The Barents Sea ice sheet – a sedimentological discussion

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Sediment sampling and shallow seismic profiling in the western and northern Barents Sea show that the bedrock in regions with less than 300 m water depth is unconformably overlain by only a thin veneer (< 10 m) of sediments. Bedrock exposures are probably common in these areas. The sediments consist of a Holocene top unit, 0.1–1.5 m in thickness, grading into Late Weichselian glaciomarine sediments. Based on average sedimentation rates (^{14}C-dating) of the Holocene sediments, the transition between the two units is estimated to 10,000–12,000 B.P. The glaciomarine sediments are commonly 1–3 m in thickness and underlain by stiff pebbly mud, interpreted as till and/or glaciomarine sediments overrun by a glacier. In regions where the water depth is over 300 m the sediment thickness increases, exceeding 500 m near the shelf edge at the mouth of Bjørnøyrenna. In Bjørnøyrenna itself the uppermost 15–20 m seem to consist of soft glaciomarine sediments underlain by a well-defined reflector, probably the surface of the stiff pebbly mud. Local sediment accumulations in the form of moraine ridges and extensive glaciomarine deposits (20–60 m in thickness) are found at 250–300 m water depth, mainly in association with submarine valleys. Topographic highs, probably moraine ridges, are also present at the shelf edge. Based on the submarine morphology and sediment distribution, an ice sheet is believed to have extended to the shelf edge at least once during the Pleistocene. Spitsbergenbanken and the northern Barents Sea have also probably been covered by an ice sheet in the Late Weichselian. Lack of suitable organic material in the glacigenic deposits has prevented precise dating. Based on the regional geology of eastern Svalbard, a correlation of this younger stage with the Late Weichselian is indicated.

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Introduction

The question of a Barents Sea ice sheet represents an outstanding problem in the reconstruction of former glaciations on the northern hemisphere. With regard to the Late Weichselian the views currently held on the glacial history of the region can be summarized:

(1) Total glaciation of the Barents Sea (Grosswald 1980; Andersen 1981; Hughes *et al.* 1981, maximum model). Extensive glaciation of the Barents Sea is also suggested by Hoppe (1970) and Kvasov (1978).
(2) Glaciation of the shallower regions with Bjørnøyrenna and Storfjordrenna as calving bays (Matisov 1980).
(3) No glaciation significantly beyond the coasts of Svalbard (Baranowski 1977; Boulton 1979a, b).

Essential elements in Grosswald's (1980) concept of a total glaciation are:

(1) A continuation of the 'Egga moraines' (end-moraines on the Norwegian shelf (Andersen 1968)), northwards along the shelf edge west of the Barents Sea (Koteniov *et al.* 1976).
(2) Presence of stiff pebbly mud in large parts of the Barents Sea implying till deposits (Diebner 1968).
(3) Moraine ridges in northern Russia formed from a glacial advance from the northwest at the end of the Late Weichselian or in the early Holocene (Grosswald *et al.* 1974).

Matisov (1980 and numerous earlier publications) based his conclusion on a geomorphological study of the sea floor. A main line of argument was ridge complexes near the mouths of submarine valleys, especially those extending out from Spitsbergenbanken.

The main arguments for Boulton's hypothesis of a non-glaciated Barents Sea are:

(1) The probable presence of extensive glaciomarine sediments in the Barents Sea.
(2) Earlier observations of till (e.g. Diebner 1968) are doubtful.
(3) Little apparent evidence of glacial erosion.

Boulton (1979b) argues that the main Barents Sea basin has not been glaciated at all during the Pleistocene.

Essentials for the discussion of a Late Weichselian Barents Sea ice sheet have in general been:

(1) The presence of undated high beaches on Kong Karls Land.
(2) The apparent straight-line emergence curves for Kong Karls Land and Hopen published by Hoppe (1970).
(3) Glacial striae on Hopen (Hoppe *et al.* 1969). These, however, have been reinterpreted as non-glacial (Hoppe 1981).

Boulton (1979a) suggested that the high beaches were probably very old and that the anomalous pattern of the uplift curves on Hopen and Kong Karls Land were the result of one, or a combination of the following three possibilities:

(1) Uplift of the islands may have been influenced by a substantial glacier regeneration on Svalbard during the late Holocene ('Little Ice Age').
(2) Uplift could have been restrained during the Holocene by a rapid eustatic sea level rise.
(3) Uplift may have been influenced by a tectonic component.

A tectonic uplift has also been suggested by Semevsky (1967).

Recent years' detailed glacial geology studies on Kong Karls Land have, however, revealed an early Holocene age for the high beaches 100 m above sea level (Salvigsen 1981). Furthermore, an asymptotic or normal emergence curve has been found. Similar emergence curves have also been published for Nordaustlandet (Salvigsen 1978) and Edgeøya and Barentsøya (Knape 1971), which combined with the observations on Kong Karls Land strongly suggest that a Late Weichselian ice sheet also covered much of the northern Barents Sea (Salvigsen 1981).

In this paper new information on the stratigraphy and facies of the Quaternary sediments in the Barents Sea is related to the question of glaciations.

The investigations have been conducted in the south-western (Bjørnøyrenna), northwestern (Spitsbergenbanken), and the northern (W of 35°E) Barents Sea, and only these areas have been taken into consideration.

Sediment distribution and thickness

The principal findings on sediment type, distribution and composition can be summarized as follows (Figs. 3, 4, & 5):

(1) Stiff pebbly mud (till and/or glaciomarine sediments overrun by a glacier) covered by soft mud with pebbles (glaciomarine deposits). In areas with <300 m water depth, the thicknesses of the two units are in general <15 m and <3 m, respectively.
(2) Large sediment accumulations are present in the western part of the major troughs (Bjørnøyrenna and Storfjordrenna) and exceed 500 m in thickness near the shelf edge, decreasing towards the central and inner parts of the troughs.
(3) In regions with >300 m water depth, the glaciomarine sediments increase in thickness, 15–20 m, and are overlain by fine-grained Holocene mud, rich in foraminifera and organic debris. Thickness of the Holocene mud is commonly <1.5 m. The fine-grained mud is also localized in shallower areas, especially in smaller depressions. The stiff pebbly mud is probably also present underneath the glaciomarine sediments in these areas.
(4) Transverse moraine ridges are present in the troughs radiating out from Spitsbergenbanken. Ridges are also parallel to the shelf break in Bjørnøyrenna and west of Spitsbergenbanken.
(5) The boundary between the bedrock and the sediments is seen as a well-defined angular unconformity.
(6) On Spitsbergenbanken the glacial sediments have been reworked by currents and mixed with Holocene bioclastics. A gravelly lag is also common in shallower (<100 m) parts in the northern and central Barents Sea.

Distribution of the glaciomarine deposits

The soft sediments sampled from Bjørnøyrenna/Storfjordrenna, and the central and northern Barents Sea are characterized by an olive-grey unit, 0.1–1.5 m thick, underlain by blue-grey sediments (Fig. 6a, b).

A similar sequence is found on the northern slope of Spitsbergenbanken, while on the southern slope stiff pebbly mud is frequently exposed

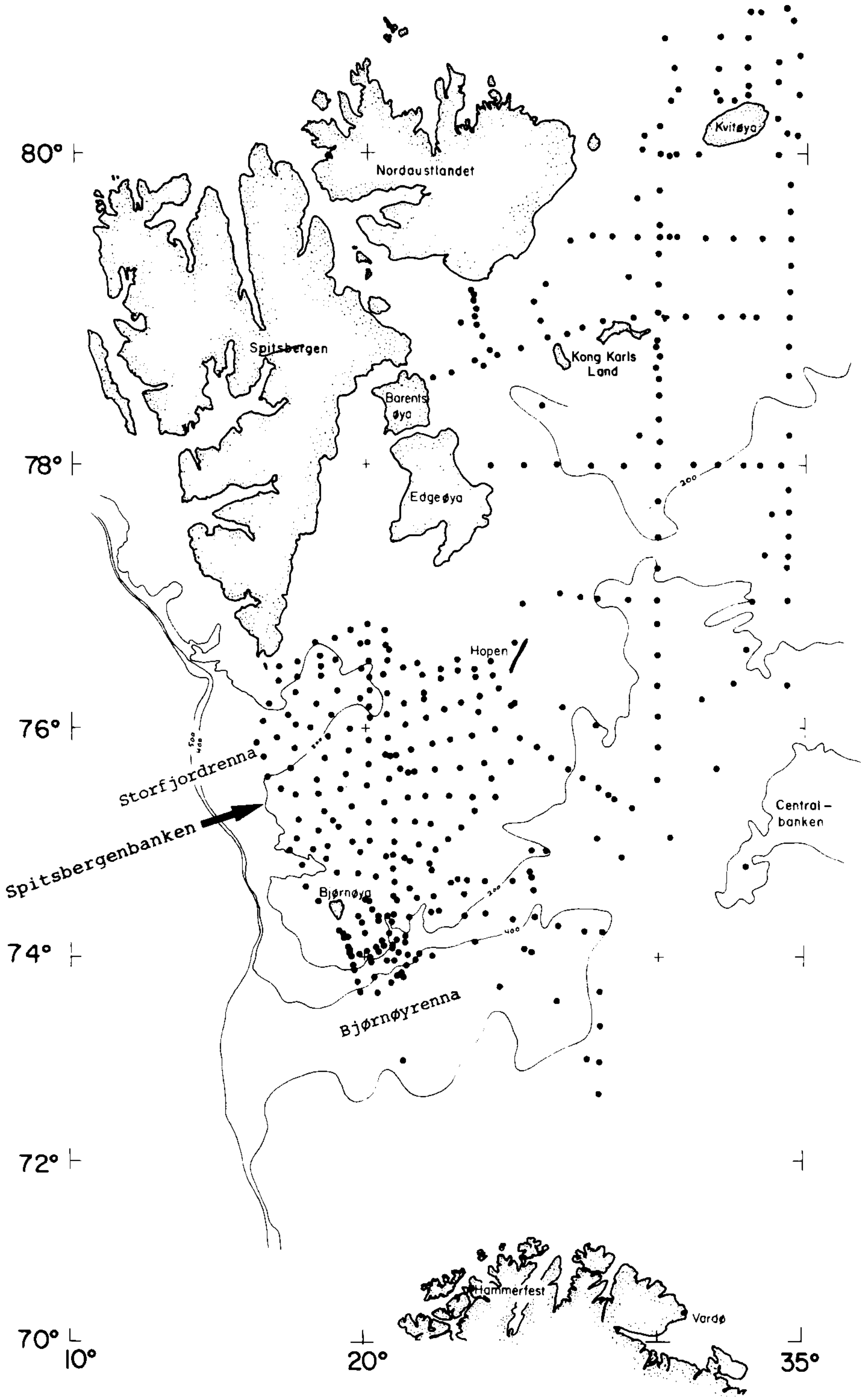


Fig. 1. Sediment samples obtained during geological surveys in the Barents Sea by the Norwegian Polar Research Institute and the Norwegian Petroleum Directorate. In general a 3 m long gravity corer is used, except for Spitsbergenbanken (<75–100 m water depth) where the samples are obtained by grab. Also location map for cores shown in Fig. 6.

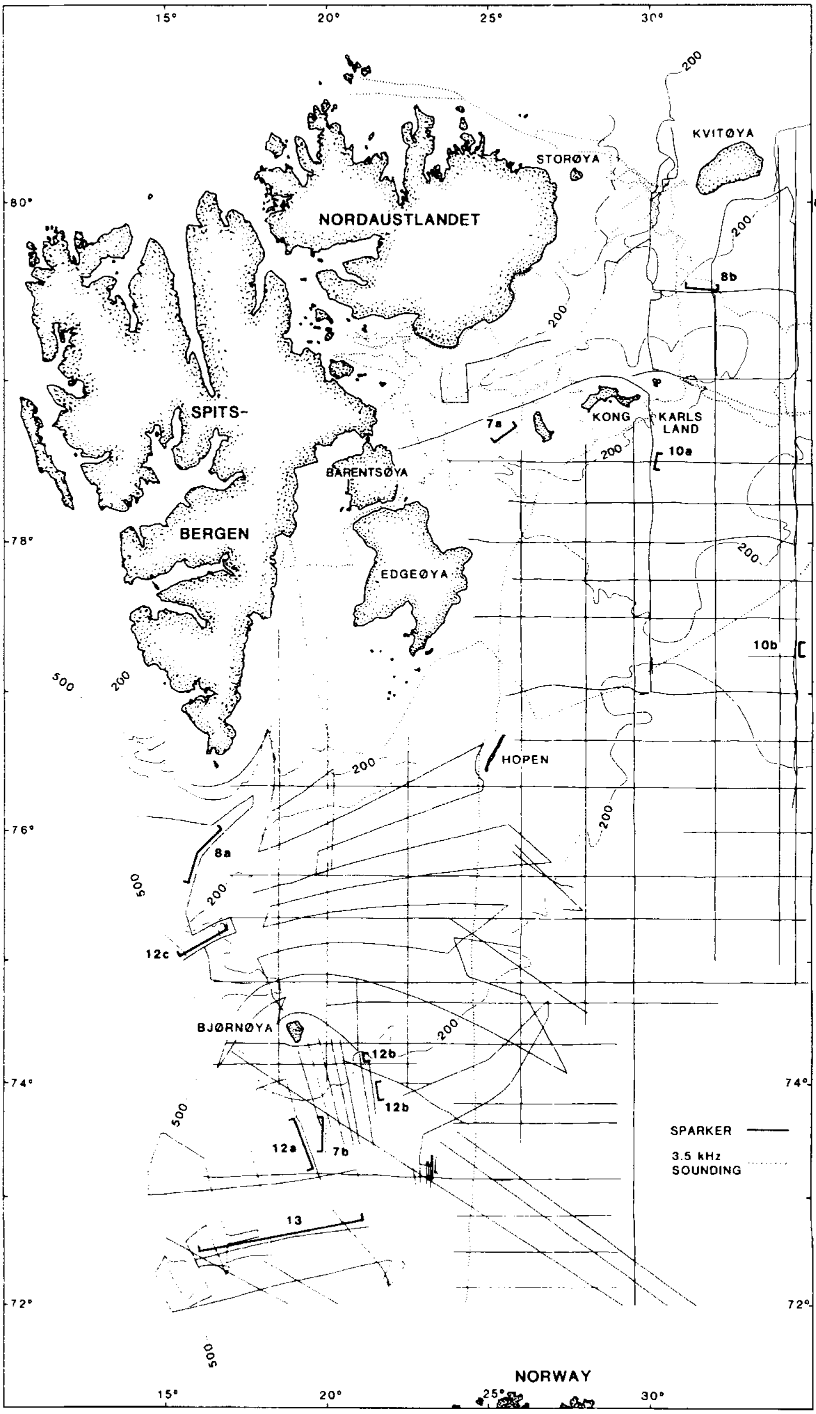


Fig. 2. Shallow seismic profiles in the western and northern Barents Sea obtained by the Norwegian Petroleum Directorate and the Norwegian Polar Research Institute. The numbers refer to seismic profiles presented.

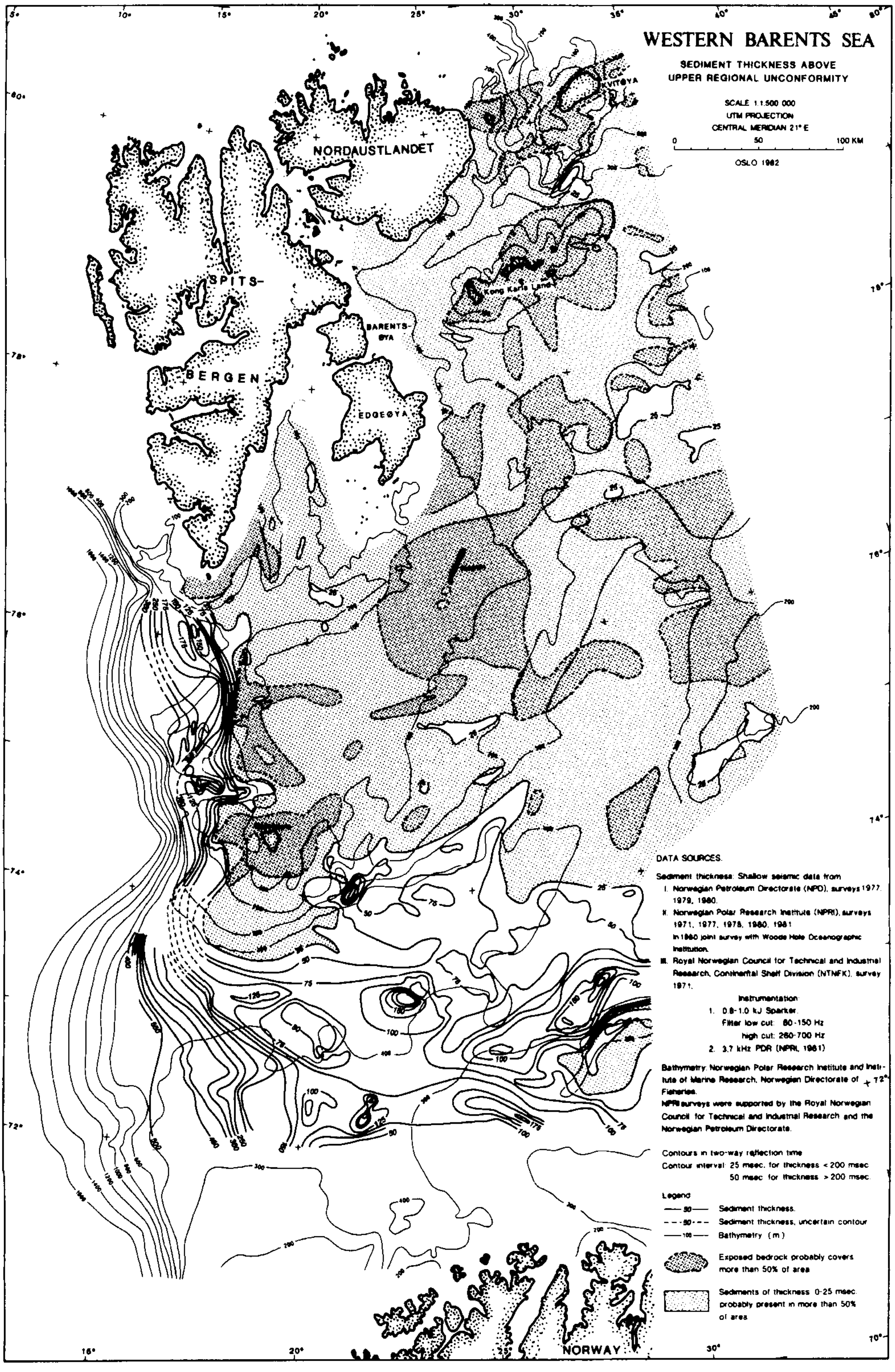


Fig. 3. Sediment distribution map of the northern and western Barents Sea.

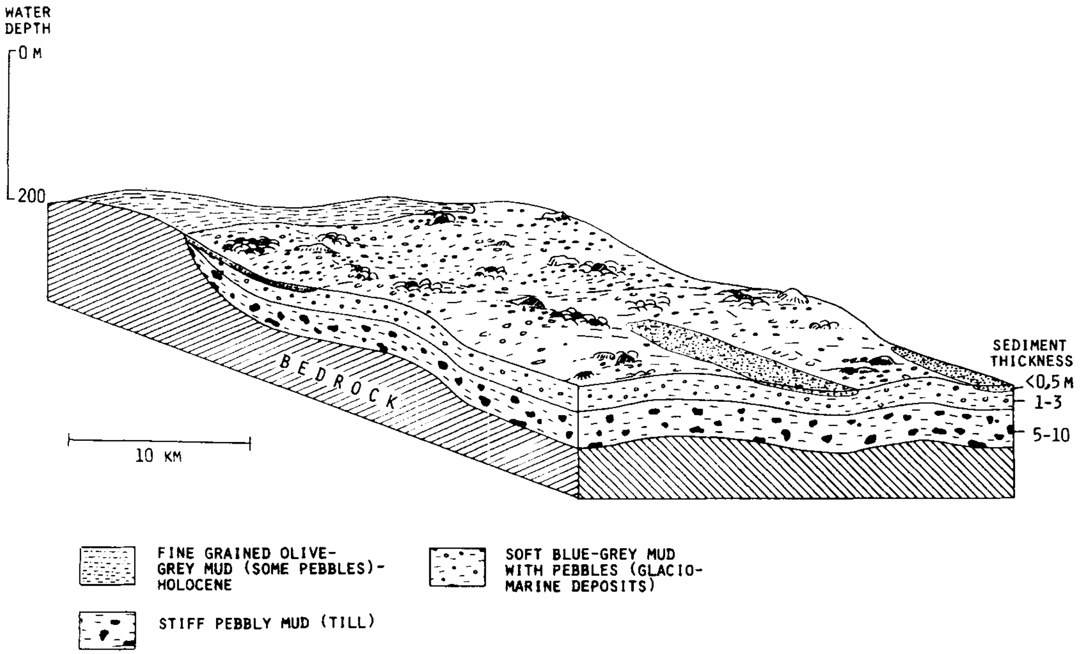


Fig. 4. Generalized block diagram illustrating the sediment distribution in the northern and central Barents Sea.

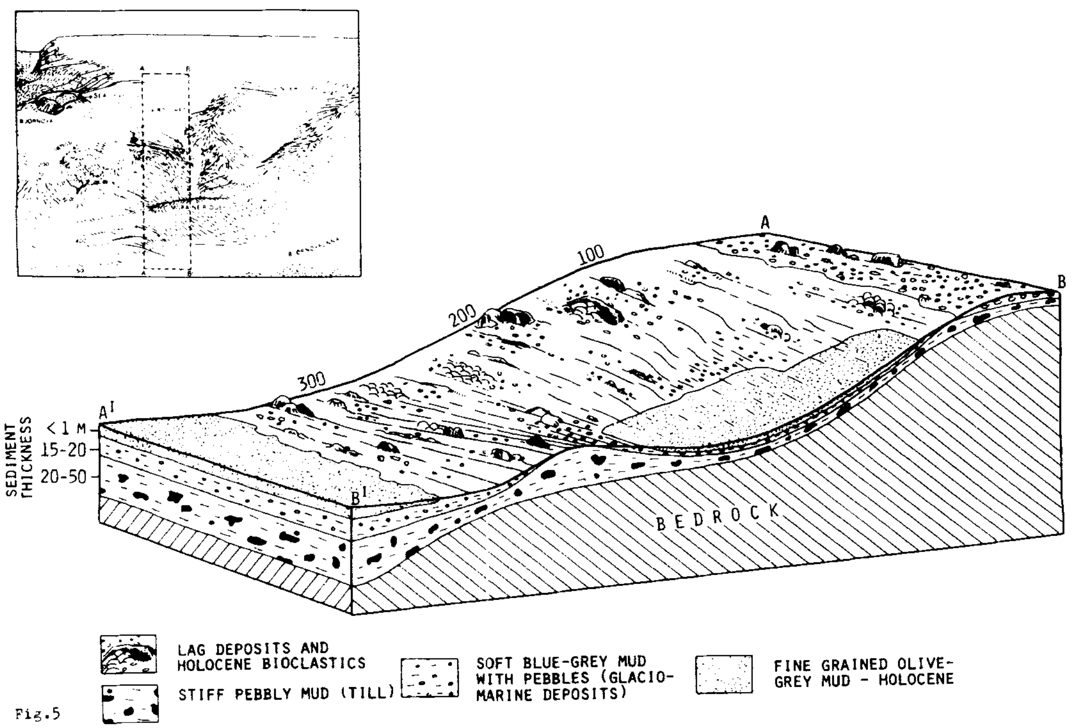


Fig. 5. Generalized block diagram illustrating the sediment distribution on the slope south of Spitsbergenbanken and northern part of Bjørnøyrenna.

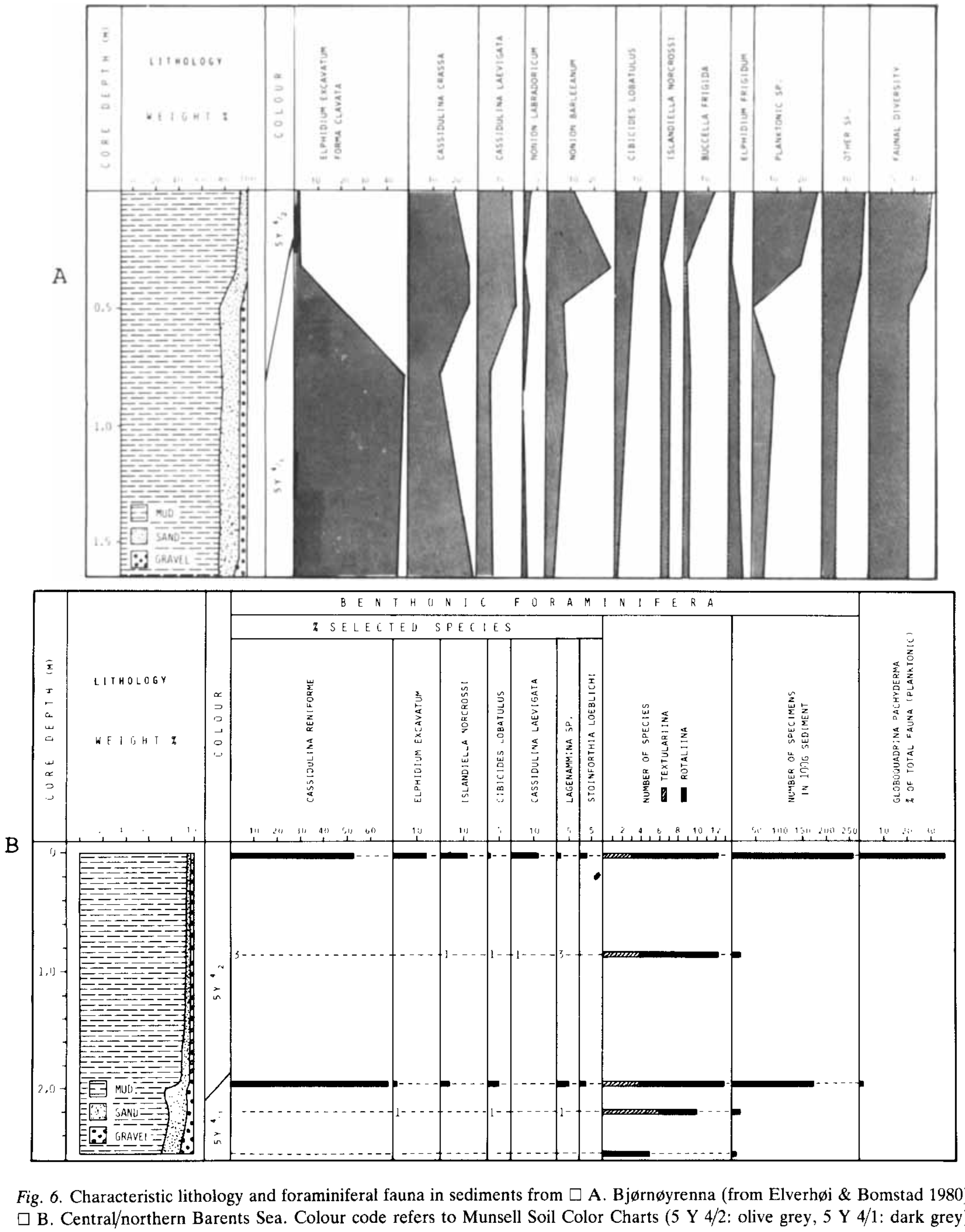


Fig. 6. Characteristic lithology and foraminiferal fauna in sediments from □ A. Bjørnøyrenna (from Elverhøi & Bomstad 1980). □ B. Central/northern Barents Sea. Colour code refers to Munsell Soil Color Charts (5 Y 4/2: olive grey, 5 Y 4/1: dark grey). For location, see Fig. 1.

at the seabed down to 350 m water depth (Bjørlykke *et al.* 1978).

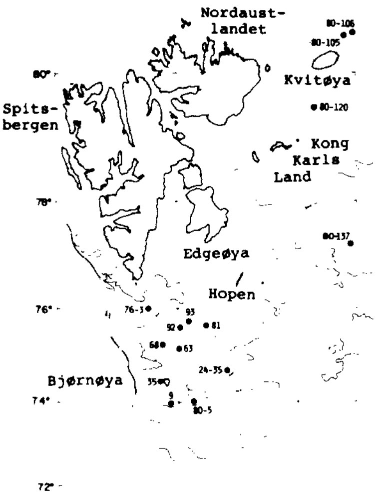
In the northern and central parts of the Barents Sea both units are typical glaciomarine deposits, soft mud with ice-rafted pebbles. The olive-grey unit is rich in organic debris and foraminifera. The blue-grey unit, however, has a higher content of pebbles and a very low content of foraminifera, all with affinities to cold water (Fig. 6b), showing a more glacially influenced depositional environment than the overlying olive-grey deposits. In Bjørnøyrenna and Storfjordrenna the olive-grey unit very seldom contains pebbles, but the underlying unit is similar to that found in northern and central regions.

In some cores from the shallower areas (< 200 m water depth) in the central and northern regions, a thin lag of pebbles and shell fragments indicates a minor erosional episode at the transition from the olive-grey unit to the underlying blue-grey one. ^{14}C-dating, core 137, Table 1, indicates a mid-Holocene age for this event. However, generally, and for all the deeper parts, the boundaries are transitional with regard to colour, texture, as well as foraminifera assemblage (Fig. 6a, b), indicating a continuous sedimentary sequence.

^{14}C-datings of molluscs in the middle and lower parts of the olive-grey unit give an early/mid-Holocene age (Table 1). All datings from cores have been obtained on whole bivalves of *Astarte* sp. in life position. These molluscs live just below

Table 1. ^{14}C-datings of sediments from the western and northern Barents Sea. Datings of surface samples from Spitsbergenbanken are also included (data from Bjørlykke *et al.* 1978).

SAMPLE NR	WATER DEPTH (M)	MATERIAL	^{14}C-AGE YEARS BP	DEPTH IN CORE (M)	AVERAGE DEPOSITIONAL RATE (CM/1000 Y)	LAB. REF. NUMBER
80-5	275	Mollusc Astarte Sp.	8.060 ± 310	0.25	3.1	T - 3830
24-35	145	"	4.210 ± 330	0.10	3.4	T - 3396
76-3	300	"	7.230 ± 340	0.19	2.6	T - 3333
80-137	125	"	4.290 ± 160	0.35	8.2	T - 3832
80-137	125	"	6.670 ± 120	0.50	7.5	T - 3834
80-120	300	"	5.780 ± 270	0.10	1.7	T - 4171
80-105	149	"	8.580 ± 290	0.26	2.3	T - 3831
80-106	165	"	7.750 ± 200	0.30	3.9	T - 3833
92	50	Mollusc Mya truncata	4.370 ± 130	Surface		T - 1798
81	58	"	2.390 ± 110	"		T - 1799
93	30	"	8.730 ± 110	"		T - 1687
9	158	"	9.140 ± 100	"		T - 2871
81	58	Mollusc Saxicava	280 ± 110	"		T - 1808
35	60	Barnacles	2.250 ± 120	"		T - 1800
68	35	"	990 ± 110	"		T - 1797
92	56	"	2.340 ± 120	"		T - 1801
63	35	"	640 ± 70	"		T - 1686



the sediment surface and are too big to have been recycled because of bioturbation.

Until now there has been no success in obtaining datable material from the blue-grey unit, but the transition to the overlying Holocene unit can tentatively be dated to the end of the Late Weichselain (10,000–12,000 B.P.):

(1) There is apparently no sign of a hiatus between the olive-grey and blue-grey deposits.
(2) An early Holocene to mid-Holocene age was obtained for the lower part of the olive-grey deposits.
(3) In the few shallower areas with sign of erosion at the transition, the erosional episode is of early/mid-Holocene age.
(4) A marked lithostratigraphic boundary between glaciomarine and younger non-glacigenic sediments is dated to 10,000 B.P. in the area just south of the Barents Sea (Vorren *et al.* 1978).

A Late Weichselian age for at least the uppermost part of the blue-grey sediment in Bjørnøyrenna is also seen from data published by Grosswald (1972). In a 'core taken at a sea depth of 370 m between Bear Island and the northern tip of Norway', 12,385 ±280 B.P. (St.-3341) was obtained on a shell in a depth interval of 37–52 cm. This layer is grey in colour, containing pebbles and a foraminiferal assemblage similar to that found in our blue-grey unit.

The lithology of the blue-grey glaciomarine sediments is homogeneous with no sign of erosional episodes. The recovered foraminiferal fauna is also uniform, consisting of only extremely cold water species, suggesting that the blue-grey deposits form a single depositional unit. However, it should be noted that a complete section through the blue-grey sediments into the underlying stiff pebbly mud has only been obtained in a limited number of cores, confined to the southern slope off Spitsbergenbanken and from the northern Barents Sea. No final conclusion can thus be drawn on whether the blue-grey glacio-

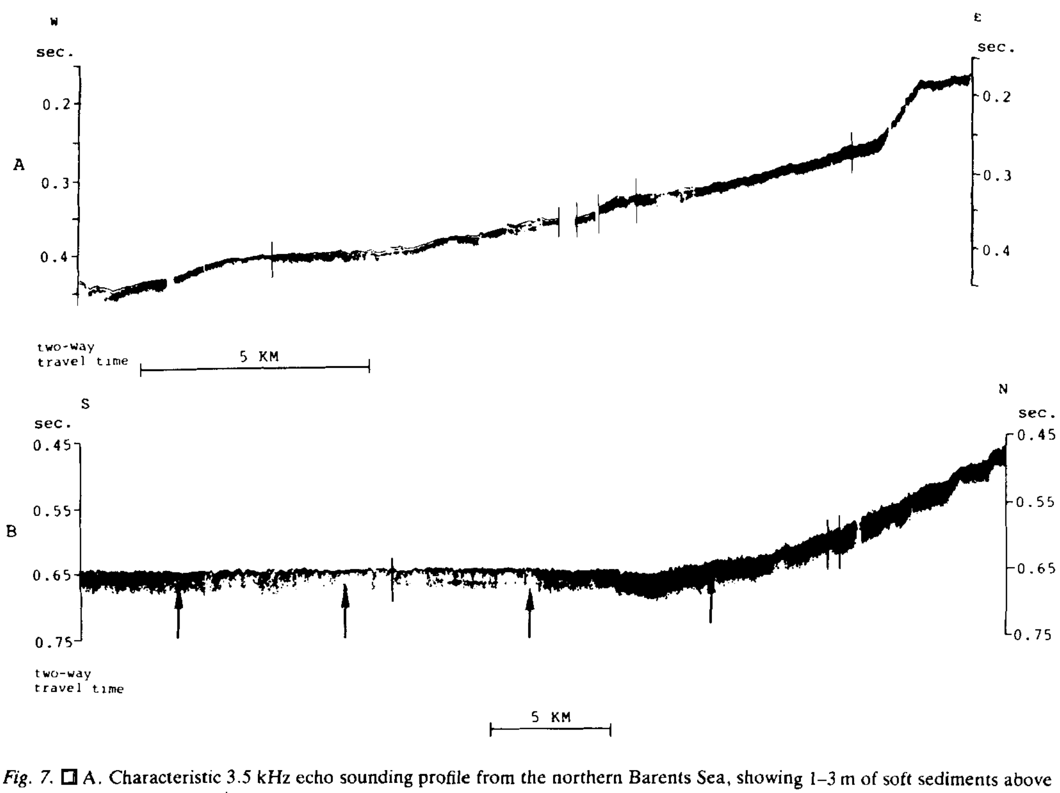


Fig. 7. □ A. Characteristic 3.5 kHz echo sounding profile from the northern Barents Sea, showing 1–3 m of soft sediments above a well defined reflector–till/bedrock. □ B. 3.5 kHz echo sounding profile from Bjørnøyrenna, southeast of Bjørnøya. The lower boundary of the glaciomarine sediments is shown by the arrows. For location of the profiles, see Fig. 2.

marine sediments have been deposited continuously or include periods of erosion/non-deposition.

The thickness of the glaciomarine (blue-grey) sediments has been obtained from sediment coring, and by 3.5 kHz echo sounder recores (Figs. 2, 7). A 3.5 kHz echo sounding profile south of Bjørnøya shows the blue-grey glaciomarine deposits apparently increasing to 15–20 m into Bjørnøyrenna (Fig. 7b). These sediments have earlier been interpreted as glacial till or moraine deposits from data mainly based on 3.5 kHz echo sounding (Damuth 1978). On the lower part of the slope from Spitsbergenbanken, the thickness seems to be <2 m, as found by sediment coring.

In Storfjordrenna and also in a trough northeast of Kong Karls Land, thick (40–60 m) deposits have been recorded on sparker profiles (Fig. 8a, b). Based on their acoustically transparent character and lack of internal reflectors, these deposits probably consist of soft, homogeneous sediments. There are also 3.5 kHz echo sounding profiles across the deposit northeast of Kong Karls Land. Sediment coring, supplemented with ^{14}C-dating (core 76–3, 80–120, Table 1), revealed the blue-grey glaciomarine sediments below half a metre of Holocene deposits. Because of their homogeneous composition, the blue-grey glaciomarine sediments sampled near the seabed almost certainly make up the entire accumulations. In a depression south of Kong Karls Land, and also at the innermost part of Bjørnøyrenna, similarly acoustically transparent sediments are found below the Holocene sediments. These deposits are also interpreted as consisting of the blue-grey glaciomarine sediments.

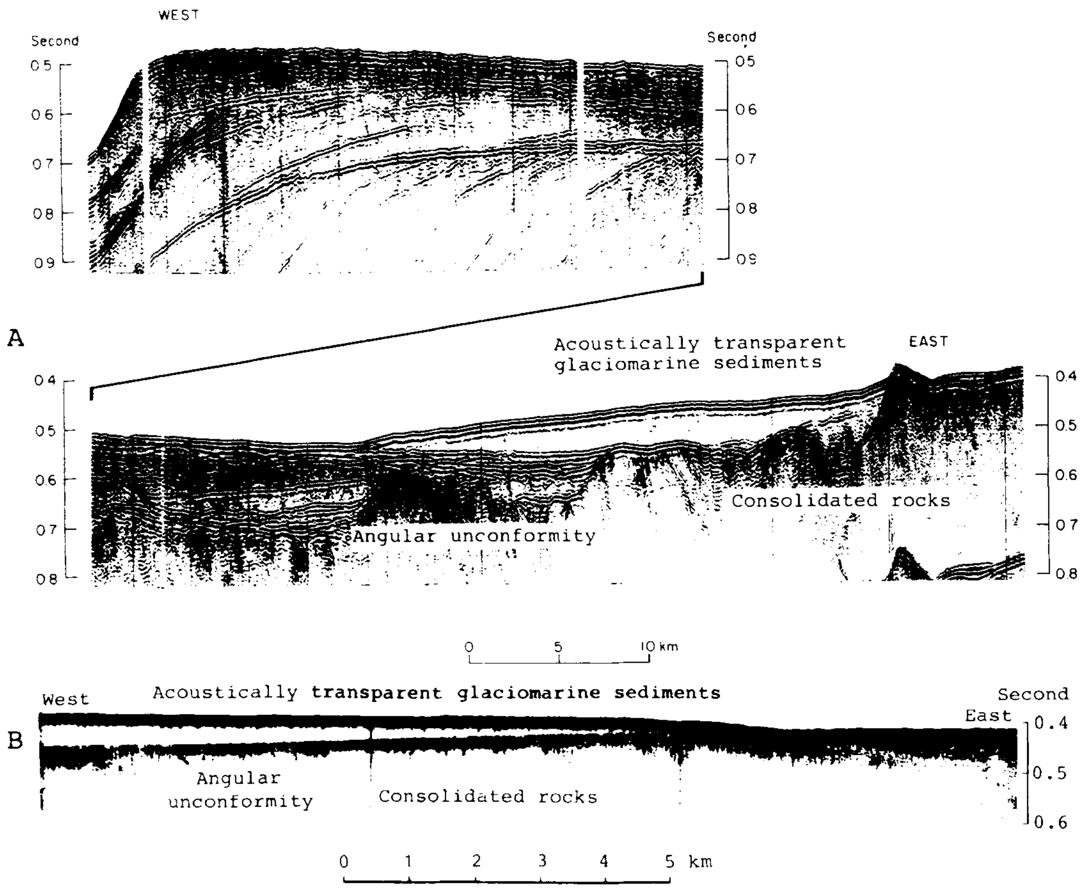
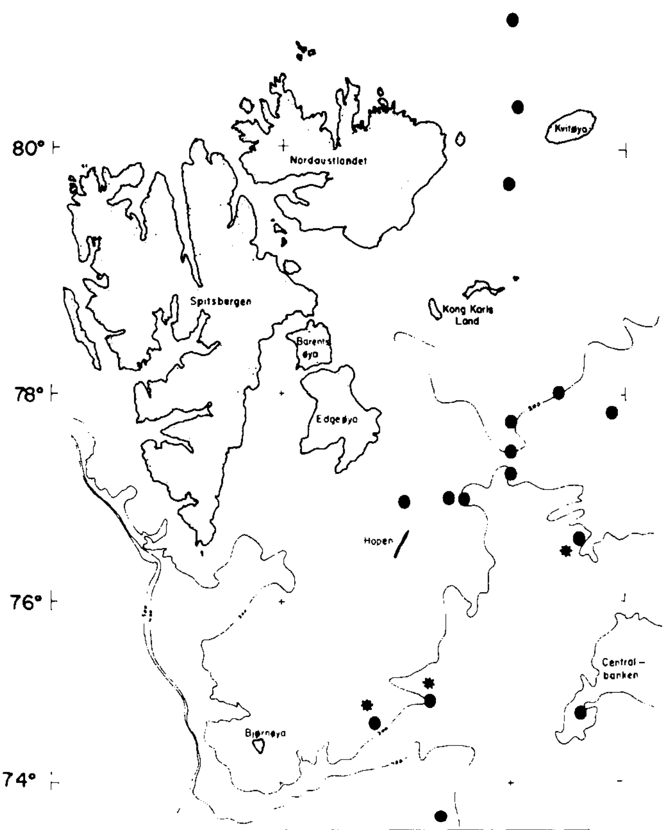


Fig. 8. ☐ A. Sparker profile from the outer part of Storfjordrenna. The extension of acoustically transparent deposits is confined to the east by a bedrock sill. ☐ B. Sparker profile across a trough northeast of Kong Karls Land. The acoustically transparent deposits are found at water depths >300 m (from Kristoffersen *et al.* in press). For location of the profiles, see Fig 2.



	Fine-grained olive-grey mud 0 - 20 cm	Fine-grained olive-grey mud >20 cm	Soft blue-grey mud with scattered pebbles	Stiff pebbly mud
Shear strength t/m2	0.8 - 1.2	0.5 - 0.7	0.3 - 0.5	4 - 6
Water content %	70 - 75	70 - 75	35 - 50	15 - 20

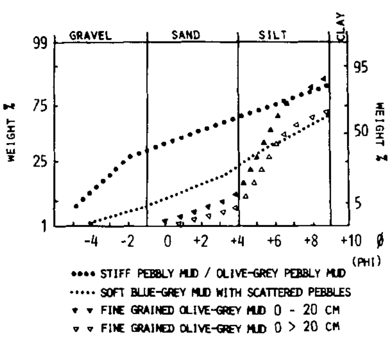


Fig. 9. Map showing localities where stiff pebbly mud has been sampled and investigated. Shear strength and water content determinations from the different lithologies are listed. Grain-size analyses for the samples are shown. *: analysed samples. Analyses: Norwegian Geotechnical Institute.

The stiff pebbly mud

Texture and distribution

In regions shallower than 300 m, the stiff pebbly mud was sampled at ten localities during the surveys in 1978 and 1980 (Fig. 9). Geotechnical tests made on three of the samples show shear strength values in the range of 4–6 t/m^2 (40–60 kN/m^2), which is an order of magnitude higher than that found for normally consolidated surface sediments, e.g. the sample from Bjørnøyrenna (Fig. 9). Because of the stiffness only 20–30 cm of this type of deposit was obtained by gravity coring. Larger samples were collected with the 1 m^3 grab. Lumps of the same material were also recovered with a pipe dredge.

These sediments seem to be very thin in regions shallower than 300 m (Fig. 10). From the sparker records the sediment thickness above bedrock is found in general to be <15 m (because of the pulse width, no resolution is obtained in the first 10–15 m below sea bottom). Supported with data from the 3.5 kHz echo sounding and the sediment coring, the sediment thickness is estimated to be <5 m. In some areas the bedrock is exposed, exemplified with a bottom photograph (Fig. 11). There has been no sampling through the stiff pebbly mud into the bedrock.

In areas deeper than 300 m there is a general thickening of sediments above bedrock (Fig. 12a). Based on the 3.5 kHz echo sounding and sediment coring, the upper 15–20 m of the deposit in Bjørnøyrenna probably consists of soft sediments. The reflector seen on the 3.5 kHz profile (Fig. 7) is thinning out to only 1–2 m on the lower part of the slope from Spitsbergenbanken. Sediment coring close to the profile showed exposure of the stiff pebbly mud, to which the reflector is correlated. Consequently the stiff pebbly mud seems to extend into Bjørnøyrenna.

Depositional mechanism

In addition to a basal till origin, stiff pebbly sediments may form from ice-rafted deposits compacted by various factors (a mud flow origin is excluded):

(a) *Sediment loading.* – Removal of overlying sediments due to gravity flow, however, is unlikely because of the low gradient. Alternatively, submarine erosion of glaciomarine sediments would have developed lag deposits, which have not been found.

(b) *Action of permafrost* (Williams 1967). – Subsea permafrost has to form out from land (or beneath a cold glacier). A Late Weichselian drop in sea level of 100–130 m would cause subaerial exposure of parts of the Barents Sea. The stiff pebbly mud, however, is sampled at water depths well below and away from what could have been exposed during that regression. Assuming tectonic stability, the stiff pebbly mud is further sampled below water depths that can have been subaerially exposed during former, larger Pleistocene regressions.

According to the above, the stiff pebbly mud is most likely a till and/or glaciomarine deposits overrun by a grounded ice. At water depths shallower than 300 m, i.e. Spitsbergenbanken and the northern Barents Sea with only a thin sediment cover and frequent exposure of the bedrock, the stiff pebbly mud is tentatively classified as basal till. In areas deeper than 300–400 m, with considerable thickness of sediments above the bedrock, the stiff pebbly mud may, however, have been of glaciomarine origin. According to Dreimanis (1978), these sediments may be classified as deformation till.

Ice marginal features

Ridge complexes and areas of relative topographical highs that are not caused by bedrock have been observed in the following regions:

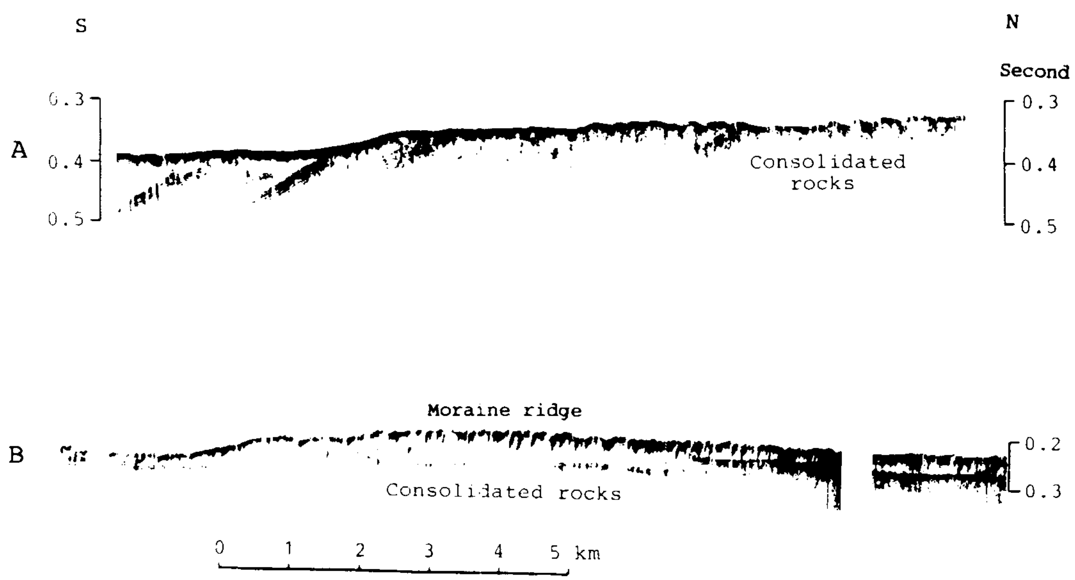


Fig. 10. Sparker profiles from the northern Barents Sea illustrating: □ A. The general existence of only a thin (<15 m) cover of sediments above the bedrock, forming a well-defined angular unconformity with the sea floor. □ B. An up to 50 m thick accumulation of glacigenic sediments on Storbanken at 150 m water depth. The accumulation is probably a moraine (from Kristoffersen *et al.* in press). For location of the profiles, see Fig. 2.

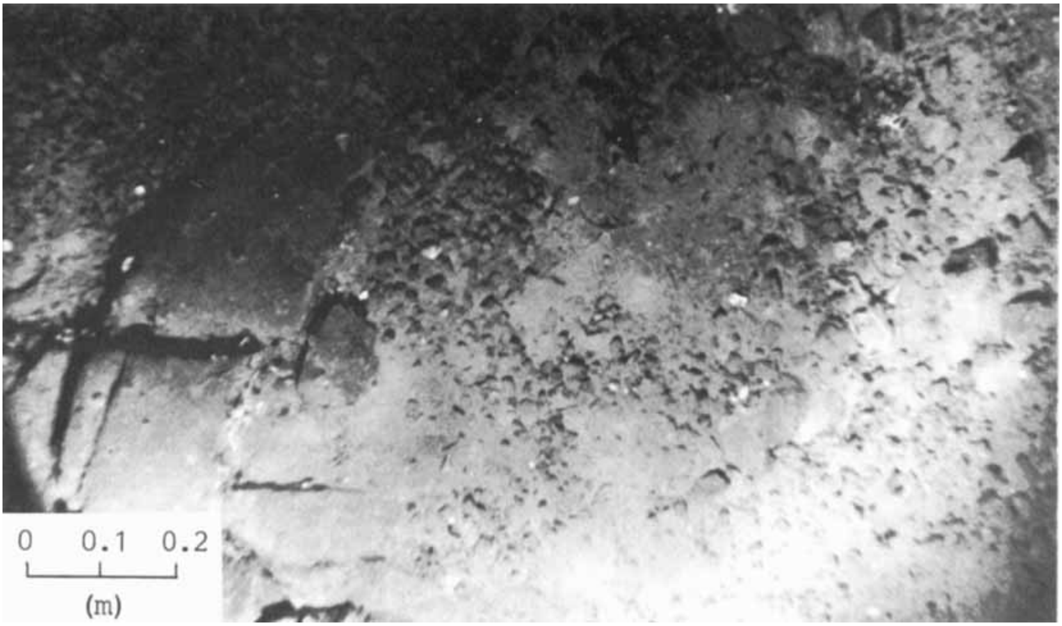


Fig. 11. Bottom photograph from the northern Barents Sea. Bedrock exposed in the left part of the photograph. 80° 24′ N, 29° 55′ E, 240 metres water depth (published with the permission of C. Craine.)

(1) In the mouth of troughs radiating from Spitsbergenbanken (Fig. 12b).
(2) Near the shelf edge at the mouth of Bjørnøyrenna and Storfjordrenna (Fig. 8a and 13).
(3) On the upper slope/shelf edge west of Spitsbergenbanken (Fig. 12c).
(4) On Storbanken, central Barents Sea (Fig. 10b).

(1) Both Leirdjupet (SE of Bjørnøya) and Kveithola (NW of Bjørnøya) form overdeepened troughs where the outer high is caused by sediment accumulation. In adjacent areas, only a sparse cover of sediment is present (Fig. 3).

In Leirdjupet the ridge has an asymmetric pattern, with the steepest slope facing southwards (Fig. 12b). The surface, especially the north facing part, is hummocky. Stiff pebbly mud was recovered from the surface. With the exception of a minor reflector in the lower part, no other evidence of internal structures has been obtained so far. From the geometry, the location in front of a valley, and the sediment distribution in adjacent areas, this feature appears to be deposited by a glacier flowing down Leirdjupet.

The thickness (approx. 100 m) and 'width' (approx. 10 km) of the ridge in Leirdjupet are much larger than commonly found for end moraines on land. On the northern Norwegian shelf, features interpreted as end moraines are also very wide, 5–15 km (Rokoengen *et al.* 1979). Vorren & Elvsborg (1979) suggest that the broad appearance of these shelf deposits reflects a moraine complex rather than a single end moraine. It should be noted that the shelf moraines were deposited by ice influenced by buoyancy. The erosional power of the ice is then strongly reduced in its frontal areas and deposition is likely to start far back from the ice front.

(2) In the central parts of the mouth of Bjørnøyrenna there is a 50 m high sediment accumulation (Fig. 13). The ridge feature, supported with the truncated reflectors, suggests a glacial origin, probably an end moraine. Sparker profiles north of 73°N do not show any northward continuation of the high. Grosswald (1980) and Andersen (1981) suggest a continuation of the 'Egga moraine' to the north. Available bathymetric data from the area, however, are very limited and do not form a reliable data base for detailed contouring. Our seismic profiles also stop southward at 72°N. At the present stage, a con-

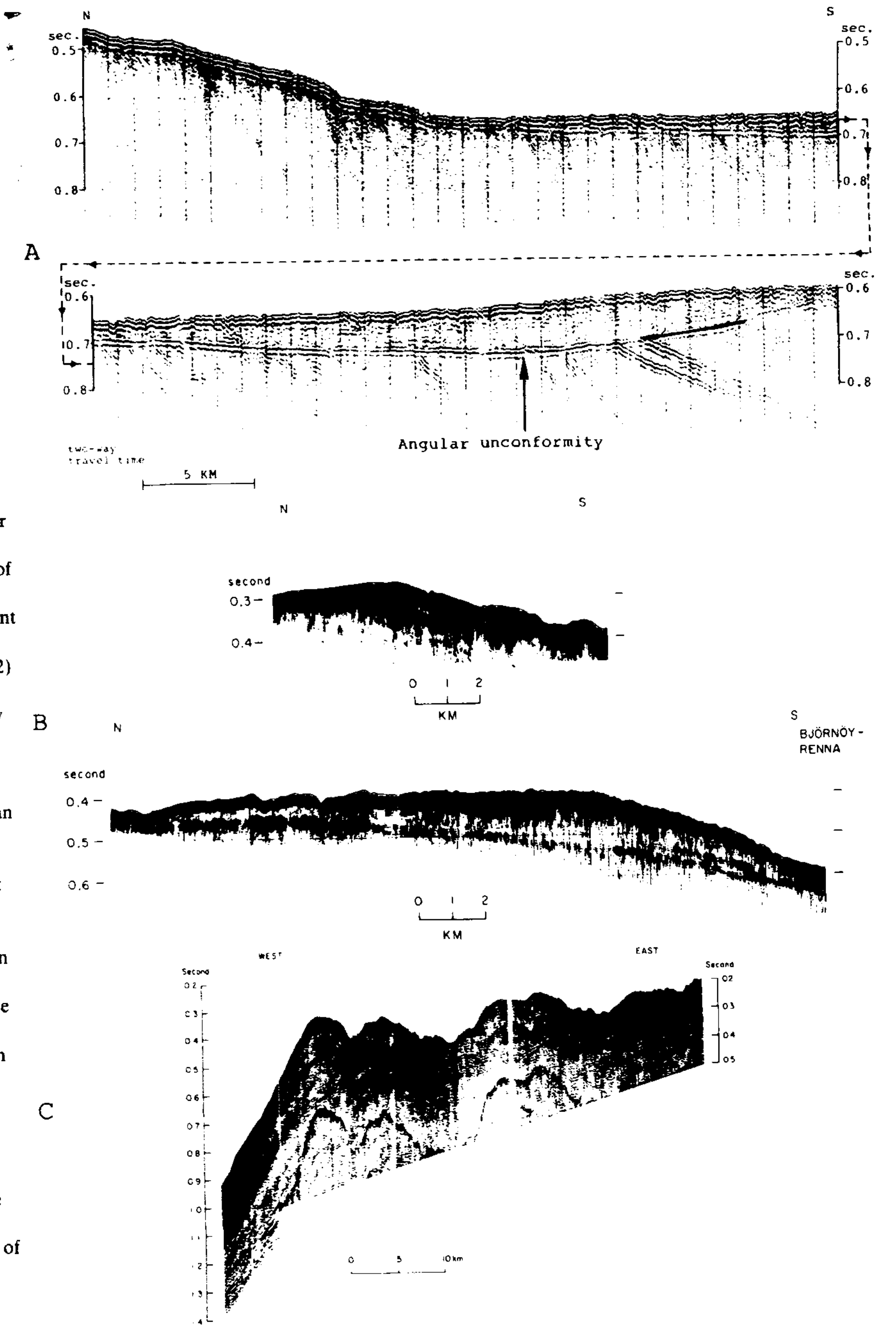


Fig. 12. □ A. Sparker profile from Bjørnøyrenna south of Bjørnøya, illustrating (1) increasing sediment thickness into Bjørnøyrenna, and (2) the well-defined angular unconformity between the bedrock and sediments. □ B. Sparker profile from Leirdjupet showing an up to 150 m thick accumulation of glacigenic deposits at 300 m water depth. The accumulation is probably deposited in the frontal zone of a southward moving ice sheet. A minor moraine ridge is seen at approximately 200 m water depth (above). (From Elverhøi & Kristoffersen 1977.) □ C. Sparker profile across probable moraine ridges west of Spitsbergenbanken. For location of the profiles, see Fig. 2.

nection between the observed high and the 'Egga moraine' remains an open question.

The mouth of Storfjordrenna (Fig. 8a) also forms a topographical high relative to the inner parts. The reflection pattern on the sparker records shows truncated reflectors, indicating episodes where glacial advance and erosion were followed by deposition as the ice sheet retreated, instead of a continuous build-up and progradation.

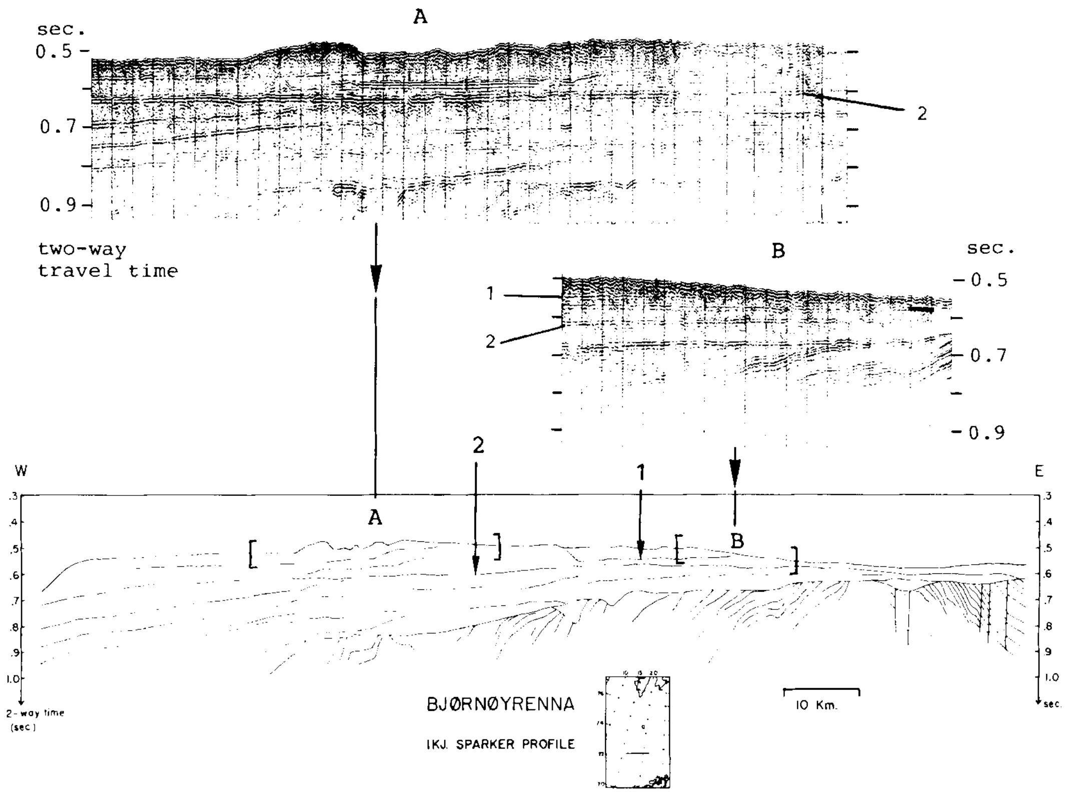


Fig. 13. Interpreted sparker profile from the mouth of Bjørnøyrenna. Note that the outer high is caused by sediment accumulated above reflector 2. For location, see Fig. 2.

(3) On the slope west of Spitsbergenbanken, the bottom is hummocky with a relative scale of 25–50 m (Fig. 12c) forming ridges oriented almost parallel to Spitsbergenbanken. Based on their geometry and orientation, these features are interpreted as end moraines deposited by an ice sheet advancing from Spitsbergenbanken.

(4) The morphology of the ridge strongly suggests a glacial origin, most likely an end moraine.

In addition to these features, local accumulations are found

(1) at the innermost part of Storfjordrenna,
(2) at 150–200 m water depth in the troughs extending radially out from Spitsbergenbanken (Fig. 12b),
(3) on the southern slope off Spitsbergenbanken, and
(4) at Storbanken and Sentralbanken.

Sediment sampling in the areas of 2, 3, and 4 showed stiff pebbly mud, indicating till (and/or glaciomarine deposits overrun by a glacier).

Erosional features

The sediments are everywhere commonly uncomformably overlying the bedrock (e.g. Figs. 8b and 12a). Of special importance are the overdeepened regions in central parts of the Barents Sea (Fig. 14). As these features are formed by excavation into the bedrock (Fig. 3), they are most likely due to glacial erosion.

Discussion

The sediment distribution and stratigraphy (till overlain by glaciomarine sediments grading into postglacial deposits) clearly demonstrate that the Barents Sea has been covered by grounded ice

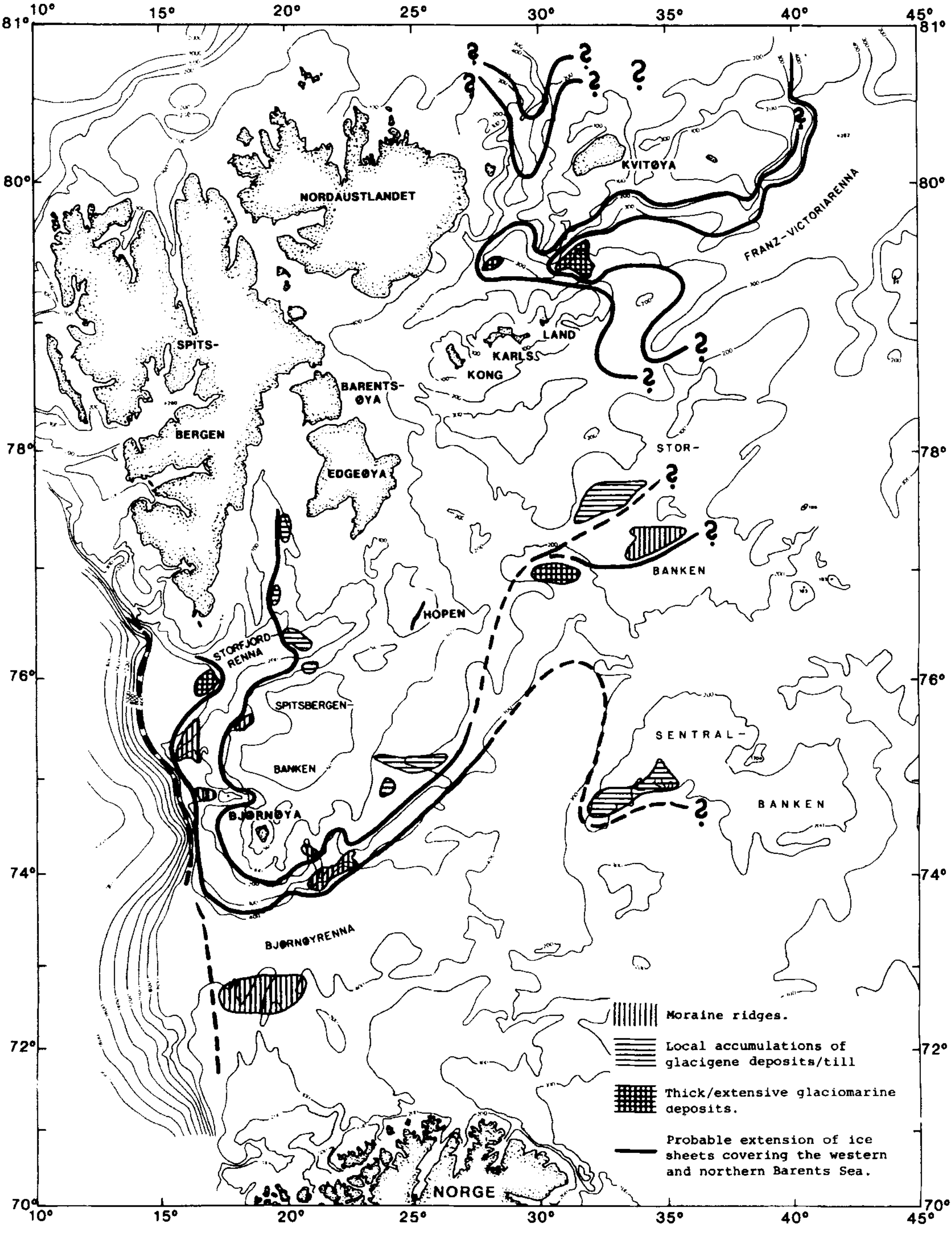


Fig. 14. Bathymetric map showing features related to former ice margins in the western and northern Barents Sea.

at least once. Overdeepened regions south of Kong Karls Land further indicate considerable glacial erosion in the northern Barents Sea. The depositional chronology cannot be established yet because of lack of datable material and inadequate knowledge on the stratigraphy of the glaciomarine deposits. At this stage only a preliminary discussion may be attempted on the extent and age of Barents Sea glaciations.

Sediment distribution in relation to glaciations

The extension of an ice sheet can be reconstructed from the distribution of (1) ice marginal features such as moraine ridges, and (2) areas covered by till or glacially compacted and reworked deposits. In a marine environment the distribution and thickness of glaciomarine deposits have to be included.

As a possible reference for the ice sheets in the northern Barents Sea, at least during their retreat, observations from Austfonna at Nordaustlandet may be applied. This is an ice cap, 100 × 50 km, terminating in the sea along half its circumference. Considerable parts of the ice cap are believed to be below pressure melting point, while central parts may be at pressure melting point (Schytt 1969). Sediment loaded meltwater discharge into the sea seems to confirm the existence of areas at pressure melting point beneath the ice cap. Preliminary studies of the sedimentation outside the ice cap (Pfirman, pers. comm. 1981; Solheim & Elverhøi 1982) show that the major part of both the suspended matter and the ice-rafted material is deposited relatively close (within 10 to 15 km) to the ice front. With reference to these results, thick glaciomarine sediments with well-defined limits should be regarded as ice marginal features.

The Barents Sea ice sheets were grounded below sea level, i.e. marine ice sheets. The stability and extension of such ice sheets are to a large extent controlled by the sea level (e.g. Thomas 1979). A marine ice sheet covering an area of low relief like the Barents Sea is thus likely to extend down to a common water depth over large regions. This, in turn, makes it possible to reconstruct the margins of such ice sheets into areas lacking well-defined marginal features.

Ice marginal features are situated around Spitsbergenbanken at approximately 250–300 m water depth (Fig. 14). From the fact that these features are observed at the same water depth, we propose that they define the outline of an ice sheet covering Spitsbergenbanken.

In the northern and central Barents Sea, ice marginal features are found at somewhat shallower water depth, except for the glaciomarine deposit at 300 m water depth northeast of Kong Karls Land (Fig. 14). However, on the western slope off Sentralbanken and in the inner part of Bjørnøyrenna at approximately 300 m water depth, there is a thickening of both the glaciomarine and its underlying deposits. Based on this change in sediment thickness and the glaciomarine accumulations in the northern Barents Sea, we propose a continuous ice sheet covering the central and northern Barents Sea in the Late Weichselian. Furthermore, we also propose that it was connected with the ice sheet on Spitsbergenbanken. To the north a coalescence of the ice on Nordaustlandet/Storøya and Kvitøya is proposed. Due to findings of till on the shelf north of these islands we further propose that the ice extended further north, confined to a water depth corresponding to a present water depth of 250 to 300 m. The extension to the northeast is defined by the Franz-Victoriarenna and the glaciomarine accumulation in its inner part (Fig. 14).

Ice marginal features, somewhat less extensive than the previous ones, are found at about 150–200 m water depth around Spitsbergenbanken, in the inner parts of Storfjordrenna and Bjørnøyrenna and on Storbanken (Fig. 14). Similarly, as for the marginal features and change in sediment thickness at 250 to 300 m water depth, we relate these latter features to an ice sheet somewhat smaller in extent than the former one (Fig. 14). We also propose a similar, smaller ice sheet in the northernmost Barents Sea in the Late Weichselian.

A more extensive – and older – ice sheet is, however, witnessed by findings of till (or glaciomarine sediments overrun by a glacier) in Bjørnøyrenna and a moraine ridge at the mouth of the trough. As illustrated in Fig. 14, this extensive ice cover is believed to have reached to the shelf edge in the west.

Possible age of the Barents Sea glaciations

Pre-Late Weichselian. – On Svalbard an early Weichselian glaciation seems to have been of a larger extent than the Late Weichselian (Salvigsen & Nydal 1981). Such an ice may also have covered considerable parts of the Barents Sea.

Late Weichselian. – The northern extent of the Scandinavian ice sheet is still a subject of controversy. Andersen (1968 and 1981) tentatively placed the maximum limit on the outer continental shelf, defined by the 'Egga moraines'. Based on sediment coring and shallow seismic reflection, Rokoengen *et al.* (1979) also suggested a glacial extension to the outer continental shelf. Vorren *et al.* (1978) demonstrated that the shelf outside Troms was deglaciated 13,000–14,000 B.P. Until now the detailed stratigraphical investigations have been concentrated in the nearshore areas, while information from the outer shelf off northern Norway is limited. Available data do not provide an adequate basis to prove or disprove the existence of a grounded glacier on the outer shelf with a possible extension into Bjørnøyrenna.

On Svalbard, Hoppe (1970) suggested a large continuous ice sheet covering Svalbard with an extension into the northern and northwestern Barents Sea. Investigations by Salvigsen (1977) and Salvigsen & Nydal (1981), however, have shown the existence of more local and limited glaciations of the western part of Spitsbergen, while Salvigsen (1981) suggested that a continuous ice sheet covered eastern Svalbard, including Kong Karls Land.

Recent investigations on Storøya, a small island just east of Nordaustlandet (Fig. 1), show an emergence curve similar to those found elsewhere in eastern Svalbard (Häggblom 1982), indicating an expanded Late Weichselian ice sheet also in that part of the northern Barents Sea. Concerning Hopen, the existence of a Late Weichselian ice sheet in the area has been disputed (e.g. Boulton 1979a). It should be noted, however, that only two levels older than 4,000 years B.P. have been dated so far. Additionally, it seems unreasonable that the displacement on Hopen should have been caused by tectonic movements, in contrast to the rest of eastern Svalbard, since the whole area is on the same basement platform. It seems more likely that the displacement on Hopen is also due to glacial unloading, indicating that Hopen and its adjacent areas were covered by a Late Weichselian ice sheet as proposed by Hoppe (1970).

Bjørnøya, the small island on the western flank of Spitsbergenbanken, was deglaciated 11,500 B.P. according to gytje dates (Hyvärinen 1972). Lack of 'recent' glacial features led Boulton (1979a) to suggest a non-glaciated island. According to Salvigsen and Nydal (1981), Bjørnøya may have escaped glaciation during the Late Weichselian in common with areas in western Spitsbergen. An ice-free Bjørnøya does not, therefore, necessarily contradict the concept of an ice sheet further east on Spitsbergen. Alternatively, as proposed by Hoppe (1970), Bjørnøya may have been covered by only a thin ice sheet due to its position very close to the shelf edge. The general deglaciation may further have been followed by local ice cap formation, partly or completely destroying older traces of glacial movements.

From the above regional geological considerations, it seems likely that the northern Barents Sea and also Spitsbergenbanken seem to have been covered by grounded ice which in turn is compatible with the sediment distribution. From the sediment distribution it cannot, however, be concluded whether this ice sheet extended to the shelf edge, i.e. a total glaciation as proposed by Grosswald (1980) and Hughes *et al.* (1981) (maximum model), or was confined to the Spitsbergenbanken and the central and northern Barents Sea.

Comments on the idea of a non-glaciated Barents Sea

Even though the shoreline displacement in eastern Svalbard strongly indicates the presence of a Late Weichselian ice sheet in the northern Barents Sea, the possibilities of a non-glaciated northern Barents Sea should be taken into consideration. Such a concept implies that the blue-grey glaciomarine sediments in the area have to include deposits from the time when a former ice sheet retreated from the region. However, the sediments show no sign of erosion, reflecting the Late Weichselian regression.

Hiatuses can on the other hand be present as non-depositional episodes. The very low content of foraminifera (10 per 100 g sediment) makes stratigraphical interpretation problematic. The fauna observed in the cores from the northern Barents Sea is composed of species with affinities to cold water, reflecting a High Arctic glacial environment (Fig. 6). This is in contradiction to the finding of pre-Late Weichselian shells, drift wood, and whale bones on Kong Karls Land, which in turn indicate a pre-Late Weichselian climate similar to the present (Salvigsen 1981). A response to such conditions has not been traced in the samples. Theoretically, these sediments could have been removed, but it seems reasonable that such an event should also be recorded in the underlying sediment. However, the lowermost part of the blue-grey glaciomarine sediments are inadequately sampled and the existence of hiatuses cannot be totally rejected. A more detailed investigation of the stratigraphy of the blue-grey sediments is in progress.

Conclusion

The sediment sequence of till (and/or glaciomarine sediments overrun by a glacier) overlain by glaciomarine deposits which in turn grade into postglacial sediments (Holocene age), demonstrates that the western and northern (West of 35°E) Barents Sea has at least once been covered by grounded ice.

Moraine ridges along the western continental shelf edge, especially at the mouth of Bjørnøyrenna, indicate the occurrence of a large-scale glaciation in the Barents Sea. Moraine ridges and thick glaciomarine accumulations are found radially to Spitsbergenbanken at 150 to 200 m and 250 to 300 m water depth, respectively. At the same water depths, similar ice marginal features are also found in the central and northern Barents Sea. Based on these features and regional geological considerations we propose the existence of a marine ice sheet covering the northern part of the Barents Sea and Spitsbergenbanken during the Late Weichselian. Whether this ice sheet represents a major halt during the retreat of a more extensive ice sheet or the outer limit, is not clear.

It should be noted that such a model is in conflict with:

(1) the idea of large-scale, catastrophic break-up at the end of the Late Weichselian as suggested by Grosswald (1980) and Denton & Hughes (1981);
(2) the existence of a Late Weichselian ice shelf covering the Norwegian-Greenland Sea, as proposed by Kellogg (1980); and
(3) the idea of a non-glaciated Barents Sea, as suggested by Boulton (1979a, b).

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