A climatic record for the last 12,000 years from a sediment core on the Mid-Norwegian Continental Shelf

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The local depositional environment in Late Weichselian and Holocene time is inferred from investigations including sedimentology, geotechnical properties, biostratigraphy, stable isotopes and radiocarbon dates from a 265 cm long vibrocorer sample from 165 m water depth at 64°59′N and 9°14′E. The lower part of the core is interpreted to be extensively remoulded by iceberg scouring, while the top 160 cm gives a continuous record for the last 12,000 years. Three radiocarbon dates and a volcanic ash zone (Vedde Ash Bed) provide ages ca. every 600 years for the period 12,000 to 10,000 years BP. Minimum content of boreal foraminifera (representing the most arctic conditions) occurred from before 12,000 to about 11,800 and from 11,000 to 10,400 years BP. The transition from arctic to boreal conditions is very marked at about 10,300 ± 200 years BP. Later minima of boreal foraminifera (colder events) are recorded around 10,000 to 9000 years BP, with variations shorter than the time resolution. The core provides a detailed record during the deglaciation period of Scandinavia after 12,000 years BP, and shows good correlation to land data. The upper part of the core, representing the last 9000 years, shows maximum content of the boreal *Trifarina angulosa* (optimal climatic conditions) around 5000 years BP and then decreasing values up to present time.

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The purpose of this paper is to present and discuss the studies of sediments, foraminiferal faunas and stable isotopes in a vibrocorer sample (B78-2/2) taken from 165 m water depth at Viknaryggen (64°59′N, 9°14′E) northeast of Haltenbanken off Trøndelag, Mid-Norway (Figs. 1 & 2). The core was selected for detailed investigation because of its exceptionally good potential for radiocarbon dating control and its fairly high sedimentation rate in Late Weichselian time, providing good time resolution.

The sediments and benthonic foraminifera in the core were described by Løfaldli & Rokoengen (1980), who also presented faunal lists for all subsamples. Later, the planktonic foraminifera were studied in more detail by Skarbø and oxygen and carbon isotope measurements were performed by Erlenkeuser.

The study area

The main topographical features in the study area are shown in Fig. 1. The two large banks, Sklinnabanken and Haltenbanken, with minimum water depths of about 140 m and 90 m respectively, are separated by a northwest–southeast trending channel. Viknaryggen forms a ridge or spur extending northeastwards from Haltenbanken into this channel (Fig. 2). The minimum water depth is 140 m and the ridge is surrounded by water depths exceeding 200 m.

Near the coast the seabed topography is very irregular due to the outcropping crystalline rocks extending some distance offshore from mainland Norway. Further offshore the crystalline rocks are overlain by sediments of Mesozoic and Tertiary age (Bugge et al. 1984; Rokoengen et al. 1988).

The thickness of Quaternary deposits exceeds 200 m below the highest part of Viknaryggen (Rise et al. 1988). Based on the interpretation of shallow seismic records, the whole ridge is believed to consist of morainic material with an average seismic velocity calculated to 1800 to 2000 m/s (Bugge et al. 1978). A sample from the top of the ridge (B77-112/1, Fig. 2), below 5 cm of gravel, consists of a clay with silt, sand and gravel and has a shear strength of about 70 kN/m^2. This sediment is interpreted as a till, thus supporting the seismic data.

The surface of Viknaryggen has been subject to heavy scouring by icebergs (Lien 1983). The till is covered by irregular patches and pockets of soft younger material and the selected core is believed to have been taken from one of these sediment pockets (Løfaldli & Rokoengen 1980).

Many of the topographic features found on the Norwegian Continental Shelf are characteristic of glaciated areas, as already pointed out by Nansen (1904) and Holtedahl (1940). Holtedahl (1955) concluded that the inland ice had reached the shelf edge during the last glaciation. Opinions are divided regarding the age of the deposits and the timing of the deglaciation of the

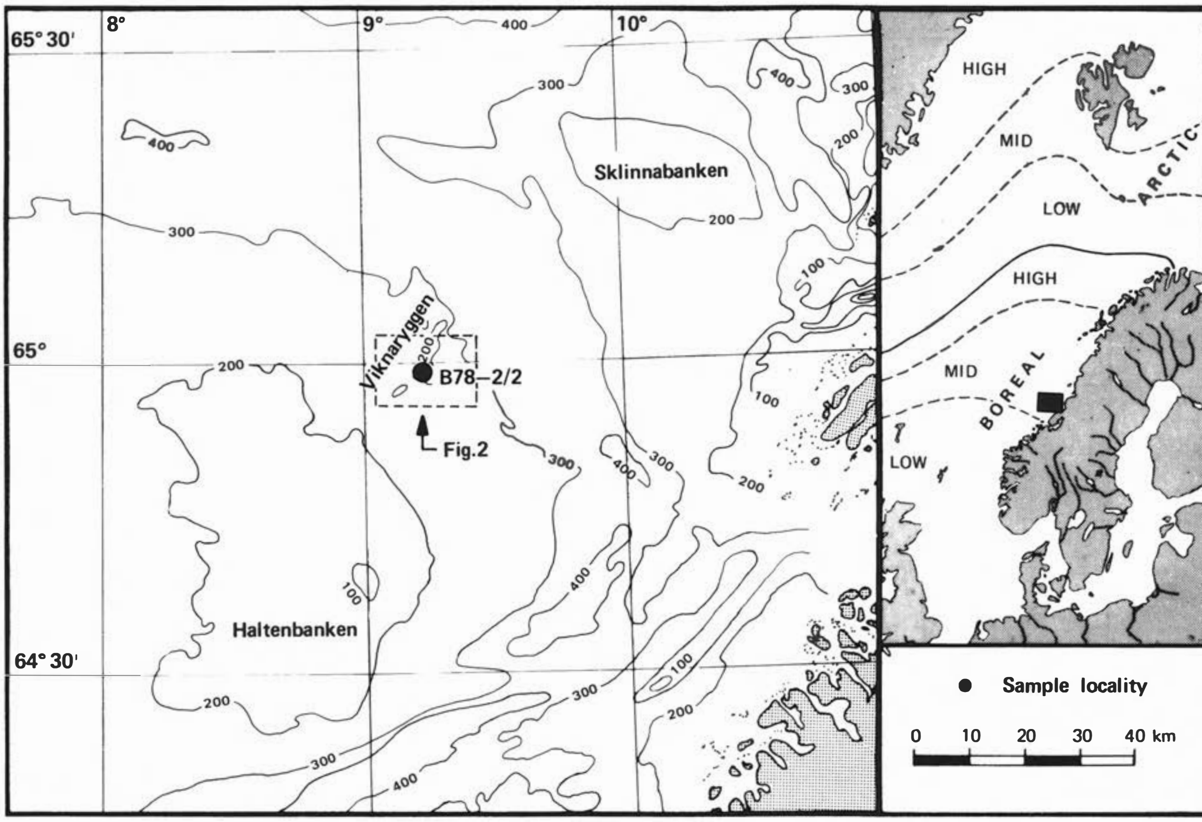

Fig. 1. Location map. Depth contours (meters) based on soundings by the Hydrographic Office of Norway. Present distribution of arctic and boreal fauna after Feyling-Hanssen (1955).

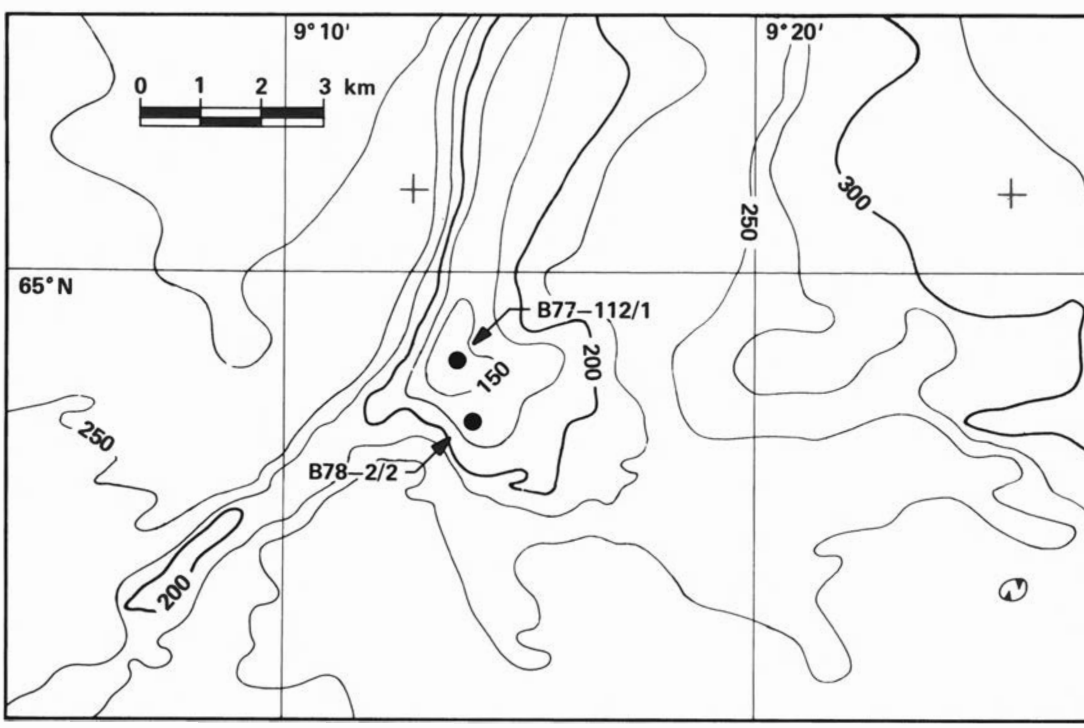

Fig. 2. Bathymetric chart showing Viknaryggen with sample localities.

continental shelf. Andersen (1979b) suggested an age of about 20,000 years for the large moraines on the shelf edge, while investigations by Rokoengen (1979) and Bugge (1980) indicate an age as young as 13,000 years BP for the last ice extension to the shelf edge.

The frontal zone between the Norwegian Current (NC) water masses, with salinities (S) > 35‰, and the Norwegian Coastal Current (NCC; S < 35‰) water masses is highly variable both in position and time. The less saline water of the NCC may spread out far to the west, or may be constricted to a comparatively narrow zone along the coast. On the broad outer shelf off Mid-Norway, the NCC water layer is usually thin (<100 m), and NC water constitutes the bottom water on most of the shelf (Rey 1981; Johannessen 1986). At Haltenbanken, the present current conditions in winter appear to be a clockwise circulation around the bank with a central cone of almost stationary water (Eide 1979).

In Late Weichselian time the water depth on Haltenbanken was considerably less than today, and it is also likely that the current conditions were different.

Core description and datings

Lithologically, core B78-2/2 can be divided into four main units, I–IV (Fig. 3).

The lowermost unit, IV (265–160 cm), consists of a clay with silt, sand and gravel. It is soft with an undrained shear strength of 10 kN/m^2, but contains lenses of firmer material. The remoulded shear strength at 260 cm is 2 kN/m^2, which gives a sensitivity (undrained shear strength divided by remoulded shear strength) of 5. The liquid limit is 25.4%, the plasticity index 12.6% and the natural water content is very close to the liquid limit.

The geotechnical properties show that the sample has not been overconsolidated by thick ice. The lowermost unit has a grain size distribution resembling glaciomarine clays found in other areas on the Norwegian Continental Shelf (Gunleiksrud & Rokoengen 1980; Bugge 1980; Vorren et al. 1983). The origin of the material could be iceberg scouring and mixing of materials on the sea bottom.

The next unit, III (160–155 cm), consists of a gravelly sand. This coarse layer could represent a lag from an erosional event or ice dropped material. The lithic component of the gravel fraction is, as in the rest of the core, totally dominated by crystalline rocks.

Unit II, above the gravelly sand, consists of 60 cm of silty, sandy clay (155–95 cm) containing layers rich in macrofossils (Fig. 3). The lithic content of sand and gravel is lower than in the underlying clay, and the grain size distribution resembles the glaciomarine clays or soft sensitive clays found on the Norwegian Continental Shelf.

Traces of volcanic ash are found in the subsample at 105 cm, and ash is common at 110 cm, but not found below. Considering resedimentation and bioturbation, the primary ash zone is believed to be situated at or just below 110 cm. The ash layer is correlated with the Vedde Ash Bed found in western Norway and dated to 10,600 ± 60 years BP (Mangerud et al. 1984).

Unit I, at the top of the core (95–0 cm), in contrast to the lower part, is mainly composed of sand and gravel with only about 20% silt and clay. It also contains a zone with abundant macrofossils from 95 to 70 cm (Fig. 3), but in the top 40 cm only fragments of macrofossils are found.

Four levels have been radiocarbon dated in core B78-2/2 (Fig. 3 and Table 1). Following the procedures of Gulliksen (1979) the standard deviations were kept as low as ±100 to 110 years. A crucial point is whether or not the dated material is of the same age as the sediments in which it is found. The good preservation of the dated macrofossils indicates that they could only have been transported a short distance. Thus we assume that they have ages very close to the time of sediment deposition.

The foraminiferal sand at 20 cm might contain older reworked material or younger material could have been added by bioturbation. Neither of these processes seems to have been very active, and the date is assumed to represent the depositional age.

In core B78-2/2, the average sedimentation rate during the last 11,800 years was 1.3 cm/100 years. The average sedimentation rate in the intervals between radiocarbon datings shows a marked decrease with time (Table 2). The range is estimated by assuming an uncertainty of ±5 cm in the position of the dated sample, and one standard deviation in the ages.

To estimate the age of the sediments between the dated levels, an interpolation must be made. Two methods: linear interpolation and interpolation based on inferred sedimentation rate, have been used between the five dated levels and are compared in Fig. 3.

The linear interpolation is the simplest and most used method. This scale is also used in Figs. 5, 6 and 7 and in the following discussion.

The ages can also be estimated from sedimentation rate based on abundance of foraminifera (see Fig. 4 below), assuming constant production and preservation between pairs of dated levels.

In the well-dated interval between 12,000 and 10,000 years BP the difference between the two scales is up to 200–300 years. Both interpolation methods introduce possible errors that, together with the standard deviation of the datings, will give an uncertainty of at least ±200 years and possibly more even in this relatively well-dated core. In the following discussion quoted ages have an accuracy of ca. ±200 years.

Below 160 cm the calculated sedimentation rates become very high, but due to lack of radiocarbon dating control, the ages are only tentative (Fig. 3). Linear extrapolation (assuming a constant sedimentation rate) would give an age of about 14,000 years BP at the base of the core. Our judgement is that 12,000 years BP is closer to the correct value. It should therefore be stressed that linear extrapolation downwards in glacial cores, where depositional rates can be very high, may give far too old ages.

In most areas on the Norwegian Continental Shelf with water depths less than 150 m, the net deposition the last 10,000 years has been much less than in core B78-2/2 (Vorren et al. 1978; Rokoengen et al. 1979; Sejrup et al. 1981; Hald & Vorren 1984).

In core B78-2/2 the sedimentation rate is also high compared to deep sea cores and the effects of bioturbation, which is a severe problem in the deep sea (e.g. Kellog et al. 1978; Ruddiman 1977; Ruddiman &

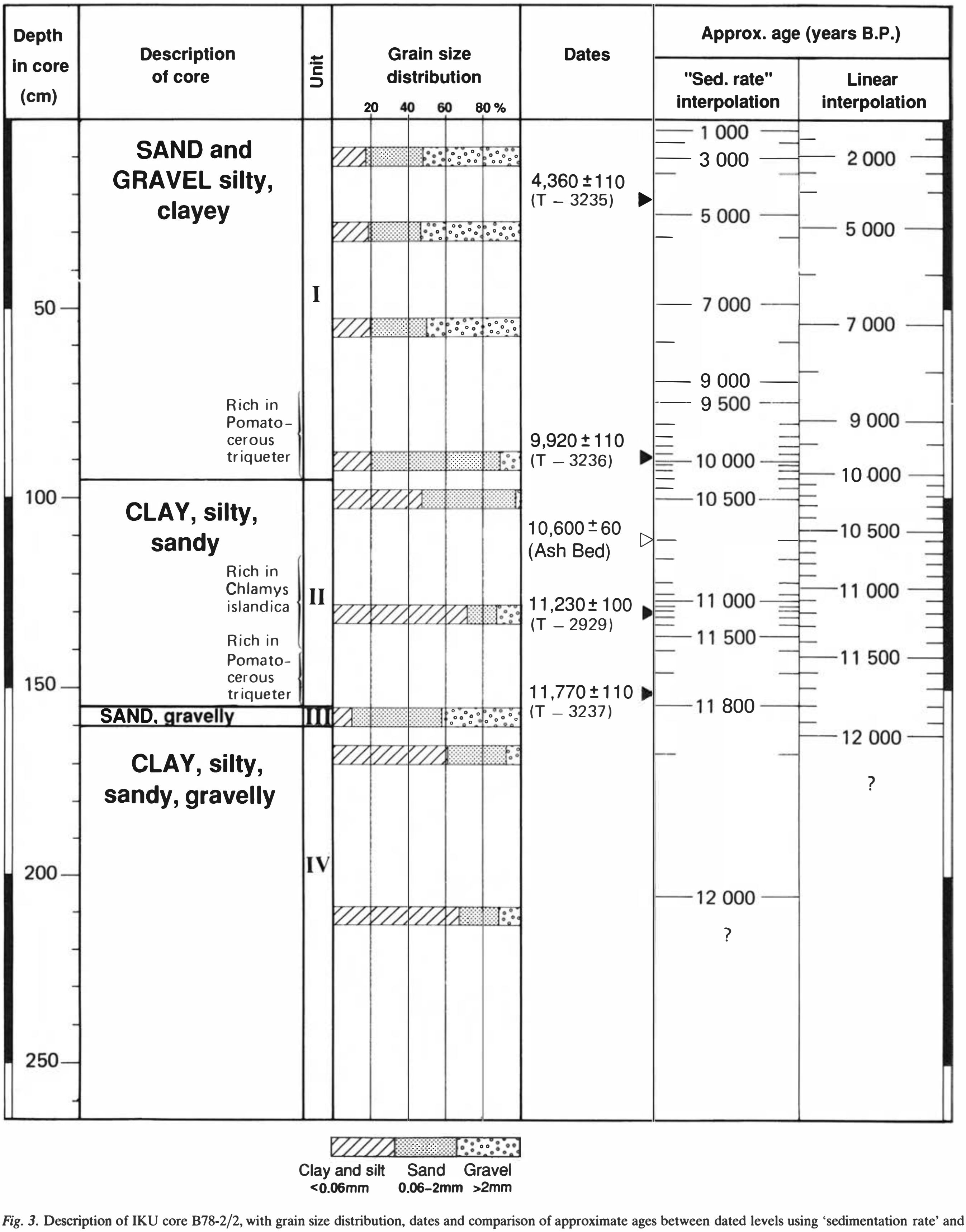

Fig. 3. Description of IKU core B78-2/2, with grain size distribution, dates and comparison of approximate ages between dated levels using 'sedimentation rate' and 'linear' interpolation (see text for explanation).

Table 1. Radiocarbon dates in core B78-2/2.

Depth below sea bed (cm)	Sample material	Sample weight (g)	Lab. ref.	Radiocarbon date (years BP)
20	Foraminiferal sand	88.0	T-3235	4,360 ± 110
90	Pomatoceros triqueter etc.	22.5	T-3236	9,920 ± 110
130	Chlamys islandica	20.0	T-2929	11,230 ± 100
150-155	Pomatoceros triqueter, Chlamys islandica etc.	24.0	T-3237	11,770 ± 110

Table 2. Net sedimentation ranges in core B78-2/2 between radiocarbon dated levels.

Interval cm	Length cm	Interval years	Sedimentation rate cm/100 years Average (Range)
0–20	20 ± 5	4,360–present	0.45 (0.3–0.6)
20–90	70 ± 5	9,920–4,360	1.25 (1.1–1.4)
90–130	40 ± 5	11,230–9,920	3.1 (2.3–4.1)
130–152	22 ± 5	11,770–11,230	4.1 (2.3–8.2)
160–265	105 ± 5	12,000(?)–11,770	>50(?)

McIntyre 1981), are minimized and resolution greatly increased. Detailed variations are recorded in both foraminiferal faunas and isotopic composition in core B78-2/2 (Figs. 4, 5, 6, 7). Between 160 and 80 cm the sampling interval used for foraminifera was 5 cm with 1 cm thick samples. Single points will represent events of approximately 200 years duration or less varying with rate of deposition. It is evident that an investigation with a higher sampling interval would have lost many of the details of the fluctuations.

In the top of the core, the sedimentation rate is so much lower that probably only events of more than 1000 years duration could be identified with confidence.

Benthonic foraminifera

Thirty-one samples were prepared and analysed for foraminifera according to the methods described by Feyling-Hanssen (1958, 1983). The details about the faunas and faunal lists are given by Løfaldli & Rokoengen (1980). Between 400 and 1000 specimens were counted in each sample except in the relatively poor samples at 220 and 230 cm. The number of specimens in 1 g of sediment, number of benthonic species and faunal diversity (the number of ranked species whose cumulative percentage accounts for 95% of the total fauna, Walton 1964) were calculated (Fig. 4).

The faunas show marked variations (Løfaldli & Rokoengen 1980), and four foraminiferal assemblage zones (1–4) are defined, all of which contain both planktonic and benthonic species (Fig. 4):

Zone 4 (265–160 cm) is dominated by the arctic form of *Elphidium excavatum, Cassidulina reniforme* and *Cibicides lobatulus*. It comprises the gravelly sandy clay of the sedimentological unit IV supposed to represent a mixed glaciomarine sediment. The content of foraminifera is less than 100 specimens per gram sediment and the zone could well represent a mixture of faunas deposited in low and mid-arctic conditions respectively.

Zone 3 (160–122 cm) has much higher content of foraminifera than the zone below (Fig. 4), but is dominated by the same species. The foraminiferal assemblage seems to be a glaciomarine shelf fauna deposited in a low-arctic environment.

Zone 2 (122–97 cm) is dominated by *Cibicides lobatulus* (Fig. 4). This zone shows a transition to more boreal conditions in the upper part, but represents a low-arctic shelf fauna. The lower part of the zone has a noteworthy high relative content of planktonic foraminifera.

Zone 1 (97–0 cm) has *Trifarina angulosa* as the dominant species. The fauna is boreal and typical of a shelf fauna in fairly deep water (similar to the present depth).

Water masses today can be related to foraminiferal groups of arctic and boreal affinity and thus the past distribution of these groups can be used to reconstruct watermass changes. Foraminiferal faunas representing different water masses have been defined by several workers on the Norwegian Continental Shelf (Feyling-Hanssen 1971, 1981, 1983; Miljeteig 1975; Rokoengen et al. 1979; Sejrup et al. 1980; Løfaldli & Rokoengen 1980; Qvale 1981, 1985; Hald & Vorren 1984, 1987; Nagy & Qvale 1985; Hald et al. 1989; Hald & Steinsund in press). The faunas have varied, however, due to local conditions and different interpretations.

In the present work we have mainly followed Feyling-Hanssen (1983) and defined an *arctic group* (A) and a *boreal group* (B) subdivided into groups b1 and b2:

Arctic group A: Astronion gallowayi, Buccella frigida, Cassidulina reniforme, Elphidiella arctica, Elphidium excavatum, Nonion labradoricum, Islandiella helenae, Islandiella norcrossi, Stainforthia loeblichi and *Triloculina trihedra.*

Boreal group b1: Trifarina angulosa, Bulimina marginata, Uvigerina peregrina and *Hyalinea balthica.*

Boreal group b2: Cassidulina laevigata and *Elphidium albiumbilicatum.*

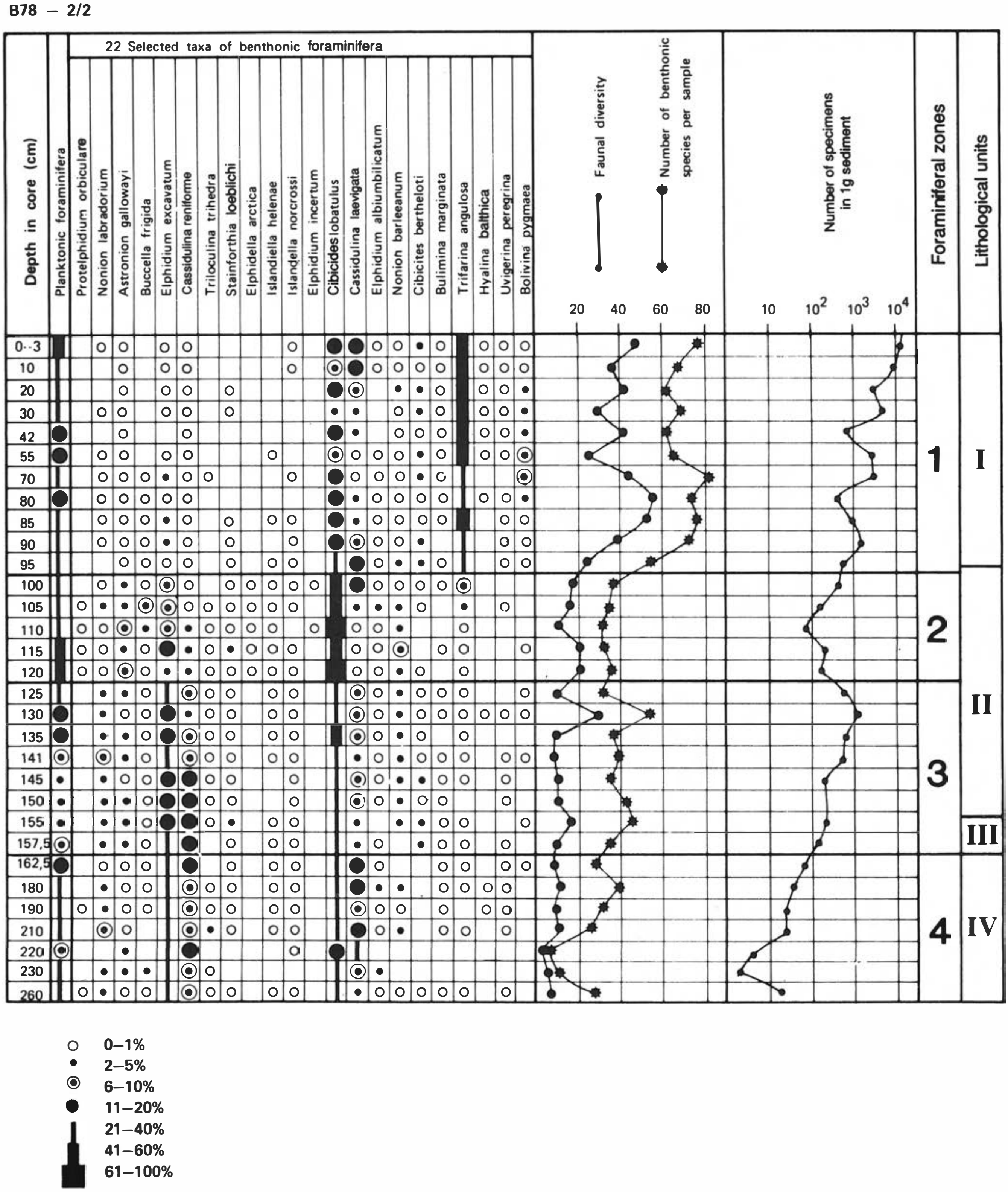

Fig. 4. Range chart for planktonic foraminifera (in % of total benthonic and planktonic content) and 22 selected taxa of benthonic foraminifera in core B78-2/2.

The rest of the foraminifera are cosmopolitan with *Cibicides lobatulus* being the most abundant.

In the arctic group (A) the 10 arctic–boreal species counting at least 1% in one or more subsamples have been included. The highest percentages are made up of the arctic form of *Elphidium excavatum* and *Cassidulina reniforme*. Of the others, only *Nonion labradoricum, Astronion gallowayi* and *Buccella frigida* counted for more than 5% in at least one sample (Fig. 4).

The boreal group (b1) corresponds to the 'boreal-

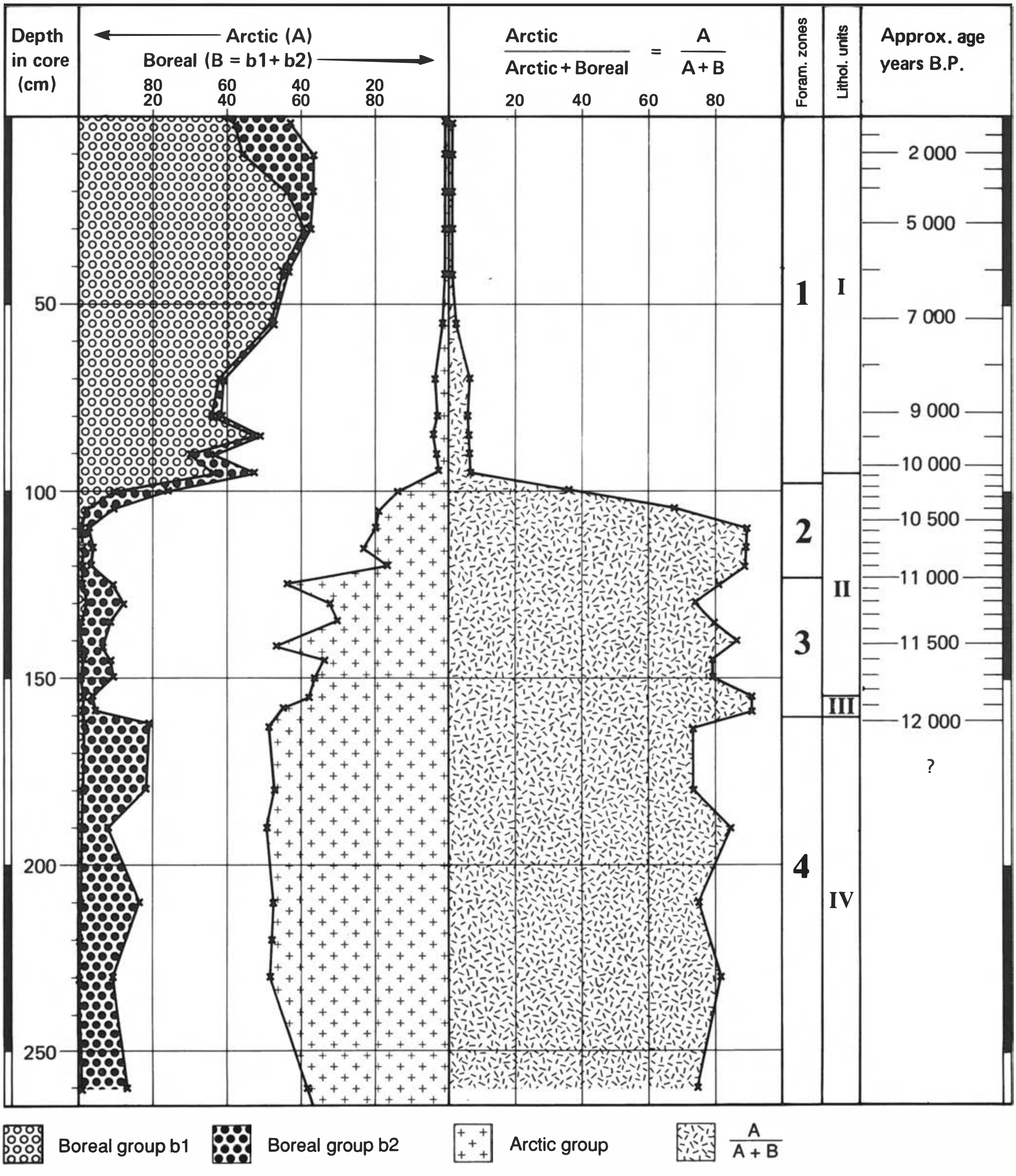

Fig. 5. Distribution of boreal and arctic benthonic foraminiferal fauna groups, ratio between the groups and approximate age.

lusitanian group' used by Løfaldli & Rokoengen (1980) and contains four species. The dominant one is *Trifarina angulosa* that made up more than 50% of the benthonic fauna in several samples. *Trifarina angulosa* is restricted to the upper part of the core as it accounts for less than 1% below 105 cm. The other three species are only present with about 1% or less. This group is believed to reflect the warmest conditions.

The second boreal group (b2) includes *Cassidulina laevigata* and *Elphidium albiumbilicatum*. The former comprises a maximum of 24% of the total benthonic fauna and the latter 5%. These two foraminifera occur throughout the whole core. Especially *Cassidulina laevigata* has been discussed and also subdivided into one boreal and one more arctic variant (Mackensen & Hald 1988). Even not subdivided in the present study, this may explain the apparent high content of boreal fauna below 160 cm.

The described subdivision of benthonic faunas has been used to construct Fig. 5. The foraminifera in the lower part of the core, below 160 cm, are believed to reflect resedimentation of faunas of different origin. The fauna is thus not suitable for climatic reconstructions and therefore omitted in the following.

The amount of arctic (group A) foraminifera in the benthonic fauna varies from nearly 50% to less than 1% (Fig. 5) and the amount of boreal foraminifera in the benthonic fauna from less than 5% to more than 60%. Foraminiferal group b1 shows a very strong increase from less than 2% at 105 cm (10,400 years BP) to 36% at 95 cm (10,100 years BP). Below 105 cm the content of group b1 species is very low.

The content of the total boreal group B shows a minimum value below 5% in the gravel layer 160–155 cm (up to 11,800 years BP). In the clay above (lithological unit II) the lower values are above 5% with a maximum of 12% at 130 cm (11,200 years BP). The boreal foraminifera show the most marked minimum in the core with values below 5% between 120 and 110 cm (10,900–10,600 years BP). From 100 to 80 cm (10,300 to 8000 years BP), the variations are too rapid to be properly recorded with the sample interval used and the rate of deposition. Two 'single point' maxima are recorded at 95 cm (10,100 years BP) and 85 cm (9500 years BP) respectively. Higher up the B group accounts for more than 50%, with over 60% between 30 and 10 cm (5000 to 2000 years BP) and about 55% at the top of the core.

The ratio between the arctic group and the sum of the groups (A/A + B) provides a useful index because it is not affected by changing concentrations of cosmopolitan species. The index shows the same trends between 160 and 100 cm as the boreal group and far less resemblance to the arctic group (Fig. 5). Maxima occur below 155 cm (11,800 years BP) and from 120 to 105 cm (11,000–10,400 years BP). In addition, a smaller maximum is found at 140 cm (11,500 years BP) corresponding to a peak in arctic foraminifera (Figs. 4, 5).

Planktonic foraminifera

The main results from the analyses of planktonic foraminifera are shown in Fig. 6. The number of planktonic specimens in 1 g sediment varies from less than 10 in the lower part of the core to more than 1000 in the top, and the content of planktonic foraminifera in the total fauna varies from less than 5% to more than 55%. The lower part of the core (265–160 cm) had values between 10 and 30%, probably mainly due to resedimentation. The highest relative content of planktonic foraminifera in the total fauna is recorded at 120 and 115 cm (10,900–10,750 years BP). This is caused by the low (<100) number of benthonic specimens per gram sediment. Possible explanations could be increased sedimentation rate or lower rate of production as both number of planktonic and benthonic foraminifera are low from 120 to 105 cm (10,900–10,400 years BP), (see Figs. 4 and 6).

Neogloboquadrina pachyderma is the dominant species below 100 cm. Higher up in the core *Globigerina bulloides* and *Globigerina quinqueloba* are also common (Fig. 6).

The transition from polar to subpolar conditions is recorded as a change from sinistral (left) to dextral (right) coiled *Neogloboquadrina pachyderma* (Fig. 6). The main transition occurs between 105 and 90 cm (10,400–9900 years BP). The maximum change in oxygen isotope composition (see below and Fig. 7) for the same species is found from 100 to 95 cm.

Secondary calcite growth on *Neogloboquadrina pachyderma* tests is also shown in Fig. 6. High calcite growth is believed to indicate unfavourable conditions for this species. This could be caused by cold or low salinity water masses or low nutrients. The highest content of secondary calcite growth is recorded between 90 and 60 cm (about 10,000 to 7000 years BP).

Isotopic measurements

Stable isotope analyses (Fig. 7 and Table 3) were performed at selected levels on the benthonic foraminifera *Elphidium excavatum* and *Cassidulina laevigata* and on the planktonic *Neogloboquadrina pachyderma* as described by Erlenkeuser (1985).

Oxygen isotopes: the benthic record

Assuming that *Cassidulina laevigata* calcifies in isotopic equilibrium with the ambient water (Erlenkeuser 1985), the $\delta^{18}O$ value of the surface sample yields an 'isotopic' water temperature of about 7°C in agreement with observed temperatures (Rey 1981). The calculation is based on the palaeotemperature equation of Shackleton (1974):

$$t°C = 16.9 - 4.38\ (\delta_c - \delta_w) + 0.1\ (\delta_c - \delta_w)^2$$

with $\delta_c = \delta^{18}O = 2.4‰$ PDB as measured and δ_w, the isotopic composition of the water, calculated as $-0.08‰$ for a salinity of 35.0‰ after Craig & Gordon (1965), applying their regression coefficient for Norwegian–Greenland Sea waters of 0.61‰ of δ_w versus ‰ of salinity.

The oxygen isotope record of *Cassidulina laevigata* shows the typical drop in values (Fig. 7) at the second step of the last deglaciation (Duplessy et al. 1981). In core B78-2/2 however, the drop is gradual from 110 to 80 cm. The benthic $\delta^{18}O$ result at 60 cm depth (ca. 7500 years BP) is considered an anomaly, but would be of

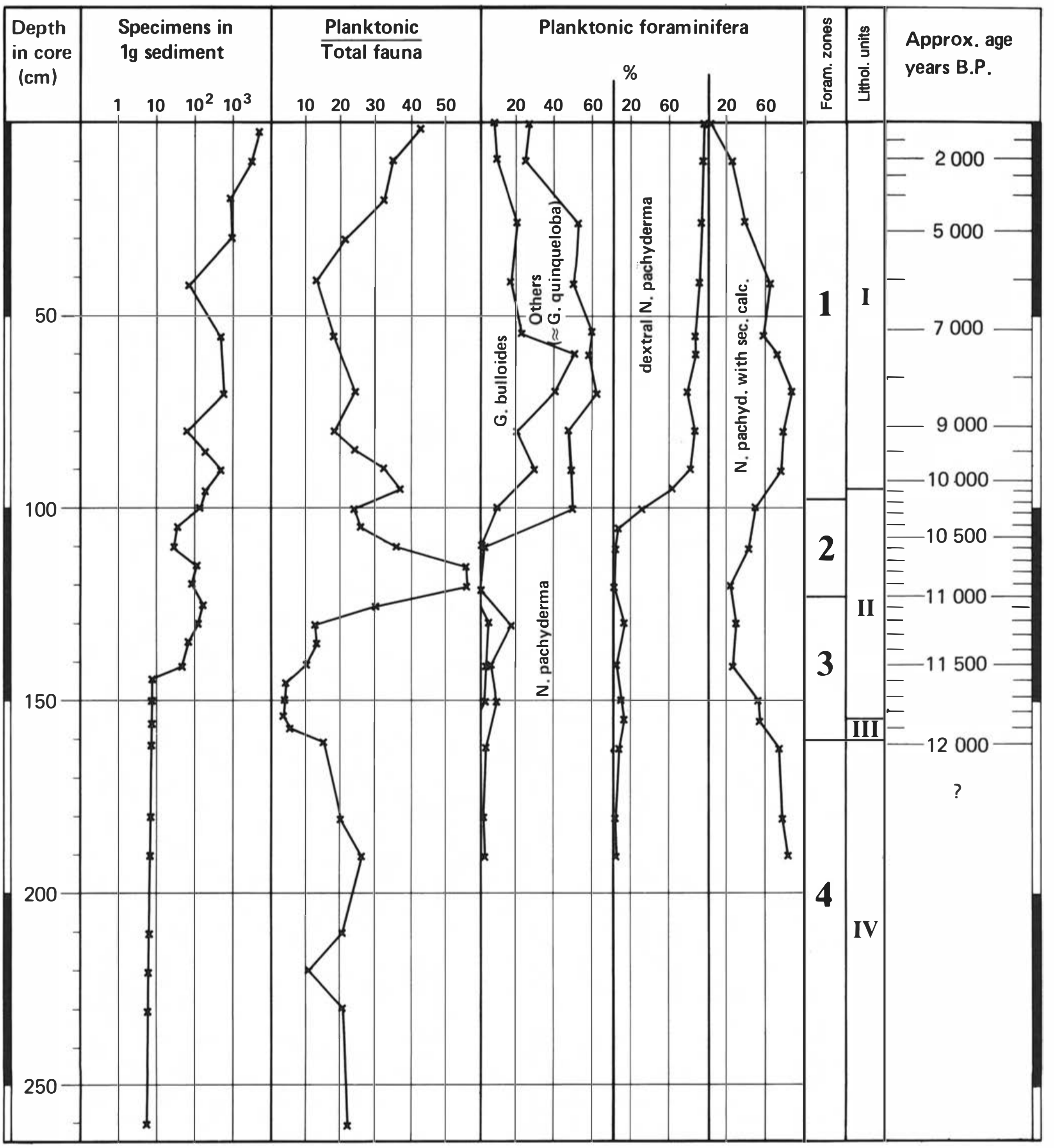

Fig. 6. Planktonic foraminifera: Number of specimens per gram sediment. Content of planktonic fauna (in % of total fauna). Total planktonic fauna composed of *Neogloboquadrina pachyderma* (sinistral and dextral), *Globigerina bulloides* and 'others' totally dominated by *Globigerina quinqueloba*. % dextral *Neogloboquadrina pachyderma* of total dextral and sinistral content. % of *Neogloboquadrina pachyderma* with secondary calcite.

great interest if it did mark an episode that could be confirmed in future studies.

The $\delta^{18}O$ drop shown by *Cassidulina laevigata* is missing in the *Elphidium excavatum* record. The most obvious explanation is that the low content of *Elphidium excavatum* found in the upper part of the core (Fig. 4) is composed of resedimented late glacial specimens.

Oxygen isotopes: the planktonic record

The $\delta^{18}O$ profile of the planktonic foraminifer *Neogloboquadrina pachyderma* (Fig. 7 and Table 3) is linked to oceanographic changes of the surface and subsurface waters. *Neogloboquadrina pachyderma* has a likely habitat depth of some 50 to 100 m (Kellog et al. 1978), and

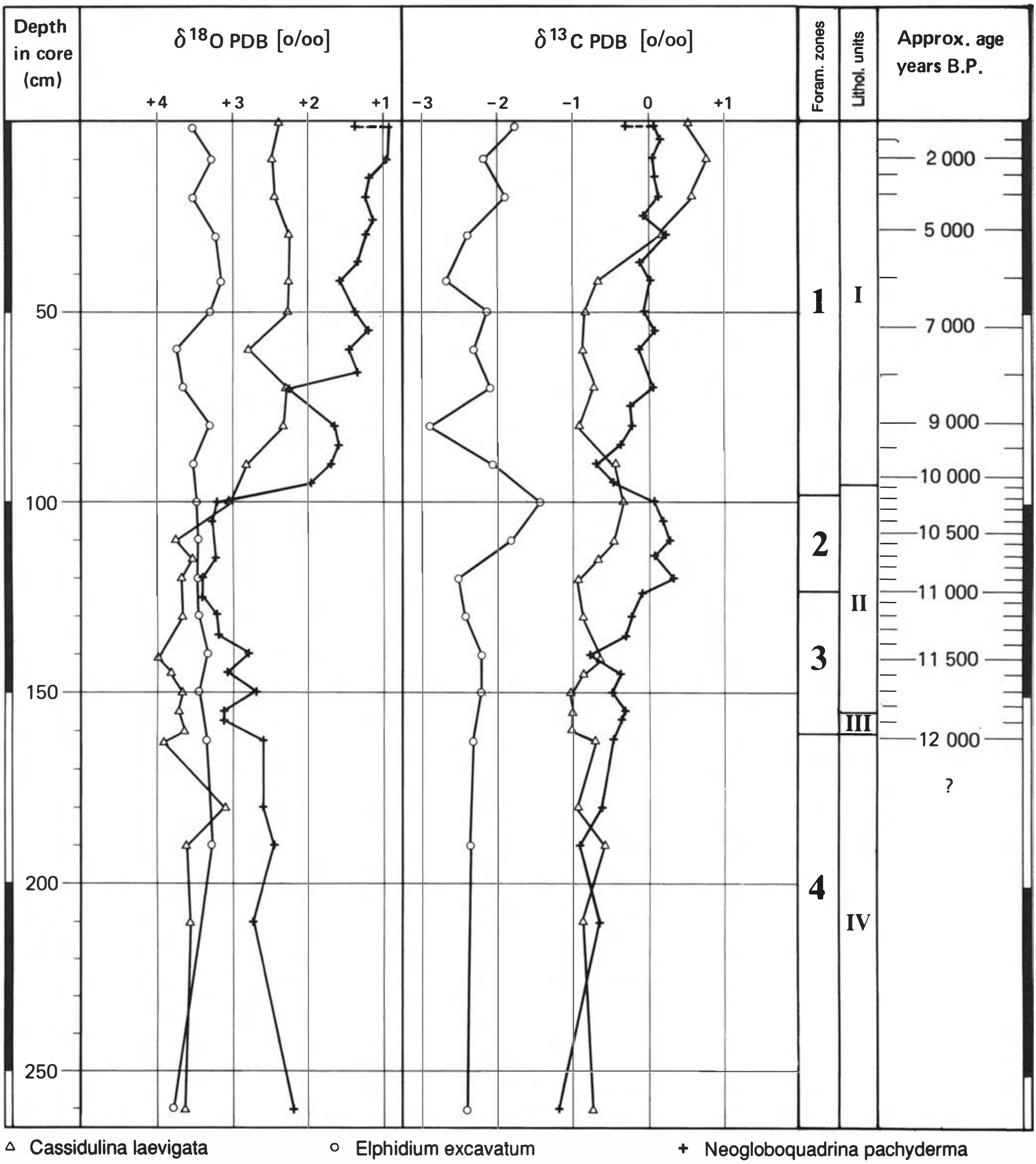

Fig. 7. Isotopic measurements in core B78-2/2.

the isotopic composition hence traces a subsurface water rather than the surface layer itself.

The top isotope level of *Neogloboquadrina pachyderma* is noisy (0.9 to 1.4‰). Along with the possible variance of the salinity in the frontal zone of the Norwegian Current and the Norwegian Coastal Current, this span results in a wide range of possible isotopic temperatures.

The $\delta^{18}O$ values of *Neogloboquadrina pachyderma* are lighter throughout the core than those of *Cassidulina laevigata*. The difference is most pronounced in the upper part of the core, indicating better developed stratification in the water column.

The transition to lighter isotopic values starts at 100 cm in the planktonic curve. The isotope value at 70 cm sample depth is somewhat uncertain as it is only seen in one sample, but could represent an interval of a rather

Table 3. Oxygen and carbon isotope data from core B78-2/2.

	Neogloboquadrina pachyderma				*Cassidulina laevigata*				*Elphidium excavatum*			
Depth in core (cm)	$\delta^{13}C$ ‰ PDB	Int error ‰	$\delta^{18}O$ ‰ PDB	Int error ‰	$\delta^{13}C$ ‰ PDB	Int error ‰	$\delta^{18}O$ ‰ PDB	Int error ‰	$\delta^{13}C$ ‰ PDB	Int error ‰	$\delta^{18}O$ ‰ PDB	Int error ‰
0–3	−0.27	0.06	0.87	0.20	0.51	0.02	2.37	0.02	−1.78	0.09	3.52	0.04
0–3	0.03	0.09	1.39	0.04	—	—	—	—	—	—	—	—
5	0.15	0.01	1.14	0.01	—	—	—	—	—	—	—	—
10	0.05	0.08	0.95	0.01	0.77	0.01	2.49	0.01	−2.18	0.04	3.29	0.01
15	0.06	0.03	1.19	0.01	—	—	—	—	—	—	—	—
20	0.13	0.06	1.21	0.03	0.58	0.06	2.45	0.01	−1.90	0.08	3.51	0.02
26	−0.09	0.02	1.14	0.01	—	—	—	—	—	—	—	—
30	0.22	0.04	1.20	0.02	0.16	0.05	2.25	0.04	−2.40	0.05	3.21	0.02
37	−0.12	0.05	1.34	0.03	—	—	—	—	—	—	—	—
42	0.01	0.06	1.58	0.04	−0.66	0.09	2.27	0.07	−2.67	0.13	3.15	0.07
50	−0.08	0.10	1.36	0.04	−0.83	0.07	2.26	0.02	−2.12	0.07	3.30	0.06
55	0.07	0.01	1.19	0.02	—	—	—	—	—	—	—	—
60	−0.12	0.08	1.45	0.05	−0.86	0.06	2.80	0.04	−2.32	0.09	3.73	0.04
66	−0.09	0.02	1.31	0.01	—	—	—	—	—	—	—	—
70	0.05	0.03	2.25	0.02	−0.74	0.09	2.28	0.01	−2.10	0.04	3.65	0.01
75	−0.25	0.03	1.99	0.03	—	—	—	—	—	—	—	—
80	−0.22	0.04	1.63	0.03	−0.93	0.05	2.34	0.04	−2.90	0.07	3.30	0.04
85	−0.39	0.03	1.58	0.02	—	—	—	—	—	—	—	—
90	−0.70	0.06	1.68	0.03	−0.44	0.03	2.82	0.03	−2.07	0.07	3.51	0.05
95	−0.47	0.03	1.95	0.01	—	—	—	—	—	—	—	—
100	0.07	0.02	3.18	0.03	−0.32	0.10	3.01	0.01	−1.43	0.04	3.47	0.02
105	0.18	0.03	3.25	0.01	—	—	—	—	—	—	—	—
110	0.26	0.04	3.33	0.01	−0.47	0.06	3.79	0.03	−1.83	0.06	3.43	0.04
115	0.09	0.01	3.20	0.01	−0.67	0.05	3.52	0.03	—	—	—	—
120	0.32	0.11	3.37	0.04	−0.95	0.07	3.68	0.07	−2.54	0.02	3.44	0.02
125	−0.10	0.03	3.38	0.01	—	—	—	—	—	—	—	—
130	−0.24	0.03	3.18	0.02	−0.89	0.05	3.68	0.04	−2.44	0.09	3.42	0.05
135	−0.30	0.02	3.18	0.04	—	—	—	—	—	—	—	—
140	−0.78	0.11	2.79	0.08	−0.65	0.07	3.99	0.02	−2.21	0.04	3.32	0.02
145	−0.39	0.04	3.05	0.01	−0.88	0.03	3.81	0.01	—	—	—	—
150	−0.50	0.04	2.67	0.02	−1.04	0.04	3.65	0.01	−2.23	0.09	3.44	0.04
155	−0.31	0.02	3.13	0.02	−1.01	0.03	3.72	0.04	—	—	—	—
160	−0.36	0.03	3.12	0.01	−1.04	0.05	3.64	0.10	—	—	—	—
160–165	−0.47	0.03	2.57	0.03	−0.70	0.05	3.93	0.07	−2.32	0.05	3.34	0.04
180	−0.63	0.03	2.57	0.01	−0.94	0.03	3.09	0.02	—	—	—	—
190	−0.88	0.10	2.44	0.04	−0.56	0.04	3.60	0.03	−2.39	0.09	3.23	0.02
210	−0.63	0.03	2.70	0.01	−0.89	0.03	3.55	0.02	—	—	—	—
260	−1.18	0.04	2.17	0.05	−0.73	0.09	3.61	0.03	−2.42	0.03	3.85	0.02

homogeneous water column. The complete disappearance of the $\delta^{18}O$ difference between the planktic and benthic foraminifers at a time already well within the Holocene is unexpected and deserves further investigation. It could represent a short cooling in the Holocene, possibly comparable to observations by Hald & Vorren (1984).

Carbon isotopes

Variations in $\delta^{13}C$ reflect mainly the ageing of the respective water masses since the last thorough gas-exchange with the atmosphere, and the longer the water body was out of contact with the atmosphere, the lighter is the carbon isotope composition of the dissolved inorganic carbon and of the foraminifera living therein. Different factors interfere, however, in a complex way, and the interpretation of the carbon isotope signal is by no means unique. It is evident that, for reconstructing oceanographic changes through time, this picture can only be a rough and often tentative approach, which for instance does not consider the ecological situation, which may have undergone appreciable changes through the different climatic stages and the associated oceanographic regimes (Erlenkeuser 1985; Zahn et al. 1986).

In the following discussion the core below 160 cm is omitted as before. The comparatively deep habitat of the planktonic *Neogloboquadrina pachyderma* (Kellogg et al. 1978) should also be considered.

Below 125 cm (10,900 years BP) the carbon isotope values of *Neogloboquadrina pachyderma* are lighter than the Holocene level. This indicates a somewhat aged, no longer well-aerated water mass, that could be found below an extensive layer of melt water.

For the interval 120 to 100 cm (10,900–10,300 years BP) the $\delta^{13}C$ profile of *Neogloboquadrina pachyderma* records a water mass which was even better oxygenated (less aged) than at present. This points to a reduced extension and/or stability of a possible low density surface layer in the eastern Norwegian Sea. After a little delay the deeper water column also became better ventilated (Fig. 7). The $\delta^{13}C$ record of *Neogloboquadrina* *pachyderma* in this interval probably reflects the results of the Younger Dryas cooling.

The pronounced light $\delta^{13}C$ excursion of *Neogloboquadrina pachyderma* during the interval 100 to 75 cm (10,300–9000 years BP) most likely reflects the subsurface water being cut off by an extended meltwater lid, which developed under the discharge from the rapidly waning ice sheet on Scandinavia. It is interesting to note, however, that the deeper water of the *Cassidulina laevigata* habitat remained at a comparatively high carbon level.

The remainder of the Holocene does not exhibit significant changes in $\delta^{13}C$ for *Neogloboquadrina pachyderma*, but the comparatively low Holocene $\delta^{13}C$ level could suggest some blocking of the vertical advection by a surface layer of some stability. Supply with freshly aerated water is even less at the sea bed as recorded by the benthonic *Cassidulina laevigata* below about 40 cm sample depth (6000 years BP). Higher in the core a marked increase in the $\delta^{13}C$ level is found for *Cassidulina laevigata* (Fig. 7).

Discussion

Deglaciation

The mapping and dating of the last deglaciation on land has been one of the main fields of research in Scandinavian Quaternary geology for a long time (Andersen 1979b; Andersen et al. 1981, 1982; Berglund 1979; Mangerud 1980; Mørner 1979; Sørensen 1979 and many others). The dating problem is evident within the time-scale encountered, and has been given special attention (e.g. Andersen 1979a).

The location of core B78-2/2 and its time resolution provides a good opportunity for comparison with adjacent land areas.

The most informative climatic record for the period 12,000 to 10,000 years BP is probably given by the ratio of the arctic fauna compared to the total arctic and boreal faunas. The boreal fauna shows the same trends, however (Fig. 5), and, as it also gives fluctuations after 10,000 years BP, it is used in the further discussion (as also recommended by Feyling-Hanssen 1983).

The core interval 160–75 cm (12,000–9000 years BP) starts with a cold event ending about 11,800 years BP. Then follows a period of nearly 1000 years with higher content of boreal foraminifera reaching a maximum about 11,200 years BP (and a small minimum at about 11,500 years BP), (see Fig. 8). The samples with lowest content of boreal foraminifera are from 120, 115 and 110 cm depth in the core (about 10,900 to 10,600 years BP). The same main trends are also found in the planktonic record of the dextral *Neogloboquadrina pachyderma* (Fig. 6).

After about 10,500 years BP follows the most marked

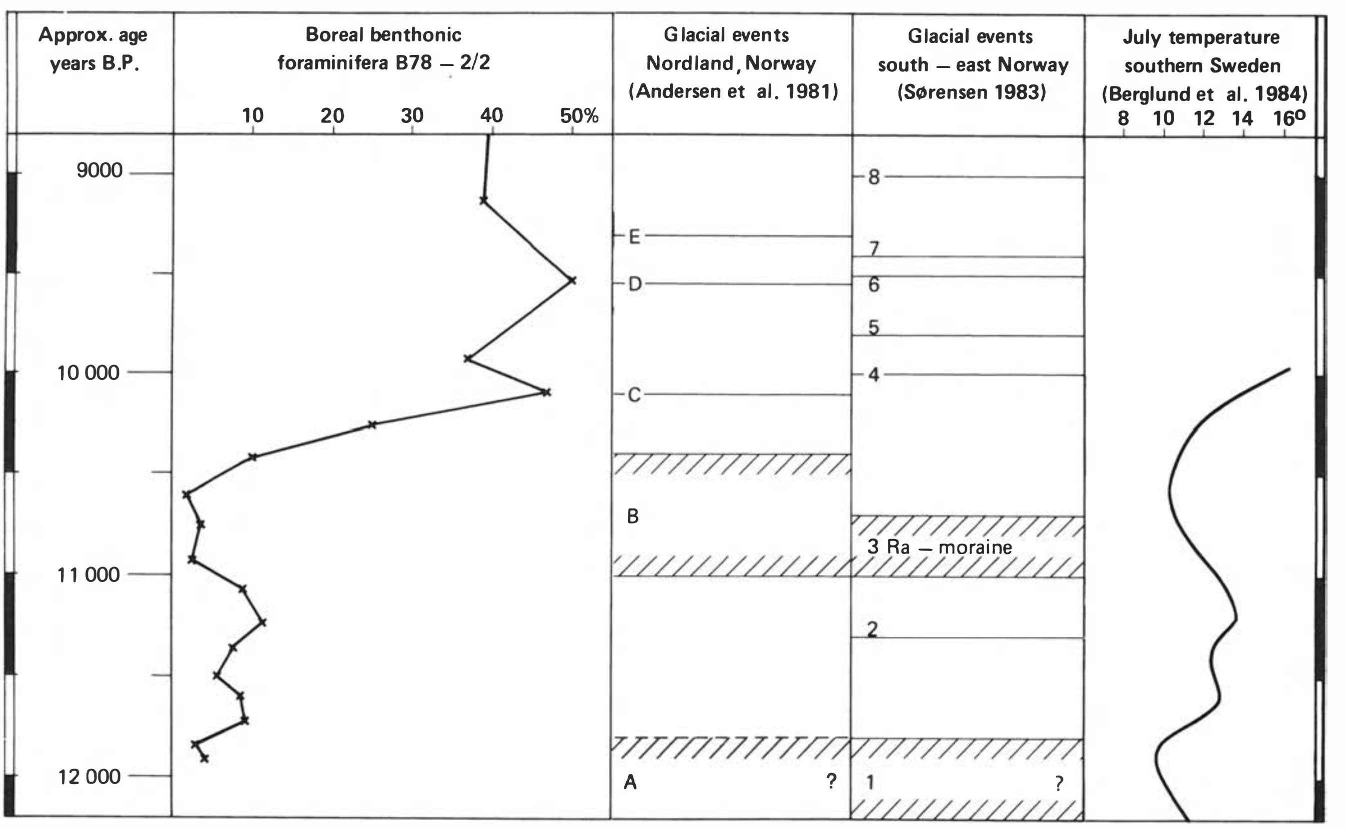

Fig. 8. Correlation of boreal foraminifera in core B78-2/2 for the period 12,000–9000 years BP with glacial events in Nordland and the Oslofjord area and climatic changes on land in Southern Sweden.

increase in boreal foraminifera. The resolution is not sufficient to record all fluctuations accurately, but two maximum values are found (Fig. 8). These events are only of a few hundred years' duration.

In Fig. 8 the content of boreal benthonic foraminifera in the core is compared with July temperature in Sweden inferred from vegetation (Berglund et al. 1984) and glacial events in Nordland (Andersen et al. 1981) and southeast Norway (Sørensen 1983).

The oldest event in core B78-2/2 from before 12,000 to about 11,800 years BP, can clearly be correlated to the Swedish data and is also possibly present in the Oslofjord area. Andersen et al. (1981) stress that the 'A' event in Nordland must be younger than about 13,000 years BP and older than about 11,800 years BP given by several radiocarbon dates. The age assigned at 12,300 years BP is by correlation to Troms, and we consider it likely that the 'A' event could end about 11,800 years BP (Fig. 8).

The '11,500 years BP event' recorded in core B78-2/2 may possibly be correlated to events in southern Scandinavia as a small decrease in temperature in Sweden and glacial event 2 in southeast Norway (Fig. 8). In Nordland an event of this age would probably have been destroyed by the large Younger Dryas 'B' event. The most optimal (boreal) conditions occurred around 11,200 years BP.

The very marked minimum of boreal foraminifera at 11,000 to 10,400 years BP corresponds to the 'B' event (Tjøtta–Tromsø–Lyngen glacial event) of Andersen et al. (1981) and the 'Ra-moraine' of Sørensen (1983), reflecting the Younger Dryas cooling.

The correlation with land data after 10,500 years BP is limited by the time resolution. Andersen et al. (1979, 1981) have by detailed mapping found glacial events at 10,100 ± 100, 9550 ± 100 and 9300 ± 100 years BP from Nordland in this period. In the Oslofjord area (Fig. 8) a number of events have been recorded (Sørensen 1983). The data do not permit a detailed correlation, but rapid fluctuations are found in both land and sea data. The minimum value at 90 cm (about 9900 years BP, Fig. 8) probably correlates to the 'C' event of Andersen et al. (1981).

The deglaciation of central Norway was most likely completed about 8500 years BP (Andersen 1980). This is believed to be reflected in core B78-2/2 by the drop in arctic foraminifera between 70 and 55 cm (Fig. 5). Unfortunately the dating in the core is uncertain (see Fig. 3).

The correlation with the records from land indicates that the content of boreal foraminifera in core B78-2/2 has changed in response to regional climatic variations.

Transition from arctic to boreal conditions

On the Norwegian Continental Shelf the transition from arctic to boreal conditions is normally very marked (Vorren et al. 1978; Rokoengen et al. 1979; Sejrup et al. 1980, 1984; Holtedahl & Bjerkli 1982; Jansen et al. 1983, 1988; Hald & Vorren 1984, 1987; Rise & Rokoengen 1984; Nagy & Ovale 1985; Jansen 1987; Hald et al. 1989 and others). This is generally believed to have resulted from the onset of influx of warm Atlantic water.

From the records of benthonic and planktonic foraminifera and the $\delta^{18}O$ measurements (Figs. 5, 6, 7) it is evident that the main boundary, found around 100 cm in core B78-2/2, marks the change from arctic to boreal water masses and the resolution makes it possible to describe the transition in some detail.

The ratio between arctic and sum of boreal and arctic benthonic foraminifera decreases from about 90% at 110 cm to less than 10% at 95 cm (Fig. 5). The boreal group b1 with *Trifarina angulosa* as the most frequent species increases from about 10 to 35% between 100 and 95 cm. In the same sample interval $\delta^{18}O$ values drop for *Neogloboquadrina pachyderma* accompanied by a change from 23% to 64% of the dextral (right) coiled species (Fig. 6). The boreal group b2 (Fig. 5) with *Cassidulina laevigata* starts to increase in number slightly before group b1 (believed to need warmer conditions than b2). The $\delta^{18}O$ measurements show a gradual transition from 110 to 80 cm. Sedimentologically the change from clay to sand sediments is recorded at 95 cm (Fig. 3).

The main transition from arctic to boreal conditions is thus in core B78-2/2 recorded within a 10 cm interval between 105 and 95 cm, which corresponds to a period of some 400 years. The differences in time of response for the different parameters seem to be well documented demonstrating a climatic development in the water masses.

The timing of the transition in the interval 105–95 cm would be 10,550–10,300 years BP using a timescale corrected for depositional rate assuming constant foraminiferal production and 10,450–10,100 years BP using linear interpolation between dated levels (Fig. 3). Considering all parameters showing the transition from arctic to boreal conditions, the age should be within the interval 10,300 ± 200 years BP, but the uncertainty is at least ±200 years even in this well-dated core.

The observed transition is probably time transgressive. While boreal conditions were established on the outer part of the shelf, arctic conditions may still have prevailed near the retreating continental ice cap. Rise & Rokoengen (1984) discussed the transition on the northern North Sea Plateau. It was best dated in sample A79-135 at about 61°22'N containing a *Mya truncata* in life position. This shell was infilled with sand containing a boreal foraminiferal fauna. Believing that the infill of the shell happened shortly after its death (probably months rather than years, T. Holte, pers. comm.), the transition to boreal conditions must have happened before (or just at) that time dated to 10,330 ± 110 years BP.

Data further south in the North Sea and Skagerrak indicate that the transition there could have been somewhat later and closer to 10,000 years BP (Rise & Rokoengen 1984; Stabell & Thiede 1985).

Development after the deglaciation

The upper 80 cm of the core has less resolution than the lower part, but shows interesting variations in content of boreal foraminifera (Figs. 4, 5) that can be compared by the results reported by Hald & Vorren (1984) off Troms, Nagy & Ovale (1985) in the Skagerrak and others.

Based on Norwegian land data Hafsten (1974) divided the last 9000 years into three periods: A pre- and early warm period between 9000 and 8200 years BP, an optimum climatic period between 8200 and 3500 years BP, and a colder period from 3500 years BP to the present. The content of the boreal-lusitanian foraminiferal fauna (b1, Fig. 5) shows fluctuations in good agreement with this, while the total boreal fauna has a later decrease (in the upper 10 cm) in agreement with the late Holocene trends (Berglund 1983).

An important oceanographic change is reflected by the carbon isotopes of *Cassidulina laevigata* at about 40 cm depth (about 6000 years BP). They suggest a change to a better aerated, i.e. less aged, water than was prevailing in the time before (Fig. 7). From about the same level a decrease in secondary calcite growth on *Neogloboquadrina pachyderma* tests is recorded (Fig. 6), indicating more favourable conditions for this species. The 40 cm level could mark the onset of the present current regime in the area with Norwegian Current water masses forming the bottom water and with Norwegian Coastal Current water above. The timing can be compared to the possible onset of the Norwegian Coastal Current at about 7000 years BP, derived from planktonic foraminiferal evidence in a Skagerrak core (Thiede 1985), considering the uncertainties of dating for both cores in this time interval.

Conclusions

1. The local depositional environment in the last 12,000 years is described based on a regional background (from shallow seismic and sampling) and detailed investigations including sedimentology, geotechnical properties, biostratigraphy, stable isotopes and radiocarbon dates from a 265 cm long vibrocorer sample (B78-2/2) from 165 m water depth at 64°59′N and 9°14′E, northeast of Haltenbanken on the Mid-Norwegian Continental Shelf.
2. The core, B78-2/2, has exceptional potential for age control compared with all other samples studied so far by IKU. In the period 12,000 to 10,000 years BP, three radiocarbon datings and a volcanic ash zone (Vedde Ash Bed) give dates ca. every 600 years. Even so, all ages quoted could have an uncertainty of at least ±200 years. The inaccuracies are probably often underestimated in less well-dated cores.
3. The arctic and boreal foraminiferal groups defined give a detailed record of the fluctuations in depositional environment. For climatic interpretations the best single parameter for the whole time span seems to be the content of boreal benthonic foraminifera (dominated by *Cassidulina laevigata* and *Trifarina angulosa* in core B78-2/2).
4. The most reliable depositional interpretations from the foraminiferal faunas are achieved in combination with shallow seismic, sedimentological and geotechnical investigations. The lower 265–160 cm of the core B78-2/2 gives for example high values of boreal foraminifera. It is, however, interpreted as a mixture of older sediments due to extensive iceberg scouring, while the top 160 cm is believed to give a continuous record for the last 12,000 years.
5. The main change from arctic to boreal conditions is very marked at about 10,300 ± 200 years BP. It is recorded earlier by the benthonic species *Cassidulina laevigata* than in *Trifarina angulosa*, the transition from sinistral (left) to dextral (right) coiled planktonic *Neogloboquadrina pachyderma*, and the change from clay to sand deposition. The drop in $\delta^{18}O$ values for *Neogloboquadrina pachyderma* is also very marked, while that of *Cassidulina laevigata* is more gradual from 10,500 to 9,000 years BP.
6. The minimum content of boreal foraminifera (most arctic conditions) occurred from before 12,000 to about 11,800 and from 11,000 to 10,400 years BP, with a smaller minimum about 11,500 BP. Two later minima of boreal foraminifera (colder events) are recorded around 10,000 to 9000 years BP, with variations shorter than the time resolution.
7. The core B78-2/2 provides a detailed record for the Scandinavian deglaciation period after 12,000 years BP from a point outside the glaciated area, and shows good correlation to land data.
8. The top 70 cm representing the last 9000 years shows maximum content of the boreal *Trifarina angulosa* (optimal climatic conditions) at about 5000 years BP, and then decreasing content up to present time.
9. The isotopic findings present a record of interesting changes that warrant further study of the oceanographic changes through time in cores from comparable locations along the Norwegian coast, in order to substantiate the present results and to better understand the response to the dramatic climatic changes during the transition from the last glaciation to the present time.

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