Deglaciation of the Continental Shelf off Southern Troms, North Norway

TORE O. VORREN, MAGNE EDVARDSEN, MORTEN HALD
& ELSEBETH THOMSEN

Vorren, T. O., Edvardsen, M., Hald, M. & Thomsen, E. 1983: Deglaciation of the continental shelf off southern Troms, North Norway. Norges geol. Unders. 380, 173–187.

Based on lithostratigraphical and seismic studies, four (possibly five) glacial events are recognized in Andfjorden. The two oldest, the I- and G-events are represented by basal tills. The continental ice sheet probably reached the shelf edge during deposition of these tills. Both the I- and G-events are older than c. 19,000 YBP and possibly younger than c. 36,000 YBP. The uncertain glacial event is represented by a questionable moraine ridge complex 20–25 km from the shelf edge. The Flesen event is represented by end moraines c. 50 km from the shelf edge; an age of 16,000–15,000 YBP is suggested. The D-event is identified as a glaciomarine sedimentary unit with high frequencies of ice-dropped clasts. During D-time the ice sheet crossed the sedimentary/crystalline boundary in Malangsdjupet; in Andfjorden it was probably situated just shoreward of this boundary. The age of the D-event is 14,000–13,000 YBP.

T. O. Vorren, M. Hald & E. Thomsen, Institute of Biology and Geology, University of Tromsø, N-9000 Tromsø, Norway.

M. Edvardsen, Norwegian Petroleum Directorate, N-4000 Stavanger, Norway

Introduction

The purpose of the investigation upon which this article is based is to elucidate the deglaciation history of the continental shelf off the southern part of Troms based on stratigraphical studies. For a review of earlier work on the deglaciation history of this area we refer to Vorren & Elvsborg (1979).

The areas chosen are two troughs, Andfjorden and Malangsdjupet (Fig. 1). There are two main reasons for this choice; 1: The depth of these troughs exceeds 300 m which is a critical depth for iceberg plough marks in this area. Above this depth the stratigraphy of the upper sediment layers was disturbed by Weichselian iceberg ploughing (Lien & Myhre 1977, Vorren et al. 1982). 2: These shelf areas are adjacent to land areas which are under consideration as possible non-glaciated areas during the Weichselian (Ahlmann 1919, Undås 1938, 1967, Grønlie 1941, Dahl 1955, Bergstrøm 1973, Ives 1975).

Physiographic setting

The main bathymetric features of the investigated area (Fig. 1) are two glacial troughs, Malangsdjupet and Andfjorden, with maximum depths of 455 and 505 m, respectively. The area in between comprises a shallow bank, Sveinsgrunnen, with depths less than 100 m.

The bedrock on the shelf comprises Mesozoic and Tertiary sedimentary rocks while older crystalline rocks occur along the coast and on land (Fig. 1).

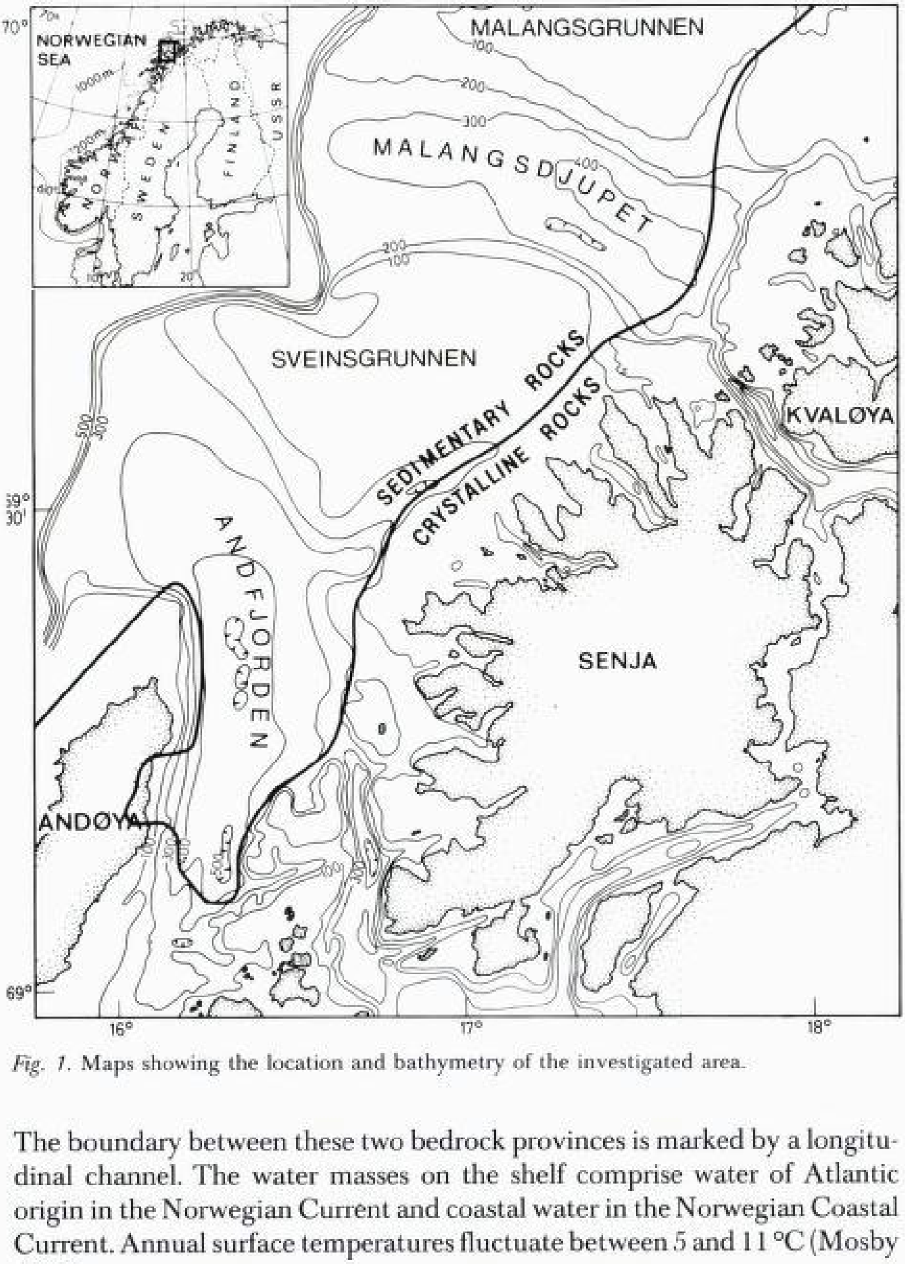

Fig. 1. Maps showing the location and bathymetry of the investigated area.

The boundary between these two bedrock provinces is marked by a longitudinal channel. The water masses on the shelf comprise water of Atlantic origin in the Norwegian Current and coastal water in the Norwegian Coastal Current. Annual surface temperatures fluctuate between 5 and 11 °C (Mosby 1968).

Material and methods

Altogether 120 gravity cores (inner diameter 100 mm) have been sampled and investigated by us (Fig. 2). At several of the sampling stations two or more cores have been recovered in order to achieve good stratigraphic control and partly to get enough material for radiocarbon dating.

The cores were split in two parts at the laboratory. Various geotechnical

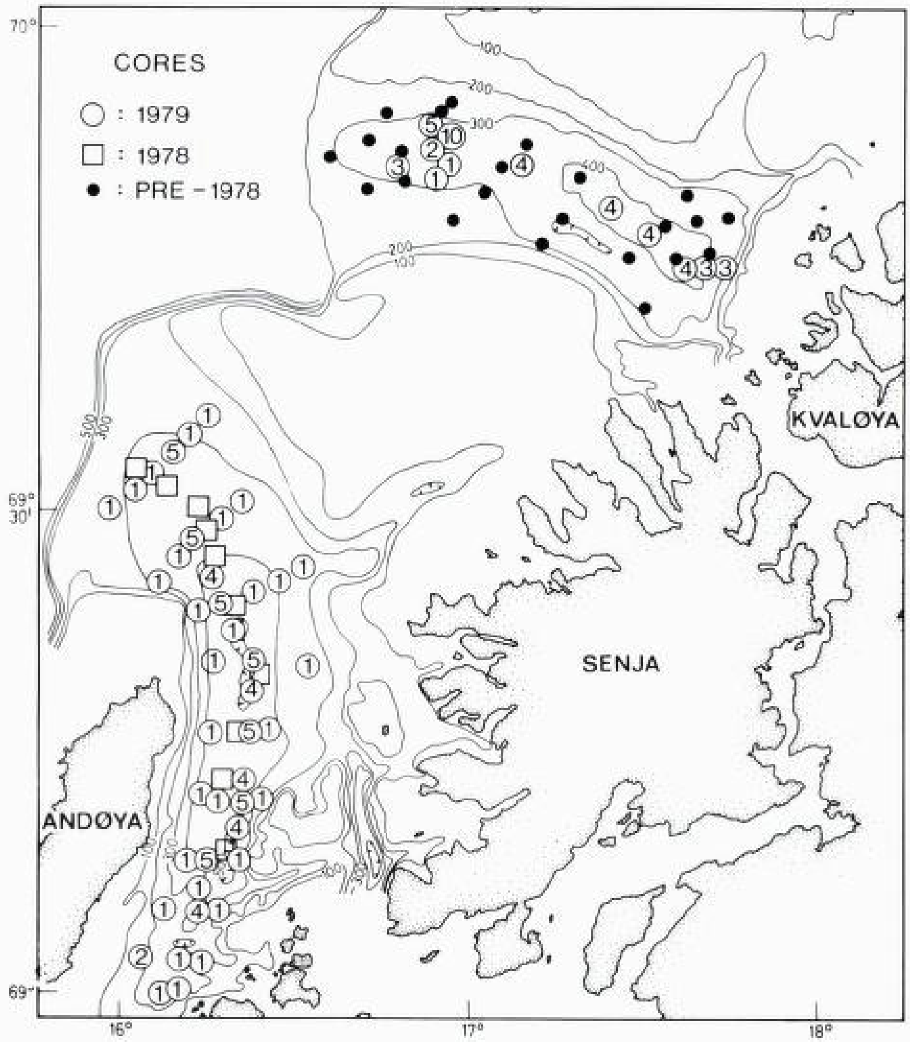

Fig. 2. Station map. Number of cores from each 1979-station is indicated. Only one core was recovered from each 1978 and pre-1978 stations. The pre-1978 cores are described by Elvsborg (1979).

and sediment-petrographical investigations were carried out: colour-determination using Munsell Color Charts; water content; shear strength by fall-cone test (Hansbo 1957); granulometric analysis by wet sieving and pipette analysis; carbonate content by gasometric analysis (Gross 1971); clay mineralogy by XRD and 'pebble' counts on the fraction 1–2 mm. A useful parameter for differentiating between various types glacigenic sediments and to quantify the ice drop activity was the number of lithoclasts in the 1–2 mm grade per 100 g dry sediment (Vorren et al. 1982).

The studies of the seismic stratigraphy are based on sparker profiles kindly put at our disposal by the Norwegian Continental Shelf Institute. The profiles have previously been described by Bugge & Rokoengen (1976).

Seismic stratigraphy

The greatest thickness of Quaternary sediments is found at the mouth of the troughs and at some scattered locations on the inner part of the shelf according to Rokoengen et al. (1979) (Fig. 3A). Based on the seismic studies they infer three glacial units (Fig. 3B) which were related to three glacial terminal events. In our opinion many parts of their glacial units represent local thickening of the Quaternary deposits, e.g. erosional remnants, which cannot be related to terminal events.

We have paid particular attention to Andfjorden. Even with all the available profiles at hand we feel confident on only one terminal moraine complex. This moraine complex is located c. 50 km from the shelf edge (Figs. 4 and 5). We name this complex the Flesen moraine after some skerries to the east of the moraine complex. Another ridge complex, 20–25 km from the shelf edge, is located on the eastern side of the trough. This ridge-system may be end moraines deposited in front of a glacier moving north along Andfjorden, or from a glacier moving westwards from Senja, or it may represent slide deposits. Additional data are needed before the genesis of this ridge system can be safely interpreted.

The thickness of the total postglacial glaciomarine/marine sediments in Andfjorden has been mapped (Fig. 4); a maximum thickness of about 50 m has been registered. This seismic sequence is characterized by parallel internal reflectors and a smooth surface. It should be noted that the sequence

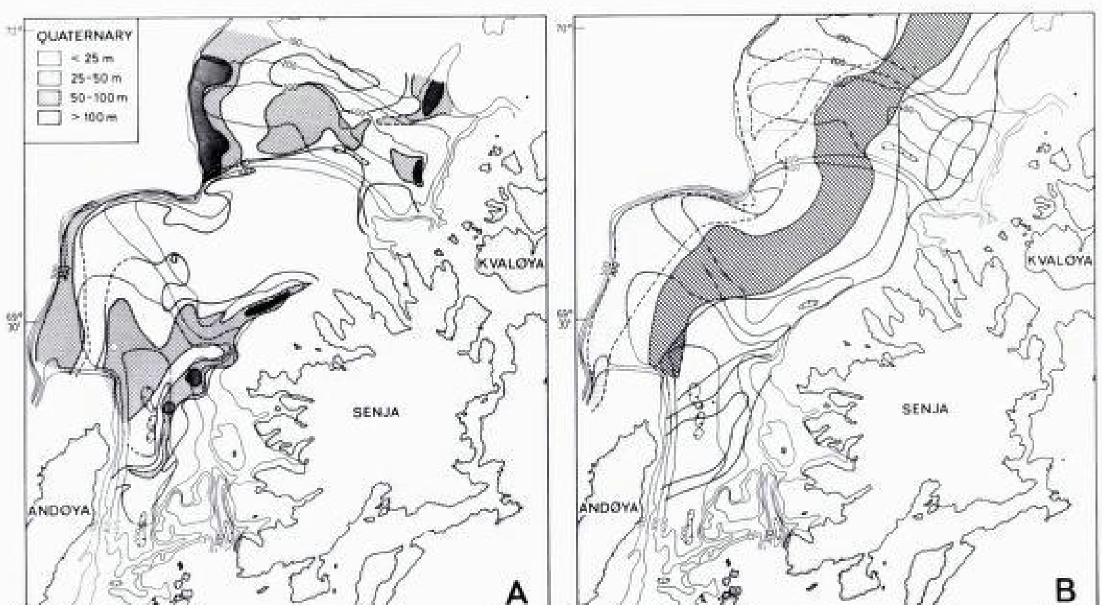

Fig. 3. A: Thickness of Quaternary sediments in milliseconds two-way travel time (equals metres if seismic velocity is 2000 m/sec). B: Glacial units. – After Rokoengen et al. (1979).

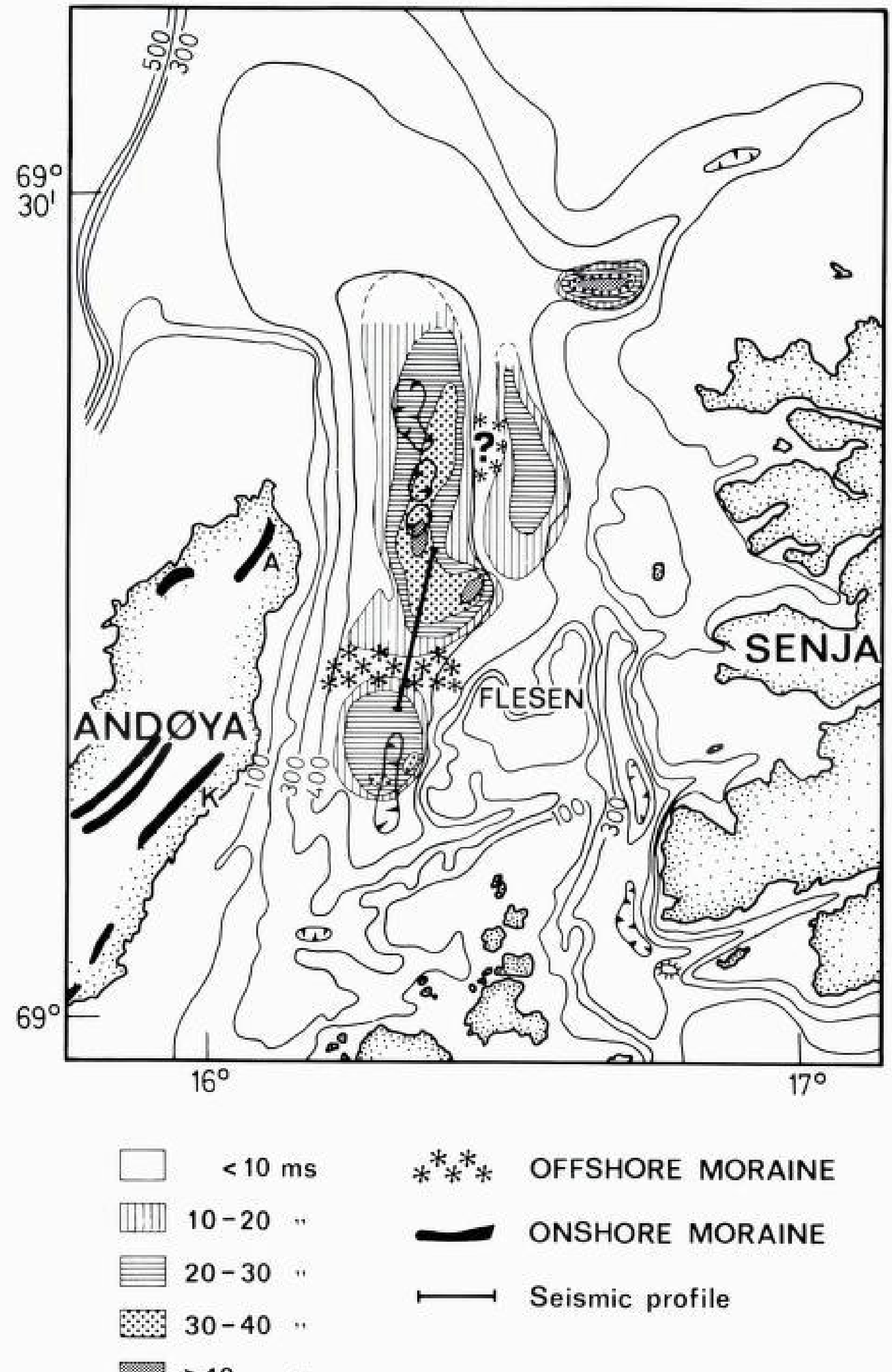

Fig. 4. Thickness of the postglacial glaciomarine/marine sediments in Andfjorden in millisecond two way travel time. Position of the submarine Flesen moraine and the questionable moraine (?) are indicated. The A and K denotes the Aeråsen moraine and the Kirkeraet ridge, respectively. Position of profile shown in Fig. 5 is indicated.

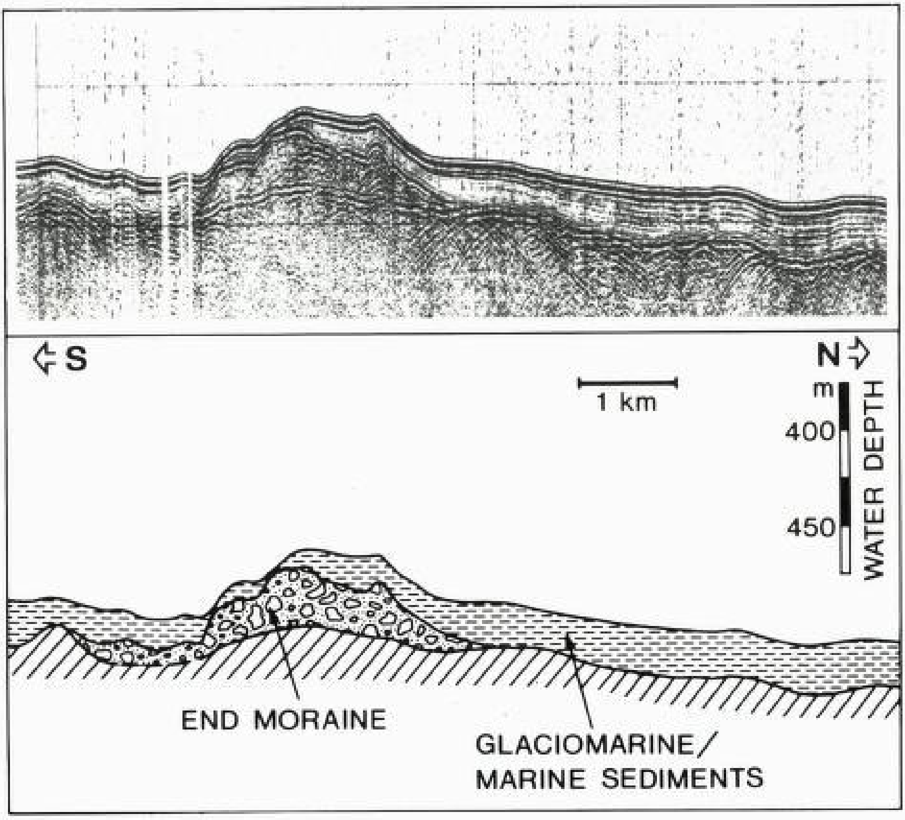

Fig. 5. Seismic (sparker) profile, with interpretation, across the Flesen moraine. Location is shown in Fig. 4.

overlies the Flesen moraine (Fig. 5) but thins on the proximal flank. The low boundary of the sequence is probably diachronous, becoming progressively younger towards the south. In the outer and marginal part of Andfjorden the sequence is lacking. This is partly due to bottom current erosion.

Lithostratigraphy

A generalized composite stratigraphy based on cores from the outer and central part of Andfjorden show nine lithostratigraphic units (Fig. 6). The same stratigraphic units, except units tG and tH, are found in Malangsdjupet. In the following a brief description and interpretation of the lithostratigraphic units is given; a more comprehensive discussion is given in Vorren et al. (1982).

The unit tA subcrop map (Fig. 7), indicates that units lying directly beneath unit tA become progressively older seawards. Thus there exists a hiatus of increasing length seawards (and towards the basin margins) between the late Holocene tA unit and underlying units. This situation has

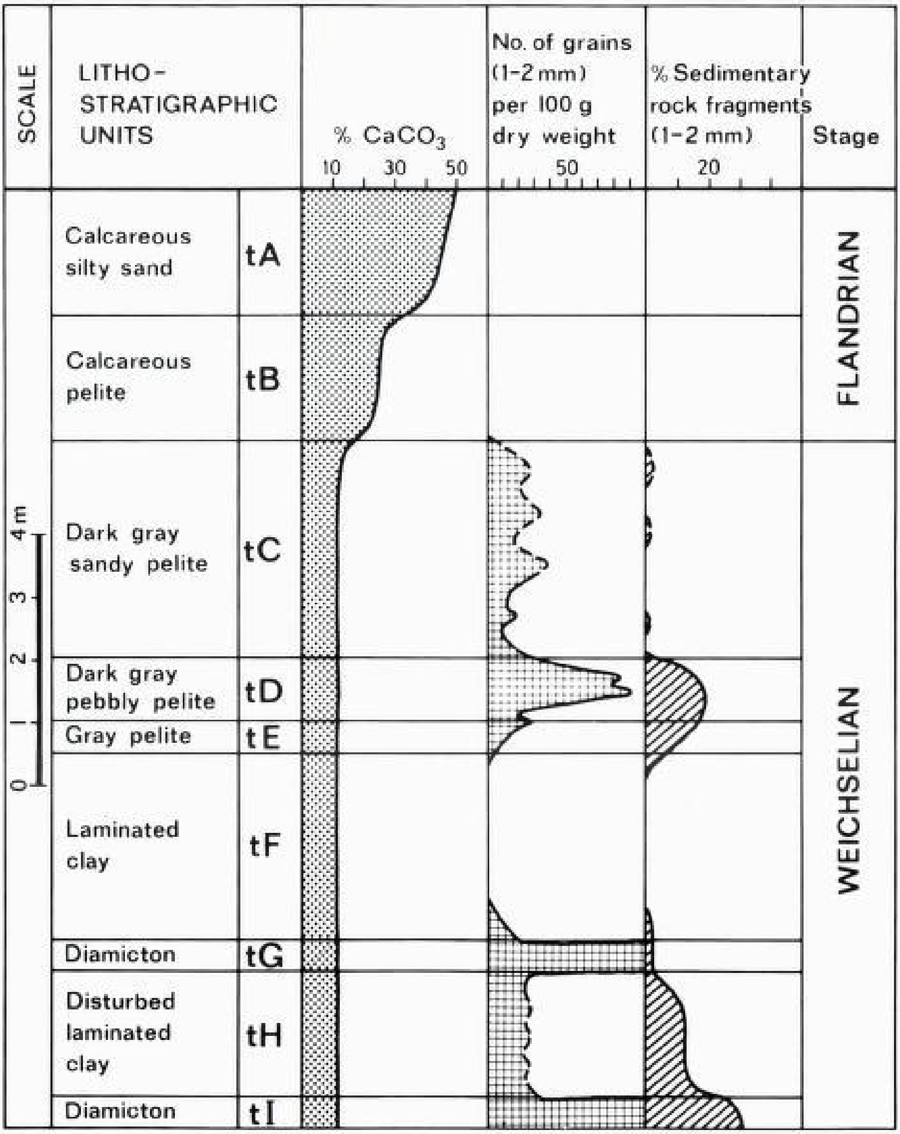

Fig. 6. Generalized composite lithostratigraphy of the upper beds in the outer and central reaches of Andfjorden.

given us the opportunity to construct a rather long stratigraphy based on only 5 m long cores. However, in most of the deeper parts of the throughs the Holocene sequence is so thick that we are not able to recover Weichselian sediments.

The window with unit tC sediments west of Flesen must be due to local thinning of the Holocene sequence over the Flesen moraine ridge (Fig. 5 and 6). The diamictons in the outer parts of Andfjorden and Malangsdjupet are represented by the tI and tG-units. In the inner parts of Andfjorden the diamictons are of a different composition.

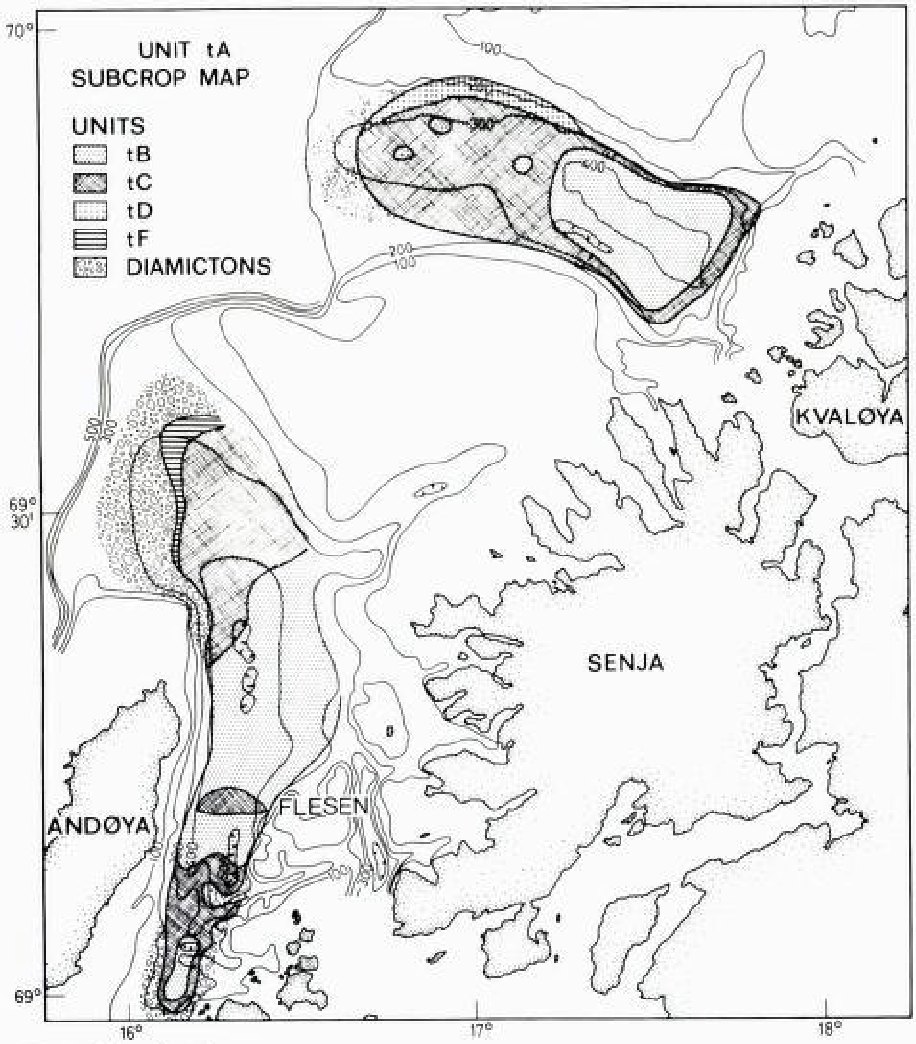

Fig. 7. Unit tA subcrop map.

Unit tI is a very dark grey diamicton. The upper boundary which is sharp, is sometimes represented by a sandy gravelly horizon. The low water content (15–20%) and the shear strength indicate overconsolidation. Macrofossils of boreo-arctic species occur as fragments, many of which are abraded. We are fairly certain that unit tI represents a true basal till.

Unit tH is a disturbed laminated clay found in outer Andfjorden. It is overlain by unit tG which is a dark grey diamicton. Compared with unit tI, unit tG contains less lithoclasts and has lower frequencies of sedimentary rocks. Like unit tI, unit tG only contains transported macrofossils. We believe that the most likely genesis of unit tG is as a basal till, although a proximal glaciomarine deposit should not be totally ruled out.

Unit tF is a (dark) olive-grey laminated clay. The maximum thickness found in the cores is 74 cm in Malangsdjupet and 195 cm in Andfjorden. The natural water content is 28–35% and the shear strength is normally between 0.4 and 1.0 t/m^2. The clay and silt which predominates in the grain-size composition is probably derived from suspension.

Ice-rafted grains occur only in the lower and upper part of this unit in Andfjorden. No macrofossils are found and the foraminiferal assemblage is characterized by a very low number of specimens per gram sediment. Taxa that at present are restricted to polar shelf areas dominate the lower part of unit tF, whilst there is an increase in the cosmopolitan *C. laevigata* upwards. The undisturbed lamination and the foraminiferal assemblage indicate a reatricted benthic fauna reflecting rather unfavourable ecological conditions. The fine texture indicates a low energy regime. We thus interpret these sediments as having been deposited in an environment which was covered with sea-ice, at least seasonally.

Unit tE is a 20–40 cm thick, light-coloured marine clay. The boundary with unit tF is transitional; it is placed where lamination is no longer visible. Unit tE resembles tF, except for a slightly higher dropstone content, and a massive structure. The massive structure, we believe, is the result of bioturbation. Small pectinids and sponge spicules occur, indicating a more diverse fauna than in tF-time.

Unit tD is a very dark grey pebbly pelite. The boundary with tE can be seen by a colour change. The thickness is 60–70 cm in Malangsdjupet and 70–90 cm in the outer reaches of Andfjorden, increasing shorewards to at least 190 cm. In the outer reaches this unit is massive; in the middle reaches it contains scattered light-coloured laminae; and in the inner reaches it is weakly bedded and laminated. The natural water content is 38–35% and the undrained shear strength about 0.7 t/m^2. This unit is characterized by a relatively high content of dropstones and by a high frequency of sedimentary rocks among the clasts in the outer reaches, decreasing southwards in Andfjorden.

Yoldiella spp., and the low saline indicator *Elphidium excavatum* (Smith 1970, Ellison & Nichols 1976) dominate the macrofauna and microfauna respectively. We believe that the tD-unit was deposited in a cold, near-glacier environment with a high iceberg influx.

Unit tC is a very dark grey sandy pelite. The lower boundary in some cores is marked by a thin (<0.5 cm) sandy layer/lens, but mostly it is barely visible. The boundary is defined by a minimum in dropstone content which is also the level at which sedimentary rock clasts almost disappear. Scattered lenses of sand and burrows occur frequently in this unit. Turbidites are found in the high relief parts of the inner reaches. Generally this unit contains fewer dropstones than tD and has a higher sand content which increases upwards. The natural water content is 25–35% and the shear strength 0.4–1.5 t/m^2 *Bathyarca glacialis* is a characteristic pelecypod and *Cassidulina reniforme* and *Nonion labradoricum* dominates the foraminifera assemblage. These species have at present an affinity for polar waters. We interpret the tC-unit as having been deposited in an iceberg environment, but with water masses being more temperate and dynamic than during tD-time.

Unit tB and tA comprise Holocene calcareous mud and sand, rich in shells of boreal molluscs and foraminifera reflecting the present hydrographic conditions. In the outer reaches unit tB is missing. The older part of the Holocene there is represented by a winnowing period with lag development.

Age

Radiocarbon dates have been obtained from units which contain macrofossils in sufficiently large quantities. These dates number 19 from the pre-Holocene units in the 1979 cores (Fig. 8 & Table 1). In order to obtain sufficient dating material some samples had to be taken from several cores. The cores were then very carefully correlated assuring that the material was recovered from corresponding stratigraphic levels. The dates fall in two distinct groups; between 10.000 YBP and 14.000 YBP and older than 36.000 YBP.

Fifteen of the dates are from material from unit tC. The two dates T-3634 and T-4035 are from material close to the lower boundary while T-3637 is close to the upper boundary. These date unit tC to between 10.000 and 13.000 YBP.

Three dates were obtained from unit tD. Dating T-3638 ($37.580 \pm ^{2210}_{1720}$) is from a crushed and abraded, obviously resedimented fragment of *Mya truncata*. The dated material from Malangsdjupet (T-3234) is collected from several cores, some of which had a very thin (or missing) overlying tC-unit. The age is definitely too young, possibly due to burrowing of more recent fauna into the underlying unit tD. The T-3633 dating accords with the dates from unit tC. The high standard deviation is due to the small sample size. An estimate of the sedimentation rate suggests that the lower boundary of unit tD is about 14,000 years old.

Dates from unit tI, T-3511, $36{,}760 \pm ^{1870}_{1510}$ and T-2499, $38{,}850 \pm ^{4070}_{2780}$ (Elvsborg 1979), if they represent finite ages, indicate that the glacier advanced over the outer shelf area after approximately 36,000 YBP.

The ages of the undated units tE, tF, tG and tH can only be estimated. The sedimentation rate seems to have been higher for unit tE and especially for tF than for the overlying units. As a rough estimate we believe that tE and tF were deposited within a period of a thousand years or so.

The interpretation of unit tG as a basal till implies that the lower boundary is a priori an erosional unconformity representing a hiatus of unknown length. The sandy-gravelly layer on top of this unit may represent a period of winnowing and, thus, also this boundary represents a hiatus of unknown length. This interpretation is supported by the presence of an up to 50 m-thick postglacial glaciomarine/marine sequence of mostly pre-tE sediments in the inner part of the trough (Fig. 4). Either the sedimentation rate must have been much higher in the inner parts during tF-time, or another possibility is a period during pre tE-time with erosion/non-deposition in the outer areas and sedimentation in the inner areas.

Table 1. Radiocarbon dates of pre-Holocene fossils from cores recovered from Andfjorden and Malangsdjupet in 1979. The T-number denotes the Trondheim-laboratory number.

No.	Core	Fossils	Weight	% Dated	Unit	YBP
T-3233	2-9	Astarte cf. crenata	2,4	90%	tC	11 820 ± 340
T-3234	2-3, 10	Y. intermedia, N. pernula				
		Y. lenticula, Scaphopoda indet	3.0	90%	tD	12 150 ± 340
		B. glacialis				
T-3390	56-1, 2, 3 & 4	B. glacialis, N. pernula	3.9	90%	tC	11 250 ± 270
		Astarte sp., Thyasira sp.				
		Scaphopoda indet, Y. intermedia				
T-3388	56-1 & 2	B. glacialis	1.8	90%	tC	12 430 ± 620
T-3389	56-1	Astarte cf. crenata	4.2	90%	tC	12 380 ± 270
T-3511	2-3, 4, 5, 7, 8, 9, 10,	Shell fragments	13.–	80%	tI	36 760 $\pm\frac{1870}{1510}$
	3-1, 2, 4-1, T-5-1					
T-3633	15-1, 2, 3, 4 & 5	Y. intermedia, Y. lenticula	1.3	95%	tD	13 630 ± 1250
T-3634	15-1, 2, 3, 4 & 5	Ophiura sp., Yoldia sp.	1.7	95%	tC	12 910 ± 420
	17-1	B. glacialis, N. pernula				
		Lunatia sp.				
T-3635	51-3	B. glacialis	1.8	95%	tC	12 320 ± 350
T-3636	51-4	B. glacialis	1.7	95%	tC	10 940 ± 390
T-3637	25-3	A. cf. crenata, B. glacialis				
		Y. lenticula, N. minuta	1.2	95%	tC	10 240 ± 510
		N. pernula, Ophiura sp.				
T-3638	9-1	M. truncata	6.1	90%	tD	37 580 $\pm\frac{2210}{1720}$
T-4030	33-1	B. glacialis	1.6	95%	tC	11 310 ± 280
T-4029	33-1	B. glacialis	3.2	90%	tC	12 140 ± 310
T-4033	33-1	B. glacialis, N. pernula	1.8	90%	tC	12 200 ± 350
T-4034	33-2	B. glacialis	1.1	95%	tC	11 240 ± 430
T-4035	33-4	B. glacialis	2.0	90%	tC	13 050 ± 350
	33-4					
T-4032	33-5	B. glacialis	2.8	90%	tC	11 920 ± 280
T-4031	31-1	B. glacialis	1.5	95%	tC	11 080 ± 380

Discussion and conclusions

Based on the results of the lithostratigraphic and seismic study we have constructed a tentative time-distance diagram (Fig. 9). Focusing on Andfjorden where the stratigraphy is most complete; four (or possibly five) glacial events can be discerned. They are represented by: two tills (the tI and tG-events), one (two) end moraine; (the Flesen and (?) events) and the glaciomarine unit tD (the D-event). These events are discussed briefly below and tentatively correlated with the terrestrial moraines on Andøya. Several people have contributed to the moraine studies on Andøya (Reusch 1903, Enquist 1918, Holmsen 1924, Undås 1938, 1967, Grønlie 1941, Møller & Sollid 1972, Bergstrøm 1973). It should, however, be noted that there is no general agreement, either on such fundamental questions as the genesis of the accumulations, or on correlation and chronology.

At the time of deposition of the tills tI and tG, the continental ice sheet probably reached the shelf edge. How far the ice front receded during the

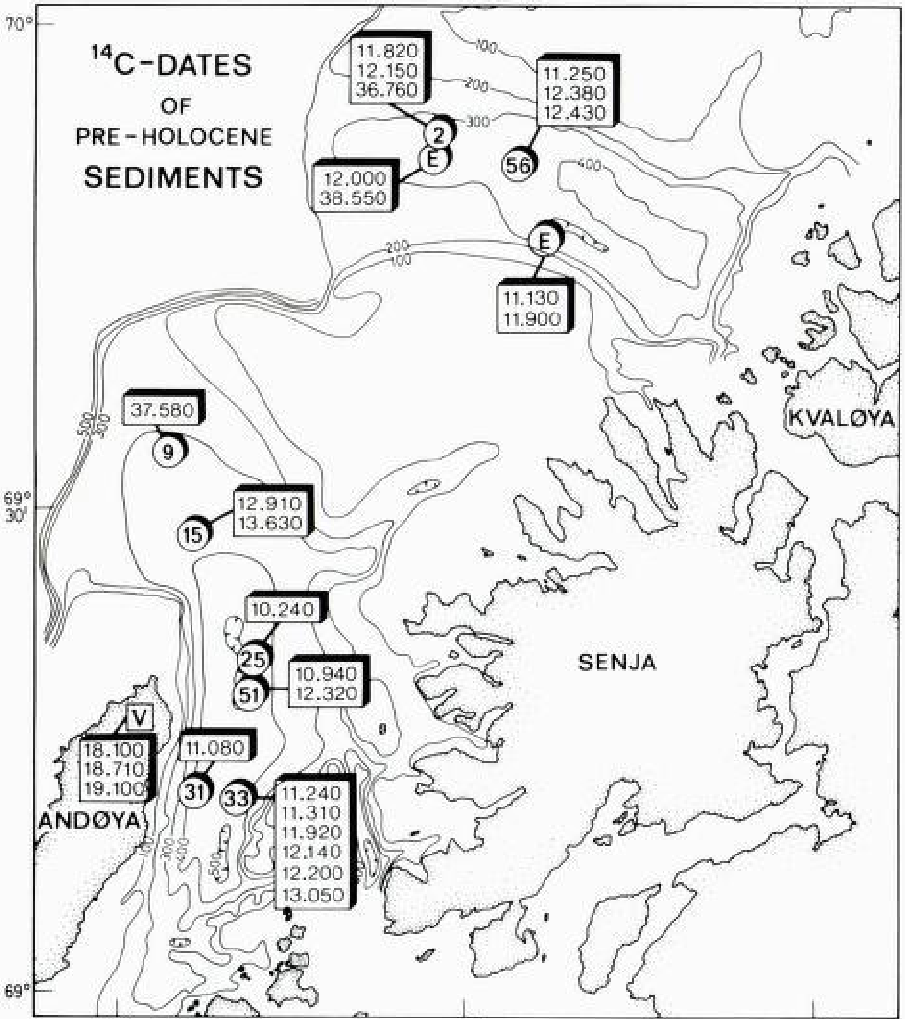

Fig. 8. Radiocarbon dates of Late Weichselian and older continental shelf sediments, cf. Table 1. The E-localities in Malangsdjupet are from Elvsborg (1979). The oldest postglacial dates onshore, V, are from K. D. Vorren (1978).

deposition of the laminated clay, unit tH, is unknown. According to the radiocarbon dates these two events must be older than c. 14,000 YBP and possibly younger than 36,000 YBP (if T-3511 and T-2499 are finite dates). Radiocarbon dates from the northern tip of Andøya (Fig. 8) indicate that this area was deglaciated before 18–19,000 YBP (K. D. Vorren 1978). It seems doubtful that the whole of Andfjorden could be glaciated without the ice sheet covering the northern tip of Andøya at the same time. Thus, the tI- and tG-events may also be older than 18–19,000 YBP. Another, slight possibility is that the tG-units are correlatable with the oldest indisputable continental end moraine on Andøya, namely the Aeråsen moraine (Fig. 4), which probably just predates the 18–19,000 YBP-dates (K. D. Vorren 1978).

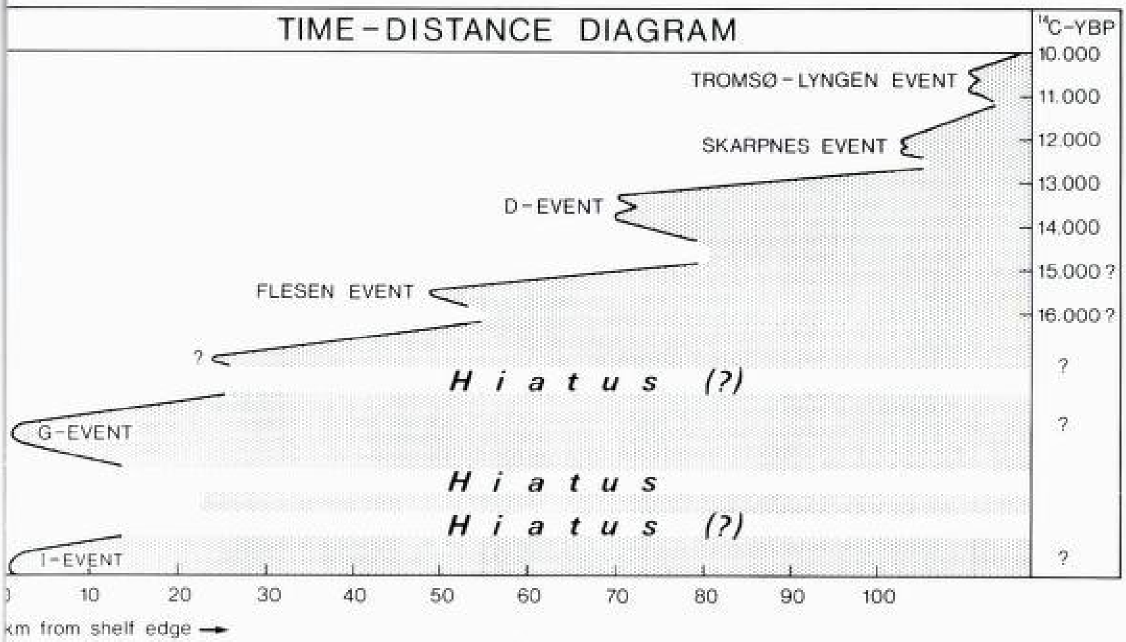

Fig. 9. Time- distance diagram for the margin of the continental ice-sheet in Andfjorden and adjacent shoreward areas.

Both the uncertain end moraine (20–25 km from the shelf edge) and the Flesen end moraine are overlain by unit tD-sediments. Thus the moraines must be older than c. 14,000 YBP. K. D. Vorren (1978) has recorded a cool event at c. 15,000–16,000 YBP. This may possibly be correlated with the Flesen event. The Flesen end moraine may possibly be correlated with the accumulation «Kirkeraet» on Andøya (Fig. 4). This accumulation is believed to be an end moraine by Holmsen (1924), Grønlie (1941) and Møller & Sollid (1972). Reusch (1903) and Bergstrøm (1973), however, interpret it as a shore phenomenon.

During later phases of deposition of unit tF and tE the ice front probably receded landward of the sedimentary/crystalline boundary (Fig. 1). This is indicated by a high content of land derived clay minerals in the upper part of unit tF and in unit tE. The extent of the continental ice sheet during the D-event is indicated by the dropstone composition. Large amounts of sedimentary dropstones in Malangsdjupet indicate that the ice sheet terminated beyond the sedimentary/crystalline boundary. The situation is somewhat more complicated in Andfjorden. There we find relatively high frequencies of sedimentary rock fragments in the outer part and very low frequencies in the inner part. The sedimentary rock fragments in Andfjorden must have been drifted in by icebergs from Malangsdjupet and elsewhere. Topographic conditions indicate that the ice margin may have halted at the submarine ridge system between Senja and Andøya and in the inner shallow part of Andfjorden. Possibly the end moraines on southern Andøya at Åse, Bjørnskinn and Bjørnskinnsmyra (Møller & Sollid, 1972, Bergstrøm 1973) may correlate with the D-event.

Two glacier advances marked by pronounced end moraines in the fjord areas have been dated to 12,500–12,000 YBP (Skarpnes event) and 11,000–10,000 YBP (Tromsø–Lyngen event), respectively (Andersen 1968, Vorren & Elvsborg 1979).

Acknowledgements. This paper is a contribution to the IGCP-Project 'Quaternary Glaciation in the Northern Hemisphere' which is financially supported by the Norwegian Council for Science and the Humanities. The radiocarbon datings were carried out at the Laboratory of Radiologic Dating, Trondheim, under the supervision of Dr. R. Nydal and siv.ing. S. Gulliksen. The seismic profiles were put to our disposal by K. Rokoengen, the Continental Shelf Institute, Trondheim. M. Raste and M. Berntsen did much of the laboratory analysis. The figures were drawn by H. Falkseth. To all these persons we offer our sincere thanks.

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