Late Cainozoic stratigraphy of the Tampen area (Snorre and Visund fields) in the northern North Sea, with emphasis on the chronology of early Neogene sands

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This study is based on biostratigraphic analysis of upper Cainozoic strata in eight exploration and production wells from the Tampen area (Snorre and Visund fields), and one well from the Troll field. Dating of the units is based primarily on planktonic and benthic foraminifera. Eleven fossil assemblages have been defined in sediments from the Lower Oligocene to the Pleistocene. In addition, strontium isotope, lithologic and petrophysical log analyses have been performed, and the studied wells have been correlated along regional 2-D and 3-D seismic lines.

In the Troll area the Pleistocene rests unconformably on the Lower Oligocene. The upper part of the Upper Oligocene is absent in all the Tampen wells. In the Visund area (block 34/8) there is a hiatus of more than 2 m.y. between Oligocene and Lower Miocene strata, and in the Snorre area (blocks 34/4 and 34/7) there is a hiatus of more than 18 m.y. between Oligocene and Upper Miocene deposits.

The Neogene section has been subdivided into five major lithologic units. In the Visund area, a Lower Miocene unit (1) of predominantly fine-grained, silty sediments has been identified. A major hiatus separates this unit from the overlying Utsira Formation (2), which in the northern North Sea comprises a thick lower part composed of quartzose sand and a thinner upper part of glauconitic sand. The main sands of the Utsira Formation are not present in any of the studied wells, but preliminary results from well 35/11-1 indicate a Late Miocene to possible latest Middle Miocene age for this unit. The glauconitic part of the Utsira Formation (Late Miocene to earliest Early Pliocene in age) overlies the Oligocene strata in the Snorre area and the Lower Miocene deposits in the Visund area. To the east it may drape over the main Utsira Formation sands or partly interfinger with these. It is overlain by a basal upper Pliocene unit (3) consisting of gravity flow deposits. Cores from this unit exhibit ice-rafted pebbles and have a glacio-marine affinity. A thick complex of Upper Pliocene prograding wedges (4) downlap the basal Pliocene unit in the Tampen area and the Utsira Formation in the eastern part of the basin. It is unconformably overlain by a Pleistocene unit at the top (5).

An important feature of the Neogene succession is a large incised valley/canyon system which developed in a north-westerly direction from block 35/8 (off Sognefjorden) to about 62∞N. This erosive system cuts into the basal Upper Pliocene unit in block 34/3 and is thus much younger than has been previously suggested.

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Introduction

Sands are commonplace in the Lower Neogene succession of the northern North Sea. These sands usually occur at the base of the Neogene and are separated by a large hiatus from the Oligocene sediments of the underlying Hordaland Group (Isaksen & Tonstad 1989). They reach a gross thickness in excess of 200 m in the central parts of the basin (Quadrant 30; Fig. 1), and are distributed laterally as a composite sand body with an elongate, north-south orientation.

The Utsira Formation was first defined by Deegan & Scull (1977) and later by Isaksen & Tonstad (1989) as a sand rich interval of Middle to Late Miocene age (well type section in 16/1-1).

However, the term "Utsira Formation" has commonly been used imprecisely by geological consultants and other scientists/geologists, and has in many cases been applied to all sandy Neogene units in the northern North Sea, regardless of lithofacies, age and depositional environment. In the Snorre and Visund areas (Fig. 1), for example, Upper Pliocene turbiditic sands and lowstand sequences have been included in the Utsira Formation. The reason for this is that these sands were previously assigned to the Miocene age, based on Miocene index fossils which we now consider to be reworked. However, our work on recently cored sections and sidewall cores from wells in the Snorre and Visund fields provides new information regarding the Neogene succession of this part of the North Sea.

Our investigation of nine hydrocarbon exploration and production wells is a combined biostratigraphical, seismostratigraphical, lithostratigraphical and geochemical study. The main purpose was to improve the chronology of the Neogene sequences and better constrain the age of the main sequence boundaries. A secondary objective has been to use microfauna to interpret depositional environments. Emphasis has

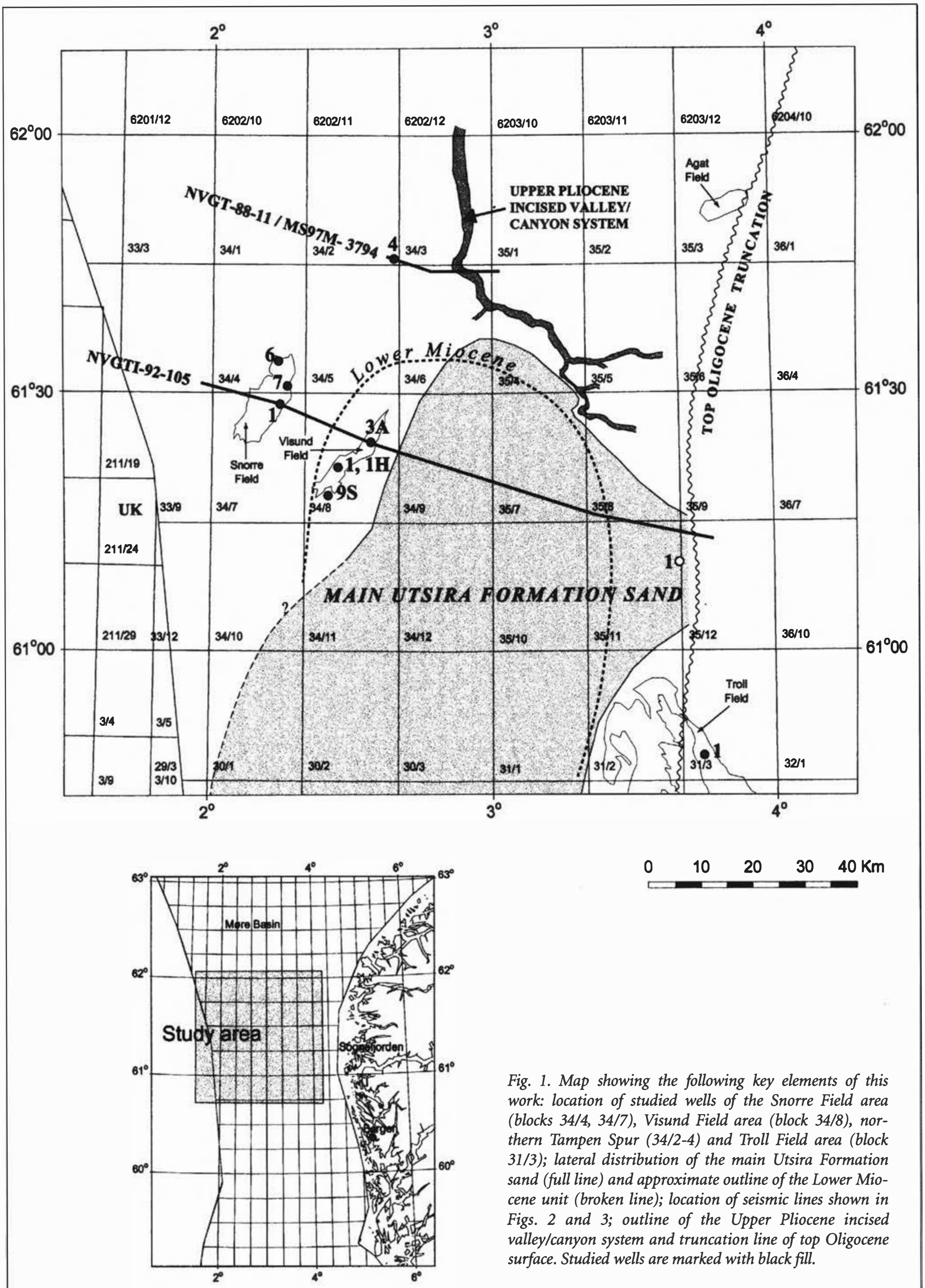

Fig. 1. Map showing the following key elements of this work: location of studied wells of the Snorre Field area (blocks 34/4, 34/7), Visund Field area (block 34/8), northern Tampen Spur (34/2-4) and Troll Field area (block 31/3); lateral distribution of the main Utsira Formation sand (full line) and approximate outline of the Lower Miocene unit (broken line); location of seismic lines shown in Figs. 2 and 3; outline of the Upper Pliocene incised valley/canyon system and truncation line of top Oligocene surface. Studied wells are marked with black fill.

been placed on the lower part of the Nordland Group (Isaksen & Tonstad 1989), including the Utsira Formation. The prograding Upper Pliocene unit has been studied in detail in two wells, whereas the Pleistocene is considered in one well only. All absolute ages referred to in the present study are based on Berggren et al. (1995). In order to ensure that the results reported here are consistent with electronic logs and other technical information, all depths are expressed as metres below the rig floor (m RKB).

In the Viking Graben, the main period of hydrocarbon generation took place during the late Cainozoic. Precise dating of the Neogene succession is therefore important in oil and gas exploration because it provides constraints on burial history models. An improved chronology of the Neogene succession is also of crucial importance in understanding the basin evolution and sedimentary history of the area.

Previous work

The northern North Sea has been extensively explored, and many hydrocarbon exploration and production wells have been drilled. Unpublished routine biostratigraphic datings for most of these wells have been performed by consultants commissioned by oil companies. However, the upper Cainozoic succession has usually not been given high priority, and the datings are often inadequate.

Based on the analysis mainly of ditch cutting samples from a number of wells, King (1983, 1989) published a detailed foraminiferal zonation for the Cainozoic of the entire North Sea. A detailed probabilistic foraminiferal zonation was established by Gradstein & Bäckström (1996) for the North Sea and the Haltenbanken areas.

In recent years, several papers and reports have been published dealing with the chronology of upper Cainozoic deposits in exploration wells from the northern North Sea area; Eidvin et al. (1991), Steurbaut et al. (1991), Seidenkrantz (1992; Upper Pliocene and Pleistocene), Eidvin & Riis (1992) and Gradstein et al. (1992, 1994). Rundberg & Smalley (1989) performed age determinations from exploration wells based on strontium isotope stratigraphy. In the present paper we present the results of new analyses of the three wells described in the report by Eidvin & Riis (1992) and one of the wells described in that of Eidvin et al. (1991) and the paper of Rundberg & Smalley (1989). In addition the present study includes analyses of five new wells.

Sejrup et al. (1995) have investigated cores from a geotechnical borehole from the Troll Field (Fig. 1), which penetrated the base Pleistocene unconformity. The cores from this borehole were subjected to palaeomagnetic, amino acid and foraminiferal analyses.

Rokoengen et al. (1983), Rundberg (1989), Jordt et al. (1995 and in press), King et al. (1996), Sejrup et al. (1996), Gregersen et al. (1997), Gregersen (1998) and Martinsen et al. (1999) have performed important regional seismic studies from the Neogene succession of the northern North Sea area.

The study area and geologic setting

Eight of the wells selected for this study are situated in the Tampen Spur area of the northern North Sea (Fig. 1). Wells 34/7-1, 34/4-7 and 34/4-6 are located on the Snorre field. Wells 34/8-9S, 34/8A-1H, 34/8-1, 34/8-3A are situated on the Visund field and 34/2-4 is located on the northern Tampen Spur close to the Møre Basin.

The Tampen Spur is a Mesozoic structural high situated west of the northern Viking Graben. The high exhibits a NNE-orientation, plunging towards the Møre Basin to the north. The structure at Lower Cretaceous level is overlain by Upper Cretaceous and Cainozoic sediments. Deep marine mudstones dominate the lower Tertiary sediments of the northernmost North Sea. Turbiditic sands are found adjacent to the Shetland Platform to the west, and to the Fennoscandian High to the east. The Eocene-Oligocene transition is characterized by an abrupt lithological shift from greenish, very fine-grained mudstones, to brownish, coarser mudstones. This change in lithology marks a shift to a colder climate, and also coincides with the onset of the "mid-Tertiary" compressional regime that affected the entire North Atlantic region. Oligocene sediments comprise coarsening-upward mudstones with glauconitic siltstones at the top, introducing shallower marine environments at the transition to the Neogene deposits (Rundberg 1989).

Seismic stratigraphic framework

A cross-section showing the post-Oligocene succession in the Norwegian part of the northern North Sea is illustrated on the seismic line in Fig. 2. The succession has been subdivided into sequences as follows: (1) the lower Miocene sequence at the base; (2) the Middle/Upper Miocene-basal Lower Pliocene sequence comprising the Utsira Formation; (3) the basal Upper Pliocene sequence; (4) the thick prograding Upper Pliocene complex; and (5) the Pleistocene sequence at the top.

Along the axis of the basin, there is a well-defined seismic sequence (1) reaching about 200 m in thickness (Fig. 2). The sequence (Early Miocene in age) has a low amplitude, continuous reflection pattern internally, and appears to onlap the basin margins. The base is marked by onlap onto the top Oligocene unconformity. The top is defined to the west by toplap truncation, and to the east by a prominent reflector marking the base of the sandy Utsira Formation. The sequence pinches out to the east and west respectively (Fig. 2). It is only recorded in

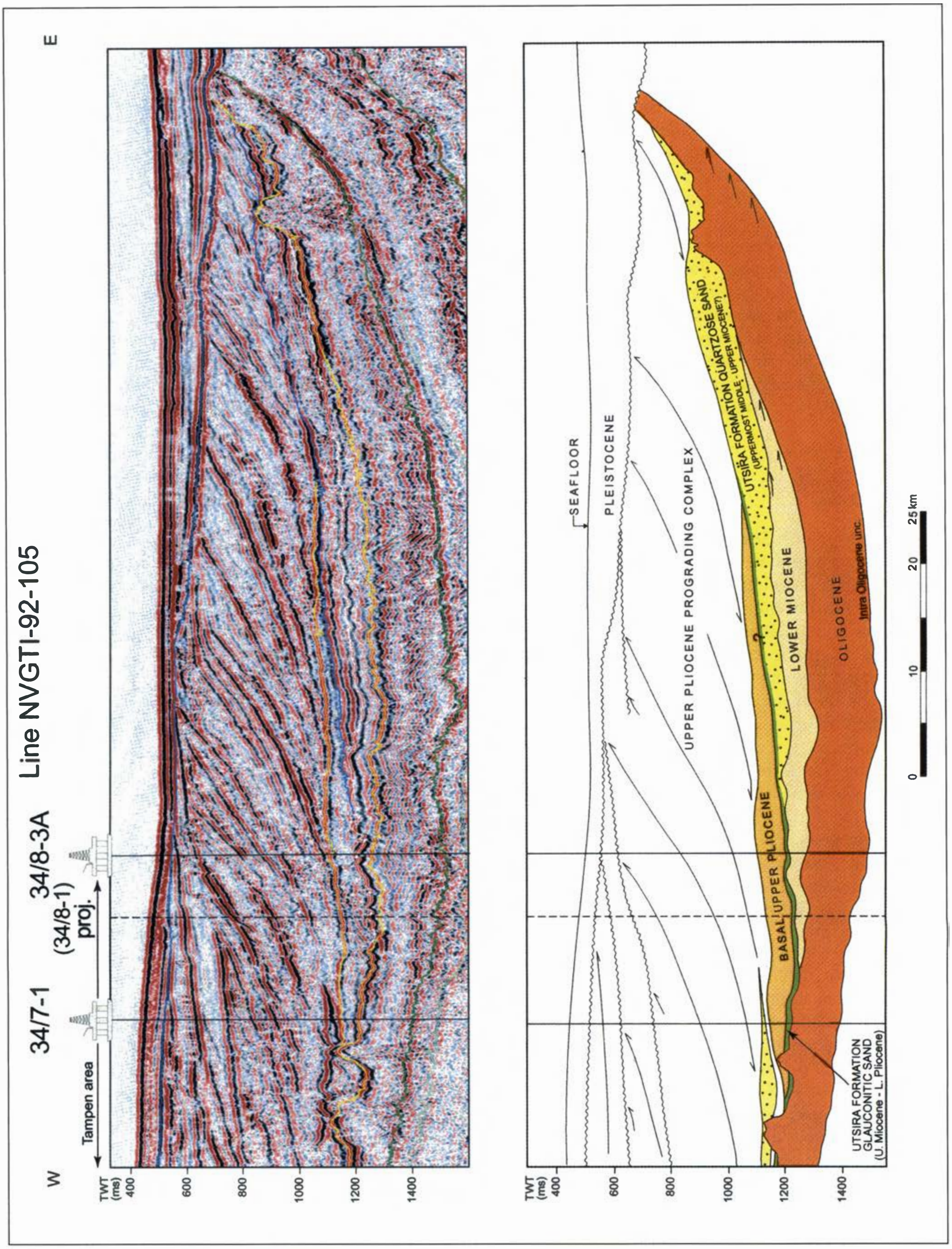

Fig. 2. (A) Seismic line NVGTI-92-105 across the Norwegian northern North Sea through wells 34/8-3A (Visund area) and 34/7-1 (Snorre area) illustrating the basin architecture and major depositional sequences of the upper Cainozoic. (B) Interpreted version of line NVGTI-92-105 showing major depositional sequences. The glauconitic sand unit is considered to overlie or partly interdigitate with the main Utsira Formation sand to the east. Note that the Upper Pliocene sand penetrated in well 34/7-1 is not a part of the Utsira Formation. Location of the line is shown in Fig. 1.

wells in the Visund field in the Tampen area. The areal distribution of the sequence is shown in Fig. 1. To the north, the sequence pinches out at about 61°30'N. Southwards, the sequence is more difficult to map due to the gradual development of a chaotic internal seismic character.

The overlying Utsira Formation (2) comprises a thick lower part of mainly quartzose sand, and a thinner upper part of glauconitic sand. The lower part is not present in any of the studied wells, but preliminary results from a study of this almost totally fossil-barren unit in well 35/11-1 (Fig. 1) indicate a Late Miocene to possible latest Middle Miocene age. It is thickest in the east and thins westwards towards the Tampen area (Fig. 2). The areal extent of the lower sand is shown in Fig. 1. The upper glauconitic part of the Utsira Formation (Late Miocene-earliest Early Pliocene in age) is present in the Tampen wells. It is not clearly resolved on seismic sections, but is readily defined on wireline logs. It is about 15 m thick in block 34/4 and up to 50 m thick in block 34/8. In Fig. 2, the glauconitic part is shown overlying the Lower Miocene deposits in Visund well 34/8-3A and the Oligocene deposits in Snorre well 34/7-1. It may drape over, or may partly interfinger with the main Utsira Formation sands. The top of the Utsira Formation is defined on seismic in the east by the noticeable downlap of Upper Pliocene clinoforms. To the west, the transition to the overlying glauconitic sands and the basal Upper Pliocene sequence can be identified by a strong seismic event. To the north and northeast, the Utsira Formation sands were removed by erosion during the Pliocene, but time-equivalent sequences are probably present to the west of the Agat area (Fig. 1) and along the Møre margin (Y. Rundberg, personal observation).

In the Tampen area, a distinct seismic sequence (3) is identified at the base of the prograding Upper Pliocene complex. It is about 70 m thick in the Snorre wells and pinches out towards the east and west. The sequence is interpreted to consist of lowstand gravity deposits, laid down at the head of the prograding complex during an early phase of development.

The extensive incised valley/canyon system shown in Fig. 1 is an important feature of the Neogene strata of the northern North Sea. The system incises into the Oligocene deposits in the eastern part of the basin over an extensive area. As shown in Fig. 3, the incision postdates the basal Upper Pliocene sequence seen in well 34/2-4 (see Discussion).

The Upper Pliocene complex is characterized by thick, westward prograding clinoforms (4). The base of the prograding complex is defined by the termination of downlap reflections against the underlying surface. In the Tampen area a thickness of up to 700 ms (approximately 650 m) is recorded. The Upper Pliocene strata comprise a number of individual sequences that prograde in a northwesterly direction. These are separated by several truncation surfaces, three of which are shown in Fig. 2. The lowermost truncation surface is only partly preserved. The middle truncation surface is the most pronounced and can be mapped across the entire northern North Sea. At certain locations in the eastern part of the northern North Sea, the Upper Pliocene strata rest directly on Oligocene sediments (Fig. 2).

The Pleistocene sequence (5) is identified below the seafloor with its prominent lower boundary showing distinct onlap reflection terminations above and toplap truncations below. The seismic sequence attains a thickness of about 200 m close to the Norwegian margin, as seen in well 31/3-1 (Fig. 1), and thins to a few tens of metres in the Tampen area.

Material and methods

In most of the studied wells, the biostratigraphic analyses were performed largely on ditch cutting samples. Sidewall cores were available in wells 34/4-7 (12 cores) and 34/7-1 (14 cores). In wells 34/8A-1H and 34/8-9S the work is based on material from cored sections in the base Upper Pliocene.

In general, no samples have been available that are shallower than about 100 m below the seafloor. Consequently the Pleistocene section is not sampled in the Snorre and Visund fields. However, this section is investigated in well 31/3-1 in the Troll field and by Sejrup et al. (1995). In wells 34/2-4, 34/4-7, 34/7-1 and 34/8-3A the work started in the lower part of the Upper Pliocene strata. Samples from the upper part of the Upper Pliocene deposits were not used. Ditch cuttings are usually sampled at 10 m intervals in upper Cainozoic sections. All the available samples were analysed, with the exception of some of the thicker units where intervals of 20-30 m were chosen (Tables 1 and 2).

The samples were analysed primarily for planktonic and benthic foraminifera. Reworked *Bolboforma* (calcareous cysts) were recorded in the Upper Miocene and Upper Pliocene sections in several wells. Pyritised diatoms were used to establish the stratigraphy in Lower Miocene and Oligocene deposits.

Between 50 and 100 g of material were used to analyse conventional core samples and cuttings. Sidewall cores contain less sample material, and thus produce incomplete, non-representative faunal assemblages. Sidewall core and conventional core analyses do, however, provide useful *in situ* assemblages, because the material is generally not contaminated by cavings.

Fossil identifications were performed in the 106-500 μm fraction. In some cases the fraction larger than 500 μm and the fraction less than 106 μm were also studied. If it was possible, 300 individual fossils were selected from each sample. In order to optimize the identification of the foraminiferal assemblages, a number of samples rich in terrigenous grains were gravity-separated in heavy liquid. In such cases, 1000-1500 individuals were analysed in fossil rich samples. The stratigraphically

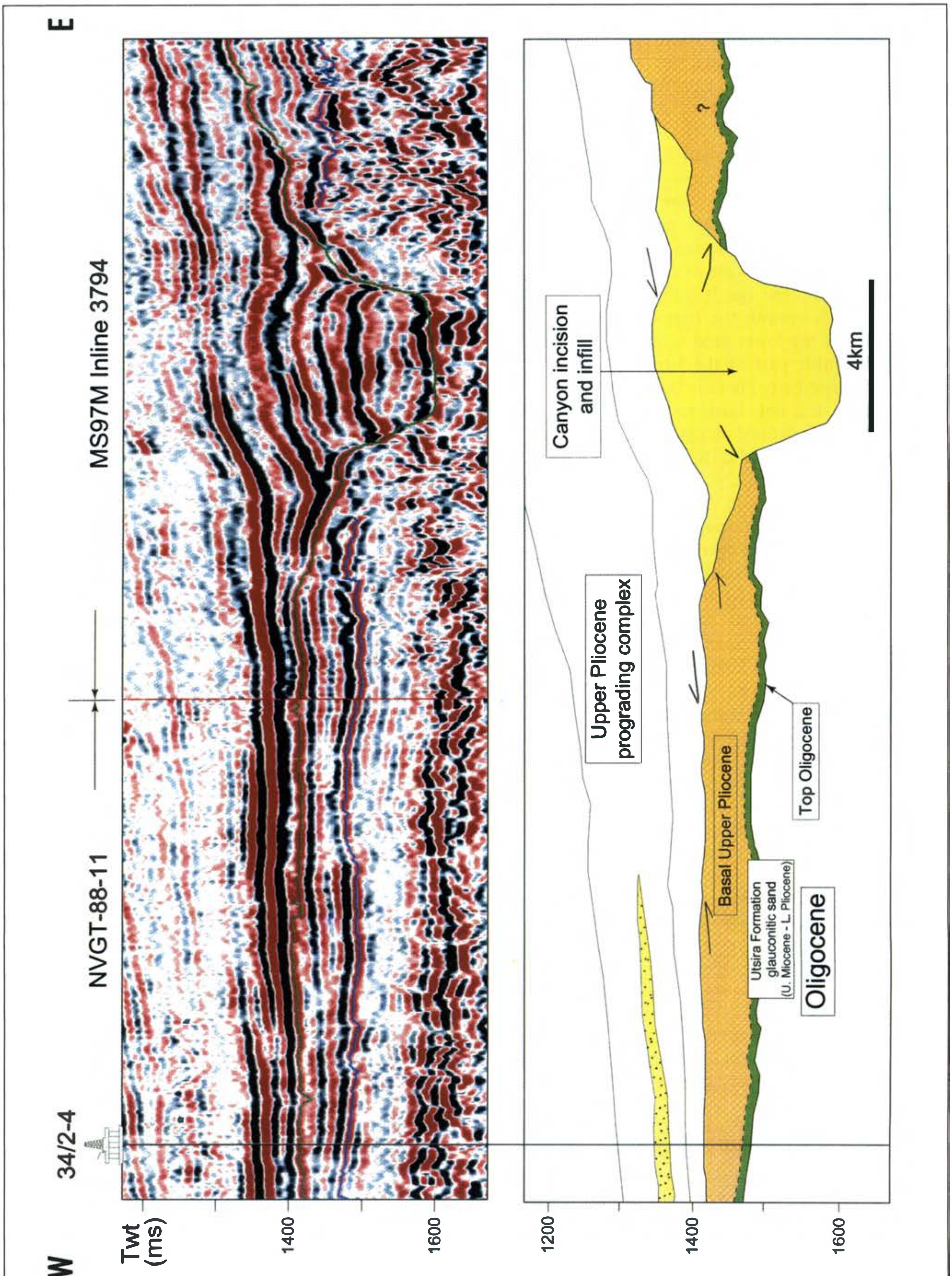

Fig. 3. Seismic composite line (NVGT-88-11 and MS97M inline 3794) showing the stratigraphy in well 34/2-4 and a deep canyon, incised into Oligocene strata. The line illustrates that the incision postdates deposition of the basal Upper Pliocene sequence. Location of the line is shown in Fig. 1.

SAMPLES ANALYSED IN WELL 31/3-1

430.0 m DC	470.0 m DC	510.0 m DC	550.0 m DC
440.0 m DC	480.0 m DC	520.0 m DC	560.0 m DC
450.0 m DC	490.0 m DC	530.0 m DC	580.0 m DC
460.0 m DC	500.0 m DC	540.0 m DC	

SAMPLES ANALYSED IN WELL 34/8-1

440.0 m DC	680.0 m DC	1020.0 m DC	1160.0 m DC
460.0 m DC	700.0 m DC	1030.0 m DC	1170.0 m DC
480.0 m DC	730.0 m DC	1050.0 m DC	1180.0 m DC
490.0 m DC	750.0 m DC	1060.0 m DC	1190.0 m DC
500.0 m DC	780.0 m Dc	1070.0 m DC	1200.0 m DC
510.0 m DC	800.0 m DC	1080.0 m DC	1220.0 m DC
520.0 m DC	830.0 m DC	1090.0 m DC	1240.0 m DC
530.0 m DC	850.0 m DC	1100.0 m DC	1260.0 m DC
550.0 m DC	880.0 m DC	1110.0 m DC	1280.0 m DC
560.0 m DC	900.0 m DC	1120.0 m DC	1300.0 m DC
580.0 m DC	920.0 m DC	1130.0 m DC	1320.0 m DC
600.0 m DC	950.0 m DC	1140.0 m DC	1340.0 m DC
630.0 m DC	980.0 m DC	1150.0 m DC	1360.0 m DC
650.0 m DC	1000.0 m DC		

SAMPLES ANALYSED IN WELL 34/8-9S

1109.68 m Core	1110. 52 m Core	1111.74 m Core	1112.63 m Core

SAMPLES ANALYSED IN WELL 34/8A-1H

1070.2 m Core	1084.1 m Core	1088.2 m Core	1102.0 m Core
1083.2 m Core	1086.1 m Core	1101.3 m Core	

SAMPLES ANALYSED IN WELL 34/8-3A

1000.0 m DC	1080.0 m DC	1160.0 m DC	1230.0 m DC
1010.0 m DC	1090.0 m DC	1170.0 m DC	1240.0 m DC
1020.0 m DC	1100.0 m DC	1180.0 m DC	1260.0 m DC
1030.0 m DC	1110.0 m DC	1190.0 m DC	1270.0 m DC
1040.0 m DC	1120.0 m DC	1200.0 m DC	1280.0 m DC
1050.0 m DC	1130.0 m DC	1210.0 m DC	1290.0 m DC
1060.0 m DC	1140.0 m DC	1220.0 m DC	1300.0 m DC
1070.0 m DC	1150.0 m DC		

Table 1. Samples analysed in wells 31/3-1, 34/8-1, 34/8-9S, 34/8A-1H and 34/8-3A. DC = ditch cutting sample.

SAMPLES ANALYSED IN WELL 34/4-6

540.0 m DC	800.0 m DC	1070.0 m DC	1210.0 m DC
550.0 m DC	820.0 m DC	1100.0 m DC	1220.0 m DC
560.0 m DC	850.0 m DC	1110.0 m DC	1230.0 m DC
570.0 m DC	870.0 m DC	1120.0 m DC	1240.0 m DC
600.0 m DC	900.0 m DC	1130.0 m DC	1250.0 m DC
620.0 m DC	920.0 m DC	1140.0 m DC	1270.0 m DC
650.0 m DC	950.0 m DC	1150.0 m DC	1290.0 m DC
670.0 m DC	970.0 m DC	1170.0 m DC	1310.0 m DC
700.0 m DC	1000.0 m DC	1180.0 m DC	1330.0 m DC
720.0 m DC	1020.0 m DC	1190.0 m DC	1350.0 m DC
750.0 m DC	1050.0 m DC	1200.0 m DC	1370.0 m DC
770.0 m DC			

SAMPLES ANALYSED IN WELL 34/4-7

1000.0 m DC	1060.0 m DC	1100.0 m DC	1180.0 m DC
1010.0 m DC	1061.0 m SWC	1120.0 m DC	1190.0 m DC
1010.0 m SWC	1063.0 m SWC	1130.0 m DC	1190.0 m SWC
1020.0 m DC	1070.0 m DC	1134.0 m SWC	1192.0 m SWC
1030.0 m DC	1076.0 m SWC	1140.0 m DC	1200.0 m DC
1038.0 m SWC	1080.0 m DC	1150.0 m DC	1204.0 m SWC
1040.0 m DC	1090.0 m DC	1160.0 m DC	1210.0 m DC
1050.0 m DC	1100.0 m DC	1168.0 m SWC	1220.0 m DC
1057.0 m SWC	1104.0 m SWC	1170.0 DC	

SAMPLES ANALYSED IN WELL 34/7-1

1000.0 m DC	1060.0 m DC	1102.5 m SWC	1150.0 m DC
1010.0 m DC	1062.6 m SWC	1110.0 m DC	1155.0 m SWC
1020.0 m DC	1070.0 m DC	1114.4 m SWC	1160.0 m DC
1020.5 m SWC	1973.0 m SWC	1120.0 m DC	1166.0 m SWC
1030.0 m DC	1080.0 m DC	1123.0 m SWC	1170.0 m DC
1040.0 m DC	1083.5 m SWC	1130.0 m DC	1180.0 m DC
1041.5 m SWC	1090.0 m DC	1130.0 m SWC	1190.0 m DC
1050.0 m DC	1094.0 m SWC	1140.0 m DC	1200.0 m DC
1052.0 m SWC	1100.0 m DC	1143.0 m SWC	

SAMPLES ANALYSED IN WELL 34/2-4

1300.0 m DC	1390.0 m DC	1470.0 m DC	1540.0 m DC
1310.0 m DC	1400.0 m DC	1480.0 m DC	1550.0 m DC
1320.0 m DC	1410.0 m DC	1490.0 m DC	1560.0 m DC
1330.0 m DC	1420.0 m DC	1500.0 m DC	1570.0 m DC
1340.0 m DC	1430.0 m DC	1510.0 m DC	1580.0 m DC
1350.0 m DC	1440.0 m DC	1520.0 m DC	1590.0 m DC
1360.0 m DC	1450.0 m DC	1530.0 m DC	1600.0 m DC
1370.0 m DC	1460.0 m DC		

Table 2. Samples analysed in wells 34/4-6, 34/4-7, 34/7-1 and 34/2-4. SWC = sidewall cores, DC = ditch cutting sample.

important fossils are reported in the range charts in Figs. 5-13. Separate range charts for fossils recorded in ditch cutting samples and those recorded in sidewall cores are presented for wells 34/4-7 and 34/7-1. The range charts for the sidewall cores in wells 34/4-7 and 34/7-1, and those for the cored sections in wells 34/8A-1H and 34/8-9S, show all the fossils recorded.

The lithologic analyses are based on a visual examination both of the samples prior to treatment, and also of the dissolved and fractionated material after preparation. Owing to problems caused by caved material, only a very generalized description was deemed appropriate for most sections. However, the sidewall cores in wells 34/4-7 and 34/7-1 and the short conventional cores in wells 34/8A-1H and 34/8-9S allowed more accurate lithologic descriptions of these parts. These samples are of crucial importance to the reconstruction of the basin history.

Strontium isotope analyses were performed on parts of sections in most wells. Analysis was conducted mainly on tests of calcareous foraminifera, but mollusc fragments were also utilized in some wells. The material was taken mainly from sidewall and conventional cores, but ditch cutting samples were also used. The ages for these samples were obtained by comparing the $^{87}Sr/^{86}Sr$-ratio to the global strontium isotope curves of Farrell et al. (1995) and Howarth and McArthur (1997).

Lithology, lithostratigraphy and log correlations

A lithostratigraphic log correlation of the studied wells is presented in Fig. 4.

The Lower-Upper Oligocene strata of the Hordaland Group represents the oldest sediments sampled in the Tampen wells. In the Snorre wells (blocks 34/4 and 34/7), there is an abrupt change in lithology at about 1150-1200 m, and the Oligocene deposits can readily be distinguished from the overlying strata by a change in colour and mineral composition. The upper part of the section displays a weakly serrated, low gamma log profile in all wells (Fig. 4). Oligocene sediments consist primarily of silty mudstones at the top, and are characterized by being brown to yellow and the ubiquitous presence of sponge spicules and glauconite. The microflora is dominantly siliceous, but small amounts of calcareous microfossils are also recorded.

In the Visund area (block 34/8), the Oligocene deposits are overlain by Lower Miocene sediments of the Hordaland Group (unit 1) which attain thickness of almost 100 m in well 34/8-3A. The log responses show a stable, weakly serrated pattern which indicates uniform lithology. The upper boundary is defined by an abrupt increase in both gamma radiation and sonic velocities (Fig. 4). Lithologically, these sediments are very similar to the Oligocene deposits with common glauconite and a rich siliceous flora. Calcareous microfossils are largely absent.

Overlying the Oligocene strata, a 15 m thick, highly radioactive unit 2 is clearly distinguished in the three Snorre wells 34/7-1, 34/4-7, 34/4-6. We propose that this unit is part of the Utsira Formation, and probably represents an upper glauconitic part of this formation. The transition from the underlying Oligocene sediments is marked by an abrupt change to higher gamma and sonic values (Fig. 4). In the Snorre wells, gamma radiation decreases towards the top of the unit, which is also defined by marked changes in the sonic and gamma log responses.

The unit expands eastwards to about 50 m in Visund wells 34/8-1 and 34/8-3A. The upper boundary is less well defined in this area, but is taken at a pattern change in the velocity logs. The gamma radiation is also lower than in the Snorre wells (Fig. 4). Sidewall cores taken from this unit in wells 34/4-7 and 34/7-1 contain almost exclusively glauconitic sand, which explains the high gamma radiation in the Snorre area, and suggests that the entire interval consists of such sediments. Slightly lower gamma levels and a greater thickness in the Visund wells probably indicate a lower glauconite content than is observed in the wells to the west. However, ditch cutting samples from these sections are also rich in glauconitic sand. The glauconite grains vary from dark to light green. The dark fractions are indicative of high maturity and a high content of K_2O (Smalley & Rundberg 1990). The samples contain fair amounts of microfossils, comprising mostly calcareous benthic foraminifera and sponge spicules.

The basal Upper Pliocene unit of the Nordland Group (unit 3) is distinguished from the overlying and the underlying units by its characteristic monotonous gamma and sonic log profile. This is best illustrated in the Snorre wells, where the sonic logs clearly display a more serrated profile than in the units above and below (Fig. 4). The upper boundary is defined by an abrupt increase in gamma and sonic values. This is particularly marked in wells 34/7-1 and 34/4-7. The thickness of the unit is relatively uniform in blocks 34/4 and 34/7 (65-75 m).

Towards the east in the Visund area, the unit expands to about 100 m in well 34/8-1 and to 145 m in well 34/8-9S. In wells 34/8-1 and 34/8-A-1H, repeated cycles of increasing gamma radiation at intervals of 5-10 m are recorded. These probably reflect a series of small scale coarsening-upward units. In well 34/8-A-1H, about 11 m of core was recovered from a 30 m interval from the lower part of the unit (Fig. 4). The lithology encountered in the core is predominantly a very fine sandy siltstone throughout with a fine sandstone at the base. The sands are generally structureless, although faint laminations have been observed in the siltstones. The gamma log indicates that the cores have most likely been taken in the fine-grained sections. Three large (up to 5 cm) and several small ice-rafted pebbles of metamorphic rock have been found at different levels in the core. Coarse fragments of coal and small mud clasts also occur at some levels. At the base there is a diffuse transition to fine-grained, structureless sand.

In well 34/8-9S, a 4 m long core was recovered from the base of the unit. This core consists mainly of homogeneous, silty mudstone. Large (5-10 cm), mud clasts occur scattered throughout the core, and ice-rafted pebbles are common. The mud clasts mainly exhibit a shallow marine foraminiferal fauna in contrast to the deeper shelf fauna which is present elsewhere in the unit. The sediments in the two cores are interpreted as gravity flow deposits with a glacio-marine imprint.

The prograding Upper Pliocene complex of the Nordland Group (unit 4) reaches a maximum thickness of about 700 m in the Tampen area. Log responses are characterized by fairly stable patterns throughout, and commonly show higher gamma levels than the underlying sediments. The relatively high radioactive character of the Upper Pliocene deposits are most likely the result of the high potassium content of the sediments with abundant illite and K-feldspar (Rundberg 1989). The dominant lithology consists of immature, poorly sorted and sand-poor clastics. Sands are rare in the Tampen wells, with the exception of a 20 m thick interval at the base of the unit (Fig. 4). This interval consists of two blocky sand bodies separated by a thinner mudstone. It can be correlated between all of the Snorre wells in this study, and is interpreted as the eastern extension of thicker sands that occur in wells further to the west (Fig. 2). The sands in well 34/2-4 occur at an equivalent stratigraphic position and are most likely the same as those of the Snorre wells.

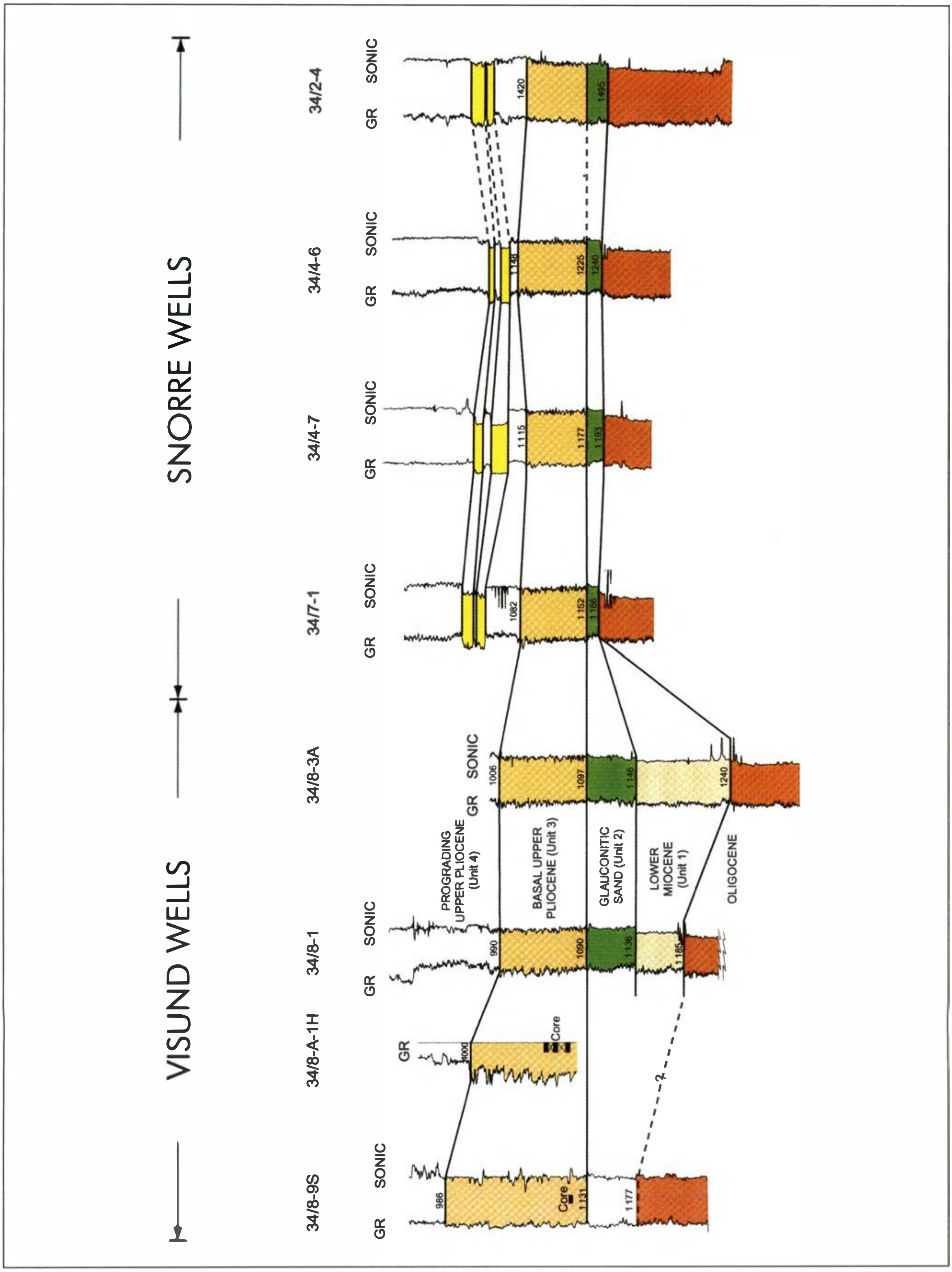

Fig. 4. Log correlation diagram of wells from the Visund area (block 34/8), wells from the Snorre area (blocks 34/4 and 34/7) and well 34/2-4 on the northern Tampen Spur. Note position of conventional cores in wells 34/8-9S and 34/8-A-1H. GR = gamma ray log. Depths in metres below rig floor (RKB).

According to Rundberg (1989), the coarser constituents include quartz, plagioclase, K-feldspar, epidot, amphiboles and rock fragments (chiefly gneissose and granitic). Glauconites are rare, but shell debris is occasionally observed. The clay mineralogy also differs markedly from the underlying Miocene and Oligocene units. Illite and chlorite are most abundant, but smectite and kaolinite are also present.

In well 31/3-1 on the Troll field, the Pleistocene (unit 5) can be distinguished from the underlying Oligocene sediments by abrupt wireline log changes. The lithology of this unit is very similar to that of the Upper Pliocene, reflecting deposition in a partly glacial environment. A detailed lithologic description based on shallow cores from a geotechnical borehole near well 31/3-1 has been presented by Sejrup et al. (1995).

Biostratigraphic correlation

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

In this study the fossil assemblages are correlated primarily with the biozonation of King (1983, 1989), who outlines a micropalaeontological zonation for Cainozoic sediments in the North Sea. Gradstein & Bäckström's (1996) faunal zonation from the North Sea and Haltenbanken, the zonation by Stratlab (1986) and the work of Eidvin et al. (1998) are also used extensively. In addition, a number of articles describing benthic foraminifera from onshore basins in the area surrounding central and southern North Sea are utilized. The zonations of planktonic foraminifera (Weaver 1987, Weaver & Clement 1986, 1987, Spiegler & Jansen 1989) and *Bolboforma* (Spiegler & Müller 1992, Müller & Spiegler 1993) from ODP and DSDP drillings in the Norwegian Sea and the North Atlantic are also very important for the dating of the sediments. Correlation with these zones yields the most accurate age determinations, because the zones are calibrated with both nannoplankton and palaeomagnetic data. The zonations of King (1983, 1989) and Gradstein & Bäckström (1996) are based on the last appearance datums (LADs) of the various taxa. The planktonic foraminifera and *Bolboforma* zonations from the ODP and DSDP drillings are based on first appearance datums (FADs).

Fossil assemblages

In the nine wells examined in this study a system of eleven fossil assemblages is devised (N-A to N-G; Figs. 5-13). These stratigraphical units are informally designated as assemblages and are regarded as informal zones. This designation is preferred because the stratigraphy of the region seems not yet mature for the introduction of a detailed, formal zonal scheme. The boundaries between the assemblages are based on the last appearance datums (LADs) of selected taxa which mostly have been chosen because of their chronostratigraphic importance. Most of the selected taxa have well-documented, consistent ranges on a regional scale. The individual assemblages comprise both planktonic and benthic forms. Fossil assemblages based on a combination of planktonic and benthic forms are applicable on a regional scale where planktonic/benthic ratios are often highly variable. The assemblages are described from top to base of the successions, following the order in which they are normally encountered in offshore borehole studies. Abbreviation of the assemblage designation are: N = northern North Sea.

WELL 31/3-1

NONION LABRADORICUM - NEOGLOBOQUADRINA PACHYDERMA (SINISTRAL) ASSEMBLAGE

Designation: N-A.

Definition: The top of the assemblage extends to the uppermost investigated sample (430 m). The base is marked by the highest occurrence of *Turrilina alsatica*.

Depth range: 430-540 m

Material: Eleven ditch cutting samples at 10 m intervals.

Age: Pleistocene.

Lithostratigraphic group: Nordland Group.

Correlation: Subzone NSB 16x of King (1989), Zone NSR 13 of Gradstein & Bäckström (1996) and *Neogloboquadrina pachyderma* (sinistral) Zone of Spiegler & Jansen (1989).

In-place assemblage: This interval contains a rich benthic fauna of mainly calcareous foraminifera. *Elphidium excavatum, Bulimina marginata, Nonion affine, Cassidulina teretis, Islandiella norcrossi* and *N. labradoricum* occur most frequently. Other important species include *Cibicides lobatulus, Haynesina orbiculare, Angulogerina angulosa, Bolivina skagerrakensis, Islandiella helenae* and *Virgulina loeblichi* (Fig. 5).

Planktonic foraminifera are quite common, but less frequent than the benthic taxa. *N. pachyderma* (both encrusted and unencrusted varieties of sinistrally coiled individuals) is dominant. Other important species include *N. pachyderma* (dextral) and *Turborotalia quinqueloba*. A few specimens of *Globigerina bulloides* are also recorded.

Reworked assemblage: Reworked benthic calcareous and planktonic foraminifera from the Upper Cretaceous are recorded sporadically throughout the interval.

Remarks: All the benthic foraminifera here regarded as *in situ* are extant species typically associated with Pliocene-Pleistocene deposits of the Norwegian margin.

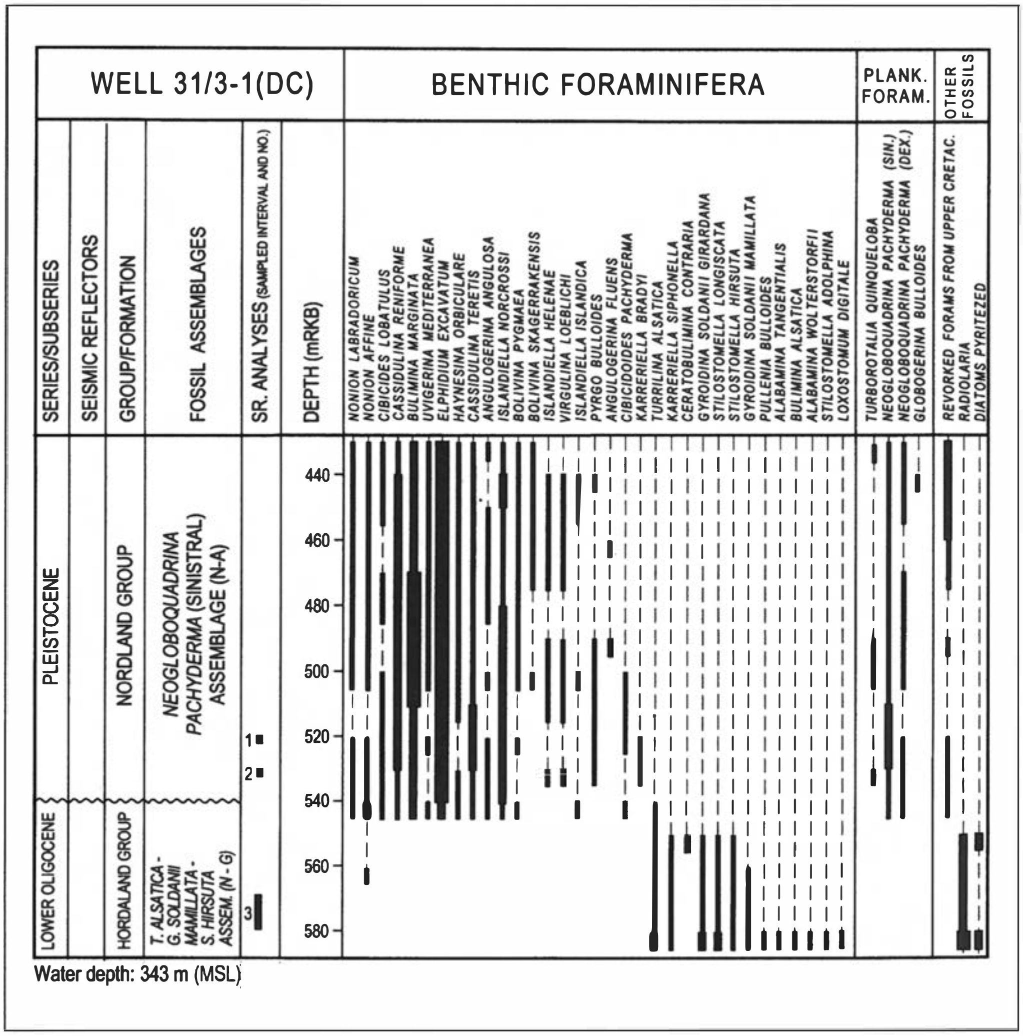

Fig. 5. Range chart of the most important index fossils in the investigated interval of well 31/3-1. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. DC = ditch cutting samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, SR. ANALYSES = strontium isotope analyses.

N. pachyderma (sinistral, encrusted) has its first frequent occurrence at 1.8 Ma (Weaver & Clement 1986, Spiegler & Jansen 1989). This test morphology has only sporadic occurrences in older sediments. *N. labradoricum* also appears to be restricted to Pleistocene deposits on the Norwegian shelf. King (1989) employs *N. labradoricum* as the nominate taxa for the Pleistocene Subzone NSB 16x of the northern North Sea. This indicates a Pleistocene age for this interval. The lowermost part of the Pleistocene is probably not present. This is based on the fact that *C. grossus* and *E. hannai* are not recorded. According to King (1989) and Eidvin et al. (1999) the LADs of both these species are in early part of Early Pleistocene.

Sejrup et al. (1995) have investigated a cored geotechnical borehole, also from the Troll field, near well 31/3-1. The borehole just penetrates the base Pleistocene angular unconformity. The cores from this borehole have been subjected to palaeomagnetic, amino acid and foraminiferal analyses. The base of the Pleistocene section in this borehole is dated to approximately 1.2 Ma by means of paleomagnetic polarity reversal chronology. A similar age is probable for the base of the N-A assemblage.

TURRILINA ALSATICA – GYROIDINA SOLDANII MAMILLATA – STILOSTOMELLA HIRSUTA ASSEMBLAGE

Designation: N-G

Definition: The top of assemblage is taken at the highest occurrence of *T. alsatica*. The base of the assemblage is not defined.

Depth range: 540-580 m.

Age: Early Oligocene.

Material: Four ditch cutting samples at 10-20 m intervals.

Lithostratigraphic group: Hordaland Group.

Correlation: Subzones NSB 7a or 7b of King (1989) and Zones NSR 7A or 7B of Gradstein & Bäckström (1996).

Assemblage: This interval contains a high diversity fauna of mainly calcareous benthic foraminifera. The most important taxa are *G. soldanii girardana* and *T. alsatica*. Other characteristic species include *Stilostomella longiscata*, *S. adolphina*, *S. hirsuta*, *Karreriella siphonella*, *Ceratobulimina contraria*, *G. soldanii mamillata*, *P. bulloides*, *Bulimina alsatica*, *Loxostomum digitale*, *Alabamina wolterstoffi* and *Alabamina tangentialis* (Fig. 5).

Remarks: *T. alsatica* and *G. soldanii girardana* are known from the Lower Oligocene to the lowermost Lower Miocene succession in the North Sea (King 1989). According to Gradstein & Bäckström (1996) these species are known from Lower Oligocene to lowermost Upper Oligocene deposits in the North Sea. *G. soldanii mamillata* is also known from Lower Oligocene to the lowermost Upper Oligocene strata from the same area (King 1989, Gradstein & Bäckström 1996). *L. digitale* and *A. wolterstoffi* are known from the Oligocene succession in Belgium (Batjes 1958) and *S. longiscata, S. adolphina, S. hirsuta, A. tangentialis* and *C. contraria* are recorded from the upper part of the Lower Oligocene succession in Denmark (Ulleberg 1974).

WELL 34/8-1

CIBICIDES GROSSUS - ELPHIDIELLA HANNAI - GLOBIGERINA BULLOIDES - NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B1.

Definition: The top of the assemblage extends to the uppermost investigated sample (440 m). The base is marked by the highest occurrence of *Ehrenbergina variabilis.*

Depth range: 440-1090 m.

Material: 34 ditch cutting samples at 10-30 m intervals.

Age: Late Pliocene.

Lithostratigraphic group: Nordland Group.

Correlation: Subzones NSB 15a of King (1989) and *Neogloboquadrina atlantica* (sinistral) Zone of Spiegler & Jansen (1989).

In-place assemblage: This interval contains a rich benthic fauna of mainly calcareous foraminifera. The fauna is relatively uniform throughout the entire section, but this observation is partly due to extensive caving. *E. excavatum* occurs most frequently. Other characteristic taxa include *Angulogerina fluens, Cibicides scaldisiensis, B. marginata, N. affine, C. grossus, E. hannai* and *Islandiella islandica* (upper and lower part; Fig. 6).

Planktonic foraminifera are also quite common, but less frequent than the benthic foraminifera. Important planktonic species include *G. bulloides, N. atlantica* (sinistral), *N. pachyderma* (sinistral, unencrusted), *N. pachyderma* (dextral), *Globorotalia inflata* (upper part) and *N. atlantica* (dextral; upper part). *T. quinqueloba* is scarce throughout.

Reworked assemblage: Reworked fossils are recorded sporadically throughout. These are agglutinated foraminifera from the lower Tertiary, benthic calcareous and planktonic foraminifera from the Upper Cretaceous and *Inoceramus* prisms from the Upper Cretaceous. At the base of the interval a few specimens of *Eponides pygmeus* and *Cibicides telegdi*, probably from the Miocene and *Bolboforma subfragori* from the Middle-Upper Miocene, are recorded.

Remarks: With the exception of *C. grossus* and *E. hannai* all the *in situ* benthic foraminifera are extant species. According to King (1989) *C. grossus* and *E. hannai* are found in the northern North Sea in Upper Pliocene to Lower Pleistocene deposits. FADs of these species are considerably higher than the Lower/Upper Pliocene boundary (3.56 Ma). *C. grossus* is, however, recorded in deposits as old as the late Middle Miocene on the Vøring Plateau (T. Eidvin, personal observation) and as old as the Late Miocene in the Netherlands. However, *E. hannai* is known from Upper Pliocene deposits in the latter area (Doppert 1980).

Only the unencrusted variety of sinistrally coiled *N. pachyderma* is recorded in this interval. The encrusted variety of this form is dominating the planktonic foraminiferal fauna in the Norwegian Sea after 1.8 Ma (Weaver & Clement 1986, Spiegler & Jansen 1989). The fact that this form is not recorded indicates that Pleistocene sediments are not sampled in this well. This is also supported by the fact that *Nonion labradoricum* is also missing in this assemblage. King (1989) use *N. labradoricum* as the nominate taxon for the Pleistocene Zone NSB 16x of the northern North Sea, and this taxa has been recognized in the Pleistocene section in well 31/3-1. However, Pleistocene sediments are probably present in parts of the 90 m unsampled section.

N. atlantica (dextral) is quite common in the upper part of this unit. This taxa is known from an upper *N. atlantica* (dextral) Zone which is described from the Vøring Plateau in Upper Pliocene deposits. LAD of this species is approximately 1.9 Ma in that area (Spiegler & Jansen 1989). On the Vøring Plateau the upper *N. atlantica* (dextral) Zone lies above a *N. atlantica* (sinistral) Zone. The *N. atlantica* (sinistral) Zone is also rich on *G. bulloides*, but *N. atlantica* (dextral) is scarce in this zone. LAD of *N. atlantica* (sinistral) is about 2.4 Ma on the Vøring Plateau. In well 34/8-1 *N. atlantica* (dextral) occurs, quite numerously, together with *N. atlantica* (sinistral) and *G. bulloides*, and consequently seems to have a somewhat different occurrence than in the Norwegian Sea. The top of the N-B1 assemblage is probably close to 2.4 Ma.

EHRENBERGINA VARIABILIS ASSEMBLAGE

Designation: N-C1.

Definition: The top of the assemblage is taken at the highest occurrence of *E. variabilis.* The base is marked by the highest occurrence of Diatom sp. 4 (King 1983) and Diatom sp. 5 (King 1983).

Depth range: 1090-1140 m.

Material: Five ditch cutting samples at 10 m intervals.

Age: Late Miocene to earliest Early Pliocene (partly based on strontium isotope analysis).

Lithostratigraphic formation: Utsira Formation.

Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler

& Jansen (1989), *G. subglobosa - E. variabilis* Zone of Stratlab (1986), *C. telegdi – E. pygmeus – N. atlantica* (dextral) Zone (M-H) and *E. variabilis - G. subglobosa - N. atlantica* (dextral) Zone (M-I) of Eidvin et al. (1998).

In-place assemblage: There are slightly fewer microfossils in this interval than in the overlying interval. In this assemblage the benthic fauna includes calcareous foraminifera and sponge spicules. A few agglutinated foraminifera are also recorded. Sponge spicules (both rod-shaped and *Geodia* sp.) are significantly more common than foraminifera. The most frequently occurring foraminifera are *A. fluens, C. teretis* and *N. affine*. Other important species include *E. variabilis, Pullenia bulloides, E. pygmeus* and *Globocassidulina subglobosa. C. telegdi* and *Martinottiella communis* (agglutinated) are also recorded at a few levels (Fig. 6).

Planktonic foraminifera include *G. bulloides* and *N. atlantica* (sinistral) which are dominant. Other species are *N. pachyderma (sinistral, unencrusted), N. atlantica (dextral), N. pachyderma* (dextral), *T. quinqueloba* and *G. inflata.*

Reworked assemblage: Presumed reworked *Bolboforma* from the uppermost Middle Miocene and lowermost Upper Miocene are recorded sporadically throughout and include *B. subfragori, B. metzmacheri, B. clodiusi, B. compressibadenensis, B. fragori* and *B. pseudohystrix.*

Remarks: Most of the benthic foraminifera are known from almost the entire Neogene succession. Some of these and some of the planktonic foraminifera are probably caved. *E. variabilis* is recorded from the Upper Oligocene to Lower Miocene of Germany (Grossheide & Trunco 1965, Spiegler 1974), from the Upper Miocene on the Norwegian Sea continental shelf (Stratlab 1986, Eidvin et al. 1998) and from the Upper Oligocene to Lower Pliocene on the Norwegian continental shelf (Skarbø & Verdenius 1986). *E. pygmeus* and *C. telegdi* are recorded from the Upper Oligocene and older deposits in Denmark and Germany (Grossheide & Trunko 1965, Hausmann 1964, Kummerle 1963 and Ulleberg 1974). On the Norwegian Sea continental shelf these species are known from Upper Miocene deposits according to Eidvin et al. (1998) and from Upper Miocene-Lower Pliocene deposits according to Stratlab (1986). *G. subglobosa* is known from the Middle to Upper Miocene of Belgium (Doppert 1980) and from the Upper Oligocene to Upper Miocene of Germany (Spiegler 1974). In the central North Sea *G. subglobosa* is recorded from Upper Oligocene to basal Upper Pliocene deposits (Eidvin et al. 1999), and on the Norwegian Sea continental shelf from Upper Miocene deposits (Stratlab 1986, Eidvin et al. 1998). *M. communis* is known from Middle to Upper Miocene deposits on the Vøring Plateau (Osterman & Qvale 1989).

N. atlantica (dextral) is known to occur in the uppermost Upper Pliocene and in the Upper Miocene on the Vøring Plateau (Spiegler & Jansen 1992, Müller & Spiegler 1993). Consequently, these can be caved from the overlying assemblage or they can be *in situ* Upper Miocene specimens.

DIATOM SP. 4 – DIATOM SP. 5 ASSEMBLAGE

Designation: N-E.

Definition: The top of the assemblage is taken at the highest occurrence of Diatom sp. 4 and Diatom sp. 5. The base is marked by the highest occurrence of *Turrilina alsatica* and Diatom sp. 3 (King 1983).

Depth range: 1140-1170 m.

Material: Three ditch cutting samples at 10 m intervals.

Age: Early Miocene.

Lithostratigraphic group: Hordaland Group.

Correlation: Zone NSP 10 of King (1983).

Description: The greater proportion of the fossils recorded in this interval are sponge spicules (both rod-shaped and *Geodia* sp.) and radiolarians. Far fewer pyritized diatoms are recorded. Most of the diatoms are Diatom sp. 4 and Diatom sp. 5 (Fig. 6).

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

TURRILINA ALSATICA - DIATOM SP. 3 ASSEMBLAGE

Designation: N-F1.

Definition: The top of the assemblage is taken at the highest occurrence of *T. alsatica* and Diatom sp. 3. The base of the assemblage is undefined.

Depth range: 1170-1320 m (lowermost investigated sample).

Material: 10 ditch cutting samples at 10-20 m intervals.

Age: Early-Late Oligocene.

Lithostratigraphic group: Hordaland Group.

Correlation: Lower part of Subzones NSB 8a and NSP 9c and upper part of Subzone NSB 7b of King (1989) and upper part of Zone NSR 7B of Gradstein & Bäckström (1996).

Description: The fossil assemblage in this interval is also dominated by sponge spicules. Radiolarians and pyritized diatoms are also quite common. Far fewer benthic foraminifera, mainly calcareous but also some agglutinated forms, are recorded. In the diatom flora the index fossil Diatom sp. 3 is recorded. *T. alsatica* is the dominant foraminifer. Other characteristic foraminifera include *G. soldanii girardana, Trifarina gracilis, Eponides umbonatus* and *Trochammina* sp. *Rotaliatina bulimoides* and *G. soldanii mamillata* are also recorded at two levels (Fig. 6).

Remarks: *T. gracilis* is recorded from Lower Oligocene to Lower Miocene deposits on the Norwegian continental shelf (Skarbø & Verdenius 1986). Diatom sp. 3 is known from uppermost Lower Oligocene to lowermost Lower Miocene deposits in the North Sea (King 1989). According to King (1989) *T. alsatica* and *G. sol-*

danii girardana are also known from Lower Oligocene to lowermost Lower Miocene sediments in the same area. According to Gradstein & Bäckström (1996) are these species known from Lower Oligocene to lowermost Upper Oligocene deposits in the North Sea. *G. soldanii mamillata* is known from the Lower Oligocene to the lowermost Upper Oligocene from the same area (King 1989, Gradstein & Bäckström 1996). *R. bulimoides* is known from the Lower Oligocene to the lowermost Upper Oligocene according to King (1989) and from the Lower Oligocene according to Gradstein & Bäckström (1996).

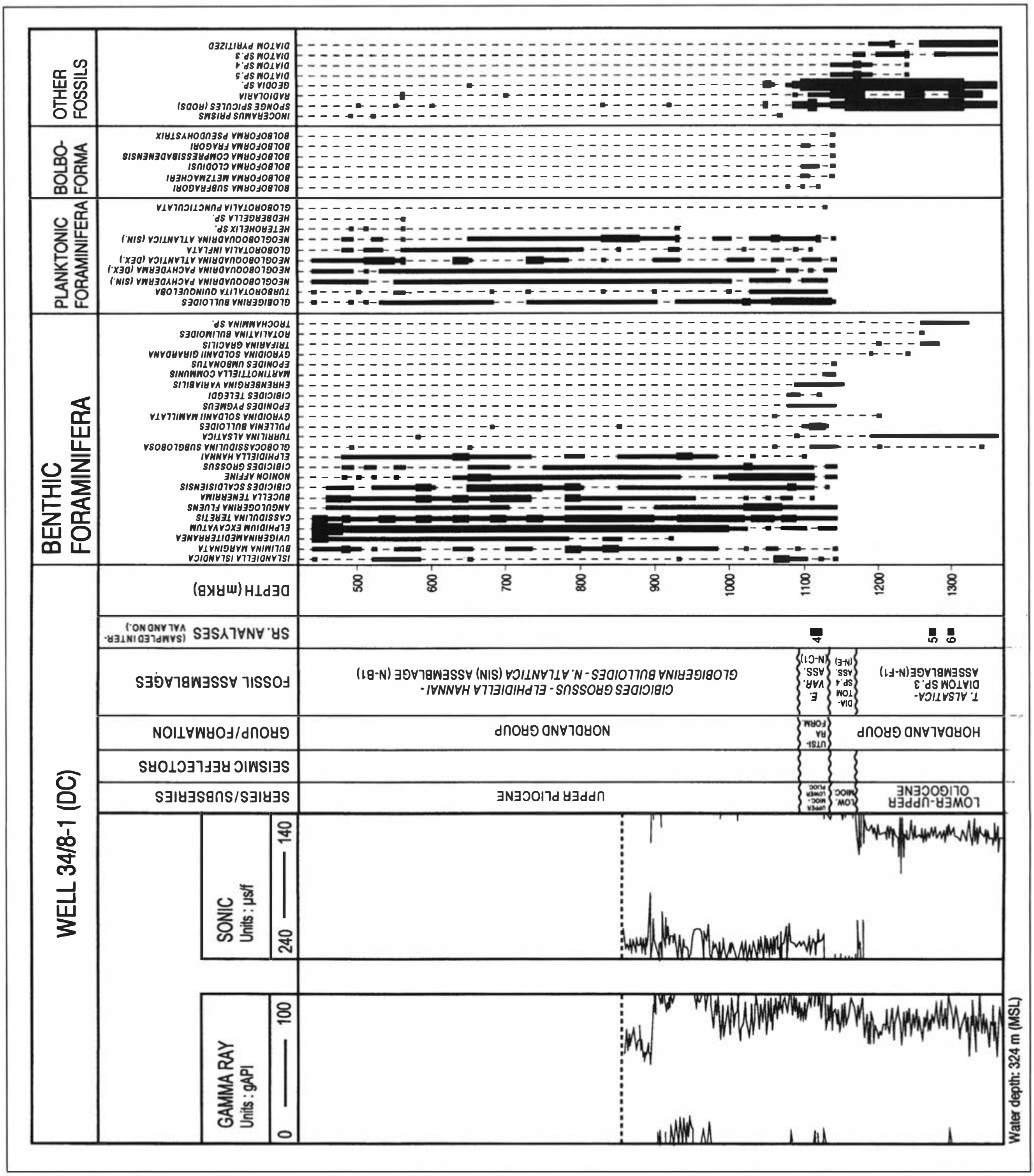

Fig. 6. Range chart of the most important index fossils in the investigated interval of well 34/8-1. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. DC = ditch cutting samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, µs/f = microseconds per foot, SR. ANALYSES = strontium isotope analyses.

WELL 34/8-9S

CIBICIDES GROSSUS – ELPHIDIUM ALBIUMBILICATUM – GLOBIGERINA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B2.

Definition: The top of the assemblage extends to the uppermost investigated sample. The base extends to the lowermost investigated sample.

Depth range: 1109.68-1112.63 m.

Material: Four conventional core samples.

Age: Late Pliocene.

Lithostratigraphic group: Nordland Group.

Correlation: Subzones NSB 15a of King (1989) and *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989).

In-place assemblage: This interval contains a rich benthic fauna of mainly calcareous foraminifera. The fauna varies considerably throughout this short section. *N. affine, C. lobatulus, C. teretis* and *E. excavatum* occur most frequently throughout the assemblage. *B. marginata, A. fluens* and *Loxostomoides lammersi* also appear consistently throughout. *E. albiumbilicatum, C. grossus* and *Elphidium groenlandicum* are common in parts of the interval. *Cibicidoides pachyderma, C. scaldisiensis, Elphidium bartletti* and *Sigmoilosis schlumbergeri* (agglutinated) are also found in parts of the section (Fig. 7).

Planktonic foraminifera are less frequent than benthic taxa. *G. bulloides* and *N. atlantica* (sinistral) are dominant. *Globigerinita glutinata, N. atlantica* (dextral) and *T. quinqueloba* occur sporadically.

Reworked assemblage: Reworked foraminifera are recorded sporadically. These are *E. pygmeus* from Miocene deposits, *Uvigerina pygmea langeri* from the Upper Miocene, *Bolboforma laevis, B. clodiusi, B. subfragori* and *B. fragori* from the Middle-Upper Miocene. A few specimens of *Heterohelix* sp. and *Inoceramus* prisms from the Upper Cretaceous are also recorded.

Remarks: According to King (1989) FADs of *C. grossus, E. albiumbilicatum* and *E. groenlandicum* are in the late part of Late Pliocene in the North Sea area. However, the occurrence of *N. atlantica* (sinistral) indicates an age that is not younger than 2.4 Ma (Spiegler & Jansen 1989).

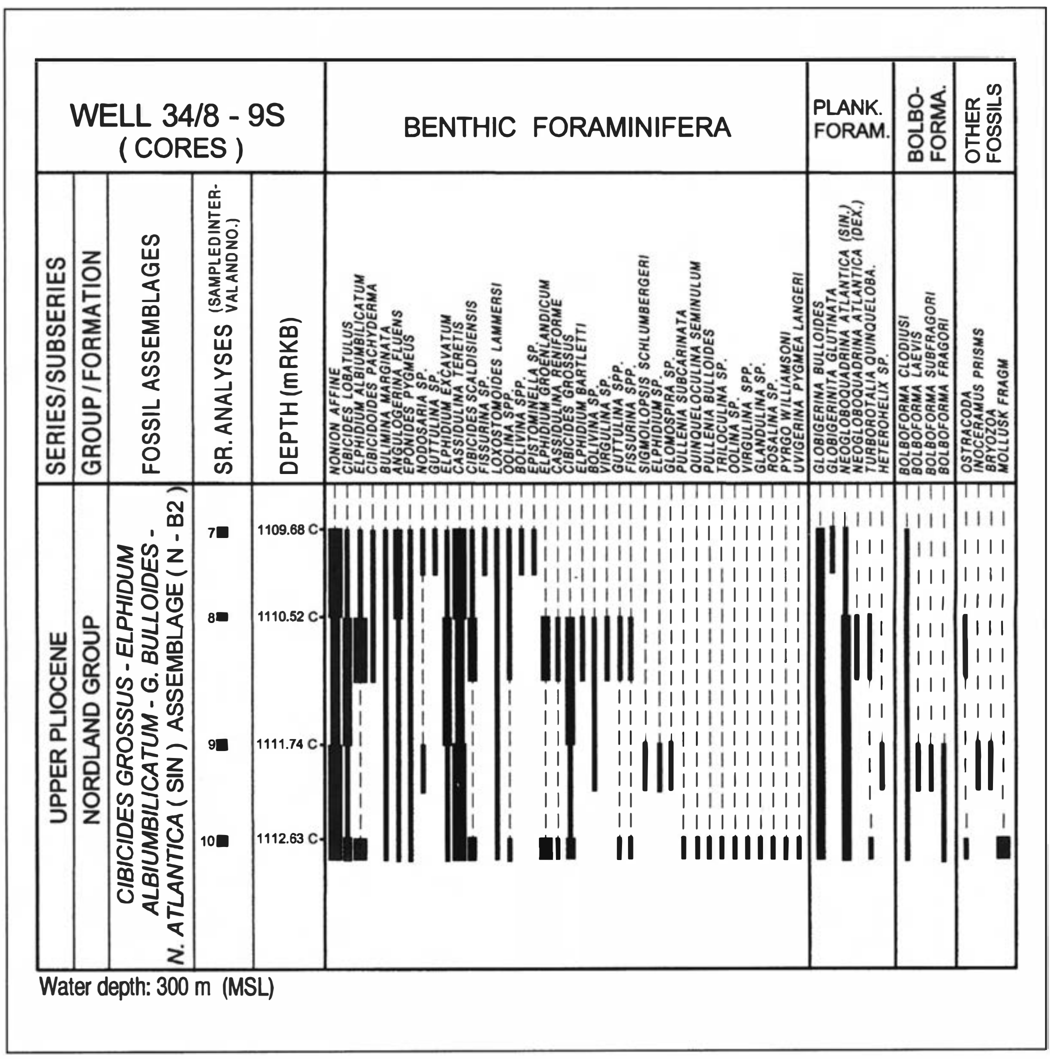

Fig. 7. Range chart of the most important index fossils in the investigated interval of well 34/8-9S. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. C = core, m RKB = metres below rig floor, m MSL = metres below mean sea level, SR. ANALYSES = strontium isotope analyses.

WELL 34/8A-1H

CIBICIDES GROSSUS – ELPHIDIELLA HANNAI – GLOBIGERIA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B1.
Definition: The top of the assemblage extends to the uppermost investigated sample. The base extends to the lowermost investigated sample.
Depth range: 1070.2-1102 m.
Material: Seven conventional core samples.
Age: Late Pliocene.
Lithostratigraphic group: Nordland Group.
Correlation: Subzones NSB 15a of King (1989) and *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989).
In-place assemblage: This interval contains a rich benthic fauna of calcareous foraminifera. The fauna varies considerably throughout this short section. *N. affine, C. lobatulus, C. teretis* all occur frequently throughout the interval. *C. grossus, E. hannai, E. albiumbilicatum, E. excavatum, A. fluens and Buccella tenerrima* are recorded in the middle part of the unit (Fig. 8).

Planktonic foraminifera are less frequent than benthic taxa, but these are also quite common in parts of the interval. *G. bulloides* and *N. atlantica* (sinistral) are dominant. *T. quinqueloba, N. pachyderma* (dextral) and *N. atlantica* (dextral) occur sporadically.
Reworked assemblage: Reworked foraminifera are recorded sporadically. These are *C. telegdi*, from Miocene deposits and *T. alsatica and G. soldanii girardana* from the Oligocene.
Remarks: The occurrence of *C. grossus, E. hannai, E. albiumbilicatum, N. atlantica* (sinistral) and *G. bulloides* indicates a Late Pliocene age that is not younger than 2.4 Ma (King 1989, Spiegler & Jansen 1989).

WELL 34/8-3A

CIBICIDES GROSSUS – ELPHIDIELLA HANNAI – GLOBIGERINA BULLOIDES –NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B1.
Definition: The top of the assemblage extends to the uppermost investigated sample (1000 m). The base is marked by the highest occurrence of *E. variabilis.*

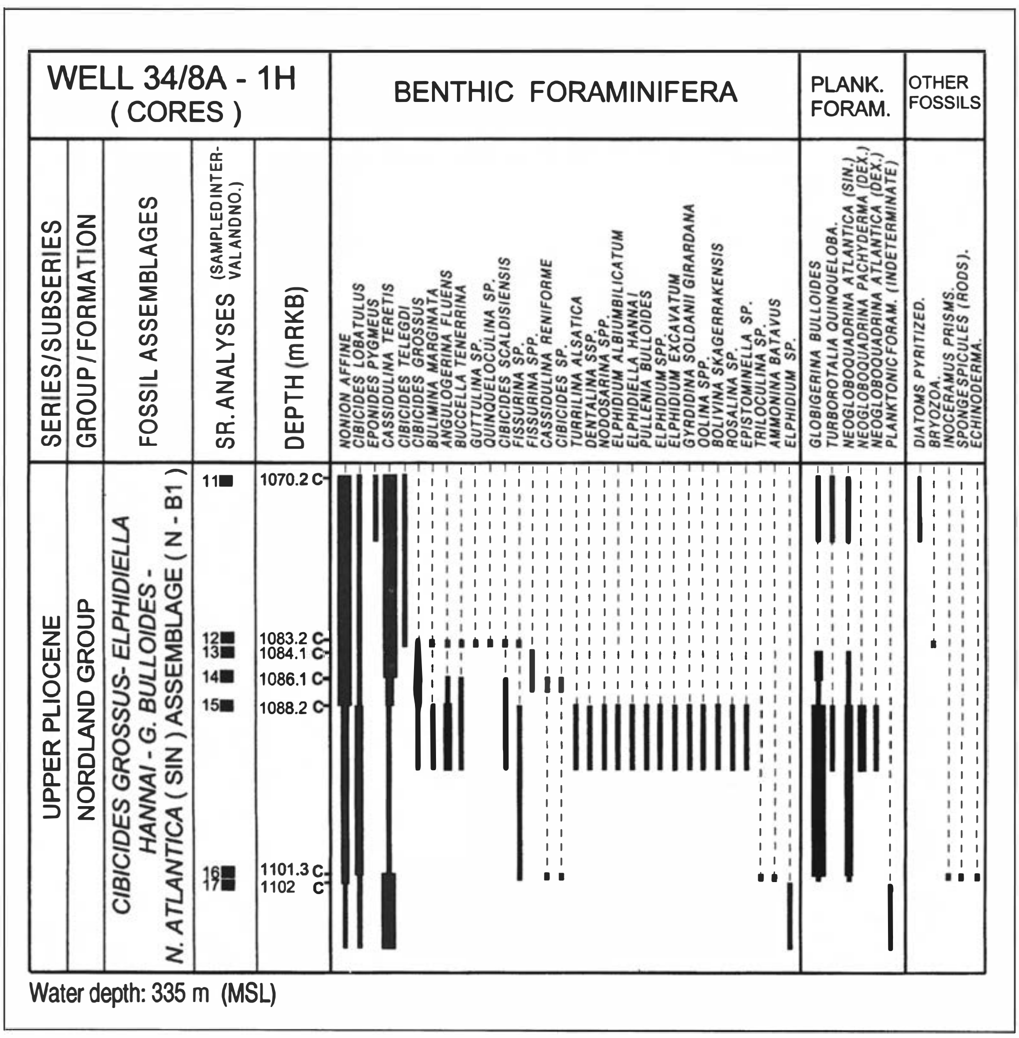

Fig. 8. Range chart of the most important index fossils in the investigated interval of well 34/8A-1H. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. C = core, m RKB = metres below rig floor, m MSL = metres below mean sea level, SR. ANALYSES = strontium isotope analyses.

Depth range: 1000-1110 m.
Material: Eleven ditch cutting samples at 10 m intervals.
Age: Late Pliocene.
Lithostratigraphic group: Nordland Group.
Correlation: Subzones NSB 15a of King (1989) and *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989).
In-place assemblage: This assemblage contains a rich benthic fauna of calcareous foraminifera. The fauna is relatively uniform throughout the interval, but this is probably partly due to extensively caved material. *N. affine, A. fluens, C. teretis* and *C. grossus* occur most frequently. Other characteristic taxa include *C. lobatulus, E. hannai, Buccella tenerrima, E. excavatum, Cassidulina reniforme and I. islandica* (lower part; Fig. 9).

Planktonic foraminifera are less frequent than the benthic taxa. *G. bulloides* and *N. pachyderma* (dextral) are dominant. Other important species include *T. quinqueloba* and *N. atlantica* (sinistral; lower part). *N. pachyderma* (sinistral) and *G. glutinata* occur sporadically.
Remarks: The occurrence of *C. grossus, E. hannai, E. albiumbilicatum, N. atlantica* (sinistral) and *G. bulloides* indicate a Late Pliocene age that is not younger than 2.4 Ma (King 1989, Spiegler & Jansen 1989).

EHRENBERGINA VARIABILIS ASSEMBLAGE

Designation: N-C1.
Definition: The top of the assemblage is taken at the highest occurrence of *E. variabilis*. The highest occurrence of *Eponides umbonatus, Stilostomella* sp. and the highest abundant occurrence of diatoms mark the base of the assemblage.
Depth range: 1110-1180 m.
Material: Seven ditch cutting samples at 10 m intervals.
Age: Late Miocene to earliest Early Pliocene (partly based on log correlation).
Lithostratigraphic formation: Utsira Formation.
Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989), *G. subglobosa - E. variabilis* Zone of Stratlab (1986), *C. telegdi – E. pygmeus – N. atlantica* (dextral) Zone (M-H) and *E. variabilis - G. subglobosa - N. atlantica* (dextral) Zone (M-I) of Eidvin et al. (1998).
In-place assemblage: There are slightly fewer microfossils in this interval than in the overlying assemblage. In this interval the benthic fauna is dominated of calcareous foraminifera and sponge spicules. A few agglutinated foraminifera are also recorded. The most frequently occurring foraminifera are *Cibicides dutemplei, C. teretis* and *N. affine* (upper part). Other characteristic taxa include *E. variabilis, A. fluens, E. pygmeus, P. bulloides, Uvigerina pygmea langeri, G. subglobosa* and *M. communis* (agglutinated; Fig. 9).

Far fewer planktonic than benthic foraminifera are recorded. Planktonic forms include *G. bulloides, N. pachyderma* (dextral), *T. quinqueloba, N. atlantica* (sinistral), *G. glutinata* and *N. atlantica* (dextral).
Reworked assemblage: A few specimens of presumed reworked *Bolboforma* from the uppermost Middle Miocene and lowermost Upper Miocene are recorded and *include B. metzmacheri, B. fragori* and *B. clodiusi.*
Remarks: *U. pygmea langeri* is described from Upper Miocene deposits of the North Sea (King 1989). *C. dutemplei* is known from the Upper Eocene to Middle Miocene of Belgium (Kaasschieter 1961, Skarbø & Verdenius 1986), from Upper Eocene to Lower Pliocene deposits in the Netherlands (Doppert 1980) and from Upper Oligocene to Upper Miocene sediments on the Norwegian continental shelf (Skarbø & Verdenius 1986).
This assemblage corresponds to the N-C1 assemblage in wells 34/8-1, 34/2-4, 34/4-6, 34/4-7 and the N-C2 assemblage in well 34/7-1.

EPONIDES UMBONATUS – STILOSTOMELLA SP. – DIATOM SP. ASSEMBLAGE

Designation: N-D.
Definition: The top of the assemblage is taken at the highest occurrence of *E. umbonatus* and *Stilostomella* sp. and the highest abundant occurrence of diatoms. The base is marked by the highest occurrence of Diatom sp. 5.
Depth range: 1180-1210 m.
Material: Three ditch cutting samples at 10 m intervals.
Age: Early Miocene.
Lithostratigraphic group: Hordaland Group.
Correlation: Probably Zone NSP 10 of King (1983).
Description: The greater proportion of the fossils recorded in this interval are diatoms, radiolarians and sponge spicules (both rod-shaped and *Geodia* sp.). Far fewer foraminifera are recorded and most of these are probably caved. However, the calcareous benthic forms *E. umbonatus* and *Stilostomella* sp. are probably *in situ* (Fig. 9).
Remarks: It is difficult to determine the precise age of this assemblage. No short-range index fossils are recorded. *E. umbonatus* are known from deposits from the Eocene to recent (Kaasschieter 1961, Mackensen 1985). *Stilostomella* sp., the sponge spicules, the radiolarians and the diatoms give only a general Early Neogene to Late Palaeogene age. However, this assemblage is very similar to the immediately underlying, Early Miocene, Diatom sp. 4 and Diatom sp. 5 assemblage (N-E). Several of the pyritized diatoms are very similar to Diatom sp. 4 and Diatom sp. 5, but the projections near the valve margin of the specimens are smaller and not as equally spaced as on the Diatom sp. 4 and Diatom sp. 5 of King (1983). However, the diatoms probably descend from Diatom sp. 4 and Diatom sp. 5 and it is probable that the N-F assemblage also is of Early Miocene age.

DIATOM SP. 4 – DIATOM SP. 5 ASSEMBLAGE

Designation: N-E.
Definition: The top of the assemblage is taken at the highest occurrence of Diatom sp. 5. The base is marked by the highest occurrence of *T. alsatica.*
Depth range: 1210-1240 m.
Material: Three ditch cutting samples at 10 m intervals.
Age: Early Miocene.
Lithostratigraphic group: Hordaland Group.
Correlation: Zone NSP 10 of King (1983).
Description: Also this assemblage is completely dominated by diatoms, radiolarians and sponge spicules (both rod-shaped and *Geodia* sp.; Fig. 9). Just a few foraminifera are recorded and these are probably caved. Several of the diatoms are Diatom sp. 4 and Diatom sp. 5.
Remarks: Diatom sp. 4 and Diatom sp. 5 are both known from Lower Miocene deposits in the North Sea (King 1983).

TURRILINA ALSATICA ASSEMBLAGE

Designation: N-F2.
Definition: The top of the assemblage is taken at the highest occurrence of *T. alsatica.* The base of the assemblage is undefined.
Depth range: 1240-1300 m (lowermost investigated sample).
Material: Six ditch cutting samples at 10-20 m intervals.
Age: Early-Late Oligocene.
Lithostratigraphic group: Hordaland Group.
Correlation: Lower part of Subzone NSB 8a and upper part of Subzone NSB 7b of King (1989) and upper part of Zone NSR 7B of Gradstein & Bäckström (1996).
Description: The fossil assemblage in this interval is also dominated by diatoms, radiolarians and sponge spicules. Far fewer foraminifera are recorded. Some of these are probably caved, but *in situ* forms include *T. alsatica, G. soldanii girardana, T. gracilis* and *Nonion* sp. A (King 1989) (Fig. 9).
Remarks: *Nonion* sp. A is recorded from Lower Oligocene to Lower Miocene deposits in the North Sea (King 1989).
This assemblage is coeval with the N-F1 assemblage in wells 34/8-1, 34/4-6, 34/4-7, 34/7-1 and the N-F3 and N-F4 assemblages in well 34/2-4.

WELL 34/4-6

CIBICIDES GROSSUS – ELPHIDIELLA HANNAI - GLOBIGERINA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B1.
Definition: The top of the assemblage extends to the uppermost investigated sample (540 m). The base is marked by the highest occurrence of *E. variabilis.*
Depth range: 540-1210 m.
Material: 34 ditch cutting samples at 10-30 m intervals.
Age: Late Pliocene.
Lithostratigraphic group: Nordland Group.
Correlation: Subzones NSB 15a of King (1989) and *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989).
In-place assemblage: This assemblage contains a rich benthic fauna of mainly calcareous foraminifera. The upper and lower parts of the assemblage contain more specimens than the middle part. The fauna is relatively uniform throughout, but this observation is partly due to extensive caving. *E. excavatum* and *C. teretis* occur most frequently. Other important species include *E. hannai, B. marginata, Cibicides lobatulus, C. grossus, E. albiumbilicatum, B. tenerrima, H. orbiculare, C. scaldisiensis, Uvigerina mediterranea* (upper part), *N. affine* (upper and lower part) and *I. islandica* (upper and lower part).
Planktonic foraminifera are also less common in the middle part of the interval. They are overall less frequent than benthic taxa and include *N. atlantica* (sinistral), *G. bulloides, N. pachyderma* (sinistral, unencrusted), *N. pachyderma* (dextral), *G. Inflata, N. atlantica* (dextral) and *T. quinqueloba* (scarce throughout; Fig. 10).
Reworked assemblage: Reworked fossils are recorded sporadically throughout. These are agglutinated foraminifera from the lower Tertiary and benthic calcareous and planktonic foraminifera from the Upper Cretaceous. At the base of the assemblage *C. dutemplei, E. pygmeus* and *C. telegdi* are recorded at some levels. These are probably reworked from Miocene deposits.
Remarks: The occurrence of *C. grossus, E. hannai, N. atlantica* (sinistral) and *G. bulloides* indicates a Late Pliocene age no younger than 2.4 Ma (King 1989, Spiegler & Jansen 1989). Pleistocene sediments are probably present in parts of the 140 m unsampled section.

EHRENBERGINA VARIABILIS ASSEMBLAGE

Designation: N-C1.
Definition: The top of the assemblage is taken at the highest occurrence of *E. variabilis.* The base is marked by the highest occurrence of *T. alsatica* and Diatom sp. 3.
Depth range: 1210-1250 m.
Material: Four ditch cutting samples at 10 m intervals.
Age: Late Miocene to earliest Early Pliocene (partly based on strontium isotope analysis).
Lithostratigraphic formation: Utsira Formation.
Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989), *G. subglobosa - E. variabilis* Zone of Stratlab (1986), *C. telegdi – E. pygmeus – N. atlantica* (dextral) Zone (M-H) and *E. variabilis - G. subglobosa - N. atlantica* (dextral) Zone (M-I) of Eidvin et al. (1998).

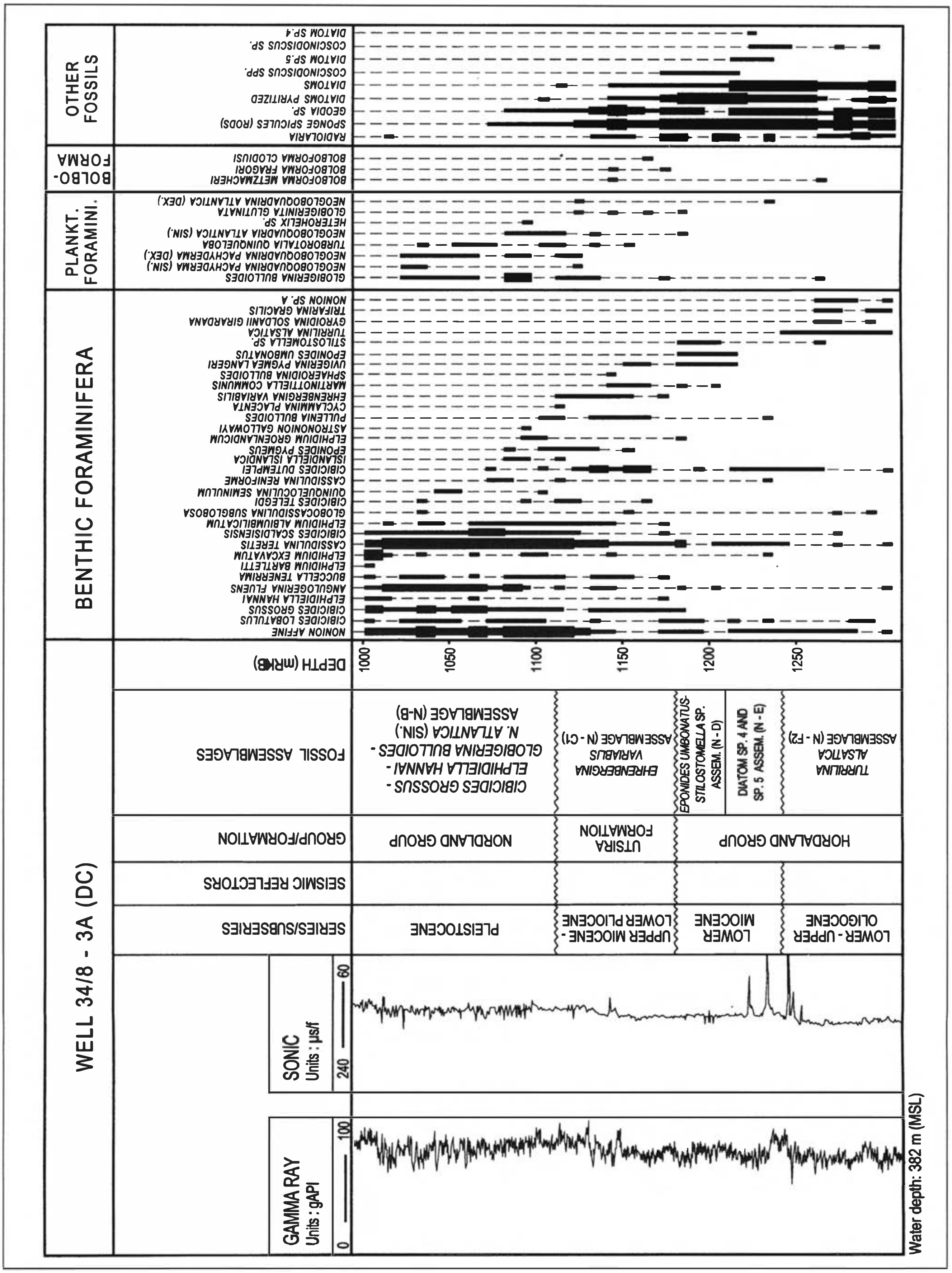

Fig. 9. Range chart of the most important index fossils in the investigated interval of well 34/8-3A. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. DC = ditch cutting samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, µs/f = microseconds per foot.

Description: There are slightly fewer foraminifera in this interval than in the lower part of the overlying interval. In addition, specimens of sponge spicules (both rod-shaped and *Geodia* sp.) are common in this assemblage. The most important benthic calcareous species are *N. affine* and *C. teretis*. Other species include *A. fluens, E. variabilis, P. bulloides, E. pygmeus, C. telegdi* and *C. dutemplei* (Fig. 10). Some of these are probably caved.

Planktonic foraminifera are less frequent than the benthic taxa and include *G. bulloides, N. atlantica* (sinistral), *G. inflata, N. pachyderma* (sinistral, unencrusted), *N. pachyderma* (dextral), *N. atlantica* (dextral) and *T. quinqueloba*. Some of these are also probably caved.

Remarks: This assemblage corresponds to the N-C1 assemblage in wells 34/8-1, 34/8-3A, 34/2-4, 34/4-7 and the N-C2 assemblage in well 34/7-1.

TURRILINA ALSATICA - DIATOM SP. 3 ASSEMBLAGE

Designation: N-F1.

Definition: The top of the assemblage is taken at the highest occurrence of *T. alsatica* and Diatom sp. 3. The base of the assemblage is undefined.

Depth range: 1250-1370 m (lowermost investigated sample).

Material: Nine ditch cutting samples at 10-20 m intervals.

Age: Early-Late Oligocene.

Lithostratigraphic group: Hordaland Group.

Correlation: Lower part of Subzones NSB 8a and NSP 9c and upper part of Subzone NSB 7b of King (1989) and upper part of Zone NSR 7B of Gradstein & Bäckström (1996).

Description: The fossil assemblage in this interval is dominated by sponge spicules, radiolarians and bryozoan fragments. Far fewer benthic calcareous foraminifera and pyritised diatoms are recorded. In the diatom flora the index fossil Diatom sp. 3 occurs consistent throughout. *T. alsatica, G. soldanii girardana* and *T. gracilis* are the dominant foraminifera. Several specimens of *G. soldanii mamillata* and *R. bulimoides* are also recorded at a few levels (Fig. 10).

Remarks: This assemblage is coeval with the N-F1 assemblage in wells 34/8-1, 34/4-7, 34/7-1, the N-F2 assemblage in well 34/8-3A and the N-F3 and N-F4 assemblages in well 34/2-4.

WELL 34/4-7

CIBICIDES GROSSUS – ELPHIDIELLA HANNAI – GLOBIGERINA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B1.

Description: The top of the assemblage extends to the uppermost investigated sample (1000 m). The base is marked by the highest occurrence of *E. variabilis.*

Depth range: 1000-1180 m.

Material: Nine sidewall cores and 18 ditch cutting samples at 10 m intervals.

Age: Late Pliocene.

Lithostratigraphic group: Nordland Group.

Correlation: Subzones NSB 15a of King (1989) and *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989).

In-place assemblage: This assemblage contains a rich benthic fauna of mainly calcareous foraminifera. *E. excavatum, C. teretis* and *C. grossus* (lower part) occur most frequently. Other important species include *Islandiella helenae, C. lobatulus, E. hannai, B. marginata, H. orbiculare, C. scaldisiensis, B. tenerrima, I. islandica* and *N. affine* (lower part) (Figs. 11a and b).

Planktonic foraminifera are less frequent than benthic taxa and include *N. atlantica* (sinistral), *G. bulloides, N. pachyderma* (sinistral, unencrusted), *N. pachyderma* (dextral) and *G. inflata. T. quinqueloba* and *N. atlantica* (dextral) are also recorded at a few levels.

Reworked assemblage: Reworked fossils are recorded sporadically in the lower part of the assemblage. These are *C. dutemplei, E. pygmeus* and *C. telegdi* from Miocene deposits, *Inoceramus* prisms from the Upper Cretaceous and Diatom sp. 3 from the Oligocene.

Remarks: The occurrence of *C. grossus, E. hannai, N. atlantica* (sinistral) and *G. bulloides* indicates a Late Pliocene age that is not younger than 2.4 Ma (King 1989, Spiegler & Jansen 1989).

EHRENBERGINA VARIABILIS ASSEMBLAGE

Designation: N-C1.

Definition: The top of the assemblage is taken at the highest occurrence of *E. variabilis.* The base is marked by the highest occurrence of *T. alsatica* and the highest consistent occurrence of Diatom sp. 3.

Depth range: 1180-1200 m.

Material: Two sidewall cores and two ditch cutting samples at 10 m intervals.

Age: Late Miocene to earliest Early Pliocene (partly based on strontium isotope analysis).

Lithostratigraphic formation: Utsira Formation.

Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989), *G. subglobosa - E. variabilis* Zone of Stratlab (1986), *C. telegdi – E. pygmeus – N. atlantica* (dextral) Zone (M-H) and *E. variabilis - G. subglobosa - N. atlantica* (dextral) Zone (M-I) of Eidvin et al. (1998).

In-place assemblage: There are slightly fewer foraminifera in this interval than in the overlying assemblage. In addition specimens of sponge spicules (both rod-shaped and *Geodia* sp.) are common in this interval. Many foraminifera, which are recorded in the ditch cutting samples (Fig. 11b), are not recorded in the sidewall cores samples (Fig. 11a), and most of these

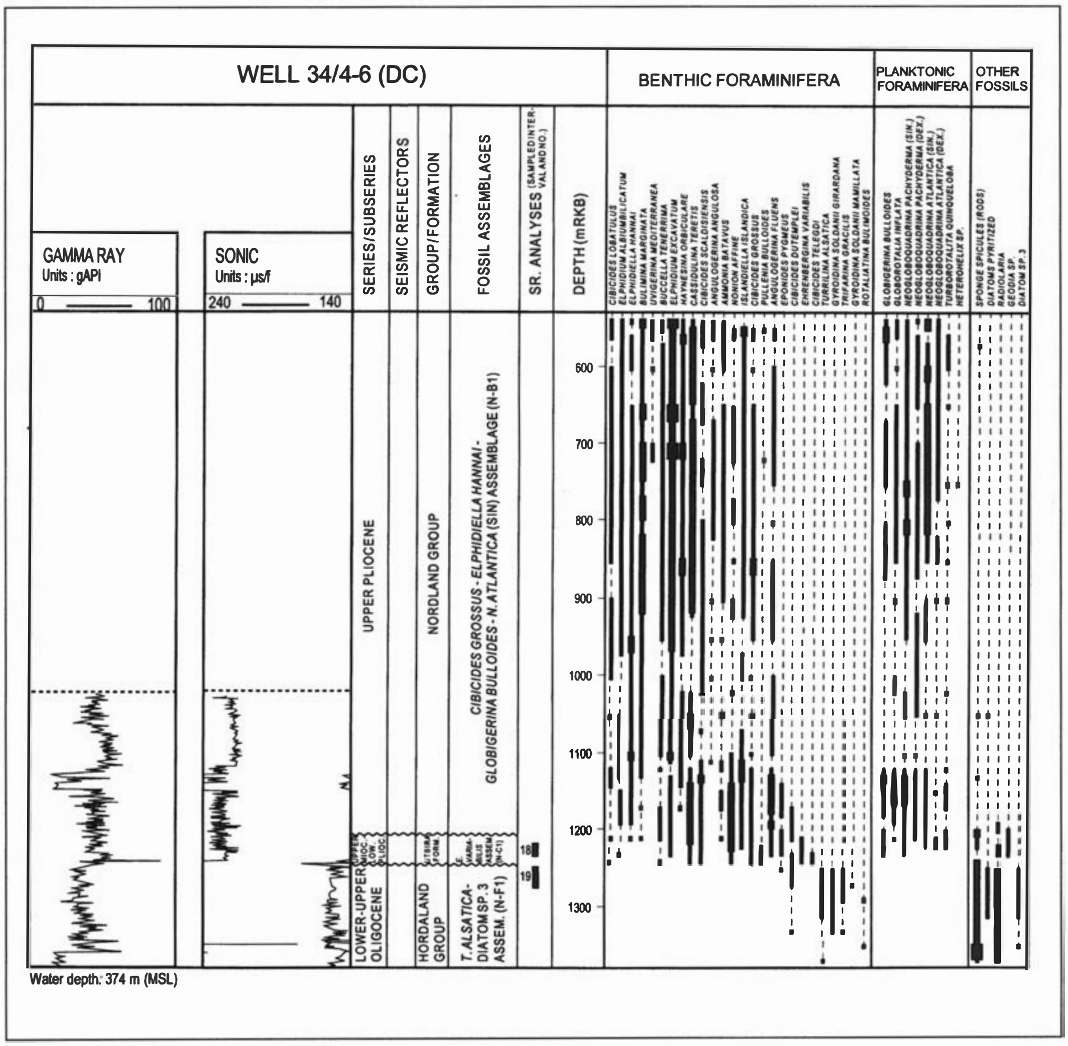

Fig. 10. Range chart of the most important index fossils in the investigated interval of well 34/4-6. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. DC = ditch cutting samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, µs/f = microseconds per foot, SR. ANALYSES = strontium isotope analyses.

are probably caved. The following benthic foraminifera are probably *in situ*: *C. teretis*, *N. affine*, *E. variabilis*, *P. bulloides*, *E. pygmeus*, *C. telegdi* and *C. dutemplei*. *N. atlantica* (sinistral), *N. atlantica* (dextral) and *G. bulloides* are probably *in situ* planktonic foraminifera.

Reworked assemblage: *T. gracilis* is probably reworked from Lower Oligocene-Lower Miocene deposits and Diatom sp. 4 is probably reworked from Lower Miocene sediments.

Remarks: This assemblage corresponds to the N-C1 assemblage in wells 34/8-1, 34/8-3A, 34/2-4, 34/4-6 and the N-C2 assemblage in well 34/7-1.

TURRILINA ALSATICA - DIATOM SP. 3 ASSEMBLAGE

Designation: N-E1.

Definition: The top of the assemblage is taken at the highest occurrence of *T. alsatica* and the highest consistent occurrence of Diatom sp. 3. The base of the assemblage is not defined.

Depth range: 1200-1220 m (lowermost investigated sample).

Material: One sidewall core and three ditch cutting samples at 10 m intervals.

Age: Early-Late Oligocene.

Lithostratigraphic group: Hordaland Group.

Correlation: Lower part of Subzones NSB 8a and NSP 9c and upper part of Subzone NSB 7b of King (1989) and upper part of Zone NSR 7B of Gradstein & Bäckström (1996).

Description: Sponge spicules and radiolarians dominate the fossil assemblage in this interval. Far fewer planktonic and benthic calcareous foraminifera and pyritized diatoms are recorded. The sidewall core sample contains only sponge spicules and diatoms (Fig. 11a). The planktonic foraminifera and several of the benthic calcareous forms are probably caved, but the following benthic forms are probably *in situ*: *T. alsatica*, *G. soldanii girardana*, *C. dutemplei* and *Guttulina* sp. (Fig. 11b).

Remarks: This assemblage is coeval with the N-F1 assemblage in wells 34/8-1, 34/4-6 and 34/7-1, the N-F2 assemblage in well 34/8-3A and the N-F3 and N-F4 assemblages in well 34/2-4.

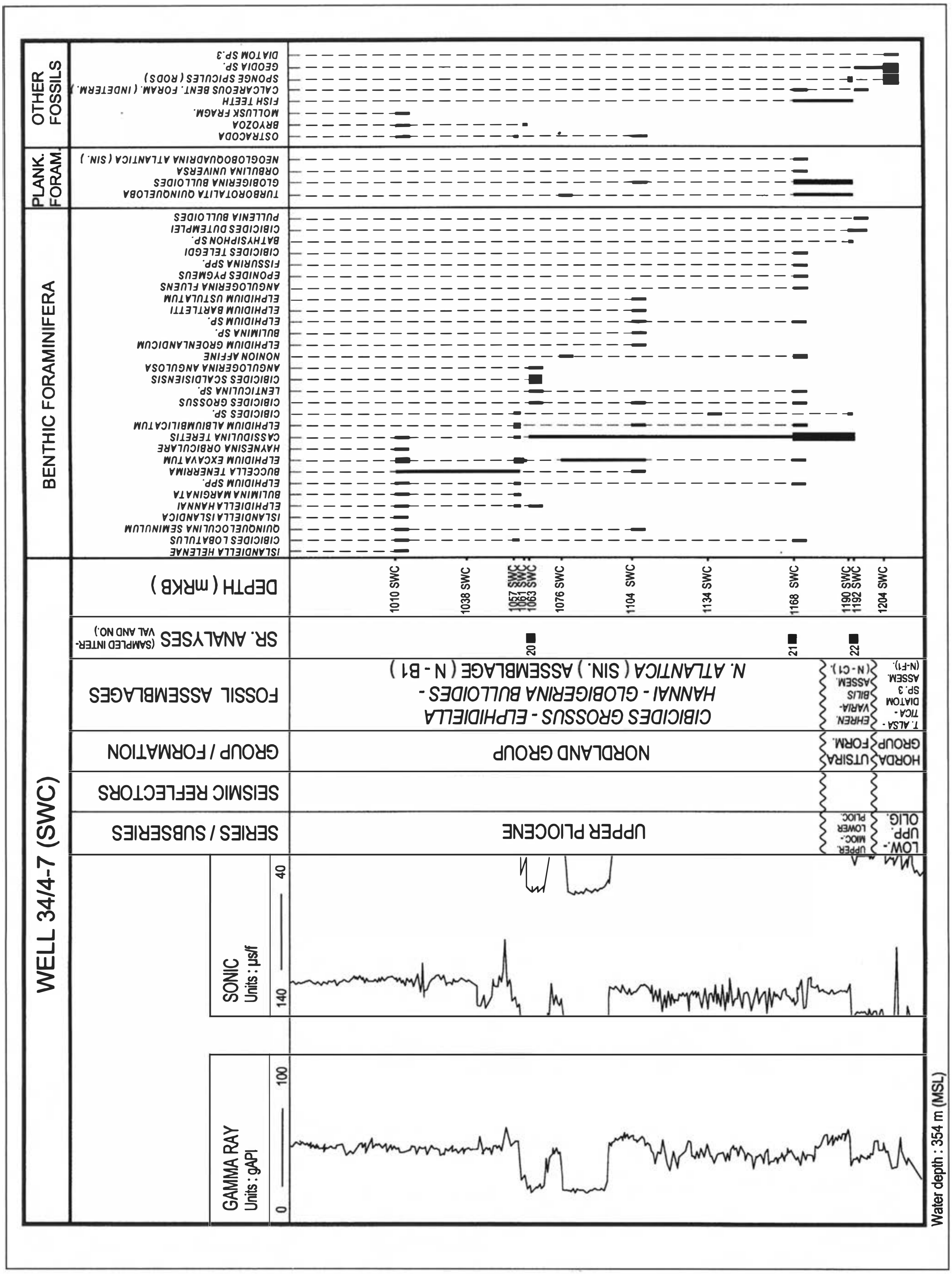

Fig. 11a. Range chart of the recorded fossils in the sidewall core samples in the investigated interval of well 34/4-7. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. SWC = sidewall core samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, µs/f = microseconds per foot, SR. ANALYSES = strontium isotope analyses.

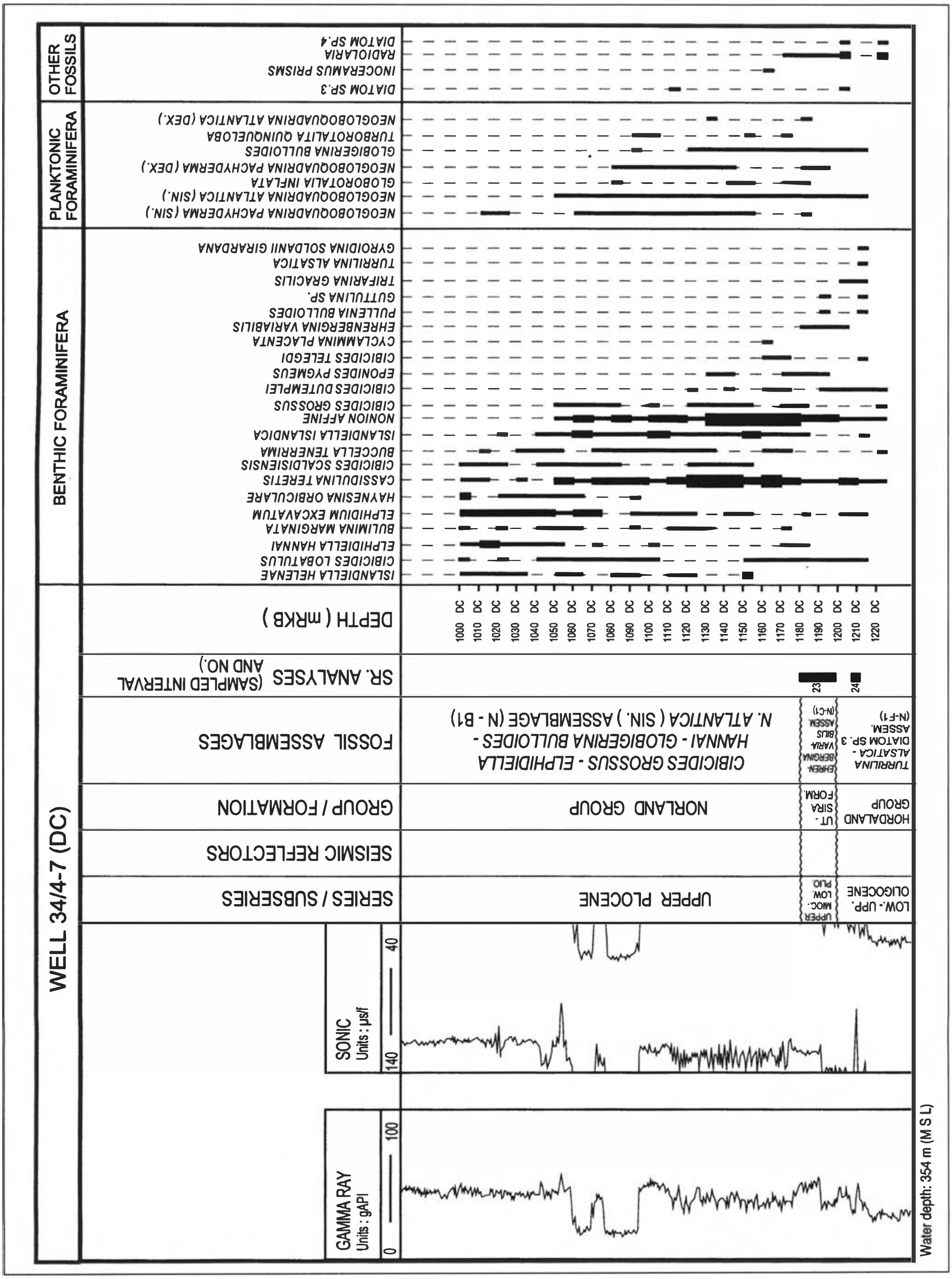

Fig. 11b. Range chart of the most important index fossils in the ditch cutting samples in the investigated interval of well 34/4-7. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. DC = ditch cutting samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, µs/f = microseconds per foot, SR. ANALYSES = strontium isotope analyses.

Well 34/7-1

CIBICIDES GROSSUS - ELPHIDIELLA HANNAI – GLOBIGERINA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B1.
Definition: The top of the assemblage extends to the uppermost investigated sample. The base is marked by the highest consistent occurrence of *C. dutemplei.*
Depth range: 1000-1150 m.
Material: 12 sidewall cores and 15 ditch cutting samples at 10 m intervals.
Age: Late Pliocene.
Lithostratigraphic group: Nordland Group.
Correlation: Subzones NSB 15a of King (1989) and *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989).
In-place assemblage: This interval contains a rich benthic fauna of mainly calcareous foraminifera. *E. excavatum*, *C. teretis* and *N. affine* occur most frequently. Other important species include *C. lobatulus*, *E. hannai*, *B. marginata*, *A. fluens*, *C. grossus*, *C. scaldisiensis* and *I. islandica* (lower part) (Figs. 12a and b).

Planktonic foraminifera are less frequent than benthic taxa and include *N. atlantica* (sinistral), *G. bulloides*, *N. pachyderma* (sinistral, unencrusted), *N. pachyderma* (dextral), *N. atlantica* (dextral; scarce) and *G. inflata* (scarce).
Reworked assemblage: Reworked fossils are recorded sporadically throughout. These are agglutinated foraminifera from the lower Tertiary and *C. dutemplei* from Miocene deposits.
Remarks: The occurrence of *C. grossus*, *E. hannai*, *N. atlantica* (sinistral) and *G. bulloides* indicates a Late Pliocene age that is not younger than 2.4 Ma (King 1989, Spiegler & Jansen 1989).

CIBICIDES DUTEMPLEI ASSEMBLAGE

Designation: N-C2.
Definition: The top of the assemblage is taken at the highest consistent occurrence of *C. dutemplei*. The base is marked by the highest occurrence of *T. alsatica* and Diatom sp. 3.
Depth range: 1150-1170 m.
Material: Two sidewall cores and two ditch cutting samples at 10 m intervals.
Age: Late Miocene to earliest Early Pliocene (partly based on log correlation).
Lithostratigraphic formation: Utsira Formation.
Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989), *G. subglobosa - E. variabilis* Zone of Stratlab (1986), *C. telegdi – E. pygmeus – N. atlantica* (dextral) Zone (M-H) and *E. variabilis - G. subglobosa - N. atlantica* (dextral) Zone (M-I) of Eidvin et al. (1998).
Assemblage: There are slightly fewer foraminifera in this assemblage than in the overlying interval. In addition, specimens of sponge spicules and radiolarians are common. Calcareous foraminifera are only recorded in the ditch cutting samples (Fig. 12b) and most of these are probably caved. The small sidewall core samples contain only sponge spicules and agglutinated foraminifera (Fig. 12a), but the following benthic foraminifera are probably *in situ*: *C. dutemplei*, *C. teretis*, *N. affine*, *E. pygmeus*, *C. telegdi and Trochammina quinqueloba* (agglutinated). *N. atlantica* (sinistral) and *G. bulloides* are probably *in situ* planktonic foraminifera.
Remarks: Although *E. variabilis* is not recorded in any of the samples, the assemblage is correlated with the N-C1 assemblage in wells 34/8-1, 34/8-3A, 34/4-6, 34/4-7 and 34/2-4. However, *E. variabilis* are recorded in the uppermost sample in the immediately underlying assemblage, and are probably caved from this interval.

TURRILINA ALSATICA - DIATOM SP. 3 ASSEMBLAGE

Designation: N-F1.
Definition: The top of the assemblage is taken at the highest occurrence of *T. alsatica* and *G. soldanii girardana*. The base of the assemblage is not defined.
Depth range: 1170-1200 m (lowermost investigated sample).
Material: Four ditch cutting samples at 10 m intervals.
Age: Early-Late Oligocene.
Lithostratigraphic group: Hordaland Group.
Correlation: Lower part of Subzones NSB 8a and NSP 9c and upper part of Subzone NSB 7b of King (1989) and upper part of Zone NSR 7B of Gradstein & Bäckström (1996).
Description: There are fewer foraminifera in this assemblage than in the overlying interval. The assemblage contains radiolarians, diatoms and calcareous foraminifera. In the diatom flora the index fossil Diatom sp. 3 is recorded. The planktonic foraminifera and several of the benthic calcareous forms are probably caved, but the following benthic foraminifera are probably *in situ*: *T. alsatica*, *T. gracilis*, *G. soldanii girardana*, *R. bulimoides and C. dutemplei* (Fig. 12b).
Remarks: This assemblage is coeval with the N-F1 assemblage in wells 34/8-1, 34/4-6, 34/4-7, the N-F2 assemblage in well 34/8-3A and the N-F3 and N-F4 assemblages in well 34/2-4.

WELL 34/2-4

CIBICIDES GROSSUS – ELPHIDIELLA HANNAI – GLOBIGERINA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B1.
Definition: The top of the assemblage extends to the uppermost investigated sample (1300 m). The base is marked by the highest occurrence of *E. variabilis.*

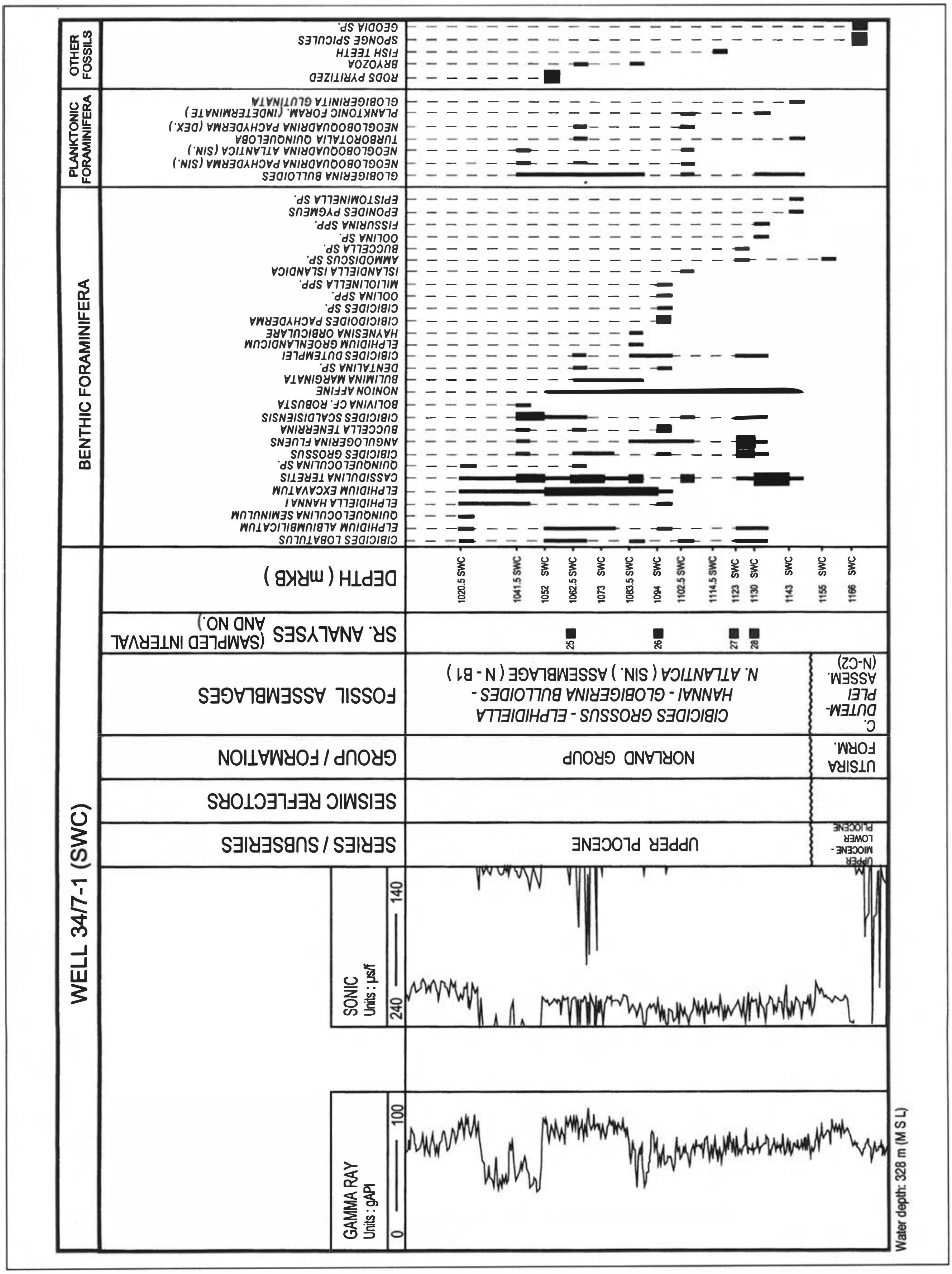

Fig. 12a. Range chart of the recorded fossils in the sidewall core samples in the investigated interval of well 34/7-1. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. SWC = sidewall core samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, µs/f = microseconds per foot, SR. ANALYSES = strontium isotope analyses.

Depth range: 1300-1470 m.
Material: 16 ditch cutting samples at 10-20 m intervals.
Age: Late Pliocene.
Lithostratigraphic group: Nordland Group.
Correlation: Subzones NSB 15a of King (1989) and *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989).

In-place assemblage: This interval contains a rich benthic fauna of mainly calcareous foraminifera. *C. teretis* occurs most frequently. Other important species include *C. grossus*, *E. hannai*, *B. marginata*, *A. fluens*, *B. tenerrima*, *C. scaldisiensis*, *Quinqueloculina seminulum* and *E. excavatum*.

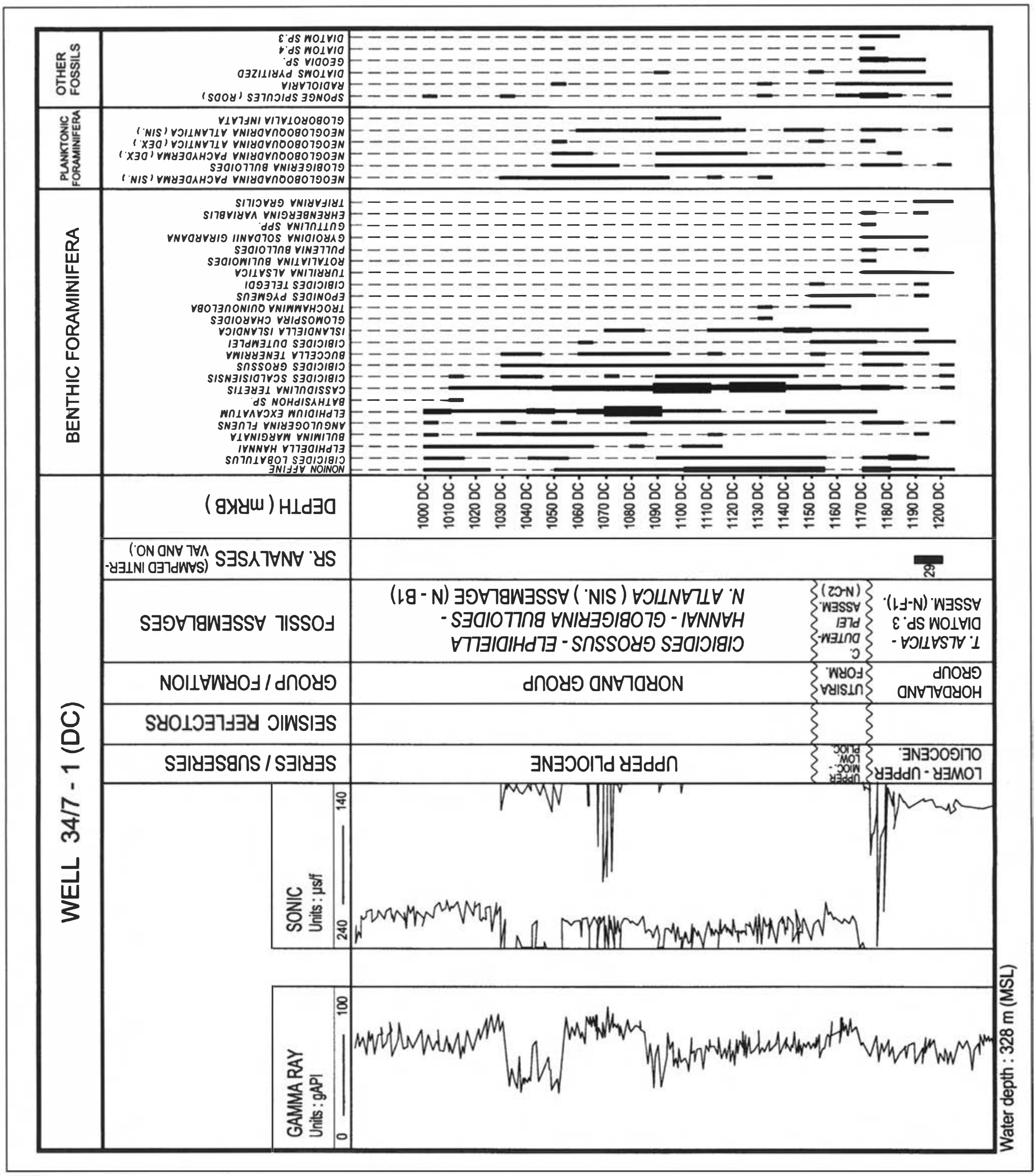

Fig. 12b. Range chart of the most important index fossils in the ditch cutting samples in the investigated interval of well 34/7-1. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. DC = ditch cutting samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, µs/f = microseconds per foot, SR. ANALYSES = strontium isotope analyses.

Planktonic foraminifera are also quite common, but less frequent than the benthic taxa. The most important planktonic foraminifera include *G. bulloides*, *N. atlantica* (sinistral), *N. pachyderma* (sinistral, unencrusted) and *N. pachyderma* (dextral). *N. atlantica* (dextral) and *T. quinqueloba* are recorded as rare at a few levels (Fig. 13).

Reworked assemblage: Reworked fossils are recorded sporadically throughout. These are agglutinated foraminifera from the lower Tertiary and *Inoceramus* prisms from the Upper Cretaceous. At the base of the interval *C. dutemplei*, *G. subglobosa*, *E. pygmeus*, *C. telegdi* and *T. alsatica* are recorded at some levels. *C. dutemplei*, *G. subglobosa*, *E. pygmeus* and *C. telegdi* are probably reworked from the Miocene and *T. alsatica* from the Oligocene.

Remarks: The occurrence of *C. grossus*, *E. hannai*, *N. atlantica* (sinistral) and *G. bulloides* indicates a Late Pliocene age that is not younger than 2.4 Ma (King 1989, Spiegler & Jansen 1989).

EHRENBERGINA VARIABILIS ASSEMBLAGE

Designation: N-C1.

Definition: The top of the assemblage is taken at the highest occurrence of *E. variabilis*. The base is marked by the highest occurrence of *G. soldanii girardana*.

Depth range: 1470-1520 m.

Material: Five ditch cutting samples at 10 m intervals.

Age: Late Miocene to earliest Early Pliocene (partly based on strontium isotope analysis).

Lithostratigraphic formation: Utsira Formation.

Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989), *G. subglobosa - E. variabilis* Zone of Stratlab (1986), *C. telegdi – E. pygmeus – N. atlantica* (dextral) Zone (M-H) and *E. variabilis - G. subglobosa - N. atlantica* (dextral) Zone (M-I) of Eidvin et al. (1998).

Description: There are slightly fewer foraminifera in this assemblage than in the lower part of the overlying assemblage. In addition, specimens of sponge spicules (rod-shaped and *Geodia* sp.) are common in this assemblage. The most important benthic calcareous foraminifera include *E. variabilis*, *E. pygmeus*, *C. dutemplei*, *C. telegdi*, *C. teretis* and *N. affine*. A few specimens of *G. subglobosa* are also recorded. Some of these and a few of the other recorded species (Fig. 13) are probably caved.

Planktonic foraminifera are less frequent than in the immediately overlying interval. *N. atlantica* (sinistral) and *G. bulloides* occur most frequently. *N. atlantica* (dextral), *T. quinqueloba* and *G. inflata* are also recorded at a few levels. Some of these are also probably caved.

Remarks: This assemblage corresponds to the N-C1 assemblage in wells 34/8-1, 34/8-3A, 34/4-6, 34/4-7 and the N-C2 assemblage in well 34/7-1.

GYROIDINA SOLDANII GIRARDANA ASSEMBLAGE

Designation: N-F3.

Definition: The top of the assemblage is taken at the highest occurrence of *G. soldanii girardana*. The base is marked by the highest occurrence of Diatom sp. 3.

Depth range: 1520-1550 m.

Material: Three ditch cutting samples at 10 m intervals.

Age: Early-Late Oligocene.

Lithostratigraphic group: Hordaland Group.

Correlation: Lower part of Subzone NSB 8a and upper part of Subzone NSB 7b of King (1989) and upper part of Zone NSR 7B of Gradstein & Bäckström (1996).

Description: The fossil assemblage in this interval is dominated by sponge spicules. Far fewer benthic foraminifera (mostly calcareous but also a few agglutinated forms), planktonic foraminifera, radiolarians and pyritised diatoms are recorded. The planktonic foraminifera and several of the benthic calcareous forms are probably caved, but the following benthic foraminifera are probably *in situ*: *C. dutemplei*, *G. soldanii girardana*, *T. gracilis*, *C. placenta* (agglutinated) and *Cribrostomoides* sp. (agglutinated) (Fig. 13).

Remarks: *T. gracilis* is recorded from Lower Oligocene to Lower Miocene deposits on the Norwegian continental shelf (Skarbø & Verdenius 1986). *G. soldanii girardana* is known from Lower Oligocene to lowermost Lower Miocene sediments in the North Sea (King 1989). According to Gradstein & Bäckström (1996) is *G. soldanii girardana* known from the Lower Oligocene to the lowermost Upper Oligocene in the same area. This assemblage is probably coeval with the N-F1 assemblage in wells 34/8-1, 34/4-6, 34/4-7, 34/7-1 and the N-F2 assemblage in well 34/8-3A.

DIATOM SP. 3 ASSEMBLAGE

Designation: N-F4.

Definition: The top of the assemblage is taken at the highest occurrence of Diatom sp. 3. The base of the assemblage is not defined.

Depth range: 1550-1600 m (lowermost investigated sample).

Material: Six ditch cutting samples at 10 m intervals.

Age: Early-Late Oligocene.

Lithostratigraphic group: Hordaland Group.

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

Description: The fossil assemblage in this interval is nearly completely dominated by sponge spicules (both rod-shaped and *Geodia* sp.), radiolarians and pyritised diatoms. In the diatom flora the index fossil Diatom sp. 3 is recorded (Fig. 13).

Remarks: This assemblage is probably coeval with the N-F1 assemblage in wells 34/8-1, 34/4-6, 34/4-7, 34/7-1 and the N-F2 assemblage in well 34/8-3A.

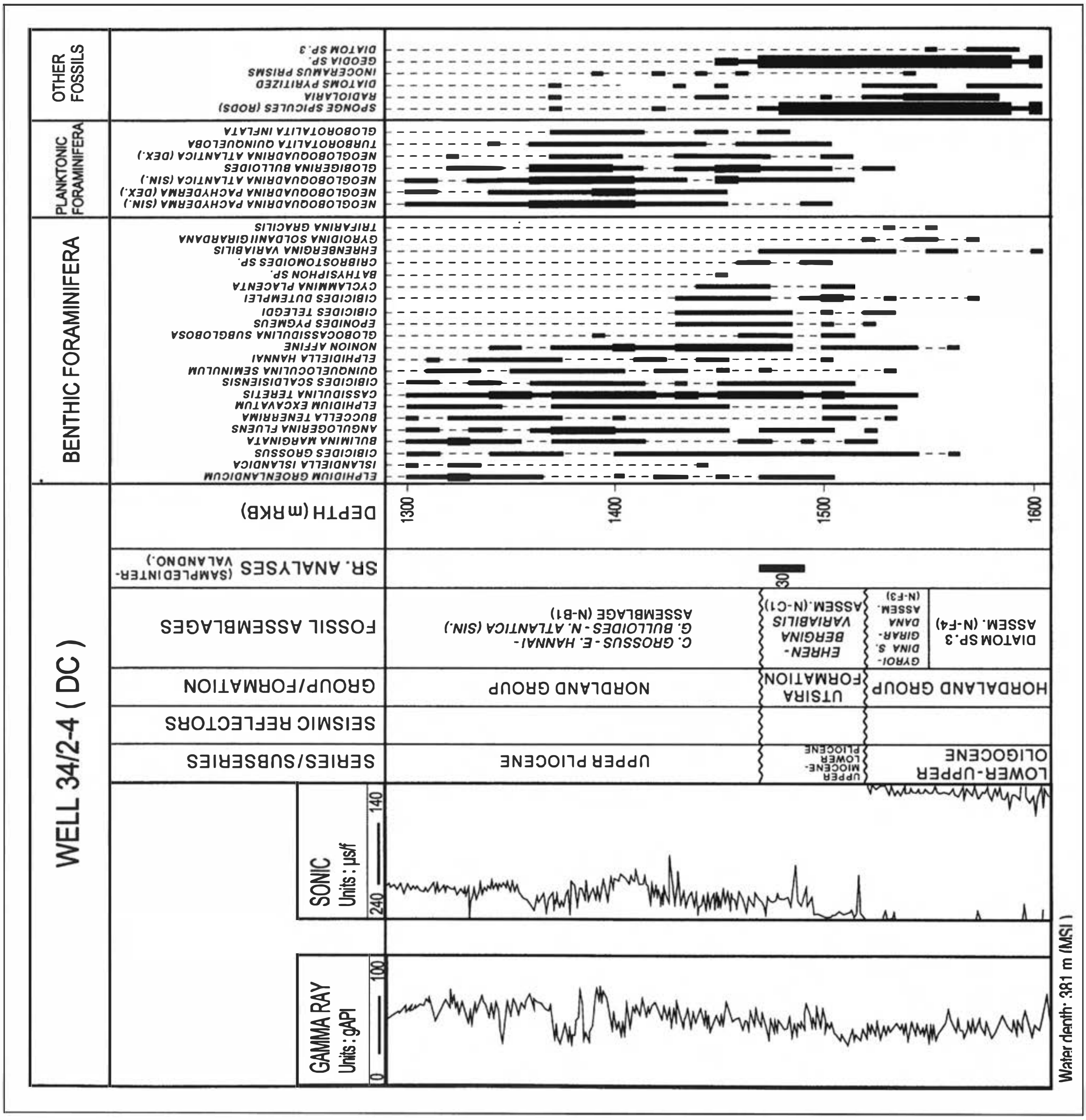

Fig. 13. Range chart of the most important index fossils in the investigated interval of well 34/8-1. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. DC = ditch cutting samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, µs/f = microseconds per foot, SR. ANALYSES = strontium isotope analyses.

Strontium isotope stratigraphy

The strontium isotopic record of Neogene seawater is documented by Hodell et al. (1990, 1991) and Farrell et al. (1995). In order to better constrain the age determinations of stratigraphic boundaries recognised in this study, strontium isotope analyses were performed on 30 samples from selected parts of sections in most wells (Tables 3 and 4, Figs. 5-8 and 10-14). The samples were analysed according to procedures described by Eidvin et al. (1999).

The analyses chiefly utilized tests of calcareous foraminifera, but in a few cases, samples of mollusc shell fragments were used. The tests were taken mainly from sidewall and conventional cores, but ditch cutting samples were also used. Analyses were performed preferentially on foraminifer taxa with well-documented stratigraphic ranges, especially when analysing tests from ditch cutting samples.

In Tables 3 and 4, the ages of samples younger than 6.5 Ma are determined according to the Sr-record of

Sample no. (1)	Well	Depth (m)	Sequence	$^{87}Sr/^{86}Sr$ Lab A (2)	S.E. (3)	Age (4) (Ma)	Age (5) (Ma)	Remarks (6)
4	34/8-1	1110-1130	Glauc. sand	0.709023	17	4.6	5.0	DC
5	34/8-1	1280	Oligocene	0.708026	45	-	28.3	DC, 4 bl.
6	34/8-1	1300	Oligocene	0.708042	47	-	27.8	DC, 1 bl.
11	34/8A-1H	1070.2	B. U. Plioc.	0.708999	29	5.1	5.6	Core, 4 bl.
12	34/8A-1H	1083.2	B. U. Plioc.	0.709018	12	4.7	5.2	Core
13	34/8A-1H	1084.1	B. U. Plioc.	0.709029	16	4.4	4.9	Core
14	34/8A-1H	1086.1	B. U. Plioc.	0.709011	13	4.8	5.3	Core
15	34/8A-1H	1088.2	B. U. Plioc.	0.709026	14	4.5	5.0	Core
16	34/8A-1H	1101.3	B. U. Plioc.	0.709038	18	4.0	4.5	Core, 8 bl.
17	34/8A-1H	1102.0	B. U. Plioc.	0.709062	13	2.3	2.4	Core
18	34/4-6	1220-1240	Glauc. sand	0.708997	14	5.1	5.6	DC
19	34/4-6	1250-1280	Oligocene	0.708114	17	-	26.2	DC
20	34/4-7	1063	Progr. Plioc.	0.709068	15	2.0	2.2	SWC
21	34/4-7	1168	B. U. Plioc	0.709046	13	3.5	3.7	SWC
22	34/4-7	1192	Glauc. sand	0.709019	13	4.7	5.1	SWC
23	34/4-7	1180-1200	Glauc. sand	0.709007	13	5.0	5.4	DC
24	34/4-7	1210	Oligocene	0.708064	39	-	27.4	DC, 5 bl.
25	34/7-1	1062.5	Progr. Plioc.	0.709080	14	1.7	1.9	SWC
26	34/7-1	1094	B. U. Plioc.	0.709075	15	1.8	2.0	SWC
26A	34/7-1	1102.5	B. U. Plioc.	0.709022	15	4.6	5.1	SWC, 3 bl.
27	34/7-1	1123	B. U. Plioc.	0.709034	20	4.2	4.7	SWC
28	34/7-1	1130	B. U. Plioc.	0.709073	29	1.8	2.1	SWC, 8 bl.
29	34/7-1	1190-1200	Oligocene	0.708120	29	-	26.1	DC, 4 bl.
30	34/2-4	1470-1490	Glauc. Sand	0.709055	11	2.5	2.6	DC

(1) Sample numbers refer to Figs. 5–13
(2) All results are normalised to SRM-987 = 0.710235 and to $^{86}Sr/^{88}Sr$ = 0.1194
(3) S.E. = standard error of the mean (two-sigma x 10^{-6})
(4) Age according to Farrell et al. (1995), (0-6 m.y. interval only)
(5) Age according to Howarth and McArthur (1997). Note that all results have been normalised to 0.710248 when using the Look-up Table
(6) DC = ditch cuttings; SWC = sidewall core; bl = blocks (denotes small sample, age based on x/10 blocks; 1 bl = 10 individual measurements)

Table 3. Strontium isotope ratios of Cainozoic samples analysed in laboratory A.

both Farrell et al. (1995) and Howarth & McArthur (1997). The ages of older samples are based on the Sr-record of Howarth & McArthur (1997). If not stated otherwise, all ages reported in the text are based on Farrell et al. (1995). Our discussions in this paper are chiefly based on ages derived from the mean strontium isotope value of two or more samples.

It is important to note that the curve of Farrell et al. (1995) gives slightly younger ages than that of Howarth & McArthur (1997) in the range between 2 and 6 Ma. The results from the analyses of the Neogene parts of the wells are plotted in Fig. 14. This figure also shows a slightly modified version of Farrell et al.'s (1995) curve. The figure demonstrates the precision of the method and the margin of error of a single data point. In the flat part of the curve (2.5-4.5 Ma), the $^{87}Sr/^{86}Sr$-ratio changes very little through time. As a result, the precision, using a standard deviation of 0.0000020, is much less (about ±1 Ma) than in the steeper part of the curve (about ±0.2Ma).

Sample no. (1)	Well	Depth (m)	Sequence	$^{87}Sr/^{86}Sr$ Lab A (2)	S.E. (3)	Age (4) (Ma)	Age (5) (Ma)	Remarks (6)
1	31/3-1	520	Pleistocene	0.709177	12	0	0	DC
2	31/3-1	530	Pleistocene	0.709174	12	0	0.2	DC
3	31/3-1	570 - 580	Oligocene	0.707863	12	-	32.8	DC
7	34/8-9S	1109.68	B. U. Plioc.	0.709086	11	1.9	2.1	Core
8	34/8-9S	1110.52	B. U. Plioc.	0.709013	13	5.1	5.3	Core
9	34/8-9S	1111.74	B. U. Plioc.	0.709007	13	5.2	5.6	Core
10	34/8-9S	1112.63	B. U. Plioc.	0.709054	12	3.9	4.3	Core
10A	34/8-9S	1112.63	B. U. Plioc.	0.708978	10	5.6	6.2	Core
11	34/8A-1H	1070.2	B. U. Plioc.	0.709078	9	2.2	2.3	Core
12	34/8A-1H	1083.2	B. U. Plioc.	0.709080	9	2.2	2.2	Core
13	34/8A-1H	1084.1	B. U. Plioc.	0.709057	9	3.9	3.9	Core
14	34/8A-1H	1086.1	B. U. Plioc.	0.709050	9	4.2	4.5	Core
15	34/8A-1H	1088.2	B. U. Plioc.	0.709073	9	2.3	2.4	Core
16	34/8A-1H	1101.3	B. U. Plioc.	0.709097	10	1.7	2.1	Core

All explanations as in Table 3

Table 4. Strontium isotope ratios of Cainozoic samples analysed in laboratory B.

The Pleistocene succession was sampled in well 31/3-1 on the Troll field. The two ditch cutting samples taken just above the base of the section (sample numbers 1 and 2 in Table 4 and Fig. 5), have an Sr-isotope composition close to that of present day seawater. Taking the uncertainty of the method into account this corresponds to a maximum age of 0.5 Ma. According to Sejrup et al. (1995), the base of the Pleistocene section is dated to approximately 1.2 Ma in a cored geotechnical borehole, located nearby. The young ages in well 31/3-1 might be derived from caved material in the Sr samples.

Samples 20 and 25 (Table 3) were sidewall cores taken from the prograding Upper Pliocene succession in wells 34/7-1 and 34/4-7, respectively. Their mean value (0.709074) corresponds to an age of 1.9 Ma according to Farrell et al. (1995) and 2.1 Ma according to Howard & McArthur (1997). These ages agree with those suggested by biostratigraphic data.

Most of our samples have been taken from the basal Upper Pliocene unit. Samples from the core in well 34/8A-1H were analysed in two different laboratories. The strontium isotope values measured at laboratory A (Table 3, Fig. 8) were systematically higher than those obtained from laboratory B (Table 4, Fig. 8). The mean values of seven samples (11-17) analysed at laboratory A (0.709026), and of the same samples analysed at laboratory B (0.709061), give ages of 4.5 and 2.3 Ma, respectively. This suggests both Early and Late Pliocene ages for the core samples in this unit. Four sidewall cores analysed at laboratory A, also from the basal Upper Pliocene unit (samples 21, 26-28, Table 3), give a mean value of 0.709050 and a corresponding age of 3.0 Ma. Four core samples from the base of this unit in well 34/8-9S were analysed at laboratory B only (samples 7-10 in Table 4 and Fig. 7). The results obtained from these samples varied significantly, yielding ages from 1.9 to 5.6 Ma.

The upper glauconitic unit of the Utsira Formation sands has been sampled in five of the Tampen wells. The Sr-isotopic results are very similar for all samples, with the exception of sample 30 in well 34/2-4 which is probably erroneous. The values from samples 4, 18, 22 and 23 (Table 3) correspond to ages of 4.6, 5.1, 4.7 and 5.0 Ma, respectively, according to Farrell et al. (1995). Following Howarth & McArthur (1997), the corresponding ages are 5.0, 5.6, 5.1 and 5.4 Ma. These samples are taken from a period when the isotopic composition of seawater changed rapidly. The data suggest that the glauconitic unit was deposited close to the Miocene/Pliocene boundary (5.23 Ma), which agrees with the age estimated from biostratigrapic data.

The Oligocene was sampled from ditch cuttings in four of the Tampen wells. All samples were taken from the upper part of the unit (samples 5, 6, 19, 24, 29, Table 3). The Sr values range from 0.708026 to 0.708120, and correspond to ages of about 26-28 Ma. The values are similar to those obtained from the Branden Clay and the

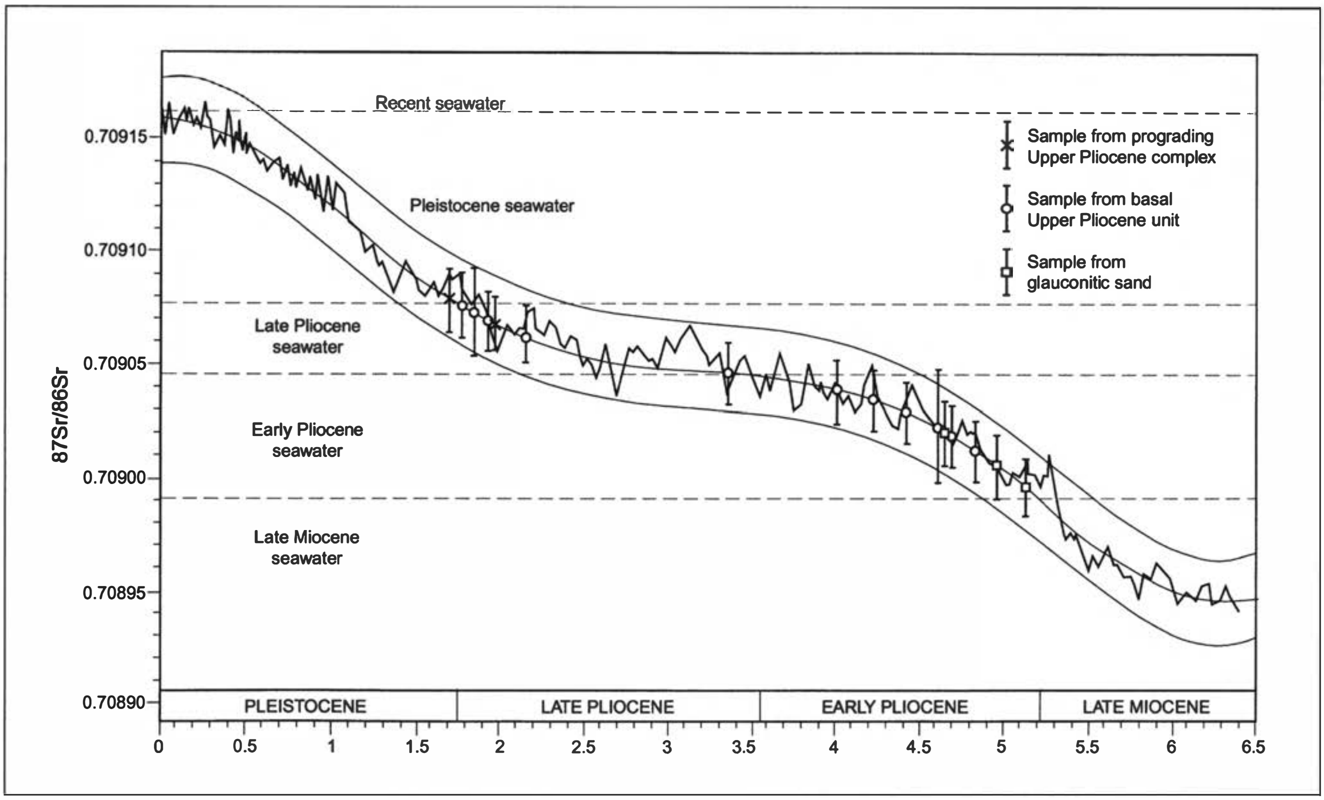

Fig. 14. Curve showing strontium isotope evolution of seawater from 6.5 Ma to recent (modified after Farrell et al. 1995). Outer envelope represents confidence interval (± $19x10^{-6}$). Ages have been derived by plotting the Sr-isotope results to the mean polynomial curve. Only Sr-isotope results from laboratory A are shown. All values are plotted relative to SRM-987 = 0.710235.

lower part of the Vejle Fjord Formation in Denmark (Y. Rundberg, unpublished data). These results indicate that deposits from a large interval in the Upper Oligocene is absent in the Tampen area.

The lower part of the Oligocene succession was analysed in well 31/3-1 on the Troll field. One sample from this unit, taken just below the base Pleistocene unconformity, gives an age of 32.8 Ma (sample 3 in Table 4 and Fig. 1). This agrees with the age reported by Rundberg & Smalley (1989) from the same well, and also with that reported by Sejrup et al. (1995) for the same unit.

In summary, strontium isotope stratigraphy has been useful for dating all analysed units, with the exception of the basal Upper Pliocene section. Values from this interval varied considerably and gave no conclusive age determination. There could be several other reasons for inconsistent strontium ages in addition to precision problems in the interval 2.5-4.5 Ma. These may include analytical errors, reworking or caved fossil tests, impurities within the tests and other factors. Although many of the values obtained in this unit correspond to an Early Pliocene age, we suggest a Late Pliocene age required that the biostratigraphic data and the age correlation of these are correct. This age is also in agreement with sequence stratigraphic interpretation, inasmuch as that the unit consists of gravity flow deposits which we interpret to be genetically linked to the Upper Pliocene prograding system.

Palaeoenvironments

The determination of bathymetric environments used in this study is according to van Hinte (1978), who defines the following; inner neritic: 0-30 m, middle neritic: 30-100 m, outer neritic: 100-200 m and upper bathyal: 200-600 m.

Lower Oligocene

The Lower Oligocene N-G assemblage is only recorded in well 31/3-1 from the Troll field (Figs. 15-17). The assemblage contains medium to high diversity calcareous benthic foraminiferal fauna. Radiolarians and pyritized diatoms are also quite common. A few agglutinated benthic foraminifera are recorded, but no planktonic foraminifera. With the exception of *P. bulloides*, all of the recorded foraminifera are extinct species. According to Skarbø & Verdenius (1986) were *S. longiscata*, *S. adolphina* and *S. hirsuta* shallow water dwelling forms. *T. alsatica* and *G. soldanii mamillata* are described as shallow to deep-water forms (Skarbø & Verdenius 1986, Gradstein & Bäckström 1996), and *C. contraria*, *K. siphonella* and *P. bulloides* as deep-water forms (Skarbø & Verdenius 1986). The absence of planktonic foraminifera suggests a restricted connection with the open ocean, or the fact that thin walled tests of planktonic foraminifera are more prone to dissolution. The N-G assemblage indicates an outer neritic to upper bathyal depositional environment.

Lower to Upper Oligocene

Lower-Upper Oligocene deposits are recorded in wells 34/8-1 (assemblage N-F1; Visund field), 34/8-3A (assemblage N-F2; Visund field), 34/7-1, 34/4-7, 34/4-6 (assemblage N-F1; Snorre field) and well 34/2-4 (assemblages N-F3 and N-F4; Figs. 15 and 16). The fossil assemblages in these intervals are dominated by sponge spicules, radiolarians and pyritized diatoms. Far fewer benthic foraminifera are recorded, and these are mainly calcareous forms, although some agglutinated forms are also present. No *in situ* planktonic foraminifera are recorded. Assemblage N-F4 in well 34/2-4 contains only sponge spicules, radiolarians and pyritized diatoms. All the recorded foraminifera are extinct species with the exception of *E. umbonatus. G. soldanii girardana* and *T. gracilis* occur in most intervals and were deep-water forms (Skarbø & Verdenius 1986). *G. soldanii mamillata* and *T. alsatica* were deep to shallow water forms (Skarbø & Verdenius 1986, Gradstein & Bäckström 1996). *C. dutemplei*, which is recorded in some of the units, was a deep to shallow water form (Skarbø & Verdenius 1986). *E. umbonatus*, which is recorded over only limited intervals, has a recent bathymeteric range extending mainly along the lower part of the continental slope (Mackensen et al. 1985, Sejrup et al. 1981), but it is suggested that this species inhabited shallower water during the Oligocene. The high concentration of radiolarians and diatoms indicates a relatively deep, open marine environment. Low oxic to hypoxic bottom conditions, indicated by the presence of agglutinated foraminifera, may have caused the dissolution of planktonic foraminiferal tests. In conclusion, the bathymetric environment was probably upper bathyal during deposition of the Lower-Upper Oligocene succession.

Lower Miocene

Lower Miocene deposits are recorded in the Visund field wells 34/8-1 (assemblage N-E) and 34/8-3A (assemblages N-D and N-E; Figs. 15 and 16). Most of the fossils recorded in these units are diatoms, radiolarians and sponge spicules (both rod-shaped and *Geodia* sp.). The N-D assemblage in well 34/8-3A contains sporadic calcareous benthic foraminifera including *E. umbonatus*, which in recent sedimentary environments is a deep water form (Mackensen et al., 1985, Sejrup et al. 1981). The high concentration of radiolarians and diatoms indicates relatively deep, open marine environments. The scarcity of planktonic and benthic calcareous foraminifera indicates hypoxic bottom conditions and dissolution of most calcareous tests. The bathymetric environment was probably upper bathyal during the deposition of the Lower Miocene succession.

Upper Miocene to lowermost Lower Pliocene

Upper Miocene to lowermost Lower Pliocene deposits contain the N-C1 assemblage which is recorded in wells 34/8-1, 34/8-3A (Visund field), 34/4-7, 34/4-6 (Snorre field) and well 34/2-4 to the north. Sediments of this age also contain the N-C2 assemblage in well 34/7-1 (Snorre field; Figs. 15 and 16). These glauconitic sandy units contain only a fair number of microfossils. The benthic assemblages in these deposits include calcareous foraminifera and sponge spicules. A few agglutinated foraminifera are also recorded. Sponge spicules (both rod-shaped and *Geodia* sp.) are significantly more common than foraminifera. *In situ* planktonic foraminifera are scarce. Of the *in situ* benthic foraminiferal species, about one half is extinct. According to Skarbø & Verdenius (1986) the extinct *E. variabilis, C. dutemplei* and *U. pygmea langeri* are indicaters of deep to shallow water conditions, whereas *M. communis* was a deep-water form. In recent deposits, *P. bulloides, N. affine* and *C. teretis* have a bathymeteric range extending mainly along the upper part of the continental slope and outer shelf. However, *N. affine* and *C. teretis* also occur on middle and inner shelf areas in smaller numbers (Mackensen et al. 1985, Sejrup et al. 1981). The sponge spicules *Geodia* sp. are indicators of deep to shallow-water environments (Skarbø & Verdenius 1986). No fossils typical of shallow marine conditions are recorded in these deposits, and most of the benthic fossils indicate deposition in the deeper part of the shelf. However, planktonic foraminifera are few in number, and these are common in the deep shelf deposits of Late Miocene age in the central North Sea (Eidvin et al. 1999) and on the Norwegian Sea continental shelf (Eidvin et al. 1998). This may be explained by the fact that planktonic foraminifera are more buoyant and more readily sorted out than most benthic foraminifera, or that the thin walled tests of planktonic foraminifera are more readily dissolved. A further explanation may be that some of the benthic forms known from recent deposits, inhabited shallower water depths during the Late Miocene. The interpretation of bathymetric conditions based only on biostratigrapic criteria during deposition of these units is therefore somewhat complex and inconclusive. However, glauconitic facies are most common on outer present-day shelves (200-300 m; Odin & Matter 1981, Van Houten & Purucker 1984), and we propose that the sedimentary environments during the latest Miocene to earliest Pliocene probably were outer neritic.

Upper Pliocene

Upper Pliocene sediments containing the N-B1 assemblage are recorded in wells 34/8-1, 34/8A-1H, 34/8-3A (Visund field), 34/7-1, 34/4-7, 34/4-6 (Snorre field) and 34/2-4. Sediments of this age also contain the N-B2 assemblage in well 34/8-9S (Visund field; Figs. 15 and

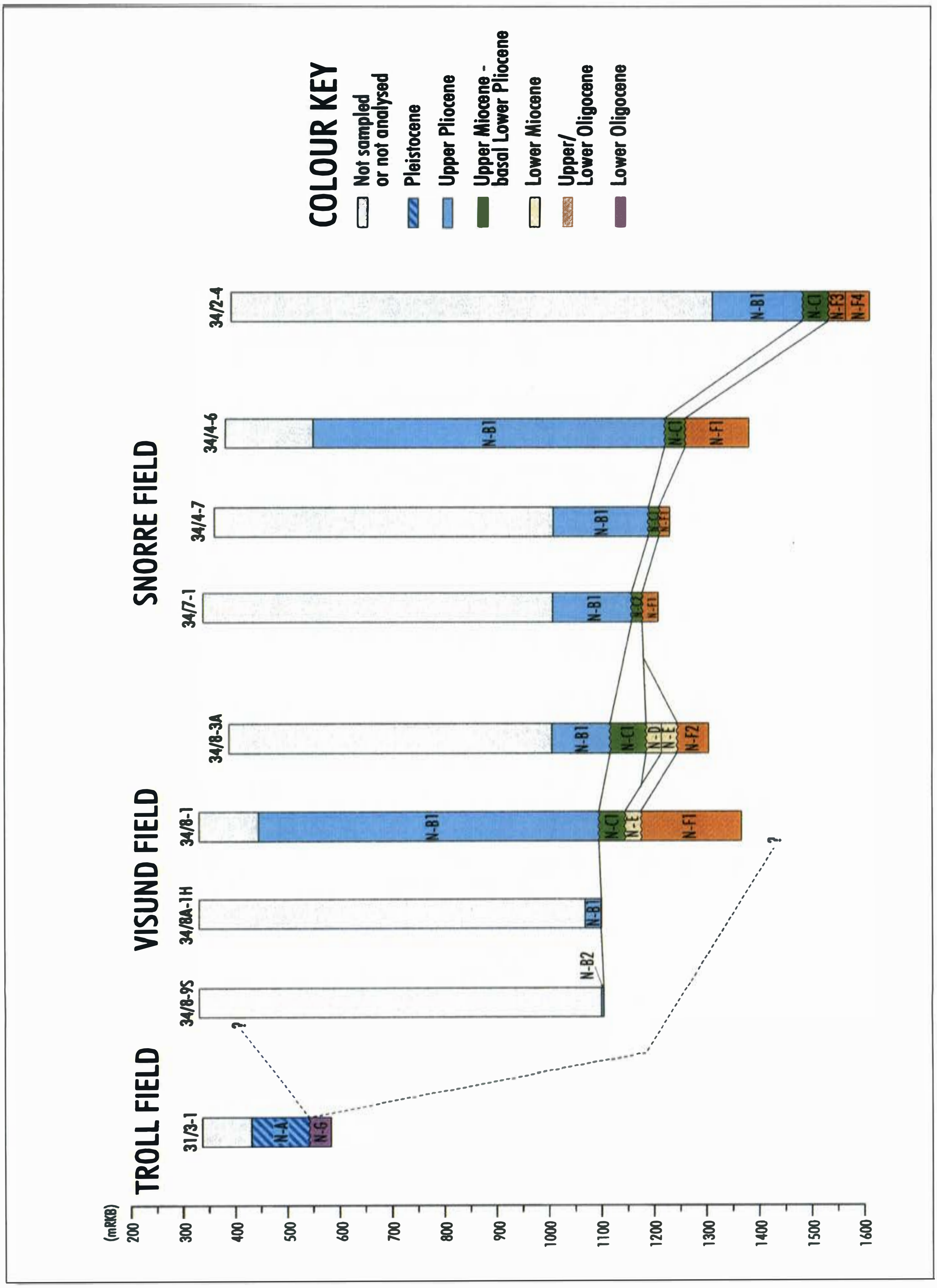

Fig. 15. Correlation of fossil assemblages between the wells studied. The vertical axis is metres below rig floor.

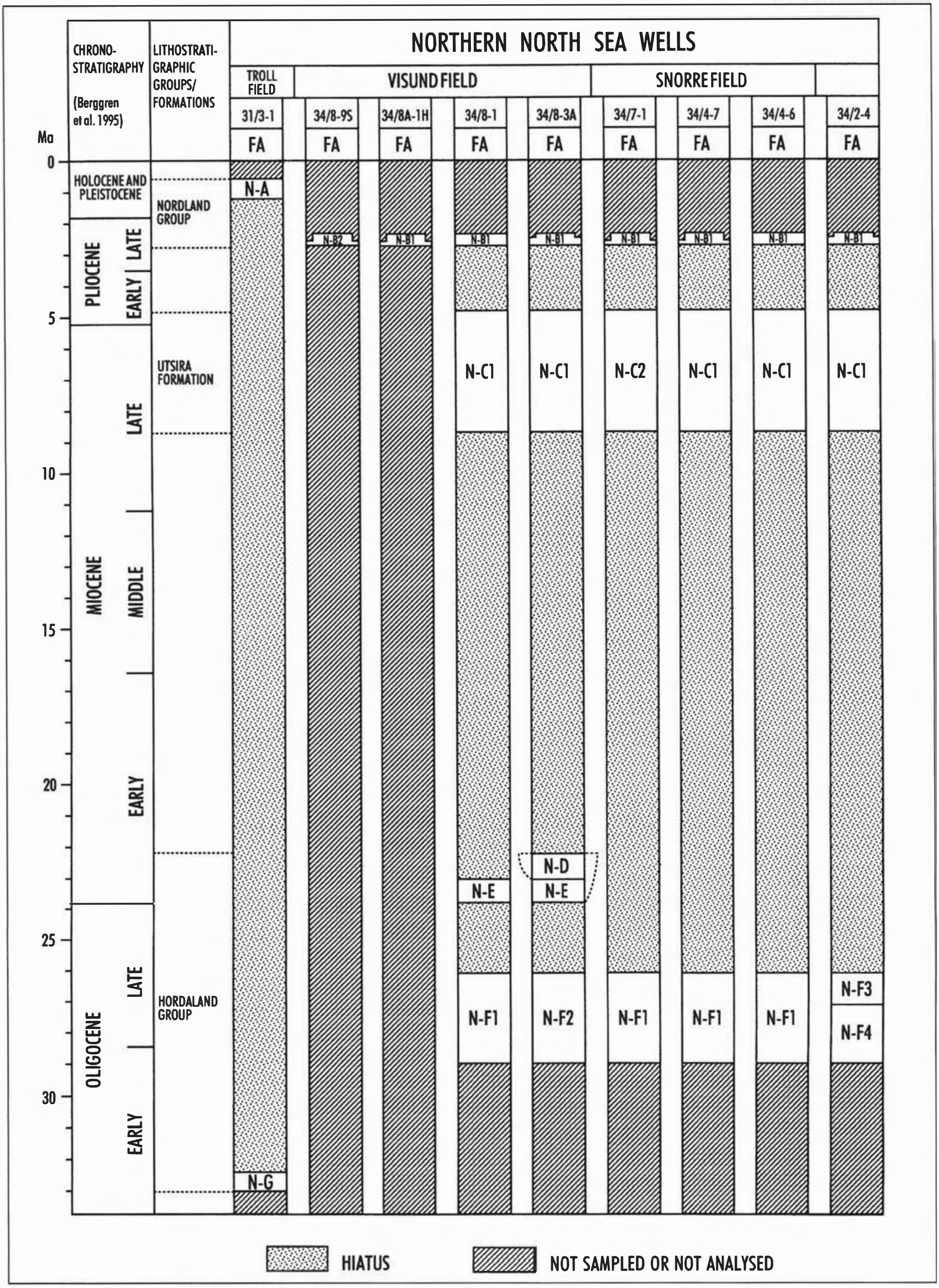

Fig. 16. Correlation of the fossil assemblages between the well studied. The vertical axis is in Ma. FA = fossil assemblages.

16). The assemblages in these deposits are dominated by calcareous benthic foraminifera. Planktonic foraminifera are also quite common in certain intervals, but are generally less frequent than benthic species. The fauna is relatively uniform throughout these units, but this observation is partly due to extensive caving. With the exception of *C. grossus* and *E. hannai*, all the *in situ* benthic foraminifera are extant. According to Skarbø & Verdenius (1986) and King (1989), *E. hannai* inhabited shallow-water, whereas *C. grossus* was a deep to shallow water form. The extant *N. affine* and *C. teretis* which are common in most intervals are most common in deeper shelf environments. *C. reniforme* which is common in certain intervals primarily inhabits upper slope and outer shelf. It is also found in smaller numbers on the middle and inner shelf (Mackensen et al. 1985, Sejrup et al. 1981). *C. lobatulus* which is common in most sections primarily inhabits the inner part of the shelf, but is also found on the middle and outer shelf (Sejrup et al. 1981). Several shallow-water forms of the genus *Elphidium* including *E. groenlandicum*, *E. albiumbilicatum* and *E. bartletti*, occur in varying abundances in most intervals (Skarbø & Verdenius 1986). The deep to shallow-water forms *E. excavatum*, *C. scaldisiensis*, *H. orbiculare*, *B. marginata*, *I. norcrossi* and *I. islandica*, also occur in varying numbers in most intervals (Skarbø & Verdenius 1986).

The basal Upper Pliocene unit was sampled in detail in the cored sections in wells 34/8A-1H and 34/8-9S. Analyses revealed that shallow marine foraminifera were concentrated in clasts interpreted as being included within the debris flow deposits and therefore transported into position. In the autochthonous clays and silts the observed planktonic species and benthic foraminifera are typical of the deeper parts of the shelf. The fossil fauna in most intervals within the Upper Pliocene units indicates deposition in outer neritic to upper bathyal bathymetric environments. The presence of a high concentration of ice-rafted pebbles, together with the occurrence of several polar foraminifera of the genera *Elphidium* and *Islandica* indicate cold water conditions during most of the Late Pliocene.

The well-resolved clinoformal pattern of the Upper Pliocene deposits (Fig. 2) gives a direct estimate of the palaeo-water depths of this time. During a late stage of progradation the height of the prograding system is close to 400 m. Such large depths were probably not present at the initial phase of progradation and at the time when the basal Upper Pliocene unit was deposited. Although much of the oldest part of the system has been eroded, we suggest that the water depth was in the order of 150-200 m at the onset of progradation, and that it gradually increased to a maximum of about 400 m as the system evolved during Late Pliocene. Significant changes in water depths, however, took place at periods when the erosion surfaces were formed.

Pleistocene

Pleistocene sediments, containing the N-A assemblage, are sampled only in well 31/3-1 (Troll field; Figs. 15-17). This assemblage is also dominated by calcareous benthic foraminifera. Planktonic foraminifera are noticeably less frequent than the benthic taxa, but even these are quite numerous in the lower part of the unit. All the taxa are extant species. According to Skarbø & Verdenius (1986) *N. labradoricum*, *C. reniforme*, *B. marginata*, *E. excavatum*, *H. orbiculare*, *C. teretis*, *A. angulosa*, *I. norcrossi*, *I. helenae*, *I. islandica*, and *A. fluens* inhabit deep to shallow-water environments. *N. affine* and *Pyrgo bulloides* are deep-water forms and *C. lobatulus* and *U. mediterranea* inhabit shallow-water environments. This indicates that Pleistocene sediments were probably deposited in middle neritic environments. A higher concentration of planktonic foraminifera in the lower part of the interval may indicate somewhat greater water depth during the deposition of this unit (middle to outer neritic). A high concentration of ice-rafted pebbles and the common occurrences of polar foraminifera of the genera *Elphidium* and *Islandiella* plus *C. reniforme* indicate cold water conditions. The presence of several boreal forms, such as *U. mediterranea*, *A. angulosa* and *B. skagerrakensis* indicates that the cold environments were separated by shorter and warmer interglacials (Feyling-Hanssen 1983).

Discussion

Utsira Formation

In the type section in the southern Viking Graben, the Utsira Formation comprises an alternating series of sands and claystones with a gross thickness in excess of 400 m. Isaksen & Tonstad (1989) suggested a shallow marine depositional environment for the Utsira Formation sands and a Middle to Late Miocene age. Rundberg & Smalley (1989) and Smalley & Rundberg (1990) reported Sr-isotopic ages in well 30/3-1 of 13.5 and 18.0 Ma for the Utsira Formation based on analyses of mollusc fragments taken from ditch cutting samples. However, Goll & Skarbø (1990) challenged these datings by disputing the use of unidentified mollusc fragments, and themselves proposed an age of 8-9 Ma for the formation in the same well. Their conclusions were based on a biostratigraphical correlation with boreholes on the Vøring Plateau. In recent work by Eidvin et al. (1999; referring to well 15/12-3) and supported by the same author's personal observation in wells 16/1-2, 16/1-4 and 24/12-1, a latest Middle Miocene to Early Pliocene age is proposed for the Utsira Formation. Preliminary results from well 35/11-1 to the east of the study area indicate a Late Miocene to possible latest Middle Miocene age (T. Eidvin, personal observation). In this well the formation occurs as a coarse-grained, quartzose sand.

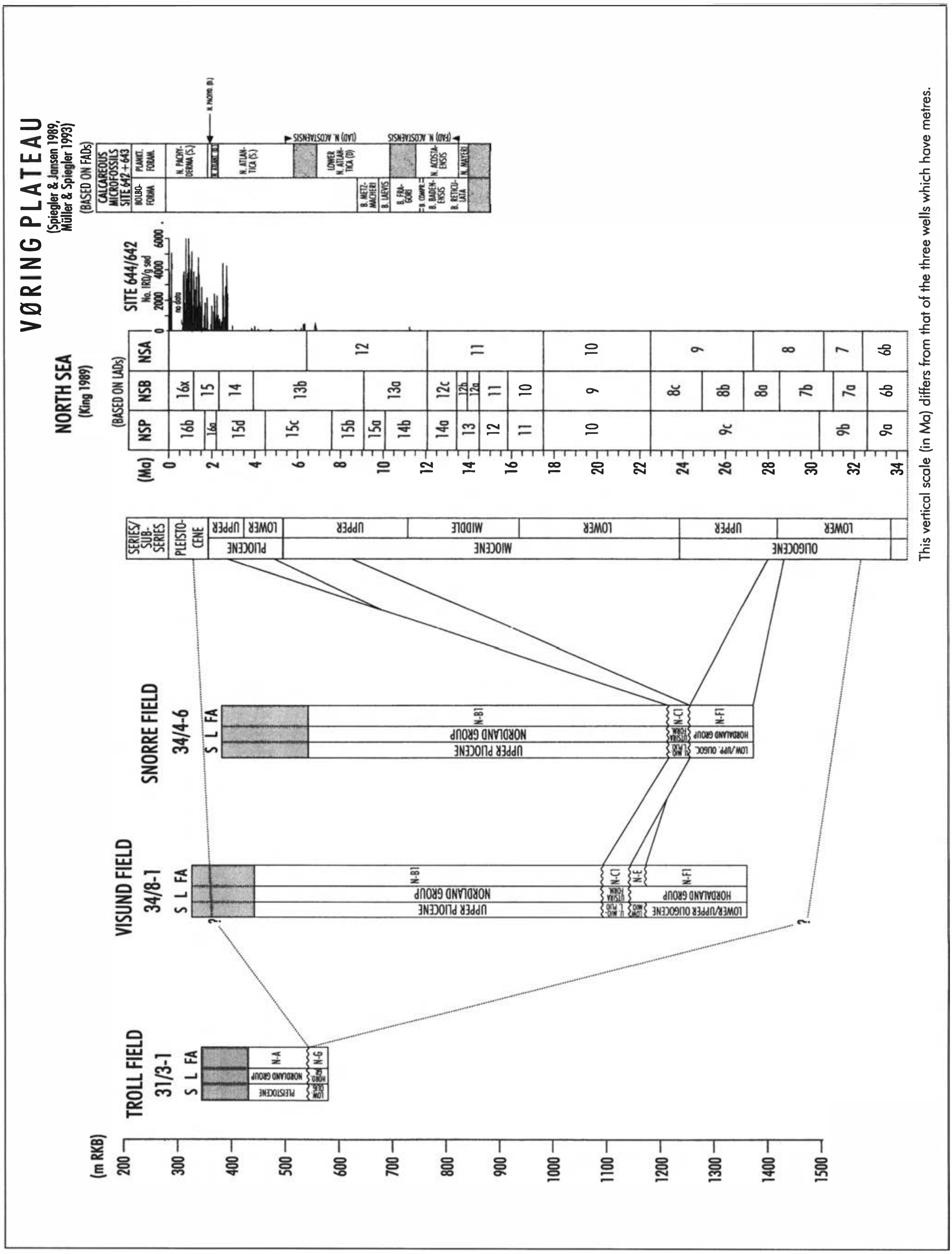

Fig. 17. Correlation of faunal assemblages between well 31/3-1, 34/8-1 and 34/4-6 as well as from the wells to King's (1989) North Sea fossil zonation and to the fossil zonation of the ODP sites 642 and 643 on the Vøring Plateau (Spiegler & Jansen 1989, Müller & Spiegler 1993). The shaded part of the wells is not sampled. The IRD curve is after Jansen & Sjøholm (1991) and Fronval & Jansen (1996). S = series/subseries, L = lithostratigraphic units, FA = fossil assemblages.

In blocks 30/6 and 30/3, the Utsira Formation comprises an approximately 200 m thick stacked series of sands with minor finer-grained interbeds. The sands are predominantly quartzose, but contain also beds rich in calcareous shell debris and glauconite. Rundberg (1989) discussed the overall depositional framework of the Utsira Formation and suggested a model involving accumulation of sands in a shallow marine setting following tectonic uplift of the northernmost North Sea area. In his regional study, Gregersen (1997) favoured a turbiditic origin of the sands, whereas Martinsen et al. (1999) indicated a shallow marine origin largely in agreement with the model by Rundberg (1989).

The main Utsira Formation sands are not recorded in any of the wells examined in the present work, and we have not made detailed seismic investigations of these deposits. The overlying glauconite rich sands in the Tampen area contain no shallow marine fossils. This may give indirect support to a turbiditic origin for the underlying main Utsira Formation sands, and this is in turn indicated by their massive character and blocky gamma-ray nature.

As mentioned previously, the term "Utsira Formation" has been used imprecisely by many consultants and other scientists/geologists and has generally been applied to all sandy intervals at the base of the Neogene section in the northern North Sea. Investigations of the Tampen wells described in this paper, show that lowstand deposits and turbiditic sands that belong to the Upper Pliocene prograding complex have erroneously been included in the Utsira Formation (Fig. 2). These sediments are separated from the underlying Utsira Formation proper by a hiatus encompassing the later Early Pliocene and earliest Late Pliocene. In some areas, it is difficult to differentiate between sands of Miocene and Late Pliocene age, and it has therefore been appropriate to include all lower Neogene sands within the Utsira Formation. We propose that the term "Utsira Formation" should only be used for sands of Miocene to Early Pliocene age and not for those belonging to the Upper Pliocene prograding complex. In this part of the basin, the top of the Utsira Formation is defined as the top of the glauconite-rich unit close to the Miocene-Pliocene transition. Further work on the lower Neogene sandy sequences, particularly in the Gullfaks/Statfjord region, will be required in order to obtain a regional lithostratigraphic overview, and resolve the chronostratigraphy of the late Tertiary in the northern North Sea.

Utsira Formation/glauconitic unit

We interpret that the glauconite-rich sand that overlies the Oligocene deposits in the Snorre wells and the lower Miocene in the Visund wells drapes over the main Utsira Formation further east. This interpretation is illustrated in Fig. 2. This model is based on the observation of comparable glauconite-rich intervals at the top of the Utsira Formation sand in wells from blocks 30/3 and 30/6 to the south (Rundberg 1989). Gregersen (1998) reported a high gamma peak which was interpreted to represent a glauconite-rich sand bed at the top of the Utsira Formation in blocks 35/10 and 35/11 (north-west of the Troll field; Fig. 1). The present work proposes that the glauconitic sand of the Tampen area was deposited during the latest Miocene and into the earliest Pliocene. However, there are indications that these sands may have been deposited over a longer period, and that they interfinger with the main Utsira Formation sands to the east. Firstly, the sand unit is about 15 m thick, homogeneous, and according to sidewall cores and log data, rich in glauconite minerals. This may indicate that the unit consists of a series of stacked units, each representing a condensed interval. Secondly, the recorded *Bolboforma* species observed in wells 34/8-1 and 34/8-3A, indicate an age of 12 Ma (Spiegler & Müller 1992) for this unit. This age, combined with the Sr-isotopic data from the unit, indicate a period of about 6-7 m.y. characterized by an overall low rate of sedimentation. However, *Bolboforma* are not recorded in any of the other wells in the Tampen area, indicating that they most likely are reworked. If this is the case, it is likely that the *E. variabilis* (N-C1) assemblage is younger than the *Bolboforma* zones of Spiegler & Müller (1992) and Müller & Spiegler (1993) recorded in the North Atlantic and the Norwegian Sea. The youngest of these zones (*B. metzmacheri* Zone) corresponds to an interval of between 10.0-8.7 Ma based on calibration with nannoplankton and palaeomagnetic data. This suggestion is based on the comparison of the observations from the Norwegian Sea continental shelf where the *E. variabilis* and *Bolboforma* assemblages are present in the same wells (Stratlab 1986, Eidvin et al. 1998). The young Sr-ages obtained from this unit also support this view, and indicate a period of condensed deposition of approximately 3.5 m.y. However, Gradstein & Bäckström (1996) have observed the LAD of *B. metzmacheri* stratigraphically above that of *E. variabilis* in the North Sea, which is not in concurrence with our view. The authors agree with Gradstein & Bäckström (1996) that further studies of the late Miocene are required to resolve this question.

The basal Upper Pliocene unit

In previous papers and in well reports from the Snorre and Visund areas, the basal Upper Pliocene unit has commonly been assigned a Miocene age and consequently been included in the Utsira Formation. In a study of wells 34/2-4 and 34/2-6, Eidvin & Riis (1992) reported a Late Miocene age for this unit and also included it in the Utsira Formation. Gradstein et al. (1992) assigned the unit an Early Miocene age in well 34/8-1. Steurbaut et al. (1991), assigned the lower part of the unit in well 34/4-1 to the Early Pliocene, but were unable to determine the age of the upper part. It must be emphasized that all of these datings were based on ditch cuttings, and that consequently the unit boundaries were based on the LADs of selected taxa. The present work, which has utilized cores from wells 34/8-9S and 34/8A-1H (Figs. 7 and 8), and sidewall cores from wells 34/4-7 and 34/7-1 (Figs. 11a and 12a), has demonstrated an *in situ* Upper Pliocene fauna within this unit, and has shown that the older fossils are reworked.

There is good evidence from the cores of a glacio-marine influence within the sediments from this unit. Glacio-marine sediments of the Vøring Plateau have been the subject of studies by Jansen & Sjøholm (1991) and Fronval & Jansen (1996). These studies demonstrated the presence of ice-rafted material in sediments as old as 12.6 Ma. The frequency of ice-rafted material increases during the period between 7.2 and 6.0 Ma, but remains relatively low between 6.0 Ma and 2.75 Ma. A marked increase in the supply of such material after about 2.75 Ma reflects the expansion of the northern European glaciers (Fig. 17). The maximum age of the basal Upper Pliocene unit of the Tampen area is therefore assigned to be 2.75 Ma.

Origin of the incised valley/canyon system west of Sognefjorden

The large incised valley/canyon system (Fig. 1) was first described by Rundberg et al. (1995). These workers proposed that it was formed as part of a fluvial system resulting from uplift of the northernmost North Sea during the Miocene. Martinsen et al. (1999) also favoured a Miocene age and a fluvial origin. Gregersen (1998) published a study based on the interpretation of 3-D seismic and concluded that the channel-like system was formed prior to deposition of the Utsira Formation, and further proposed a latest Oligocene or earliest Miocene age for the incision.

The present authors' seismic interpretation indicates that the timing of the valley/canyon incision is best resolved by correlating from wells in the northernmost part of the North Sea where the Neogene succession is preserved. In this area, it is evident from both 2-D and 3-D seismic data that the erosive event postdates deposition of the basal Upper Pliocene unit. This relationship is illustrated in Fig. 3. Therefore, we propose that the elongate erosive system is Late Pliocene in age. The dimension of the erosive form, from 1-4 km wide and 150-200 m deep (Figs. 1 and 3), is a magnitude larger than for normal large fluvial streams. The structure is therefore considered to have formed by valley incision more than single fluvial channeling, alternatively as a submarine canyon, or a combination.

Although glacial conditions prevailed at North Sea latitudes during Late Pliocene, a subglacial origin of the canyon is not considered likely. Expansion of ice sheets out onto the shelf probably first took place at about 1.2 Ma (Jansen & Sjøholm 1991, Sejrup et al. 1995). The climatic deterioration at this time is also shown in the oxygen isotope record (Mix et al. 1995).

At this time, the northern North Sea area is interpreted to have been a shelf platform with slope and deeper basin settings developed in the present day Møre Basin to the north. The incised valley system thus cuts deeply into the entire palaeoshelf. This would require a large fall in relative sea level, as indicated from seismic data. This fall in relative sea level resulted in subaerial exposure of marginal parts of the northern North Sea basin. The fluvial incision of the emerged shelf was accompanied by uplift and erosion of the Fennoscandian landmass, followed by large-scale progradation and rapid subsidence of the palaeoshelf. The progradational Upper Pliocene shelf sediments demonstrate that the fall in relative sea level was succeeded by a rapid rise in relative sea level, creating the accommodation needed for this regressive unit.

We propose that, at the time of valley/canyon incision, the shelf edge probably had an east-west orientation close to 62°N. Subaerial exposure has affected much of the eastern part of the basin, such as the areas between 61°15'N and the Agat area at 62°N, where another deep erosive system is observed (Rundberg & Eidvin 1999). This latter system cuts into shelf sediments which are eroded to the south, and is most likely fluvial in origin. The west of the Sognefjorden valley incision is closely contemporaneous with the Agat incision, but the shelf exposure was probably more extensive in the west of the Sognefjorden area.

The present authors therefore favour a model whereby fluvial drainage prevailed over much of quadrant 35. However, in block 34/3 we propose a continuation of the incised valley as a submarine canyon migrating towards the north and cutting into the outer palaeoshelf. This submarine canyon may have supplied sediment to a slope canyon or a turbidite channel system at the southern margin of the Møre Basin. It is also possible that large-scale slumping on the palaeoslope of the Møre Basin may have introduced retrogressive failure and the development of elongate shelf canyons or channels similar to those described in models presented by Talling (1998) and Eyles & Lagoe (1998).

The question if the incision was controlled by glacial eustacy or tectonics remains to be aired. According to data presented by Shackleton et al. (1995), a eustatic sea-level fall in the order of 50-60 m was associated with glacial stage G6 at about 2.75 Ma. Our seismic interpretation and palaeogeographic reconstruction suggest that a larger relative sea-level fall than this must have taken place in the northern North Sea at the time of incision. It is important to note that our model also requires a succeeding rapid rise in sea level to create the accommodation space needed for the regressive Upper Pliocene unit. We therefore propose that tectonic mechanisms exerted major control of sea-level changes that led to exposure and incision of the eastern marginal parts of the northern North Sea basin.

Summary and conclusion

In summary, we conclude the following:

1) In the Troll area Pleistocene deposits rest unconformably on Lower Oligocene strata. The upper part of the Upper Oligocene is absent in all the Tampen wells studied. In the Visund area (block 34/8) there is a hiatus of more than 2 m.y. between Oligocene and Lower Miocene deposits. In the Snorre area (blocks 34/4 and 34/7) there is a hiatus of more than 18 m.y. between the Oligocene and the Upper Miocene (Fig. 16).

2) A previously undescribed Lower Miocene unit has been identified and mapped at the top of the Hordaland Group in the Visund area. A large hiatus separates this unit from the overlying beds.

3) The quartzose sands of the Utsira Formation are not recorded in any of the studied wells, but preliminary results from well 35/11-1 indicate a Late Miocene to possible latest Middle Miocene age for the formation. A glauconitic part of the Utsira Formation (Late Miocene to earliest Early Pliocene in age) is present in the Tampen wells. This unit overlies the Oligocene strata in the Snorre area and the Lower Miocene strata in the Visund area. East of these areas, we propose that the unit drapes over, or partly interfingers with the main Utsira Formation sands.

4) A distinct seismic unit is identified at the base of the Upper Pliocene prograding complex. Cores from this unit contain sands and silts that are interpreted to be gravity flow deposits, and contain mudstone clasts that include shallow marine fauna interpreted to have been transported into deeper water. Ice-rafted debris is also common in the cores. The fauna is typical of the Late Pliocene, but reworked Miocene forms are also quite common.

5) We believe that the Utsira Formation requires a new and precise definition as a basis for further stratigraphic study in the northern North Sea. The present authors propose that the top of the formation should be assigned to the end of the period of restricted sedimentation, characterized by glauconite rich sands. This point in time is close to the Miocene-Pliocene boundary, as we have demonstrated in the Tampen wells. Thus, we recommend that sands belonging to the basal Upper Pliocene unit or to the Upper Pliocene prograding complex should not be included in the Utsira Formation. There is also a need for a clearer definition of the base of the Utsira Formation because there remains considerable confusion, in some areas further to the south, whether the sands belong to the Skade or to the Utsira Formations.

6) The elongate erosive channel-like structure west of Sognefjorden, which has been described as Miocene in age, appears to be younger. The structure is inferred to have formed as an incised valley in the proximal areas and as a submarine canyon in its extension further to the north into the Møre Basin. The valley/canyon incision postdates deposition of the basal Upper Pliocene unit in the Tampen area, which was deposited in a lowstand setting. We propose that the erosive drainage system evolved during the Late Pliocene, initiated by a large fall in relative sea level. This was succeeded by a rise in relative sea level giving accommodation for the progradation of the Upper Pliocene shelf wedge.

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