretis Tappan. Mackensen and Hald, 1988, pl. 1, figs. 8–15.

Elphidium excavatum forma *clavatum* Cushman

Elphidium clavatum Cushman. Feyling-Hanssen et al., 1971, pl. 11, figs. 10–13.
Elphidium excavatum (Terquem) forma *clavata* Cushman. Feyling-Hanssen, 1972, pls. 1, 2.

Islandiella helenae Feyling-Hanssen and Buzas

Islandiella helenae Feyling-Hanssen and Buzas, 1976, text figs. 1–4.

Islandiella norcrossi (Cushman)

Islandiella norcrossi (Cushman). Loeblich and Tappan, 1953, pl. 24, fig. 2; Feyling-Hanssen et al., 1971, pl. 8, figs. 1, 2.

Melonis barleeanus (Williamson)

Nonion barleeanum (Williamson). Feyling-Hanssen et al., 1971, pl. 9, figs. 15–18; Østby and Nagy, 1982, pl. 3, fig. 15.
Nonion zaandamae (van Voorthuysen). Loeblich and Tappan, 1953, pl. 15, figs. 11, 12.

Nonion labradoricum (Dawson)

Nonion labradoricum (Dawson). Feyling-Hanssen et al., 1971, pl. 10, figs. 1, 2; Østby and Nagy, 1982, pl. 3, fig. 17a, b.