Upper Cainozoic stratigraphy in the central North Sea (Ekofisk and Sleipner fields)

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The investigation is based on analyses of planktonic and benthonic foraminifera and *Bolboforma* carried out in the uppermost Palaeogene and Neogene of the production well 2/4-C-11 (56°33′ N, 3°13′ E) on the Ekofisk Field and the exploration well 15/12–3 (58°14′ N, 1°53′ E) on the Sleipner Field. The analyses are based primarily on ditch cuttings, but in well 2/4-C-11, 49 sidewall cores and six short conventional cores were also available. Strontium isotope and paleomagnetic analyses were also carried out in well 2/4-C-11. A 420 m-thick accumulation of Lower Miocene sediments is present in the Ekofisk area. The Middle Miocene comprises approximately 180 m, and the Upper Miocene is represented by an approximately 500 m-thick interval. A hiatus is present in the Middle Miocene, and the middle part of the Middle Miocene is missing. A thin interval (approximately 120 m) of Lower Pliocene sediments is found overlying the Upper Miocene. Uppermost, a thick accumulation of Upper Pliocene–Pleistocene sediments (approximately 1000 m) is in place. More than half of this was deposited during the Pleistocene. The entire Upper Pliocene is represented in this area. This contrasts to the northern North Sea, as well as areas further north, where sediments of this epoch are partially missing in a hiatus comprising the lowermost part of the Upper Pliocene. In the Sleipner area the Lower and Middle Miocene are approximately 160 m and 180 m thick, respectively. The Upper Miocene (approximately 100 m) and the Lower Pliocene (approximately 40 m) thin from the Ekofisk towards the Sleipner Field. Uppermost, an approximately 900 m-thick succession of Upper Pliocene–Pleistocene sediments is present. Nearly two-thirds of this accumulation are Pleistocene in age.

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Introduction

The study area is located in the intra-cratonic North Sea Basin (Fig. 1). The central North Sea is a key area for studying Upper Cainozoic sediments on the Norwegian continental shelf. This area has subsided almost throughout the entire period, allowing more than 2 km of mostly marine clastic sediments to accumulate. Jordt et al. (1995) subdivided the Cainozoic of the Norwegian sector of the North Sea into 10 seismic sequences and documented large hiati in Pliocene and Miocene deposits. In the Neogene, major hiati are related to tectonic events in the Middle Miocene and to the climatic changes causing glaciation in the Late Pliocene and Pleistocene. Precise dating is important in order to obtain a reliable correlation between the preserved Neogene successions within the North Sea. Understanding of the Neogene geological development is necessary to construct basin models and to analyse the Late Cainozoic tectonism and glaciation of the region.

In the present study, the Neogene sections are almost complete. Consequently, the wells from this area are well suited for a detailed biostratigraphical analysis, and they allow the study of sediments not present further north and east.

The primary objective of this combined biostratigraphic and seismostratigraphic study is to date the sediments and main seismic sequence boundaries. A secondary objective is to interpret depositional environments based on microfaunal contents. Using the various dating and correlation methods available (Sr-isotope, paleomagnetic analyses, planktonic foraminifera, etc.), our effort was placed on applying the most effective methods according to the stratigraphic level under investigation. Emphasis was placed on correlating planktonic fossil fauna with fossil zones from ODP/DSDP sites in the Norwegian Sea, as these zones are paleomagnetically calibrated. The study of well 2/4-C-11 is based on that of Eidvin et al. (1993b), but it has been updated and revised.

Absolute ages used in the biostratigraphic schemes and strontium isotope seawater curves are based on Berggren et al. (1985). For comparison purposes, fossil zonation schemes correlated to absolute ages of Berggren et al. (1995) are also shown.

In order to ensure that the results reported here are consistent with electric logs and other technical information, all depths are expressed as meters below the rig floor (mRKB).

Previous work

Many hydrocarbon exploration and production wells have been drilled in the Norwegian, British and Danish sectors in the central North Sea. Most of these wells were analysed by biostratigraphic consultants, but none of these routine biostratigraphic studies are publicly available. Traditionally, the Upper Cainozoic has not been given high priority, and consequently, the dating is often insufficient. This applies particularly to the earliest drilled wells.

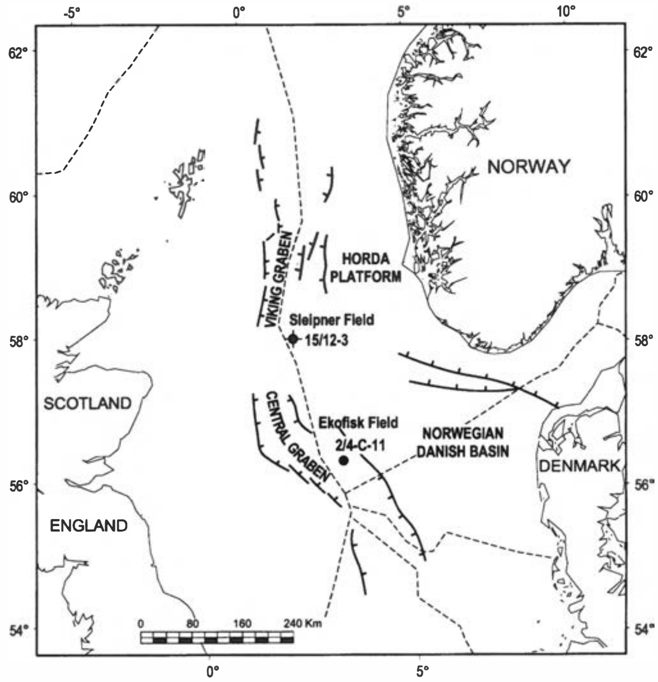


Fig. 1. Location of investigated wells. Main structural features are after Bjørslev Nielsen et al. (1986). Stippled lines show boundaries between national sectors.

Based on material from numerous wells, King (1983, 1989) published a general foraminiferal zonation for Cainozoic sediments, which comprises the whole North Sea area. Gradstein & Bäckström (1996) provide a similar zonation for the North Sea and Haltenbanken areas.

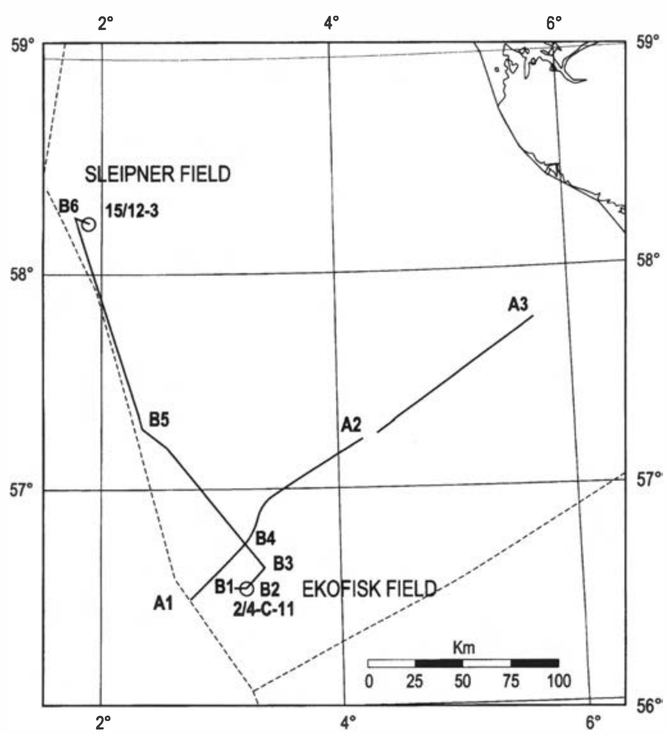


Fig. 2. Map showing wells and seismic lines. Stippled lines show boundaries between national sectors.

Redatings of Cainozoic sediments in exploration and production wells were published by Gradstein & Berggren (1981), Moe (1983), Knudsen & Asbjörndottir (1991) (Upper Pliocene and Pleistocene), Gradstein et al. (1992, 1994), Eidvin et al. (1993b), Michelsen et al. (1994), Konradi (1996) and Laursen et al. (1997). Pedersen (1995) made a biostratigraphic study of the Upper Pliocene/Pleistocene boundary based on a number of exploration wells from the central North Sea. Cores from a Pleistocene geotectonic drilling on the Fladen area have been investigated by Sejrup et al. (1987).

Important regional seismic studies were carried out by Bjørslev Nielsen et al. (1986), Cameron et al. (1987, 1993), Jensen & Schmidt (1992), Jordt et al. (1995), Michelsen et al. (1994), Sørensen & Michelsen (1995) and Sørensen et al. (1997).

Seismic interpretation

As an additional support to the correlation, the two studied wells were tied together by regional 2D seismic lines. Four main seismic sequence boundaries were identified, tied to the wells and interpreted along the transects shown in Fig. 2. The resulting seismic profiles (Figs. 3, 4) show the time thickness variations in the Neogene succession, and indicate a Neogene depocenter in the 2/4-C-11 area.

The wells have been tied by synthetic seismograms provided by the operators. In well 2/4-C-11, a direct correlation cannot be made, because the seismics do not cover the platform area, and because a gas chimney was present above the field. This problem was resolved by tying the well 2/4-B-19 in the northern part of the field to the seismics, and then correlating the logs between wells 2/4-B-19 and 2/4-C-11.

Pleistocene

The BP (base Pleistocene) reflector is the lower boundary of a heterogeneous succession. In the thick, basinal areas, Pleistocene reflection patterns are commonly continuous and parallel. Such a pattern is interpreted as typical for glacio-marine sediments. In the upper 2–300 milliseconds, deep erosional channels occur at different levels, and are most abundant in the Norwegian-Danish Basin. Because of their great and variable depths (200 m or more), the larger channels have been tentatively interpreted as subglacial features (Dangerfield 1992; Sejrup et al. 1991). In the uppermost parts of this sediment package, and in the eastern parts of profile A1–A3 (Fig. 3), the Pleistocene sequence is characterized by discontinuous reflections, indicating a stronger glacial influence on the sediments.

The BP reflector itself is defined as the boundary between the heterogeneous Pleistocene reflectors and the prograding Upper Pliocene succession. The exact location of the reflector is not always easy to identify, particularly in the westernmost areas where the Pliocene progradation

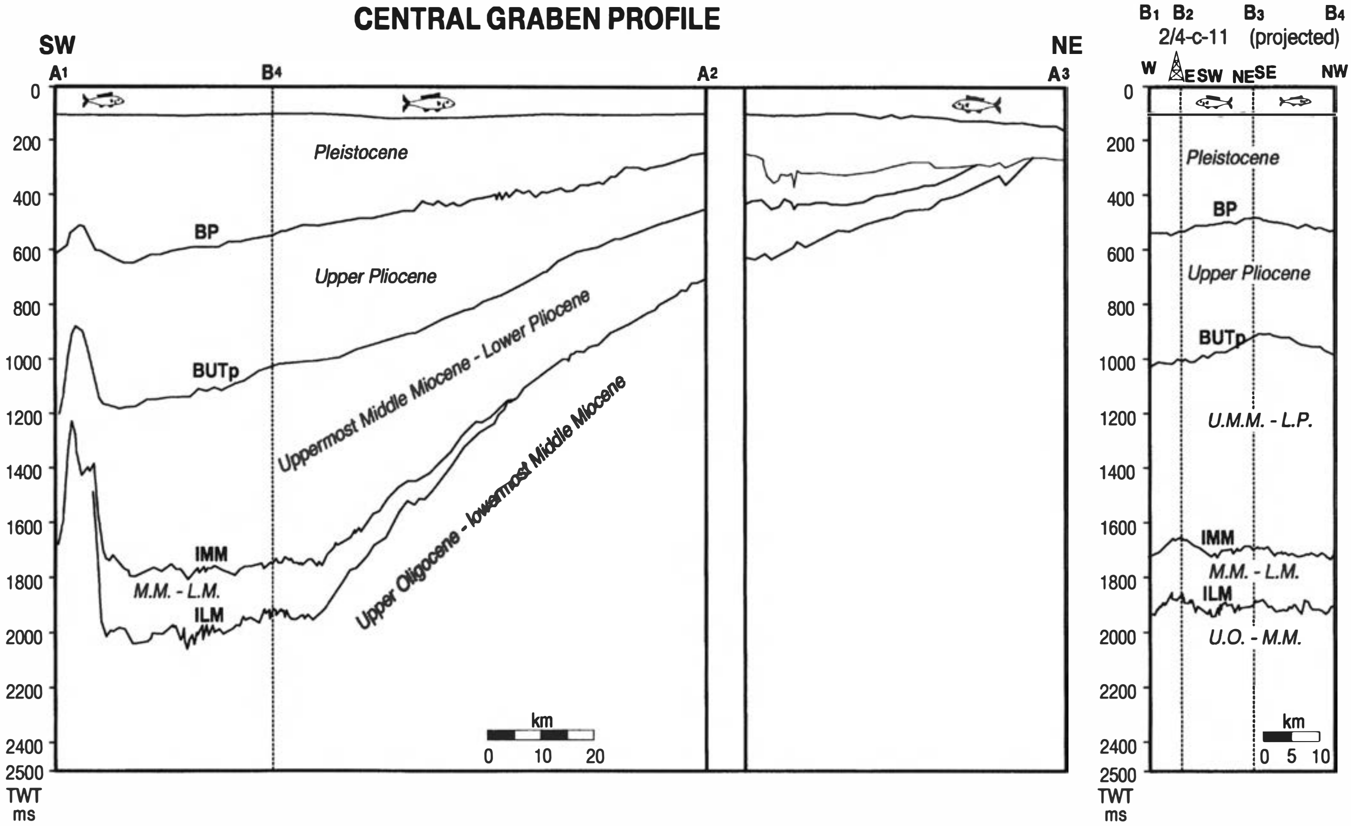


Fig. 3. Interpreted seismic line across the Central Graben through well 2/4-C-11. BP = base Pleistocene, BUTp = base Upper Pliocene, IMM = intra-Middle Miocene, ILM = intra-Lower Miocene, UMM-LP = uppermost Middle Miocene to Lower Pliocene, MM-LM = Middle to Lower Miocene, UO-MM = Upper Oligocene to Middle Miocene.

is poorly defined. A weak onlap on the BP reflector is indicated along the margins of the Pleistocene depocenter.

The BP reflector is correlated to the base of the Pleistocene in the wells analysed. In well 2/4-C-11, the logs and sediment samples show no significant difference between the sections dated to Pleistocene and Late Pliocene, respectively. In well 15/12–3, the BP reflector is correlated to the top of a section with higher velocities than the overlying clays.

Upper Pliocene

The BUTp (base Upper Pliocene) reflector is the base of a seismic section which shows progradation from the east. Low angle clinoforms with rather good continuity are typical for most of the area covered by the profiles (Fig. 2). The westernmost parts seem to be in a distal position relative to the source area, and here the clinoforms are very gently dipping or give way to parallel, nearly horizontal reflections.

The BUTp reflector is correlated to the base of the Upper Pliocene in the wells. In 2/4-C-11 logs, the reflector is picked at the base of a section with upward coarsening, silty clay succession. In 15/12–3, the reflector corresponds to the top of the sands of the Utsira Formation.

Profile B1–B6 (Fig. 4) shows the decreasing thickness of the Upper Pliocene clays from the Central Graben depocenter towards the Sleipner area. In the northern part of the profile, some channel-like features are noted in the lower part of the sequence. Across these features, reflectors seem to be deformed into synclines, which were filled in with flat-lying sediments. The seismic pattern indicates soft sediment deformation involving the underlying Upper Miocene–Lower Pliocene sediments. Soft sediment deformation is extensively developed further north, in the Utsira Formation.

Upper Miocene and Lower Pliocene

The IMM (intra-Middle Miocene) reflector is a prominent seismic boundary which corresponds to the boundary between the Hordaland and Nordland Groups. In the Sleipner area, the seismic unit between the BUTp and IMM reflectors comprises mainly the sandy Utsira Formation, and its character is very different from that of the Ekofisk area.

In the Ekofisk area, the Upper Miocene to Lower Pliocene section consists of parallel, rather continuous, close to horizontal reflectors. The section thickens into the Central Graben depocenter, but there are no clear indications of any direction of progradation. At its base, a faint onlap has been observed on the lower boundary at IMM. In the Ekofisk area, the section may be tentatively divided into a lower part with more continuous internal reflections

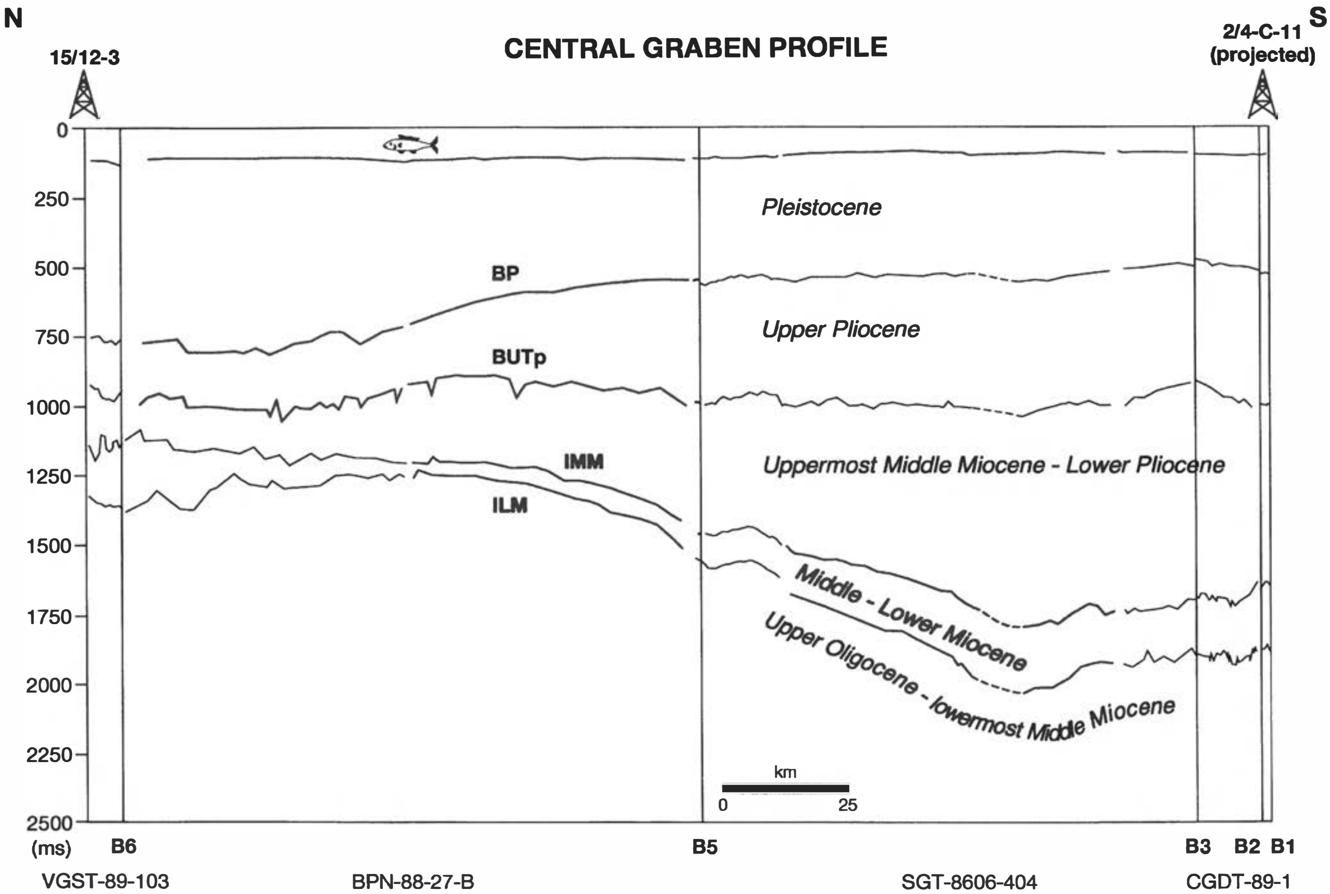


Fig. 4. Interpreted seismic line along the Central Graben through wells 15/12–3 and 2/4-C-11. BP = base Pleistocene, BUTp = base Upper Pliocene, IMM = intra-Middle Miocene, ILM = intra-Lower Miocene.

and an upper part with less continuity. This change takes place within the Upper Miocene, and the Miocene–Pliocene boundary does not seem to have any seismic expression.

At the lower boundary of the interval, the IMM reflector is well defined by a conspicuous change in internal deformation, the underlying unit being strongly faulted. It is known from regional mapping that the IMM reflector commonly defines the top of gas chimneys and that it coincides with the latest phase of major salt movement in the Central Graben. Pressure build-up above hydrostatic commonly starts downhole at the IMM unconformity. However, above the major chalk fields, gas chimneys and undercompacted clays are also encountered in the Upper Miocene and Lower Pliocene succession.

In the Sleipner area, the Upper Miocene and Lower Pliocene succession is thin, and it is locally strongly deformed, apparently by movement of the underlying clays. Locally, onlaps and internal boundaries can be interpreted. The difference in seismic character is related to the facies shift from the clay succession in the south to the sandy Utsira Formation in the north. The IMM reflector at the base of the succession is a deformed surface with variable reflection strength. It corresponds to the base of the Utsira Formation.

In profile B1–B6 (Fig. 4), the deformation of the Miocene in the northern part of line BPN-88-27 coincides with the distribution of the Utsira Formation, which is well constrained by well data. We suggest that the deposition of the sand loaded and facilitated drainage of pore water in the underlying clay, causing synsedimentary deformation.

It should also be noted that the correlation of the BUTp reflector from the south to the north is not straightforward because of the deformation and facies shifts. Biostratigraphic data show that the base of the Upper Pliocene is situated within the Utsira Formation, while the seismic boundary is interpreted on the top of the formation. However, a detailed interpretation is difficult, and much more seismic work would be required to define the exact relation between the upper part of the Utsira Formation and the lower parts of its clay-rich equivalent in the south.

Middle and Lower Miocene

The unit between the ILM (intra-Lower Miocene) and IMM reflectors belongs to the upper part of the Hordaland Group. The ILM reflector is typically developed as the top of a set of strong, continuous reflectors. In the Ekofisk area, the ILM reflector, although faulted, seems to form the base of several small-scale faults which deform the unit above.

Table 1. Samples analysed in wells 2/4-C-11 and 15/12-3. SWC = sidewall core, DC = ditch cutting sample, *samples not included in the range chart because of lack of space.

SAMPLES ANALYSED IN WELL 2/4-C-11

190.0 m SWC	713.3 m DC	1325.9 m DC	1719.9 m Core*
238.0 m SWC	731.5 m DC	1342.0 m SWC	1724.9 m Core
249.0 m SWC	737.0 m SWC	1344.2 m DC	1728.2 m DC
313.0 m SWC	749.8 m DC	1362.0 m SWC*	1745.0 m SWC*
330.0 m SWC	766.0 m SWC	1362.5 m DC	1746.5 m DC
342.0 m SWC	768.1 m DC	1380.7 m DC	1764.8 m DC
347.0 m SWC	786.4 m DC	1400.0 m SWC	1783.1 m DC
360.0 m SWC	804.7 m DC	1405.0 m SWC	1792.0 m SWC
369.0 m SWC	812.0 m SWC	1408.2 m DC	1801.4 m DC
373.0 m SWC*	823.0 m DC	1426.5 m DC	1819.7 m DC
374.7 m Core*	859.5 m DC	1453.9 m DC	1837.9 m DC
374.9 m SWC	877.8 m DC	1472.2 m DC	1852.3 m SWC
383.2 m DC	914.4 m DC	1481.3 m DC	1856.7 m DC
399.0 m SWC	932.7 m DC	1486.0 m SWC	1874.5 m DC
402.0 m SWC	951.0 m DC	1494.0 m SWC	1911.1 m DC
408.0 m SWC	965.0 m SWC	1499.6 m DC	1929.4 m DC
411.0 m DC	978.4 m DC	1517.9 m DC	1953.8 m SWC
421.0 m SWC	996.7 m DC	1536.2 m DC	1956.8 m DC
429.8 m DC	1004.0 m SWC	1556.0 m SWC*	1975.0 m DC
436.0 m SWC	1015.0 m DC	1554.5 m DC	2002.5 m DC
457.0 m SWC*	1033.3 m DC	1557.7 m Core*	2020.5 m DC
457.2 m DC	1051.6 m DC	1559.6 m Core*	2039.1 m DC
475.5 m DC	1069.8 m DC	1563.2 m Core*	2057.4 m DC
487.0 m SWC	1077.0 m SWC	1561.5 m Core*	2084.8 m DC
502.9 m DC	1088.1 m DC	1563.6 m DC	2112.3 m DC
528.2 m Core*	1115.6 m DC	1581.9 m DC	2121.4 m DC
530.3 m DC	1133.9 m DC	1600.2 m DC	2148.8 m DC
535.4 m Core	1161.3 m DC	1618.5 m DC	2167.1 m DC
531.9 m Core*	1166.0 m Core	1629.0 m SWC	2194.6 m DC
540.0 m SWC	1163.4 m Core*	1636.8 m DC	2203.7 m DC
557.7 m DC	1162.6 m Core*	1655.1 m DC	2220.0 m DC
568.0 m SWC	1160.9 m Core*	1664.7 m DC	2240.3 m DC
576.0 m SWC*	1188.7 m DC	1672.0 m SWC*	2258.6 m DC
576.0 m DC	1197.9 m DC	1673.4 m DC	2276.9 m DC
594.5 m DC	1225.3 m DC	1679.0 m SWC	2303.1 m Core*
621.8 m DC	1243.6 m DC	1691.6 m DC	2298.7 m Core
632.0 m SWC*	1261.9 m DC	1707.0 m SWC	2304.3 m DC
630.9 m DC	1280.2 m DC	1709.9 m DC	2322.6 m DC
658.4 m DC	1293.0 m SWC	1710.7 m Core*	2340.9 m DC
665.0 m SWC	1302.0 m SWC	1712.5 m Core*	2357.3 m SWC
676.7 m DC	1307.0 m SWC*	1714.6 m Core	2368.3 m DC
685.8 m DC	1307.6 m DC	1718.2 m Core*	
707.0 m SWC	1314.0 m SWC	1722.2 m Core	

SAMPLES ANALYSED IN WELL 15/12-3

200.0 m DC	620.0 m DC	970.0 m DC	1280.0 m DC
220.0 m DC	640.0 m DC	980.0 m DC	1290.0 m DC
240.0 m DC	660.0 m DC	1000.0 m DC	1300.0 m DC
260.0 m DC	680.0 m DC	1010.0 m DC	1310.0 m DC
280.0 m DC	700.0 m DC	1020.0 m DC	1320.0 m DC
300.0 m DC	720.0 m DC	1040.0 m DC	1330.0 m DC
320.0 m DC	740.0 m DC	1060.0 m DC	1340.0 m DC
340.0 m DC	760.0 m DC	1080.0 m DC	1360.0 m DC
360.0 m DC	780.0 m DC	1100.0 m DC	1370.0 m DC
380.0 m DC	790.0 m DC	1110.0 m DC	1380.0 m DC
400.0 m DC	800.0 m DC	1120.0 m DC	1400.0 m DC
420.0 m DC	820.0 m DC	1140.0 m Dc	1420.0 m DC
440.0 m DC	840.0 m DC	1150.0 m DC	1430.0 m DC
460.0 m DC	850.0 m DC	1160.0 m DC	1440.0 m DC
480.0 m DC	860.0 m DC	1180.0 m DC	1450.0 m DC
500.0 m DC	880.0 m DC	1200.0 m DC	1460.0 m DC
520.0 m DC	890.0 m DC	1220.0 m DC	1480.0 m DC
540.0 m DC	900.0 m DC	1240.0 m DC	1500.0 m DC
560.0 m DC	920.0 m DC	1250.0 m DC	1520.0 m DC
580.0 m DC	940.0 m DC	1260.0 m DC	
600.0 m DC	960.0 m DC	1270.0 m DC	

In the Sleipner area, the ILM reflector commonly defines the base of synsedimentary deformation. The unit between the ILM and IMM thins to the east, and is best developed in the Central Graben depocenter. Fig. 4 shows that the unit is thin in an area between Sleipner and Ekofisk. The ILM reflector can be identified with rather high confidence across this saddle area. Seismically, there is no well-defined boundary below the ILM reflector corresponding to the Oligocene–Miocene boundary.

Material and methods

Micropaleontological analyses

From both wells 2/4-C-11 and 15/12-3, ditch cutting samples were obtained with a 10-m sampling interval through most of the examined sections. In well 2/4-C-11, six conventional cores were taken at the following intervals: 373.5–374.8 m, 527.3–535.7 m, 1160.7–1166.2 m, 1556.9–1563.2 m, 1710.5–1725.5 m and 2297–2305.2 m. Forty-nine sidewall cores were also available from this well. These were taken at variable intervals throughout the investigated section. All the sidewall cores, 21 samples from the conventional cores and most of the available ditch cutting samples were analysed for planktonic and benthonic foraminifera. In addition, the Middle to Upper Miocene section was also analysed for *Bolboforma* (calcareous cysts), and the Upper Oligocene to Lower Miocene section was analysed for diatoms (Table 1).

When drilling with exploration rigs, the sampling does not commence before the well has reached a depth of ca. 100 m below the sea floor. Consequently, the uppermost 84 m of well 2/4-C-11 and 89 m of well 15/12-3 could not be analysed.

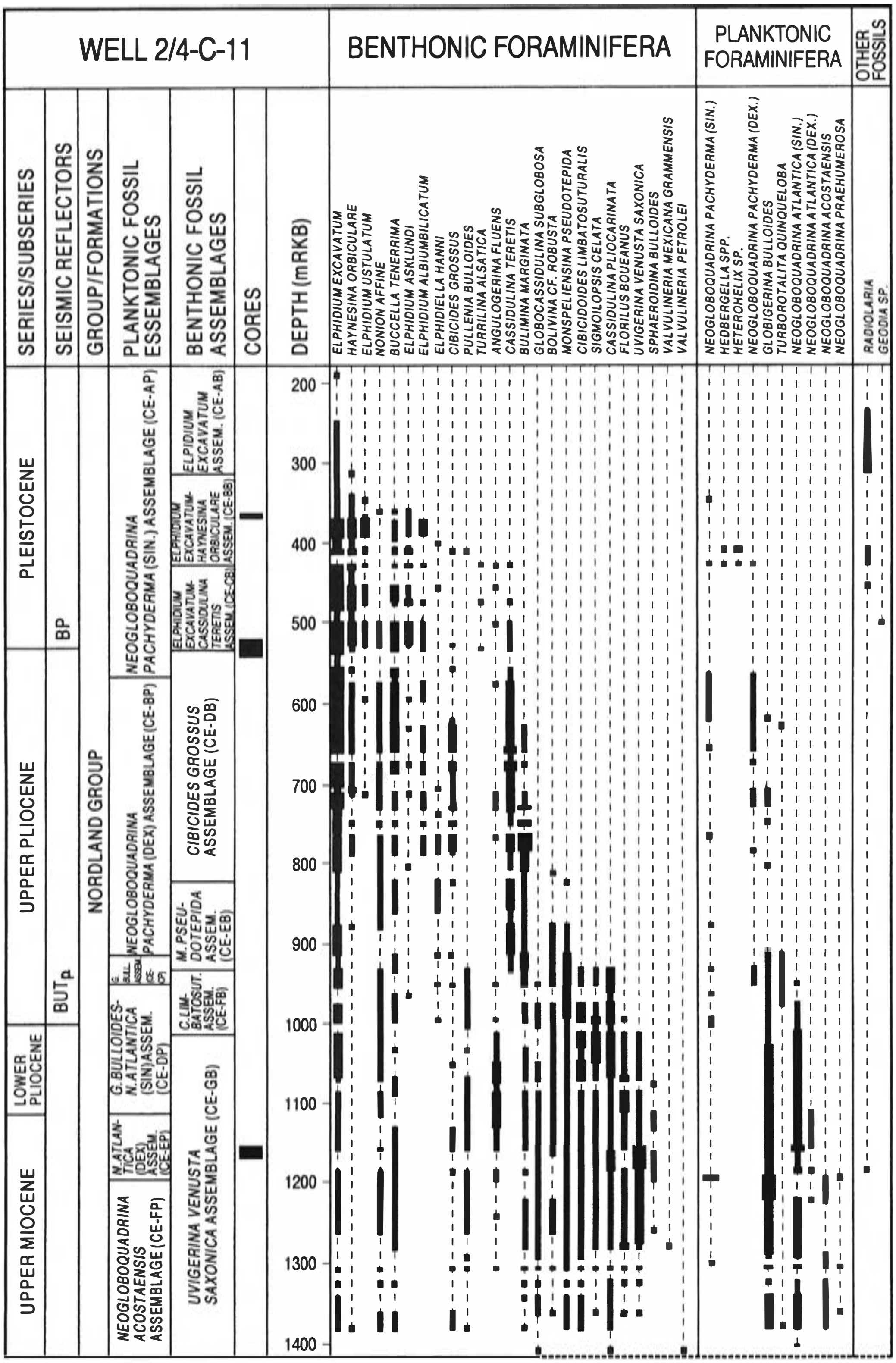
For analyses of conventional core samples and the cuttings, 50–100 g material were used. Only 10–20 g were available from the sidewall cores. The fossil identifications were carried out in the 106–500 μm fraction. In some samples the fractions <63–106 μm and >500 μm were also investigated. Whenever possible, 300 individuals were picked from each sample. In order to identify the microfossil assemblages better, several samples rich in mineral grains were also gravity-separated in a heavy liquid. Consequently, in fossil-rich samples, 1000–1500 individuals were inspected. The stratigraphically important fossils are reported in the range charts in Figs. 5a and b and 7a and b. Eidvin et al. (1993b) present range charts of all registered species in well 2/4-C-11, but without some modifications performed in this study. Complete range charts for well 15/12-3 can be obtained from the first author.

Other analyses

Strontium isotope analyses were performed by the Institute for Energy Technology, Kjeller, Norway, on calcareous material (i.e. mainly tests of calcareous foraminifera and *Bolboforma*). The analysed material was mainly taken from sidewall cores, but conventional core material and one ditch cutting sample, all from well 2/4-C-11, were also included. Ages for these samples were obtained by comparing the $^{87}Sr/^{86}Sr$ ratio to a global strontium isotope curve.

The lithologic analyses are based on visual examination, both of the samples prior to treatment and of the dispersed and fractionated material after preparation. Petrophysical logs were also employed in the descriptions.

A



Water depth: 72 m MSL (106m RKB)

Fig. 5a. Range chart of the stratigraphically important microfossils in the upper part of the investigated interval of well 2/4-C-11. BP = base Pleistocene, BUTp = base Upper Pliocene, mRKB = meters below rig floor, mMSL = meters below mean sea level.

B

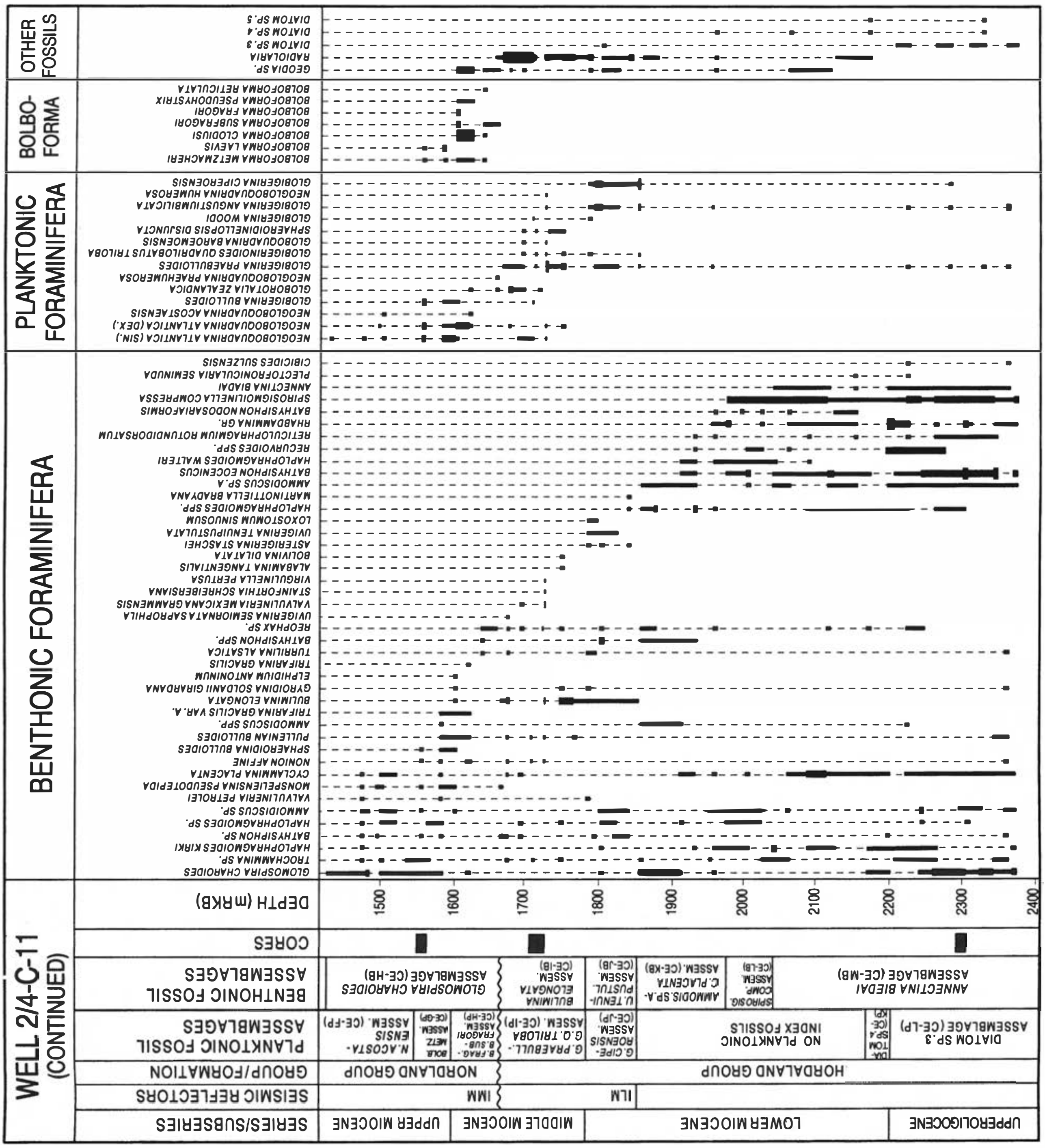


Fig. 5b. Range chart of the stratigraphically important microfossils in the lower part of the investigated interval of well 2/4-C-11. IMM = intra-Middle Miocene, ILM = intra-Lower Miocene, mRKB = meters below rig floor.

Paleomagnetic analyses were performed by CB-Magneto, Stavanger, Norway on material from the two uppermost conventional cores (373.5–374.8 m and 527.2–535.7 m).

Biostratigraphic correlation

The standard Cainozoic biostratigraphic scheme is based on planktonic foraminifera and calcareous nannoplankton established for tropic and subtropic areas. Towards the north the assemblages become progressively less diverse, and many key species are missing in the North Sea (King 1983).

The fossil assemblages in the wells 2/4-C-11 and 15/12-3 are primarily correlated with the biozonation of King (1983, 1989), where a micropalaeontological zonation for Cainozoic sediments of the North Sea is outlined.

Gradstein & Bäckström's (1996) faunal zonation from the North Sea and Haltenbanken is also extensively used. In the Pleistocene sections the work of Knudsen & Asbjörndóttir (1991) is used. In addition, several articles that describe benthonic foraminifera from onshore basins from the area surrounding central and southern North Sea are used. Correlation with the planktonic foraminifer zones of Poore (1979), Weaver (1987), Weaver & Clement (1986, 1987) and Spiegler & Jansen (1989) and the *Bolboforma* zones of Quale & Spiegler (1989), Spiegler & Müller (1992) and Müller & Spiegler (1993), established through ODP/DSDP drilling in the Norwegian Sea and the North Atlantic, is especially important for dating of the sediments. Correlating with these zones may also yield quite accurate ages, since the zones are calibrated with nannoplankton and paleomagnetic data. The zonations of King (1983, 1989) and Gradstein & Bäckström (1996) are based on the last appearance datums (LADs) of the various taxa. The zonations of planktonic foraminifera and *Bolboforma* from the ODP/DSDP drilling are based on the first appearance datums (FADs). It is important to note that King (1989) was published prior to the publications of ODP Leg 104 on the Vøring Plateau in the Norwegian Sea. Consequently, the ages of King's planktonic foraminifer and *Bolboforma* zones differ somewhat from the ages of corresponding planktonic foraminifer zones of Spiegler & Jansen (1989) and *Bolboforma* zones of Quale & Spiegler (1989), and especially the revised *Bolboforma* zonation of Müller & Spiegler (1993).

The fossil assemblages are somewhat different in the two investigated areas. The main difference is a larger proportion of agglutinated forms in Miocene and Oligocene deposits in the Ekofisk area compared to the Sleipner site. Consequently, we describe the faunal trends at each site separately.

Stratigraphy of well 2/4-C-11

Fossil assemblages

In this well, a system of 13 assemblages based on benthonic foraminifera (CE-AB to CE-MB) and 12 assemblages based on planktonic fossils (CE-AP to CE-LP) is devised. The boundaries between the assemblages are based on the LADs of selected taxa, which have been chosen because of their chronostratigraphic importance. Most of the selected taxa have well-documented, consistent ranges on a regional scale. The assemblages are described from top to base of the succession, following the order in which they are normally encountered in offshore borehole studies. Abbreviations of the assemblage designations are as follows: C = Central North Sea, E = Ekofisk Field, B = Benthonic and P = Planktonic (Figs. 5a, b, 8, 9).

Benthonic assemblages

ELPHIDIUM EXCAVATUM ASSEMBLAGE

Designation: CE-AB.

Definition: The top of the assemblage extends to the uppermost investigated sample (190 m). The base is marked by the highest occurrence of *Haynesina orbiculare*.

Depth range: 190–313 m.

Material: Three very small sidewall cores.

Age: Middle to Late Pleistocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Zone NSB 17 of King (1983) and probably Zones Jo 4 and Jo 5 of Knudsen & Asbjörndóttir (1991).

Description: Very few foraminifera occur in these small sidewall cores. Rare occurrences of *E. excavatum* and *Elphidium* sp. are the only representatives (Fig. 5a).

Remarks: This interval contains so few foraminifera that it is difficult make a good correlation. However, the assemblage is clearly of Pleistocene age (see below).

ELPHIDIUM EXCAVATUM – HAYNESINA ORBICULARE ASSEMBLAGE

Designation: CE-BB.

Definition: The top of the assemblage is taken at the highest occurrence of *H. orbiculare*. The base is marked by the highest occurrence of *Cassidulina teretis*.

Depth range: 313–429.8 m.

Material: One conventional core sample at 374.7 m, 11 sidewall cores and three ditch cutting samples.

Age: Early Pleistocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Zone Jo 6 of Knudsen & Asbjörndóttir (1991) and Zone NSB 17 of King (1983).

Description: This assemblage contains a medium-rich benthonic fauna of calcareous foraminifera. *E. excavatum* and *H. orbiculare* occur most frequently. Other characteristic species include *Elphidium ustulatum*, *Buccella tenerrima*, *Elphidium asklundi* and *Elphidium albiumbilicatum* (Fig. 5a). Mollusc fragments are also common.

Remarks: The benthonic foraminifera in this assemblage are characteristic Pliocene–Pleistocene taxa. All the recorded species are extant. Knudsen & Asbjörndóttir (1991) have described an *E. excavatum – H. orbiculare* assemblage Zone (Jo 6) from the Josephine boring (30/13-2x) in the easternmost part of the British sector. Correlation based on benthonic foraminifera between 30/13-2x and the BGS borehole BH 81/34 indicates that Zone Jo 6 is slightly older than the Brunhes/Matuyama boundary (Knudsen & Asbjörndóttir 1991). BH 81/34 has been cored, and the cores have been magneto-stratigraphically investigated (Stoker et al. 1983). In well 2/4-C-11, material in the core present at 373.5–374.8 m shows reverse polarity, which supports deposition during the Matuyama Chron.

CASSIDULINA TERETIS – ELPHIDIUM EXCAVATUM ASSEMBLAGE

Designation: CE-CB.

Definition: The top of the assemblage is taken at the highest occurrence of *C. teretis*. The base is marked by the highest occurrence of *Cibicides grossus*.

Depth range: 429.8–530.3 m.

Material: One conventional core sample at 528.2 m, three sidewall cores and four ditch cutting samples.

Age: Early Pleistocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Zone Jo 7 of Knudsen & Asbjörndóttir (1991), Zone NSR 13 of Gradstein & Bäckström (1996) and Zone NSB 17 of King (1983).

Description: This assemblage contains a rich benthonic fauna of calcareous foraminifera. *E. excavatum* occurs frequently throughout. Other important species include *H. orbiculare*, *E. ustulatum*, *B. tenerrima*, *E. asklundi* and *C. teretis* (Fig. 5a). Mollusc fragments are also common.

Remarks: The foraminifera in this assemblage are characteristic Pliocene–Pleistocene taxa. All the recorded species are extant. Knudsen & Asbjörndóttir (1991) describe a *C. teretis – E. excavatum* assemblage Zone (Jo 7) in Lower Pleistocene sediments of borehole 30/13-2x.

CIBICIDES GROSSUS ASSEMBLAGE

Designation: CE-DB.

Definition: The top of the assemblage is taken at the highest occurrence of *C. grossus*. The base is marked by the highest occurrence of *Monspeliensina pseudotepida*.

Depth range: 530.3–823 m.

Material: Two conventional core samples at 531.9 and 535.4 m, nine sidewall cores and 15 ditch cutting samples.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Subzones NSB 15a and b of King (1989), Zone Jo 8 of Knudsen & Asbjörndóttir (1991), *C. grossus* Zone of Pedersen (1995) and Zone NSR 12B of Gradstein & Bäckström (1996).

Description: This interval contains a rich benthonic fauna of calcareous foraminifera. *E. excavatum* and *C. teretis* occur most frequently. Other important species include *Bulimina marginata*, *C. grossus*, *H. orbiculare*, *N. affine*, *B. tenerrima*, *E. albiumbilicatum* and *Elphidiella hannai* (lower part) (Fig. 5a).

Remarks: King (1989), Gradstein & Bäckström (1996), Knudsen & Asbjörndóttir (1991) and Pedersen (1995) place the Pliocene/Pleistocene boundary at the highest occurrence of *C. grossus*. According to Knudsen & Asbjörndottir (1991) and Pedersen (1995), the age of the Pliocene/Pleistocene boundary is 2.3 m.y. based on Zagwijn (1985, 1989). However, King (1989) gives this boundary an age of 1.61 m.y. based on Berggren et al. (1985). A calibration of the *C. grossus* Zone (CE-DB) in well 2/4-C-11 based on a comparison with the planktonic foraminiferal zones indicates that the top of the *C. grossus* Zone is close to ca. 1.6 m.y. in this area. However, the core at 527.3–535.7 m shows reverse polarity, indicating deposition slightly before or slightly after the Olduvai normal polarity Subchron (1.66–1.88 Ma).

MONSPELIENSINA PSEUDOTEPIDA ASSEMBLAGE

Designation: CE-EB.

Definition: The top of the assemblage is placed at the highest occurrences of *M. pseudotepida*. The base is defined by the highest occurrence of *Cibicidoides limbatosuturalis*.

Depth range: 823–932.7 m.

Material: Two sidewall cores and four ditch cutting samples.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Subzone NSB 14b of King (1989), Zone NSR 12A of Gradstein & Bäckström (1996) and Zone Jo 10 of Knudsen & Asbjörndóttir (1991).

Description: This assemblage contains a rich benthonic fauna of mainly calcareous foraminifera. A few agglutinated taxa are also present. *C. teretis*, *B. marginata*, *M. pseudotepida* and *E. excavatum* are common. Other characteristic species include *N. affine* and *B. tenerrima* (Fig. 5a).

Remarks: A *M. pseudotepida* Subzone (NSB 14b) is described from lower part of Upper Pliocene in the North Sea (King 1989).

C. grossus and *E. hannai* are also recorded in assemblage CE-EB in ditch cutting samples. These forms are not recorded in sidewall cores, indicating that the specimens are caved.

CIBICIDOIDES LIMBATOSUTURALIS ASSEMBLAGE

Designation: CE-FB.

Definition: The top of the assemblage is taken at the highest occurrence of *C. limbatosuturalis*. The base is marked by the highest occurrence of *Uvigerina venusta saxonica*.

Depth range: 932.7–1015 m.

Material: Two sidewall cores and four ditch cutting samples.

Age: Early to Late Pliocene.

Lithostratigraphic unit: Nordland group.

Correlation: Subzone NSB 14a of King (1989).

Description: This interval is characterized by a rich benthonic fauna of mainly calcareous foraminifera. Taxa are slightly more numerous in this assemblage than in the immediately overlying section. *M. pseudotepida* and *Cassidulina pliocarinata* occur frequently throughout. Other important species include *C. limbatosuturalis*, *N. affine*, *Pullenia bulloides*, *B. marginata*, *Sigmoilopsis celata* (agglutinated), *Bolivina* cf. *robusta*, *Globocassidulina subglobosa* and *E. excavatum* (Fig. 5a).

Remarks: King (1989) describes a *C. limbatosuturalis* Subzone (NSB 14a) from Lower to Upper Pliocene in the North Sea. According to King (1989), the lower part of Subzone NSB 14a is close to the Lower/Upper Pliocene boundary.

E. excavatum is recorded in ditch cutting samples, not in sidewall cores, indicating that this species is caved.

UVIGERINA VENUSTA SAXONICA ASSEMBLAGE

Designation: CE-GB.

Definition: The top of the assemblage is defined by the highest occurrence of *U. venusta saxonica*. The base is indicated by the highest occurrence of *Glomospira charoides*.

Depth range: 1015–1426.5 m.

Material: Three conventional core samples from 1162.6–1166 m, nine sidewall cores and 20 ditch cutting samples.

Age: Late Miocene to Early Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Zone NSB 13 of King (1989).

Description: This interval contains a very rich benthonic fauna of mainly calcareous foraminifera. Taxa are even more numerous in this assemblage than in the immediately overlying assemblage. *U. venusta saxonica*, *Florilus boueanus*, *C. pliocarinata* and *C. limbatosuturalis* occur most frequently. Other important species include *Bolivina* cf. *robusta*, *G. subglobosa*, *B. marginata*, *A. fluens*, *P. bulloides* and *N. affine* (Figs. 5a, b).

Remarks: An *U. venusta saxonica* Zone (NSB 13) is described from Upper Miocene to Lower Pliocene deposits in the North Sea (King 1989).

GLOMOSPIRA CHAROIDES ASSEMBLAGE

Designation: CE-HB.

Definition: The top of the assemblage is defined by the highest occurrence of *G. charoides*. The base is indicated by the highest consistent occurrence of *Bulimina elongata*.

Depth range: 1426.5–1664.7 m.

Material: Three conventional core samples from 1559.6–1563.2 m, four sidewall cores and 14 ditch cutting samples.

Age: Middle to Late Miocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Zone NSA 12 of King (1989) and probably Zone NSR 9B of Gradstein & Bäckström (1996).

In-place assemblage composition: There are significantly fewer foraminifera in this interval than in the overlying assemblages. Both agglutinated and calcareous taxa are present, but the agglutinated species are dominant. *G. charoides* is the most common agglutinated species. Other important agglutinated taxa include *Bathysiphon* ? sp. A (King 1989), *Bathysiphon* spp., *Trochammina* spp., *Cyclammina placenta*, *Haplophragmoides* spp. and *Ammodiscus* sp. *M. pseudotepida*, *Eponides umbonatus*, *Sphaeroidina bulloides*, *N. affine* and *P. bulloides* are the dominant calcareous taxa. In addition, sponge spicules (rod-shaped and *Geodia* sp.) occur in this assemblage (Fig. 5b).

Reworked assemblage composition: Valvulineria petrolei, *Trifarina gracilis*, *Gyroidina soldanii girardana*, *Elphidium antoninum* and *Turrilina alsatica* are recorded from the lower part of the interval. These taxa have been derived from Upper Oligocene to Lower Miocene sediments.

Remarks: King (1989) describes an unnamed Zone (NSA 12), which is the youngest significant assemblage with agglutinated foraminifera in the North Sea, characterized mainly by long-ranging species. This zone is known from Middle to Upper Miocene sediments. The base of assemblage CE-HB coincides with a regional seismic reflector.

BULIMINA ELONGATA ASSEMBLAGE

Designation: CE-IB.

Definition: The top of the assemblage is taken at the highest occurrence of *B. elongata*. The base is marked by the highest occurrence of *Uvigerina tenuipustulata*.

Depth range: 1664.7–1783.1 m.

Material: Seven conventional core samples from 1710.7–1724.9 m, three sidewall cores and six ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Probably Subzone NSB 12a and Zone NSB 11 of King (1989) and probably Zone NSR 8B of Gradstein & Bäckström (1996).

Description: There are even fewer foraminifera in this assemblage than in the immediately overlying assemblage. Both calcareous and agglutinated taxa are present. Calcareous taxa are somewhat more numerous. *B. elongata* is most common. Other characteristic species include *P. bulloides*, *Valvulineria mexicana grammensis*, *Stainforthia schreibersina*, *Virgulinella pertusa*, *Bolivina dilatata*, *T. alsatica*, *Alabamina tangentialis* and *Uvigerina semiornata saprophila*. *C. placenta*, *G. charoides*, *Trochammina* sp., *Bathysiphon* sp. and *Reophax* sp. are the most important agglutinated taxa (Fig. 5b).

Remarks: According to King (1989), the LAD of *B. elongata* is observed somewhat above the Middle/Upper Miocene boundary, but this form is common only in the Middle Miocene. *U. semiornata saprophila* (recorded at one level in the middle part of the unit), *B. dilatata*, *A. tangentialis*, *S. schreibersiana* and *V. pertusa* are known from the lower part of Middle Miocene (King 1989; Doppert 1980). The index fossils of Subzones NSB 12a and b (middle part of the Middle Miocene), designated by King (1989), are missing in this interval. This indicates that this unit only represents sediments of the lower part of the Middle Miocene and that there is a hiatus between this unit and the overlying unit. *T. alsatica* is probably reworked from Oligocene deposits.

UVIGERINA TENUIPUSTULATA ASSEMBLAGE

Designation: CE-JB.

Definition: The top of the assemblage is defined by the highest occurrence of *U. tenuipustulata*. The base is marked by the highest occurrence of *Ammodiscus* sp. A (King 1989).

Depth range: 1783.1–1856.7 m.

Material: The assemblage has been observed in two sidewall cores and four ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSB 10 of King (1989), lower part of Zone NSR 8B of Gradstein & Bäckström (1996) and Zone FD of Doppert (1980).

Description: In this interval, foraminifera are as sparse as in the immediately overlying assemblage. Both agglutinated and calcareous taxa are present. Calcareous forms are most important in the upper part of the assemblage, and agglutinated forms are most common in the lower part. *B. elongata* is the most frequent calcareous form. Other characteristic calcareous taxa include *U. tenuipustulata*, *A.*

querichi staeschei, *V. petrolei* and *Loxostomum sinuosum*. *G. charoides*, *Bathysiphon* spp., *Martinottiella bradyana*, *Haplohragmoides* spp. and *Ammodiscus* sp. are the most important agglutinated taxa (Fig. 5b).

Remarks: King (1989) defined an *U. tenuipustulata* Zone (NSB 10) from the upper part of the Lower Miocene in the North Sea. According to King (1989), the LAD of *A. staeschei* is in the lower part of the Middle Miocene. In well 2/4-C-11, *A. querichi staeschei* does not reach higher than *U. tenuipustulata*. This may indicate that *A. querichi staeschei* is caved from the overlying interval, without being recorded there, or that the LAD of this form is different in well 2/4-C-11 than in the zonation of King (1989). The base of the CE-JB assemblage coincides with a regional seismic reflector.

AMMODISCUS SP. A – *CYCLAMMINA PLACENTA* ASSEMBLAGE

Designation: CE-KB.

Definition: The top of the assemblage is taken at the highest occurrence of *Ammodiscus* sp. A. The base is marked by the highest occurrence of *Spirosigmoilinella compressa*, which is synonymous with *Spirosigmoilinella* sp. A of King (1989) according to S. Bäckström and F. Gradstein (personal communication 1998).

Depth range: 1856.7–1975 m.

Material: One sidewall core and five ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Probably lower part of Zone NSA 11 of King (1989) and lower part of Zone NSR 8B of Gradstein & Bäckström (1996).

Description: This assemblage contains a rich benthonic fauna of agglutinated foraminifera. *G. charoides* is most common. Other important taxa include *Ammodiscus* sp. A, *Ammodiscus* spp., *C. placenta*, *Reticulophragmium rotundidorsatum*, *Haplophragmoides* spp., *Bathysiphon* spp., *Haplophragmoides walteri* and *Bathysiphon eocenicus* (Fig. 5b).

Remarks: According to King (1989), the LAD of *Ammodiscus* sp. A in the lower part of the Lower Miocene is slightly above the LAD of *S. compressa*. This is also the case in well 2/4-C-11.

SPIROSIGMOILINELLA COMPRESSA ASSEMBLAGE

Designation: CE-LB.

Definition: The top of the assemblage is taken at the highest occurrence of *S. compressa*. The base is marked the highest occurrence of *Annectina biedai* (Gradstein & Kaminski 1997), which is synonymous with *Ammodiscus* sp. B of King (1989) according to S. Bäckström and F. Gradstein (personal communication 1998).

Depth range: 1975–2039.1 m.

Material: Three ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSA 10 of King (1989) and lower part of Zone NSR 8B of Gradstein & Bäckström (1996).

Description: A rich foraminiferal fauna of agglutinated species is found in this unit. *S. compressa* appears frequently throughout the entire unit. Other important taxa include *C. placenta*, *H. walteri*, *B. eocenicus*, *B. nodosariformis* and *Recurvoides* spp. (Fig. 5b).

Remarks: King (1989) describes a *Spirosigmoilinella* sp. A (synonymous with *S. compressa*) Zone (NSA 10) in Lower Miocene deposits in the North Sea.

ANNECTINA BIEDAI ASSEMBLAGE

Designation: CE-MB.

Definition: The top of the assemblage is taken at the highest occurrence of *A. biedai*. The base of the assemblage is undefined.

Depth range: 2039.1–2368.3 m (lowermost studied sample).

Material: Two conventional core samples at 2298.7 and 2303.1 m, one sidewall core and 17 ditch cutting samples.

Age: Late Oligocene to Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSA 9 and probably the lower part of Zone NSR 8A of King (1989), and the upper part of Zone NSR 7A of Gradstein & Bäckström (1996).

Description: This interval contains a rich benthonic fauna of mainly agglutinated foraminifera. *S. compressa*, *B. eocenicus* and *C. placenta* all occur frequently throughout. Other important species include *Ammodiscus* sp. A, *A. biedai*, *R. rotundidorsatum* and *Rhabdammina* (Fig. 5b).

The calcareous forms have sporadic occurrences with the following taxa present: *Plectofrondicularia seminuda*, *Cibicides sulzensis* and *Rolfina arnei*. According to Laursen (1994), *R. arnei* is synonymous with *Rotalia* sp. 1 of Larsen & Dinesen (1959) and *Glabratella* ? sp. A of King (1989).

Remarks: King (1989) described an *Ammodiscus* sp. B (synonymous with *A. biedai*) Zone (NSA 9) from Upper Oligocene to Lower Miocene sediments in the North Sea. *P. seminuda* is known from the Lower Oligocene to the Lower Miocene in the North Sea (King 1989). *C. sulzensis* is described from Oligocene deposits on the Norwegian continental shelf (Skarbø & Verdenius 1986). *R. arnei* is recorded from Upper Oligocene to Lower Miocene deposits in Denmark (Larsen & Dinesen 1959) and in the North Sea (King 1989; Laursen 1994).

Planktonic assemblages

NEOGLOBOQUADRINA PACHYDERMA (SINISTRAL) ASSEMBLAGE

Designation: CE-AP.

Definition: The top of the assemblage extends to the uppermost investigated sample (190 m). The base of the assemblage is marked by the highest consistent occurrence of *N. pachyderma* (dextral).

Depth range: 190–568 m.

Material: One conventional core sample at 374.7 m and three conventional core samples from 528.2–535.4 m, 18 sidewall cores and nine ditch cutting samples.

Age: Pleistocene.

Lithostratigraphic unit: Nordland Group.

Correlation: N. pachyderma (sinistral) Zone of Weaver & Clement (1986), *N. pachyderma* (sinistral) Zone of Spiegler & Jansen (1989) and Subzone NSP 16b of King (1989).

Description: Very few planktonic foraminifera are recorded from this unit. Sporadic occurrences of *N. pachyderma* (sinistral), *N. pachyderma* (dextral) (in one interval) and the reworked Upper Cretaceous forms *Hedbergella* sp. and *Heterohelix* sp. are the only representatives (Fig. 5a).

Remarks: A *N. pachyderma* (sinistral) Zone is described by Weaver & Clement (1986) from the North Atlantic and by Spiegler & Jansen (1989) from the Vøring Plateau in sediments younger than 1.7 Ma. At these open ocean sites, an encrusted variety of the sinistrally coiled *N. pachyderma* dominates over an unencrusted form. The encrusted variety occurs only very sporadically in older sediments, but the unencrusted variety also occurs in older Pliocene deposits. In well 2/4-C-11, only *N. pachyderma* (sinistral, unencrusted) is recorded. The reason for this is not that the deposits are older than 1.7 Ma, but probably that the specimens registered in this interval are small juvenile forms, and that the larger encrusted forms have not reached this shallow marine area.

NEOGLOBOQUADRINA PACHYDERMA (DEXTRAL) ASSEMBLAGE

Designation: CE-BP.

Definition: The top of the assemblage is taken at the highest consistent occurrence of *N. pachyderma* (dextral). The base is placed at the highest consistent occurrence of *Globigerina bulloides*.

Depth range: 568–914.4 m.

Material: Seven sidewall cores and 16 ditch cutting samples.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: N. pachyderma (dextral) Zone of Weaver (1987), Weaver & Clement (1987) and Spiegler & Jansen (1989) and Subzone NSP 16a of King (1989).

Description: Although planktonic foraminifera are sparse in this interval, they are significantly more common than in the immediately overlying section. *N. pachyderma* (dextral) are dominant. Other species include *N. pachyderma* (sinistral, unencrusted), *G. bulloides* and *Turborotalia quinqueloba* (Fig. 5a).

Remarks: A *N. pachyderma* (dextral) Zone is described by Weaver (1987) and Weaver & Clement (1987) from the North Atlantic (DSDP Leg 94) and by Spiegler & Jansen (1989) from the Vøring Plateau in Upper Pliocene deposits. On the Vøring Plateau the zone is accurately dated to 1.84–1.7 Ma.

GLOBIGERINA BULLOIDES ASSEMBLAGE

Designation: CE-CP.

Definition: The top of the assemblage is taken at the highest consistent occurrence of *G. bulloides*. The base is marked by the highest occurrence of *Neogloboquadrina atlantica* (sinistral).

Depth range: 914.4–951 m.

Material: Two ditch cutting samples.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Globigerina bulloides Zone of Weaver & Clement (1986).

Description: Planktonic foraminifera are significantly more common in this assemblage than in the immediately overlying section. *G. bulloides* and *T. quinqueloba* occur most frequently. Other species include *N. pachyderma* (sinistral, unencrested) and *N. pachyderma* (dextral) (Fig. 5a).

Remarks: A *G. bulloides* Zone is described from the North Atlantic (DSDP Leg 94) in Upper Pliocene deposits and is accurately dated to 2.3–2.1 Ma (Weaver & Clement 1986).

GLOBIGERINA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: CE-DP.

Definition: The top of the assemblage is taken at the highest occurrence of *N. atlantica* (sinistral). The base is taken at the highest occurrence of *N. atlantica* (dextral).

Depth range: 951–1115.6 m.

Material: Three sidewall cores and eight ditch cutting samples.

Age: Early to Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: N. atlantica (sinistral) Zone of Weaver & Clement (1986), *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989) and Subzone NSP 15d of King (1989).

Description: This interval contains a rich planktonic foraminiferal fauna. *G. bulloides* and *N. atlantica* (sinistral) occur frequently throughout the unit. *N. pachyderma* (sinistral, unencrusted) is recorded from the upper part of the interval (Fig. 5a).

Remarks: A *N. atlantica* (sinistral) Zone is described from the North Atlantic in Upper Pliocene deposits (Weaver & Clement 1986), and from the Vøring Plateau in Lower to Upper Pliocene deposits (Spiegler & Jansen 1989). The LAD of *N. atlantica* (sinistral) is, in both areas, ca. 2.3 Ma (Weaver & Clement 1986; Spiegler & Jansen 1989). On the Vøring Plateau, there is a marked dominance of this species together with *G. bulloides* in Pliocene deposits older than this. *G. bulloides* is also found in the warmest interglacials of the last 1 Ma, however (Kellogg 1977).

NEOGLOBOQUADRINA ATLANTICA (DEXTRAL) ASSEMBLAGE

Designation: CE-EP.

Definition: The top of the assemblage is defined by the highest occurrence of *N. atlantica* (dextral). The base is characterized by the highest occurrence of *Neogloboquadrina acostaensis*.

Depth range: 1115.6–1197.9 m.

Material: Three conventional core samples from 1162.6–1166 m and four ditch cutting samples.

Age: Late Miocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989) and upper part of *N. atlantica* (dextral)/*N. acostaensis* Zone of Weaver (1987) and Weaver & Clement (1987).

Description: This assemblage contains a rich planktonic foraminiferal fauna, where *G. bulloides* and *N. atlantica* (sinistral) are most common. *N. atlantica* (dextral) also occurs throughout (Fig. 5a).

Remarks: Spiegler & Jansen (1989) describe a lower *N. atlantica* (dextral) Zone from Upper Miocene sediments on the Vøring Plateau. Weaver (1987) and Weaver & Clement (1987) report a *N. atlantica* (dextral)/*N. acostaensis* Zone from Upper Miocene sediments in the North Atlantic (DSDP Leg 94).

NEOGLOBOQUADRINA ACOSTAENSIS ASSEMBLAGE

Designation: CE-FP.

Definition: The top of the assemblage is taken at the highest occurrence of *N. acostaensis*. The base is taken at the highest occurrence of *Bolboforma metzmacheri*.

Depth range: 1197.9–1554.5 m.

Material: Ten sidewall cores and 18 ditch cutting samples.

Age: Late Miocene.

Lithostratigraphic unit: Nordland Group.

Correlation: N. acostaensis Zone of Spiegler & Jansen (1989), lower part of *N. atlantica* (dextral)/*N. acostaensis* Zone of Weaver (1987) and Weaver & Clement (1987) and Subzone NSP 15a of King (1989).

Description: The upper part of this assemblage contains a moderately rich planktonic foraminiferal fauna. In the lower part planktonic foraminifera are much less frequent. Pyritized diatoms occur sporadically throughout the interval. *G. bulloides*, *N. atlantica* (sinistral) and *N. acostaensis* occur most frequently. Other species include *Globorotalia puncticulata*, *Neogloboquadrina praehumerosa* and *N. atlantica* (dextral) (Figs. 5a, b).

Remarks: *N. acostaensis* is reported from deposits of Late to Middle Miocene age on the Vøring Plateau (Spiegler & Jansen 1989; Müller & Spiegler 1993). Weaver (1987) and Weaver & Clement (1987) describe a *N. atlantica* (dextral)/*N. acostaensis* Zone from the Upper Miocene in the North Atlantic. King (1989) describes a *N. acostaensis* Zone above a *B. metzmacheri* Zone from the Upper Miocene in the North Sea.

BOLBOFORMA METZMACHERI ASSEMBLAGE

Designation: CE-GP.

Definition: The top of the assemblage is taken at the highest occurrence of *B. metzmacheri*. The base is marked by the highest occurrence of *Bolboforma fragori* and *B. subfragori*.

Depth range: 1554.5–1600.2 m.

Material: Three conventional core samples from 1559.6–1563.2 m, one sidewall core and three ditch cutting samples.

Age: Late Miocene.

Lithostratigraphic unit: Nordland Group.

Correlation: B. metzmacheri Zone of Spiegler & Müller (1992) and Müller & Spiegler (1993), Zone NSR 10 of Gradstein & Bäckström (1996) and Subzone NSP 14b of King (1983).

Description: This assemblage contains a rich planktonic fauna of foraminifera and *Bolboforma*. The most important foraminfera are *N. atlantica* (sinistral) and *N. atlantica* (dextral). *N. continuosa* and *Orbulina universa* are also recorded. *B. laevis* is the most common *Bolboforma*. *B. metzmacheri* is also recorded (Fig. 5b).

Remarks: The stratigraphically important planktonic foraminifera registered in this interval are mentioned above. *B. metzmacheri* is described from deposits with an age of 9.2–7.9 Ma from the North Atlantic and the Vøring Plateau (Spiegler & Müller 1992; Müller & Spiegler 1993).

BOLBOFORMA FRAGORI – BOLBOFORMA SUBFRAGORI ASSEMBLAGE

Designation: CE-HP.

Definition: The top of the assemblage is taken at the highest occurrence of *B. fragori* and *B. subfragori*. The base is marked by the highest occurrence of *Globigerina praebulloides*.

Depth range: 1600.2–1664.7 m.

Material: One sidewall core and four ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Nordland Group.

Correlation: *B. fragori*/*B. subfragori* Zone of Spiegler & Müller (1992) and Müller & Spiegler (1993) and Subzone NSP 14a of King (1983).

Description: The upper part of this interval contains a moderately rich planktonic fauna, while its lower part contains a sparse planktonic assemblage. *Bolboforma* are dominant, with subordinate foraminifera. *B. clodiusi* and *B. subfragori* are the most common *Bolboforma* species. *B. fragori*, *B. pseudohystrix* and one specimen of *B. reticulata* are also recorded. *N. atlantica* (dextral) is the most important foraminifer. Other foraminifera include *N. atlantica* (sinistral), *N. acostaensis*, *N. pachyderma* (sinistral, unencrusted) and the *Globorotalia zealandica*/*G. praescitula* group (Fig. 5b).

Remarks: The known stratigraphic ranges of the most important planktonic foraminifera are discussed above under the descriptions of assemblages CE-EP and CE-FP. A *B. fragori*/*B. subfragori* Zone is described from deposits with an age of ca. 11.5–9.6 Ma from the North Atlantic and the Vøring Plateau (Spiegler & Müller 1992; Müller & Spiegler 1993).

Poore (1979) describes *G. zealandica* and *G. praescitula* from Lower Miocene to lower Middle Miocene deposits of the North Atlantic (Leg 49). These foraminifera have probably been reworked from deposits which correspond to the immediately underlying assemblage. The base of assemblage CE-HP coincides with a regional seismic reflector which represents a depositional hiatus.

GLOBIGERINA PRAEBULLOIDES – GLOBIGERINOIDES QUADRILOBATUS TRILOBA ASSEMBLAGE

Designation: CE-IP.

Definition: The top of the assemblage is taken at the highest occurrence of *G. praebulloides*. The base is marked by the highest occurrence of *Globigerina ciperoensis*.

Depth range: 1664.7–1783.1 m.

Material: Seven conventional core samples from 1710.7–1724.9 m, three sidewall cores and six ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSP 12 of King (1983) and Zone NSR 8B of Gradstein & Bäckström (1996).

Description: This assemblage contains a rich planktonic fauna of foraminifera and radiolaria, where *G. praebulloides* is the most common foraminifer. Other species include *G. quadrilobatus triloba*, *G. zealandica/G. praescitula* and *Sphaeroidinellopsis disjuncta* (Fig. 5b).

Remarks: G. quadrilobatus triloba is described from Middle Miocene deposits in the North Sea (King 1983). *G. zealandica/G. praescitula* are described from the Lower Miocene to lower Middle Miocene in the North Atlantic (Leg 49) (Poore 1979) and in the North Sea (King 1983). *G. praebulloides* is known from Oligocene to lower Upper Miocene (common in Middle Miocene) deposits in the North Atlantic (Poore 1979) and from Oligocene to lower Middle Miocene deposits in the North Sea (Gradstein & Bäckström 1996). Poore (1979) suggests that a clear separation of *G. praebulloides* and *G. bulloides* may be difficult in extra-tropical regions. This is supported by the present study. *S. disjuncta* is known from Lower to Middle Miocene sediments in the North Sea (Gradstein & Bäckström 1996).

The *Bolboforma badenensis* and *B. reticulata* Zones known from the North Atlantic (Spiegler & Müller 1992) and the *B. badenensis/B. reticulata* Zone known from the Vøring Plateau (Müller & Spiegler 1993) are not recorded in this well. These zones are recorded from deposits with an age of ca. 14–11.5 Ma (Spiegler & Müller 1992). This indicates that the CE-IP assemblage only represents sediments of the lower part of the Middle Miocene and that there is a hiatus between this unit and the overlying unit.

GLOBIGERINA CIPEROENCIS ASSEMBLAGE

Designation: CE-JP.

Definition: The top of the assemblage is taken at the highest occurrence of *G. ciperoensis*. The base is marked by the lowest consistent occurrence of *G. ciperoensis*.

Depth range: 1783.1–1856.7 m.

Material: Two sidewall cores and four ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Lower part of Zone NSR 8B of Gradstein & Bäckström (1996).

Description: This assemblage contains a rich planktonic fauna of foraminifera and radiolaria. *G. ciperoensis* and *Globigerina angustiumbilicata* are the most common foraminifera. Other characteristic species include *Globigerina woodi*, *G. praebulloides* and *G. quadrilobatus triloba* (Fig. 5b).

Remarks: G. ciperoensis is described from Upper Oligocene to Lower Miocene deposits in the North Atlantic (Poore 1979) and in the North Sea (Gradstein & Bäckström 1996). *G. woodi* is known from Upper Oligocene to Lower Pliocene sediments in the North Atlantic (Poore 1979). *G. angustiumbilicata* is recorded from Upper Oligocene to Lower Pliocene deposits (Kennet & Srinivasan 1983). This indicates an Early Miocene age for this interval, since Late Oligocene can be ruled out (see below).

UNDEFINED INTERVAL

Depth range: 1856.7–2167.1 m.

Material: One sidewall core and 14 ditch cutting samples.

Lithostratigraphic unit: Hordaland Group.

Description: This interval contains no planktonic fossils of stratigraphic importance. Only a few unidentified radiolaria and pyritized diatoms are recorded (Fig. 5b).

DIATOM SP. 4 ASSEMBLAGE

Designation: CE-KP.

Definition: The top of the assemblage is taken at the highest consistent occurrence of Diatom sp. 4 (King 1983). The base is marked by the highest consistent occurrence of Diatom sp. 3 (King 1983).

Depth range: 2167.1–2203.7 m.

Material: One ditch cuttings sample.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSP 10 of King (1983).

Description: This interval contains a moderately rich flora of pyritized diatoms. The index fossils Diatom sp. 4 and Diatom sp. 5 (King 1983) are found in this flora (Fig. 5b).

Remarks: Diatom sp. 4 and Diatom sp. 5 are both known from Lower Miocene deposits in the North Sea (King 1983).

DIATOM SP. 3 ASSEMBLAGE

Designation: CE-LP.

Definition: The top of the assemblage is taken at the highest consistent occurrence of Diatom sp. 3 (King 1983). The base of the assemblage is undefined.

Depth range: 2203.7–2368.3 m (lowermost studied sample).

Material: Two conventional core samples at 2298.7 and 2303.1 m, one sidewall core and nine ditch cutting samples.

Age: Late Oligocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Subzone NSP 9c of King (1989).

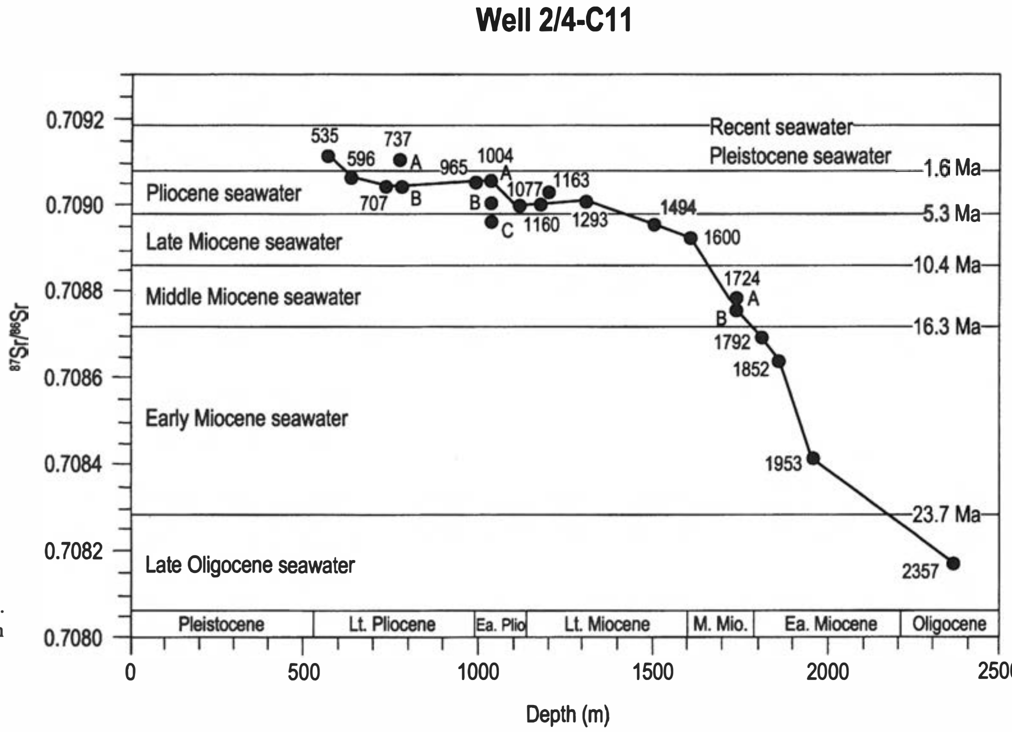


Fig. 6. Strontium isotope ratios plotted as a function of depth in well 2/4-C-11. Biostratigraphical datings are shown on the horizontal axis. The Sr isotope zonation is after Hodell et al. (1990). Chronology is after Berggren et al. (1985).

Description: This assemblage contains a moderately rich flora of pyritized diatoms. In this flora the index fossil Diatom sp. 3 is found. The assemblage also contains a few specimens of the following planktonic foraminiferal taxa: *G. ciperoensis*, *G. angustiumbilicata* and *G. praebulloides* (Fig. 5b).

Table 2. Strontium isotope data from well 2/4-C-11. All measurements refer to the international standard NBS 987 = 0.710240.

Depth (m)	Sample[1]	$^{87}Sr/^{86}Sr$	S.E.[2]	Age (m.y.)[3]	Comments[4]
535.4	BF	0.709105	± 15	1.4	Core, 8 bl.
596	BF	0.709068	± 11	2.0	SWC
707	BF	0.709047	± 11	2.5–4.5	SWC
737A	BF	0.709108	± 8	1.4	SWC
737B	BRY	0.709047	± 11	2.5–4.5	SWC
965	BF	0.709051	± 11	2.5–4.5	SWC
1004A	PF	0.709056	± 13	2.5–4.5	SWC
1004B	BF	0.708964	± 10	5.5	SWC
1004C	MOL	0.709003	± 8	5.0	SWC
1077	BF	0.708993	± 16	5.1	SWC
1160.7	BF	0.709007	± 10	5.0	Core
1163.4	BF	0.709022	± 12	4.8	Core
1293	BF	0.709004	± 19	5.0	SWC, 7 bl.
1494	BF	0.708951	± 10	5.5–8.0	SWC
1600	BOL	0.708928	± 28	8.0	Cuttings, 2bl.
1724A	MOL	0.708781	± 9	14.0	Core
1724B	BF	0.708756	± 13	14.8	Core
1792	PF	0.708697	± 18	16.9	SWC, 4bl.
1953	BF	0.708407	± 12	21.3	SWC
2357.3	BF	0.708165		25.6	SWC, 2bl.

[1] BF = bethonic foraminifera; PF = planktonic foraminifera; BRY = bryozoan fragment; MOL = mollusc fragment; BOL = Bolboforma.
[2] S.E. = standard error of the mean $(2\delta)\cdot 10^{-6}$.
[3] Age according to Hodell et al. (1990, 1992). Max. precision ± 0.5 Ma.
[4] Samples from: sidewall core (SWC), core or cuttings. bl. = blocks.

Remarks: Diatom sp. 3 is known from Upper Oligocene to lowermost Lower Miocene deposits in the North Sea (King 1989). Strontium isotope analyses indicate that an Early Miocene age can be ruled out.

Strontium isotope stratigraphy

Several papers describing the strontium (Sr) isotopic evolution of Cainozoic seawater were published during the 1980s (Burke et al. 1982; Koepnick et al. 1985; DePaolo & Ingram 1985; DePaolo 1986; Hess et al. 1986). Since these studies, segments of the seawater curve have been increasingly well documented, and for the Neogene portion of the curve, the most detailed record was presented by Hodell et al. (1990, 1991). As a consequence of these studies, Sr isotope stratigraphy is emerging as a powerful tool of dating and correlation of marine sediments. The method has particularly high potential for chronostratigraphical studies of post-Eocene sections.

In this study, we use Sr isotope stratigraphy to constrain better the ages for the Neogene section in well 2/4-C-11. In order to avoid problems with cavings, we used samples from sidewall cores and conventional cores (except for one ditch cutting sample). Most of the samples consisted of benthonic foraminifera, but at some levels we also used planktonic foraminifera, *Bolboforma*, *Bryozoa* and mollusc fragments. Furthermore, to avoid problems with reworking, we preferentially used taxa of well-documented stratigraphic range. Consequently, at some levels, relatively small samples were used.

A problem with obtaining Sr ages from foraminifera in siliciclastic basins is the common presence of impurities such as clay, pyrite, glauconite, etc. within the foraminiferal chambers. Addition of Sr from such materials leads to increased Sr isotopic ratios and hence younger ages, as demonstrated by Eidvin et al. (1993b). Careful cleaning of the foraminifera by washing and centrifugation processes normally does not help to resolve this problem. In this study, we overcame the problem by using a very weak acid (0.1 N HCl) to dissolve the foraminiferal tests. Such a weak acid is thought effective in minimizing addition of Sr from foreign matter. Stronger acids (e.g. 2.0 N HCl) dissolve the whole sample, and Sr from foreign matter thus increases the Sr isotopic ratios, resulting accordingly in younger ages.

The results from our study are presented in Table 2 and Fig. 6. The Sr ratios in Fig. 6 are plotted as a function of depth in the well. Biostratigraphic ages, as interpreted from the well data, are also shown along the horizontal axis. This illustration provides an adequate way of comparing results obtained from biostratigraphy and Sr isotope stratigraphy. Also shown in Fig. 6 are Sr isotopic zonations of Neogene seawater.

From Fig. 6 we can see a good correlation between biostratigraphy and Sr isotopic data. The uppermost sample (535 m) has a Sr isotopic composition that gives an Early Pleistocene age (ca. 1.4 Ma), whereas the sample from 596 m gives a Late Pliocene age (ca. 2.0 Ma). Assuming a constant sedimentation rate, these two results indicate the Upper Pliocene/Pleistocene boundary (ca. 1.6 Ma) to be at about 560 m, which is close to the biostratigraphic placing of this boundary (ca. 530 m).

The Sr values are then essentially stable from 596–1004 m, and correspond to deposition within the 2.5–4.5 m.y. time span, a period with little changes in seawater Sr composition (Hodell et al. 1990, 1991). These ages are also in good agreement with the biostratigraphic interpretation.

Between depths of 1004 and 1077 m, there is a small, but clear drop in the Sr isotopic ratio, and from 1077 to 1293 m we again measure stable Sr ratios. The isotopic composition at 1077 m corresponds to an age of 5.1 Ma, which suggests that the drop in Sr ratio corresponds to the time period 4.5–5.5 m.y., in which seawater Sr isotopic composition changed rapidly (Hodell et al. 1990, 1991).

Our data (from 596–1293 m) apparently mirror the two Sr isotopic plateaus (2.5–4.5 and 5.5–9.0 m.y.) published by Hodell et al. (1989, 1991). The isotopic difference we measure between the plateaus is, however, only half of that measured by Hodell et al. (1990, 1991). As the biostratigraphic data for samples at 1160, 1163 and 1293 m point to Late Miocene ages, we believe therefore that our Sr values for this lower plateau are slightly elevated. This could be explained by slight Sr contamination, or the values could reflect the uppermost level of uncertainty of the isotopic analyses.

The sample at 1600.2 m is the only one taken from ditch cuttings. It consists of specimens of the index fossils *Bolboforma subfragori*, and is taken from the top of the CE-HP assemblage. The top of the equivalent assemblage in the North Atlantic and in the Norwegian Sea is dated to 9.6 Ma (Spiegler & Müller 1992; Müller & Spiegler 1993). The Sr composition of this sample corresponds to deposition during the Late Miocene period with stable Sr seawater composition (5.5–9 m.y.). Because of the precise biostratigraphic dating for this sample, we suggest that the oldest age (ca. 9.0 Ma) is most correct.

Below 1600 m the samples show distinctly decreasing Sr signatures with depth, yielding ages between 14 and 25 Ma. Through this interval, Sr isotope stratigraphy has extremely good resolution. At 1724 m two samples were analysed: a mollusc fragment (sample A) gave an age of 14.0 Ma, whereas benthonic foraminifera (sample B) gave an age of 14.8 Ma. The isotopic difference between these two samples falls within the resolution of the method (± 0.000030).

Samples at 1792, 1852 and 1953 m all yield Early Miocene ages, viz. 16.9, 17.8 and 21.3 Ma. These ages support the biostratigraphic datings in this interval. The deepest sample (2357 m) was very small, and was therefore treated manually in the mass spectrometer. The sparse amount of Sr gave 20 stable measurements corresponding to a Late Oligocene age of 25.6 Ma. This age is in good agreement with the biostratigraphic data.

Lithology and lithostratigraphy

Upper Oligocene and Middle Miocene (Hordaland and Nordland Groups)

This interval belongs to the Hordaland and Nordland Groups after Isaksen & Tonstad (1989). Studies of the petrophysical logs, the sidewall core samples and the ditch cutting samples show that this section contains mostly fine-grained material. Mostly clay is found in the samples, but small proportions of silt and fine-grained sand are also recorded. The conventional cores at 2297–2305.2 m (Upper Oligocene) and 1710.5–1725.5 m (Middle Miocene) contain mainly clay, but throughout the cores there are several thin beds with silt and fine-grained sand. These beds are probably distal turbidites.

Upper Miocene and Lower Pliocene (Nordland Group)

This section also contains mostly clay. The conventional cores at 1556.9–1563.2 m and 1160.7–1166.2 m (Upper Miocene) both consist of homogeneous clay-rich material.

Upper Pliocene and Pleistocene (Nordland Group)

In the lower part of the Pleistocene and the Upper Pliocene sections, the petrophysical logs indicate fine-grained deposits. The drill cuttings, sidewall cores and conventional cores from this section all contain a clay-rich diamicton with small proportions of sand, silt and pebbles. The pebbles, of both sedimentary and crystalline lithology, are interpreted as ice-rafted material and are found down to 900 m.

Petrophysical logs show that the uppermost ca. 300 m of the well contains thick sand beds with a fine-grained interval in between. The few sidewall cores from this unit contain mostly clay. These deposits are interpreted as glacial and glaciofluvial sediments.

The glaciomarine sediments of the Vøring Plateau have been the subjects of studies by Jansen & Sjøholm (1991) and Fronval & Jansen (1996). These investigations show traces of ice-rafted material in sediments as old as nearly 12 Ma. The frequency of such ice-rafted material increases during the period of 6.5–5.5 Ma, which correlates with the Messinian Stage. The frequency of ice-rafted material remains relatively low between 5.5 Ma and 2.6 Ma, but the great increase in the supply of such material after about 2.6 Ma reflects the marked expansion of northern European glaciers (Fig. 8). Shelf deposits from the last period contain large quantities of ice-rafted material further north in the North Sea (well 15/12–3, Eidvin & Riis 1992), on the Norwegian Sea continental shelf (Eidvin et al. 1998a) and in the Barents Sea (Eidvin et al. 1993a, 1998b).

The comparatively small quantities of ice-rafted detritus found in the Lower Pleistocene/Upper Pliocene section of well 2/4-C-11 indicate a smaller frequency of icebergs over this area than over the areas further north.

Paleoenvironments

Definition of bathymeteric zones are according to van Hinte (1978); inner neritic: 0–30 m, middle neritic: 30–100 m, outer neritic: 100–200 m and upper bathyal: 200–600 m.

Upper Oligocene and lower part of Lower Miocene

The fossil assemblage in this interval consists mainly of agglutinated foraminifera and pyritized diatoms. This foraminiferal fauna indicates deep water with dysoxic bottom conditions. A small proportion of benthonic calcareous foraminifera indicates short periods with better vertical water circulation and more oxygen at the sea bottom. The environment was probably upper bathyal during deposition of this section.

Upper part of Lower Miocene and lower part of Middle Miocene

This interval contains a rich planktonic foraminiferal fauna. A large proportion of planktonic foraminifera in coastal areas indicates open marine and fairly deep water conditions. The benthonic faunal component is dominated by calcareous forms, but agglutinated taxa are also recorded. At this time the sea level was probably at its highest during the Neogene, and during periods with high relative sea level there was better vertical water circulation in the Central Graben area (King 1989). Regional seismics show that this section thins out on the flanks of the Central Graben, but it is possible that the flank areas are covered with a thin transgressive section not detectable on seismic data. This section was probably also deposited in an upper bathyal environment.

Upper part of Middle Miocene and lower part of Upper Miocene

This interval shows a consistent occurrence of agglutinated foraminifera. The lower part of the interval is quite rich in planktonic taxa, but in its upper part only a few planktonic foraminifera occur. Such an agglutinated foraminiferal fauna, as found in this well in Middle/Upper Miocene deposits, is restricted to the deeper part of the Central Graben (King 1989). The scarcity of planktonic foraminifera in the upper part is probably due to dissolution of calcareous tests. According to King (1989), the sea level was somewhat lower during the Middle/Late Miocene than during than during the Early/Middle Miocene, causing less vertical water circulation in the deeper part of the Central Graben. The interval was probably deposited in an outer neritic to upper bathyal environment.

Upper part of Upper Miocene and Lower Pliocene

This section contains a rich planktonic fauna. The calcareous benthonic forms *N. affine* and *P. bulloides* occur consistently throughout the section. Today, *P. bulloides* and *N. affine* have a biogeographic range extending mainly along the upper part of the continental slope. *N. affine* is also common in outer shelf areas (Sejrup et al. 1981; Mackensen et al. 1985). Very few shallow water indicators belonging to the genus *Elphidium* are recorded. According to King (1989), the sea level was rising again during the late part of the Late Miocene and Early Pliocene. This section was probably deposited in an upper bathyal to outer neritic environment.

Lower part of Upper Pliocene

In most of the lower part of the Upper Pliocene planktonic foraminifera occur consistently (Fig. 5a). In this part, *N. affine* and *P. bulloides* also occur consistently. Shallow water indicators belonging to the genus *Elphidium* are scarce. The lower part of Upper Pliocene was probably deposited in an outer to middle neritic environment. A large proportion of boreal benthonic foraminifera, a small number of arctic forms and absence of glacigenic material all indicate transitional water conditions.

Upper part of Upper Pliocene

Planktonic foraminifera vary from scarce to common in this interval (Fig. 5a). The deep water form *N. affine* occurs consistently throughout most of the interval. Shallow water indicators belonging to the genus *Elphidium* are scarce to common. This interval was probably deposited in a middle neritic environment. Glacigenic material, a larger content of arctic benthonic foraminifera and a smaller content of

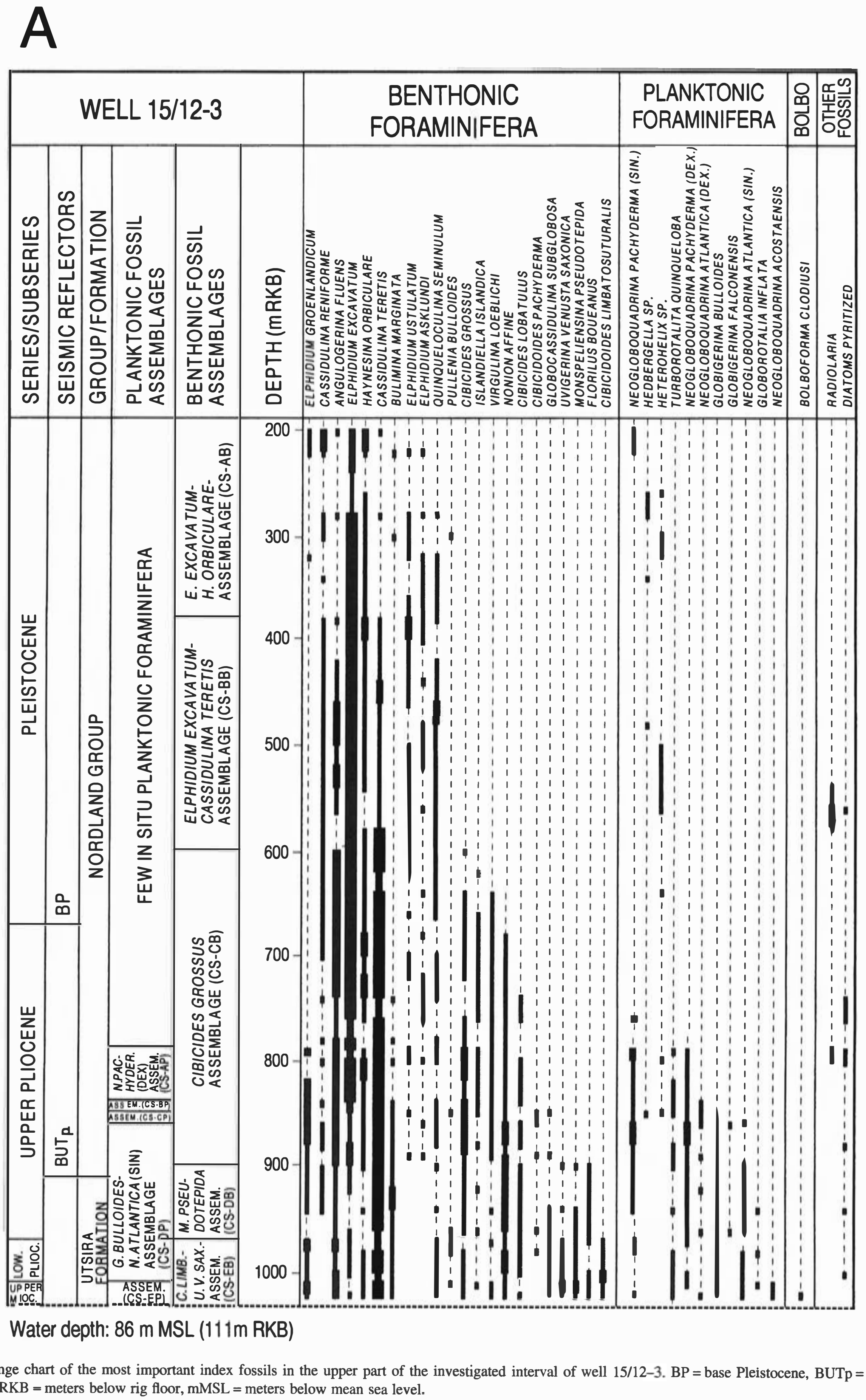


Fig. 7a. Range chart of the most important index fossils in the upper part of the investigated interval of well 15/12-3. BP = base Pleistocene, BUTp = base Upper Pliocene, mRKB = meters below rig floor, mMSL = meters below mean sea level.

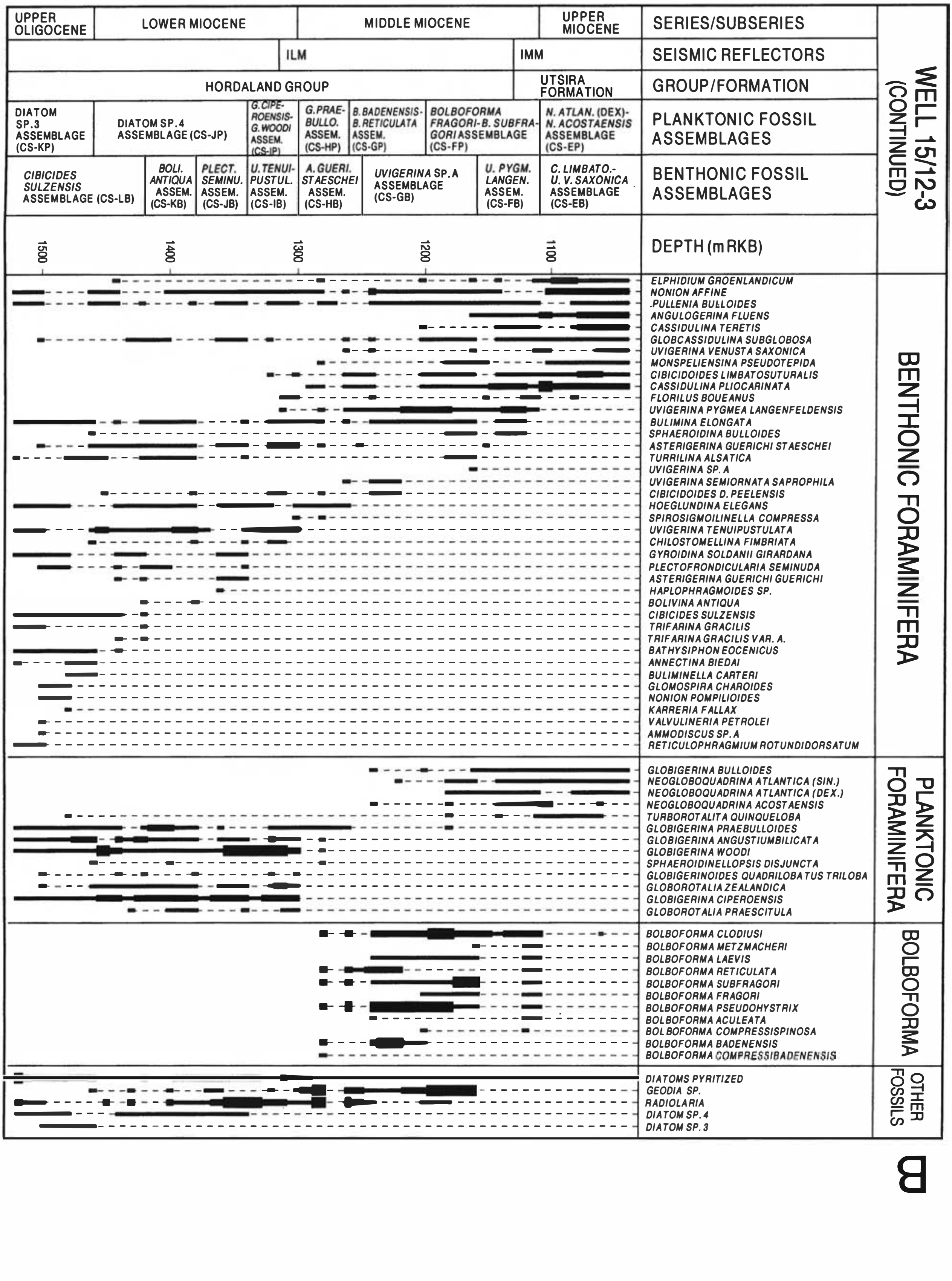


Fig. 7b. Range chart of the most important index fossils in the lower part of the investigated interval of well 15/12–3. IMM = intra-Middle Miocene, ILM = intra-Lower Miocene, mRKB = meters below rig floor.

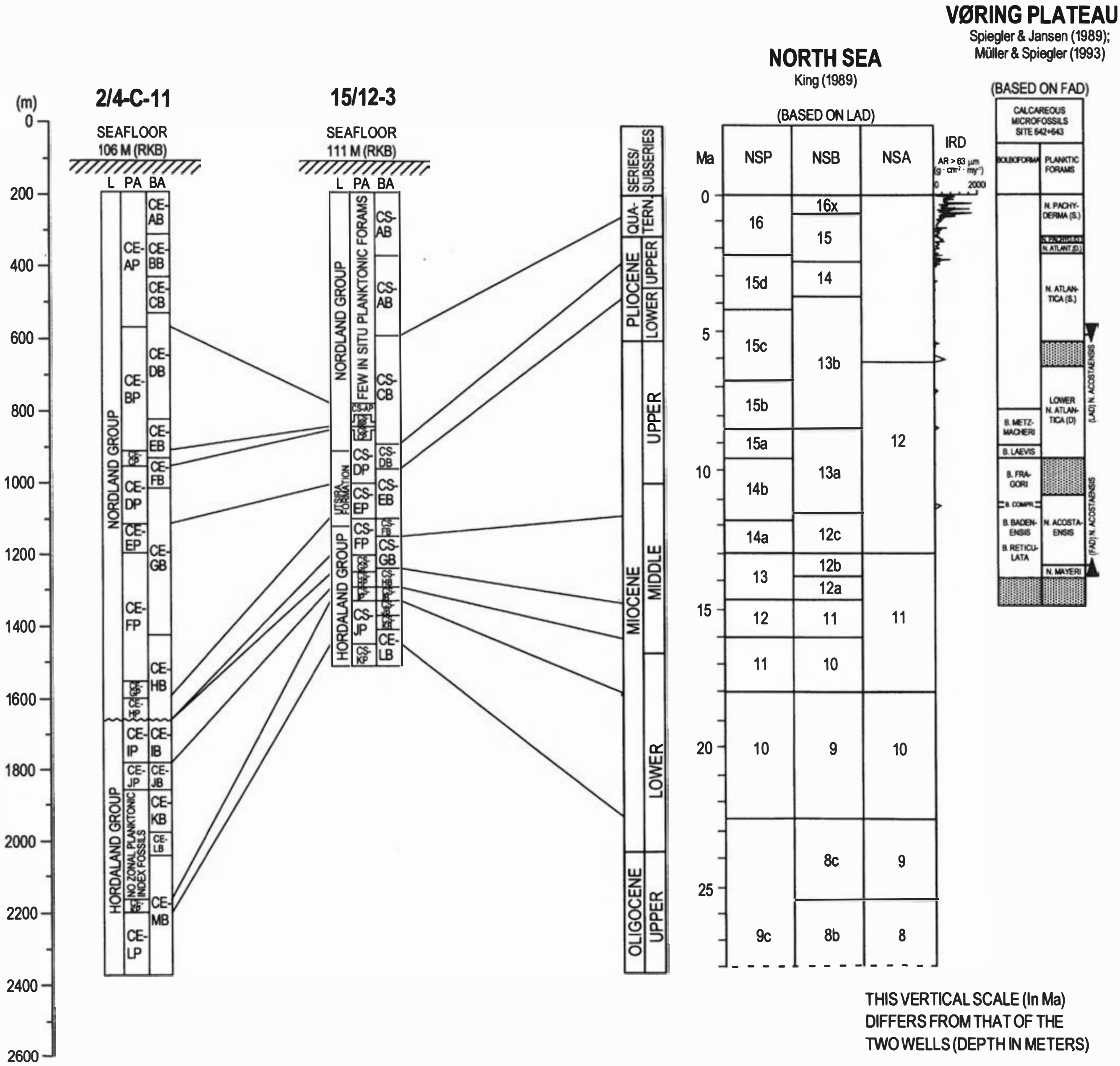


Fig. 8. Correlation of faunal assemblages between the wells studied, from the wells to King's (1989) North Sea fossil zonation and to the fossil zonation of ODP sites 642 and 643 on the Vøring Plateau (Spiegler & Jansen 1989; Müller & Spiegler 1993). The IRD curve is after Jansen & Sjøholm (1991) and Fronval & Jansen (1996). L = lithostratigraphic units, PA = planktonic fossil assemblages, BA = benthonic fossil assemblages, AR = accumulation rate, mRKB = meters below rig floor.

boreal forms all indicate considerably colder water than during the early Late Pliocene.

Pleistocene

The Pleistocene deposits contain very few planktonic foraminifera, indicating fairly shallow marine conditions. A shallow marine environment is also indicated by a large proportion of the benthonic foraminiferal genus *Elphidium.* Glacigenic material and a high content of arctic benthonic foraminifera indicate cold water conditions. The Pleistocene interval was probably deposited in an inner neritic environment.

Stratigraphy of well 15/12–3

Fossil assemblages

In this well, a system of 12 assemblages based on benthonic foraminifera (CS-AB to CS-LB) and 11 assemblages based on planktonic fossils (CS-AP to CS-KP) is

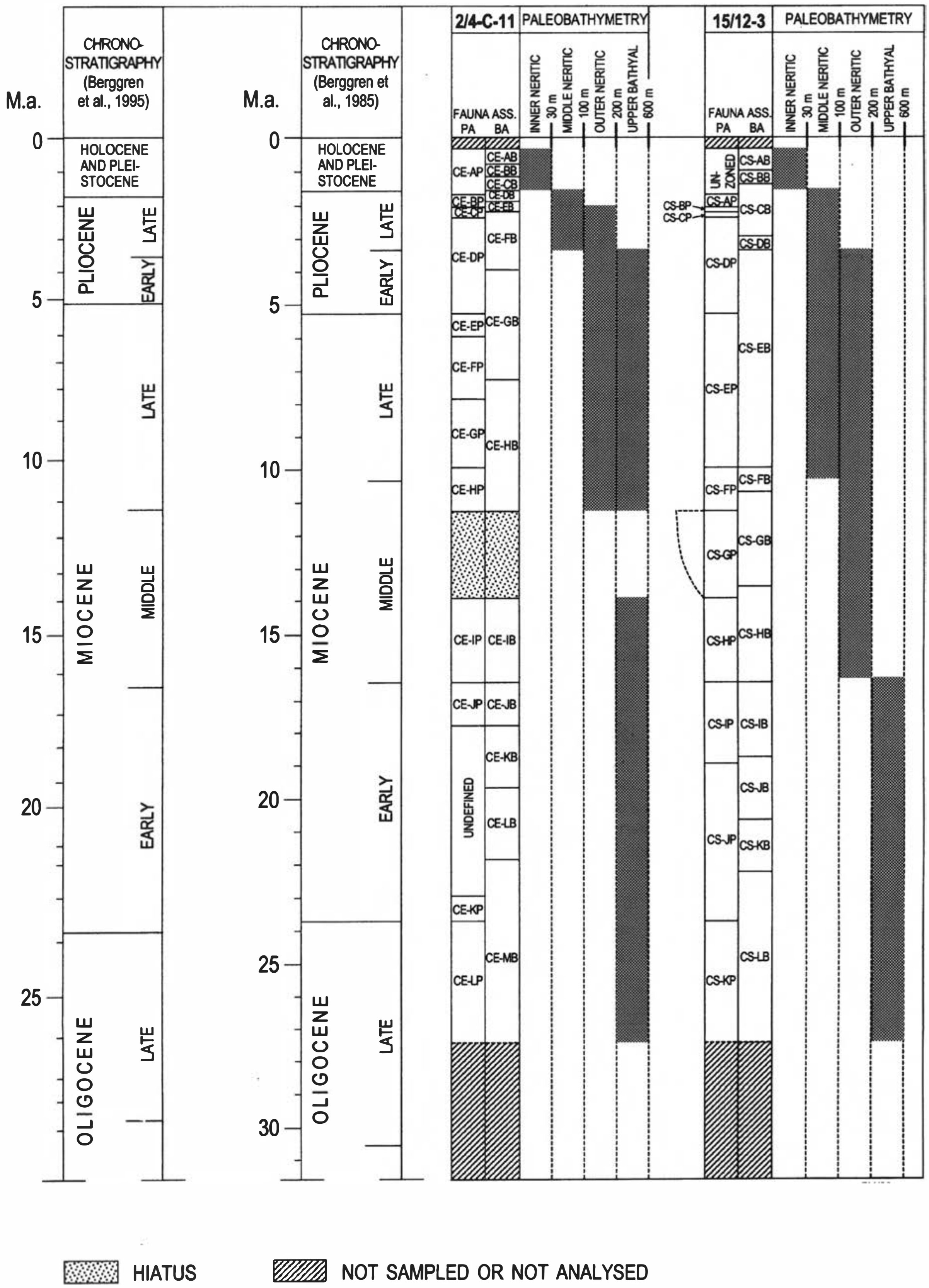


Fig. 9. Paleobathymetry and correlation of the faunal assemblages between the wells studied. Definition of bathymeteric zones according to van Hinte (1978). Vertical axis is Ma. Time scales of Berggren et al. (1985, 1995) are presented. PA = planktonic fossil assemblages, BA = benthonic fossil assemblages.

employed (Figs. 7a, b, 8, 9). As in well 2/4-C-11, the boundaries between the assemblages are based on the LADs of selected taxa. S = Sleipner Field.

Benthonic assemblages

ELPHIDIUM EXCAVATUM – HAYNESINA ORBICULARE ASSEMBLAGE

Designation: CS-AB.

Definition: The top of the assemblage extends to the uppermost investigated sample (200 m). The base is taken at the highest consistent occurrence of *Cassidulina teretis*.

Depth range: 200–380 m.

Material: Nine ditch cutting samples.

Age: Early to Middle Pleistocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Zone Jo 6 of Knudsen & Asbjörndóttir (1991) and Zone NSB 17 of King (1983).

Description: The assemblage contains a medium-rich benthonic fauna of calcareous foraminifera. *E. excavatum* occurs most frequently. Other important taxa include *H. orbiculare*, *C. reniforme*, *E. ustulatum* and *E. asklundi* (Fig. 7a).

Remarks: The benthonic foraminifera in this assemblage belong to characteristic Pliocene–Pleistocene taxa. All the recorded taxa are extant. Knudsen & Asbjörndóttir (1991) have described an *E. excavatum – H. orbiculare* assemblage Zone (Jo 6) from the well 30/13-2x in the British sector. This zone is slightly older than the Brunhes/Matuyama boundary.

ELPHIDIUM EXCAVATUM – CASSIDULINA TERETIS ASSEMBLAGE

Designation: CS-BB.

Description: The top of the assemblage is taken at the highest consistent occurrence of *Cassidulina teretis*. The base is marked by the highest occurrence of *Cibicides grossus*.

Depth range: 380–600 m.

Material: 11 ditch cutting samples.

Age: Early Pleistocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Zone Jo 6 of Knudsen & Asbjörndóttir (1991) and Zone NSB 17 of King (1983).

Description: This interval contains a rich benthonic fauna of calcareous foraminifera. *E. excavatum* occurs frequently throughout. Other important taxa include *C. teretis*, *H. orbiculare*, *C. reniforme*, *A. fluens*, *E. ustulatum* and *Q. seminulum* (Fig. 7a).

Remarks: The foraminifera in this interval are characteristic Pliocene–Pleistocene taxa, and all the recorded species are extant. Knudsen & Asbjörndottir (1991) describe a *C. teretis – E. excavatum* assemblage Zone (Jo 7) in Lower Pleistocene sediments of borehole 30/13-2X (British sector).

CIBICIDES GROSSUS ASSEMBLAGE

Designation: CS-CB.

Definition: The top of the assemblage is taken at the highest occurrence of *C. grossus*. The base is marked by the highest occurrence of *M. pseudotepida*.

Depth range: 600–900 m.

Material: 18 ditch cutting samples.

Age: Late Pliocene to Early Pleistocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Subzones NSB 15a and b of King (1989), Zone Jo 8 of Knudsen & Asbjörndóttir (1991) and Zone NSR 12 of Gradstein & Bäckström (1996).

Description: This assemblage contains a very rich benthonic fauna of mainly calcareous foraminifera. Taxa are slightly more numerous in this assemblage than in the immediately overlying section. *E. excavatum*, *A. fluens* and *C. teretis* all occur frequently throughout. Other important species include *C. grossus*, *H. orbiculare*, *Islandiella islandica*, *Virgulina loeblichi* and *N. affine* (Fig. 7a).

Remarks: The LAD of *C. grossus*, in the southern part of the North Sea, is close to the Upper Pliocene/Pleistocene boundary. Further north it became extinct somewhat later (King 1989). This becomes apparent when one compares the LAD of *C. grossus* in wells 2/4-C-11 and 15/12–3. In the Ekofisk area, the LAD of *C. grossus* is just above the *N. pachyderma* (dextral) assemblage (Fig. 5a). In the Sleipner area, the LAD of *C. grossus* is quite high above this planktonic foraminiferal assemblage (Fig. 7a). On the Vøring Plateau, the base of the *N. pachyderma* (dextral) Zone is dated to 1.84 m.y. based on paleomagnetic investigations (Spiegler & Jansen 1989). This indicates that *C. grossus* becomes extinct as late as Early Pleistocene in the Sleipner area.

In this well we have placed the Upper Pliocene/Pleistocene boundary at the regional seismic reflector at ca. 670 m. However, it is not possible to conclude definitely that this level accurately represents the boundary.

MONSPELIENSINA PSEUDOTEPIDA ASSEMBLAGE

Designation: CS-DB.

Description: The top of the assemblage is taken at the highest occurrence of *M. pseudotepida*. The base is marked by the highest consistent occurrence of *C. limbatosuturalis* and *U. venusta saxonica*.

Depth range: 900–970 m.

Material: Four ditch cutting samples.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group and Utsira Formation.

Correlation: Subzone NSB 14b of King (1989), Zone NSR 12A of Gradstein & Bäckström (1996) and Zone Jo 10 of Knudsen & Asbjörndóttir (1991).

Description: This assemblage contains a very rich benthonic fauna of mainly calcareous foraminifera. *C. teretis* and *N. affine* are common. Other characteristic species include *M. pseudotepida*, *E. groenlandicum*, *A. fluens*, *B. marginata* and *C. lobatulus* (Fig. 7a).

Remarks: A *M. pseudotepida* Subzone (NSB 14b) is described from the lower part of the Upper Pliocene of the North Sea (King 1989).

CIBICIDOIDES LIMBATOSUTURALIS – UVIGERINA VENUSTA SAXONICA ASSEMBLAGE

Designation: CS-EB.

Definition: The top of the assemblage is taken at the highest consistent occurrence of *C. limbatosuturalis* and *U. venusta saxonica*. The base is marked by the highest occurrence of *U. pygmea langenfeldensis*.

Depth range: 970–1110 m.

Material: Nine ditch cutting samples.

Age: Late Miocene to Early Pliocene.

Lithostratigraphic unit: Utsira Formation.

Correlation: Subzone NSB 14a and Subzone NSB 13b of King (1989).

Description: This interval contains a rich benthonic fauna of mainly calcareous foraminifera. *C. limbatosuturalis*, *U. venusta saxonica*, *N. affine*, *A. fluens*, *C. teretis* (upper part) and *C. pliocarinata* (lower part) all occur frequently. Other important taxa include *P. bulloides*, *G. subglobosa*, *M. pseudotepida* and *F. boueanus* (Figs. 7a, b).

Remarks: King (1989) describe a *C. limbatosuturalis* Subzone (NSB 14a) and an *U. venusta saxonica* Subzone (NSB 13b) from Lower Pliocene to Upper Miocene deposits in the North Sea. According to King (1989), Subzone NSB 14a is very thin in the northern part of the North Sea. This is probably also the case in the Sleipner area, where the LADs of *C. limbatosuturalis* and *U. venusta saxonica* are found in the same sample. The result is that only Subzone NSB 13b can be recorded in well 15/12–3. The top of this zone is of Early Pliocene age, according to King (1989).

UVIGERINA PYGMEA LANGENFELDENSIS ASSEMBLAGE

Designation: CS-FB.

Definition: The top of the assemblage is taken at the highest occurrence of *U. pygmea langenfeldensis*. The base is marked by the highest occurrence of *Uvigerina* sp. A (King 1989).

Depth range: 1110–1160 m.

Material: Four ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Utsira Formation and Hordaland Group.

Equivalent zones: Subzone NSB 13a of King (1989).

Description: This assemblage contains a moderately rich benthonic fauna of mainly calcareous foraminifera. There are somewhat fewer specimens than in the immediately overlying section. *U. pygmea langenfeldensis* and *C. pliocarinata* are botn common. Other characteristic taxa include *P. bulloides*, *G. subglobosa*, *C. limbatosuturalis*, *B. elongata* and *Sphaeroidina bulloides* (Fig. 7b).

Remarks: U. pygmea langenfeldensis is described from Middle Miocene deposits of the North Sea (King 1989). *S. bulloides* is known from Upper Oligocene to Upper Miocene sediments of The Netherlands (Doppert 1980).

UVIGERINA SP. A ASSEMBLAGE

Designation: CS-GB.

Definition: The top of the assemblage is taken at the highest occurrence of *Uvigerina* sp. A (King 1989). The base is marked by the highest consistent occurrence of *Asterigerina guerichi staeschei.*

Depth range: 1160–1250 m.

Material: Five ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Subzone NSB 12b of King (1989).

Description: This interval contains a moderately rich benthonic fauna of mainly calcareous foraminifera. There are somewhat fewer taxa in this interval than in the immediately overlying section. *U. pygmea langenfeldensis* occurs most frequently. Other characteristic taxa include *P. bulloides*, *G. subglobosa*, *C. limbatosuturalis*, *Uvigerina* sp. A, *B. elongata* and *S. bulloides* (Fig. 7b).

Remarks: A *Uvigerina* sp. A Subzone (NSB 12b) is described from Middle Miocene sediments in the North Sea (King 1989).

ASTERIGERINA GUERICHI STAESCHEI ASSEMBLAGE

Designation: CS-HB.

Definition: The top of the assemblage is taken at the highest consistent occurrence of *A. guerichi staeschei*. The base is marked by the highest occurrence of *U. tenuipustulata*.

Depth range: 1250–1300 m.

Material: Five ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSB 11 of King (1989), probably Zone FD of Doppert (1980) and probably Zone NSR 9A of Gradstein & Bäckström (1996).

Description: This assemblage contains a moderately rich benthonic fauna of mainly calcareous foraminifera. There are slightly fewer specimens in this assemblage than in the immediately overlying section. No species occur frequently, but important taxa are *U. pygmea langenfeldensis*, *B. elongata*, *A. guerichi staeschei*, *U. semiornata saprophila*, *Cibicidoides d. peelensis*, *Hoeglundina elegans*, *N. affine* and *P. bulloides* (Fig. 7b).

Remarks: An *A. guerichi staeschei* Zone (NSB 11) is described from lower Middle Miocene deposits in the North Sea (King 1989).

UVIGERINA TENUIPUSTULATA ASSEMBLAGE

Designation: CS-IB.

Description: The top of the assemblage is taken at the highest occurrence of *U. tenuipustulata*. The base is marked by the highest occurrence of *Plectofrondicularia seminuda*.

Depth range: 1300–1340 m.

Material: Four ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSB 10 of King (1989).

Description: Benthonic taxa are slightly more numerous in this assemblage than in the immediately overlying section. Calcareous foraminifera are dominant, but a few agglutinated forms are also recorded. *U. tenuipustulata* and *A. guerichi staeschei* occur most frequently. Other characteristic taxa include *B. elongata*, *Cibicidoides d. peelensis*, *H. elegans*, *S. compressa* (agglutinated), *Chilostomellina fimbriata*, *Stainforthia screibersina*, *P. bulloides*, *N. affine* and *Cibicidoides pachyderma* (Fig. 7b).

Remarks: An *U. tenuipustulata* Zone (NSB 10) is described from Lower Miocene sediments in the North Sea (King 1989).

PLECTOFRONDICULARIA SEMINUDA ASSEMBLAGE

Designation: CS-JB.

Definition: The top of the assemblage is taken at the highest occurrence of *P. seminuda*. The base is marked by the highest occurrence of *Bolivina antiqua*.

Depth range: 1340–1380 m.

Material: Three ditch cutting samples.

Lithostratigraphic unit: Hordaland Group.

Age: Early Miocene.

Correlation: Zone NSB 9 of King (1989).

Description: There are somewhat fewer taxa in this assemblage than in the immediately overlying assemblage. Calcareous benthonic foraminifera are dominant, but a few agglutinated species are also recorded. No species occur frequently, but important taxa are *Eponides umbonatus*, *A. guerichi staeschei*, *Turrilina alsatica*, *H. elegans*, *U. tenuipustulata*, *G. soldanii girardana*, *P. seminuda*, *A. guerichi guerichi*, *P. bulloides*, *N. affine*, *C. pachyderma* and *Haplophragmoides* sp. (agglutinated) (Fig. 7b).

Remarks: A *P. seminuda* Zone (NSB 9) is described from Lower Miocene deposits of the North Sea (King 1989).

BOLIVINA ANTIQUA ASSEMBLAGE

Designation: CS-KB.

Definition: The top of the assemblage is taken at the highest occurrence of *B. antiqua*. The base is marked by the highest occurrence of *Cibicides sulzensis*.

Depth range: 1380–1420 m.

Material: Two ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Subzone NSB 8c of King (1989).

Description: This assemblage contains a moderately rich benthonic fauna of calcareous foraminifera. No species occur frequently, but important taxa are *B. elongata*, *A. guerichi staeschei*, *T. alsatica*, *H. elegans*, *U. tenuipustulata*, *C. fimbriata*, *B. antiqua*, *N. affine* and *P. bulloides* (Fig. 7b).

Remarks: King (1989) describes a *B. antiqua* Subzone (NSB 8c) from Upper Oligocene to lowermost Lower Miocene deposits in the North Sea. Here, the assemblage is of Early Miocene age.

CIBICIDES SULZENSIS ASSEMBLAGE

Designation: CS-LB.

Definition: The top of the assemblage is taken at the highest occurrence of *C. sulzensis*. The base of the assemblage is undefined.

Depth range: 1420–1520 m (lowermost studied sample).

Material: Eight ditch cutting samples.

Age: Late Oligocene to Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Probably Subzone NSB 8c or Subzone NSB 8b of King (1989), and probably the lower part of Zone NSR 8B or Zone NSR 8A of Gradstein & Bäckström (1996).

Description: Taxa are slightly more numerous in this interval than in the immediately overlying section. Calcareous forms are most important, but agglutinated forms are also common. No species are very numerous, but important calcareous taxa are *C. sulzensis*, *E. umbonatus*, *B. elongata*, *A. guerichi staeschei*, *T. alsatica*, *H. elegans*, *U. tenuipustulata*, *B. antiqua*, *Trifarina gracilis*, *Valvulineria petrolei*, *Karreria fallax*, *Buliminella carteri*, *Nonion pompilioides*, *P. bulloides* and *N. affine*. Important agglutinated taxa are *S. compressa*, *Bathysiphon eocenicus*, *Ammodiscus* sp. A, *A. biedai*, *Glomospira charoides*, *R. rotundidorsatum* and *Spirosigmoilinella* spp. (Fig. 7b).

Remarks: *C. sulzensis* is originally described from Upper Oligocene deposits in Belgium (Batjes 1958). According to King (1989), the following taxa are known from Lower Oligocene to Lower Miocene deposits in the North Sea: *T. alsatica*, *V. petrolei*, *K. fallax*, *S. compressa*, *Ammodiscus* sp. A and *A. biedai*. According to Batjes (1958), *N. pompilioides*, *T. gracilis* and *B. carteri* are known from Upper Oligocene sediments in Belgium.

Planktonic assemblages

UNDEFINED INTERVAL

Depth range: 200 (uppermost investigated sample)–790 m.

Material: 30 ditch cutting samples.

Lithostratigraphic unit: Nordland Group.

In-place assemblage composition: Just a few specimens of *N. pachyderma* (sinistral, unencrusted) are recorded from the upper and lower parts of this interval.

Reworked assemblage composition: Heterohelix sp. and *Hedbergella* sp. are recorded sporadically throughout the interval. These taxa are derived from Upper Cretaceous sediments.

NEOGLOBOQUADRINA PACHYDERMA (DEXTRAL) ASSEMBLAGE

Designation: CS-AP.

Definition: The top of the assemblage is taken at the highest occurrence of *N. pachyderma* (dextral). The base is marked by the highest occurrence of *N. atlantica* (dextral).

Depth range: 790–840 m.

Material: Three ditch cutting samples.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: N. pachyderma (dextral) Zone of Weaver (1987), Weaver & Clement (1987) and Spiegler & Jansen (1989); Subzone NSP 16a of King (1989).

Description: Although planktonic foraminifera are sparse in this interval, they are significantly more common than in the immediately overlying section. Most important species are *N. pachyderma* (dextral) and *N. pachyderma* (sinistral, unencrusted). *T. quinqueloba* and the Upper Cretaceous forms *Hedbergella* sp. and *Heterohelix* sp. are also recorded (Fig. 7a).

Remarks: A *N. pachyderma* (dextral) Zone is described by Weaver (1987) and Weaver & Clement (1987) from the North Atlantic (DSDP Leg 94) and by Spiegler & Jansen (1989) from the Vøring Plateau in Upper Pliocene deposits. On the Vøring Plateau, the zone is accurately dated to 1.84–1.7 Ma.

NEOGLOBOQUADRINA ATLANTICA (DEXTRAL) ASSEMBLAGE

Designation: CS-BP.

Definition: The top of the assemblage is taken at the highest occurrence of *N. atlantica* (dextral). The base is marked by the highest occurrence of *G. bulloides.*

Depth range: 840–850 m.

Material: One ditch cutting sample.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Upper *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989).

Description: Planktonic foraminifera are slightly more numerous in this assemblage than in the immediately overlying assemblage. The following taxa are recorded: *N. atlantica* (dextral), *N. pachyderma* (sinistral, unencrusted), *N. pachyderma* (dextral) and *T. quinqueloba* (Fig. 7a).

Remarks: An upper *N. atlantica* (dextral) Zone is described from the Vøring Plateau in Upper Pliocene deposits, and is accurately dated to 2.3–1.84 Ma (Spiegler & Jansen 1989).

GLOBIGERINA BULLOIDES ASSEMBLAGE

Designation: CS-CP.

Definition: The top of the assemblage is taken at the highest occurrence of *G. bulloides.* The base is marked by the highest occurrence of *N. atlantica* (sinistral).

Depth range: 850–860 m.

Material: One ditch cutting sample.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: *G. bulloides* Zone of Weaver & Clement (1986).

Description: In this assemblage, planktonic foraminifera are as numerous as in the immediately overlying assemblage. *G. bulloides, N. atlantica* (dextral), *N. pachyderma* (dextral) and *N. pachyderma* (sinistral, unencrusted) occur most frequently. Other species include *T. quinqueloba* and the redeposited Upper Cretaceous forms *Hedbergella* sp. and *Heterohelix* sp. (Fig. 7a).

Remarks: A *G. bulloides* Zone is described from the North Atlantic (DSDP Leg 94) in Upper Pliocene deposits and is accurately dated to 2.3–2.1 Ma (Weaver & Clement 1986).

GLOBIGERINA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: CS-DP.

Definition: The top of the assemblage is taken at the highest occurrence of *N. atlantica* (sinistral). The base is marked by the highest occurrence of *N. acostaensis.*

Depth range: 860–1010 m.

Material: 10 ditch cutting samples.

Age: Early to Late Pliocene.

Lithostratigraphic unit: Nordland Group and Utsira Formation.

Correlation: *N. atlantica* (sinistral) Zone of Weaver & Clement (1986), *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989) and Subzone NSP 15d of King (1989).

Description: This interval contains a moderately rich planktonic foraminiferal fauna. Taxa are significantly more numerous in this interval than in the immediately overlying section. *G. bulloides, N. atlantica* (sinistral), *N. pachyderma* (sinistral, unencrusted) and *N. pachyderma* (dextral) occur most frequently. Other species include *Globigerina falconensis, T. quinqueloba* and the Upper Cretaceous forms *Hedbergella* sp. and *Heterohelix* sp. (Fig. 7a).

Remarks: A *N. atlantica* (sinistral) Zone is described from the North Atlantic in Upper Pliocene deposits (Weaver & Clement 1986), and from the Vøring Plateau in Lower to Upper Pliocene deposits (Spiegler & Jansen 1989). The LAD of *N. atlantica* (sinistral) is, in both areas, ca. 2.3 Ma (Weaver & Clement 1986; Spiegler & Jansen 1989). On the Vøring Plateau, there is a marked dominance of this species together with *G. bulloides* in Pliocene deposits older than this. *G. bulloides* is also found in the warmest interglacials of the last 1 Ma (Kellogg 1977).

NEOGLOBOQUADRINA ATLANTICA (DEXTRAL) – *NEOGLOBOQUADRINA ACOSTAENSIS* ASSEMBLAGE

Designation: CS-EP.

Definition: The top of the assemblage is taken at the highest occurrence of *N. acostaensis.* The base is marked by the highest occurrence of *B. fragori* and *B. subfragori.*

Depth range: 1010–1110 m.

Material: Six ditch cutting samples.

Age: Late Miocene.

Lithostratigraphic unit: Utsira Formation.

Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989); *N. atlantica* (dextral)/*N. acostaensis* Zone of Weaver (1987) and Weaver & Clement (1987); Subzone NSP 15a of King (1989).

In-place assemblage composition: There are somewhat fewer planktonic foraminifera in this interval than in the immediately overlying section. *N. acostaensis, G. bulloides* and *N. atlantica* (sinistral) occur most frequently. Other important taxa include *N. atlantica* (dextral), *T. quinqueloba, N. pachyderma* (dextral), *Globigerinita inflata* (upper part) and *G. puncticulata* (lower part) (Figs. 7a, b).

Reworked assemblage composition: A few specimens of *B. clodiusi* are recorded from the middle part of the interval. This form has probably been derived from deposits which correspond to the immediately underlying assemblage.

Remarks: Spiegler & Jansen (1989) describe a lower *N. atlantica* (dextral) Zone from Upper Miocene sediments on the Vøring Plateau, and Weaver (1987) and Weaver & Clement (1987) record a *N. atlantica* (dextral)/*N. acostaensis* Zone from Upper Miocene sediments in the North Atlantic (DSDP Leg 94). *N. acostaensis* is reported from deposits of Late to Middle Miocene age on the Vøring Plateau (Spiegler & Jansen 1989; Müller & Spiegler 1993). King (1989) describes a *N. acostaensis* Zone from Upper Miocene deposits in the North Sea.

BOLBOFORMA FRAGORI – BOLBOFORMA SUBFRAGORI ASSEMBLAGE

Designation: CS-FP.

Definition: The top of the assemblage is taken at the highest occurrence of *B. fragori* and *B. subfragori*. The base is marked by the highest occurrence of *Bolboforma badenensis*.

Depth range: 1110–1200 m.

Material: Six ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Utsira Formation and Hordaland Group.

Correlation: B. fragori/B. subfragori Zone of Spiegler & Müller (1992) and Müller & Spiegler (1993) and Subzone NSP 14a of King (1983).

Description: This assemblage contains a rich planktonic fauna of foraminifera and *Bolboforma*. *Bolboforma* are dominant, while foraminifera are subordinate. *B. clodiusi* is the most common *Bolboforma*. Other important species include *B. fragori*, *B. subfragori*, *B. pseudohystrix* and *B. laevis*. *B. metzmacheri*, *B. aculeata* and *B. compressispinosa* are also recorded. *G. bulloides*, *N. atlantica* (sinistral), *N. atlantica* (dextral) and *N. acostaensis* are the most important foraminifera (Fig. 7b).

Remarks: The known stratigraphic ranges of the most important planktonic foraminifera are discussed above under the descriptions of the CE-DP and CS-EP assemblages. A *B. fragori/B. subfragori* Zone is described from deposits with an age of ca. 11.5–9.6 Ma from the North Atlantic and the Vøring Plateau (Spiegler & Müller 1992; Müller & Spiegler 1993).

Spiegler & Müller (1992) and Müller & Spiegler (1993) describe a *B. metzmacheri* Zone (lowermost Upper Miocene) above the *B. fragori/B. subfragori* Zone in the North Atlantic and on the Vøring Plateau. In well 15/12–3, *B. metzmacheri* does not reach higher than *B. fragori* and *B. subfragori*. This may indicate that *B. metzmacheri* is caved from the overlying assemblage, without being recorded there, or that the LAD of this form is slightly different in the Sleipner area than in the North Atlantic and in the Norwegian Sea.

BOLBOFORMA BADENENSIS – BOLBOFORMA RETICULATA ASSEMBLAGE

Designation: CS-GP.

Definition: The top of the assemblage is taken at the highest occurrence of *B. badenensis*. The base is marked by the highest consistent occurrence of *Globigerina praebulloides*.

Depth range: 1200–1260 m.

Material: Four ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: B. badenensis and *B. reticulata* Zones of Spiegler & Müller (1992); *B. badenensis/B. reticulata* Zone of Müller & Spiegler (1993), and probably Zone NSP 13 of King (1983).

Description: This assemblage contains a rich planktonic fauna of mainly *Bolboforma*. A few planktonic foraminifera are also recorded. *B. clodiusi*, *B. pseudohystrix*, *B. badenensis* and *B. reticulata* are the most common *Bolboforma*. Other species include *B. laevis*, *B. subfragori*, *B. fragori*, *B. compressispinosa* and *B. compressibadenensis*. The few foraminifera include *G. bulloides*, *N. atlantica* (sinistral) and *N. acostaensis* (Fig. 7b).

Remarks: Spiegler & Müller (1992) describe a *B. badenensis* Zone and a *B. reticulata* Zone from the North Atlantic, and Müller & Spiegler (1993) describe a *B. badenensis/B. reticulata* Zone from the Vøring Plateau. These zones are recorded from deposits with an age of ca. 14–11.5 Ma (Spiegler & Müller 1992).

GLOBIGERINA PRAEBULLOIDES ASSEMBLAGE

Designation: CS-HP.

Definition: The top of the assemblage is taken at the highest consistent occurrence of *G. praebulloides*. The base is marked by the highest occurrence of *G. ciperoensis* and the highest consistent occurrence of *G. woodi*.

Depth range: 1260–1300 m.

Material: Four ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSP 12 of King (1983) and Zone NSR 8B of Gradstein & Bäckström (1996).

Description: This interval contains a rich planktonic fossil assemblage of radiolaria, *Bolboforma*, foraminifera and pyritized diatoms. Radiolaria and *Bolboforma* are dominant, while foraminifera and diatoms being subordinate. *B. pseudohystrix* is the most common *Bolboforma*, followed by *B. reticulata*, *B. badenensis*, *B. compressibadenensis* and *B. subfragori*. *G. praebulloides* is the most common foraminifer. Other species include *N. mayeri*, *G. angustiumbilicata*, *G. woodi* and *S. disjuncta* (Fig. 7b).

Remarks: G. praebulloides is known from Oligocene to lower Upper Miocene (common in Middle Miocene) deposits in the North Atlantic (Poore 1979) and from Oligocene to lower Middle Miocene deposits in the North Sea (Gradstein & Bäckström 1996). *G. woodi* is known from Upper Oligocene to Lower Pliocene sediments in the North Atlantic (Poore 1979). *S. disjuncta* is known from Lower to Middle Miocene sediments in the North Sea (Gradstein & Bäckström 1996). *G. angustiumbilicata* is known from Upper Oligocene to Lower Pliocene deposits (Kennet & Srinivasan 1983). This indicates an early Middle Miocene age for this interval. The *Bolboforma* recorded in this interval are probably caved.

GLOBIGERINA CIPEROENSIS – GLOBIGERINA WOODI ASSEMBLAGE

Designation: CS-IP.

Definition: The top of the assemblage is taken at the highest occurrence of *G. ciperoensis* and the highest consistent occurrence of *G. woodi*. The base is marked by the highest occurrence of Diatom sp. 4 (King 1983).

Depth range: 1300–1340 m.

Material: Four ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Lower part of Zone NSR 8B of Gradstein & Bäckström (1996).

Description: This interval contains a rich planktonic fossil assemblage of foraminifera, radiolaria and pyritized diatoms. *G. ciperoensis* and *G. woodi* occur most frequently of the foraminifera. Other important species are *G. praebulloides*, *G. angustiumbilicata*, *G. zealandica*, *G. praescitula* and *G. quadrilobatus triloba* (Fig. 7b).

Remarks: The known stratigraphic ranges of most of the planktonic foraminifera are discussed above under the description of assemblage CS-GP. *G. ciperoencis* is described from Upper Oligocene to Lower Miocene deposits in the North Atlantic (Leg 49) (Poore 1979) and in the North Sea (Gradstein & Bäckström 1996). *G. zealandica* and *G. praescitula* are known from Lower Miocene to lower Middle Miocene sediments from the North Atlantic (Poore 1979). This indicates an Early Miocene age for this interval.

DIATOM SP. 4 ASSEMBLAGE

Designation: CS-JP.

Definition: The top of the assemblage is taken at the highest occurrence of Diatom sp. 4 (King 1983). The base is marked by the highest occurrence of Diatom sp. 3 (King 1983).

Depth range: 1340–1460 m.

Material: Nine ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSP 10 of King (1983).

Definition: This assemblage contains a rich planktonic fossil assemblage of pyritized diatoms, foraminifera and radiolaria. Diatom sp. 4 occurs throughout the zone. *G. ciperoensis* and *G. woodi* occur most frequently of the foraminifera. Other important species include *G. praebulloides*, *G. zealandica*, *G. praescitula*, *G. angustiumbilicata* and *S. disjuncta* (Fig. 7b).

Remarks: The known stratigraphic ranges of the planktonic foraminifera are discussed previously, under the descriptions of the CS-HP and CS-IP assemblages. Diatom sp. 4 is known from Lower Miocene deposits in the North Sea (King 1983).

DIATOM SP. 3 ASSEMBLAGE

Designation: CS-KP.

Definition: The top of the assemblage is taken at the highest occurrence of Diatom sp. 3 (King 1983). The base of the assemblage is undefined.

Depth range: 1460–1520 m.

Material: Four ditch cutting samples.

Age: Late Oligocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Subzone NSP 9c of King (1989).

Description: This interval contains a moderately rich planktonic fossil assemblage of pyritized diatoms and foraminifera. Diatom sp. 3 and Diatom sp. 4 occur throughout. *G. praebulloides*, *G. angustiumbilicata*, *S. disjuncta* and *G. ciperoensis* occur most frequently among foraminifera (Fig. 7b).

Remarks: Diatom sp. 3 is known from Upper Oligocene to lowermost Lower Miocene deposits in the North Sea (King 1989). The stratigraphic range of the benthonic foraminifera in this interval indicates that Lower Miocene can be ruled out. Most of the recorded planktonic foraminifera are probably caved.

Lithology and lithostratigraphy

Upper Oligocene to lower part of Middle Miocene (Hordaland Group)

The petrophysical logs and ditch cutting samples show that this section contains mostly clay, with small proportions of sand, silt and limestone.

Upper part of Middle Miocene to lower part of Upper Pliocene (Utsira Formation)

Light grey sand dominates this interval. The sand contains mainly quartz grains, but some glauconite grains are also present. The lower part of the section also contains quite a large proportion of silt and clay. Mollusc fragments are common in the sandiest part of the section.

Robertson Research (1996) describes a Tampen Spur Sandstone Member (informal name) which lies above and is separated from the Utsira Formation by a clay-rich interval. According to Robertson Research (1996), the Tampen Spur Sandstone Member is of latest Early Pliocene age and is mainly located in the northern North Sea, but can perhaps also be followed to the Norwegian Quadrant 15.

The sandy section in well 15/12–3 is interpreted as a single unit not subdivided by significant clay intervals. This sandy unit corresponds to the Utsira Formation of the type well (Isaksen & Tonstad 1989), and in this paper is called the Utsira Formation. However, the age of its upper part is younger than in the type well. The relation between the younger part of the sandy unit in well 15/12–3 and the Tampen Spur Sandstone Member of Robertson Research (1996) has not been investigated in this study.

Upper part of Upper Pliocene and Pleistocene (Nordland Group)

The samples in the lower part of the Pleistocene/upper part of the Upper Pliocene section contain a diamicton dominated by clay, but with a large proportion of pebbles of both crystalline and sedimentary origin. These sediments are attributed to glaciomarine environments.

The ditch cutting samples from the uppermost ca. 300 m of the well contain a sandy diamicton. The petrophysical logs from this section show that the sand is concentrated in thick beds with fine-grained intervals between. These sediments are interpreted as glacial and glaciofluvial depositions.

The large proportion of ice-rafted pebbles indicates that sediments are deposited after the great increase in ice-rafted detritus at the Vøring Plateau. This event started at about 2.6 Ma (Jansen & Sjøholm 1991; Fronval & Jansen 1996).

Paleoenvironments

Upper Oligocene

Pyritized diatoms dominate the planktonic fossil assemblage in this interval. Foraminifera and radiolaria are far less numerous. Calcareous foraminifera dominate the benthonic fauna, but agglutinated forms are also common. Calcareous benthonic deep water indicators such as *P. seminuda* and *C. sulzensis* (Skarbø & Verdenius 1986) are recorded. The content of agglutinated foraminifera is probably a response to somewhat restricted vertical water circulation. The Upper Oligocene section was probably deposited in an upper bathyal environment.

Lower Miocene

The Lower Miocene contains a rich planktonic assemblage including foraminifera, radiolaria and pyritized diatoms. The deep water indicators *N. affine* and *P. bulloides* occur consistently throughout. Several more deep water indicators, such as *P. seminuda*, *B. antiqua* and *C. sulzensis* (Skarbø & Verdenius 1986), are also recorded. This section was probably deposited in an upper bathyal environment.

Middle Miocene

In this interval planktonic fossils are common. Species of *Bolboforma* is the dominant group. Planktonic foraminifera are far less numerous, except in the lower part, where these are also common. The deep water indicators *N. affine* and *P. bulloides* occur consistently throughout the interval. This section was probably deposited in an outer neritic environment.

Upper Miocene and Lower Pliocene

The Upper Miocene and Lower Pliocene make up of the bulk of the sandy Utsira Formation. According to Isaksen & Tonstad (1989), the Utsira Formation is a shallow marine deposit. However, the consistent occurrence of planktonic foraminifera and *Bolboforma*, and the benthonic deep water indicators *N. affine* and *P. bulloides*, suggest that the formation was deposited in deeper water in this area. According to Rundberg (1989), the northern North Sea area was a shallow marine passage between deeper water to the south and north during the Late Miocene. The corresponding sediments in the Ekofisk area are deep water depositions. The depositional environment in the Sleipner area was probably in a middle position between the Ekofisk area and the northern North Sea area, and was probably middle to outer neritic.

Upper Pliocene

Planktonic foraminifera are common throughout most of this section; the largest proportion is found in its middle part. The upper and lower parts contain fewer planktonic specimens. The deep water indicator *N. affine* and the shallow water indicators of the genus *Elphidium* occur consistently in the Upper Pliocene. The Upper Pliocene section was probably deposited in a middle neritic environment. Glacigenic material and the consistent occurrence of both boreal and arctic benthonic foraminifera indicate cold to transitional water conditions.

Pleistocene

The Pleistocene section contains very few planktonic foraminifera, indicating little contact with open ocean and fairly shallow marine conditions. Shallow marine conditions are also indicated by a large proportion of the benthonic genus *Elphidium*. A large proportion of ice-rafted pebbles in the sediments and a high content of arctic benthonic foraminifera indicate cold water conditions. The Pleistocene section was probably deposited in an inner neritic environment.

Summary and correlation between well sites

Upper Oligocene to lower part of Lower Miocene

The unit below the intra-Lower Miocene reflector (ILM on Fig. 4), i.e. the lower part of the Lower Miocene and the investigated part of the Upper Oligocene, contains mostly clay with small proportions of silt, sand and some limestone stringers.

No planktonic index fossils are found in the upper part of this unit in the Ekofisk well. In the lower part, the same diatom index fossils are found in both areas (assemblages CE-KP/CE-LP and CS-JP/CS-KP). The benthonic fauna is very different in the two areas. In the Ekofisk well almost exclusively agglutinated forms have been recorded, while in the Sleipner well there are almost exclusively calcareous forms in the upper part of the unit. In the lower part calcareous forms are dominant, but some agglutinated forms are also found. This indicates deposition in a somewhat restricted basin in the Ekofisk area, as opposed to the better ventilated basin at the Sleipner site. The water depth was probably upper bathyal in both areas (Fig. 9).

Upper part of Lower Miocene to lower part of the Middle Miocene

The ILM reflector (Fig. 4), which lies in the upper part of the Lower Miocene in both wells, marks the base of two basins with a threshold in between. The wells penetrate the deepest part of each basin. The IMM reflector (Fig. 4) is developed in the upper part of the Middle Miocene in both wells. Below this reflector there is a hiatus in the Ekofisk well, and the middle part of Middle Miocene is missing in this area. In the Sleipner well it is not possible to detect a hiatus. In both areas this unit contains mostly clay with small proportions of silt and sand.

The same planktonic index fossils are found in both areas. However, in the lowermost planktonic assemblages (CE-JP and CS-IP), there are far more *G. woodi* compared to *G. ciperoensis* in the Sleipner area than in the Ekofisk area. This indicates somewhat different pathways to the open ocean from the two areas. In addition, the benthonic index foraminifera are identical in the two areas within the lower part of the unit (assemblages CE-JB and CS-IB). This is not the case for the upper part, but this interval can be correlated by means of the planktonic fossils. Throughout the whole unit there are far more agglutinated foraminifera in the Ekofisk area than in the Sleipner area. This indicates deposition in a more restricted basin in the Ekofisk area. The water depth was probably upper bathyal in both areas during the late Early Miocene, and during the early Middle Miocene in the Ekofisk area. In the Sleipner area the water depth was probably outer neritic during the early Middle Miocene (Fig. 9). The late Cenozoic climatic cooling had not yet commenced (Fronval & Jansen 1996).

The sedimentary unit between the seismic reflectors ILM and IMM can only be detected on seismic data in the Central Graben. This unit thins out on the flanks of the basin. These sediments have probably very little permeability, since they function as a pressure barrier in the Tertiary in the Central Graben.

Upper part of Middle Miocene to Lower Pliocene

Lower Pliocene, Upper Miocene and the uppermost part of Middle Miocene form one seismic unit. This unit thins towards north, and the IMM reflector lies much deeper in the Ekofisk area than in the Sleipner area (Fig. 4). In the Ekofisk area the unit contains mostly clay. Northwards there is a shift in lithology, and the deposits turn into the Utsira sand in the Sleipner area.

The same planktonic index fossils are found in both areas. This is also the case for the benthonic fauna in the Lower Pliocene and upper part of the Upper Miocene, but in the lower part of the Upper Miocene and upper part of the Middle Miocene, the benthonic fauna is somewhat different. In the Ekofisk well this section contains a large proportion of agglutinated forms, while the Sleipner well contains only calcareous foraminifera. This indicates deposition in a deeper and more restricted basin in the Ekofisk area than at the Sleipner site. A greater water depth in the Ekofisk area is also indicated by the faunas in the Early Pliocene and late part of the Late Miocene, but at that time there was well developed vertical water circulation in both areas (Fig. 9). The foraminiferal fauna indicates an upwards cooling trend.

Upper Pliocene

The BUTp reflector (Fig. 4) lies at approximately the same depth level in the two areas, and the Upper Pliocene section thins towards the north. In the Sleipner area the BUTp reflector marks the top of the Utsira Formation, and in well 15/12–3 the top of this formation is slightly above the Lower/Upper Pliocene boundary.

In the Ekofisk area the Upper Pliocene section contains a clay-rich diamicton with small proportions of sand, silt and ice-rafted pebbles (down to 900 m). In the Sleipner area the Upper Pliocene section above the Utsira Formation also contains a clay-rich diamicton, but with larger proportions of silt, sand and ice-rafted pebbles. The Utsira Formation is dominated by sand.

The same benthonic and planktonic index foraminifera are found in both areas. The only major exception is the upper *N. atlantica* (dextral) assemblage, which is only recorded in well 2/4-C-11. However, this unit is very thin both in the Ekofisk area and on the Vøring Plateau (Spiegler & Jansen 1989), and therefore its absence does not necessarily suggest the presence of a hiatus. The water was probably somewhat deeper in the Ekofisk (outer to middle neritic) than in the Sleipner area (middle neritic) in the early part of the Late Pliocene. In the late part of Late Pliocene the water depth was probably middle neritic in both areas (Fig. 9). The water conditions during the Late Pliocene were probably cold to transitional.

The Upper Pliocene is relatively complete in both wells, and its lower part, i.e. deposits from 3.5–2.6 Ma, is also present. In most areas on the Norwegian continental shelf north of the Central Graben, there is probably a hiatus in the Upper Pliocene, and the lower part of Upper Pliocene is probably missing (Eidvin & Riis 1992; Eidvin et al. 1993a, 1998a, 1998b).

Pleistocene

The seismic profile (Fig. 4) shows that the Pleistocene deposits thicken towards north, from the Ekofisk towards the Sleipner area. The lower part of the Pleistocene section in well 2/4-C-11 contains a clay-rich diamicton with small proportions of sand, silt and ice-rafted pebbles. In well 15/12–3 this part also contains a diamicton dominated by clay, but with a much larger proportion of ice-rafted pebbles. The Lower Pleistocene deposits are, in both areas, interpreted as glaciomarine and marine sediments. The uppermost ca. 300 m of both wells 2/4-C-11 and 15/12-3 (Middle to Upper Pleistocene) contain thick sand beds with fine-grained intervals between. These deposits are interpreted as glacial and glaciofluvial sediments.

The same Pleistocene benthonic index foraminifera are found in both areas (Figs. 8, 9). However, the LAD of *C. grossus* is somewhat later in the Sleipner area than in the Ekofisk area. The planktonic foraminifera are too few to erect a planktonic zonation scheme. The foraminiferal fauna indicates shallow marine, cold water conditions in both areas (Fig. 9).

The Lower Pleistocene accumulation area in the Central Graben probably represents the depocenter for the sediments transported by the rivers flowing northwards from the northwestern European mainland. The Middle and Upper Pleistocene depositional processes were probably controlled mainly by the three latest and largest glaciations, i.e. Elsterian, Saalian and Weichselian (Cameron et al. 1987; Sejrup et al. 1987).

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