Post-Eocene strata of the southern Viking Graben, northern North Sea; integrated biostratigraphic, strontium isotopic and lithostratigraphic study

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Based on an extensive study of biostratigraphic and strontium isotopic data from wells in the southern Viking Graben and eastern flank of the Utsira High we present an improved chronology of the post-Eocene section of the northern North Sea. Emphasis has been placed on the sandy Utsira and Skade formations. Detailed analyses of foraminiferal and *Bolboforma* fossil assemblages supported by strontium isotopic data from six exploration and two production wells suggest that the Skade sands were deposited mainly during the Early Miocene whereas the Utsira sands were deposited during the Late Miocene and Early Pliocene. All biostratigraphic data are presented in range charts and have been integrated with wireline log and seismic data. Strontium isotope stratigraphy has been used as an additional dating tool and has proved powerful in the sandy sections. This work also demonstrates a need for an update or modification of the lithostratigraphic nomenclature of the post-Eocene succession in the Norwegian North Sea, and a proposal for a revision is presented.

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Introduction

In this paper we present an improved chronology of the post-Eocene section in blocks 15/9, 16/1, 24/12 and 25/10 of the Norwegian North Sea (Fig. 1).

Our investigation includes data from six exploration wells (15/9-13, 15/12-3, 24/12-1, 16/1-2, 16/1-4 and 25/10-2) and two production wells (15/9-A-11 and 15/9-A-23) located in the southern Viking Graben and on the western flank of the Utsira High. It is a combined biostratigraphically, seismostratigraphical, lithostratigraphical and geochemical study. Well 15/12-3 has previously been investigated by Eidvin et al. (1999), but has been reanalysed and reinterpreted in this study.

The main purpose has been to improve the chronology of the upper Cainozoic sequences and to constrain better the age of the main sequence boundaries. Emphasis has been placed on the upper part of the Hordaland Group including the Skade Formation and the lower part of the Nordland Group including the Utsira Formation. The Upper Pliocene has been studied in two wells, and the lower part of the Upper Pliocene has been investigated in four wells. The lower part of Pleistocene is considered in two wells. The error in the definition of Utsira and Skade type wells (Fig. 2), as described by Rundberg & Eidvin (2005), has evidently caused much confusion and many problems for stratigraphic workers in the northern North Sea. These problems have also demonstrated a need for updating the existing lithostratigraphic nomenclature of the Upper Cainozoic (Isaksen & Tonstad 1989), and we present a proposal for its revision.

This paper forms the third part of our study of the upper Cainozoic succession in the central and northern North Sea. A stratigraphical investigation of the upper Cainozoic succession in the Tampen area was presented in Eidvin & Rundberg (2001) and a synthesis of the Oligocene to Miocene depositional history of the northern and central North Sea was presented in Rundberg & Eidvin (2005).

All absolute ages referred to in the present study are based on Berggren et al. (1995), and all depths are expressed as meters below the rig floor (m RKB).

Previous works

Biostratigraphy

Although extensively explored by a number of exploration and production wells, the biostratigraphy of the post-Eocene section of the southern Viking Graben has not previously been treated in detail. In most of these wells, contracted consultants have carried out routine biostratigraphic dating. Traditionally, the Upper Cainozoic has been given low priority, and the datings are consequently often insufficient. Correlation of wells based on a variety of consultant-generated data can often be problematic, because of different taxonomic nomenclature and interpretations. Unpublished consultant reports are often particularly inadequate with regard to the use of planktonic foraminifera and *Bolboforma* (calcareous microfossils of uncertain origin). One reason for this is that planktonic/benthic ratios are very low in some sections. In this study we overcame this problem by pre-

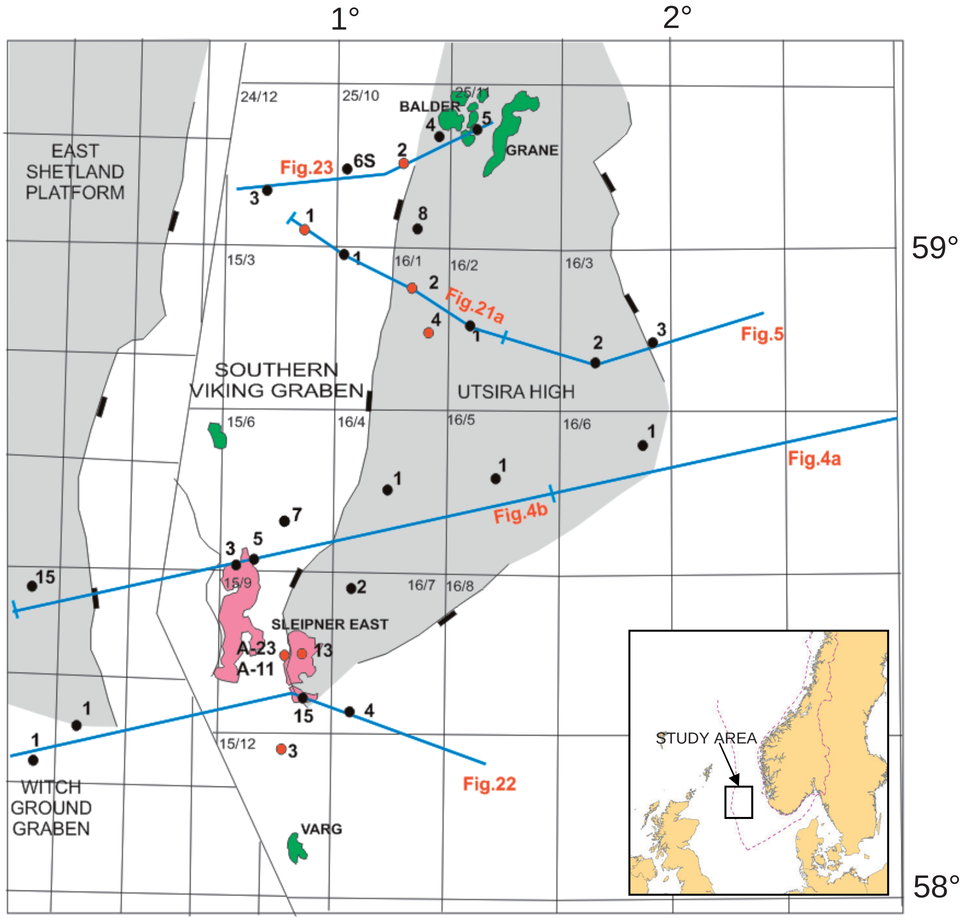


Figure 1. Study area showing major structural elements, location of studied wells (red) and wells (black) that are shown on seismic sections and log correlations. Blue lines show location of seismic lines.

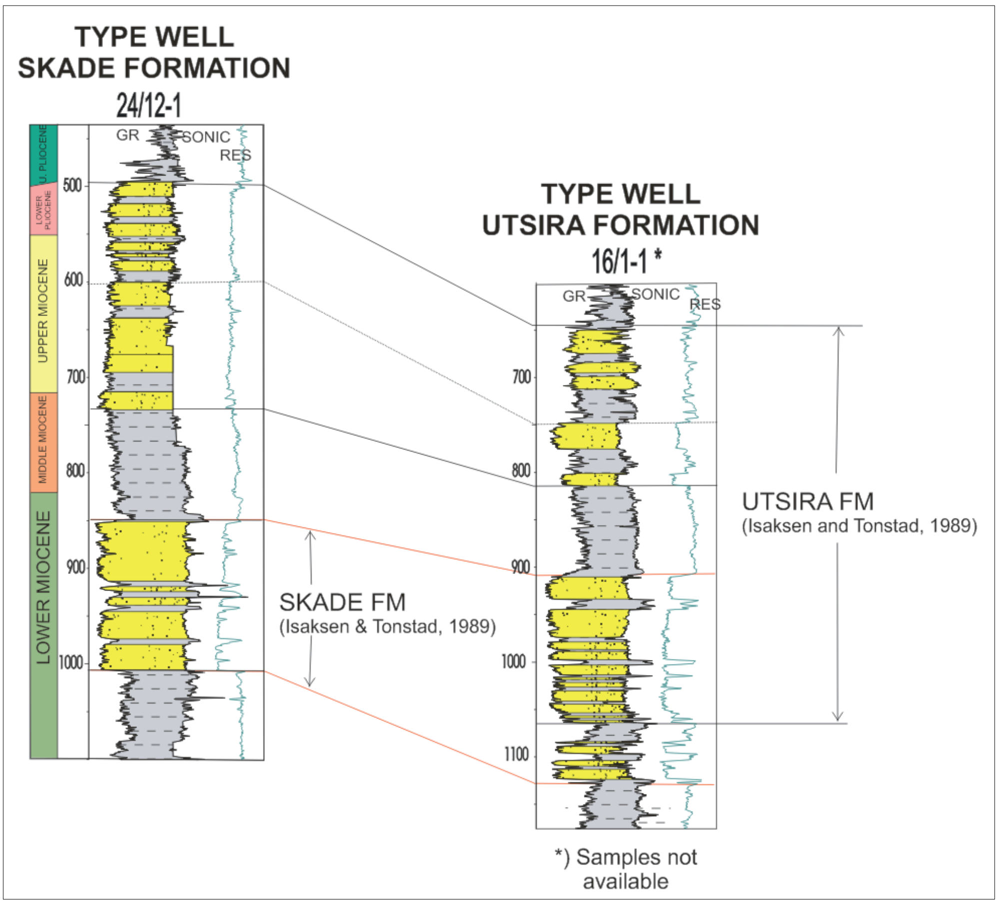


Figure 2. Correlation conflict between the Utsira and Skade formations, in which the lower part of the Utsira Formation in type well 16/1-1 correlates with the Skade Formation in its type well 24/12-1 (from Rundberg & Eidvin 2005).

paring and analysing large sediment samples. Another reason is that the tests of *Bolboforma* are very small and some species are difficult to identify without the use of the electron microscope.

Based on the analysis mainly of ditch cutting samples but including also samples from sidewall cores and conventional cores from a large number of exploration wells, King (1983, 1989) published a detailed foraminiferal zonation for the Cainozoic of the entire North Sea. Gradstein & Bäckström (1996) established a similar foraminiferal zonation for the North Sea and the Haltenbanken areas based on the analysis of the same kind of material in a number of wells.

In recent years, several papers have been published dealing with the chronology of upper Cainozoic deposits in exploration wells from the central and northern North Sea areas. Rundberg & Smalley (1989) performed age determinations in a number of exploration wells based on strontium isotope analysis of mollusc fragments in ditch cutting samples. Knudsen & Asbjörnsdóttir (1991) have investigated the Upper Pliocene and Pleistocene in an exploration well in the English sector based on the analysis of benthic foraminifera in ditch cutting samples. Seidenkrantz (1992) studied the same succession in several exploration wells on the Gullfaks field based on the analysis of the same kind of fossils and material. Gradstein et al. (1992, 1994) published data from the entire Cainozoic succession in a number of exploration wells based on the analysis of dinoflagellate cysts, benthic and planktonic foraminifera in mainly ditch cutting samples but including sidewall cores and conventional cores. Konradi (1996) has analysed the post mid-Miocene succession in an exploration well in the Danish sector based on the analysis of benthic foraminifera in ditch cutting samples. Eidvin et al. (1999) and Eidvin & Rundberg (2001) have investigated the Oligocene to Pleistocene succession in a number of exploration wells based on analysis of benthic and planktonic foraminifera, *Bolboforma* and strontium isotopes in mainly ditch cutting samples, but including sidewall cores and conventional cores. Piasecki et al. (2002) investigated the Lower Pliocene succession (upper part of the Utsira Formation) on the Sleipner field based on the analysis of dinoflagellate cysts in a cored sample. Head et al. (2004) have investigated the base Upper Pliocene section on the same oil field based on analysis of dinoflagellate cysts, benthic and planktonic foraminifera in three cored samples.

Lithostratigraphy

The first stratigraphic subdivision of the Cainozoic was presented by Deegan & Scull (1977). They subdivided Eocene to Recent strata into the Hordaland and Nordland groups. The only formation defined by these authors within the post-Eocene was the sandy Utsira Formation at the base of the Nordland Group. Isaksen & Tonstad (1989) adopted this nomenclature, and also introduced two sandy formations in the Oligocene part of the Hordaland Group, which they termed Skade and Vade formations, present in the Viking Graben and central North Sea, respectively.

In the UK part of the basin, Knox & Holloway (1992) established the Westray Group as a new lithostratigraphic unit. It formed the uppermost of two groups which they had introduced to replace the Hordaland Group. They introduced the Lark Formation for the distal, mudstone-

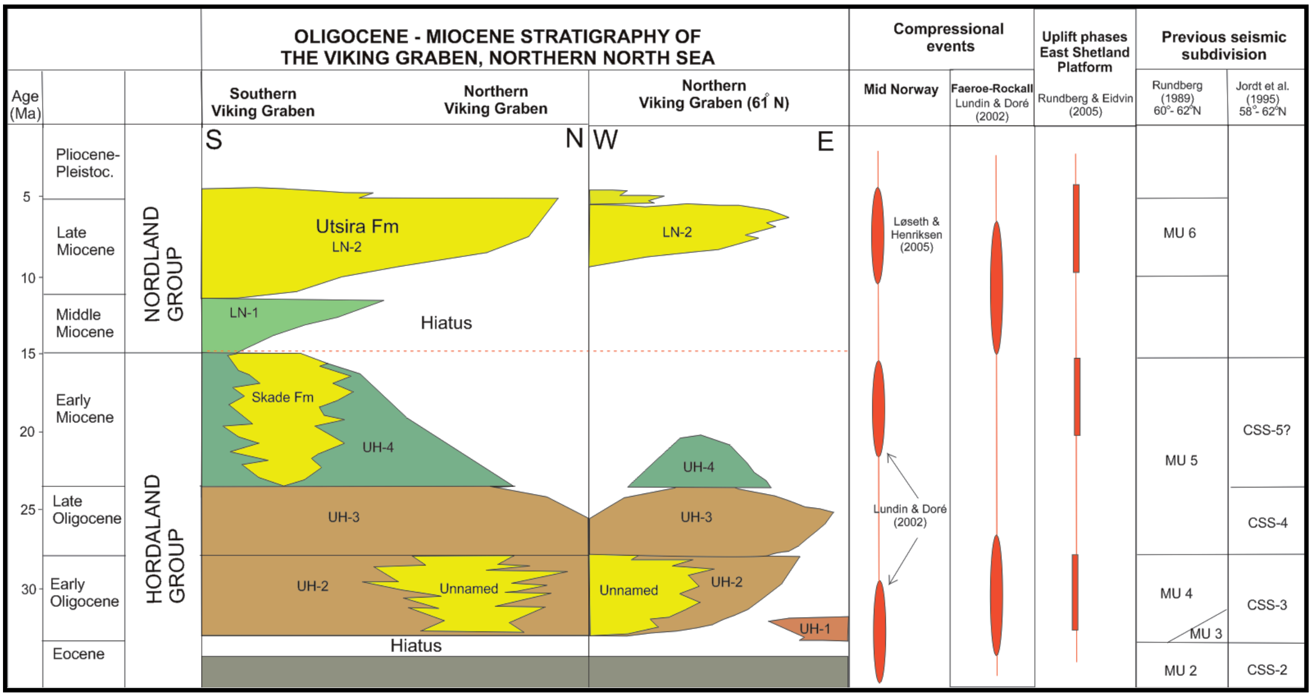


Figure 3. Oligocene-Miocene lithostratigraphy of the Norwegian northern North Sea (modified from Rundberg & Eidvin 2005).

dominated facies of the Westray Group and used the Skade Formation for glauconitic sandstones and siltstones of shelf-facies. Fyfe et al. (2002) published an updated lithostratigraphy of the central and North Sea, based on Isaksen and Tonstad (1989), Knox & Holloway (1992), Eidvin et al. (1999) and Eidvin & Rundberg (2001).

Recently, Rundberg & Eidvin (2005) presented a revised lithostratigraphic and chronostratigraphic subdivision of the Oligocene-Miocene of the Norwegian northern North Sea (Fig. 3). They assigned the Skade Formation to the Early Miocene, and not to the Oligocene, as suggested by Isaksen & Tonstad (1989) and a more precise age assignment was given to the Utsira Formation. Furthermore, Rundberg & Eidvin (2005) demonstrated an error, or inconsistency, in the definition of the Skade and Utsira formations. As presented in Fig. 2, there is an overlap in definitions of the Utsira and Skade formations in which the Skade Formation, as defined in type well 24/12-1, correlates with the lower part of the Utsira Formation as defined in type well 16/1-1.

Sequence stratigraphy

Regional sequence stratigraphic studies on the post-Eocene of the northern North Sea have been presented by Rokoengen & Rønningsland (1983), Rundberg (1989), Jordt et al. (1995), Gregersen et al. (1997, 1998), Martinsen et al. (1999), Galloway et al. (1993), Galloway (2002), Eidvin & Rundberg (2001) and Rundberg & Eidvin (2005). The most detailed works have focussed on the Utsira Formation, first by Gregersen et al. (1997) and later by Galloway (2002). The latter represents a milestone in the understanding of this unique sandy system, with a thorough discussion of the depositional pattern.

Post-Eocene structural and depositional history of the southern Viking Graben

The main structural elements of the study area are shown in Fig. 1. The structural setting is depicted by the two regional transects shown in Figs. 4 and 5. These figures illustrate the Palaeocene-Eocene sedimentary and structural pattern, characterized by Palaeocene gravity-flow deposition in the southern Viking Graben (SVG) and on the eastern flank of the Utsira High, and Eocene subsidence of the SVG and relative uplift of the Utsira High. The Grane and Balder fields represent two important hydrocarbon traps that developed as a response to the structural activity. This history is well-known and will not be outlined further here.

The post-Eocene sedimentary and structural history, however, is less well described. Important accounts have been presented by Rundberg (1989), Galloway et al. (1993), Galloway (2002), Jordt et al. (1995), Gregersen et al. (1997), Faleide et al. (2002) and Rundberg & Eidvin (2005).

Recently, Rundberg & Eidvin (2005) presented a tec-

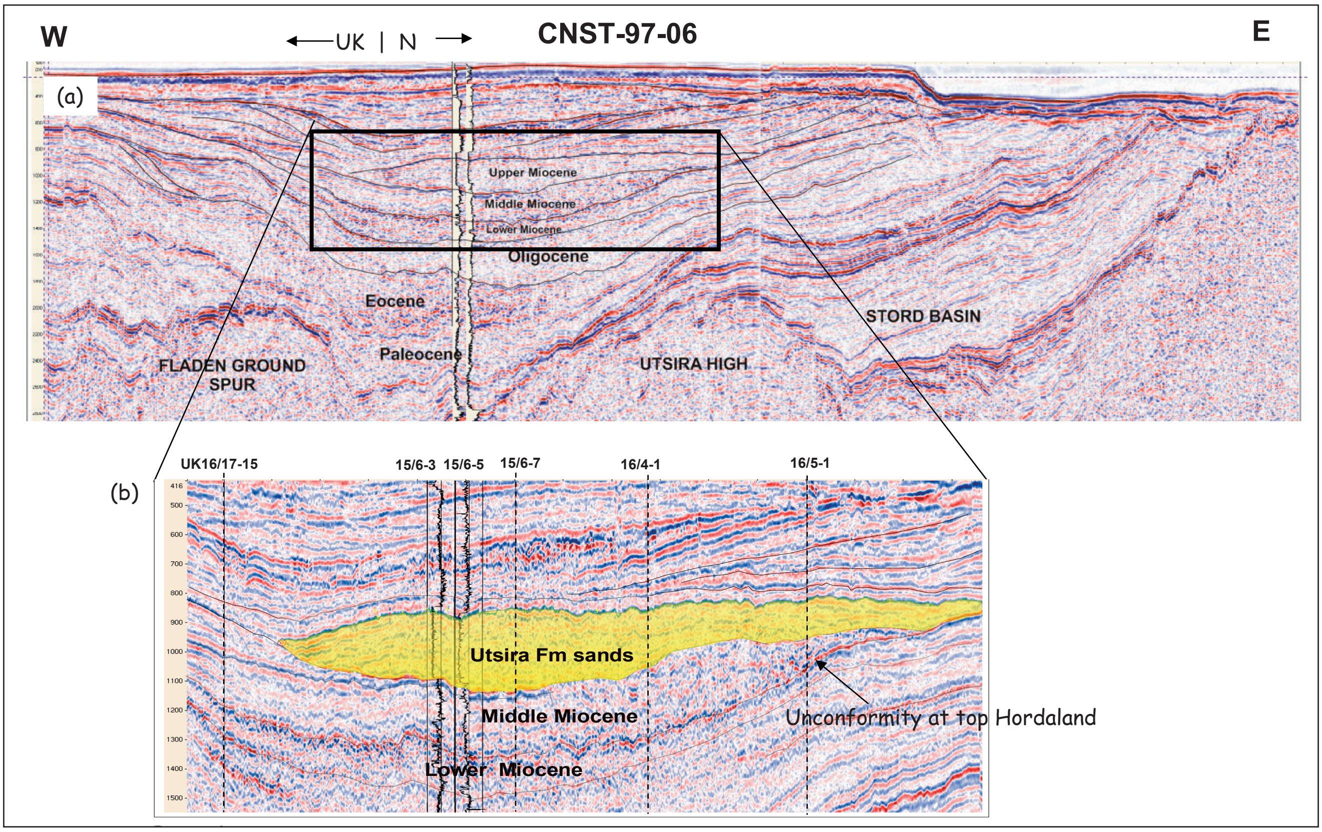


Figure 4. (a) Regional seismic line across the southern Viking Graben and Utsira High close to wells 15/6-3 and 15/6-5, (GR-logs displayed); (b) detail from line shown above with projections of wells that are used in log correlation (Fig.18). Location of line shown in Fig. 1.

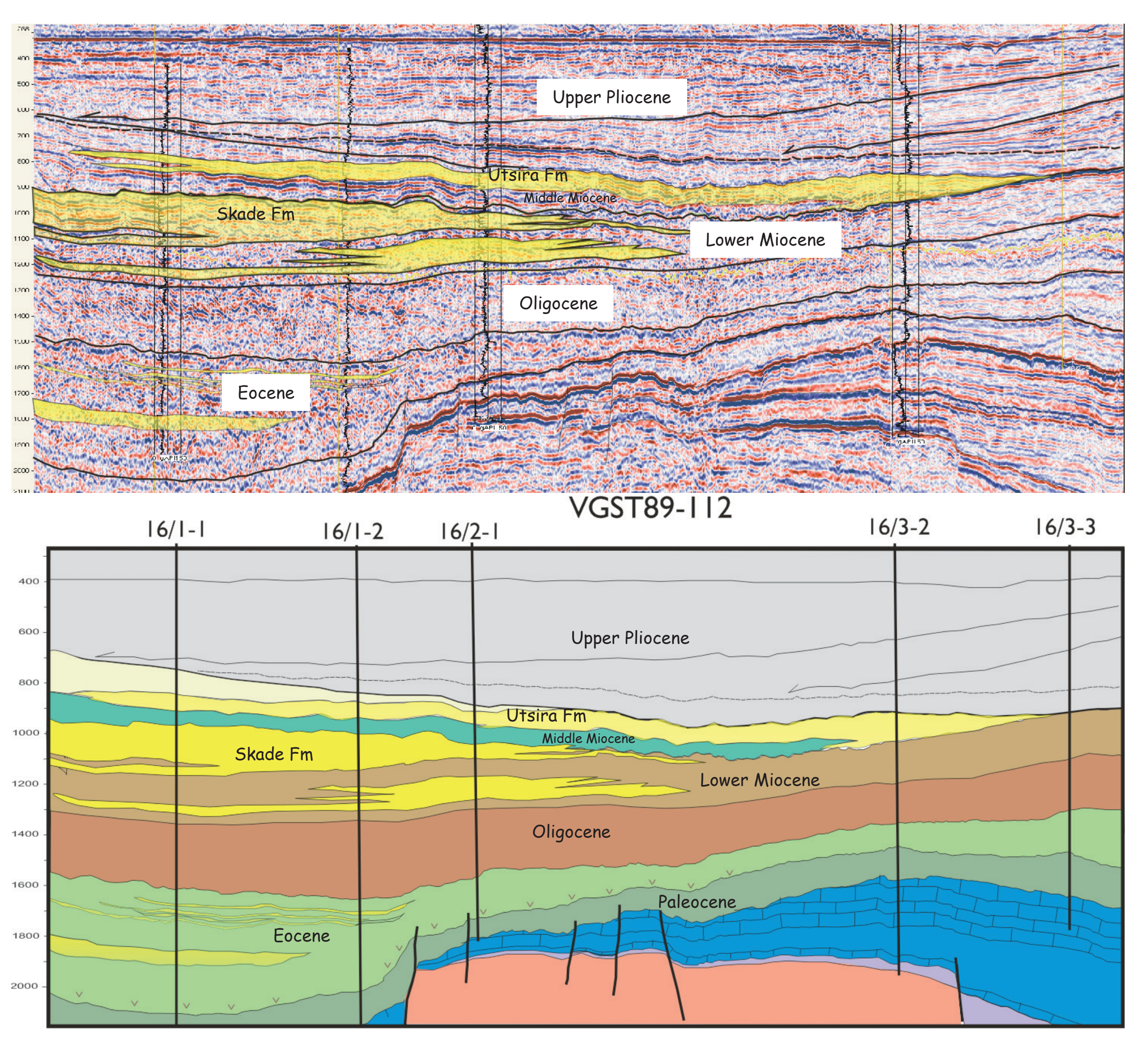


Figure 5. (a) Regional seismic line across the southern Viking Graben and Utsira High; (b) interpretation of line above. Location of line shown in Fig. 1.

tonostratigraphic framework for the Oligocene-Miocene of the northern North Sea. They suggested that the structural and stratigraphic changes seen in the northern North Sea were closely linked to the larger scale structural evolution of the NW European passive margin. Structural doming on the mid-Norwegian margin, for example, coincides fairly well with uplift of the northern North Sea Basin. As a response to this uplift, a distinct unconformity was created (referred to as the mid-Miocene unconformity) in the northern North Sea Basin. In Fig. 3, this is illustrated by a northwards increasing stratigraphic break. In regional transects across the southern Viking Graben and Utsira High, this unconformity is particularly conspicuous, as exemplified in Figs. 4a and 5a. Below the mid-Miocene unconformity, Oligocene and Lower Miocene strata are present across the entire basin, suggesting relatively deep marine conditions. Above the mid-Miocene unconformity, Middle Miocene strata and also much of the Utsira sands are restricted to the central part of the basin, denoting a dramatic relative sea-level fall with infill of sediments within the southern Viking Graben.

Rundberg & Eidvin (2005) suggested that the post-Eocene of the northern North Sea was affected by three phases of coarse clastic input. The first phase of sandy deposition took place during Early Oligocene and was concentrated to areas north of 60°N (unnamed Oligocene sands in Fig. 3). Gravity-flow sands with gross thicknesses in excess of 400 m were sourced from the East Shetland Platform and deposited in a fairly deep-water environment. The second phase of coarse clastic input took place during Early Miocene and was concentrated mainly to the southern Viking Graben. This deposition comprises gravity-flow sands belonging to the Skade Formation, which reaches a gross thickness of about 400 m in the

Fig. 6a

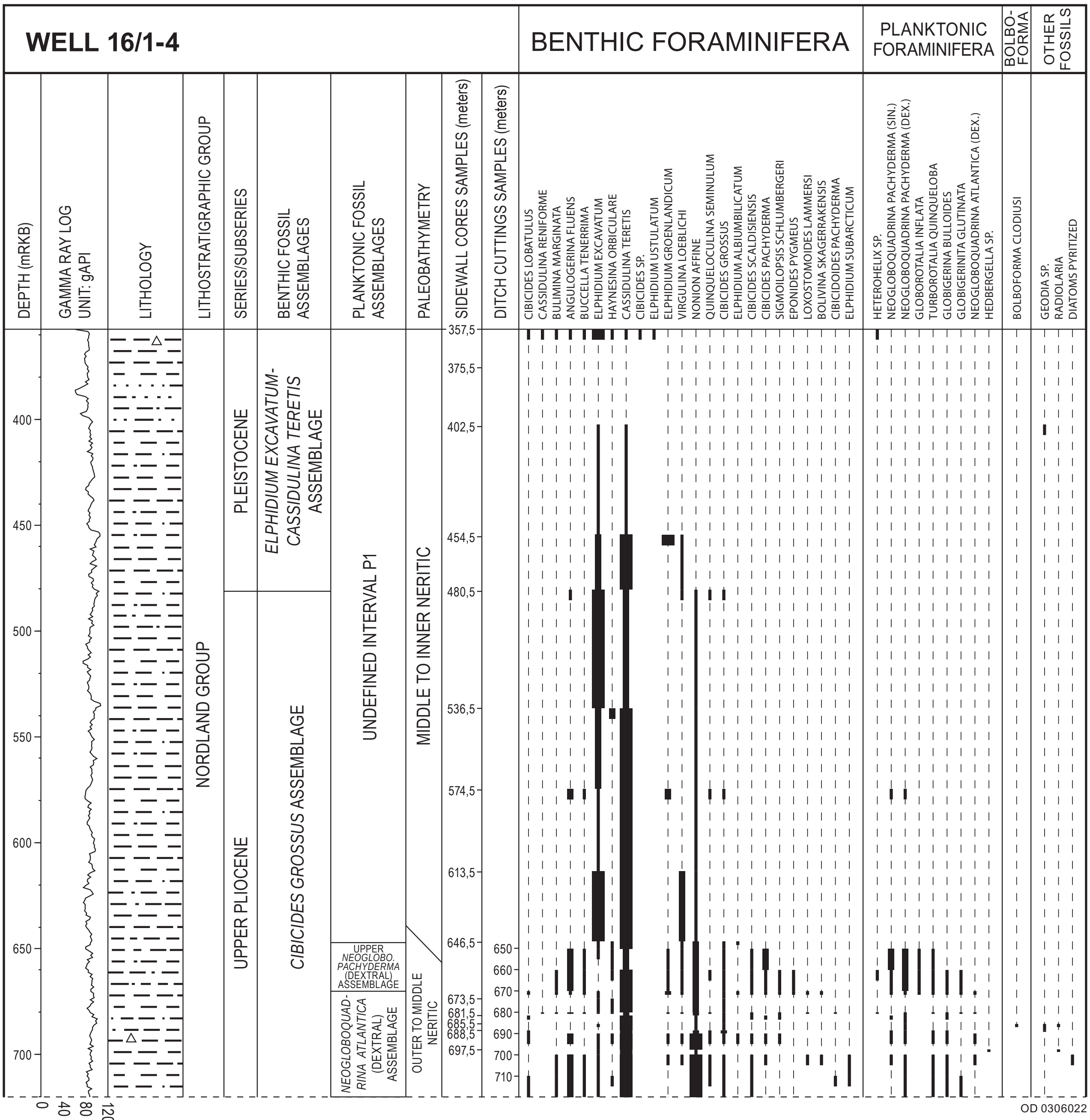


Figure 6a. Range chart of the most important index fossils, fossil assemblages, gamma ray log, lithology, lithostratigraphic unit, series/subseries, paleobathymetry, and samples investigated in the upper part of well 16/1-4. For abbreviations and key to symbols, see Fig. 6c.

study area (Fig. 5). The third phase of coarse clastic input relates to the sands of the Utsira Formation, which were deposited during Late Miocene and Early Pliocene (in some wells the deposition started during latest Middle Miocene).

Material and methods

Samples. In most of the studied wells, the biostratigraphic analyses were performed largely on ditch cutting samples. Sidewall cores were available in well 16/1-4 (48 cores). In wells 15/9-A-11 and 15/9-A-23, the work is based on material from cored sections in basal part of Upper Pliocene and Lower Pliocene deposits, respectively. The Pleistocene succession is analysed in well 15/12-3 and 16/1-4, but the uppermost approximately 90 m in well 15/12-3 and approximately 220 m in well 16/1-4 are not sampled. Ditch cuttings are usually sampled at 10 m intervals in upper Cainozoic sections, and we have analysed all the available samples. However, some of the stored samples contain so little material that they could not be released for analyses. This is especially the case for some sections of of wells 16/1-4 and 24/12-1, but these sections are analysed in other wells.

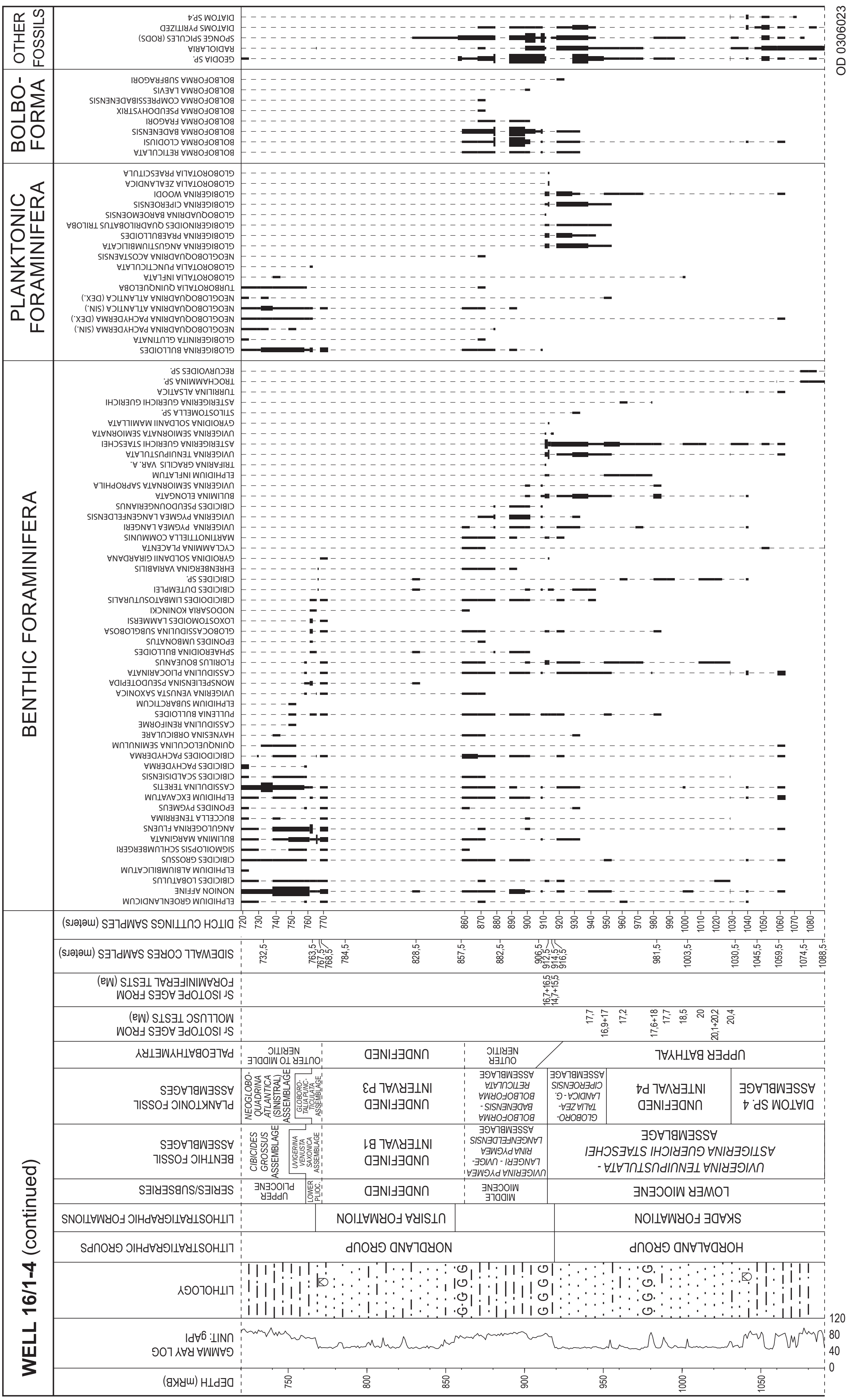


Figure 6b. Range chart of the most important index fossils, fossil assemblages, gamma ray log, lithology, lithostratigraphic units, series/subseries, paleobathymetry, strontium isotope ages and samples investigated in the middle part of well 16/1-4. For abbreviations and key to symbols, see Fig. 6c.

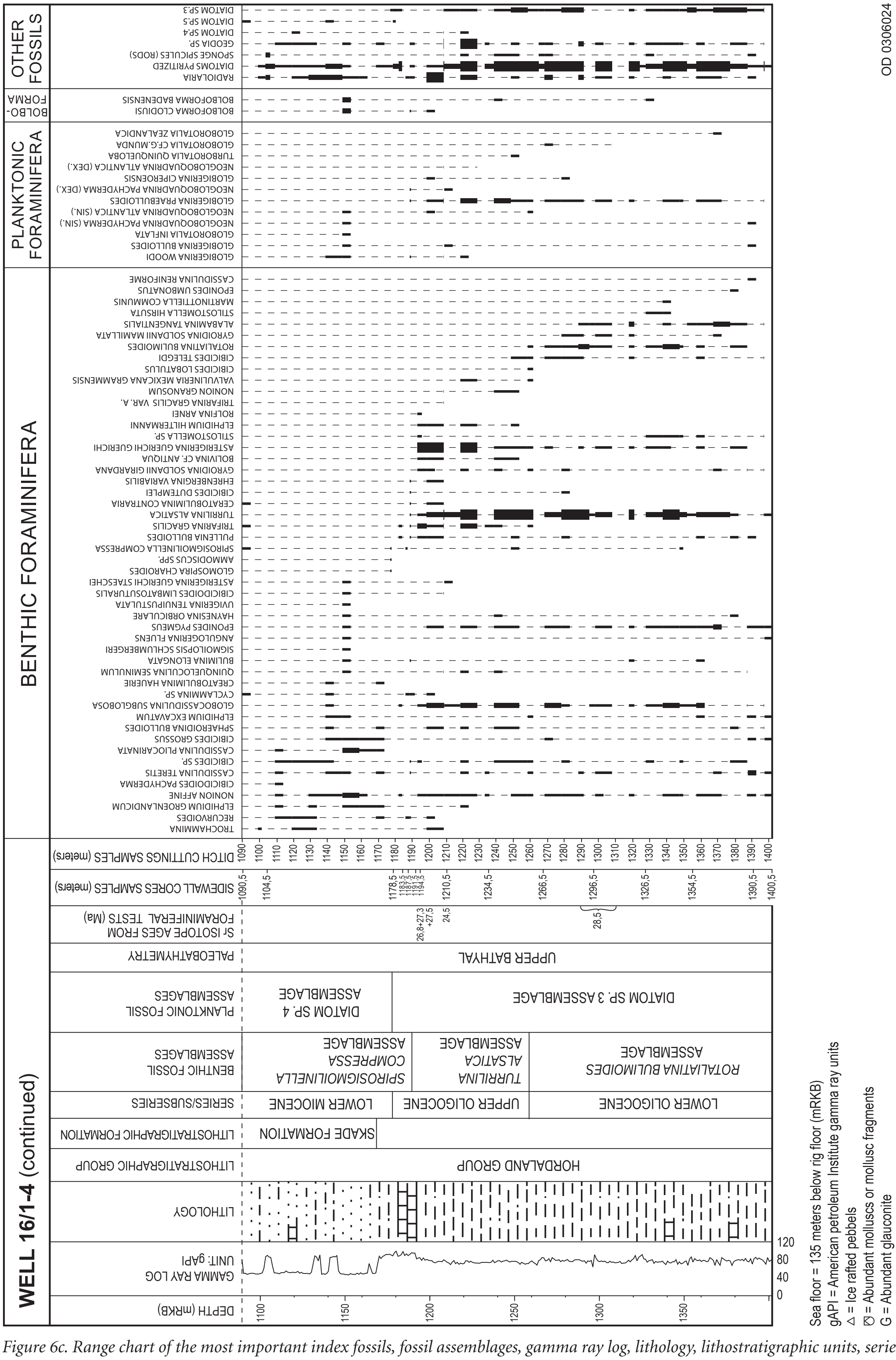


Figure 6c. Range chart of the most important index fossils, fossil assemblages, gamma ray log, lithology, lithostratigraphic units, series/subseries, paleobathymetry, strontium isotope ages and samples investigated in the lower part of well 16/1-4.

Altogether 365 ditch cutting samples, 48 sidewall cores and four samples from conventional cores were analysed, primarily for planktonic and benthic foraminifera and *Bolboforma*. Pyritized diatoms were used to establish the stratigraphy in Lower Miocene and Oligocene deposits.

Between 50 g and 100 g of material were used to analyse conventional core samples and ditch cuttings. Sidewall cores contain less sample material, and thus sometimes 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 possible, 300 individual fossils were selected for each sample. In order to optimise the identification of the foraminiferal assemblages, most samples rich in terrigenous grains were gravity-separated in heavy liquid. In such cases, 1000-1500 individuals were analysed in fossil-rich samples.

The lithologic analyses are based on visual examination 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 generalised description was deemed appropriate for most sections. However, the sidewall cores in well 16/1-4 and the short conventional cores in wells 15/9-A-11 and 15/9-A-23 allowed more accurate lithologic descriptions to be performed.

Strontium isotope analyses. In total, 215 samples were analysed for Sr isotopic composition. The analyses were mainly conducted on tests of calcareous foraminifera and mollusc fragments. In some samples, *Bolboforma* were also used. The analytical work was conducted by the Mass Spectrometry Laboratory at the University of Bergen, Norway. All Sr isotopic ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$ and to NIST 987 = 0.710248. Sr values were converted to age estimates using the SIS Look-up table of Howard & McArthur (1997). The within-run precision for single analyses was commonly of the order of ± 7 to 9×10^{-6}. The precision of the analyses, however, is considered to be of the order of $\pm 20 \times 10^{-6}$, which is the long-term precision of the mass spectrometer using the standard reference material. See also Chapter 7 for more details about Sr isotope stratigraphy.

Biostratigraphic zonation

The standard Cainozoic biostratigraphic zonation is based on planktonic foraminiferal and calcareous nannoplankton distributions established in tropical and subtropical areas. In middle and high latitudes, the assemblages become progressively less diverse and many key species are lacking (King, 1983).

In this study, the fossil assemblages are correlated primarily with the biozonation of King (1983, 1989), which outlines a micropalaeontological zonation for Cainozoic sediments in the North Sea. Gradstein & Bäckström's (1996) faunal zonation from the North Sea and Haltenbanken is also extensively used. In addition, a number of articles describing benthic foraminifera from onshore basins in the area surrounding the central and southern North Sea are utilized. The zonations of planktonic foraminifera (Weaver 1987, Weaver & Clement 1986 and 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 dating 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 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 eight wells examined in this study, a system of 18 assemblages based on benthic foraminifera and 18 assemblages based on planktonic fossils is devised. Three intervals with very poor planktonic faunas (undefined intervals P1, P2 and P3) and one interval with very poor benthic foraminiferal fauna (undefined interval F1) are also described. These units are presented in the Appendix. The total results are also summarized in stratigraphic range charts (Figs. 6 through 13). Correlation of fossil assemblages between the studied wells is shown in Fig. 14. Correlation of fossil assemblages between wells 15/12-3, 16/1-4 and 16/1-2 to the fossil zonation of King (1989) and the planktonic fossil zonation in the ODP sites on the Vøring Plateau is shown in Fig. 15. Correlation of planktonic fossil assemblages between wells 24/12-1 and 25/10-2 with the planktonic fossil zonation in the ODP sites on the Vøring Plateau is shown in Fig. 16.

Log correlations, log markers and seismic illustrations

Four log correlations profile (profiles 1-4) of Oligocene - Miocene strata are shown in Figs. 17 through 20. The correlations are calibrated with seismic and biostratigraphic data in key wells of the study area.

In the southern Viking Graben (Fig. 18, profile 2), seven gamma ray maxima or peaks (GR1-GR7) were identified within the mudstone-dominated Oligocene-Miocene section. The stratigraphic sequences bounded by these peaks have been mapped in a number of wells using the GR-markers as a guiding tool (see below for further details). Between wells that are relatively closely spaced, the correlations can be carried out with good precision and a high degree of confidence. Jump corre-

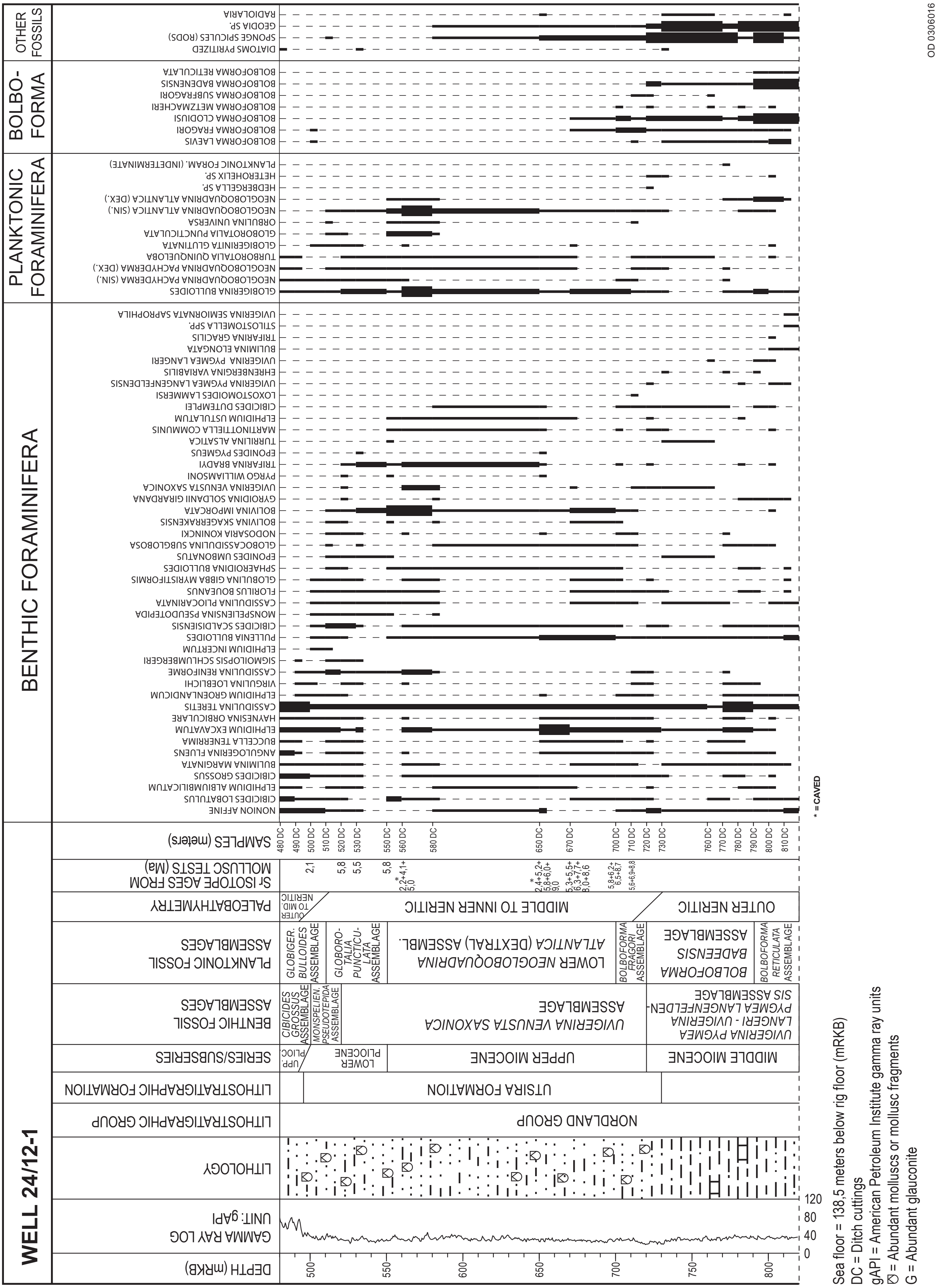


Figure 7a. Range chart of the most important index fossils, fossil assemblages, gamma ray log, lithology, lithostratigraphic units, series/subseries, paleobathymetry, strontium isotope ages and samples investigated in the upper part of well 24/12-1.

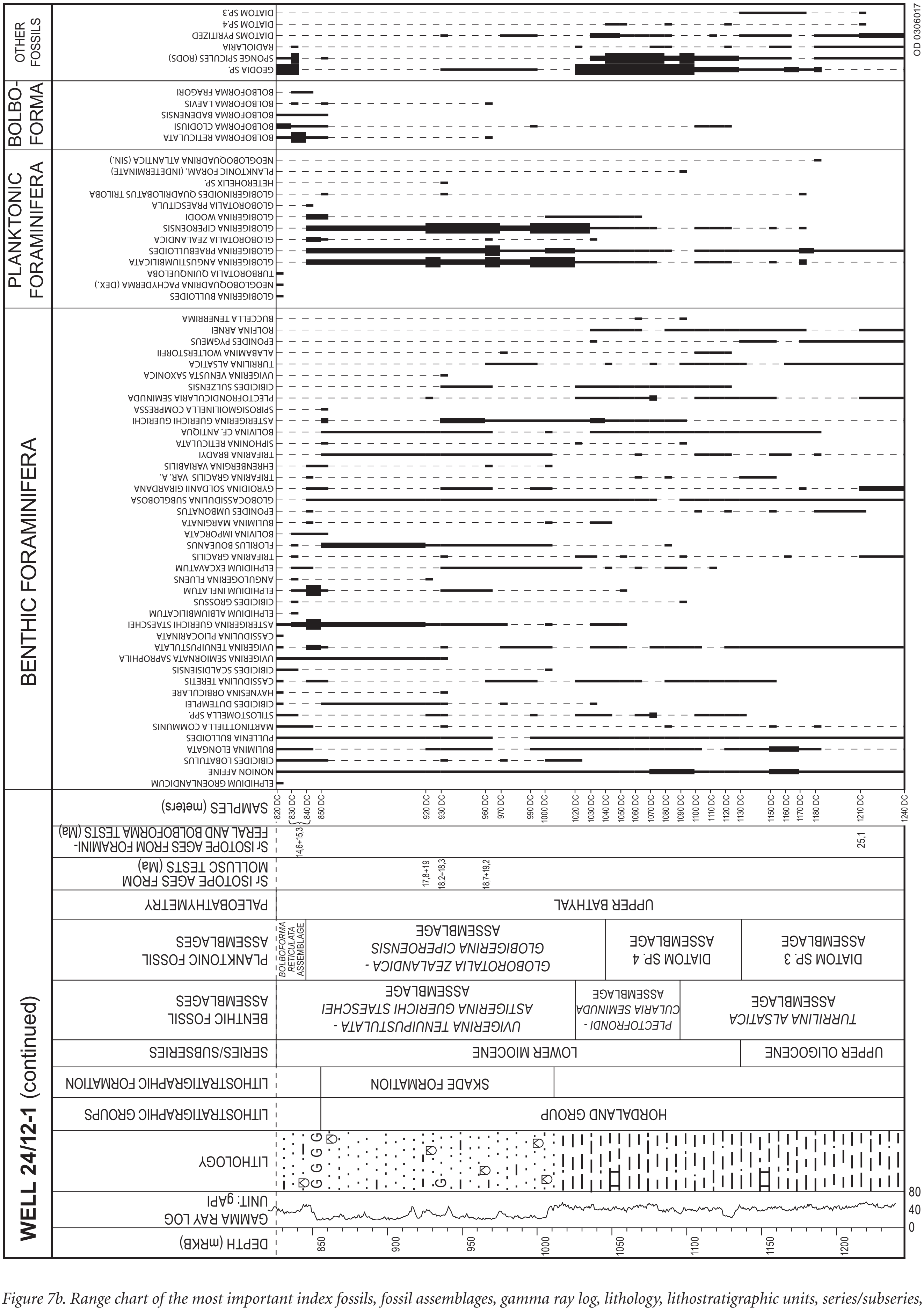


Figure 7b. Range chart of the most important index fossils, fossil assemblages, gamma ray log, lithology, lithostratigraphic units, series/subseries, paleobathymetry, strontium isotope ages and samples investigated in the lower part of well 24/12-1. For abbreviations and key to symbols, see Figure 7a.

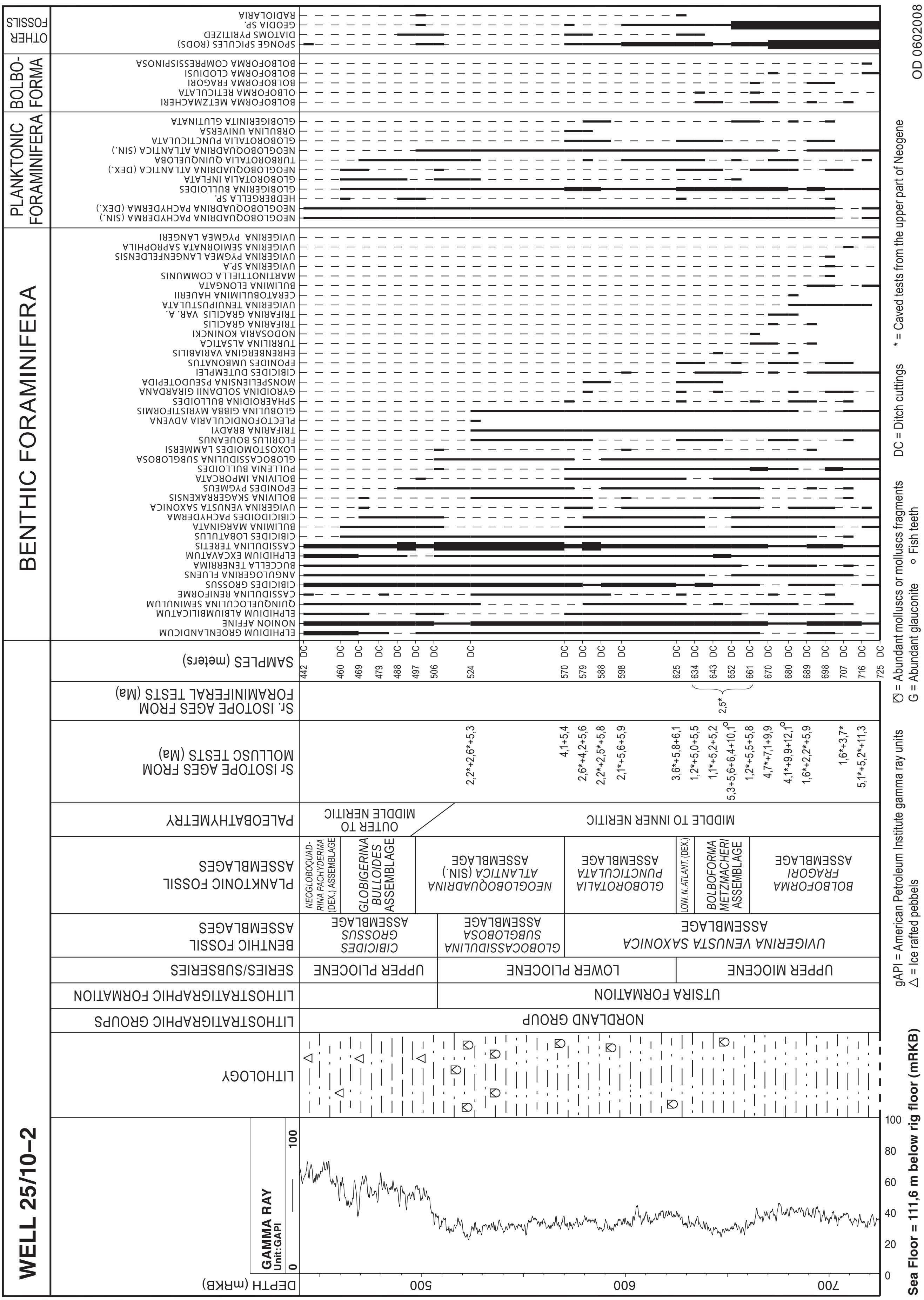


Figure 8a. Range chart of the most important index fossils, fossil assemblages, gamma ray log, lithology, lithostratigraphic units, series/subseries, paleobathymetry, strontium isotope ages and samples investigated in the upper part of well 25/10-2.

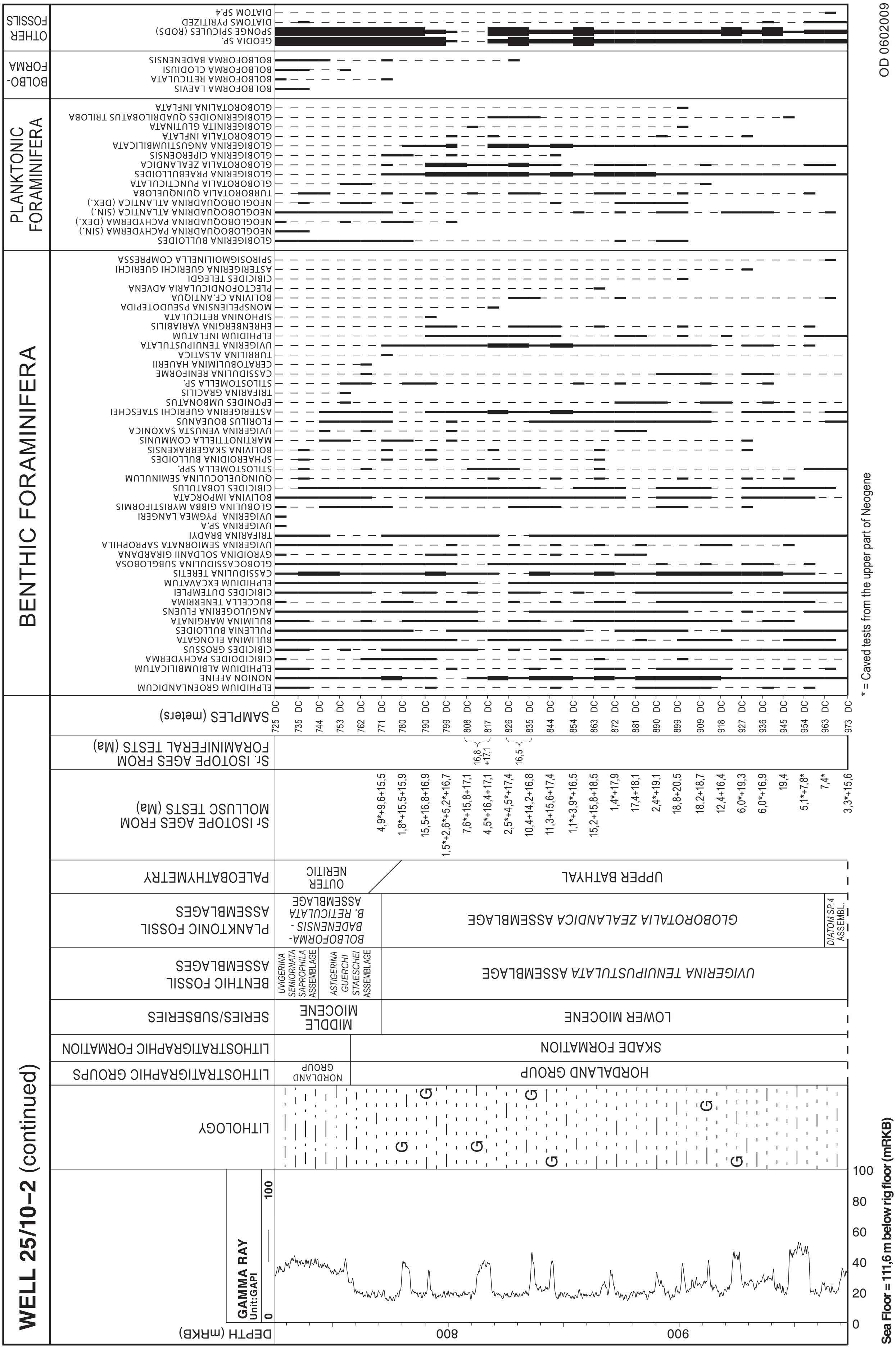


Figure 8b. Range chart of the most important index fossils, fossil assemblages, gamma ray log, lithology, lithostratigraphic units, series/subseries, paleobathymetry, strontium isotope ages and samples investigated in the middle part of well 25/10-2. For abbreviations and key to symbols, see Figure 8a.

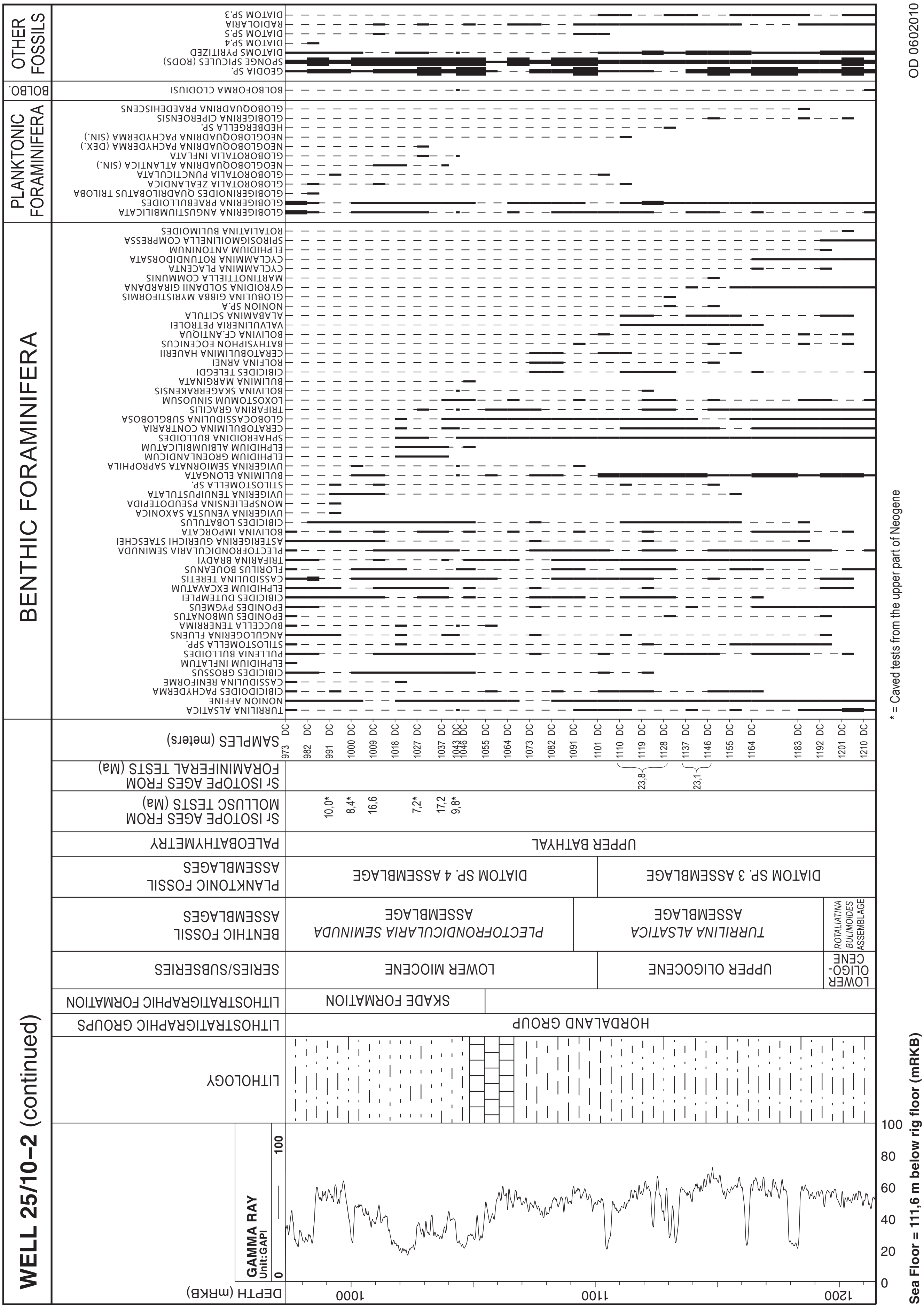


Figure 8c. Range chart of the most important index fossils, fossil assemblages, gamma ray log, lithology, lithostratigraphic units, series/subseries, paleobathymetry, strontium isotope ages and samples investigated in the lower part of well 25/10-2. For abbreviations and key to symbols, see Figure 8a.

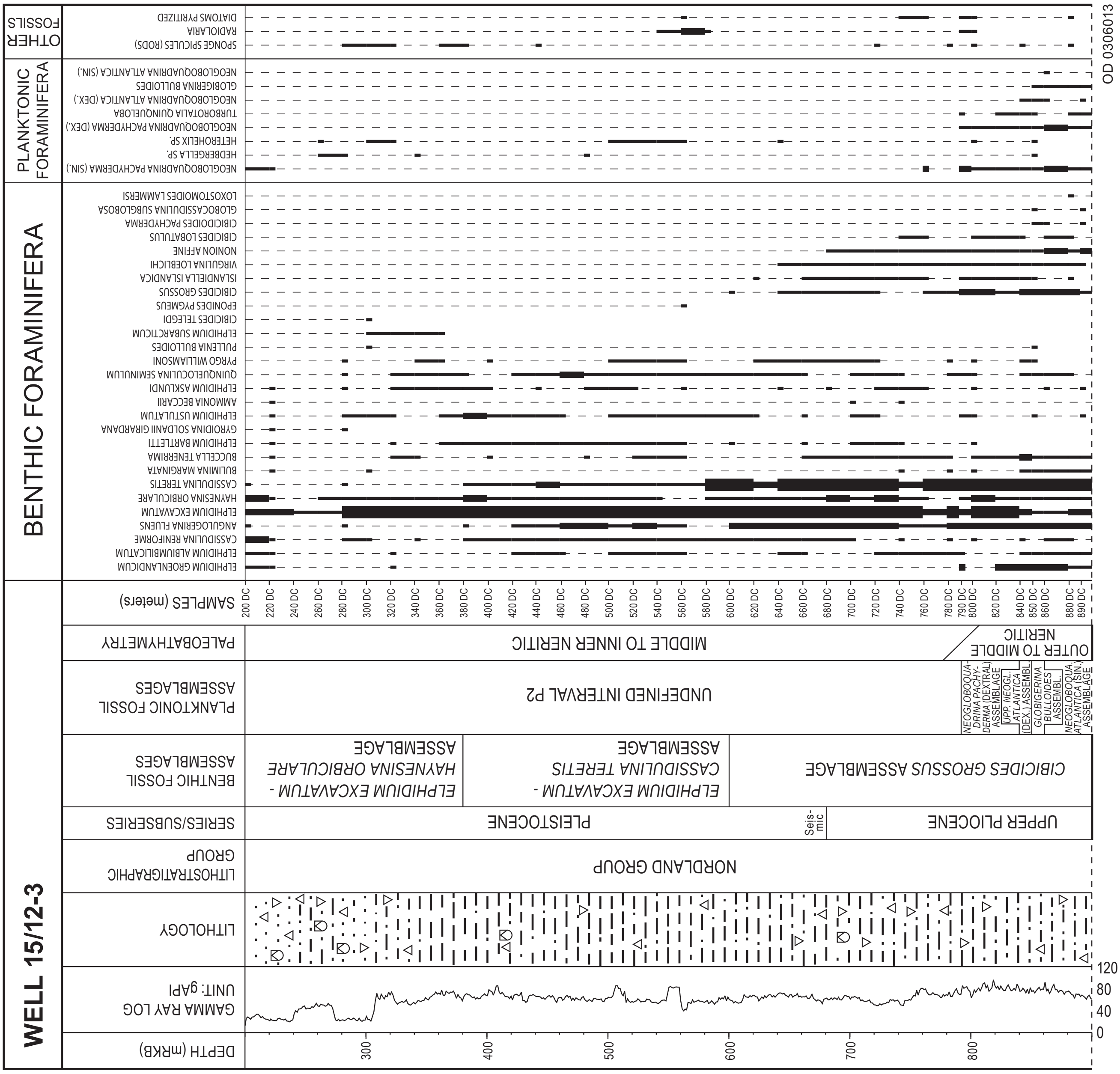


Figure 9a. Range chart of the most important index fossils, fossil assemblages, gamma ray log, lithology, lithostratigraphic units, series/subseries, paleobathymetry and samples investigated in the upper part of well 15/12-3. For abbreviations and key to symbols, see Fig. 9b.

lation over large distances, however, can easily bring in errors, as the wireline log responses change laterally and some of the markers disappear. In a northwards direction, the Skade Formation sandstones occupy much of the Lower Miocene section, and only some of the markers can be distinguished.

Log profile 1 (Fig. 17) shows six wells located along the regional seismic transect in Fig. 5a. The type wells of the Utsira and Skade formations, 16/1-1 and 24/12-1 respectively, are included in this profile. Seismically, the correlation of the sands can be viewed in more detail in Fig. 21a. The correlation of the Skade sands is readily apparent, whereas it is less obvious how the thick Utsira sands in well 24/12-1 relate to the thinner sands to the east. Figure 21b shows the interpretation of Rundberg & Eidvin (2005), who subdivided the Utsira Formation along this profile into two subunits; (1) a lower subunit characterised by dominantly blocky sands, and (2) an upper subunit displaying a distinct coarsening-upward trend. The upper subunit clearly thins in an eastward direction and was interpreted as a progradational system downlapping the underlying blocky sands. According to Galloway's (2002) model of the Utsira Formation, the sands in the area of well 24/12-1 represent deposits linked to the eastward migrating Shetland strandplain, whereas the blocky sands belong to the system of shoal sands in the southern Viking Graben.

Log profile 2 (Fig. 18) shows six wells, which can be tied to the regional seismic transect in Figs. 4a and 4b. This profile illustrates the blocky GR

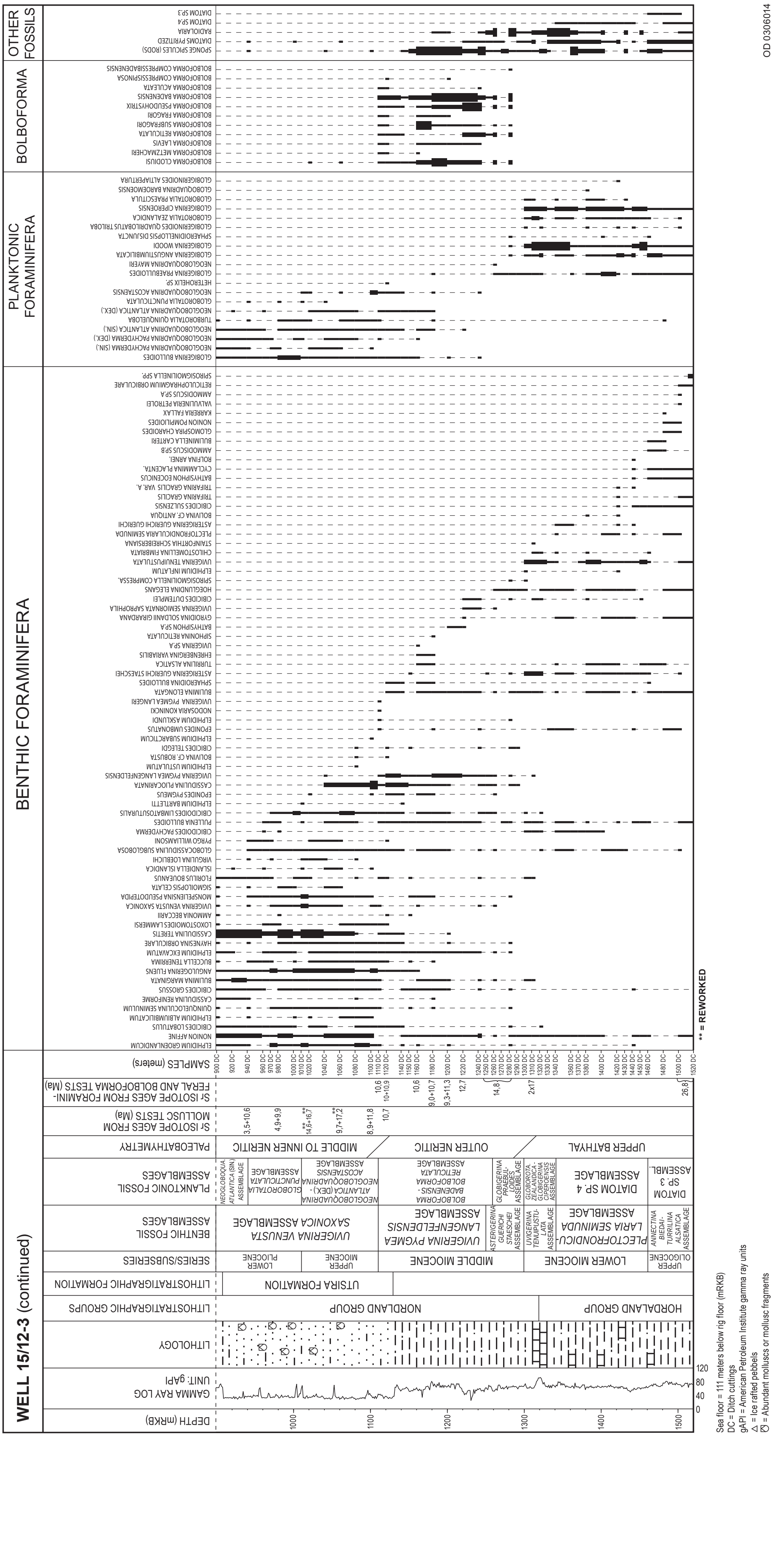


Figure 9b. Range chart of the most important index fossils, fossil assemblages, gamma ray log, lithology, lithostratigraphic units, series/subseries, paleobathymetry, strontium isotope ages and samples investigated in the lower part of well 15/12-3.

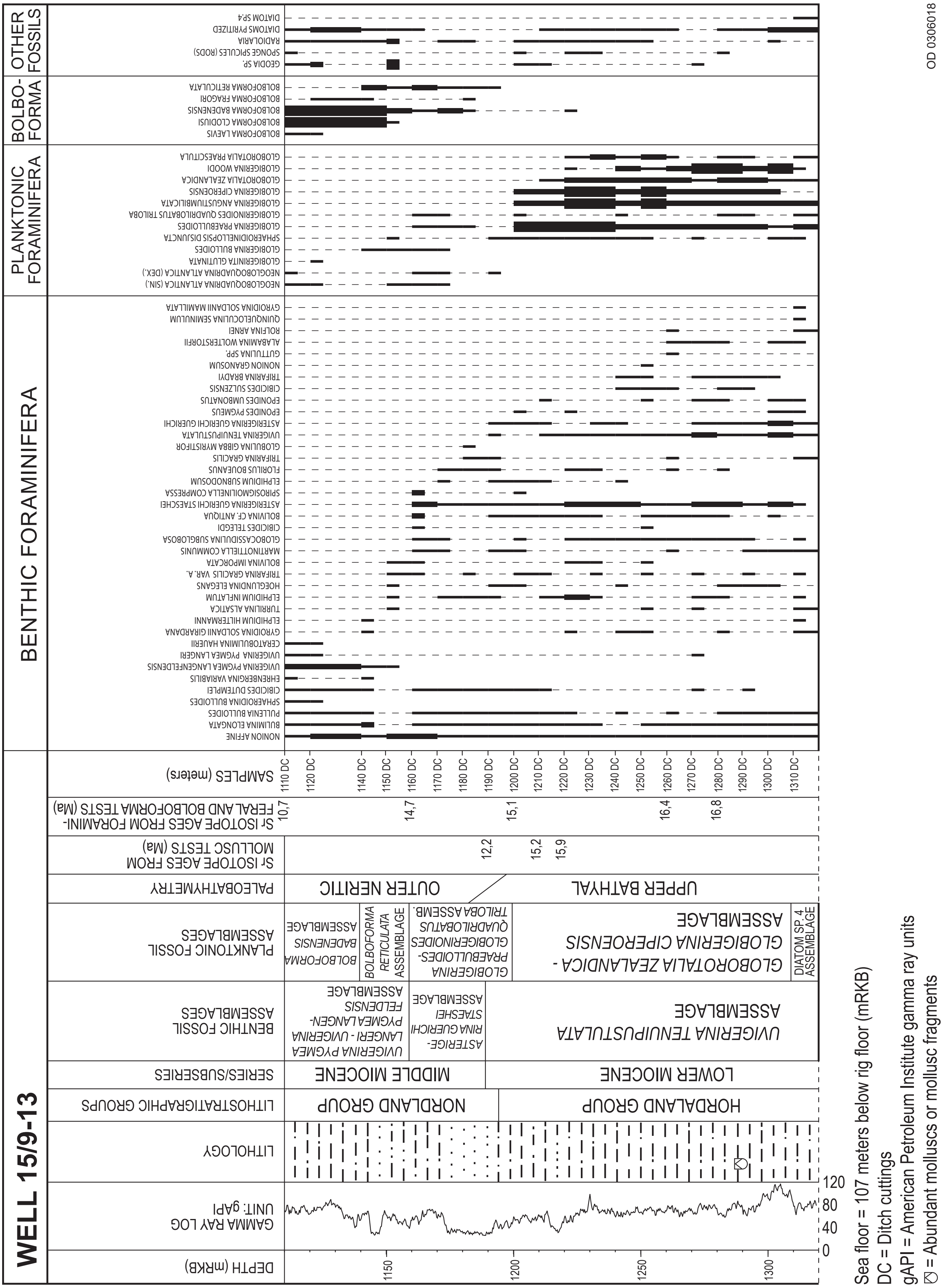


Figure 10a. Range chart of the most important index fossils, fossil assemblages, gamma ray log, lithology, lithostratigraphic units, series/subseries, paleobathymetry, strontium isotope ages and samples investigated in the upper part of well 15/9-13.

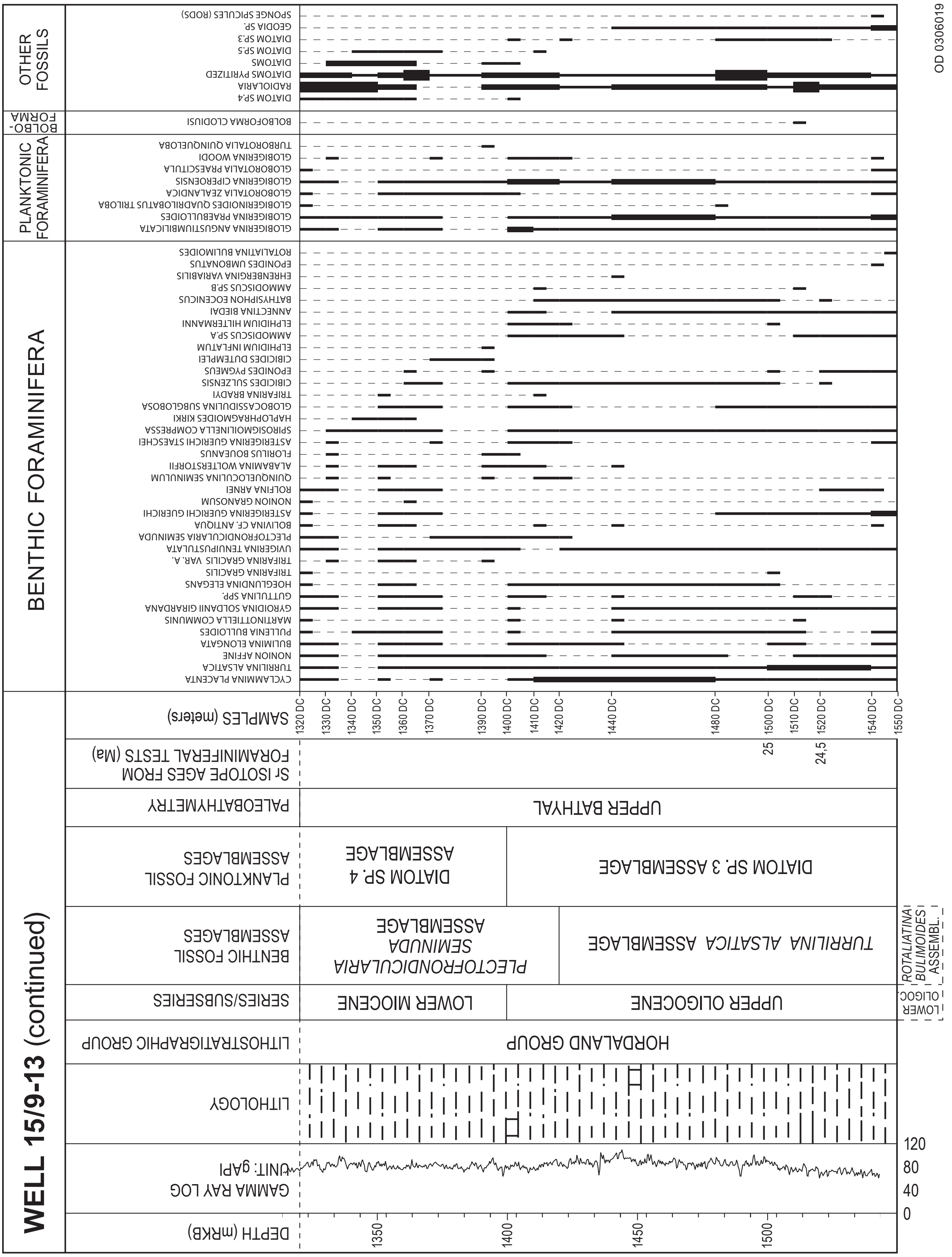


Figure 10b. Range chart of the most important index fossils, fossil assemblages, gamma ray log, lithology, lithostratigraphic unit, series/subseries, paleobathymetry, strontium isotope ages and samples investigated in the lower part of well 15/9-13. For abbreviations and key to symbols, see Fig. 10a.

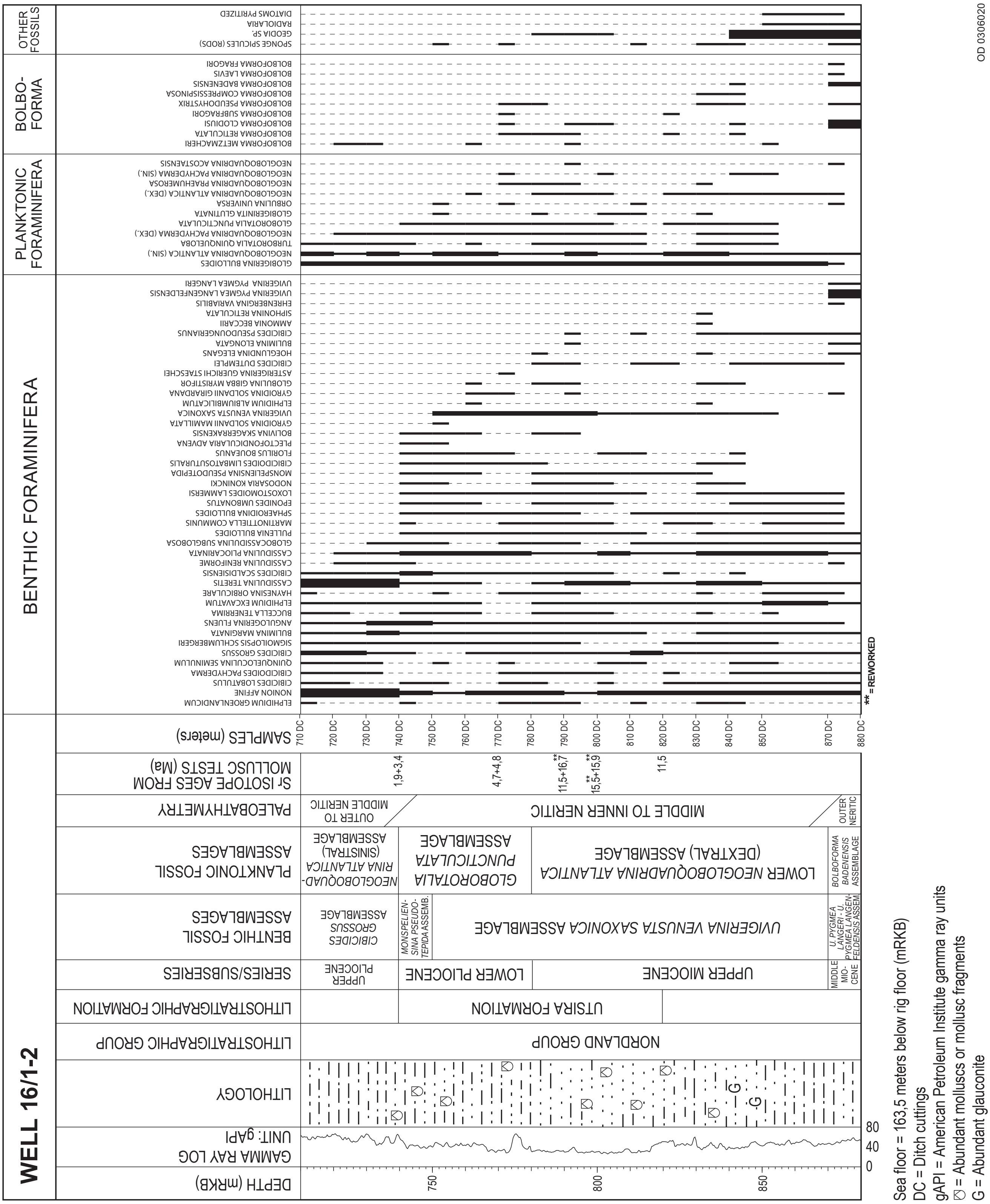


Figure 11. Range chart of the most important index fossils, fossil assemblages, gamma ray log, lithology, lithostratigraphic units, series/subseries, paleobathymetry, strontium isotope ages and samples investigated in well 16/1-2.

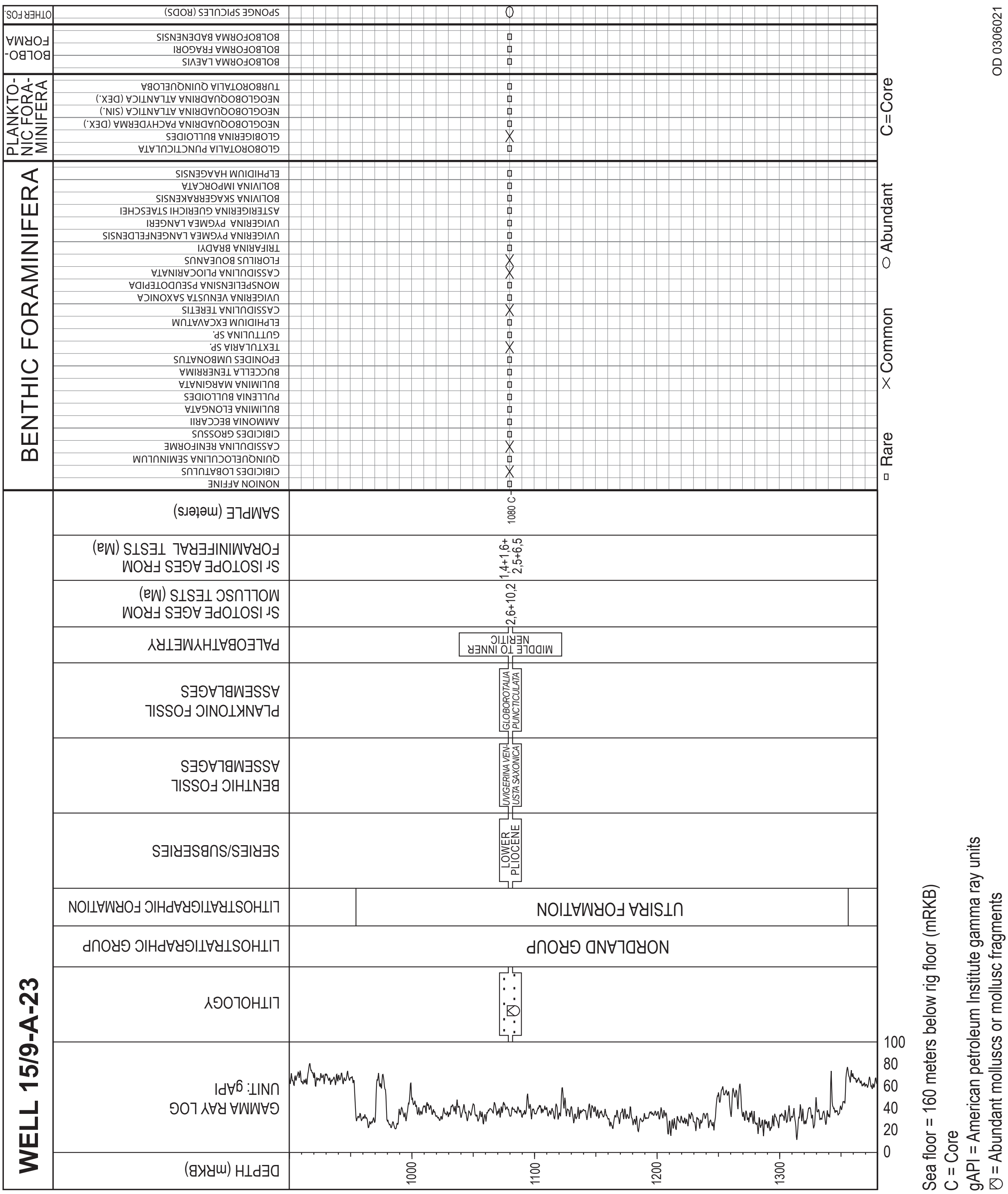
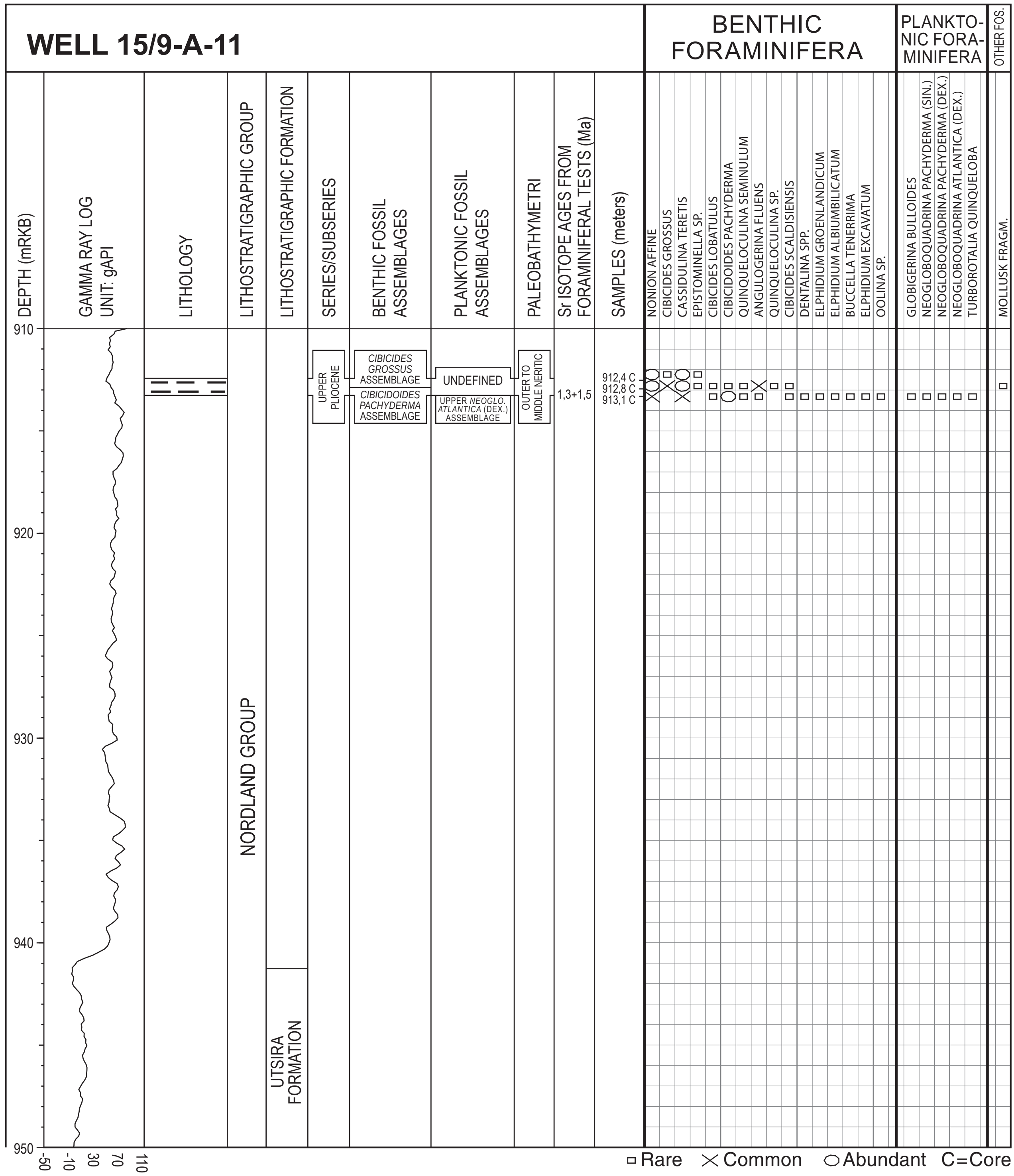


Figure 12. Range chart of the most important index fossils, fossil assemblages, gamma ray log, lithology, lithostratigraphic units, series/subseries, paleobathymetry, strontium isotope ages and samples investigated in well 15/9-A-23.



Sea floor = 160 meters below rig floor (mRKB)
C = Core
gAPI = American Petroleum Institute gamma ray units

OD 0306015

Figure 13. Range chart of the most important index fossils, fossil assemblages, gamma ray log, lithology, lithostratigraphic unit, series/subseries, paleobathymetry, strontium isotope ages and samples investigated in well 15/9-A-11.

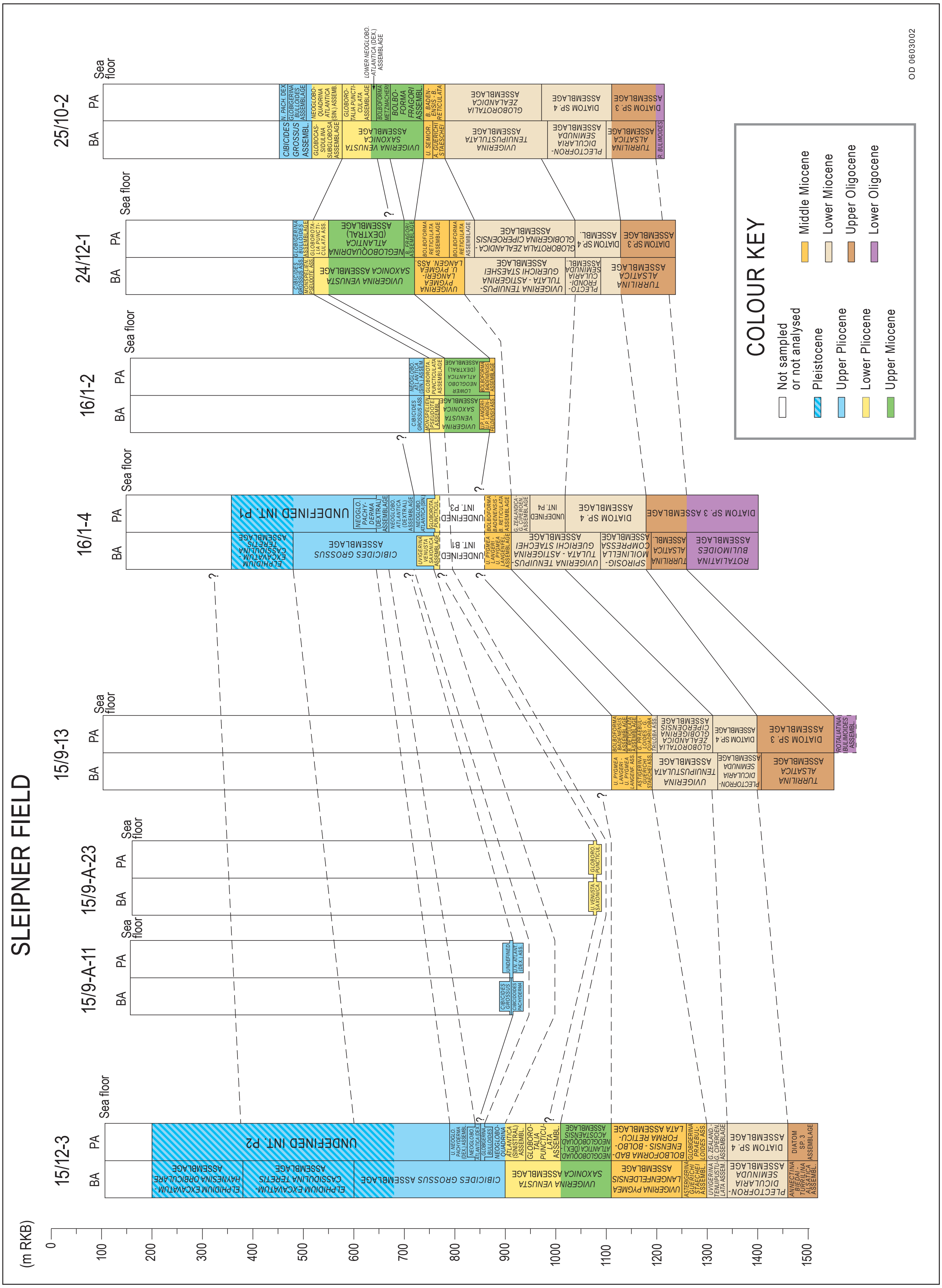


Figure 14. Correlation of fossil assemblages between the wells studied. The vertical axis is in meters below the rig floor. BA = benthic fossil assemblages and PA = Planktonic fossil assemblages.

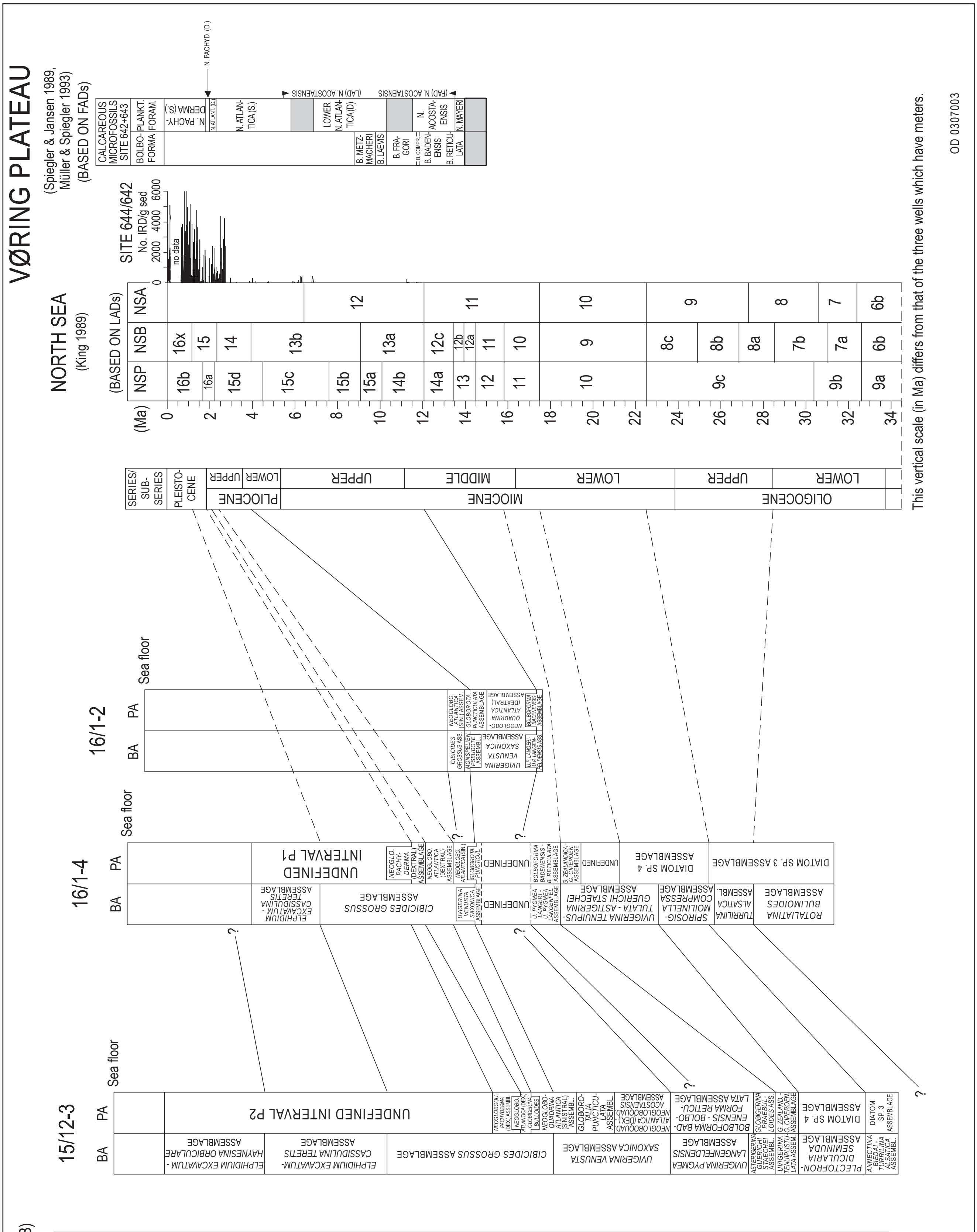


Figure 15. Correlation of fossil assemblages between wells 15/12-3, 16/1-4 and 16/1-2 calibrated to King's (1989) North Sea fossil zonation and to the fossil zonation of the ODP sites 642 and 643 on the Vøring Plateau (Spiegler & Jansen 1989, Müller & Spiegler 1993). The IRD curve is after Jansen & Sjøholm (1991) and Frondval & Jansen (1996). BA = benthic fossil assemblages and PA = Planktonic fossil assemblages.

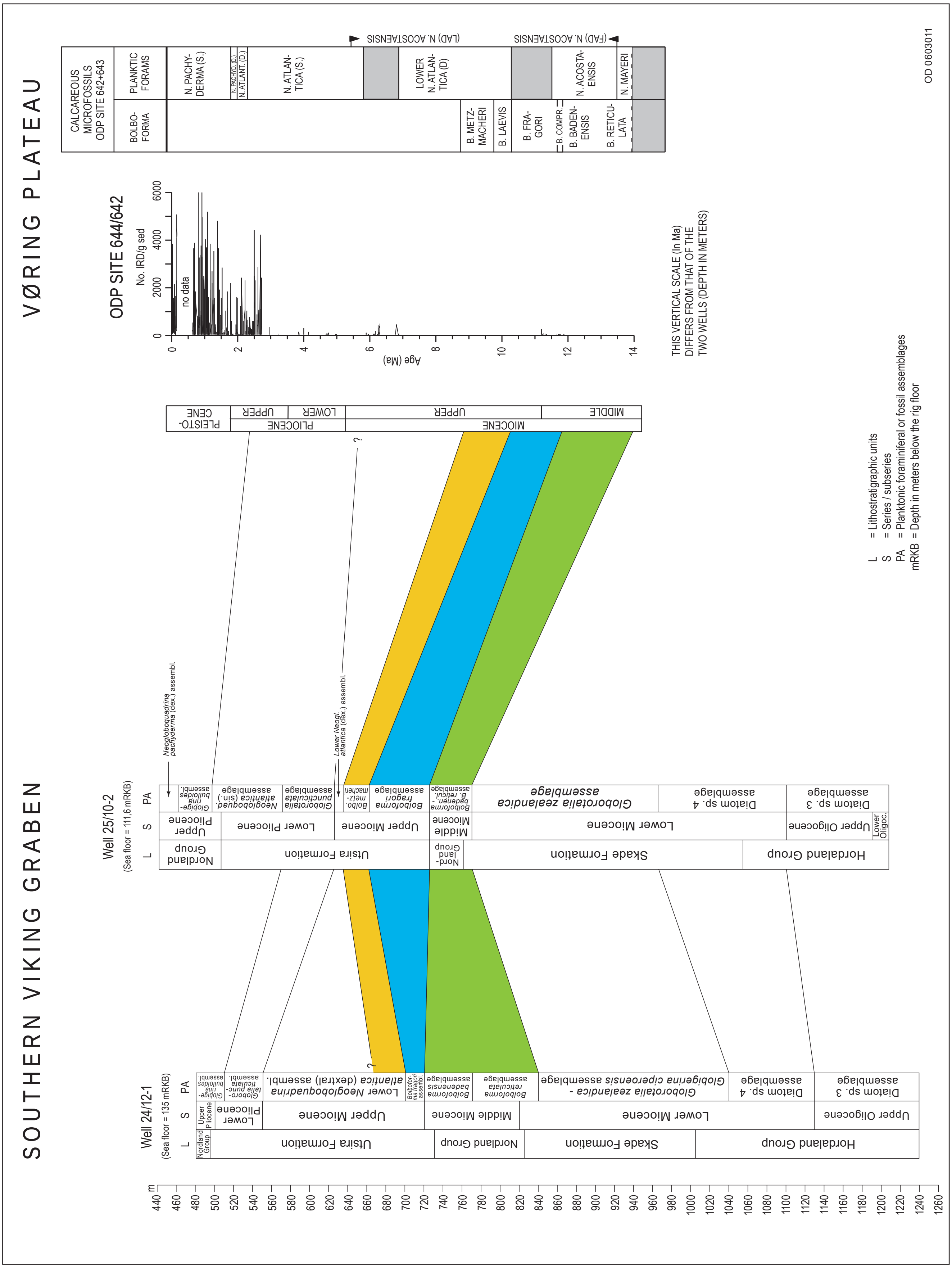


Figure 16. Correlation of planktonic fossil assemblages between wells 24/12-1 and 25/10-2 calibrated to the fossil zonation of the ODP sites 642 and 643 on the Vøring Plateau (Spiegler & Jansen 1989, Müller & Spiegler 1993). The correlation lines for the Bolboforma assemblages are shown in colours. The IRD curve is after Jansen & Sjøholm (1991) and Frondval & Jansen (1996).

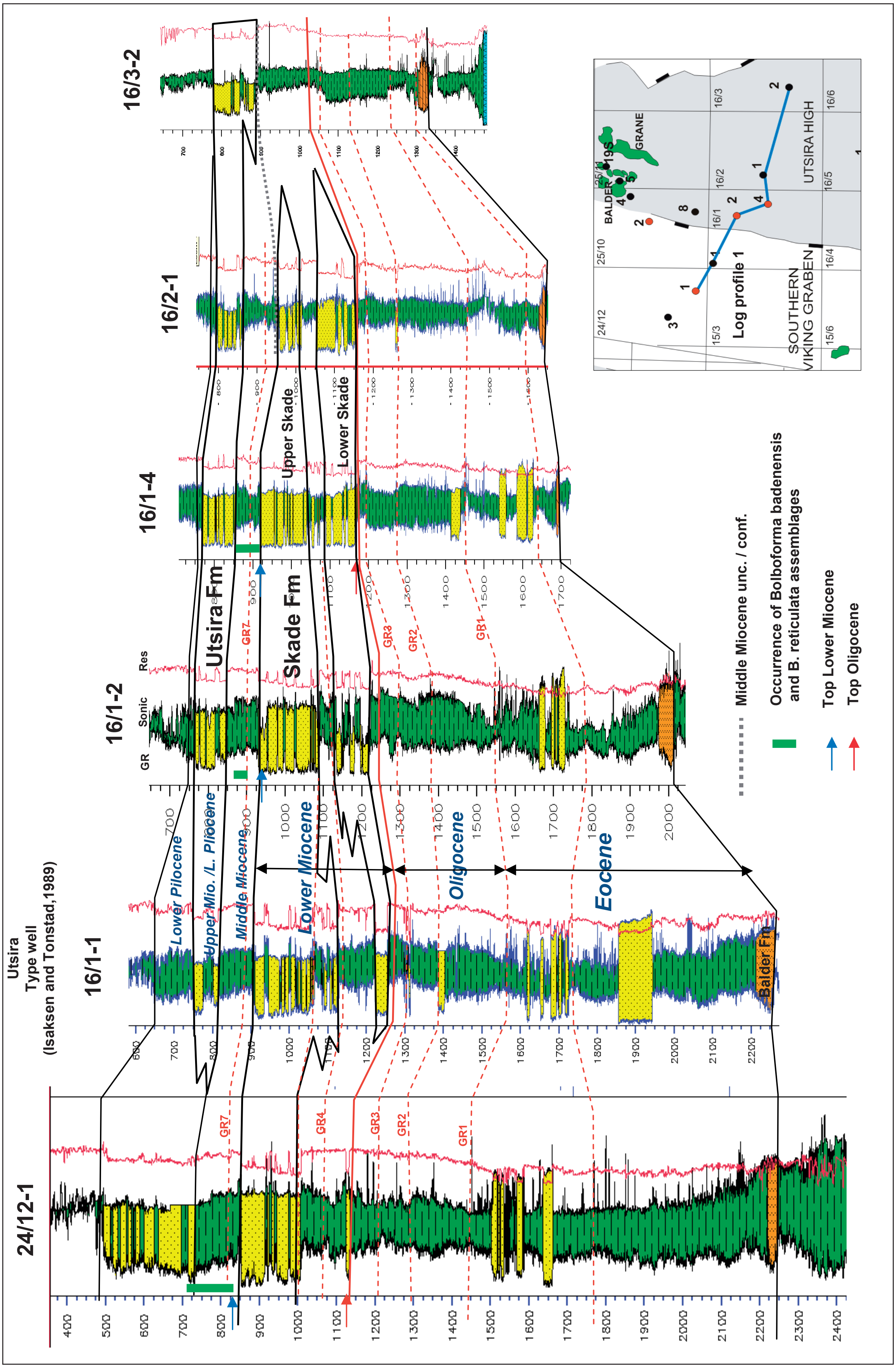


Figure 17. Log correlation (profile 1) between wells along seismic section presented in Figs. 5 and 21a.

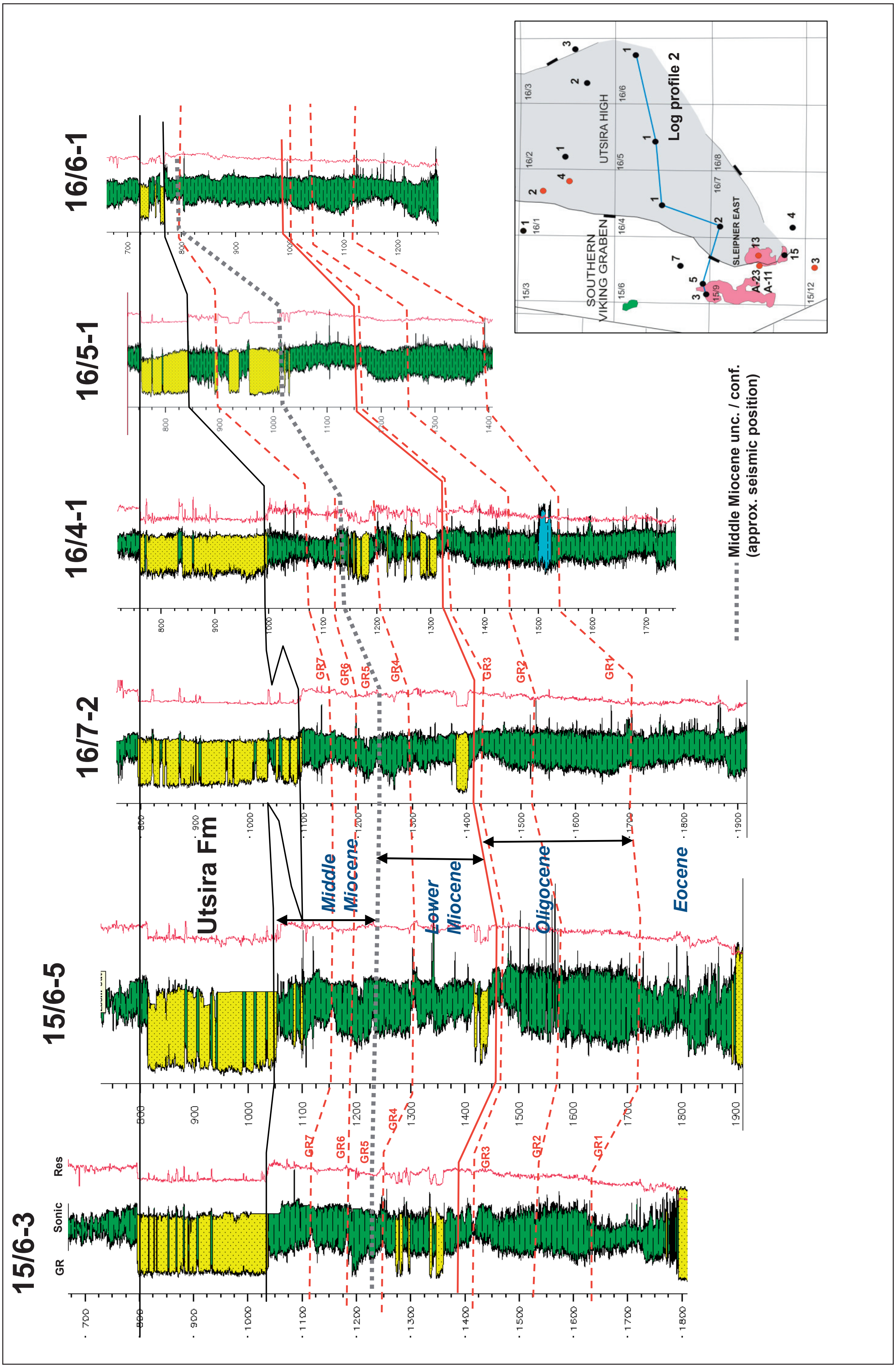


Figure 18. Log correlation (profile 2) between wells along seismic section presented in Fig 4b.

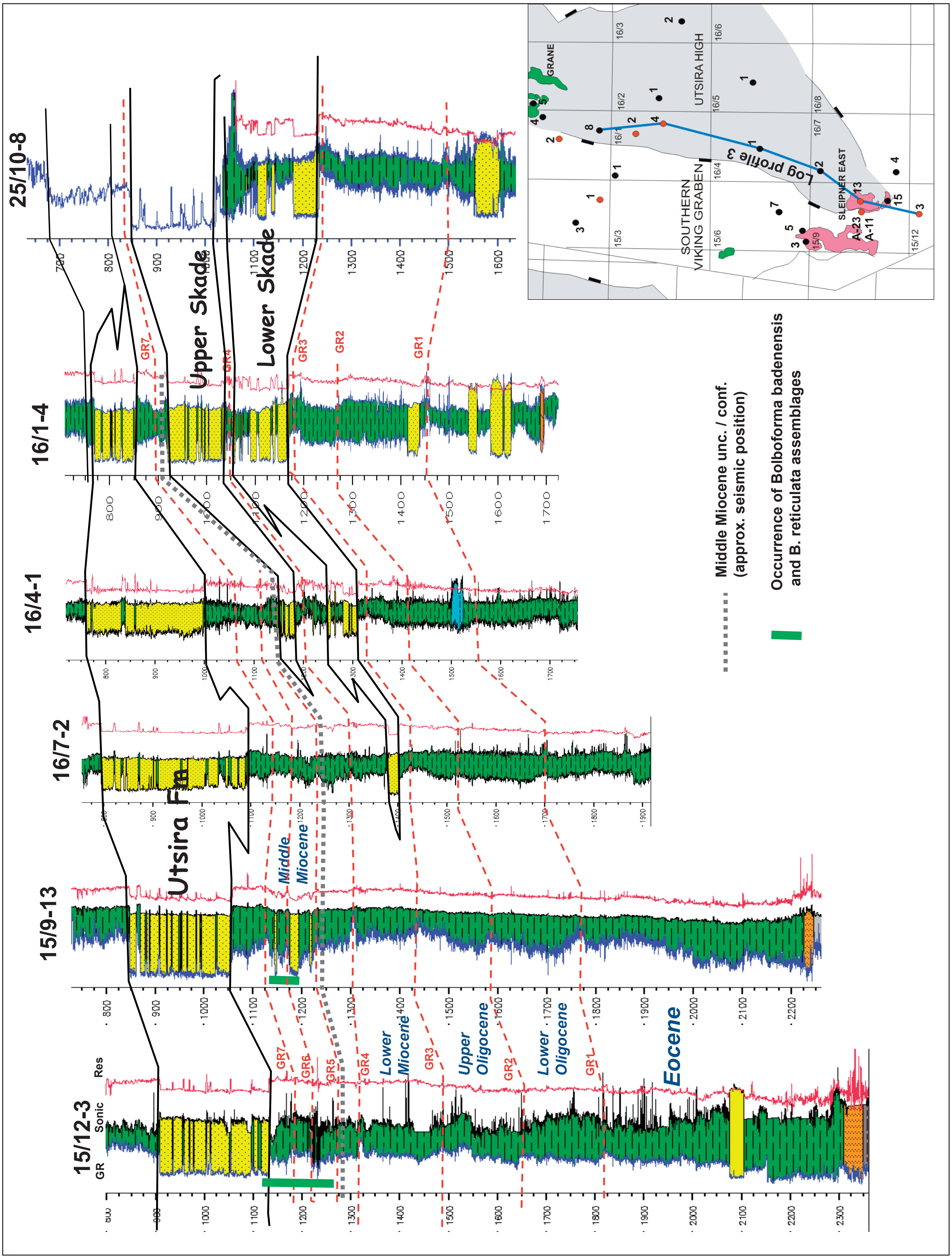


Figure 19. North-south log correlation (profile 3) between wells located along the western margin of Utsira High.

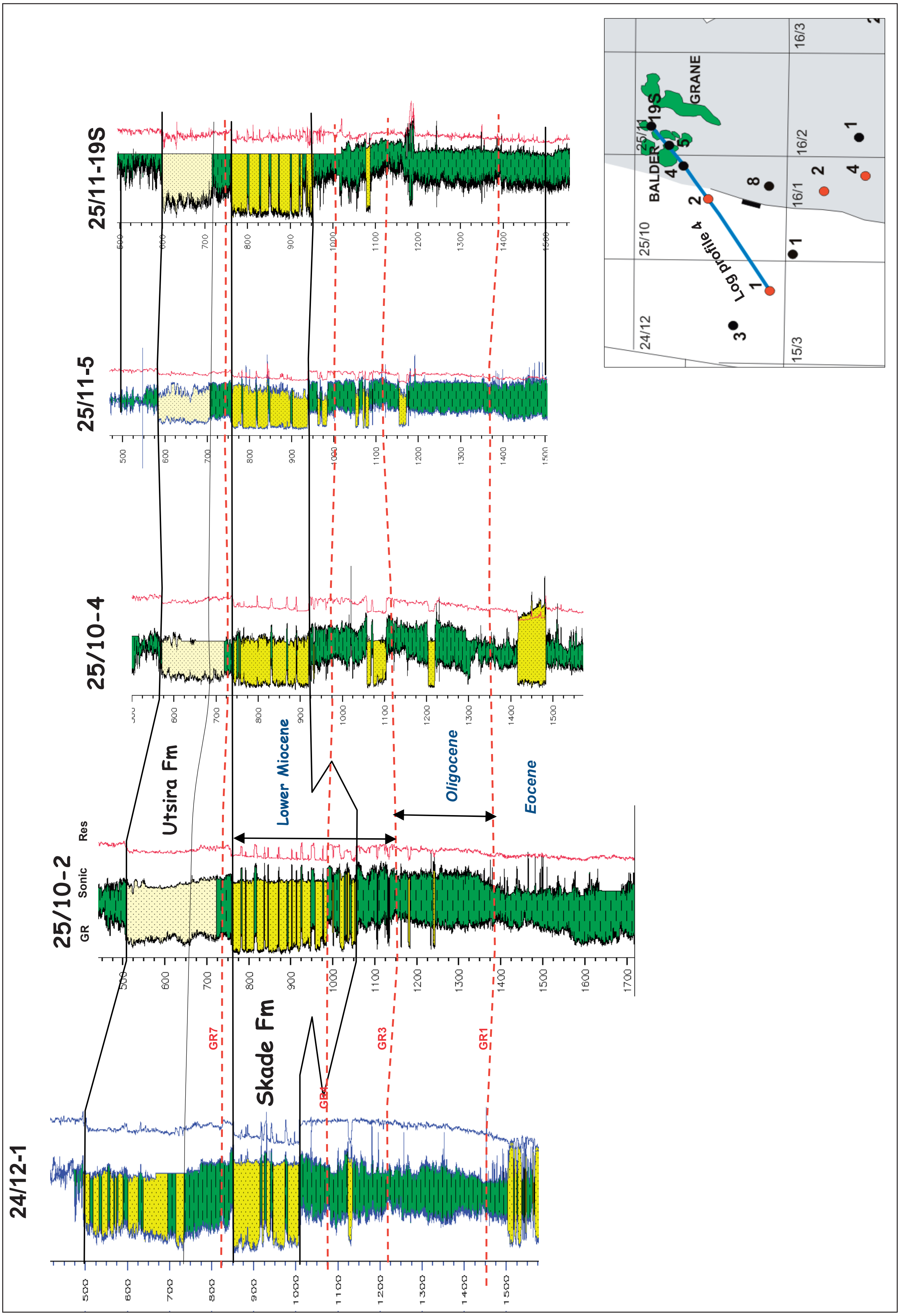


Figure 20. Log correlation (profile 4) between wells along the seismic section presented in Fig. 23.

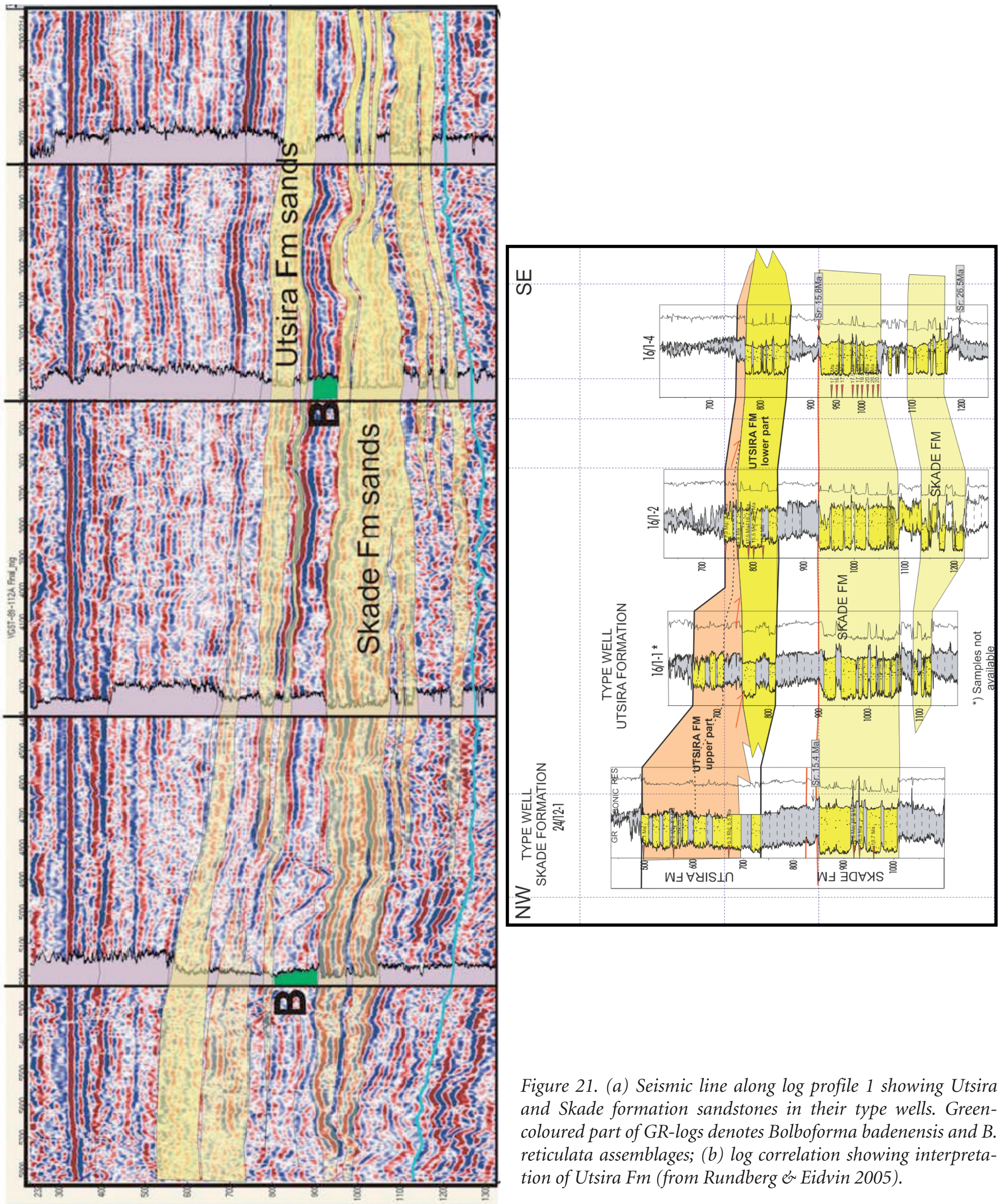


Figure 21. (a) Seismic line along log profile 1 showing Utsira and Skade formation sandstones in their type wells. Green-coloured part of GR-logs denotes Bolboforma badenensis and B. reticulata assemblages; (b) log correlation showing interpretation of Utsira Fm (from Rundberg & Eidvin 2005).

response, which is characteristic for the Utsira sands of the SVG, and also shows the correlation of the mud-prone strata below using the GR-markers (see below). Seismically, along this profile, the Middle Miocene forms an infilling sequence which clearly postdates the mid-Miocene unconformity.

Log profile 3 (Fig. 19) shows the N-S oriented correlation from the studied wells 15/12-3 and 15/9-13 in the Sleipner area to wells 16/1-4 and 25/10-8, the latter close to the Balder Field. This correlation illustrates the southward thickening of the Middle Miocene and the relationship between the Utsira and Skade sands. The composite seismic section shown in Fig. 22 crosses log profile 3 between wells 15/12-3 and 15/9-13. Centrally in the SVG, the mid-Miocene unconformity (or conformity) defines a broad band of moderate-amplitude reflectors.

Log profile 4 (Fig. 20) shows five wells in the northern

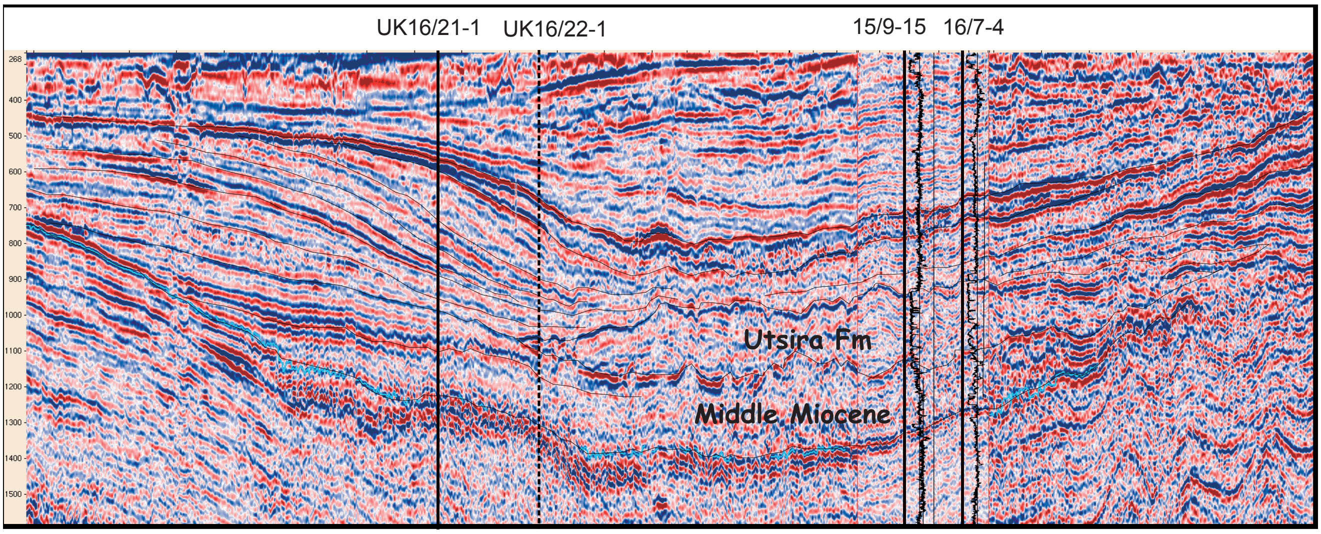


Figure 22. Seismic line across southern Viking Graben through wells 15/9-15 and 16/7-4 (Sleipner area). Location of line shown in Fig.1.

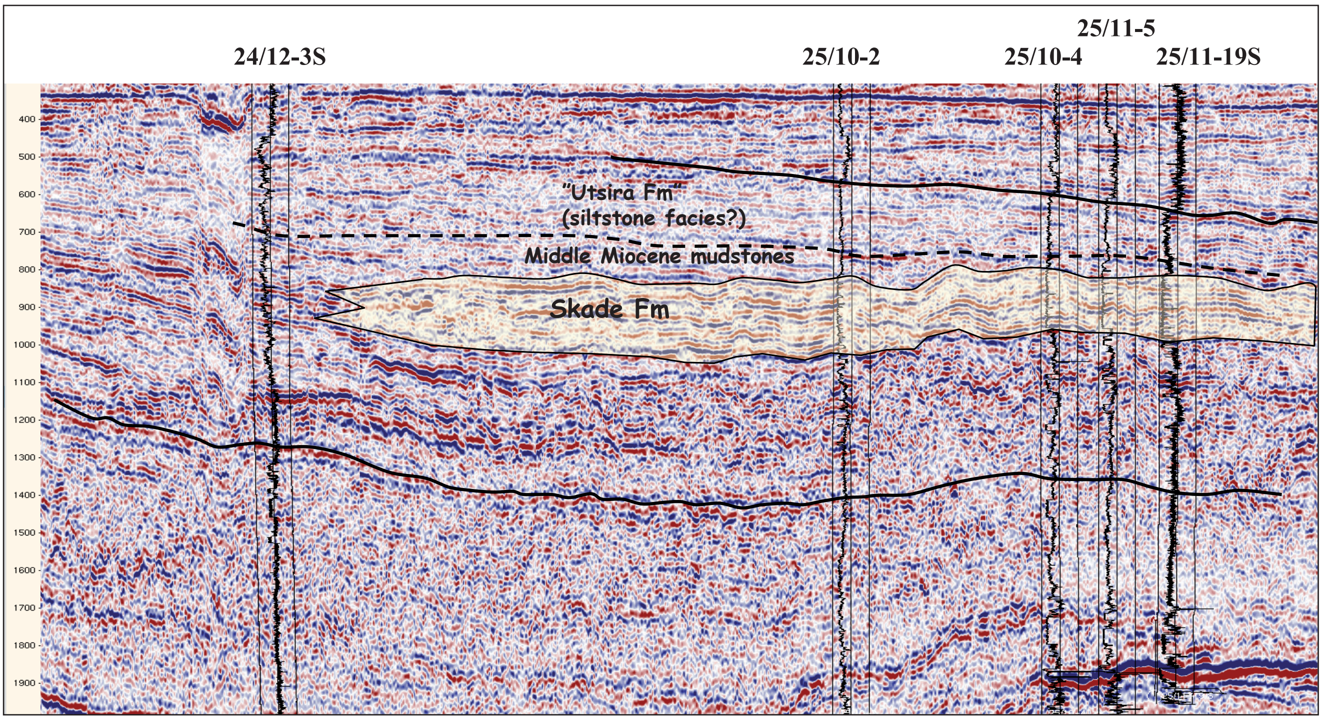


Figure 23. Seismic line across southern Viking Graben through wells along log profile 4 (Fig. 20). Location of line shown in Fig. 1.

part of the study area, from 24/12-1 via key well 25/10-2 to the Balder Field wells 25/10-4 and 25/11-5 and 19S. Noteworthy here, the Utsira Formation displays a slightly decreasing-upward GR-pattern signifying a coarsening-upward trend, whereas a blocky GR-pattern is characteristic of the Skade Formation. Seismically, the Skade Formation yields a semi-continuous, moderate-amplitude reflection pattern, whereas the Utsira sands are difficult to map precisely, with a subtle, low-amplitude reflector defining the top of the formation (Fig. 23).

Gamma Ray markers. In general, the following characteristics can be assigned to the individual GR markers:

GR1 is a high GR interval close to the Eocene-Oligocene boundary. This marker is commonly easily identified in most of the SVG wells. In some wells it is associated with higher velocity. Diagnostically, an upward increase in resistivity values starts at this marker.

GR2 This marker is present only locally within the study area and is best developed in block 15/-9 (e.g. well 15/9-13, Fig. 19). It subdivides the Oligocene into two units with upward increasing GR values. The sediments immediately above GR2 are typically marked by an abrupt fall in gamma response. Biostratigraphic data from well 16/1-4 suggest that it could represent a marker close to the top of the Lower Oligocene.

GR3 is a high gamma radiation peak or interval near the top of the Oligocene. This is commonly the most diagnostic GR peak within the Oligocene-Miocene succession and is readily identified in most wells. It is particularly well defined along profile 2 (Fig. 18).

GR4 is a very diagnostic GR peak within the top of the Lower Miocene succession. Northwards, this marker appears to correlate with the middle part of the Skade Formation (base of upper Skade sands, see Fig. 19). It is particularly well defined in blocks 15/3, 15/6 and 15/9, and is here located about 140-150 m above GR3. In many wells GR4 marks a short interval with abrupt gamma ray increase and thus appears as a distict log marker.

GR5 is a log marker close to the top of the Lower Miocene. It is less diagnostic and is best developed in wells shown in log profile 2 (Fig. 18). Northwards, GR5 correlates to increased gamma radiation at the top of the Skade sands (Fig. 19).

GR6 is a moderately strong GR peak in the basal part of the Middle Miocene succession. This marker is located about 25-30 m above GR5 in the three western wells shown on log profile 2 (Fig. 18). It occurs at the top of a distinct, upward decreasing GR log profile (e.g. 15/6-3, 15/6-5 and 16/7-2, Fig. 18). It is identified in blocks 15/5, 15/6 and 15/9. Northwards, GR6 merges with GR5 as the basal Miocene unit thins towards the margin.

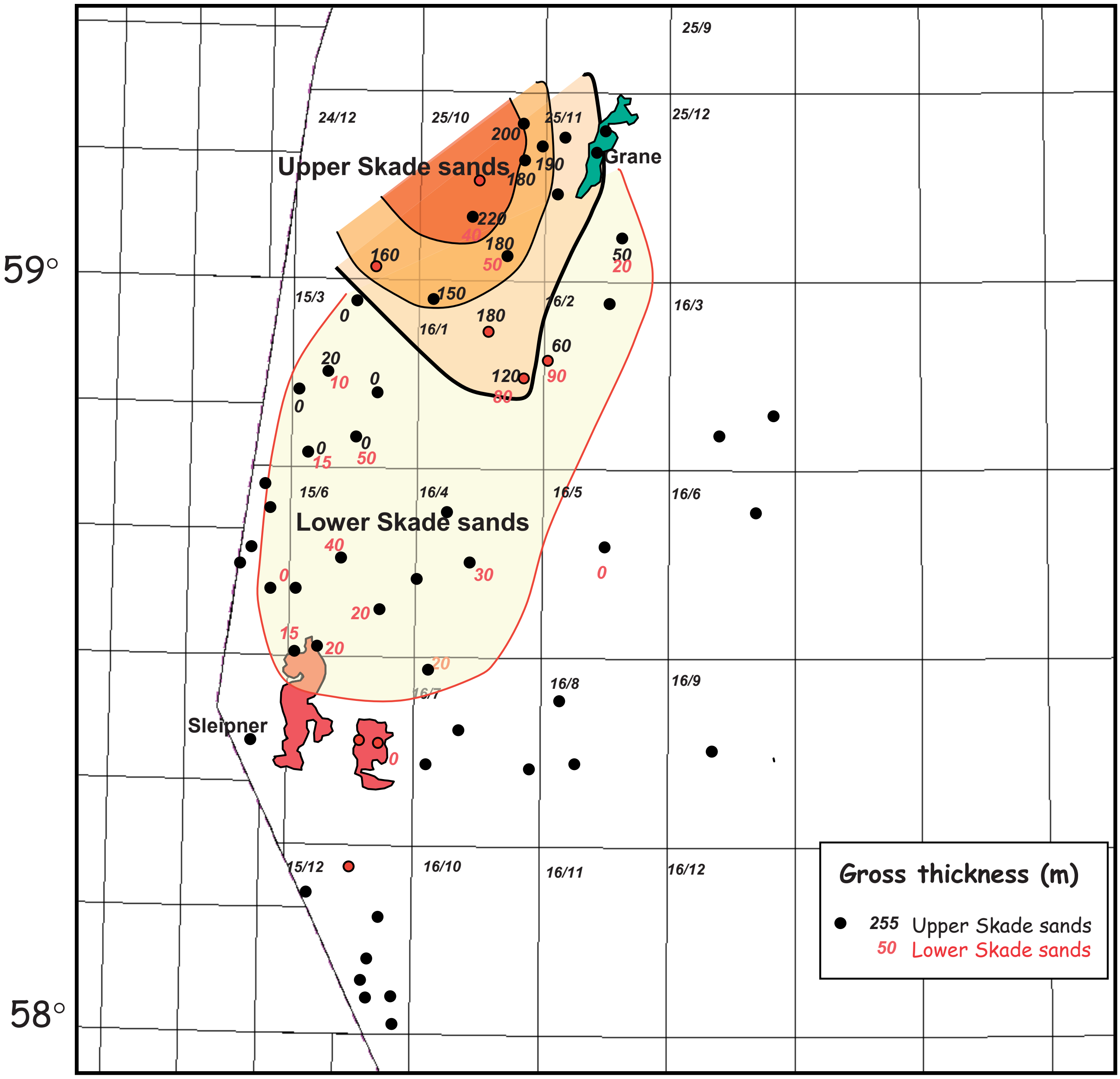


Figure 24. Outline of the Skade Formation. Upper Skade sands deposited in northern part of study area. Lower Skade sands shown in light yellowish colour.

GR7 is a high GR peak within the middle part of the Middle Miocene succession. This is the highest high-radiation GR peak in the basal part of the Neogene and probably marks a maximum transgression surface during Middle Miocene time.

Log correlation and log motifs are further described in the following chapter.

Results – Main lithostratigraphic subdivision

In this chapter, a summary of the biostratigraphic results is presented within a lithostratigraphic framework together with other data such as lithology, log motifs, boundary details and brief comments about the depositional environment. The stratigraphic breakdown below is based on the subdivision presented by Rundberg & Eidvin (2005), in which the Oligocene-Lower Miocene part of the Hordaland Group was subdivided into four units (UH-1 to 4), and the lower part of the Lower Nordland Group was subdivided into two units (LN-1 and LN-2) (Fig. 3). Unit UH-1 is a wedge unit present only along the eastern margin of the northern North Sea and is not further described here.

Hordaland Group, Upper part

Oligocene section (Units UH-2 and UH-3)

1 Distribution and thickness
Oligocene strata are present basinwide across the northern North Sea as illustrated on the seismic section in Fig. 4a. In wells located in the southern Viking Graben and the Utsira High, the Oligocene is made up of a uniform sequence of mudstones. It reaches a maximum thickness of the order of 325-350 m in blocks 15/6 and 15/9 (e.g. wells 15/6-6, 15/9-11, 13), and thins gradually northwards to about 250 m in blocks 16/1 and 16/2.

2 Lithology
The Oligocene of the southern Viking Graben consists predominantly of brownish claystones and mudstones. Sandstones are rare but have been encountered in some wells in the northern part of the study area in blocks 25/10 and 25/11 (unnamed sand in Figs. 3 and 27).

3 Log correlation and log motifs
In general, the Oligocene displays a very characteristic, slightly bell-shaped GR log profile bounded by the highly radioactive GR1-peak at the base and approximately by the GR3-peak at the top. Such a log profile is particularly diagnostic in wells within the southern Viking Graben (Figs. 18, 19). Eastwards, on the Utsira High, the log profile changes to a more regular, stable pattern, with a lower part displaying upward decreasing radioactivity values.

The bounding GR peaks, it is suggested here, represent distinct periods of condensation. GR3 at the top commonly defines a broad zone of high gamma radiation (e.g. well 16/1-4, Fig. 19). Locally, it may be possible to distinguish additional GR maxima within the Oligocene section, for example GR2 is developed as a distinct marker in some wells to the east of the southern Viking Graben (Figs. 18, 19). Biostratigraphic data from well 16/1-4 suggest that GR2 is close to the top of the Lower Oligocene.

4 Chronostratigraphy/Biostratigraphy
The chronostratigraphy of the Oligocene unit is obtained by analyses and correlation of benthic foraminifera, diatoms and strontium isotopes. The fossil assemblages in well 16/1-4 include the benthic foraminiferal *Rotaliatina bullimoides* assemblage in the Lower Oligocene and the *Turrilina alsatica* assemblage and the lowermost part of *Spirosigmoilinella compressa* assemblage in the Upper Oligocene. The planktonic Diatom sp. 3 assemblage occurs throughout the Oligocene section (Fig. 6c). In well 24/12-1, Upper Oligocene deposits include the lower part of the benthic foraminiferal *Turrilina alsatica* assemblage and the planktonic Diatom sp. 3 assemblage (Fig. 7b). In well 25/10-2, the benthic foraminiferal *Rotaliatina bulimoides* assemblage occurs in the Lower Oligocene, and the *Turrilina alsatica* assemblage in the Upper Oligocene. The planktonic Diatom sp. 3 assemblage occurs throughout the whole Oligocene section (Fig. 8c). In well 15/12-3, Upper Oligocene sediments include the benthic foraminiferal *Annectina biedai – Turrilina alsatica* assemblage and the planktonic Diatom sp. 3 assemblage (Fig. 9b). In well 15/9-13, the Lower Oligocene (lowermost investigated sample) includes the benthic foraminiferal *Rotaliatina bullimoides* assemblage. The Upper Oligocene (main part) includes the benthic foraminiferal *Turrilina alsatica* assemblage and the lowermost part of the *Plectofrondicularia seminuda* assemblage. The planktonic Diatom sp. 3 assemblage occurs through the entire Oligocene section (Fig. 10b).

5 Lower boundary
The Eocene-Oligocene boundary has not been investigated biostratigraphically. This boundary, however, can in many cases be quite precisely identified from wireline logs, by a very diagnostic upward increase in resistivity levels, particularly well illustrated in wells located to the north (Figs. 19, 20). Here, the increase in resistivity corresponds closely to the GR1 log marker. In wells located on the central part of the Utsira High, where the Eocene section is thin, the boundary is associated with an abrupt upward decrease in GR-values, as illustrated in wells 16/1-4, 16/2-1 and 16/3-2 (Fig. 17).

Lithologically, the boundary is marked by a change from extremely fine-grained, greenish or olive grey Eocene claystones to brownish, distinctly coarser Oligocene claystones (Rundberg 1989). Seismically, the boundary is commonly represented by a low-amplitude, discontinuous reflector (Fig. 23) or by a subtle change in reflection pattern.

6 Upper boundary

The top of the Oligocene is based on the last appearance datum (LAD) or first downhole occurrence of Diatom sp. 3. According to King (1989) the LAD of this species is close to (slightly younger than) the Oligocene-Miocene boundary in the North Sea area. In well completion logs the top Oligocene is difficult to correlate from well to well in the investigated area. This is probably due to the fact that different biostratigraphic workers and consultants use different index fossils for the Oligocene/Miocene boundary and also due to severe reworking of fossil tests.

Our biostratigraphical investigations show that the Oligocene-Miocene boundary can be placed just above the high-radioactive GR3 marker. For example, in well 16/1-4 (Figs. 6c, 17), the uppermost part of the Diatom sp. 3 assemblage is recorded just below the Skade sandstone at 1178.5 m (SWC). Similarly, in wells 15/9-13 and 15/12-3 to the south, the top of the Diatom sp. 3 assemblage has also been recorded very close to the GR3 marker, at 1420 and 1460 m, respectively (Figs. 10b and 9b). In one well (24/12-1), however, the LAD of Diatom sp. 3 is recorded about 80 m above the GR3 marker (Figs. 7b, 17).

In many of the southern Viking Graben wells, the boundary is overlain by sandstones (Figs. 17 through 20). Seismically, the boundary is difficult to trace but locally it is associated with a moderate-amplitude, semi-continuous reflector.

7 Environment of deposition
The fossil assemblages indicate an upper bathyal environment during deposition of the Oligocene unit (see section 8.5 and Figs. 6-10).

Lower Miocene section, incl. Skade Formation (Unit UH-4)
The Lower Miocene section comprises the uppermost part of the Hordaland Group and roughly includes sediments bounded by GR3 at the base and the mid-Miocene unconformity or its correlative conformity at the top. The latter is found to be close to the GR5 marker.

1 Distribution and thickness
The Lower Miocene section conformably overlies Oligocene strata in most of the southern Viking Graben area. It is present basinwide as illustrated in regional transects (Figs. 4 and 5). In the study area, the Lower Miocene is thickest to the north of 58°45'N within the depocentre of the Skade sandstones. It reaches a thickness of the order of 350-400 m in block 25/10, and thins in a southward direction to about 150-175 m in block 15/12, in areas where the Skade sandstones are absent. The distribution of the Skade sandstones is shown in Fig. 24.

2 Lithology
The lower Miocene section of the southern Viking Graben consists of brownish mudstones and of sandstones belonging to the Skade Formation. The sandstones commonly make up sandbodies up to 50 m in thickness. The sands are quartzose, generally fine- to medium-grained, with relatively high amounts of bioclasts in the upper part. The bioclasts display a light brownish colouration, which distinguish these from the whitish bioclasts of the Utsira Formation above. Glauconites are commonly subordinate but have locally been recorded in fair amounts.

3 Log correlation and log motifs
In mudstone-dominated sections of the southern Viking Graben, the Lower Miocene (between GR markers 3 and 5) is characterised by overall upward decreasing GR-values. Locally, the GR-pattern is more stable within the middle part of the section. Approximately 150 m above GR3, a distinct high-radioactive marker (GR4) can be identified. This GR-marker, which is very conspicuous in some wells (e.g. 15/9-13 and 15/12-3, Fig. 19), is identified in most of the wells within the mudstone-dominated part of the southern Viking Graben, and could represent a lithologic marker-bed within the Lower Miocene. In the southernmost wells (15/12-3 and 15/9-13, Fig. 19), the interval between GR3 and GR4 displays a generally stable or slightly upward decreasing GR log profile. Northwards, this interval becomes more serrated (e.g. 15/6-3, Fig. 18), probably in response to the sandier character. In a northward direction, the GR markers become difficult to identify, as sandstones dominate the lithology.

4 Chronostratigraphy/Biostratigraphy
The chronostratigraphy of the Lower Miocene section is obtained by analyses and by the correlation of benthic and planktonic foraminifera, diatoms and strontium isotopes. The fossil assemblages in well 16/1-4 include the upper (main part) of the benthic foraminiferal *Spirosigmoilinella compressa* assemblage and *Uvigerina tenuipustulata – Astigerina guerichi staeshei* assemblage. Planktonic assemblages include the Diatom sp. 4 assemblage and the *Globorotalia zealandica – Globigerina ciperoencis* assemblage (Figs. 6b, c). In well 24/12-1, the Lower Miocene deposits include the uppermost part of the benthic foraminiferal *Turrilina alsatica* assemblage, the *Plectofronicularia seminuda* assemblage and the *Uvigerina tenuipustulata – Astigerina guerichi staeshei* assemblage. Planktonic assemblages include the Diatom sp. 4 assemblage, the *Globorotalia zealandica – Globigerina ciperoensis* assemblage and the lowermost part of the *Bolboforma reticulata* assemblage (Fig. 7b). In well 25/10-2, the Lower Miocene includes the benthic foraminiferal *Plectofrondicularia seminuda* assemblage and the *Uvigerina tenuipustulata* assemblage. Planktonic assemblages include the Diatom sp. 4 assemblage and the *Globorotalia zealandica* assemblage (Figs. 8b, c). In well 15/12-3, Lower Miocene sediments include the benthic foraminiferal *Plectofrondicularia seminuda* assemblage and the *Uvigerina tenuipustulata* assemblage. Planktonic assemblages include Diatom sp. 4 assemblage and the *Globorotalia zealandica – Globigerina ciperoencis* assemblage (Fig. 9b). In well 15/9-13, the Lower Miocene includes the upper (main part) of the bentic foraminiferal *Plectofrondicu-*

laria seminuda assemblage and the *Uvigerina tenuipustulata* assemblage. Planktonic assemblages include Diatom sp. 4 assemblage, the *Globorotalia zealandica – Globigerina ciperoencis* assemblage and the lowermost part of the *Globigerina praebulloides – Globigerinoides quadrilobatus triloba* assemblage (Figs. 10a, b).

5 Lower boundary
The lower boundary is consistent with the top of the Oligocene (see above).

6 Upper boundary
The upper boundary of the Lower Miocene is consistent with the boundary between the Hordaland and Nordland groups. This boundary is developed as a distinct unconformity in the northern North Sea and towards the margins of the basin (Rundberg & Eidvin 2005). In the northern part of the study area, the top of the Lower Miocene section has been placed just above the Skade Formation sandstones (Figs. 17, 18, 19). Biostratigraphically, it is mainly based on the LAD of *Uvigerina tenuipustulata.* In well 15/9-13, the LAD of this species is recorded at 1190 m, just below the GR5 marker. Seismically, this is slightly above the high-amplitude reflector that can be associated with the mid-Miocene reflector (Figs. 4b, 22). In well 15/12-3, the LAD of *U. tenuipustulata* is at 1300 m, which is 20 m above GR4 and slightly below the seismic reflector. According to our log correlation shown in Fig. 19, there appears to be a slight difference between the biostratigraphic tops in wells 15/12-3 and 15/9-13 (biostratigraphic data being robust in both wells). For these wells, located in a graben position, we use the seismic reflector as guideline, and place the top of the Lower Miocene close to the GR5 gamma ray peak (see Fig. 19). The approximate position of this reflector is shown on the log correlation profiles (Figs. 17, 18, 19).

7 Environment of deposition
The fossil assemblages indicate an upper bathyal environment during deposition of the Lower Miocene unit (see section 8.6 and Figs. 6-10). In the study area, the Lower Miocene represents strata that are deposited within an open-marine setting. The Skade Formation sandstones are thought to represent gravity-flow deposits.

Nordland Group

Middle Miocene section (unit LN-1).
The Middle Miocene section comprises the lowermost part of the Nordland Group.

1 Distribution and thickness
The Middle Miocene section is present mainly in the central part of the basin. To the south of about 58°45'N, it forms distinct infill geometry along the subsiding southern Viking Graben (see Fig. 4). It is overlain by Utsira Formation sandstones in much of the southern Viking Graben, except in the northern part of the study area (blocks 25/10 and 11), where it is overlain by siltstones and fine-grained sands. Maximum thickness in excess of 200 m is recorded in the southern part of the study area (well 15/9-13). It thins rapidly to zero thickness eastwards and westwards as seen in the seismic sections (Figs. 4b, 22).

2 Lithology
The Middle Miocene is dominated by marine mudstones. Thin sands are present in some wells (e.g. well 15/9-13), and thicker, blocky sands have been penetrated in one well (16/5-1, Fig. 18). The mudstones display a brownish colouration and may be difficult to distinguish from underlying lithologies. The coarser mudstones are generally glauconitic.

3 Log correlation and log motifs
To the north, along log profile 1 (Fig. 17), the Middle Miocene section displays a distinct upward decreasing GR log pattern. Maximum gamma radiation, considered to be GR7, occurs in the basal part of the section, a few meters above the top of the Skade sandstones. To the south (log profiles 2 and 3, Figs. 18 and 19), the Middle Miocene has expanded in wells located within the subsiding Viking Graben. It can here broadly be separated into an upper log unit displaying generally upward decreasing GR values (above GR7), a middle unit displaying generally stable or slight upward increasing GR values (above GR6), and a basal unit displaying distinct upward decreasing GR values (above GR5).

4 Chronostratigraphy/Biostratigraphy
The chronostratigraphy of the Middle Miocene section is obtained by analyses and correlation of benthic and planktonic foraminifera, *Bolboforma* and strontium isotopes. The fossil assemblages in well 16/1-4 include the benthic foraminiferal *Uvigerina pygmea langeri – Uvigerina pygmea langenfeldensis* assemblage and the planktonic *Bolboforma badenensis – Bolboforma reticulata* assemblage (Fig. 6b). In well 16/1-2, Middle Miocene deposits include the benthic foraminiferal *Uvigerina pygmea langeri – Uvigerina pygmea langenfeldensis* assemblage and the planktonic *Bolboforma badenensis* assemblage (Fig. 11). In well 24/12-1, Middle Miocene sediments include the benthic foraminiferal *Uvigerina pygmea langeri – Uvigerina pygmea langenfeldensis* assemblage. Planktonic assemblages include the *Bolboforma reticulata* assemblage and the *Bolboforma badenensis* assemblage (Fig. 7a). In well 25/10-2, Middle Miocene deposits include the benthic foraminiferal *Astigerina guerichi staeschei* assemblage, the *Uvigerina semiornata saprophila* assemblage and the planktonic *Bolboforma badenensis – Bolboforma reticulata* assemblage (Fig. 8b). In well 15/12-3, the Middle Miocene includes the benthic foraminiferal *Asterigerina guerichi staeshei* assemblage and the *Uvigerina pygmea langenfeldensis* assemblage. Planktonic assemblages include the *Globigerina praebulloides* assemblage and the *Bolboforma badenensis – Bolboforma reticulate* assemblage (Fig. 9b). In well 15/9-13, the Middle Miocene includes the benthic foraminiferal *Astigerina guerichi staeshei* assemblage and the *Uvigerina pygmea*

langeri – Uvigerina pygmea langenfeldensis assemblage. Planktonic assemblages include the upper main part of the *Globigerina praebulloides – Globigerinoides quadrilobatus triloba* assemblage, the *Bolboforma reticulata* assemblage and the *Bolboforma badenensis* assemblage (Fig. 10a).

5 Lower boundary
The lower boundary is consistent with the top of the Hordaland Group.

6 Upper boundary
The top of the Middle Miocene is mainly taken at the LAD of *Bolboforma badenensis*. In wells 24/12-1 and 15/12-3, however, the top of the Middle Miocene unit is slightly below the LAD of *Bolboforma badenensis.* In many of the southern Viking Graben wells the top of the Middle Miocene is close to the base of the sandy Utsira Formation, e.g wells 16/1-2, 16/1-4, 24/12-1 (Fig. 17) and 15/12-3, 15/9-13 (Fig. 19).

7 Environment of deposition
The fossil assemblages indicate an outer neritic environment during deposition of the Middle Miocene (see section 8.6 and Figs. 6-11). Water depths were probably greater in the southern part of the study area than to the north, as interpreted from seismic data. The overall upward decreasing GR pattern most likely denotes that a shallowing of the basin took place during latest Middle Miocene.

Utsira Formation - Upper Miocene and Lower Pliocene section (unit LN-2)
The Upper Miocene to Lower Pliocene section in the study area comprises sandstones of the Utsira Formation and lateral equivalent siltstones.

1 Distribution and thickness
The outline of the Utsira Formation sandstones in southern Viking Graben is shown in Fig. 25. It makes up a huge sandy deposit between 58° and 59°N with a thickness in excess of 200 m recorded in blocks 15/6 and 15/9 and a maximum of 300 m in well 15/6-8A. The Utsira sands pinch rapidly out in eastward and westward direction as can be seen from seismic data (Figs. 4, 22). In a northward direction, in blocks 25/10 and 25/11, they pass into siltstones and fine-grained sands.

2 Lithology
The Utsira Formation sandstones are dominantly medium-grained. The sandstones are mainly quartzose, but glauconite is also common. Parts of the Utsira Formation are very rich in mollusc and mollusc fragments. In well 25/10-2, within the central Utsira member (proposed term, see section 8.3), the unit comprises dominantly fine-grained sands and siltstones.

3 Log correlation and log motifs
The Utsira Formation typically forms a very diagnostic blocky GR-log pattern (Figs. 18, 19), separated by thin intervals of higher radioactivity reflecting finer-grained lithologies. To the west, in blocks 15/3 and 15/5, a more serrated GR pattern is observed in some wells. Within the central Utsira member a slight coarsening-upward profile is observed (Fig. 20).

4 Chronostratigraphy/Biostratigraphy
In most wells there is a close correspondence between the Utsira Formation and the sediment column dated to Late Miocene to Early Pliocene. The chronostratigraphy is obtained by analyses and correlation of benthic and planktonic foraminifera, *Bolboforma* and strontium isotopes. Samples from the Utsira Formation in well 16/1-4 are not available, but in the nearby well 16/1-2, the unit includes the upper main part of the benthic foraminiferal *Uvigerina venusta saxonica* assemblage and the *Monspeliensina pseudotepida* assemblage. Planktonic assemblages include the upper main part of Lower *Neogloboquadrina atlantica* (dextral) assemblage and *Globorotalia puncticulata* assemblage (Fig. 11). In well 24/12, the Utsira Formation includes the uppermost part of the benthic foraminiferal *Uvigerina pygmea langeri – Uvigerina pygmea langenfeldensis* assemblage, the *Uvigerina venusta saxonica* assemblage and the *Monspeliensina pseudotepida* assemblage. Planktonic assemblages include the uppermost part of the *Bolboforma badenensis* assemblage, the *Bolboforma fragori* assemblage, the Lower *Neogloboquadrina atlantica* (dextral) assemblage, the *Globorotalia puncticulata* assemblage and the lowermost part of the *Globigerina bulloides* assemblage (Fig. 7a). In well 25/10-2, the Utsira Formation includes the benthic foraminiferal *Uvigerina venusta saxonica* assemblage and the *Globocassidulina subglobosa* assemblage. Planktonic assemblages include the *Bolboforma fragori* assemblage, the *Bolboforma metzmacheri* assemblage, the Lower *Neogloboquadrina atlantica* (dextral) assemblage, the *Globorotalia puncticulata* assemblage and the lower (main part) of the *Neogloboquadrina atlantica* (sinistral) assemblage (Fig. 8a). In well 15/12-3, the unit includes the uppermost part of the benthic foraminiferal *Uvigerina pygmea langenfeldensis* assemblage and the *Uvigerina venusta saxonica* assemblage. Planktonic assemblages include the uppermost part of the *Bolboforma badenensis – Bolboforma reticulate* assemblage, the *Neogloboquadrina atlantica* (dextral) – *Neogloboquadrina acostaensis* assemblage, the *Globorotalia puncticulata* assemblage and lowermost part of the *Neogloboquadrina atlantica* (sinistral) assemblage (Fig. 9b). The core sample taken from the upper half of the Utsira Formation in well 15/9-A-23 includes the benthic foraminiferal *Uvigerina venusta saxonica* assemblage and the planktonic *Globorotalia puncticulata* assemblage (Fig. 12).

5 Lower boundary

The lower boundary is taken at the base of the sandstones. It coincides with an abrupt downward gamma ray increase.

6 Upper boundary
The upper boundary is commonly taken at the top of the sandstones. In most wells the latter are readily defined from wireline logs (abrupt upward gamma ray increase).

7 Environment of deposition
The fossil assemblages indicate that the Utsira Formation was probably deposited mainly in a middle to inner neritic environment, and mainly middle to outer neritic for the lower part of the unit in well 25/10-2.

Upper Pliocene-Pleistocene section
Upper Pliocene and Pleistocene strata make up the upper part of the Nordland Group. The Upper Pliocene section mainly comprises sediments belonging to the huge progradational complex. It is bounded at the top by the base Pleistocene unconformity that truncates much of the Upper Pliocene succession. The Pleistocene strata above mainly comprise horizontally layered sediments in the Norwegian part of the northern North Sea, bounded by the seafloor at the top.

1 Distribution and thickness
The Upper Pliocene section overlies Oligocene and Lower Miocene strata to the east and the Utsira Formation in central parts of the northern North Sea. In the study area, the section is thickest along the axis of the southern Viking Graben, reaching about 900 m in the Sleipner area (Fig. 22).

2 Lithology
The Upper Pliocene mainly comprises immature, poorly sorted sands and mudstones. Apart from quartz and feldspars, the sands contain a high proportion of coarse granitic and metamorphic rock fragments. Shell debris occurs abundantly in parts of the section. A short conventional core taken near the base of the section in well 15/9-A-11 contains only fine-grained sediment (see also Head et al. 2004).

3 Log correlation and log motifs
In the Sleipner area, the log responses are characterised by stable patterns throughout, and commonly show fairly high GR-levels relative to the sediments below (Figs. 18, 19).

Further to the north, along log profile 1 and in the Balder/Grane field area, the basal part (about 50 m) of the Upper Pliocene displays an upward increase in GR-values, which can be attributed to a deepening of the

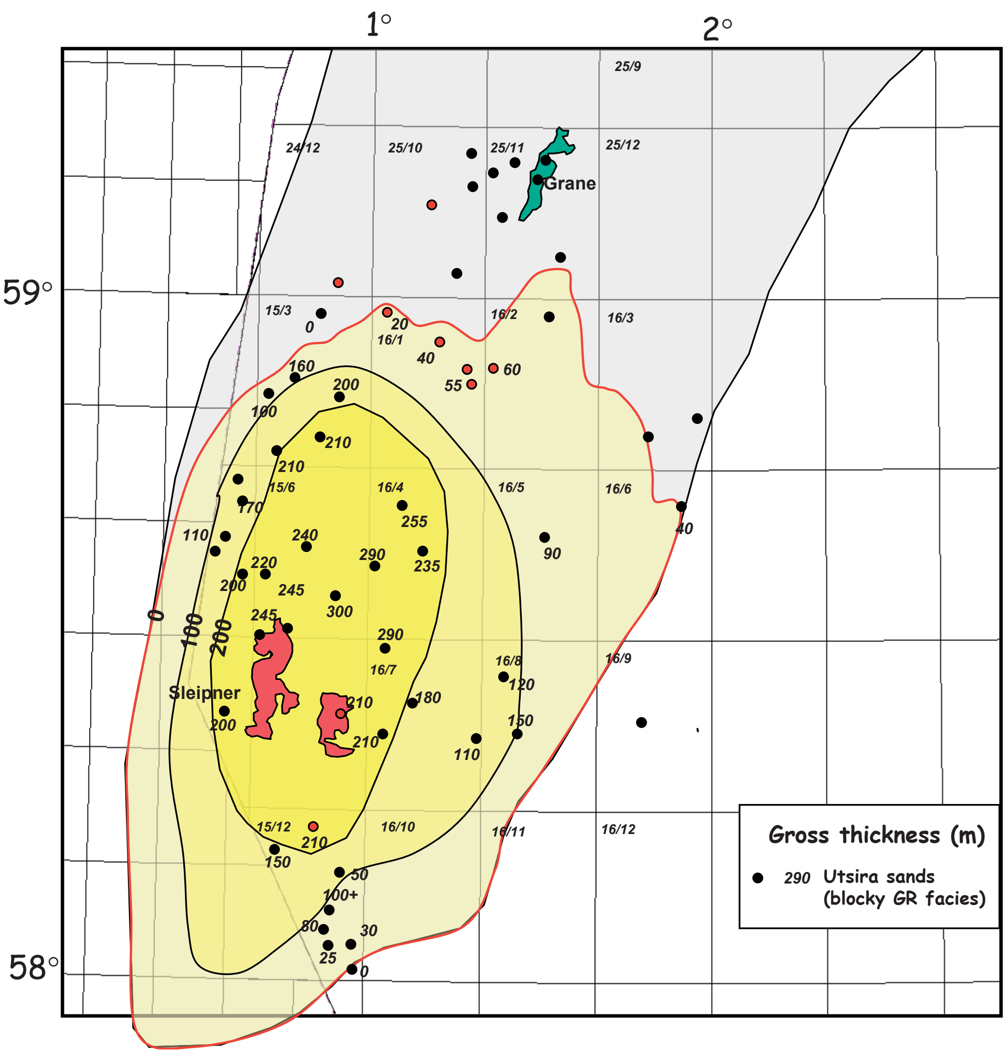


Figure 25. Outline of the Utsira Formation; southern Utsira sand member (yellow) and central Utsira member (grey).

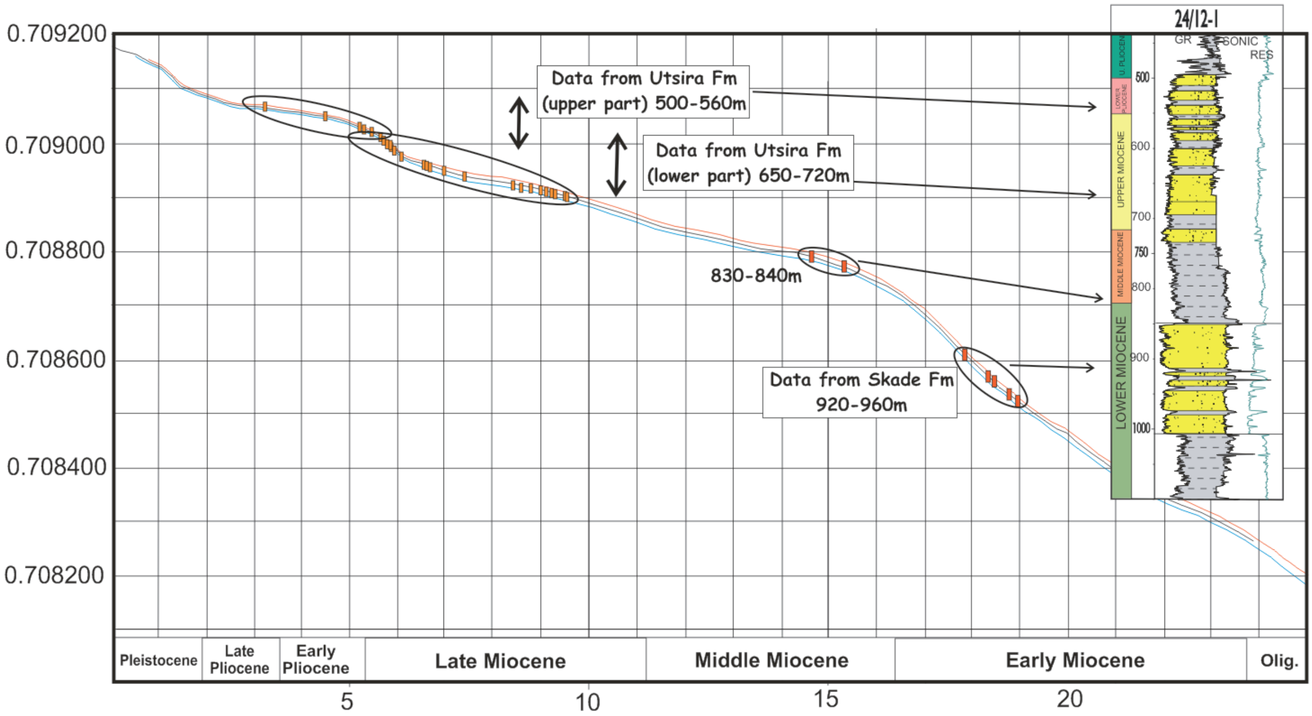


Figure 26a. Strontium isotopic data from well 24/12-1 plotted on the seawater Sr curve of Howard & McArthur (1997). Red bars denote uncertainty in the individual measurements, usually ± 7 to 9 × 10^{-6}.

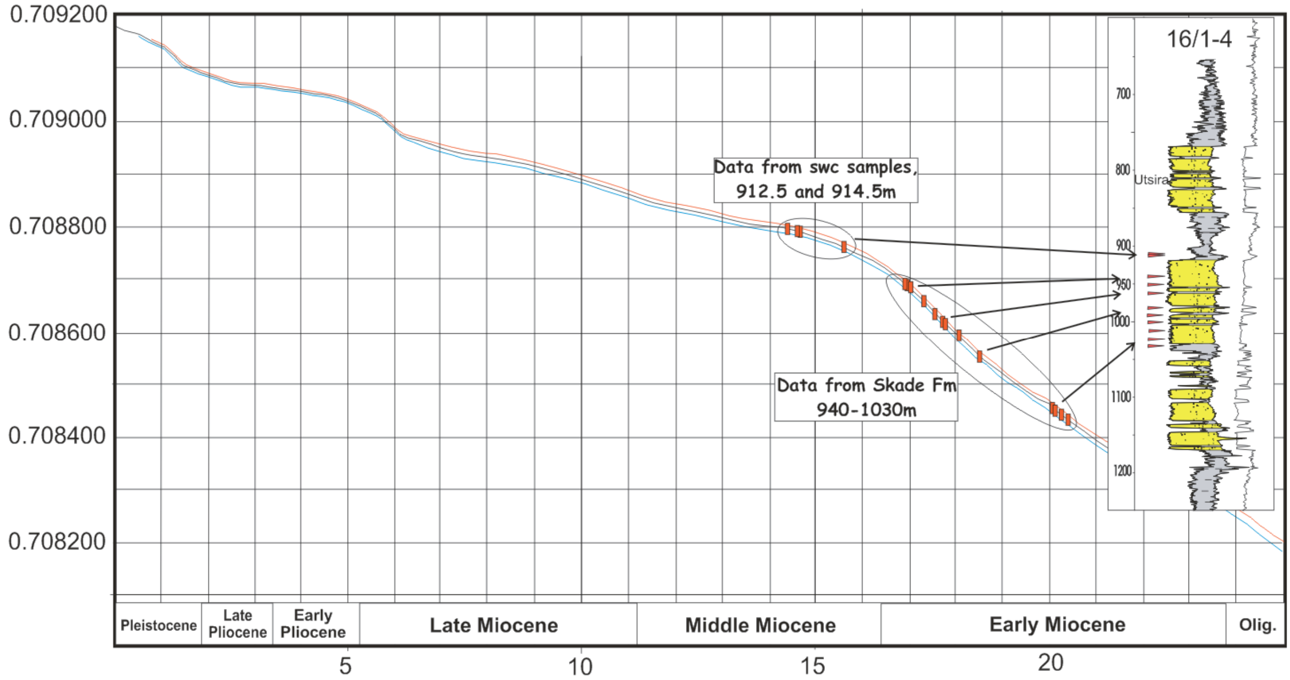


Figure 26b. Strontium isotopic data, well 16/1-4.

basin. A vague trend of repeated, 50-70 m thick, cycles with upward-increasing gamma radiation is observed in some wells (e.g. 16/1-2, Fig. 21).

4 Chronostratigraphy/Biostratigraphy

The chronostratigraphy of the Upper Pliocene - Pleistocene section is obtained by analyses and correlation of benthic and planktonic foraminifera. The Pleistocene is only investigated in wells 16/1-4 and 15/12-3, and no samples are available from the upper part of the Pleistocene. In well 16/1-4, the benthic foraminiferal assemblages include the *Cibicides grossus* assemblage and the *Elphidium excavatum – Cassidulina teretis* assemblage. Planktonic foraminiferal assemblages include the upper main part of the *Neogloquadrina atlantica* (sinistral) assemblage, the *Neogloboquadrina atlantica* (dextral) assemblage and the *Neogloboquadrina pachyderma* (dextral) assemblage (Fig. 6a, b). In well 16/1-2, only the lower part of the Upper Pliocene has been investigated and includes the benthic foraminiferal *Cibicides grossus* assemblage and the planktonic foraminiferal *Neogloboquadrina atlantica* (sinistral) assemblage (Fig. 11). In well 24/12-1, the lowermost part of the Upper Pliocene includes the benthic foraminiferal *Cibicides grossus* assemblage and the upper part of the planktonic foraminiferal *Globigerina bulloides* assemblage (Fig. 7a). Also in well 25/10-2, only the lowermost part of the Upper Pliocene has been investigated and includes the benthic foraminifera *Cibicides grossus* assemblage, the uppermost part of the planktonic foraminiferal *Neogloboquadrina atlantica* (sinistral) assemblage, the *Globigerina bulloides* assemblage and the *Neogloboquadrina pachyderma* (dextral) assemblage (Fig. 8a). In well 15/9-A-11, the short conventional core from the lower part of the Upper Pliocene includes the benthic foraminiferal *Cibicidoides pachyderma* and *Cibicides grossus* assemblages and the planktonic foraminiferal *Neogloboquadrina atlantica* (dextral) assemblage (Fig. 13).

5 Lower boundary
The lower boundary is readily apparent in most wells and is marked by abrupt changes in lithology and log responses at the top of the Utsira Formation. In the Balder-Grane area, where the Utsira Formation is less sandy (based on log responses), the transition to the Upper Pliocene being marked by an abrupt increase in gamma radiation. Seismically, the transition marks a change from an eastward to a westward-directed sedimentation pattern. In eastern marginal areas, where the Upper Pliocene overlies the Hordaland Group, the boundary is marked by a downward change to brownish, glauconitic siltstones.

6 Upper boundary
The upper boundary is represented by the seafloor.

7 Environment of deposition
The fossil assemblages indicate mainly an outer to middle neritic environment during deposition of the Upper Pliocene part and mainly middle to inner neritic during deposition of the Pleistocene part (see section 8.6 and Figs. 6-11 and 13).

Sr isotope stratigraphy

In this study we have used Sr isotope stratigraphy (SIS) on marine carbonates as an additional control on the biostratigraphic correlations. SIS is an effective tool particularly for dating of Miocene and Oligocene sections. The best resolution is for sediments older than 15 Ma. The reason for this is that seawater Sr isotopic composition changed rapidly with time during this period (e.g. Koepnick et al. 1985). For samples younger in age than 8 Ma, SIS has to be treated with more caution. This is due to less variation in the Sr isotopic composition and a relatively flat curve between 2.5 - 4.5 Ma and also to some extent between 5.5 - 8 Ma (Hodell et al. 1991, Farrell et al. 1995).

Sr isotopic analyses were performed on 215 samples (199 ditch cuttings, 8 sidewall cores and 8 conventional core samples), mostly from the sandy Utsira and Skade formations where age-diagnostic fossils were scarce. In these sections, mainly mollusc samples were used for analyses. We were not able to identify the molluscs and mollusc fragments and consequently we could not exclude caved or reworked shells. Mollusc samples, however, are limited mainly to the Utsira and Skade formations. Apparently, molluscs from the Skade Formation are considerably darker than molluscs from the Utsira Formation, probably due to diagenetic factors. This gave us some stratigraphic control of the bioclasts. In the mudstone sections, tests of calcareous foraminifera and in some sections *Bolboforma* were used. When analysing such samples from ditch cuttings we usually used tests from only one species, and picked the tests from the highest common occurrence of the species in an attempt to minimize the content of caved tests.

Caving is a common problem in the loose Neogene sediments. Bioclasts, which are abundantly present in the coarse lithologies, cave downhole and are mixed with the *in situ* carbonates. It may be difficult to differentiate between *in situ* and caved bioclasts. Such caving can in many cases easily be identified by Sr isotopic data. It requires, however, a large sampling program and a reasonable stratigraphic understanding.

We have used the SIS look-up table Version 3:10/99 of Howard and McArthur (1997) to obtain numerical ages from the Sr isotopic data. All results are presented in Tables 1 through 8. The measured $^{87}Sr/^{86}Sr$ values have been normalized to NIST (National Institute of Standards and Technology) value of 0.710248. Ages and sample depths are also shown on the biostratigraphic charts (Figs. 6 through 13).

In Figs. 26a and b, the LOWESS fitted seawater curve of Howard and McArthur (1997) with its 95% confidence limits are shown. Results from wells 24/12-1 and 16/1-4 are plotted on this curve (median line in Figs. 26 a, b) to illustrate the method. The uncertainty of each analysis (commonly on the order of $\pm$ 7 to 9 x 10^{-6}) is given by the red bar. As can be seen, the resolution is best for intervals where the curve is steep and less precise for intervals with little change in seawater Sr composition.

Results

Oligocene (Unit UH-2 and UH-3)
We analysed eleven samples based on foraminiferal tests from the Oligocene interval. All of these samples show isotopic compositions which give ages supporting the biostratigraphic correlations. In well **25/10-2,** two sam-

ples just beneath the Oligocene-Miocene boundary (biostratigraphically defined at 1100 m, 50 m above the GR3 marker) gave ages of 23.1 and 23.8 Ma (Table 1). These ages are very close to the Oligocene-Miocene boundary at 23.8 Ma (timescale of Berggren et al. 1995). In well **24/12-1**, one sample at 1210 m, 10 m above the GR3 marker, displayed a Sr composition corresponding to an age of 25.1 Ma (Table 2). In well **15/9-13**, two samples from depths of 1500 and 1520 m, both just below the GR3 peak, gave ages of about 24.5-25.0 Ma (Table 3). In well **16/1-4**, three samples from one sidewall core (1194.5 m) gave very similar isotopic signatures corresponding to ages of about 27 Ma (Table 4). This core was taken just below the broad high-radioactive GR3 marker zone in this well. At deeper levels in this well, from the interval 1290-1310 m, biostratigraphically assigned to the Early Oligocene, one sample gave an age of 28.5 Ma. In well **15/12-3**, one sample taken just below the GR3 marker gave an age of 26.8 Ma.

Lower Miocene (including the Skade Formation, Unit UH-4)

A large number of Sr isotope analyses have been carried out on the Lower Miocene section. Well **25/10-2** was extensively sampled with 62 mollusc and three foraminiferal samples taken from sands of the Skade Formation. Three samples were analysed from most depths to discriminate between *in situ* and caved samples (Table 1). The results showed consistently increasing ages with depth, from about 15 Ma at the top of the sands to about 20 Ma in the lower part. Approximately 30-40 % of the samples gave ages indicative of caving from the upper Neogene. In the basal part of the formation, molluscs were generally absent and age estimates were not obtained. Two samples analysed within this interval (1009 and 1037 m), gave ages suggestive of caving from the middle part of the Skade Formation.

In well **24/12-1** (Skade Formation type well), five mollusc samples from the Skade sands (900-960 m) gave very consistent results corresponding to ages from 17.8 to 18.7 Ma (Table 2). The Sr values plot on the steeper part of the seawater $^{87}Sr/^{86}Sr$ curve, as illustrated in Fig. 26a, within a period in which Sr isotopes have a specially good potential for dating marine strata.

In well **16/1-4,** twelve mollusc samples were analysed from the sandy intervals of the Skade Formation. It is worth noting that the samples gave results showing very consistent increasing ages with depth, from 16.9 (at 940 m) to 20.4 Ma (at 1030 m) (Table 4). Such a systematic trend suggests that the samples represent mainly *in situ* mollusc fragments, giving probably a very reliable age for the sands. Furthermore, log correlation and seismic data suggest that the sample depths in 16/1-4 can be correlated with sample depths from approximately equivalent stratigraphic levels in well 24/12-1 (Figs. 21a, b). The similar isotopic results obtained in these two wells are thus supported by log correlation and seismic data.

In well **15/12-3**, two samples based on foraminiferal tests, from depths just above the GR4 marker (at 1310 m, Fig. 19), both gave an age of 17.0 (Table 5). Such an age was also obtained from the upper part of the Skade sands to the north.

Middle Miocene (Unit LN-1)

Samples from the Middle Miocene mudstones were analysed in wells 15/12-3, 24/12-1, 16/1-4 and 15/9-13. Except for two samples in well 15/9-13, all of the samples had foraminiferal or *Bolboforma* tests.

The **15/12-3** data showed fairly consistent ages ranging from 10.6 Ma in the topmost part of the section (Table 5) to 14.8 Ma near the base. These ages are in agreement with the age given by biostratigraphical correlation. In well **24/12-1**, two samples from near the base of the mudstone section (830 to 840 m) gave ages of 14.6 and 15.3 Ma. In well **16/1-4**, three samples from sidewall cores (912.5 and 914.5 m, few metres above the top of the Skade sands) gave numerical ages of 15.5, 16.5 and 16.7 Ma, whereas one sample gave a slightly younger age of 14.7 Ma (*Burdigalian-Langhian* boundary is at 16.4 Ma according to Berggren et al. 1995). The analyses in the latter well are based on foraminiferal tests, the LADs of which are very close to the *Burdigalian-Langhian* boundary. In well **15/9-13**, at approximately the same stratigraphic position (1200, 1210 and 1220 m), three samples (one based on foraminiferal tests and two based on mollusc fragments) gave very similar Sr isotopic ratios corresponding to ages of 15.1, 15.2 and 15.9 Ma respectively (Table 3). Biostratigraphically, these samples are within the uppermost part of the Lower Miocene (Fig. 10a). Seismically, following our interpretation, they belong to the lowermost part of the Middle Miocene unit LN-1 (approximate seismic position of the mid Miocene unconformity/conformity is shown in log profile 3, Fig. 19).

Apart from some interpretation problems in the Early to Middle Miocene transition zone in well 15/9-13, the Sr isotopic data broadly support the biostratigraphic correlations. Furthermore, in the southern Viking Graben wells, the Sr isotopic data suggest that there is no distinct hiatus above the Skade sands.

Utsira Formation

In wells 25/10-2 and 24/12-1, the Utsira Formation was extensively sampled. In both wells, three mollusc samples (fragments) were commonly analysed at each sample depth. In some cases four and in one case six samples were analysed.

In well 25/10-2, 42 samples of mollusc fragments, two of fish teeth and one of foraminifera were analysed, also samples that we expected could be caved were deliberately analysed as a test. Not surprisingly, we obtained a high proportion of samples with high $^{87}Sr/^{86}Sr$ ratios yielding Late Pliocene ages (Table 1). Taking the uncertainty of the analysis into account, however, many of

Table 1. Sr isotopic data in well 25/10-2

Lithostrati-graphic unit	Sample depth	Sample type	$^{87/86}Sr$	2S error	Age	Comments
Utsira Fm a	524m (dc)	Mollusc fragments	0.709069	0.000008	2.57	Caved
Utsira Fm	524m (dc)	Mollusc fragments	0.709027	0.000009	5.27	
Utsira Fm	524m (dc)	Mollusc fragments	0.709080	0.000008	2.18	Caved
Utsira Fm	570m (dc)	Mollusc fragments	0.709021	0.000009	5.44	
Utsira Fm	570m (dc)	Mollusc fragments	0.709287	0.000008	0.00	Caved
Utsira Fm	570m (dc)	Mollusc fragments	0.709053	0.000007	4.14	
Utsira Fm	579m (dc)	Mollusc fragments	0.709052	0.000008	4.21	
Utsira Fm	579m (dc)	Mollusc fragments	0.709068	0.000009	2.62	Caved
Utsira Fm	579m (dc)	Mollusc fragments	0.709016	0.000009	5.56	
Utsira Fm	588m (dc)	Mollusc fragments	0.709078	0.000008	2.24	Caved
Utsira Fm	588m (dc)	Mollusc fragments	0.708999	0.000008	5.84	
Utsira Fm	588m (dc)	Mollusc fragments	0.709071	0.000008	2.48	Caved
Utsira Fm	598m (dc)	Mollusc fragments	0.709083	0.000009	2.09	Caved
Utsira Fm	598m (dc)	Mollusc fragments	0.708998	0.000009	5.85	
Utsira Fm	598m (dc)	Mollusc fragments	0.709013	0.000008	5.63	
Utsira Fm	625m (dc)	Mollusc fragments	0.709060	0.000007	3.59	Caved
Utsira Fm	625m (dc)	Mollusc fragments	0.708980	0.000008	6.07	
Utsira Fm	625m (dc)	Mollusc fragments	0.709002	0.000008	5.80	
Utsira Fm	634m (dc)	Mollusc fragments	0.709126	0.000008	1.19	Caved
Utsira Fm	634m (dc)	Mollusc fragments	0.709018	0.000007	5.51	
Utsira Fm	634m (dc)	Mollusc fragments	0.709038	0.000007	4.97	
Utsira Fm	634-661m (dc)	Benthic foraminifera	0.709071	0.000008	2.48	Caved
Utsira Fm	643m (dc)	Mollusc fragments	0.709028	0.000009	5.24	
Utsira Fm	643m (dc)	Mollusc fragments	0.709028	0.000009	5.24	
Utsira Fm	643m (dc)	Mollusc fragments	0.709133	0.000008	1.11	Caved
Utsira Fm	652m (dc)	Fish tooth	0.708887	0.000008	10.08	Reworked
Utsira Fm	652m (dc)	Mollusc fragments	0.708967	0.000008	6.35	
Utsira Fm	652m (dc)	Mollusc fragments	0.709015	0.000008	5.58	
Utsira Fm	652m (dc)	Mollusc fragments	0.709025	0.000008	5.30	
Utsira Fm	661m (dc)	Mollusc fragments	0.709006	0.000008	5.75	
Utsira Fm	661m (dc)	Mollusc fragments	0.709019	0.000009	5.49	
Utsira Fm	661m (dc)	Mollusc fragments	0.709028	0.000008	1.17	Caved
Utsira Fm	670m (dc)	Mollusc fragments	0.708946	0.000009	7.12	
Utsira Fm	670m (dc)	Mollusc fragments	0.708892	0.000007	9.88	
Utsira Fm	670m (dc)	Mollusc fragments	0.709045	0.000008	4.70	Caved
Utsira Fm	680m (dc)	Mollusc fragments	0.708891	0.000007	9.92	
Utsira Fm	680m (dc)	One fish tooth	0.708833	0.000008	12.10	
Utsira Fm	680m (dc)	Mollusc fragments	0.709274	0.000008	0	Caved
Utsira Fm	680m (dc)	Mollusc fragments	0.709055	0.000008	4.09	Caved
Utsira Fm	689m (dc)	Mollusc fragments	0.709078	0.000009	2.24	Caved
Utsira Fm	689m (dc)	Mollusc fragments	0.708995	0.000010	5.90	
Utsira Fm	689m (dc)	Mollusc fragments	0.709098	0.000008	1.60	Caved
Utsira Fm	707m (dc)	Mollusc fragments	0.709059	0.000008	3.68	Caved
Utsira Fm	707m (dc)	Mollusc fragments	0.709099	0.000008	1.57	Caved
Utsira Fm	716m (dc)	Mollusc fragments	0.709032	0.000008	5.13	Caved
Utsira Fm	716m (dc)	Mollusc fragments	0.708852	0.000008	11.27	
Utsira Fm	716m (dc)	Mollusc fragments	0.709028	0.000008	5.24	Caved
Skade Fm	771m (dc)	Mollusc fragments	0.708900	0.000008	9.55	
Skade Fm	771m (dc)	Mollusc fragments	0.709039	0.000009	4.94	Caved
Skade Fm	771m (dc)	Mollusc fragments	0.708765	0.000008	15.51	
Skade Fm	780m (dc)	Mollusc fragments	0.709090	0.000008	1.84	Caved
Skade Fm	780m (dc)	Mollusc fragments	0.708767	0.000009	15.45	
Skade Fm	780m (dc)	Mollusc fragments	0.708748	0.000008	15.92	
Skade Fm	790m (dc)	Mollusc fragments	0.708696	0.000008	16.84	
Skade Fm	790m (dc)	Mollusc fragments	0.708767	0.000006	15.45	
Skade Fm	790m (dc)	Mollusc fragments	0.708688	0.000008	16.94	
Skade Fm	799m (dc)	Mollusc fragments	0.709031	0.000009	5.16	Caved
Skade Fm	799m (dc)	Mollusc fragments	0.708707	0.000008	16.68	
Skade Fm	799m (dc)	Mollusc fragments	0.709105	0.000008	1.45	Caved
Skade Fm	799m (dc)	Mollusc fragments	0.709068	0.000007	2.62	Caved
Skade Fm	808m (dc)	Mollusc fragments	0.708935	0.000008	7.56	Caved
Skade Fm	808m (dc)	Mollusc fragments	0.708677	0.000007	17.09	
Skade Fm	808m (dc)	Mollusc fragments	0.708754	0.000008	15.79	
Skade Fm	808-817m (dc)	Ben. and plank. foram.	0.708698	0.000009	16.82	
Skade Fm	817m (dc)	Mollusc fragments	0.708673	0.000008	17.14	
Skade Fm	817m (dc)	Mollusc fragments	0.709048	0.000008	4.52	Caved
Skade Fm	817m (dc)	Mollusc fragments	0.708726	0.000009	16.38	
Skade Fm	817m (dc)	Benthic foraminifera	0.708674	0.000007	17.13	
Skade Fm	826m (dc)	Mollusc fragments	0.709071	0.000008	2.48	Caved
Skade Fm	826m (dc)	Mollusc fragments	0.709048	0.000009	4.52	Caved

Lithostrati-graphic unit	Sample depth	Sample type	$^{87/86}$Sr	2S error	Age	Comments
Skade Fm	826m (dc)	Mollusc fragments	0.708651	0.000008	17.40	
Skade Fm	826-835m (dc)	Benthic foraminifera	0.708720	0.000009	16.48	
Skade Fm	835m (dc)	Mollusc fragments	0.708878	0.000008	10.41	
Skade Fm	835m (dc)	Mollusc fragments	0.708798	0.000008	14.21	
Skade Fm	835m (dc)	Mollusc fragments	0.708698	0.000008	16.82	
Skade Fm	844m (dc)	Mollusc fragments	0.708852	0.000009	11.27	
Skade Fm	844m (dc)	Mollusc fragments	0.708760	0.000009	15.64	
Skade Fm	844m (dc)	Mollusc fragments	0.708648	0.000008	17.43	
Skade Fm	854m (dc)	Mollusc fragments	0.709057	0.000009	3.89	Caved
Skade Fm	854m (dc)	Mollusc fragments	0.708721	0.000008	16.46	
Skade Fm	854m (dc)	Mollusc fragments	0.709137	0.000009	1.05	Caved
Skade Fm	863m (dc)	Mollusc fragments	0.708753	0.000008	15.81	
Skade Fm	863m (dc)	Mollusc fragments	0.708777	0.000008	15.15	
Skade Fm	863m (dc)	Mollusc fragments	0.708554	0.000007	18.51	
Skade Fm	872m (dc)	Mollusc fragments	0.708609	0.000008	17.85	
Skade Fm	872m (dc)	Mollusc fragments	0.709110	0.000008	1.38	Caved
Skade Fm	881m (dc)	Mollusc fragments	0.708651	0.000007	17.40	
Skade Fm	881m (dc)	Mollusc fragments	0.708587	0.000007	18.10	
Skade Fm	890m (dc)	Mollusc fragments	0.708516	0.000008	19.05	
Skade Fm	890m (dc)	Mollusc fragments	0.709073	0.000009	2.41	Caved
Skade Fm	899m (dc)	Mollusc fragments	0.708428	0.000008	20.47	
Skade Fm	899m (dc)	Mollusc fragments	0.708535	0.000007	18.77	
Skade Fm	909m (dc)	Mollusc fragments	0.708553	0.000008	18.66	
Skade Fm	909m (dc)	Mollusc fragments	0.708575	0.000008	18.24	
Skade Fm	918m (dc)	Mollusc fragments	0.708722	0.000007	16.44	
Skade Fm	918m (dc)	Mollusc fragments	0.708828	0.000008	12.44	
Skade Fm	927m (dc)	Mollusc fragments	0.708502	0.000008	19.27	
Skade Fm	927m (dc)	Mollusc fragments	0.708986	0.000007	6.00	Caved
Skade Fm	936m (dc)	Mollusc fragments	0.708989	0.000008	5.97	Caved
Skade Fm	936m (dc)	Mollusc fragments	0.708697	0.000008	16.83	
Skade Fm	945m (dc)	Mollusc fragments	0.708493	0.000008	19.42	
Skade Fm	954m (dc)	Mollusc fragments	0.709035	0.000008	5.06	Caved
Skade Fm	954m (dc)	Mollusc fragments	0.708932	0.000007	7.81	Caved
Skade Fm	963m (dc)	Mollusc fragments	0.708938	0.000009	7.43	Caved
Skade Fm	973m (dc)	Mollusc fragments	0.709064	0.000007	3.31	Caved
Skade Fm	973m (dc)	Mollusc fragments	0.708761	0.000007	15.62	
Skade Fm	991m (dc)	Mollusc fragments	0.708888	0.000009	10.04	
Skade Fm	1000m (dc)	Mollusc fragments	0.708925	0.000009	8.43	Caved
Skade Fm	1009m (dc)	Mollusc fragments	0.708715	0.000009	16.56	
Skade Fm	1027m (dc)	Mollusc fragments	0.708945	0.000009	7.16	Caved
Skade Fm	1037m (dc)	Mollusc fragments	0.708664	0.000008	17.24	
Skade Fm	1043m (dc)	Mollusc fragments	0.708895	0.000008	9.76	Caved
Hordaland Gp	1101-1128m (dc)	Benthic foraminifera	0.708271	0.000009	23.76	
Hordaland Gp	1137-1146m (dc)	Benthic foraminifera	0.708302	0.000008	23.14	

[a] Utsira Fm in this well belongs to the proposed Central Utsira member (see text)
$^{87/86}$Sr ratios normalized to NIST-value of 0.710248

Table 1. Sr isotopic data of samples from well 25/10-2, dc = ditch cuttings.

these samples fall within the flat part of the curve (see Farrell et al. 1995) and could have ages between 2.5 - 4.5 Ma (Early/Late Pliocene boundary at 3.5 Ma). Between depths of 524 – 661 m (see Figs. 8a and 20), the bulk of the data (17 out of 31 samples) gave ages between 4.1-5.8 Ma, whereas two samples gave older ages of 6.4 and 10.1 Ma, the latter considered to be reworked. In the lower part of the formation, between depths of 670 – 716 m, the results showed much scatter, with many samples obviously having been caved from above. Excluding these, five other samples gave ages between 7.1 – 12.1 Ma. Four of these samples were taken at 670 and 680 m within the *Bolboforma fragori* fossil unit (620-661 m, see Fig. 8a). This fossil unit was also recorded in the Utsira Formation in well 24/12-1. Biostratigraphically, the top of Upper Miocene strata was defined at 625 m. This corresponds very precisely to the base of a distinct coarsening-upward unit defining the upper part of the Utsira Formation (Fig. 8a), and biostratigraphically assigned to the Early Pliocene.

In well **24/12-1,** 25 samples were analysed from the Utsira Formation. In this well, only bioclasts that were believed to represent *in situ* strata were sampled. Compared to well 25/10-2, fewer samples were considered caved (Table 4). The results varied from a minimum of 2.1 (topmost sample) to a maximum of 9.0 Ma. There is a relatively distinct trend of younger ages in the upper part of the formation (500 – 560 m), in which five of the samples have $^{87}Sr/^{86}Sr$ ratios that correspond to ages of about 5.2 – 5.8 Ma, and older ages in the lower part (650 – 710m), in which 18 samples displayed isotopic compositions corresponding to ages between 5.2 – 9.0 Ma. This is also illustrated in Fig. 26a, where the isotopic data are plotted

Table 2. Sr isotopic data in well 24/12-1

Lithostratigraphic unit	Sample depth	Sample type	$^{87/86}Sr$	2S error	Age	Comments
Utsira Fm [a]	500m (dc)	Mollusc fragments	0 709083	0.000007	2.09	Caved
Utsira Fm	520m (dc)	Mollusc fragments	0.709005	0.000009	5.76	
Utsira Fm	530m (dc)	Mollusc fragments	0.709018	0.000007	5.51	
Utsira Fm	550m (dc)	Mollusc fragments	0.708999	0.000009	5.84	
Utsira Fm	560m (dc)	Mollusc fragments	0.709037	0.000009	5.00	
Utsira Fm	560m (dc)	Mollusc fragments	0.709053	0.000009	4.14	
Utsira Fm	560m (dc)	Mollusc fragments	0.709078	0.000007	2.24	Caved
Utsira Fm	650m (dc)	Mollusc fragments	0.708914	0.000009	8.96	
Utsira Fm	650m (dc)	Mollusc fragments	0.708999	0.000009	5.84	
Utsira Fm	650m (dc)	Mollusc fragments	0.708986	0.000008	6.00	
Utsira Fm	650m (dc)	Mollusc fragments	0.709032	0.000007	5.16	
Utsira Fm	650m (dc)	Mollusc fragments	0.709073	0.000009	2.41	Caved
Utsira Fm	670m (dc)	Mollusc fragments	0.709026	0.000009	5.30	
Utsira Fm	670m (dc)	Mollusc fragments	0.709018	0.000009	5.51	
Utsira Fm	670m (dc)	Mollusc fragments	0.708929	0.000008	7.95	
Utsira Fm	670m (dc)	Mollusc fragments	0.708933	0.000009	7.69	
Utsira Fm	670m (dc)	Mollusc fragments	0.708970	0.000009	6.26	
Utsira Fm	670m (dc)	Mollusc fragments	0.708922	0.000009	8.58	
Utsira Fm	700m (dc)	Mollusc fragments	0.708962	0.000008	6.54	
Utsira Fm	700m (dc)	Mollusc fragments	0.709006	0.000009	5.75	
Utsira Fm	700m (dc)	Mollusc fragments	0.708971	0.000008	6.23	
Utsira Fm	700m (dc)	Mollusc fragments	0.708919	0.000009	8.74	
Utsira Fm	710m (dc)	Mollusc fragments	0.708918	0.000008	8.79	
Utsira Fm	710m (dc)	Mollusc fragments	0.708952	0.000009	6.87	
Utsira Fm	710m (dc)	Mollusc fragments	0.709014	0.000008	5.61	
Nordland Gr /LN-1	830-40m (dc)	Benthic foraminifera	0.708792	0.000009	14.56	
Nordland Gr /LN-1	840m (dc)	Benthic foraminifera	0.708773	0.000009	15.28	
Skade Fm	920m (dc)	Mollusc fragments	0.708523	0.000009	18.95	
Skade Fm	920m (dc)	Mollusc fragments	0.708617	0.000009	17.76	
Skade Fm	930m (dc)	Mollusc fragments	0.708570	0.000009	18.30	
Skade Fm	930m (dc)	Mollusc fragments	0.708577	0.000009	18.22	
Skade Fm	960m (dc)	Mollusc fragments	0.708538	0.000008	18.73	
Skade Fm	960m (dc)	Mollusc fragments	0.708509	0.000009	19.16	
Hordaland Gr	1210m (dc)	Benthic foraminifera	0.708187	0.000017	25.08	

a) Utsira Fm in this well belongs to the proposed Central Utsira member (see text)

Table 2. Sr isotopic data of samples from well 24/12-1, dc = ditch cuttings.

Table 3. Sr isotopic data in well 15/9-13

Lithostratigraphic unit	Sample depth	Sample type	$^{87/86}Sr$	2S error	Age	Comments
Nordland Gr / LN-1	1110m (dc)	Bolboforma	0.708871	0.000008	10.66	
Nordland Gr / LN-1	1160m (dc)	Ben. forams	0.708790	0.000008	14.66	
Nordland Gr / LN-1	1190m (dc)	Mollusc fragments	0.708831	0.000009	12.24	
Nordland Gr / LN-1	1200m (dc)	Ben. and plank. forams	0.708779	0.000011	15.09	
Nordland Gr / LN-1	1210m (dc)	Mollusc fragments	0.708776	0.000008	15.19	
Nordland Gr / LN-1	1220m (dc)	Mollusc fragments	0.708748	0.000009	15.92	
Near Nordland / Hordaland Gr boundary	1260m (dc)	Plank. foraminifera	0.708722	0.000015	16.44	
Near Nordland / Hordaland Gr boundary	1280m (dc)	Plank. foraminifera	0.708696	0.000010	16.84	
Hordaland Gr	1500m (dc)	Benthic foraminifera	0.708201	0.000029	25.0	
Hordaland Gr	1520m (dc)	Benthic foraminifera	0.708237	0.000041	24.45	

Table 3. Sr isotopic data of samples from well 15/9-13, dc = ditch cuttings.

Table 4. Sr isotopic data in well 16/1-4

Lithostratigraphic unit	Sample depth	Sample type	$^{87/86}Sr$	2S error	Age	Comments
Nordland Gr /LN-1	912.5m (swc)	Ben. and plank. foraminifera	0.708719	0.000009	16.49 a	
Nordland Gr /LN-1	912.5m (swc)	Ben. and plank. foraminifera	0.708707	0.000009	16.68 a	
Nordland Gr /LN-1	914.5m (swc)	Ben. and plank. foraminifera	0.708790	0.000010	14.66 a	
Nordland Gr /LN-1	914.5m (swc)	Ben. and plank. foraminifera	0.708768	0.000009	15.45 a	
Skade Fm	940m (dc)	Mollusc fragments	0.708623	0.000008	17.69	
Skade Fm	950m (dc)	Mollusc fragments	0.708688	0.000009	16.95	
Skade Fm	950m (dc)	Mollusc fragments	0.708689	0.000008	16.94	
Skade Fm	960m (dc)	Mollusc fragments	0.708671	0.000009	17.16	
Skade Fm	980m (dc)	Mollusc fragments	0.708593	0.000009	18.04	
Skade Fm	980m (dc)	Mollusc fragments	0.708637	0.000009	17.55	
Skade Fm	990m (dc)	Mollusc fragments	0.708619	0.000009	17.74	
Skade Fm	1000m (dc)	Mollusc fragments	0.708552	0.000009	18.54	
Skade Fm	1010m (dc)	Mollusc fragments	0.708458	0.000009	20.02	
Skade Fm	1020m (dc)	Mollusc fragments	0.708455	0.000009	20.07	
Skade Fm	1020m (dc)	Mollusc fragments	0.708444	0.000009	20.23	
Skade Fm	1030m (dc)	Mollusc fragments	0.708430	0.000009	20.44	
Hordaland Gr	1194.5m (swc)	Benthic foraminifera	0.708087	0.000008	27.47 a	
Hordaland Gr	1194.5m (swc)	Benthic foraminifera	0.708106	0.000008	26.78 a	
Hordaland Gr	1194.5m (swc)	Benthic foraminifera	0.708090	0.000009	27.26 a	
Hordaland Gr	1210.5m (swc)	Benthic foraminifera	0.708225	0.000009	24.51 a	
Hordaland Gr	1290-1310m (dc)	Benthic foraminifera	0.708042	0.000008	28.53 a	

a) from Nødtvedt 1999

Table 4. Sr isotopic data of samples from well 16/1-4, dc = ditch cuttings and swc = sidewall core.

Table 5. Sr isotopic data from well 15/12-3

Lithostratigraphic unit	Sample depth	Sample type	$^{87/86}Sr$	2S error	Age	Comments
Utsira Fm	940m (dc)	Mollusc fragments	0.709061	0.000009	3.52	
Utsira Fm	940m (dc)	Mollusc fragments	0.708873	0.000009	10.59	Reworked
Utsira Fm	980m (dc)	Mollusc fragments	0.708891	0.000008	9.92	
Utsira Fm	980m (dc)	Mollusc fragments	0.709041	0.000008	4.86	
Utsira Fm	1020m (dc)	Mollusc fragments	0.708706	0.000009	16.70	Reworked
Utsira Fm	1020m (dc)	Mollusc fragments	0.708791	0.000009	14.61	Reworked
Utsira Fm	1060m (dc)	Mollusc fragments	0.708897	0.000009	9.67	
Utsira Fm	1060m (dc)	Mollusc fragments	0.708670	0.000009	17.17	Reworked
Utsira Fm	1100m (dc)	Mollusc fragments	0.708839	0.000009	11.80	
Utsira Fm	1100m (dc)	Mollusc fragments	0.708916	0.000009	8.87	
Utsira Fm	1110m (dc)	*Bolboforma*	0.708874	0.000014	10.55	
Utsira Fm	1120m (dc)	*Bolboforma*			10 a	
Utsira Fm	1120m (dc)	*Bolboforma*	0.708882	0.000013	10.26	
Utsira Fm	1120m (dc)	Mollusc fragments	0.708870	0.000008	10.69	
Nordland Gr /LN-1	1160m (dc)	*Bolboforma*			10.6 a	
Nordland Gr /LN-1	1180m (dc)	*Bolboforma*	0.708869	0.000014	10.73	
Nordland Gr /LN-1	1180m (dc)	Benthic foraminifera	0.708913	0.000021	9.00	
Nordland Gr /LN-1	1200m (dc)	Benthic foraminifera	0.708905	0.000022	9.34	
Nordland Gr /LN-1	1200m (dc)	*Bolboforma*	0.708852	0.000012	11.27	
Nordland Gr /LN-1	1220 (dc)	*Bolboforma*			12.7 a	
Nordland Gr /LN-1	1250. 1260. 1270. 1280m (dc)	Benthic foraminifera			14.8 a	
Hordaland Gr/UH-3	1310m (dc)	Benthic foraminifera			17.0 a	
Hordaland Gr/UH-3	1310m (dc)	Planktonic foraminifera			17.0 a	
Hordaland Gr/UH-2	1500. 1520m (dc)	Benthic foraminifera			26.8 a	

a) from Nødtvedt 1999

Table 5. Sr isotopic data of samples from well 15/12-3, dc = ditch cuttings.

Table 6. Sr isotopic data from well 16/1-2

Lithostratigraphic unit	Sample depth	Sample type	$^{87/86}Sr$	2S error	Age	Comments
Utsira Fm	740m (dc)	Mollusc fragments	0.709087	0.000009	1.94	Caved
Utsira Fm	740m (dc)	Mollusc fragments	0.709063	0.000008	3.38	
Utsira Fm	770m (dc)	Mollusc fragments	0.709043	0.000009	4.78	
Utsira Fm	770m (dc)	Mollusc fragments	0.709045	0.000009	4.70	
Utsira Fm	790m (dc)	Mollusc fragments	0.708709	0.000009	16.65	Reworked
Utsira Fm	790m (dc)	Mollusc fragments	0.708846	0.000009	11.49	
Utsira Fm	800m (dc)	Mollusc fragments	0.708766	0.000009	15.48	Reworked
Utsira Fm	800m (dc)	Mollusc fragments	0.708749	0.000009	15.90	Reworked
Utsira Fm	820m (dc)	Mollusc fragments	0.708846	0.000008	11.49	

Table 6. Sr isotopic data of samples from well 16/1-2, dc = ditch cuttings.

Table 7. Sr isotopic data from well 15/9-A-23

Lithostratigraphic unit	Sample depth	Sample type	$^{87/86}Sr$	2S error	Age	Comments
Utsira Fm	1080m (core)	Mollusc fragments	0.708884	0.000009	10.19	Reworked
Utsira Fm	1080m (core)	Mollusc fragments	0.709068	0.000009	2.62	
Utsira Fm	1080m (core)	Benthic foraminifera	0.709113	0.000009	1.35	
Utsira Fm	1080m (core)	Benthic foraminifera	0.708964	0.000008	6.46	
Utsira Fm	1080m (core)	Ben. and plank. foraminifera	0.709098	0.000009	1.6	
Utsira Fm	1080m (core)	Ben. and plank. foraminifera	0.709071	0.000009	2.48	

Table 7. Sr isotopic data of samples from well 15/9-A-23.

Table 8. Sr isotopic data from well 15/9-A-11

Lithostratigraphic unit	Sample depth	Sample type	$^{87/86}Sr$	2S error	Age	Comments
Nordland Gr	913.1m (core)	Benthic foraminifera	0.709118	0.000009	1.29	
Nordland Gr	913.1m (core)	Benthic foraminifera	0.709105	0.000009	1.45	

Table 8. Sr isotopic data of samples from well 15/9-A-11.

on the seawater $^{87}Sr/^{86}Sr$ curve. As can be seen, the bulk of the data within the lower part displays Late Miocene seawater signatures of about 0.7089-0.7090. These ages are in agreement with the biostratigraphic correlations supporting the Late Miocene age assigned to the sands between 550-720 m. The lowermost samples corresponding to the *Bolboforma fragori* assemblage (Fig. 7a), show somewhat younger ages than indicated by the *Bolboforma correlations* (11.7-10.3 Ma; Fig. 16). Consequently, some of the mollusc fragments within this zone are probably caved from shallower levels of the formation.

In **well 16/1-2**, three samples from the upper subunit of the Utsira Formation had isotopic compositions corresponding to ages of 3.4, 4.7 and 4.8 Ma, whereas one sample gave a younger age of 1.9 Ma (Table 6). The Sr values fall within the flat part of the $^{87}Sr/^{86}Sr$ curve and the corresponding ages are therefore less precise. Nevertheless, they support the Early Pliocene age supplied for this subunit by biostratigraphical analyses and correlation studies. Below this interval, within the main Utsira sandbody, three samples gave Sr ages of about 15-16 Ma, whereas two other samples both gave ages of 11.5 Ma. The older ages most likely represent reworked material.

To the south, in **well 15/12-3**, 14 samples (eleven from mollusc fragments and three from *Bolboforma*) were analysed from the Utsira Formation. In this well, the data showed much scatter and no distinct trends of successively older age with depth were found (Table 5). In the upper part (940-980 m), however, two samples gave ages of 3.5 and 4.9 Ma supporting the Early Pliocene age assigned to this interval, whereas two other samples gave ages of 9.9 and 10.6 Ma. In the middle part (1020-1060 m), three samples gave ages of 14.6, 16.7 and 17.2 Ma, suggesting reworking, similar to samples from the Utsira sand in well 16/1-2. In the lower part of the sand (1100-1120 m), six samples gave fairly consistent ages between 8.9 and 11.9 Ma. Biostratigraphically, the basal part of the sand (1110-1130 m) was given a Middle Miocene age based on correlation with *Bolboforma* zones from Vøring Plateau strata (Figs. 9b and 15; slightly older than 11.9 Ma based on the LAD of *B. badenensis*). One mollusc sample from this part gave 11.8 Ma and the samples based on *Bolboforma* tests gave ages of about 11-10 Ma.

In **well 15/9-A-23**, two samples based on mollusc fragments and four samples based on foraminifera were taken from a short conventional core at 1080 m in the upper part of the Utsira sand. These data also displayed surprisingly much scatter (Table 7). Two of the samples gave Pleistocene ages (1.5-1.6 Ma), the other four samples gave ages of 2.5, 2.6, 6.5, and 10.2 Ma. Biostratigraphic correlation assigned the core to the Early Pliocene. The variation could be explained by a combination of high-frequency variation in seawater $^{87}Sr/^{86}Sr$ (see Farrell et al. 1995), analytical noise/uncertainties and reworking of mollusc fragments.

Upper Pliocene

In well 15/9-A-11 on the Sleipner field, a short core taken about 27 m (20.5 m in total vertical depth) above the top of the Utsira Formation, was sampled for Sr isotope analysis. Two foraminiferal samples displayed a Sr isotopic composition corresponding to Pleistocene ages of 1.3 and 1.5 Ma (Table 8, Fig. 13, Pliocene-Pleistocene boundary at 1.85 Ma according to Berggren et al. 1995), which are younger than the Late Pliocene age assigned from the biostratigraphic data. Although the core is taken at a deep level in the well (913.1-906 m), it belongs stratigraphically to a late stage of the prograding complex (see Fig. 4) and a latest Late Pliocene age should therefore be expected. The high-frequency variability of seawater Sr composition, as presented by Farrell et al. (1995), may, in some cases, give results, which lie outside the standard deviation.

Discussion

Problems related to the Utsira and Skade formations (Error in definition)

The error in the definition of the Skade and Utsira formations, as reported by Rundberg & Eidvin (2005, Fig. 2), has evidently caused much confusion in stratigraphic work on the Upper Tertiary sediments of the northern North Sea.

Gradstein et al. (1992, 1994) analysed the Utsira type well 16/1-1 and reported an Early Pliocene age for the upper sandy interval (approximately 685 to 823 m) and an Early Miocene age for the lower interval (823 to approximately 1125 m), the latter relating to the base Nordland Group mudstones and Skade Formation sandstones. These workers, however, did not register *Bolboforma*, but marked the last common occurrence (LCO) of radiolaria at the same stratigraphic level as we recorded the top of the *Bolboforma badenensis – B. reticulata* assemblage in the nearby wells 16/1-2 and 24/12-1. Although Gradstein et al. (1992, 1994) do not refer to formational names, their dating in the Utsira key well clearly must have raised questions for other workers.

Gregersen et al. (1997), in their extensive work on the Utsira Formation, met another problem, which we believe originates from the usage of the Utsira interval as defined by Isaksen & Tonstad (1989). For instance, Gregersen et al. (1997) reported maximum Utsira Formation thickness of about 500 m in blocks 25/10 and 25/11 (their Fig. 10), in areas not far from the Utsira type well 16/1-1. Our work in this area, however, shows that the Utsira Formation is very thin and mostly developed as fine-grained sands and siltstones. Gregersen et al. (1997) by mistake included the blocky sands of the Skade Formation in sections that they mapped as Utsira, thus creating a depocentre in an area which proved to be almost absent of Utsira sands. Such a mistake most certainly can be related to the definition in the key well. Consequently, much of their mapping and interpretations built on these data, were obviously erroneous. A problem in the Balder and Grane field areas, however, is that the sands, which prove to be Skade are termed Utsira Formation on a number of completion logs and are also been described as Utsira sandstone in the final well reports. Thus, not only Gregersen et al. (1997) but also the operators and partners of the Grane and Balder fields, have made serious stratigraphic errors in the post-Eocene section for years. This must have affected works on burial histories and the migration of hydrocarbons in the area.

Strictly speaking, the usage of the name Utsira Formation for the interval (which now proves to be Skade) was correct for wells drilled prior to 1989, according to the first definition by Deegan & Scull (1977). But after Isaksen & Tonstad (1989) introduced the Skade Formation, these sands should have been renamed. Surprisingly, as far as we know, no workers became aware of this controversy until it was recently discovered by Eidvin et al. (2002) and Rundberg & Eidvin (2005).

Jordt et al. (1995) do not refer to the Skade and Utsira formations in their work on Cainozoic strata from the North Sea Basin. Instead, they use sequential annotations only. According to the seismic illustrations (their Figs. 3A, 3B, 9 and 14), sequence CSS 5 corresponds to the Utsira Formation in the northern North Sea. This sequence is given a latest Oligocene – earliest Miocene age in their work. We believe that much of the data presented in their work are affected by correlation errors and confusion surrounding the age of the post-Eocene strata.

Sr isotope analysis in a stratigraphic context

There are two interesting aspects of our Sr isotopic dataset from the Utsira and Skade formations in the southern Viking Graben. Firstly, from the Skade Formation in wells 16/1-4, 24/12-1 and 25/10-2 we obtained remarkably good Sr isotopic data (excluding obvious caving in the latter well). In these wells, the Sr isotopic values yielded consistently increasing ages with depth, suggesting that the values were derived from *in situ* samples. Secondly, among the large number of bioclasts analysed from the Utsira Formation there were some measurements showing distinctly lower Sr isotopic ratios corresponding to ages of 15-17 Ma. Such isotopic values were recorded in the middle part of the Utsira sands in wells 16/1-2 (Table 6) and 15/12-3 (Table 5).

There are three possible ways to explain the low $^{87}Sr/^{86}Sr$ values within the Utsira Formation: (1) the Sr values represent the real composition of reworked carbonate samples; (2) the values are the result of laboratory errors; and (3) the values represent sample contamination. Although the two latter factors cannot be excluded, and it can be argued that laboratory errors are perhaps the most logical explanation, we favour geological processes or reworking to explain the results.

Such reworking follows as a result of the tectonic episode that affected the northern North Sea during Middle-Late Miocene times (Rundberg & Eidvin 2005). During this phase, the underlying sediments (Skade sands) were probably exposed in parts of the basin and subjected to severe erosion. This can be interpreted from regional seismic lines from the North Sea (e.g. Fig. 4a), and has previously also been suggested by Gregersen et al. (1997), Galloway (2002), and Martinsen et al. (1999). The depositional model of the Utsira sands, involving accumulation in a shelfal setting characterised by strong marine current systems (Rundberg 1989, Galloway 2002, Rundberg & Eidvin 2005), also fits in this picture. The Utsira sands thus most certainly contain large volumes of erosional products derived from underlying strata, and also mollusc fragments with isotopic values typical for the uppermost Skade sands could be expected from the Utsira sands. Rundberg & Smalley (1989) also recorded Sr isotopic values of about 18 Ma in samples from the Utsira Formation in well 30/3-3 further to the north. Thus, it appears that bioclasts from older sediments are commonly present within the Utsira sands of the northern North Sea.

This shows another application of strontium isotope stratigraphy and demonstrates its potential as a stratigraphic tool within sandy marine sections where biostratigraphic data are otherwise poor or absent.

Some comments to the post-Eocene lithostratigraphic nomenclature

This work demonstrates a need for an update or modification of the lithostratigraphic nomenclature of the post-Eocene succession in the Norwegian North Sea. Within the Hordaland (upper part) and Nordland groups, only two major sandy sections have been defined (Utsira and Skade formations) whereas the remaining lithologies have remained undifferentiated (Isaksen & Tonstad 1989).

Although it is beyond the scope of this paper to introduce a revised lithostratigraphic nomenclature, we find it appropriate to point to inconsistencies and suggest some changes to the present scheme. Our proposal for a revised nomenclature is shown in Fig. 27.

Hordaland Group

Units UH-2 and 3. In UK waters, Knox and Holloway (1992) introduced the term Lark Formation for mudstones of Oligocene to early Middle Miocene age (upper part of the Hordaland Group). It comprises mudstone-dominated facies below the mid-Miocene unconformity and is bounded by Eocene greenish claystones at the base (termed Horda Formation). This argillaceous section extends basinwards and represents units UH-2 and -3 in Norwegian waters. Lark Formation has already been used informally by industry consultants and stratigraphic workers in the Norwegian North Sea. In accordance with international lithostratigraphic rules and recommendations (Nystuen 1986, Salvador 1994), formation names which already have been defined in parts of the basin should also be used for equivalent strata across national borders. We therefore propose to extend the usage of the Lark Formation into Norwegian waters. Its original type section will remain unchanged but a reference section needs to be established in Norwegian waters.

The Lark Formation should thus comprise the Skade Formation sandstone in the southern Viking Graben and Vade Formation sandstone in the central North Sea. The top of the formation is equivalent to the top of Unit UH-3 (see section 6.1).

Skade Formation. We propose that the Skade Formation should be downgraded to member status, in accordance with common lithostratigraphic rules and practice during the last 15 years. Isaksen & Tonstad (1989) introduced the term Skade Formation for sands that were suggested to be Oligocene in age. Our work, however, shows that these sands are dominantly Early Miocene. Knox & Holloway (1992) adopted the term Skade Formation but used it for shallow marine sands in the UK sector, although Isaksen & Tonstad (1989) suggested the sands were deposited in deeper marine settings. Within the study area of the southern Viking Graben, we interpret the Skade Formation sands as having been deposited by gravity processes mainly in upper bathyal water depths (see section 8.5). More work needs to be done, however, on the northerly extent of the Skade Formation sands, and on its relationship to the shallow marine sands in UK waters.

Nordland Group

Utsira Formation. This formation represents a huge sedimentary depositional system in the northern North Sea. Recent mapping of the Utsira Formation suggests that it comprises two sandy depocentres (southern and northern Viking Graben), and is separated by a central area comprising an eastward prograding sandy strandplain wedging out into mudstone-dominated facies to the east (Galloway 2002, Rundberg & Eidvin 2005). Although more detailed biostratigraphic work is required for the northern and central Utsira sands we suggest the following changes; the Utsira Formation should be subdivided into at least three members, viz. southern Utsira

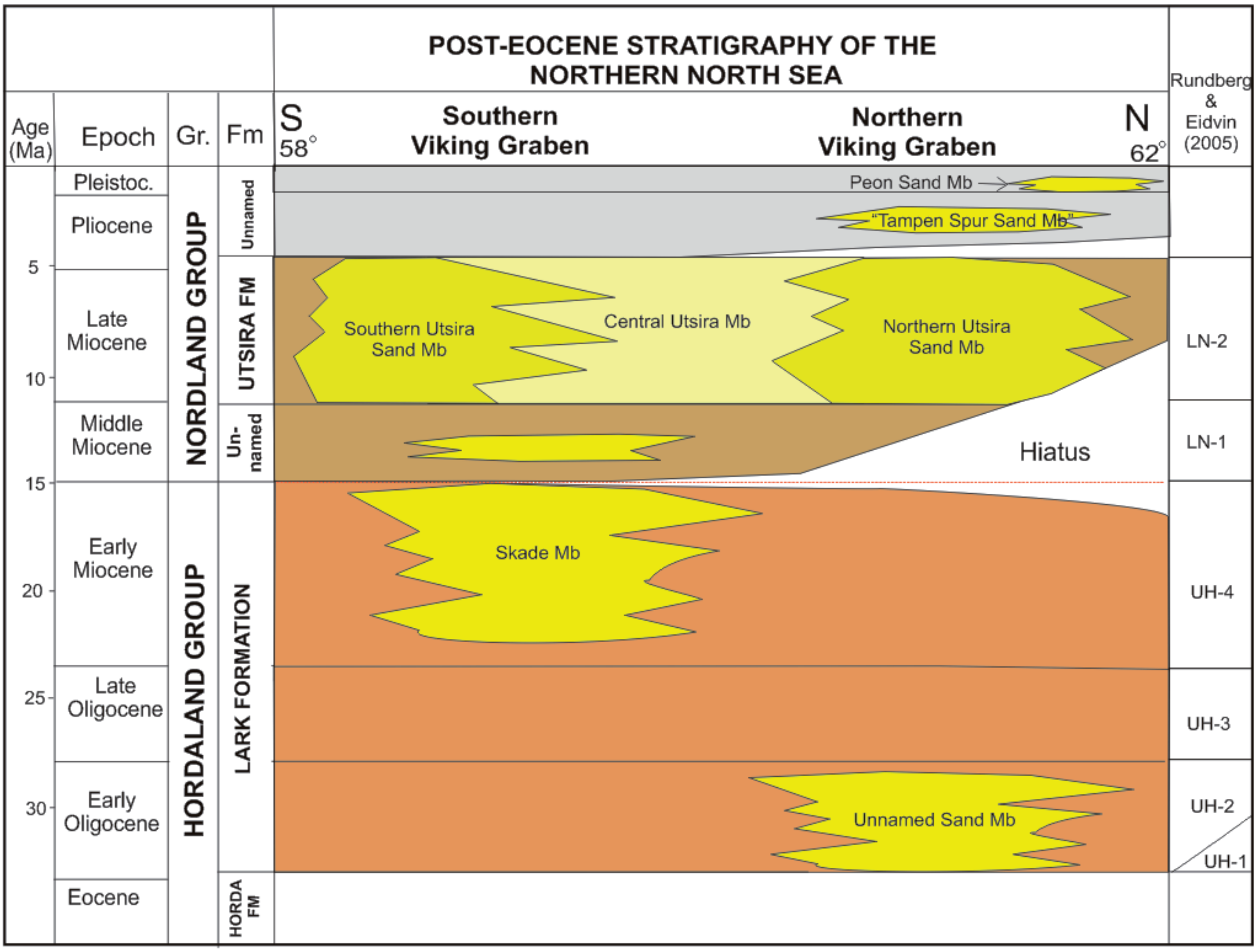


Figure 27. Proposed lithostratigraphic subdivision of post-Eocene strata in the northern North Sea.

sand member, northern Utsira sand member, and central Utsira member. Based on the obvious correlation conflict between the Utsira and Skade formations in their type wells (see Fig. 2), a revision of the base of the Utsira Formation is required. For the southern and northern Utsira sand members, the top and base of the formation should be taken from wireline logs, in which abrupt changes desine changes to mudstone facies above and below. In the type well 16/1-1 (Isaksen & Tonstad 1989), the base of the Utsira Formation should be adjusted to about 815 m. For the central Utsira member more work is required.

It should be noted that after revision of the base of the Utsira Formation, well 16/1-1 is no longer the appropriate choice as the type well for this sandy system. It penetrates only thin sand and does not represent the typical sandstones, which have become known as the Utsira Formation. Future work on the lithostratigraphic nomenclature should address this problem.

Middle Miocene section (Unit LN-1). A revision of the base of the Utsira Formation, might lead to some uncertainty about the mudstone section (Unit LN-1) above the mid-Miocene unconformity and below the Utsira sands. These sediments are Middle Miocene in age and represent the basal part of the Nordland Group. They contain the diagnostic *Bolboforma badenensis* and *B. reticulata* assemblages or the *Bolboforma badenensis-B. reticulata* assemblage and occur as an infilling unit within the southern Viking Graben. The section includes marginal, shallow marine sands, penetrated in well 16/5-1 and probably also gravity deposited sediments in central parts of the southern Viking Graben. The western part of the unit extends into UK waters. Northwards, it gradually thins to zero thickness (Rundberg & Eidvin 2005). Locally, where the Utsira sands are absent, it may be difficult to distinguish between this unit and the overlying sediments (central Utsira member). We propose that this basal section of the Nordland Group should be upgraded to the status of a formation.

Upper Pliocene-Pleistocene section. The very conspicuous Upper Pliocene prograding complex and the overlying Pleistocene deposits have not been formally named within the North Sea Basin. These sediments include gravity sands, deposited in front of the oblique clinoforms, which locally may be difficult to distinguish from the Utsira sands below, e.g. "Tampen Spur sandstone member" (Robertson Research 1996, Eidvin & Rundberg 2001). They also include the large Peon gas discovery in basal Pleistocene sands of block 35/2 (Carstens 2005).

In North Sea UK waters, the Pliocene-Pleistocene section has been subdivided into a number of formations (e.g. Fyfe et al. 2003), but these are not representative for the sediments in the Norwegian sector and thus should not be used here. Offshore mid-Norway, Dalland et al. (1988) introduced the name Naust Formation for the Upper Pliocene including the Pleistocene section. As these sediments are similar in genetic origin, reflecting the glaciation history and the main uplift of Fennoscandia, it could be appropriate to extend the usage of the term Naust Formation to the northern North Sea.

At present, however, we consider it better to wait proposing new formational name(s) for the Upper Pliocene-Pleistocene section in the North Sea. The reason for this is twofold: (1) All correlatable stratal units on the Norwegian Continental shelf have different formation names in the North Sea and offshore mid-Norway (the use of Naust Formation in the North Sea therefore is illogical); and (2) a subdivision into at least two formations should be considered as the Pleistocene is seismically clearly distinguishable in most of the Norwegian sector above a very marked truncation surface (base Pleistocene unconformity) and represents an important period of the geohistory.

Correlation of *Bolboforma* assemblages to the deep-sea record

A major finding in our detailed biostratigraphic work is the presence of *Bolboforma* assemblages in the lower part of the Utsira Formation in wells 24/12-1 and 25/10-2 and in the mudstone section below the Utsira Formation at the base of the Nordland Group. Correlation of shelfal fossil assemblages with deep-ocean *Bolboforma* zones may yield quite accurate ages, since the zones are of short duration and have been calibrated using nannoplankton and paleomagnetic data. It is particularly noteworthy that we are able to correlate the sandy Utsira Formation, in detail, with the deep-sea record since *in situ* planktonic foraminifera and *Bolboforma* are relatively scarce in these shallow shelfal deposits (Fig. 16).

In the lowermost part of the Utsira Formation in wells 24/12-1 and 25/10-2 we recorded the *Bolboforma fragori* assemblage, which correlates with the *B. fragori/B. subfragori* Zone of Spiegler & Müller (1992) and Müller & Spiegler (1993) corresponding to an age of 11.9-10.3 Ma in the ODP/DSDP boreholes in the Norwegian Sea and the North Atlantic (Fig. 16). In well 25/10-2, where the Utsira Formation is more fine-grained than in the other wells (proposed termed central Utsira member), we were also able to record the *Bolboforma metzmacheri* assemblage. The *B. metzmacheri* Zone is the youngest of the *Bolboforma* zones in the Norwegian Sea and North Atlantic and is dated to 10.0-8.7 Ma according to Spiegler & Müller (1992) and Müller & Spiegler (1993, Fig. 16). Such ages have been obtained by Sr isotope measurements of mollusc fragments in other wells with the Utsira Formation. However, the LADs of *Bolboforma* taxa in the scarce assemblages recorded in these wells are unlike the progression found in the Norwegian Sea and North Atlantic boreholes, probably due to a mixing of *in situ* and reworked specimens.

In the mudstone section between the Utsira and Skade formations at the base of the Nordland Group, we have recorded either a *Bolboforma badenensis – Bolboforma reticulata* assemblage or a *B. badenensis* assemblage and a *B. reticulata* assemblage (the Skade Formation is absent in well 15/12-3). These assemblages correlate with the *B. badenensis/B. reticulata* Zone of Spiegler & Müller (1992) and Müller & Spiegler (1993). This zone is the oldest of the *Bolboforma* zones in the North Atlantic and Norwegian Sea and is dated to slightly older than 14 to 11.9 Ma. In wells 24/12-1 and 15/12-3, the uppermost part this assemblage is within the lowermost part of the Utsira Formation indicating that, in these wells, the basal part of the Utsira Formation is slightly older than 12 Ma.

Microfossils and paleoenvironments

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

Lower and Upper Oligocene (Hordaland Group)

Pyritized diatoms dominate the planktonic fossil assemblage in these sections. Radiolaria and foraminifera are also quite common in most sections. Calcareous foraminifera dominate in a moderately rich benthic fauna. Agglutinated forms are subordinate but these are also quite common in wells 15/9-13 and 15/12-3. All the recorded foraminifera are extinct species with the exception of *Eponides umbonatus*. This species, which is recorded over limited intervals in all sections, has a recent bathymetric 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. Several other calcareous benthic deep-water indicators such as *R. arnei, Cibicides sulzensis, T. gracilis* and *G. soldanii girardana* (Skarbø & Verdenius 1986, King 1989) are also recorded. *T. alsatica, G. soldanii mamillata* (Lower Oligocene in well 16/1-4), *B. elongata* and *R. bulimoides* (Lower Oligocene in wells 16/1-4, 15/9-13 and 25/10-2) were deep- to shallow-water dwelling forms according to Skarbø & Verdenius (1986) and Gradstein & Bäckström (1996). Most of the recorded agglutinated forms are deep-water indicators according to Skarbø & Verdenius (1986) and Gradstein & Bäckström (1996). The high concentration of diatoms and radiolaria indicates a relatively deep, open-marine environment. The content of agglutinated foraminifera is probably a response to low oxic to dysoxic bottom conditions especially in the 15/12-3 and 15/9-13 areas. In conclusion, the environment was probably mainly upper bathyal during deposition of the Lower-Upper Oligocene succession.

Lower Miocene (Hordaland Group and Skade Formation)
The Lower Miocene succession contains a rich planktonic assemblage including foraminifera, pyritized diatoms and radiolaria. Foraminifera are dominant in the upper part of the section and diatoms and radiolaria are dominant in the lower part. A moderately rich to sparse benthic fauna is dominated by calcareous foraminifera except for the lower part of the Lower Miocene in well 16/1-4 where agglutinated forms are most numerous. All the recorded foraminifera are extinct species with the exception of *N. affine* and *P. bulloides*. In recent deposits, *P. bulloides* and *N. affine* have a biogeographic range extending mainly along the upper part of the continental slope and outer shelf. However, *N. affine* also occurs on middle and inner shelf areas in smaller numbers (Sejrup et al. 1981, Mackensen et al. 1985). Several calcareous benthic deep-water indicators such as *R. arnei, B.* cf. *antiqua and T. gracilis* (Skarbø & Verdenius 1986, King 1989) are recorded. Several indicators of deep- to shallow-water, according to Skarbø & Verdenius (1986), are also recorded and include *P. seminuda, U. tenuipustulata, B. elongata, U. semiornata saprophila, Trifarina gracilis* var. A, *F. boueanus* and *C. dutemplei. E. inflatum, A. guerichi guerichi* and *A. guerichi staeshei* were mainly shallow-water dwellers according to Skarbø & Verdenius (1986). The agglutinated foraminifera, which occur sporadically through most of the section and dominate the fauna in the lower part of the section in well 16/1-4, are mostly deep-water dwellers (Skarbø & Verdenius 1986 and Gradstein & Bäckström 1996). The large number of planktonic foraminifera in the upper part of the section and of diatoms and radiolaria in the lower part indicate a relative deep open-marine environment. The occurrence of agglutinated foraminifera in most of the section and the predominance in the lower part of the section in well 16/1-4 indicate short and long periods with low oxic to dysoxic bottom conditions, respectively. The environment was probably mainly upper bathyal during deposition of the Lower Miocene succession.

Middle Miocene (Nordland Group)
Planktonic fossils are common throughout the Middle Miocene section. *Bolboforma* are dominant, with subordinate foraminifera, radiolaria and pyritized diatoms. Calcareous foraminifera dominate a moderately rich benthic fauna in all wells but, locally, a few agglutinated forms are recorded. All the recorded foraminifera are extinct species with the exception of *N. affine* and *P. bulloides*, which have a recent biogeographic range extending mainly along the upper part of the continental slope and outer shelf. *N. affine* also occurs on middle and inner shelf areas in smaller numbers (Sejrup et al. 1981, Mackensen et al. 1985). However, these forms may have lived in shallower water back in the Miocene. *S. bulloides* and *M. communis* (agglutinated) were deep-water dwellers, *B. elongata, C. dutemplei, E. variabilis, U. semiornata saprophila* and *U. pygmea langeri* were deep- to shallow-water dwellers, and *A. guerichi staeschei* and *S. reticulata* were shallow-water dwellers according to Skarbø & Verdenius (1986). The high number of planktonic fossils indicates a relative deep, open marine environment. The relative sparse content of agglutinated foraminifera indicates that the sea bottom was better ventilated than during the Oligocene and Early Miocene. Collectively, the benthic and planktonic fossil assemblages indicate somewhat shallower water depths than during the Oligocene and Early Miocene, and the environment was probably mainly outer neritic during the Middle Miocene.

Upper Miocene and Lower Pliocene (Utsira Formation)
A moderately rich planktonic fossil assemblage of mainly foraminifera is recorded throughout most of the Upper Miocene and Lower Pliocene sections. *Bolboforma* are also recorded in parts of the sections, but a number of these are probably reworked. In the lower part of the section in well 25/10-2 the occurrence of *Bolboforma* and planktonic foraminifera is somewhat more consistent than in the other wells. A moderately rich benthic fauna is dominated by calcareous foraminifera. A few agglutinated forms are also recorded. Parts of the sandy Utsira Formation are very rich in molluscs and mollusc fragments (Figs. 7, 8, 9, 11 and 12). Most of the benthic foraminifera are extinct species but several extant species include *A. fluens, P. bulloides, N. affine, Bolivina skagerrakensis, C. lobatulus* and *Ammonia beccarii. A. fluens, N. affine* and *P. bulloides* have a recent biogeographic range extending mainly along the upper part of the continental slope and outer shelf. *N. affine* also occurs on middle and inner shelf areas in smaller numbers. *B. skagerrakensis* and *C. lobatulus* inhabit the inner to outer continental shelf (Sejrup et al. 1981, Mackensen et al. 1985). *A. beccari* is a shallow-water dweller according to Skarbø & Verdenius (1986), and this species is not recorded in well 25/10-2. Of the extinct species *S. bulloides* was mainly a deep-water dweller, *Loxostomoides lammersi* and *U. venusta saxonica* were deep- to shallow-water dwellers and *M. pseudotepida* and *Nodosaria koninckii* were shallow-water dwellers according to Skarbø & Verdenius (1986). Collectively, the benthic foraminiferal fauna and the concentration of planktonic fossils indicate an intermediate water depth. However, the high concentration of molluscs and mollusc fragments in parts of the Utsira Formation indicates that during several periods mussel banks formed. This again indicates that relatively shallow, high-energy environments periodically prevailed. The Upper Miocene and Lower Pliocene sediments were probably deposited mainly in a middle to inner neritic environment, and mainly in a middle to outer neritic environment in the lower part of the Utsira unit in well 25/10-2.

Lower part of the Upper Pliocene (Nordland Group)
In the lower part of the Upper Pliocene succession most of the ditch cutting samples contain a moderately rich fauna of planktonic foraminifera. However, in the short core in well 15/9-A-11, which is situated ca 27 m above the Utsira Formation, planktonic foraminifera are present in only one of three closely spaced samples (Fig. 13).

This indicates that the ditch cutting samples represent a mixture of material from beds both barren and quite rich in planktonic foraminifera. Consequently, investigation of ditch cuttings only shows large trends in the paleoenvironment. Calcareous foraminifera dominate in a a rich to very rich benthic fauna. Except for *C. grossus* all the benthic species are extant forms. *A. fluens, N. affine, C. teretis* and *C. grossus* occur frequently throughout most sections. Other important species include *C. lobatulus, B. marginata, E. excavatum, B. tenerrima, E. albiumbilicatun, Q. seminulum* and *E. groenlandicum*. According to Skarbø & Verdenius (1986) and King (1989), *C. grossus* was a deep- to shallow-water form. *A. fluens, N. affine, B. tenerrima, B. marginata, Q. seminulum* and *C. teretis* have modern biogeographic ranges extending mainly along the upper part of the continental slope and outer shelf. *N. affine, B. marginata, Q. seminulum* and *C. teretis* also occur on middle and inner shelf areas in smaller numbers. *C. lobatulus* and *E. albiumbilicatum* inhabit the inner to outer continental shelf (Sejrup et al. 1981, Mackensen et al. 1985). *E. groenlandicum* is mainly a shallow-water form and *E. excavatum* is a deep- to shallow-water form according to Skarbø & Verdenius (1986). The high concentration of planktonic foraminifera and deep shelf dwelling benthic foraminifera indicate somewhat greater water depth during deposition of the lower part of the Upper Pliocene than during the Late Miocene and Early Pliocene. The lower part of the Upper Pliocene was probably deposited mainly in an outer to middle neritic environment.

Upper part of the Upper Pliocene and Pleistocene (Nordland Group)

The upper part of the Upper Pliocene and Pleistocene succession has only been investigated in wells 15/12-3 and 16/1-4. In well 16/1-4, this unit is only sampled with sidewall cores with very little sample material and thus produces incomplete faunal assemblages. Planktonic foraminifera are scarce in both wells. Calcareous foraminifera dominate a rich to medium-rich benthic fauna of mainly calcareous foraminifera. *E. excavatum* and *C. teretis* occur most frequently. Other important species include *H. orbiculare, B. tenerrima, A. fluens, N. affine, E. groenlandicum, C. reniforme* (15/12-3), *E. bartletti* (15/12-3), *E. ustulatum* (15/12-3), *E. asklundi* (15/12-3), *Q. seminulum* (15/12-3) and *P. williamsoni* (15/12-3). *A. fluens, N. affine, B. tenerrima, Q. seminulum* and *C. teretis* have a modern biogeographic range extending mainly along the upper part of the continental slope and outer shelf. *N. affine, Q. seminulum,* and *C. teretis* also occur on middle and inner shelf areas in smaller numbers. *P. williamsoni* and *E. albiumbilicatum* inhabit the inner to outer continental shelf (Sejrup et al. 1981). *E. excavatum* and *H. orbiculare* are deep- to shallow-water species and *E. bartletti, E. ustulatum* and *E. asklundi* are all shallow-water forms according to Skarbø & Verdenius (1986). A near absence of planktonic foraminifera together with a high proportion of shallow-shelf dwelling benthic foraminifera indicate considerably shallower water depths during deposition of these sections than during deposition of the lower part of the Upper Pliocene. This is especially the case for the sandy upper part of the Pleistocene section in well 15/12-3 which is rich in mollusc fragments indicating periods with the formation of mussel banks. The upper part of the Upper Pliocene and Pleistocene were probably deposited mainly in a middle to inner neritic environment. A large proportion of ice-rafted pebbles in the sediments and a high content of arctic benthic foraminifera indicate cold-water conditions.

Conclusions

This paper is based on an extensive study of biostratigraphic and strontium isotopic data from six exploration and two production wells in the southern Viking Graben and eastern flank of the Utsira High. It represents a follow-up and documentation to our paper on the depositional history and sedimentary architecture of post-Eocene strata in the northern North Sea (Rundberg & Eidvin 2005). The main emphasis has been on the sandy Utsira and Skade formations of the Nordland and Hordaland Groups, respectively. The biostratigraphic and Sr isotopic data are presented in well summary sheets including fossil range charts, tables and one appendix. Log correlations and illustrations of interpreted seismic sections have been used to facilitate presentation of the data.

Biostratigraphically, especially the *Bolboforma* assemblages that we were able to record in many wells of the study area provided important clues in the dating of the basal part of the Utsira Formation and the lower part of the Neogene section. Also, the *Bolboforma* assemblages were important for precise correlation and better understanding of the geohistory of the basin. Correlation with the deep-ocean *Bolboforma* zones give quite accurate ages since the zones are of short duration and are calibrated using nannoplankton and paleomagnetic data.

Utsira Formation sandstones, as defined in this work, have a maximum thickness of about 300 m in the southern Viking Graben, and make up a huge sandbody, which we propose to be called the southern Utsira sand member. Northwards, the blocky sands pinch out and pass into finer-grained sediments in blocks 25/10 and 25/11 (proposed to be called the central Utsira member). The Sr isotopic dataset from the Utsira Formation shows dominantly Late Miocene and Early Pliocene ages which are in agreement with the biostratigraphic data. It is noteworthy that Early Miocene Sr isotopic signatures were obtained on a number of mollusc fragments from the Utsira Formation, suggesting reworking of fossil debris and erosion of sediments from the underlying Hordaland Group. The maximum age for the base of the Utsira Formation is about 12 Ma (in some wells slightly older than 12.3 Ma).

Our data suggest that the Skade Formation sandstones (gross thickness 300 m in well 16/1-4) were deposited throughout the Early Miocene (previously assigned to the Late Oligocene by Isaksen & Tonstad 1989). Consistent ages with depth were obtained for large parts of the Skade Formation by use of Sr isotope stratigraphy performed on mollusc fragments. This is in agreement with the biostratigraphic data.

Lithostratigraphically, our work has documented many errors in the existing nomenclature of the post-Eocene section in the Norwegian sector of the northern North Sea. Most significant is the obvious correlation conflict between the Utsira and Skade Formations (Isaksen & Tonstad 1989), which clearly must have caused confusion and problems to sequence stratigraphy workers in the northern North Sea. This error has also been incorporated into a number of completion logs and final well reports, as documented in wells from the Balder and Grane fields.

Finally, our work has demonstrated a distinctive need for an update and revision of the lithostratigraphic nomenclature in the northern North Sea. We believe that this paper can provide a good foundation for such a work.

Appendix

Fossil assemblages

In the eight wells examined in this study a system of 18 assemblages based on benthic foraminifera and 18 assemblages based on planktonic fossils is devised (Figs. 6-15). The boundaries between the assemblages are based on 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. Three intervals with very poor planktonic faunas (undefined interval P1, P2 and P3) and one interval with very poor benthic foraminiferal fauna (undefined interval F1) are also described. The descriptions of the units start with the youngest deposits and continue back in time, following the order in which they are normally encountered in offshore borehole studies.

Benthic foraminiferal assemblages and undefined intervals

ELPHIDIUM EXCAVATUM - HAYNESINA ORBICULARE ASSEMBLAGE
Definition: The top of the assemblage extends to the uppermost investigated sample. The base is taken at the highest consistent occurrence of *Cassidulina teretis*.
Depth range: 200-380 m in well 15/12-3 (Fig. 9a).
Age: Early to Middle Pleistocene.
Lithostratigraphic unit: Nordland Group.
Correlation: Zone Jo 6 of Knudsen & Asbjörndóttir (1991) and Zone NSB 17 of King (1983).
Description: The assemblage contains a medium rich benthic fauna of calcareous foraminifera. *E. excavatum* occurs most frequently. Other important taxa include *H. orbiculare, C. reniforme, E. ustulatum* and *E. asklundi.*
Remarks: The benthic foraminifera in this assemblage belong to characteristic Pliocene-Pleistocene taxa. All the recorded taxa are extant. Knudsen & Asbjörndóttir (1991) have described an *E. excavatum - H. orbiculare* assemblage Zone (Jo 6) from the well 30/13-2x in the British sector. Zone Jo 6 is slightly older than the Brunhes/Matuyama boundary.

ELPHIDIUM EXCAVATUM – CASSIDULINA TERETIS ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest consistent occurrence of *C. teretis* (well 15/12-3). It extends to the uppermost investigated sample in well 16/1-4. The base is marked by the highest occurrence of *Cibicides grossus*.
Depth range: 357.5-480.5 m in well 16/1-4 (Fig. 6a) and 380-600 m in well 15/12-3 (Fig. 9a).
Age: Early Pleistocene.
Lithostratigraphic unit: Nordland Group.
Correlation: Zone Jo 7 of Knudsen & Asbjörndóttir (1991) and Zone NSB 17 of King (1983).
Description: The assemblage is characterized by a rich to medium-rich benthic fauna of calcareous foraminifera. *E. excavatum* occurs frequently throughout. Other important taxa include *C. teretis, Cassidulina reniforme, Angulogerina fluens, E. ustulatum* and *H. orbiculare*.
Remarks: All the recorded species are extant. Knudsen & Asbjörndóttir (1991) describe a *C. teretis – E. excavatum* assemblage zone (Jo 7) in Lower Pleistocene sediments of well 30/13-2X (British sector).

CIBICIDES GROSSUS ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest occurrence of *C. grossus*. It extends to the uppermost investigated sample in wells 16/1-2 and 25/10-2. The base is marked by the highest occurrence of *Monspeliensina pseudotepida* in well 16/1-2 and 24/12-1, the highest occurrence of *Uvigerina venusta saxonica* in well 16/1-4 and 15/12-3, the highest occurrence of *Cibicidoides pachyderma* in well 15/9-A-11 and the highest occurrence of *Globocassidulina subglobosa* in well 25/10-2.
Depth range: 480.5-760 m in well 16/1-4 (Figs. 6a,b), 710-740 m in well 16/1-2 (Fig. 11), 480-500 m in well 24/12-1 (Fig. 7a), 442-506 m in well 25/10-2 (Fig. 8a), 600-900 m in well 15/12-3 (Fig. 9a) and 912.4-912.8 m in well 15/9-A-11 (only one sample analysed; Fig. 13).
Age: Late Pliocene to Early Pleistocene.
Lithostratigraphic unit: Nordland Group.
Correlation: Zone NSB 15 of King (1989), Zone Jo 8 of Knudsen & Asbjörndóttir (1991) and Zone NSR 12B of Gradstein & Bäckström (1996).
Description: The assemblage is characterized by a rich to very rich benthic fauna of mainly calcareous foraminifera. Only a sparse assemblage of four species is recorded from the investigated core sample in well 15/9-A-11. *A. fluens, Nonion affine, C. teretis* and *C. grossus* occur frequently throughout most sections. Other important species include *Cibicides lobatulus, Bulimina marginata, E. excavatum* and *E. groenlandicum.*
Remarks: The LAD of *C. grossus*, in the southern and in the southern central parts of the North Sea, is close to the Late Pliocene/Pleistocene boundary. In some areas further north in the North Sea, it became extinct somewhat later (Early Pleistocene, King 1989, Eidvin et al. 1999).

CIBICIDOIDES PACHYDERMA ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest occurrence of *C. pachyderma*. The base of the assemblage is undefined.
Depth range: 912.8-913.1 m in well 15/9-A-11 (Fig. 13).
Age: Late Pliocene.
Lithostratigraphic unit: Nordland Group.
Correlation: Subzone NSB 15a of King (1989).
Description: The unit contains a moderately rich benthic assemblage of calcareous foraminifera. *N. affine, C. pachyderma* and *C. teretis* occur most frequently. Other characteristic taxa include *C. lobatulus, A. fluens, C. scaldisiensis, E. groenlandicum* (lower part), *E. albiumbilicatum* (lower part).
Remarks: King (1989) describes a *C. pachyderma* Subzone NSB 15a from Lower-Upper Pliocene deposits in the North Sea.

MONSPELIENSINA PSEUDOTEPIDA ASSEMBLAGE.
Definition: The top of the assemblage is taken at the highest occurrence of *M. pseudotepida*. The base is marked by the highest occurrence of *U. venusta saxonica.*

Depth range: 740-750 m in well 16/1-2 (Fig. 11) and 500-520 m in well 24/12-1 (Fig. 7a).
Age: Early Pliocene.
Lithostratigraphic unit: Utsira Formation.
Correlation: Zone NSR 12A of Gradstein & Bäckström (1996), Zone Jo 10 of Knudsen & Asbjörndóttir (1991) and probably Zone NSB 14 of King (1989).
Description: The assemblage is characterized by a rich fauna of mainly calcareous foraminifera. A few agglutinated species are also recorded. *N. affine* and *Cibicides scaldisiensis* are most common. Other characteristic taxa include *A. fluens, M. pseudotepida, C. teretis, Globocassidulina subglobosa, Pullenia bulloides, Eponides umbonatus, Nodosaria konincki, Florilus boueanus, Bolivina imporcata, Sphaeroidina bulloides* and *Bolivina skagerakensis.*
Remarks: According to King (1989), in the North Sea area, *M. pseudotepida* is known from the Upper Miocene to the lower part of the Upper Pliocene, *F. boueanus* is described from the Upper Oligocene to the Lower Pliocene and *N. konincki* is recorded from the Lower to the lower part of the Upper Pliocene. *B. imporcata* is known from the Middle Miocene to the upper part of the Upper Miocene in the Netherlands (Doppert 1980). *G. subglobosa* is recorded from the Oligocene to the Lower Pliocene in the northern North Sea (Eidvin & Rundberg 2001) and on the Norwegian Sea continental shelf (Eidvin et al. 2007).

GLOBOCASSIDULINA SUBGLOBOSA ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest occurrence of *G. subglobosa*. The base is marked by the highest consistent occurrence of *Uvigerina venusta saxonica.*
Depth range: 460-497 m in well 25/10-2 (Fig. 8a).
Age: Early Pliocene.
Lithostratigraphic unit: Utsira Formation.
Correlation: Probably Zone NSR 11 and NSR 12 A of Gradstein & Bäckström (1996) and Zone NSB 14 of King (1989).
Description: The unit is characterized by a rich fauna of calcareous foraminifera. *C. teretis* occurs most frequently. Other characteristic species include *N. affine, G. subglobosa, E. groenlandicum, Quinqueloculina seminulum, A. fluens, E. excavatum, C. lobatulus* and *Eponides pygmeus. Loxostomoides lammersi, F. bouanus, Trifarina bradyi, Globulina gibba myristiformis* and *Plectofrondicularia advena* are also recorded.
Remarks: According to King (1989) are *P. advena* and *G. gibba myristiformis* known from the uppermost Upper Miocene to the lowermost Upper Pliocene in the North Sea area.

UVIGERINA VENUSTA SAXONICA ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest or highest consistent occurrence of *U. venusta saxonica*. The base is marked by the highest occurrence of *Uvigerina pygmea langenfeldensis* in well 24/12-1 and 15/12-3, and the highest consistent occurrence of *Uvigerina semiornata saprophila* in well 25/10-2. In well 16/1-4, 16/1-2 and 15/9-A-23 the base of the assemblage is undefined.
Depth range: 760-770 m in well 16/1-4 (Fig. 6b), 750-870 m in well 16/1-2 (Fig. 11), 520-720 m in well 24/12-1 (Fig. 7a), 570-725 m in well 25/10-2 (Fig. 8a), 900-1110 m in well 15/12-3 (Fig. 9b) and 1080 m (only one sample analysed) in well 15/9-A-23 (Fig. 12).
Age: Late Miocene to Early Pliocene.
Lithostratigraphic unit: Utsira Formation and Nordland Group.
Correlation: Subzone NSB 13b of King (1989).
Descrition: This interval contains a very rich to moderately rich benthic fauna of mainly calcareous foraminifera. A few agglutinated forms are also recorded. *U. venusta saxonica* (not numerous in well 25/10-2) and *N. affine* occur most frequently. Other important species include *P. bulloides, F. boueanus* and *C. teretis. A. fluens, M. pseudotepida, Loxostomoides lammersi, S. bulloides, G. subglobosa, N. konincki, Cibicidoides limbatosuturalis* and *Cibicides dutemplei* are recorded in most sections.
Remarks: According to King (1989), in the North Sea area, *U. venusta saxonica* is known from the Upper Miocene to the Lower Pliocene, *F. boueanus* is described from the Upper Oligocene to the Lower Pliocene and *C. limbatosuturalis* is recorded from the Upper Miocene to the lower part of the Upper Pliocene. *C. dutemplei* is known from Upper Oligocene to Lower Pliocene sediments in the Netherlands (Doppert 1980) and from the Upper Oligocene to the Upper Miocene on the Norwegian continental shelf (Skarbø & Verdenius 1986). *S. bulloides* is described from Upper Oligocene to Upper Miocene deposits in the Netherlands (Doppert 1980). A few specimens of *Gyroidina soldanii mamillata* from Lower Oligocene sediments, *Gyroidina soldanii girardana* and *Turrilina alsatica* from Upper Oligocene deposits and *Astigerina guerichi staeschei* from Lower to Middle Miocene sediments (King 1989) are recorded in most sections.

UNDEFINED INTERVAL B1
Depth range: 770-860 m in well 16/1-4.
Lithostratigraphic units: Utsira Formation and Hordaland Group.
Assemblage: The few small sidewall cores in this interval are almost barren, but a few specimens of the following calcareous benthic foraminifera are recorded: *Cibicides* sp., *N. affine, U. venusta saxonica, S. bulloides* and *C. dutemplei* (Fig. 6b).
Remarks: The benthic foraminifera in this interval indicate only a general Late Miocene – Early Pliocene age.

UVIGERINA PYGMEA LANGERI – UVIGERINA PYGMEA LANGENFELDENSIS ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest occurrence of *U. pygmea langenfeldensis* or *U. pygmea langeri*. In well 15/9-13 the top of the assemblage extends to the uppermost investigated sample. The base is marked by the highest occurrence of *Uvigerina tenuipustulata* or *A. guerichi staeschei.* In well 16/1-2 the base of the assemblage is not defined.
Depth range: 860-912.5 m in well 16/1-4 (Fig. 6b), 870-880 m in well 16/1-2 (Fig. 11), 720-820 m in well 24/12-1 (Fig. 7a) and 1110-1160 m in well 15/9-13 (Fig. 10a).
Age: Middle Miocene.
Lithostratigraphic units: Nordland Group and Skade Formation.
Correlation: Subzone NSB 13a and probably Zone 12 of King (1989).
Description: This assemblage contains a rich to moderately rich benthic fauna of mainly calcareous foraminifera. A few agglutinated foraminifera are also recorded. *U. pygmea langenfeldensis* are most common. Other important taxa include *U. pygmea langeri, P. bulloides, N. affine, E. variabilis, Bulimina elongata* and *C. dutemplei. G. subglobosa* and *Marttinotiella communis* (agglutinated) are also recorded in most sections.
Remarks: According to King (1989) *U. pygmea langenfeldensis* is known from the Middle Miocene and *U. pygmea langeri* from Middle to Upper Miocene deposits in the North Sea area. *M. communis* is known from the Middle Miocene of Belgium (Batjes 1958) and from the Middle Miocene to Lower Pliocene of the Netherlands (Doppert 1980). *B. elongata* is described from the Upper Oligocene to basal Upper Miocene in the North Sea (King 1989). *E. variabilis* is recorded from Upper Oligocene to Lower Pliocene deposits on the Norwegian continental shelf (Skarbø & Verdenius 1986).

UVIGERINA PYGMEA LANGENFELDENSIS ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest occurrence of *U. pygmea langenfeldensis*. The base is marked by the highest consistent occurrence of *A. guerichi staeschei.*
Depth range: 1110-1250 m in well 15/12-3 (Fig. 9b).
Age: Middle Miocene.
Lithostratigraphic units: Base Utsira Formation and Nordland Group.
Correlation: Subzone 13a and probably Zone NSB 12 of King (1989).
Description: This assemblage is characterized by a moderately rich benthic fauna of mainly calcareous foraminifera. A few agglutinated forms are also recorded. *U. pygmea langenfeldensis* is common. Other characteristic taxa include *P. bulloides, G. subglobosa, C. limbatosuturalis, B. elongata* and *S. bulloides. U. pygmea langeri* (one sample), *E. umbonatus, Uvigerina* sp. A (King 1989), *Siphonina reticulata, Bathy-*

siphon? sp. A (King 1989) and *Uvigerina semiornata saprophila* are also recorded in some samples.
Remarks: According to King (1989), in the North Sea area, *Bathysiphon*? Sp. A (agglutinated) is known from the Middle to Upper Miocene, *S. reticulata* is recorded from the Lower Oligocene to Middle Miocene and *Uvigerina* sp. A and *U. semiornata saprophila* are described from the Middle Miocene. A few specimens of *T. alsatica* are reworked from Lower Oligocene to basal Lower Miocene deposits.

UVIGERINA SEMIORNATA SAPROPHILA ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest consistent occurrence of *Uvigerina semiornata saprophila*. The base is marked by the highest occurrence of *Asterigerina guerichi staeshei.*
Depth range: 725-744 m in well 25/10-2 (Fig. 8b).
Age: Middle Miocene.
Lithostratigraphic units: Nordland Group.
Correlation: Zone NSB 12 of King (1989).
Description: This assemblage is characterized by a moderately rich benthic fauna of calcareous foraminifera. Characteristic taxa include *U. semiornata saprophila, N. affine, C. teretis, C. lobatulus, B. imporcata, P. bulloides, G. sublobosa, Trifarina bradyi, B. elongata* and *Uvigerina* sp. A.
Remarks: Uvigerina sp. A and *U. semiornata saprophila* are known from the Middle Miocene in the North Sea area according to King (1989).

ASTERIGERINA GUERICHI STAESCHEI ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest or highest consistent occurrence of *A. guerichi staeschei*. The base is marked by the highest or highest consistent occurrence of *U. tenuipustulata*.
Depth range: 744-771 m in well 25/10-2 (Fig. 8b), 1250-1300 m in well 15/12-3 (Fig. 9b) and 1160-1190 m in well 15/9-13m (Fig. 10a).
Age: Middle Miocene.
Lithostratigraphic units: Nordland Group and Skade Formation.
Correlation: Zone NSB 11 of King (1989), probably Zone FD of Doppert (1980) and probably Zone NSR 9A of Gradstein & Bäckström (1996).
Description: This assemblage contains a moderately rich benthic fauna of mainly calcareous foraminifera. *A. guerichi staeschei* occurs most frequently. Other characteristic species include *B. elongata, C. dutemplei, G. subglobosa, N. affine* and *P. bulloides.*
Remarks: A. guerichi staeschei is known from Lower to Middle Miocene deposits in the northern North Sea (King 1989).

UVIGERINA TENUIPUSTULATA – ASTERIGERINA GUERICHI STAESCHEI ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest occurrence of *U. tenuipustulata* and *A. guerichi staeschei.* The base is marked by the highest occurrence of *Plectofrondicularia seminuda* or *Spirosigmoilinella compressa.*
Depth range: 912.5-1090 m in well 16/1-4 (Fig. 6b) and 820-1020 m in well 24/12-1 (Fig. 7b).
Age: Early Miocene.
Lithostratigraphic units: Nordland Group and Skade Formation.
Correlation: Zone NSB 10 and Zone NSB 11 of King (1989), Zone NSR 8B of Gradstein & Bäckström (1996) and Zone FD of Doppert (1980).
Description: The assemblage contains a moderately rich benthic fauna of mainly calcareous foraminifera. Some agglutinated foraminifera are also recorded especially in the lower part of the section in well 16/1-4. *A. guerichi staeschei* and *U. tenuipustulata* occur most frequently. Other characteristic taxa include *B. elongata, Uvigerina semiornata semiornata, Elphidium inflatum, Trifarina gracilis var. A, C. dutemplei, N. affine, Astigerina guerichi guerichi* and *P. bulloides.*
Remarks: A. guerichi staeschei is known from Lower to Middle Miocene deposits in the northern North Sea, and *U. tenuipustulata* is known from the Lower to the basal Middle Miocene in the same area (King 1989). King (1983, 1989) describes an interval with *A. guerichi staeschei* (Zone NSB 11) above the highest occurrence of *U. tenuipustulata*. However, locally this zone may be condensed or absent, and in these areas *A. guerichi staeschei* and *U. tenuipustulata* have approximately coincident highest occurrences (King 1983). *E. inflatum* is known from the Lower to Middle Miocene and *A. guerichi guerichi* is known from the Upper Oligocene to the Lower Miocene in the North Sea area (King, 1989). *U. semiornata semiornata* is recorded from the Lower to Middle Miocene in the same area (Gradstein & Bäckström, 1996). *T. gracilis* var. A is described from Upper Oligocene to basal Middle Miocene sediments on the Norwegian continental shelf (Skarbø & Verdenius 1986). A few specimens of reworked *G. soldanii mamillata* from Lower Oligocene sediments and *T. alsatica* and *G. soldanii girardana* from Upper Oligocene to basal Lower Miocene deposits (King 1989) are recorded from some samples.

UVIGERINA TENUIPUSTULATA ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest or highest consistent occurrence of *U. tenuipustulata.* The base is marked by the highest occurrence of *P. seminuda.*
Depth range: 780-973 m in well 25/10-2 (Fig. 8b), 1300-1340 m in well 15/12-3 (Fig. 9b) and 1190-1320 m in well 15/9-13 (Fig. 10a).
Age: Early Miocene.
Lithostratigraphic units: Nordland Group and Hordaland Group in well 15/12-3 and Skade Formation and Hordaland Group in well 15/9-13.
Correlation: Zone NSB 10 of King (1989).
Description: The assemblage contains a rich to moderately rich benthic fauna of mainly calcareous foraminifera. A few agglutinated forms are also recorded. *U. tenuipustulata* and *A. guerichi staeschei* occur most frequently. Other characteristic taxa include *B. elongata, C. dutemplei, P. bulloides, N. affine, Elphidium inflatum, G. subglobosa,* and *F. boueanus.*
Remarks: U. tenuipustulata Zone (NSB 10) is recorded from Lower Miocene sediments in the North Sea. *E. inflatum* is described from the Lower to Middle Miocene in the same area. A few specimens of supposed reworked *T. alsatica* and *G. soldanii girardana*, from Upper Oligocene to basal Lower Miocene deposits and *G. soldanii mamillata,* from Lower to basal Upper Oligocene sediments (King 1989) are recorded in a some samples.

PLECTOFRONDICULARIA SEMINUDA ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest or highest consistent occurrence of *P. seminuda*. The base is marked by the highest consistent occurrence of *T. alsatica* or the highest occurrence of *A. biedai.*
Depth range: 1020-1090 m in well 24/12-1 (Fig. 7b), 973-1091 m in well 25/10-2 (Fig. 8c), 1340-1460 m in well 15/12-3 (Fig. 9b) and 1320-1420 m in well 15/9-13 (Fig. 10b).
Age: Early Miocene.
Lithostratigraphic unit: Hordaland Group.
Correlation: Zone NSB 9 and probably the uppermost part of Subzone NSB 8c of King (1989).
Description: This assemblage contains a moderately rich to sparse benthic fauna. Calcareous benthic foraminifera are dominant, but several agglutinated species are also recorded in most sections. No species are common, but important taxa are *P. seminuda, Bolivina* cf. *antique* (not recorded in well 25/10-2), *N. affine, A. guerichi guerichi* (not recorded in well 25/10-2), *B. elongata, G. subglobosa, P. bulloides. Trifarina gracilis, Stilostomella spp., U. tenuipustulata, A. guerichi staeschei, E. inflatum* and *Rolfina arnei* (lower part) are also recorded.
Remarks: P. seminuda is known from the Lower Oligocene to the Lower Miocene succession in the North Sea (King 1989). *B.* cf. *antiqua* is described from the Upper Oligocene to the lower part of the Lower Miocene in the same area (King 1989). *T. gracilis* is known from the Upper Oligocene in Belgium (Batjes 1958) and the Upper Oligocene to Middle Miocene on the Norwegian continental shelf (Skarbø & Verdenius 1986). According to Laursen (1994), *R. arnei* is synonymous with *Rotalia* sp. 1 of Larsen & Dinesen (1959) and *Glabratella*? sp. A of King (1989) and is recorded from Upper Oligocene to Lower Miocene deposits in Denmark (Larsen & Dinesen 1959) and in the North Sea (King 1989, Laursen 1994).

SPIROSIGMOILINELLA COMPRESSA ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest occurrence of *S. compressa*. The base is marked by the highest consistent occurrence of *Turrilina alsatica.*
Depth range: 1090-1190 m in well 16/1-4 (Fig. 6c).
Age: Latest Late Oligocene to Early Miocene.
Lithostratigraphic units: Skade Formation and Hordaland Group.
Correlation: Zone NSA 10 of King (1989).
Description: This interval contains a sparse benthic fauna of mainly agglutinated foraminifera, but a few calcareous species are also recorded. No species occur frequently, but characteristic taxa are *S. compressa, Trochammina sp., Recurvoides sp., Ceratobulimina hauerie (calcareous), Cyclammina sp., Ammodiscus spp.* and *Glomospira charoides.*
Remarks: King (1989) describes a *Spirosigmoilinella* sp. A (synonymous with S. *compressa*) Zone (NSA 10) in Lower Miocene deposits in the North Sea.

TURRILINA ALSATICA ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest consistent occurrence of *T. alsatica.* The base of the assemblage is undefined in wells 24/12-1 and 15/9-13. In wells 16/1-4 and 25/10-2 the base is marked by the highest occurrence of *Rotaliatina bullimoides.*
Intervals: 1190-1260 m in well 16/1-4 (Fig. 6c), 1090-1240 m in well 24/12-1 (Fig. 7b), 1091-1192 m in well 25/10-2 (Fig. 8c) and 1420-1550 m in well 15/9-13 (Fig. 10b).
Age: Late Oligocene to earliest Early Miocene (well 24/12-1 and 25/10-2).
Lithostratigraphic unit: Hordaland Group.
Correlation: NSB 8 of King (1989) and probably Zone NSR 8A and the upper part of Zone 7B of Gradstein & Bäckström (1996).
Description: The assemblage contains a moderately rich benthic fauna of mainly calcareous foraminifera. Several agglutinated forms are also recorded. Agglutinated foraminifera are most numerous in well 15/9-13. *T. alsatica* occur most frequently in all sections. Other characteristic taxa include *G. soldanii girardana, G. sublobosa, A. guerichi guerichi, B. cf. antiqua, T. gracilis, B. elongata* and *R. arnei.*
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) *T. alsatica* is known from the Lower Oligocene to the lowermost Upper Oligocene and *G. soldanii girardana* is known from the Upper Eocene to the Lowermost Miocene in the same area.

ANNECTINA BIEDAI – TURRILINA ALSATICA ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest occurrence of *A. biedai* and the highest consistent occurrence of *T. alsatica.* The base of the assemblage is undefined.
Depth range: 1460-1520 m in well 15/12-3 (Fig. 9b).
Age: Late Oligocene.
Lithostratigraphic unit: Hordaland Group.
Correlation: Zone NSB 8 and Zone NSA 9 of King (1989) and probably Zone NSR 8A and the upper part of Zone NSR 7B of Gradstein & Bäckström (1996).
Description: The assemblage contains a moderately rich benthic fauna. Calcareous forms are most important, but agglutinated forms are also common. No species is very numerous, but calcareous taxa include *B. elongata, T. alsatica, Cibicides sulzensis, G. soldanii girardana, Buliminella carteri* and *Nonion pompilioides.* Important agglutinated taxa are *Bathysiphon eocenicus, Ammodiscus* sp. A (King 1989), *A. biedai, G. charoides, Cyclammina rotundidorsatum* and *Spirosigmoilinella* spp.
Remarks: According to King (1989), *A. biedai* (synonymous with *Ammodiscus* sp. B of King 1989) and *Ammodiscus* sp. A (King 1989) are known from Lower Oligocene to lowermost Lower Miocene deposits in the North Sea area. According to Batjes (1958), *N. pompilioides, C. sulzensis* and *B. carteri* are described from Upper Oligocene sediments in Belgium.

ROTALIATINA BULIMOIDES ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest occurrence of *R. bulimoides.* The base of the assemblage is not defined.
Interval: 1260-1400.5 m in well 16/1-4 (Fig. 6c), 1192-1210 m in well 25/10-2 (Fig. 8c) and the lowermost investigated sample in well 15/9-13 (1550 m; Fig. 10b).
Age: Early Oligocene.
Lithostratigraphic unit: Hordaland Group.
Correlation: Subzone NSB 7b of King (1989) and probably Zone NSR 7A and lower part of the Zone NSR 7B of Gradstein & Bäckström (1996).
Description: This assemblage contains a moderately rich benthic fauna of mainly calcareous foraminifera. Several agglutinated forms are also recorded. *R. bulimoides* and *T. alsatica* are common in most section. Other characteristic taxa include *G. soldanii mamilliata, Stilostomella* sp. and *C. telegdi.*
Remarks: In the North Sea area *G. soldanii mamilliata* is described from the Lower Oligocene to the lowermost Upper Oligocene according to King (1989) and from the Upper Eocene to the lowermost Upper Oligocene according to Gradstein & Bäckström (1996). *R. bulimoides* is known from the Lower Oligocene to the lowermost Upper Oligocene according to King (1989) and from the Upper Eocene to the Lower Oligocene according to Gradstein & Bäckström (1996).

Planktonic fossil assemblages and undefined intervals

UNDEFINED INTERVAL P1
Depth range: 357.5-646.5 m in well 16/1-4.
Age: Late Pliocene to Pleistocene (based on benthic foraminiferal evidence).
Lithostratigraphic unit: Nordland Group.
In-place assemblage: Just a few specimens of *Neogloboquadrina pachyderma* (sinistral, unencrusted) and *Neogloboquadrina pachyderma* (dextral) are recorded in one sample (Fig. 6a).
Reworked assemblage: A few specimens of *Heterohelix* sp., from Upper Cretaceous deposits, are recorded from one sample (Fig. 6a).

UNDEFINED INTERVAL P2
Depth range: 200-790 m in well 15/12-3.
Age: Late Pliocene to Pleistocene (based on benthic foraminiferal evidence).
Lithostratigraphic unit: Nordland Group.
In-place assemblage composition: Just a few specimens of *N. pachyderma* (sinistral, unencrusted) are recorded from the upper and the lower part of this interval (Fig. 9a).
Reworked assemblage composition: Heterohelix sp. and *Hedbergella* sp. are recorded sporadically throughout the interval (Fig. 9a). These taxa are derived from Upper Cretaceous sediments.

NEOGLOBOQUADRINA PACHYDERMA (DEXTRAL) ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest consistent occurrence of *N. pachyderma* (dextral). In well 25/10-2 the top of the assemblage extends to the uppermost investigated sample. The base is marked by the highest occurrence of *Neogloboquadrina atlantica* (dextral) in well 16/1-4 and 15/12-3 and by the highest occurrence of *Globigerina bulloides* in well 25/10-2.
Depth range: 650-670 m in well 16/1-4 (Fig. 6a), 442-460 m in well 25/10-2 (Fig. 8a) and 790-840 m in well 15/12-3 (Fig. 9a).
Age: Late Pliocene.
Lithostratigraphic unit: Nordland Group.
Correlation: N. pachyderma (dextral) Zone of Weaver (1987), Weaver & Clement (1986) and Spiegler & Jansen (1989) and Subzone NSP 16a of King (1989).
Description: This assemblage contains a moderately rich to sparse fauna of planktonic foraminifera. *N. pachyderma* (dextral) is dominant. Other species include *Neogloboquadrina pachyderma* (sinistral, unencrusted), *Turborotalia quinqueloba*, and a few specimens of Heterohelix sp., from Upper Cretaceous deposits are also recorded in most wells.
Remarks: A latest Pliocene *N. pachyderma* (dextral) Zone is described by King (1989) from the North Sea, by Weaver (1987) and Weaver & Clement (1986) from the North Atlantic (DSDP Leg 94) and by Spi-

egler & Jansen (1989) from the Vøring Plateau (ODP Leg 104). On the Vøring Plateau the zone is dated to 1.9-1.8 Ma. The zone is characterized by common *N. pachyderma* (dextral). However, *N. pachyderma* (dextral) is also recorded, in smaller numbers, in Pleistocene sections in these areas, and is quite numerous in the warmest interglacials of the last 0.5 Ma (Kellogg 1977, Spiegler & Jansen 1989). It is not obvious that the top of the *N. pachyderma* (dextral) assemblage in well 16/1-4 and 15/12-3 corresponds to an age of 1.8 Ma. In the barren, immediately overlying intervals, no planktonic foraminifera may have reached the shallow marine area of these sites and consequently the correlation of the top of the assemblage is uncertain.

UPPER NEOGLOBOQUADRINA ATLANTICA (DEXTRAL) ASSEMBLAGE

Definition: The top of the assemblage is taken at the highest occurrence of *N. atlantica* (dextral). The base is marked by the highest occurrence of *Neogloboquadrina atlantica* (sinistral) in well 16/1-4 and the highest occurrence of *Globigerina bulloides* in well 15/12-3. In well 15/9-A-11 the base of the assemblage is undefined

Depth range: 670-720 m in well 16/1-4 (Fig. 6a) and 840-850 m in well 15/12-3 (Fig. 9a) and 913.1 m in well 15/9-A-11 (only on sample is analysed; Fig. 13).

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group.

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

Description: The assemblage is characterized by a moderately rich to sparse fauna of planktonic foraminifera. Taxa include *N. atlantica* (dextral), *N. pachyderma* (dextral), *N. pachyderma* (sinistral, unencrusted) and *T. quinqueloba*. In the core sample in well 15/9-A-11 a few specimens of G. bulloides are also recorded.

Remarks: An upper *N. atlantica* (dextral) Zone is described from the Vøring Plateau in Upper Pliocene deposits, and is dated to 2.4-1.9 Ma (Spiegler & Jansen 1989).

GLOBIGERINA BULLOIDES ASSEMBLAGE

Definition: The top of the assemblage is taken at the highest occurrence of G. bulloides in wells 25/10-2 and 15/12-3. In well 24/12-1 the top of the assemblage extends to the uppermost investigated sample. The base is marked by the highest occurrence of *N. atlantica* (sinistral) in wells 25/10-2 and 15/12-3 and by the highest occurrence of *Globorotalia puncticulata* in well 24/12-1.

Depth range: 480-510 m in well 24/12-1 (Fig. 7a), 460-497 m in well 25/10-2 (Fig. 8a) and 850-860 m in well 15/12-3 (Fig. 9a).

Age: Early-Late Pliocene.

Lithostratigraphic unit: Nordland Group.

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

Description: Planktonic foraminifera are quite sparse in this assemblage. Taxa include *G. bulloides, N. pachyderma* (dextral) and *T. quinqueloba. N. pachyderma* (sinistral, unencrusted) is also recorded in most sections.

Remarks: A *G. bulloides* Zone is described from the North Atlantic (DSDP Leg 94) in Pliocene sediments as young as 2.2 Ma (Weaver & Clement 1986). On the Vøring Plateau *G. bulloides* is common in Pliocene deposits older than 2.4 Ma (Spiegler & Jansen 1989). G. bulloides is also common in the warmest interglacials of the last 0.5 Ma in the North Atlantic (Kellogg 1977).

NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

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

Depth range: 720-763.5 m in well 16/1-4 (Fig. 6b), 710-740 m in well 16/1-2 (Fig. 11), 497-570 m in well 25/10-2 (Fig. 8a) and 860-940 m in well 15/12-3 (Figs. 9a,b).

Age: Early to Late Pliocene

Lithostratigraphic unit: Nordland Group.

Correlation: N. atlantica (sinistral) Zone of Weaver & Clement (1986) and Spiegler & Jansen (1989).

Description: This assemblage is characterized by a moderately rich to sparse fauna of planktonic foraminifera. *G. bulloides* and *N. atlantica* (sinistral) occur most frequently. Other characteristic species include *N. pachyderma* (dextral) and *T. quinqueloba. N. pachyderma* (sinistral, unencrusted) is also recorded in most sections and *Globorotalia inflate* in some sections.

Remarks: A N. atlantica (sinistral) Zone is described from the North Atlantic in Upper Pliocene deposits (Weaver & Clement 1986), and from the Vøring Plateau in Lower to Upper Pliocene deposits (Spiegler & Jansen 1989). The LAD of *N. atlantica* (sinistral) is, in both areas, approximately 2.4 Ma (Weaver & Clement 1986, Spiegler & Jansen 1989). On the Vøring Plateau, there is a marked dominance of this species together with *G. bulloides* in Pliocene deposits older than this. *G. bulloides* is also common in the warmest interglacials of the last 0.5 Ma (Kellogg 1977).

GLOBOROTALIA PUNCTICULATA ASSEMBLAGE.

Definition: The top of the assemblage is taken at the highest occurrence of *G. puncticulata*. The base is marked by the highest consistent occurrence of *N. atlantica* (dextral) in wells 16/1-2, 24/12-1 and 25/10-2 and the highest occurrence of Neogloboquadrina acostaensis in well 15/12-3. In wells 16/1-4 and 15/9-A-23 the base of the assemblage is undefined.

Depth range: 763.5-770 m in well 16/1-4 (Fig. 6b), 740-780 m in well 16/1-2 (Fig. 11), 510-550 m in well 24/12-1 (Fig. 7a), 570-625 m in well 25/10-2 (Fig. 8a), 940-1010 m in well 15/12-3 (Fig. 9b) and 1080 m (only one sample is analysed) in well 15/9-A-23 (Fig. 12).

Age: Early Pliocene.

Lithostratigraphic units: Nordland Group and Utsira Formation.

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

Description: The assemblage contains a moderately rich fauna of planktonic foraminifera. *G. bulloides* is most common. Other species include *N. atlantica* (sinistral), *G. puncticulata* and *N. pachyderma* (dextral). *T. quinqueloba* is also recorded in most sections, and a few specimens of Orbulina universa are recorded in well 25/10-2.

Remarks: An Early Pliocene *G. puncticulata* Zone is described by Weaver & Clement (1986) from the North Atlantic (DSDP Leg 94). FAD of *G. puncticulata* occurs at ca 4.6 Ma and its LAD occurs at ca 2.5 Ma, but the zone is defined as the interval between FAD of *G. puncticulata* and the LAD of *Globorotalia* cf. *crassula* (ca 3.4 Ma). *Globorotalia* cf. *crassula* is not recorded from the Norwegian Sea or North Sea areas (Spiegler & Jansen 1989, King 1989). In the North Atlantic the LAD of *G. puncticulata* is somewhat earlier or close to the LAD of *N. atlantica* (sinistral, approximately 2.4 Ma, Weaver & Clement 1986). According to King (1989), in the North Sea area, the LAD of *G. puncticulata* is later than that of *N. atlantica* (sinistral). This is contrary to what is observed in most wells in this study. In wells 16/1-2 and 15/9-A-23 a few specimens of supposed reworked *Bolboforma* from the uppermost Middle Miocene and the lowermost Upper Miocene are recorded in several samples. In well 16/1-2 these include *Bolboforma* metzmacheri, *Bolboforma clodiusi*, *Bolboforma subfragori, Bolboforma pseudohystrix, Bolboforma compressispinosa* and *Bolboforma reticulata.* In well 15/9-A-23 *Bolboforma fragori* and *Bolboforma laevis* are recorded. *Bolboforma badenensis* is found in both wells.

UNDEFINED INTERVAL P3

Depth range: 357.5-646.5 m in 16/1-4.

Lithostratigraphic unit: Nordland Group.

In-place assemblage: The few small sidewell cores in this interval are almost barren, but a few specimens of N. pachyderma (sinistral, unencrusted) and N. pachyderma (dextral) are recorded in one sample (Fig. 6b).

Reworked assemblage: A few specimens of Heterohelix sp., from Upper Cretaceous deposits, are recorded from one sample (Fig. 6b).

LOWER NEOGLOBOQUADRINA ATLANTICA (DEXTRAL) ASSEMBLAGE

Definition: The top of the assemblage is taken at the highest consistent occurrence of *N. atlantica* (dextral). The base is marked by the highest occurrence of *B. fragori* in well 24/12-1, the highest occurrence of *B. metzmacheri* in well 25/10-2 and the highest consistent occurrence of *B. badenensis* in well 16/1-2.
Depth range: 780-870 m in well 16/1-2 (Fig. 11), 550-700 m in well 24/12-1 (Fig. 7a) and 625-634 m in well 25/10-2 (Fig. 8a).
Age: Late Miocene.
Lithostratigraphic units: Utsira Formation and Nordland Group.
Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989) and *N. atlantica* (dextral)/*N. acostaensis* Zone of Weaver (1987) and Weaver & Clement (1987).
Description: This unit contains a moderately rich planktonic fossil assemblage of foraminifera and *Bolboforma.* Foraminifera are dominant, while *Bolboforma* are subordinate. *G. bulloides* and *N. atlantica* (sinistral) are the most frequently occurring of the foraminifera. Other characteristic taxa include *N. atlantica* (dextral), *N. pachyderma* (dextral) and *T. quinqueloba*. A few specimens of *O. universa* and *N. acostaensis* (16/1-2) are also recorded in several samples. *Bolboforma* are recorded sporadically in well 16/1-2 and these include *Bolboforma metzmacheri, B. reticulata, B. subfragori, B. pseudohystrix, B. compressispinosa* and *B. badenensis*. In well 24/12-1 *B. fragori* and *B. laevis* are recorded. *B. clodiusi* is recorded in both wells.
Remarks: Spiegler & Jansen (1989) describe a lower *N. atlantica* (dextral) Zone from Upper Miocene sediments on the Vøring Plateau, and Weaver (1987) and Weaver & Clement (1987) record a *N. atlantica* (dextral)/*N. acostaensis* Zone from Upper Miocene sediments in the North Atlantic (DSDP Leg 94). *N. acostaensis* is reported from deposits of Middle to Late Miocene age on the Vøring Plateau (Spiegler & Jansen 1989, Müller & Spiegler 1993). According to Spiegler & Müller (1992), in the North Atlantic, and according to Qvale & Spiegler (1989) and Müller & Spiegler (1993), on the Vøring Plateau, the LADs of *B. metzmacheri, B. clodiusi, B. subfragori* and *B. pseudohystrix* are recorded from the lowermost Upper Miocene sediments. The LADs of *B. badenensis, B. reticulata* and *B. compressispinosa* are reported from the uppermost Middle Miocene deposits in the same areas. In wells 16/1-2 and 24/12-1, the progression of the LADs of *Bolboforma* taxa is unlike that found in the North Atlantic. It is therefore reasonable to assume that, at least, the Middle Miocene forms are reworked. Some of the Late Miocene forms are probably *in situ*, but some of these may also be reworked.

NEOGLOBOQUADRINA ATLANTICA (DEXTRAL) - NEOGLOBOQUADRINA ACOSTAENSIS ASSEMBLAGE

Definition: The top of the assemblage is taken at the highest occurrence of *N. acostaensis*. The base is marked by the highest occurrence of *B. badenensis* and *B. reticulata.*
Depth range: 1010-1110 m in well 15/12-3 (Fig. 9b).
Age: Late Miocene.
Lithostratigraphic unit: Utsira Formation.
Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989), *N. atlantica* (dextral)/*N. acostaensis* Zone of Weaver (1987) and Weaver & Clement (1987) and Subzones NSP 15a and 15b of King (1989).
Description: The assemblage is characterized by a moderately rich fauna of mainly planktonic foraminifera. *N. acostaensis, G. bulloides and N. atlantica* (sinistral) occur most frequently. Other important taxa include *N. atlantica* (dextral), *T. quinqueloba* and *N. pachyderma* (dextral). A few specimens of *B. clodiusi* are recorded from the middle part of the interval.
Remarks: Spiegler & Jansen (1989) describe a lower *N. atlantica* (dextral) Zone from Upper Miocene sediments on the Vøring Plateau, and Weaver (1987) and Weaver & Clement (1987) record a *N. atlantica* (dextral)/*N. acostaensis* Zone from Upper Miocene sediments in the North Atlantic (DSDP Leg 94). *N. acostaensis* is reported from deposits of Late to Middle Miocene age on the Vøring Plateau (Spiegler & Jansen 1989, Müller & Spiegler 1993). King (1989) describes a *N. acostaensis* Zone from Upper Miocene deposits in the North Sea. The LAD of *B. clodiusi* is recorded in lowermost Upper Miocene sediments in the North Atlantic according to Spiegler & Müller (1992) and on the Vøring Plateau according to Qvale & Spiegler (1989) and Müller & Spiegler (1993). This form is very scarce in the present interval and it is reasonable to assume that the specimens are reworked from the immediately underlying section. However, they might also be *in situ*.

BOLBOFORMA METZMACHERI ASSEMBLAGE

Definition: The top of the assemblage is taken at the highest occurrence of *B. metzmacheri.* The base is marked by the highest occurrence of *B. fragori.*
Depth range: 634-661 m in well 25/10-2 (Fig. 8a).
Age: Late Miocene.
Lithostratigraphic unit: Utsira Formation.
Correlation: Bolboforma metzmacheri Zone of Spiegler & Müller (1992) and Müller & Spiegler (1993), *Bolboforma metzmacheri* zone of Stratlab (1988), Zone NSR 10 of Gradstein & Bäckström (1996) and Subzone NSP 14b of King (1983).
Description: The assemblage contains a moderately rich fossil assemblage of planktonic foraminifera and *Bolboforma*. Planktonic foraminifera are dominant, with subordinate *Bolboforma*. *B. metzmacheri* occurs throughout the unit. One specimen of *Bolboforma reticulata* is also recorded, but this is probably reworked from Middle Miocene deposits. *G. bulloides* is the most common foraminifera. Other characteristic taxa include *N. atlantica* (dextral), *N. atlantica* (sinistral) and *G. glutinata*.
Remarks: B. metzmacheri is described from sediments with an age of approximately 10.0-8.7 Ma in the North Atlantic and the Vøring Plateau (Spiegler & Müller 1992, Müller & Spiegler 1993)

BOLBOFORMA FRAGORI ASSEMBLAGE

Definition: The top of the interval is taken at the highest or highest consistent occurrence of *B. fragori.* The base is marked by the highest occurrence of *B. badenensis.*
Depth range: 700-720 m in well 24/12-1 (Fig. 7a) and 661-725 m in well 25/10-2 (Fig. 8a).
Age: Late Miocene.
Lithostratigraphic unit: Utsira Formation.
Correlation: B. fragori/Bolboforma subfragori Zone of Spiegler & Müller (1992) and Müller & Spiegler (1993) and Subzone NSP 14a of King (1983).
Description: The assemblage contains a moderately rich fossil assemblage of *Bolboforma* and planktonic foraminifera. *B. fragori* and *B. clodiusi* are the most common *Bolboforma* species. *B. subfragori* (24/12-1), *B. metzmacheri, B. laevis* (24/12-1) and *B. compressispinosa* (25/10-2) are also recorded. Planktonic foraminifera include *G. bulloides, N. atlantica* (sinistral), *N. pachyderma* (sinistral, unencrusted, caved), *N. pachyderma* (dextral), *T. quinqueloba, O. universa* (24/12-1) and *G. glutinata* (25/12-1).
Remarks: A B. fragori/B. subfragori Zone is known from deposits with an age of approximately 11.7-10.3 Ma from the North Atlantic and the Vøring Plateau (Spiegler & Müller 1992, Müller & Spiegler 1993). According to Berggren et al. (1995) the Middle/Late Miocene boundary is at 11.2 Ma.

BOLBOFORMA BADENENSIS ASSEMBLAGE

Definition: The top of the assemblage is taken at the highest consistent occurrence of *B. badenensis* in well 16/1-2 and 24/12-1. In well 15/9-13 the top of the assemblage extends to the uppermost investigated sample. The base is marked by the highest occurrence of *B. reticulata* in well 24/12-1 and 15/9-13. In well 16/1-2 the base of the assemblage is undefined.
Depth range: 870-880 m in well 16/1-2 (Fig. 11), 720-790 m in well 24/12-1 (Fig 7a) and 1110-1140 m in well 15/9-13 (Fig. 10a).
Age: Middle Miocene.
Lithostratigraphic units: Utsira Formation, Nordland Group and Skade Formation.

Correlation: B. badenensis Zone of Spiegler & Müller (1992), upper part of *B. badenensis/B. reticulata* Zone of Spiegler & Müller (1992) and probably Zone NSP 13 of King (1983).
Description: This unit is characterized by a rich to moderately rich fossil assemblage of *Bolboforma*, planktonic foraminifera, pyritized diatoms and radiolaria. *Bolboforma* are dominant, with subordinate foraminifera, pyritized diatoms and radiolaria. *B. clodiusi* and *B. badenensis* are the most common *Bolboforma.* Other species include *B. laevis* and *B. fragori.*
G. bulloides, N. atlantica (sinistral) and *N. atlantica* (dextral) are the most important foraminifera.
Remarks: A B. badenensis Zone is recorded from deposits with an age of 12.3-11.9 Ma from the North Atlantic (Spiegler & Müller 1992).

BOLBOFORMA BADENENSIS – BOLBOFORMA RETICULATA ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest occurrence of *B. badenensis* and *B. reticulata* (the highest consistent occurrence of *B. reticulata* in well 25/10-2). The base of the assemblage is marked by the highest occurrence of *Globigerina ciperoensis* in well 16/1-4, the highest consistent occurrence of *Globigerina praebulloides* in well 15/12-3 and the highest occurrence of *Globorotalia zealandica* in well 25/10-2.
Depth range: 860-912.5 m in well 16/1-4 (Fig. 6b), 725-771 m in well 25/10-2 (Fig. 8b) and 1110-1260 m in well 15/12-3 (Fig. 9b).
Age: Middle Miocene.
Lithostratigraphic unit: Nordland Group.
Correlation: B. badenensis and *B. reticulata* zones of Spiegler & Müller (1992), *B. badenensis/B. reticulata* Zone of Müller & Spiegler (1993) and probably Zone NSP 13 of King (1983).
Description: This assemblage contains a rich to moderately rich planktonic fauna of foraminifera and *Bolboforma. Bolboforma* are dominant with foraminifera being subordinate (wells 16/1-4 and 15/12-3). A few pyritized diatoms are also recorded. *B. badenensis* and *B. clodiusi* are the most common *Bolboforma.* Other characteristic species include *B. reticulata* and *B. laevis* and in wells 16/1-4 and 15/12-3 also *B. pseudohystrix, Bolboforma compressibadenensis* and *B. fragori.* Foraminifera include *G. bulloides, N. atlantica* (sinistral), *N. acostaensis* (16/1-4 and 15/12-3) and *N. atlantica* (dextral, well 15/12-3).
Remarks: Spiegler & Müller (1992) describe a *B. badenensis* Zone and a *B. reticulata* Zone from the North Atlantic and Müller & Spiegler (1993) describe a *B. badenensis/B. reticulata* Zone from the Vøring Plateau. These zones are recorded from deposits with an age slightly older than 14 to 11.9 Ma (Spiegler & Müller 1992).

BOLBOFORMA RETICULATA ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest occurrence of *B. reticulata.* The base is marked by the highest occurrence of *Globorotalia zealandica* and *Globigerina ciperoensis* in well 24/12-1 and the highest occurrence of *G. praebulloides* and *Globigerinoides quadrilobatus triloba* in well 15/9-13.
Depth range: 790-840 m in well 24/12-1 (Figs. 7a,b) and 1140-1160 m in well 15/9-13 (Fig. 10a).
Age: Middle Miocene.
Lithostratigraphic unit: Nordland Group and Skade Formation.
Correlation: B. reticulata Zone of Spiegler & Müller (1992), *B. badenensis/B. Reticulata* Zone of Müller & Spiegler (1993) and probably lower part of Zone NSP 13 of King (1983).
Description: This unit is characterized of a moderately rich fossil assemblage of *Bolboforma* and planktonic foraminifera, radiolaria and pyritized diatoms. *Bolboforma* are dominant, with subordinate foraminifera, radiolaria and pyritized diatoms (well 15/9-13). *B. badenensis, B. clodiusi* and *B. reticulata* are the most common *Bolboforma. B. fragori* is also recorded. Planktonic foraminifera include *G. bulloides, G. glutinata, N. atlantica* (sinistral) and *N. atlantica* (dextral, well 15/9-13).
Remarks: A B. reticulata Zone is recorded from deposits with an age of slightly older than 14.0 to 12.4 Ma from the North Atlantic (Spiegler & Müller 1992).

GLOBIGERINA PRAEBULLOIDES ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest consistent occurrence of *G. praebulloides*. The base is marked by the highest occurrence of *G. zealandica* and *G. ciperoensis.*
Depth range: 1260-1300 m in well 15/12-3 (Fig. 9b).
Age: Middle Miocene.
Lithostratigraphic unit: Nordland Group.
Correlation: Zone NSP 12 of King (1983) and upper part of Zone NSR 9A of Gradstein & Bäckström (1996).
Description: This unit contains a rich planktonic fossil assemblage of radiolaria, *Bolboforma*, foraminifera and pyritized diatoms. Radiolaria and *Bolboforma* are dominant, while foraminifera and diatoms being subordinate. *B. pseudohystrix* is the most common *Bolboforma*, followed by *B. reticulata, B. badenensis, B. compessibadenensis* and *B. subfragori. G. praebulloides* is the most common foraminifer. Other species include *Neogloboquadrina mayeri, Globigerina angustiumbilicata, Globigerina woodi* and *Spaeroidinellopsis disjuncta.*
Remarks: G. praebulloides is known from Oligocene to lower Upper Miocene (common in Middle Miocene) deposits in the North Atlantic (Poore 1979) and from Oligocene to lower Middle Miocene deposits in the North Sea (Gradstein & Bäckström 1996). *G. woodi* is known from Upper Oligocene to Lower Pliocene sediments in the North Atlantic (Poore, 1979). *S. disjuncta* is known from Lower to Middle Miocene sediments in the North Sea (Gradstein & Bäckström 1996). *G. angustiumbilicata* is known from Upper Oligocene to Lower Pliocene deposits (Kennet & Srinivasan 1983). The *Bolboforma* recorded in this interval are probably caved.

GLOBIGERINA PRAEBULLOIDES - GLOBIGERINOIDES QUADRILOBATUS TRILOBA ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest consistent occurrence of *G. praebulloides* and *G. quadrilobatus triloba.* The base is marked by the highest occurrence of *G. ciperoensis.*
Depth range: 1160-1200 m in well 15/9-13 (Fig. 10a).
Age: Early – Middle Miocene.
Lithostratigraphic unit: Skade Formation.
Correlation: Zone NSP 12 of King (1983) and the upper part of Zone NSR 9A of Gradstein & Bäckström (1996).
Description: This assemblage contains a rich planktonic fossil assemblage of radiolaria, *Bolboforma*, foraminifera and pyritized diatoms. Radiolaria and *Bolboforma* are dominant, while foraminifera and diatoms being subordinate. *B. pseudohystrix* is the most common *Bolboforma,* followed by *B. reticulata, B. badenensis, B. compessibadenensis* and *B. subfragori. G. praebulloides* is the most common foraminifer. Other species include *N. mayeri, G. angustiumbilicata, G. woodi* and *S. disjuncta* (Fig. x).
Remarks: G. quadrilobatus triloba is described from upper Lower to Middle Miocene deposits in the North Sea (King 1989). The known stratigraphic ranges of the other planktonic foraminifera recorded in this assemblage are discussed above. The *Bolboforma* found in this interval are probably caved.

GLOBOROTALIA ZEALANDICA ASSEMBLAGE
Definition: The top of the assemblage is taken at the highest occurrence of *G. zealandica.* The base is marked by the highest occurrence of Diatom sp. 4 (King 1983).
Depth range: 711-963 m in well 25/10-2 (Fig. 8b).
Age: Early Miocene.
Lithostratigraphic unit: Skade Formation.
Correlation: Zone NSP 11 and probably Zone NSP 12 of King (1983) and probably Zone NSR 8B and the lower part of Zone NSR 9A of Gradstein & Bäckström (1996).
Description: The unit is characterized by a rich assemblage of planktonic foraminifera. radiolaria and pyritized diatoms. A number of the planktonic foraminifera and a few *Bolboforma* (upper part) are probably caved, but *in situ* forms include *G. praebulloides* (common), *G. angustiumbilicata* (common), *G. zealandica, G. quadrilobatus triloba* (parts of section) and *G. ciperoensis* (parts of section).

Remarks: G. zealandica is described from the Lower to lower Middle Miocene in the North Atlantic (Poore 1979) and in the North Sea (King 1983).

GLOBOROTALIA ZEALANDICA - GLOBIGERINA CIPEROENSIS ASSEMBLAGE

Definition: The top of the assemblage is taken at the highest occurrence of *G. ciperoensis* and *G. zealandica* in well 24/12-1 and 15/12-3 and the highest occurrence of *G. ciperoensis* in well 15/9-13 and 16/1-4. The base is marked by the highest occurrence of Diatom sp. 4 (King 1983) in wells 24/12-1, 15/12-3 and 15/9-13. In well 16/1-4 the base of the assemblage is taken at the lowest consistent occurrence of *G. ciperoensis.*

Depth range: 912.5-950 m in well 16/1-4 (Fig. 6b), 840-1040 m in well 24/12-1 (Fig. 7b), 1300-1340 m in well 15/12-3 (Fig. 9b) and 1200-1310 m in well 15/9-13 (Fig. 10a).

Age: Early Miocene.

Lithostratigraphic units: Nordland Group, Skade Formation and Hordaland Group (well 15/12-3).

Correlation: Zone NSP 11 and probably Zone NSP 12 (wells 16/1-4 and 24/12-1) of King (1983) and probably Zone NSR 8B and the lower part of Zone NSR 9A of Gradstein & Bäckström (1996).

Description: The unit is characterized by a rich planktonic fossil assemblage of foraminifera, radiolaria and pyritized diatoms. Caved *Bolboforma* are also recorded in the upper part of some sections. *G. ciperoensis, G. angustiumbilicata* and *G. woodi* are the most frequently occurring of the foraminifera. Other characteristic taxa include *G. zealandica, Globorotalia praescitula* and *G. quadrilobatus triloba.*

Remarks: G. ciperoensis is known from Upper Oligocene to Lower Miocene deposits in the North Atlantic (DSDP Leg 49; Poore, 1979) and in the North Sea (Gradstein & Bäckström 1996). *G. zealandica* and *G. praescitula* are described from the Lower to lower Middle Miocene in the North Atlantic (Poore 1979) and in the North Sea (King 1983).

UNDEFINED INTERVAL P4

Depth range: 950-1030 m in well 16/1-4 (Fig. 6b).

Age: Early Miocene (based on benthic foraminiferal evidence).

Lithostratigraphic unit: Hordaland Group.

Assemblage: This interval is nearly barren of planktonic fossils. Only a few unidentified radiolaria are recorded from one sample.

DIATOM SP. 4 ASSEMBLAGE

Definition: The top of the assemblage is taken at the highest occurrence of Diatom sp. 4 (King 1983). The base is marked by the highest or highest consistent occurrence (well 15/9-13) of Diatom sp. 3 (King 1983).

Depth range: 1030-1180 m in well 16/1-4 (Figs. 6b,c), 1040-1130 m in well 24/12-1 (Fig. 7b), 973-1101 m in well 25/10-2 (Fig. 8b,c), 1340-1460 m in well 15/12-3 (Fig. 9b) and 1310-1400 m in well 15/9-13 (Figs. 10a,b).

Age: Early Miocene.

Lithostratigraphic unit: Skade Formation and Hordaland Group.

Correlation: Zone NSP 10 of King (1983).

Description: This assemblage contains a rich planktonic fossil assemblage of diatoms, radiolaria and planktonic foraminifera. Caved *Bolboforma* are also recorded in some sections. Diatom sp. 4 occurs throughout most sections. Diatom sp. 5 (King 1983) is also recorded in some wells. The planktonic foraminifera *G. ciperoensis, G. woodi, G. praebulloides* and *G. angustiumbilicata* are recorded from most sections and *G. zealandica, G. praescitula* and *S. disjuncta* are also found in some wells. Some of these may be caved.

Remarks: Diatom sp. 4 and Diatom sp. 5 are known from Lower Miocene deposits in the North Sea (King 1983, 1989).

DIATOM SP. 3 ASSEMBLAGE

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

Depth range: 1180-1400.5 m in well 16/1-4 (Fig. 6c), 1130-1240 m in well 24/12-1 (Fig. 7b), 1101-1210 m in well 25/10-2 (Fig. 8c), 1460-1520 m in well 15/12-3 (Fig. 9b) and 1400-1550 m in well 15/9-13 (Fig. 10b).

Age: Early Oligocene (well 16/1-4) to Late Oligocene.

Lithostratigraphic unit: Hordaland Group.

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

Description: The assemblage is characterized by a rich to moderately rich planktonic fossil assemblage of pyritized diatoms, radiolaria and planktonic foraminifera. Diatom sp. 3 occurs throughout all sections. Diatom sp. 4 is also recorded in most sections. The planktonic foraminifera *G. praebulloides, G. wood, G. ciperoensis* and *G. angustiumbilicata* are found in most sections. Some of these may be caved.

Remarks: Diatom sp. 3 is known from the Oligocene to the lowermost Lower Miocene in the North Sea (King 1989).

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