Cenozoic stratigraphy of the Norwegian Sea continental shelf, 64°N–68°N

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This investigation is based on six exploration wells: 6607/5-1 and /5-2 (Utgard High), 6506/12-4 (Halten Terrace), 6610/7-1, 6610/7-2 and 6610/3-1 (Nordland Ridge). Fifteen informal fauna zones are outlined. Thick, glacially derived Pleistocene and Upper Pliocene prograding shelf deposits extend along the continental margin of the Norwegian Sea. In well 6607/5-1 and 6506/12-4 Upper Pliocene outer to middle shelf deposits lie unconformably on Upper Miocene outer shelf deposits, which are well developed in these areas. A thin interval of Middle Miocene outer shelf sediments is present in well 6607/5-1. This rests unconformably upon Lower/Middle Eocene middle to outer shelf deposits, which in turn rest unconformably upon the Upper Cretaceous. In well 6506/12-4, the Upper Miocene rests unconformably on outer to middle shelf sediments from the Upper Oligocene/Lower Miocene, which in turn lie unconformably on the Lower/Middle Eocene. In well 6607/5-2 Upper Pliocene outer shelf sediments lie unconformably on the Lower/Middle Eocene. Wells 6610/7-1 and /7-2 on the Nordland Ridge penetrate the proximal, oldest parts of the glacially derived prograding sediments of Late Pliocene age, which in this area are middle to inner shelf deposits. In addition, wells 6610/7-1 and 6610/3-1 penetrate underlying Early Oligocene coastal deposits. Lower/Middle Eocene sediments lie below the coastal deposits in well 6610/7-1. In well 6610/7-2 Upper Pliocene deposits lie unconformably upon low oxic deep basin sediments from the Upper Paleocene. Seismic profiles through this area show that the Upper Pliocene glacial deposits onlap the Lower Oligocene coastal deposits.

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Introduction

Accurate dating of Cenozoic sediments on the Norwegian Sea continental shelf is important for understanding maturation and migration of hydrocarbons in this area, as well as for understanding the processes that have led to the uplift of Fennoscandia, which is the original source of the sediments.

In all of the hydrocarbon exploration wells in this area, routine biostratigraphic datings have been carried out by consultants commissioned by oil companies. Traditionally, the Cenozoic has not been given high priority, and consequently the dating of these sediments is of variable quality. The correlation of wells based on a variety of consultant-generated data can be problematic, because of the differing taxonomic nomenclature and the contrasting application and interpretation of the data. None of these routine biostratigraphic investigations are publicly available.

The primary objective of this combined biostratigraphic and seismostratigraphic investigation is to date the sediments and main seismic reflectors. The secondary objective is to interpret depositional environments based on microfaunal content. Of the various dating and correlation methods available (Sr-isotope, dinoflagellates, planktonic foraminifers, etc.), an effort was made to apply the most effective methods according to the stratigraphic level under investigation. Emphasis was placed on correlating planktonic fossil fauna with fossil zones from ODP/DSDP drillings in the Norwegian Sea, as these zones are paleomagnetically calibrated.

Wells 6607/5-1 and /5-2 on the Utgard High and Well 6506/12-4 on the Halten Terrace are included in this investigation because they are situated relatively close to the Neogene depocenters (Fig. 1). These wells penetrate the thickest parts of the Upper Pliocene prograding shelf deposits that cover the continental margin of the Norwegian Sea. Upper Miocene deposits are also well developed in these areas. Furthermore, these wells are situated close to the western margin, and the rich planktonic fossil fauna in these wells can readily be correlated to the planktonic fossil zones in the ODP/DSDP drillings in the Norwegian Sea.

Wells 6610/7-1 and /7-2 on the Nordland Ridge were analyzed because they penetrate the proximal and oldest parts of the Upper Pliocene deposits. Wells 6610/7-1 and 6610/3-1 also penetrate underlying Early Oligocene coastal deposits.

All absolute ages are based on Berggren et al. (1985). Fig. 15 shows ages based on Berggren et al. (1985, 1995).

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

Previous work

As mentioned above, all the exploration wells in this area have been analyzed by biostratigraphic consultants. Based on the results from some of these wells Stratlab (1988) published a general biozonation, comprising sediments from Trias to Pleistocene.

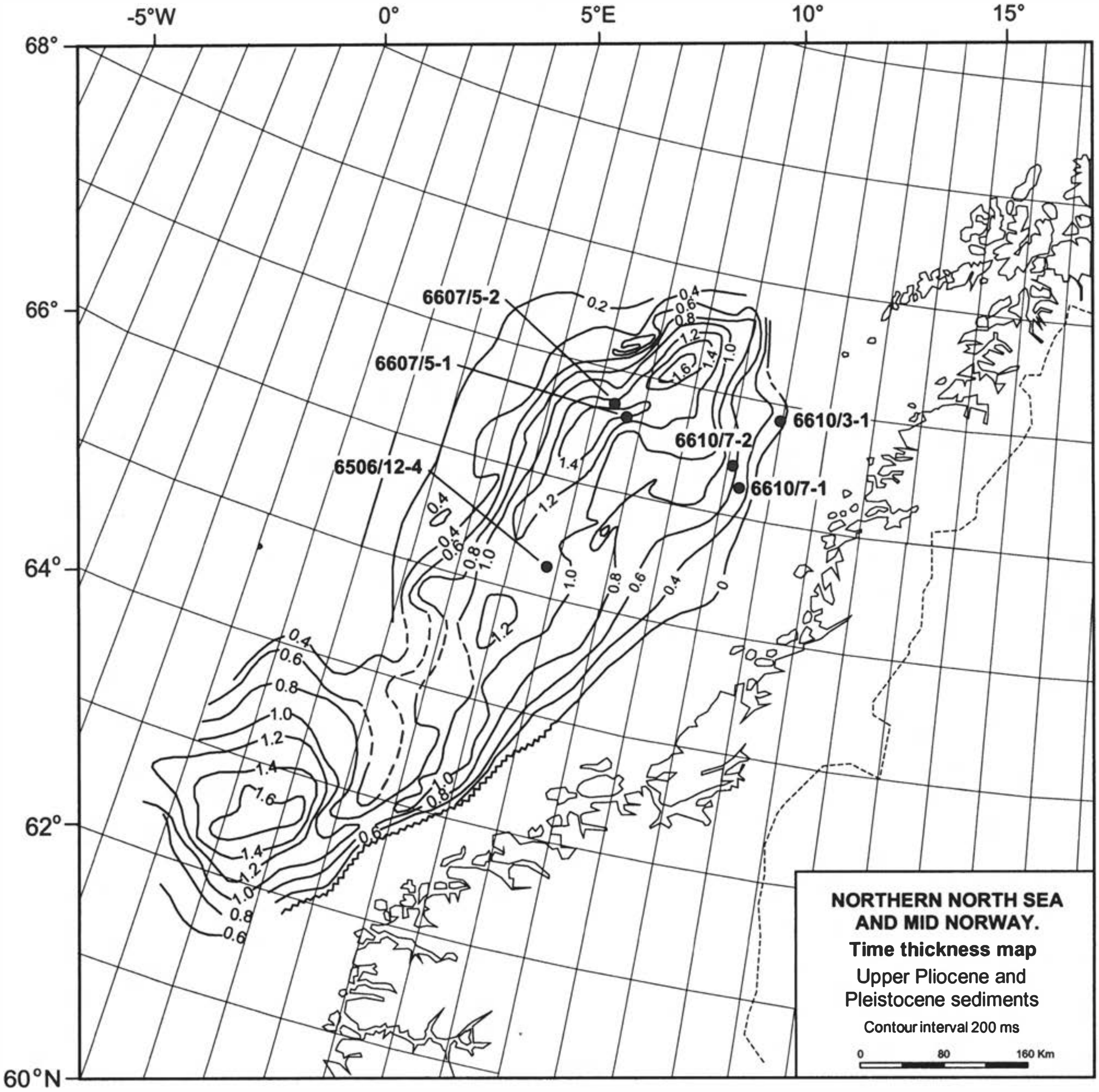


Fig. 1. Location of the wells studied superimposed on an isopach map showing the thickness of the Late Pliocene and Pleistocene sediments in two-way travel time (seconds). Seismic velocity is assumed to be about 2000 m/s in this area, so the thickness measured in kilometers is about the same as the thickness measured in seconds (based on results from Riis & Fjeldskaar 1992). The zigzag line indicates subcropping of Upper Pliocene below Pleistocene.

A general foraminifer zonation of Cenozoic sediments in the North Sea and the Haltenbanken area has been published by Gradstein & Bäckström (1996). This zonation is based on the redating of several exploration wells. Redating of Cenozoic sediments in exploration wells has also been published by Eidvin & Riis (1991) and Poole & Vorren (1993). In this paper we present the results of reanalyses of samples investigated in the two wells in Eidvin & Riis (1991). In addition, the study is extended to include a well on the Utgard High and three wells on the Nordland Ridge.

IKU-Petroleum Research has mapped and sampled outcropping beds in the eastern part of the shelf. The sediments were sampled using a vibracorer and grab at locations having thin Quaternary cover. The ages of these sediments range from Middle Jurassic to Early Neogene. Some of the results of these investigations are published in Bugge (1980), Bugge et al. (1984), Askvik & Rokoengen (1985), Rokoengen et al. (1988) and Gustavson & Bugge (1995).

In connection with geotectonic investigations on the Draugen Field (Haltenbanken), the Pleistocene part of the sequence was sampled in several short conventional cores. Stratigraphic investigations of this material, including paleomagnetic analysis, are published in Haflidason et al. (1991). A geotechnical and seismostratigraphical investiga-

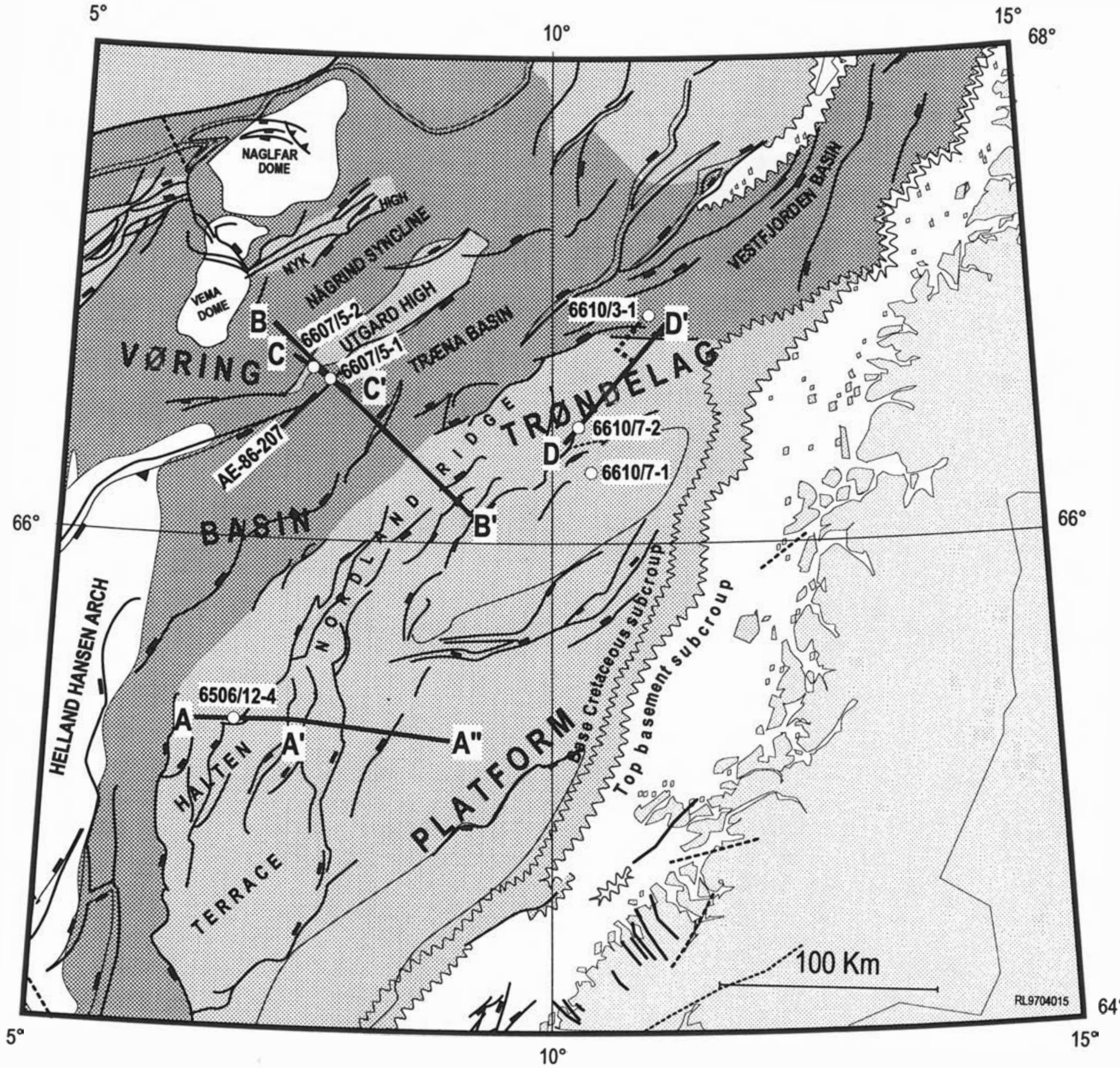


Fig. 2. Map showing wells, seismic lines and major structural elements (modified after Brekke, in press).

tion of Upper Pleistocene sediments on the Smørbukk Field (Haltenbanken) is published by Sættem et al. (1996).

Detailed seismic mapping of the Upper Cenozoic sediments in the Haltenbanken area was published in Rokoengen et al. (1995), and seismic mapping of corresponding sediments in the Nordland Ridge area has been published by Henriksen & Vorren (1996). Seismic mapping of the Upper Pliocene deposits on the Halten Terrace and on the Nordland Ridge was reported in a master's thesis at the University of Oslo (Stuevoll 1989).

Geological setting

The study area

The wells included in this study are situated in two different structural settings. Wells 6607/5-1, 6607/5-2 and 6506/12-4 are situated in the Vøring Basin, which is characterized by an exceptionally thick Cretaceous succession and a complex Cretaceous and Tertiary tectonic history (Blystad et al. 1995; Brekke, in press). Wells 6607/5-1 and 6607/5-2 are situated on the Utgard High which constitutes the eastern flank of the Late

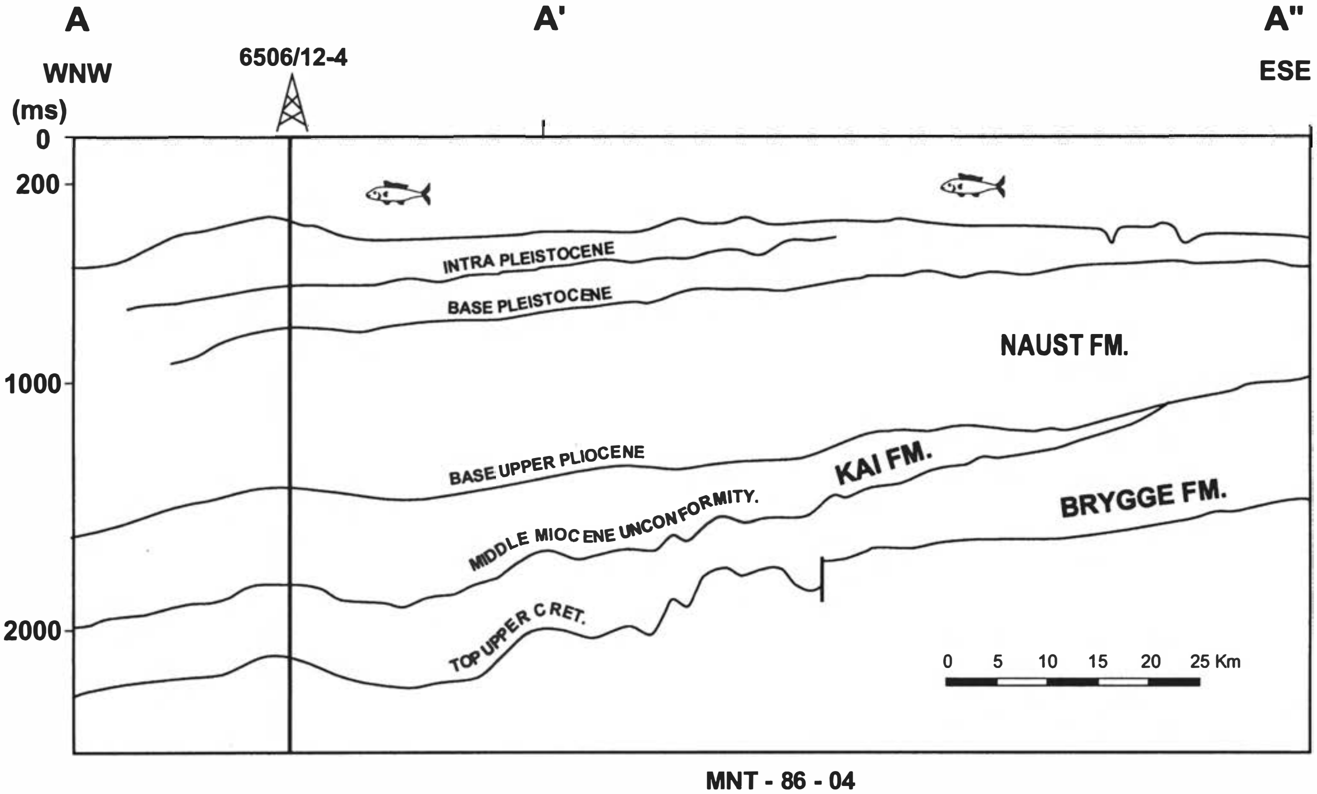


Fig. 3. Digitized seismic line MNT-86-04 through well 6506/12-4.

Cretaceous Någrind Syncline. The wells reveal a very complex and condensed Paleogene and a very thick post-Cenomanian Cretaceous succession. Wells 6610/3-1, 6610/7-2 and 6610/7-1 are situated on the tectonically more stable Late Jurassic/Early Cretaceous Trøndelag Platform (Blystad et al., 1995; Brekke in, press), characterized by a condensed Cretaceous interval and, in places, deeply eroded Tertiary succession (Fig. 2).

Seismic interpretation

The lithostratigraphic nomenclature is after Dalland et al. (1988). The base Naust Formation isopach map shown in Fig. 1 is based on the results of the study by Riis & Fjeldskaar (1992).

In the present study four seismic lines through wells 6506/12-4, 6607/5-1, 6607/5-2 and 6610/7-2 have been interpreted (Figs. 2–7). The interpreted lines on Figs. 3–5 show representative profiles through the Upper Pliocene (Naust Formation) and the Upper/Middle Miocene (Kai Formation) in the central area. The lines on Figs. 6 and 7 show profiles through the proximal part of the Upper Pliocene and the Lower Oligocene coastal deposits (Molo Formation) which is situated under the Upper Pliocene in this area.

The reflector labeled "Base Pleistocene" on profile NRGS-84-470 (Fig. 4) marks the boundary between the underlying prograding Upper Pliocene sequence and the overlying Pleistocene sequence with more parallel and sometimes discontinuous reflectors. Eastwards this reflector truncates the underlying prograding sequence, but at the well site 6607/5-1 no truncation is observed and consequently the reflector is difficult to follow westwards.

The reflector labeled 'Base Upper Pliocene' (Fig. 4) designates the base of the thick prograding sequence. The base of this sequence corresponds to the base of the Naust Formation. Fig. 4 shows that the underlying sequence is truncated further east, and in that area the Naust Formation lies unconformably on Eocene deposits. The underlying layers are truncated at a very low angle in that area and elsewhere. The nature of the reflector varies greatly, but it is recognized in that it is always situated at the base of a large prograding sequence. Often there are parallel reflectors in the underlying sequence, small faults and dome structures. This is not found in the prograding sequence.

Fig. 4 shows a reflector drawn with a dashed line. This reflector marks the boundary between two prograding sequences in the Naust Formation. Eastwards this reflector is truncated by the 'Base Pleistocene' reflector. This is a representative situation for the Naust Formation. The seismic data show a general prograding of beds from east towards west, and internal prograding sequences are truncated by the 'Base Pleistocene' reflector. This indicates that the youngest part of the the Naust Formation is eroded and missing in the eastern part of the area.

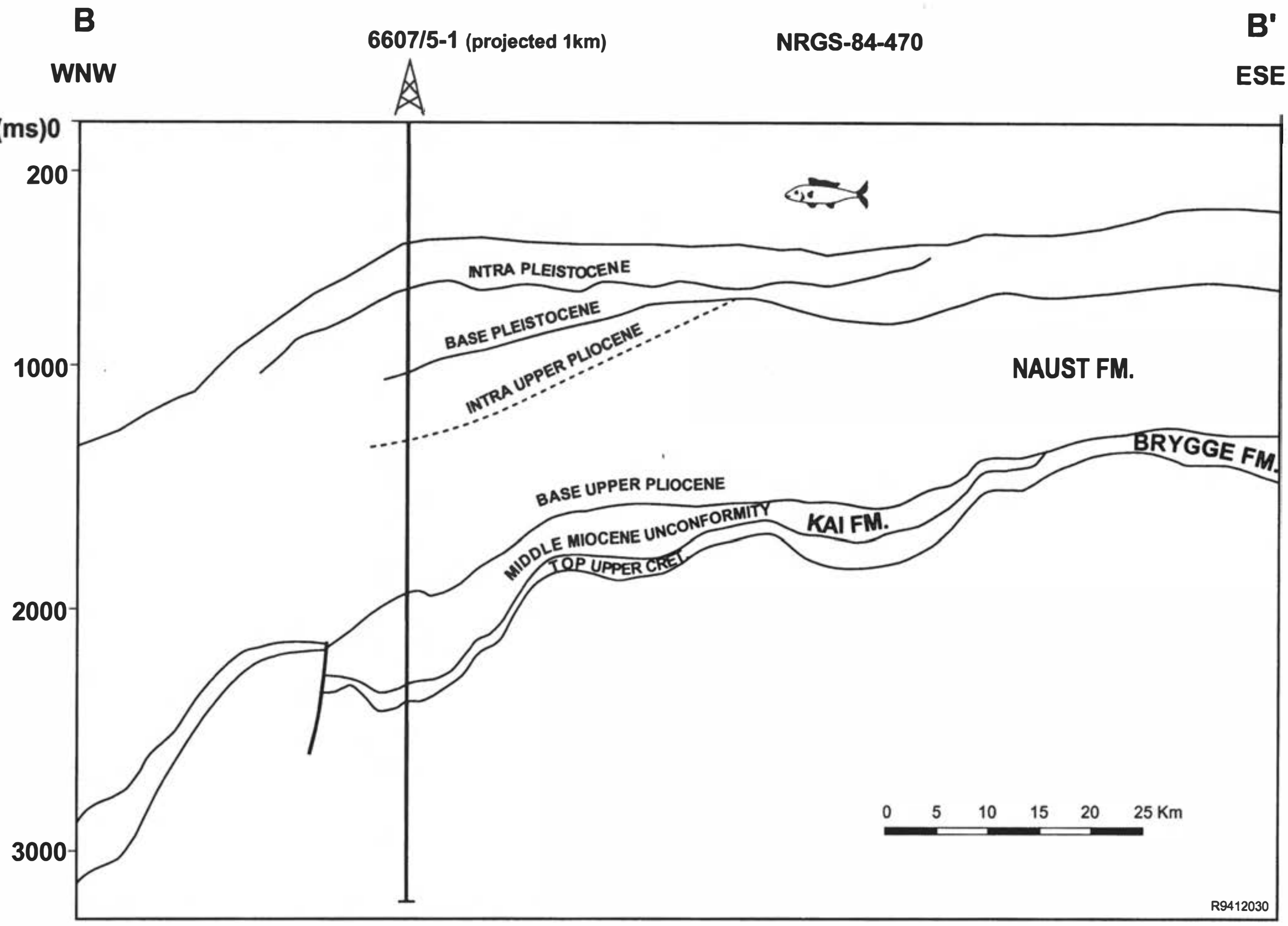


Fig. 4. Digitized seismic line NRGS-84-470. Well 6607/5-1 was tied to line NRGS-84-470 via the intersecting line AE 86-207.

The reflector labeled 'Middle Miocene Unconformity' designates a boundary between two tectonically different situations. The underlying beds (Brygge Formation) have been faulted and folded in dome structures. The overlying beds onlap the boundary. Locally, in the lowermost part of the Upper Pliocene section, some unusually strong and irregular reflectors are observed. Well 6607/5-2 indicates that these reflectors are related to a drop in sonic velocity. Common ocurrrence of the Eocene radiolarian *Cenosphaera* sp. indicates a large amount of reworked material in this part of the Upper Pliocene.

A correlation between wells 6607/5-1 and /5-2 (Fig. 5) shows a complicated pattern of unconformities and hiatuses. It demonstrates that the Paleocene onlaps the top of the Cretaceous from the west towards the east, giving a thinning of the Paleocene towards the east. Between the two wells the top of the Paleocene onlaps the truncated top of the Cretaceous, explaining the missing Paleocene in well 6607/5-1. Strata of Oligocene age are missing in both wells, and the seismic interpretation shows an important erosional unconformity of late Middle Miocene age that also explains the thinning of the Eocene succession between wells 6607/5-2 and 6607/5-1. The interpretation and the dating in well 6607/5-2 show that the Middle Miocene Unconformity is crosscut by the Base Upper Pliocene Unconformity, so that to the west of well 6607/5-2 Upper Pliocene sediments rest directly on Eocene strata, while towards the east the Eocene sequence is separated from the Upper Pliocene sequence by Upper Miocene sediments. This relationship substantiates the tectonic movements in the Early–Middle Miocene and the Late Pliocene which can also be demonstrated throughout the Vøring Basin (Blystad et al., 1995; Brekke, in press).

Profile MNT-86-04 traverses well 6506/12-4 (Fig. 3). The reflectors labeled 'Base Pleistocene' and 'Base Upper Pliocene' are similar to the same reflectors on Fig. 4. However, on Fig. 3 the Naust Formation is truncated at the well site.

The reflector labeled 'Middle Miocene Unconformity' is well developed on profile MNT-86-04 (Fig. 3), because the thickness of the section between this unconformity and the Naust Formation (i.e. the Kai Formation) is much larger in this area. The overlying deposits onlap the unconformity.

Seismic mapping of the base of the Naust Formation shows that the prograding unit has developed a very large sedimentary wedge on the Norwegian Sea continental margin. A similar wedge is developed in the northern North Sea (Fig. 1).

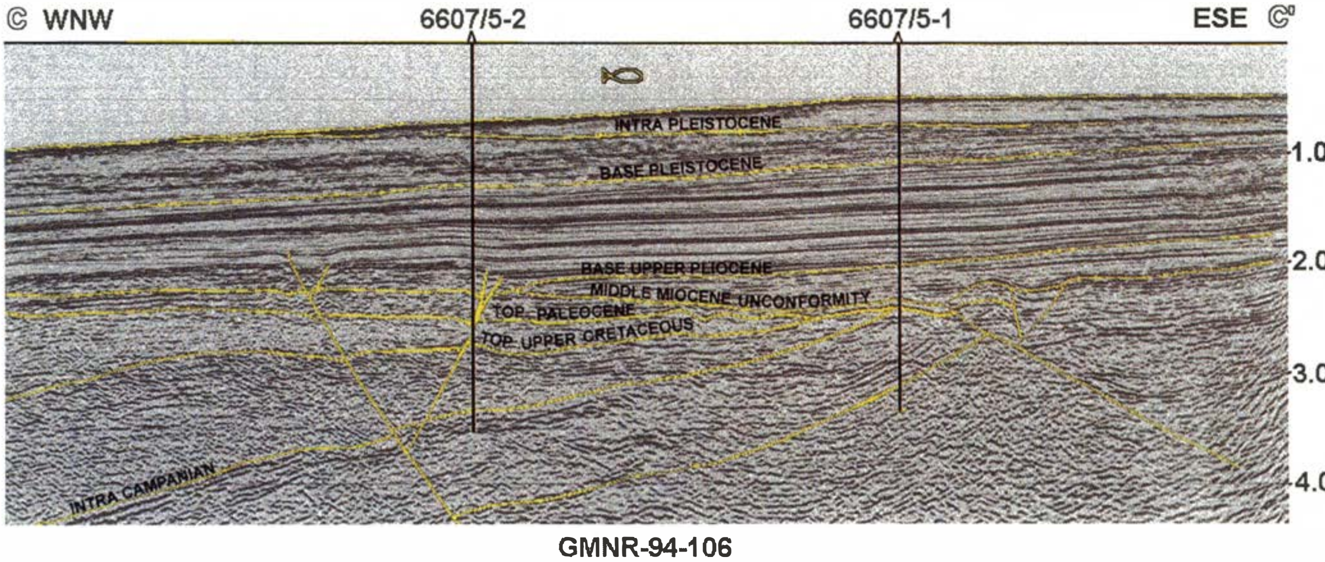


Fig. 5. Interpreted seismic line GMNR-94-106 through well 6607/5-1 and 6607/5-2.

Profiles NRGS-84-470 (Fig. 4) and GMNR-94-106 (Fig. 5) traverse the thickest part of the wedge, while profile MNT-86-04 (Fig. 3) traverses an area with average thickness.

Based on the seismic lines N3-86-315, N3-86-306 and N3-86-314 from the Nordland Ridge, it was possible to correlate the Tertiary strata between wells 6610/3-1 and 6610/7-2 (Fig. 6). The seismic correlation shows that well 6610/7-2 lies west of the Lower Oligocene coastal deposits identified in well 6610/3-1. The coastal deposit sequence is an interval of steeply dipping reflectors interpreted as a set of prograding foresets. The base of the sequence is easily identified on the seismic profiles as a consistent downlap surface. The southwestern side of the sequence can also be readily picked out seismically as an onlap surface where the flat-lying Upper Pliocene stratum in well 6610/7-2 onlaps the prograded front of the coastal deposits (Figs. 6, 7). Eastwards, the deposits thin out due to erosion of the top of the sequence. The erosion left the western boundary as a morphological ramp at the distal forsets (Fig. 6).

Material and methods

Fossil analyses

The biostratigraphic analyses are based largely on ditch-cutting samples. In well 6610/7-1 seven sidewall cores were also available. In well 6610/3-1 only five samples were analyzed and all of these were sidewall cores. Caved material will always be a problem when analyzing ditch cuttings, and consequently the biostratigraphic interpretation and correlation are based mainly on last-appearance data (LADs) of the various taxa. The analyses of the sidewall cores may to some extent reduce the problem of caved material, and in some instances it may be possible to record first-appearance data (FADs).

When drilling with exploration rigs the sampling does not commence before the well has reached a depth of between 100 m and 300 m below the sea floor. Consequently, the upper part of the borehole cannot be analyzed. Ditch cuttings are usually sampled every 10 m in those parts of the wells which are outside the reservoir intervals. In some cases the sampling interval is approximately 5 m. All the available samples are analyzed, but in some thick sequences samples are analyzed at 20-m intervals.

The samples were analysed primarily for planktonic and benthonic foraminifers, but *Bolboforma* (calcareous cysts) were used to establish the stratigraphy in the Middle Miocene–lower part of the Upper Miocene. In the Lower–Upper Oligocene and in the Upper Paleocene pyritized diatoms were used, and in the Lower/Middle Eocene radiolarians were used. The Lower Oligocene section in wells 6610/7-1 and 6610/3-1 was analysed for dinoflagellates in addition to foraminifers.

For analyses of the drill-cuttings samples, 50 g–100 g of material was used. Less material was available from the sidewall cores (10 g–30 g). Unconsolidated material was soaked in water and wet sieved and consolidated material was dissolved in diluted hydrogen peroxide. The identifications were carried out on the 0.1–0.5 mm fraction. In some cases the fractions larger than 0.5 mm and less than 0.1 mm were also studied. In the sidewall cores, material finer than 0.1 mm was saved for palynological analysis. Whenever possible, 300 individuals were picked from each sample. In order to better identify the foraminiferal assemblages, a number of samples rich in terrigenous grains were gravity-separated in heavy liquid. Consequently, in fossil-rich samples, 1000–1500 individuals were analyzed. The stratigraphically important fossils are reported in the range charts in Figs. 8a–13.

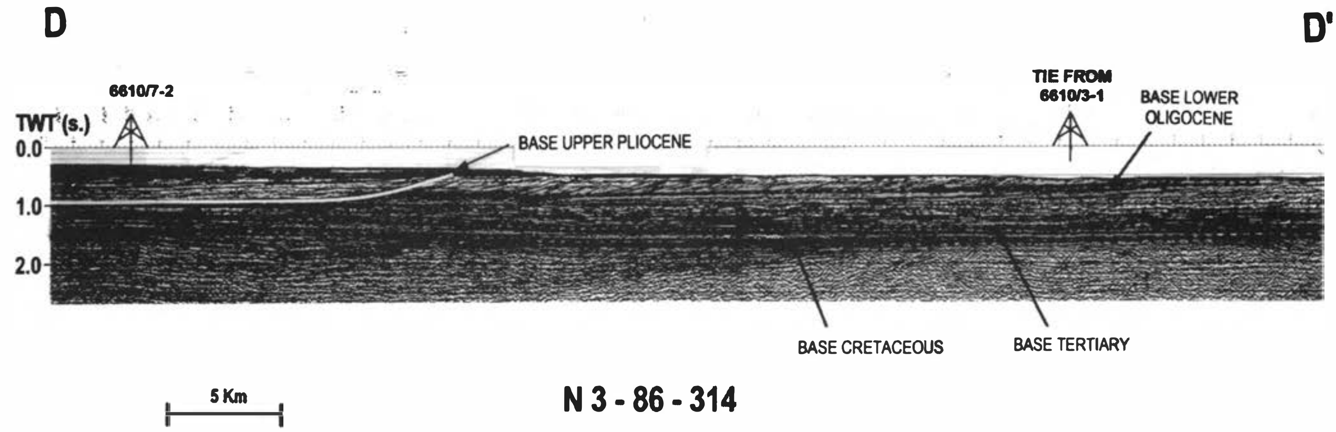


Fig. 6. Interpreted seismic line N3-86-314 through well 6610/7-2 showing the Lower Oligocene coastal deposits.

Strontium isotope analyses

Strontium isotope analyses were performed by the Institute for Energy Technology, Kjeller, Norway, on calcareous material (i.e. tests of calcareous benthic foraminifera) from two sidewall cores representing different stratigraphic levels in well 6610/3-1. Ages for these samples were obtained by comparing the $^{87}Sr/^{86}Sr$-ratio to a global strontium isotope curve. The curve compiled by the Institute for Energy Technology is based on data from DePaolo (1986), DePaolo & Ingram (1985), Hess et al. (1986), Hodell et al. (1989, 1990, 1991), Koepnick et al. (1985) and Palmer & Elderfield (1985).

Lithologic studies

The lithologic analyses are based on a visual examination of both the samples prior to treatment, and the dispersed and fractionated material after preparation. Owing to the problem of caved material, only a rough description was deemed appropriate.

Biozonation

The standard Cenozoic biostratigraphic scale is based on planktonic foraminifers and calcareous nannoplankton zonations established for tropical and subtropical areas. Towards the north the assemblages become progressively less diverse, and many key species are missing in the Norwegian and the North Seas (King, 1983).

In this work the biozonation broadly follows that of King (1983, 1989) where a micropaleontological zonation for Cenozoic sediments of the North Sea is outlined. Gradstein & Bäckström's (1996) faunal zonation from the North Sea and Haltenbanken and Stratlab's (1988) faunal zonation for the Mid-Norwegian continental shelf are also used extensively. In addition, a number of articles that describe benthonic foraminifers from onshore basins from the area surrounding the central and southern North Sea are used. Since the North Sea zonations cannot be applied in full on the Mid-Norwegian continental shelf, the zonations of planktonic foraminifers (Spiegler & Jansen 1989) and *Bolboforma* (Quale & Spiegler 1989), established through ODP/DSDP drillings in the Norwegian Sea, are very important for dating shelf sediments. Correlation with these zones may also yield quite accurate ages, since the zones are calibrated using nannoplankton and paleomagnetic data (Müller & Spiegler 1993). However, the zonations of King (1983, 1989), Gradstein & Bäckström (1996) and Stratlab (1988) are based on last-appearance data of the various taxa. The zonation of planktonic foraminifers and *Bolboforma* from the ODP/DSDP drillings is based on the first-appearance data.

Biozones

In the six wells examined in this study a system of 15 informal biozones is employed (M–A to M–O); M = Mid-Norway (Figs. 8a–15). The zones are primarily range zones based on the highest occurrence of selected taxa which have been chosen because of their chronostratigraphic importance. In other words, the selected taxa have well-documented, consistent ranges on a regional scale. The individual range zones comprise both planktonic and benthonic forms. Range zone definitions based on a combination of planktonic and benthonic forms are applicable on a regional scale where planktonic/benthonic ratios are often highly variable. We define these zones as follows:

WELL 6607/5-1 (66°38′N, 7°32′E)

NEOGLOBOQUADRINA PACHYDERMA (SINISTRAL) – *NONION LABRADORICUM* ZONE

Category: Informal partial range zone.

Designation: M–A.

Informal boundary criteria: The top of the zone extends above the uppermost investigated sample (920 m) and probably to near the sea floor. The base of the zone is marked by the highest occurrence of *Cibicides grossus*.

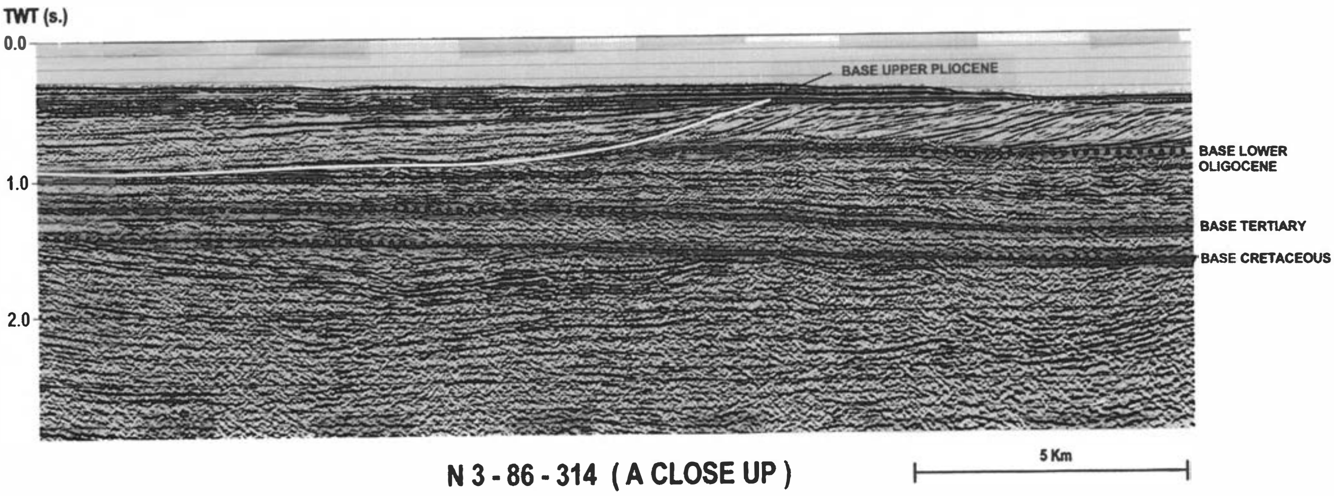


Fig. 7. Interpreted seismic line N3-86-314. A close up which shows that Upper Pliocene prograding deposits onlap the Lower Oligocene coastal deposits.

Depth range: 920 (uppermost investigated sample)–960 m.

Age: Pleistocene.

Lithostratigraphic formation: Naust Formation.

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

Assemblage: This interval contains a rich benthonic fauna consisting mainly of calcareous foraminifera. *Elphidium excavatum* and *Cassidulina reniforme* occur most frequently. Other characteristic forms are: *Nonion labradoricum, Cassidulina teretis, Virgulina loeblichi, Elphidium albiumbilicatum, Bulimina marginata, Haynesina orbiculare* and *Cibicides scaldisiensis* (Fig. 8a).

Planktonic foraminifers are represented by *N. pachyderma*. Both encrusted and unencrusted varieties of the sinistrally coiled individuals have been registered.

Remarks: *N. pachyderma* (sinistral, encrusted) has its first frequent occurrence at 1.7 Ma (Weaver & Clement 1986; Spiegler & Jansen 1989). This test morphology occurs only sporadically in older sediments. *N. labradoricum* also appears to be restricted to Pleistocene deposits on the Norwegian shelf. King (1989) employs *N. labradoricum* as the nominate taxon for the Pleistocene Subzone NSB 16x of the northern North Sea. The base of Zone M–A coincides with a weak seismic reflector which probably represents a minor hiatus.

CIBICIDES GROSSUS ZONE

Category: Informal partial range zone.

Designation: M–B.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *Cibicides grossus.* The base of the zone is marked by the highest occurrence of *Neogloboquadrina atlantica* (sinistral).

Depth range: 960–1220 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzone NSB 15b of King (1989), Zone NSR 12 of Gradstein & Bäckström (1996), C. grossa zone of Stratlab (1988) and possible *N. pachyderma* (dextral) zone and upper *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989).

Assemblage: This interval contains a rich fauna of benthonic calcareous foraminifers. *E. excavatum* and *C. reniforme* appear frequently throughout the entire sequence. *C. scaldisiensis* and *C. teretis* are frequent in the lower part of the sequence. Other important species are: *C. grossus, V. loeblichi, E. albiumbilicatum, Buccella frigida, B. marginata, Nonion affine, Cibicidoides pachyderma, Angulogerina fluens* and *Uvigerina peregrina* (Fig. 8a).

Planktonic foraminifera are represented by both encrusted and unencrusted forms of *N. pachyderma* (sinistral), which are comparatively frequent throughout the sequence. *N. pachyderma* (dextral) is scarce throughout. *Turborotalita quinqueloba, Globigerina bulloides* and *Globorotalia inflata* are found in small numbers in some intervals.

Remarks: With the exception of *C. grossus* all the benthonic foraminifera are extant species. According to King (1989) *C. grossus* is found in the northern North Sea in Upper Pliocene to Lower Pleistocene deposits. In the southern parts of the North Sea it becomes extinct somewhat earlier, close to the Pliocene/Pleistocene boundary. King (1989) establishes the time for the LAD of *C. grossus* in the northern North Sea by registering its LAD above the FAD of *N. pachyderma* (sinistral, encrusted). The FAD of *N. pachyderma* (sinistral, encrusted) at about 1.7 Ma (Spiegler & Jansen 1989) is a good marker for top Upper Pliocene, but this biostratigraphic event is difficult to observe in drill cuttings.

While working with this kind of material, the LAD occurrence of *C. grossus* is the biostratigraphic event closest to the Upper Pliocene/Pleistocene boundary. This applies to the northern North Sea and probably also to the area offshore Mid-Norway.

CIBICIDES GROSSUS–GLOBIGERINA BULLOIDES–NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ZONE

Category: Informal partial range zone.

Designation: M–C.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *N. atlantica* (sinistral). The base of the zone is marked by the highest consistent occurrence of *N. atlantica* (dextral).

(a)

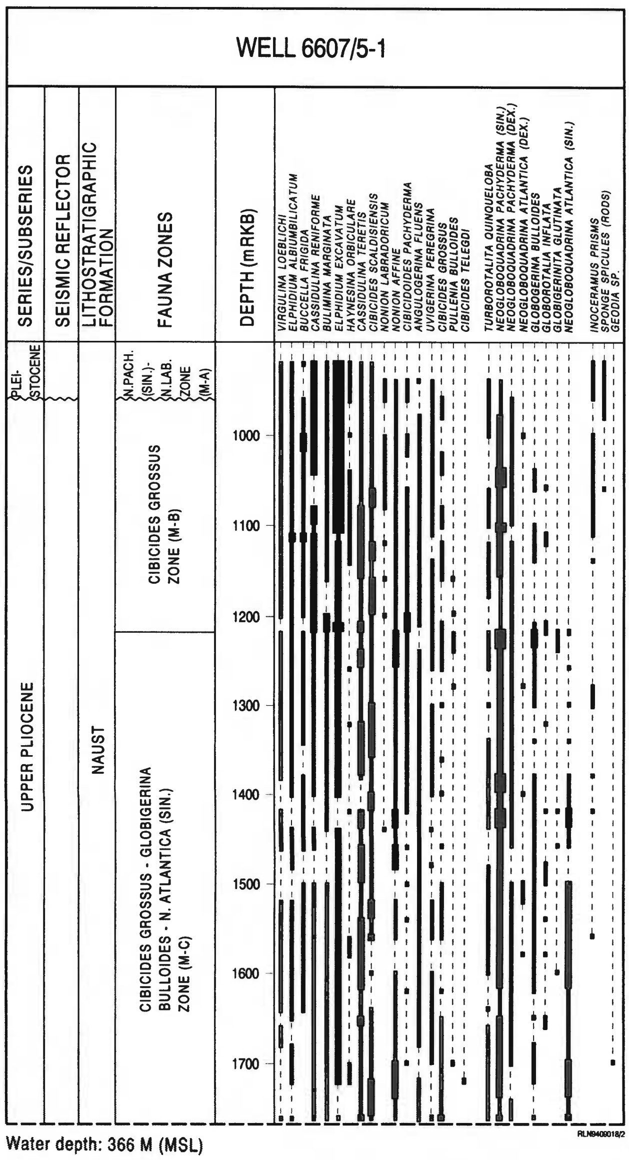


Fig. 8(a).

Depth range: 1220–2020 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzones NSB 15a and b of King (1989), *C. grossa* zone of Stratlab (1988) and *N. atlantica* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This interval contains a rich benthonic fauna of mainly calcareous foraminifera. The fauna is relatively uniform throughout the entire sequence. *E. excavatum*, *C. teretis* and *C. scaldisiensis* all occur frequently throughout. *C. grossus* occurs frequently in the lower part of the sequence, but is less common in the upper part. Other species are *N. affine*, *C. reniforme*, *B. marginata* and *B. tenerrima* (Fig. 8a, b).

Planktonic foraminifera are represented by both encrusted and unencrusted forms of *N. pachyderma* (sinistral). Both this species and *N. atlantica* (sinistral) are similarly frequent throughout the sequence. *N. pachyderma* (dextral), *G. bulloides* and *T. quinqueloba* also occur throughout, but in smaller numbers. *G. inflata*, *G. glutinata* and *N. atlantica* (dextral) are found in some intervals.

Remarks: The LAD of *N. atlantica* (sinistral) on the Vøring Plateau is at 2.3 Ma. In that area there is a marked dominance of this species together with *G. bulloides* in Pliocene deposits older than this (Spiegler & Jansen 1989). *G. bulloides* is also found in the warmest interglacials of the last 1 Ma (Kellogg 1977). According to King (1989) the FAD of *C. grossus* is observed somewhat above the Lower/Upper Pliocene boundary. The fact that the content of *C. grossus* is considerably greater at the base of the unit than in younger sediments seems to indicate that its occurrence is not caved, but is *in situ*. Therefore, the entire zone was in all likelihood deposited in the Late Pliocene. This is also supported by the fact that *E. hannai*, which according to King (1989) also has its FAD in the Upper Pliocene, is registered only at the base of the zone.

N. pachyderma (sinistral, encrusted) indicates caved material from the M–A and M–B zones. *N. atlantica* (dextral) is probably reworked from Upper Miocene material (Spiegler & Jansen 1989). Reworked agglutinated foraminifera from the Lower Cenozoic, and benthonic and planktonic calcareous foraminifera from the Upper Cretaceous are registered in this zone and in the M–A and M–B zones. The base of the M–C zone coincides with a regional seismic reflector, representing a hiatus.

CIBICIDES TELEGDI–EPONIDES PYGMEUS–N. ATLANTICA (DEXTRAL) ZONE

Category: Informal partial range zone.

Designation: M–H.

Informal boundary criteria: The top of the zone is taken at the highest consistent occurrence of *N. atlantica* (dextral). The base of the zone is marked by the highest occurrence of *Ehrenbergina variabilis* and *Globocassidulina subglobosa*.

(b)

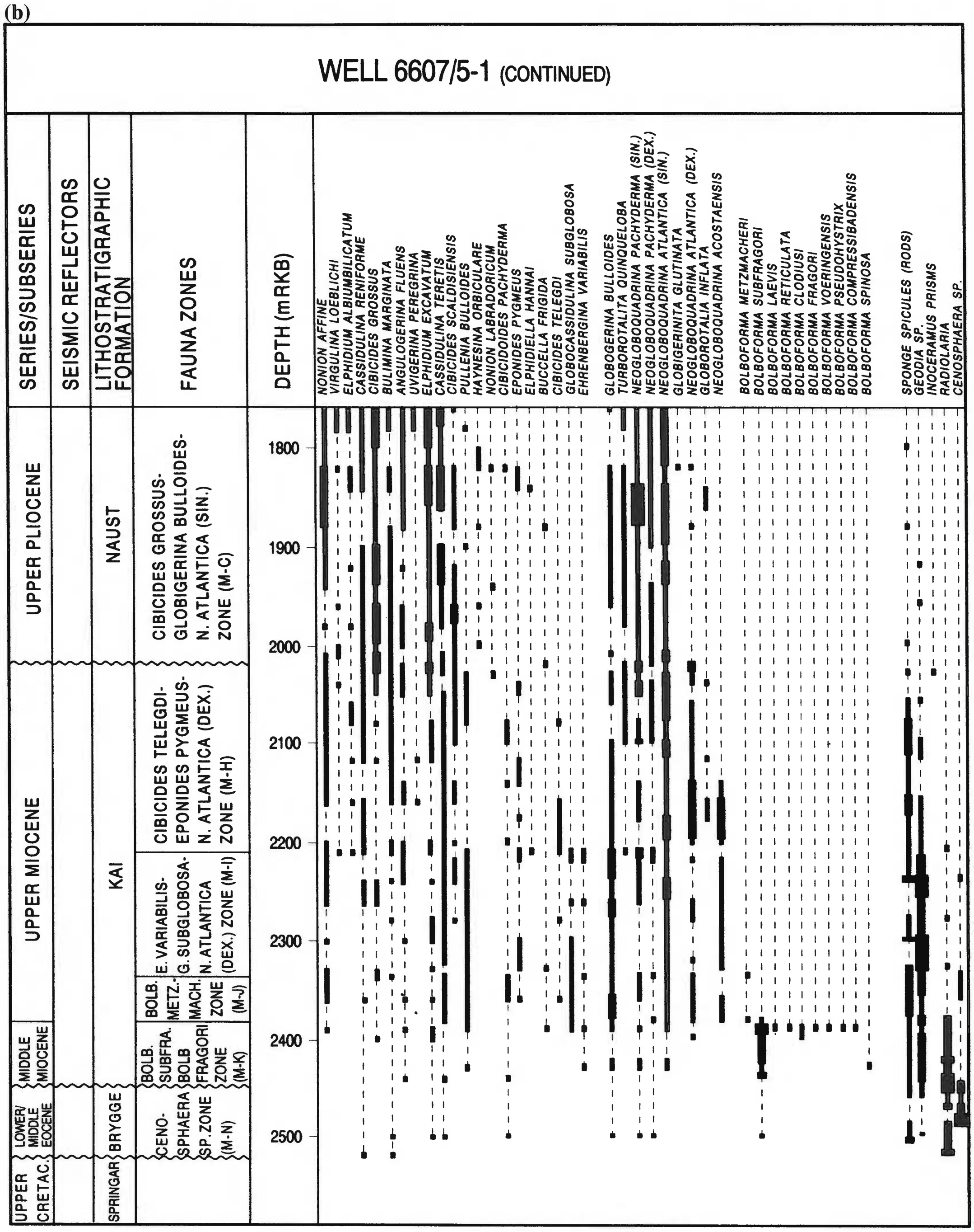


Fig. 8. (a) Range chart of the most important index fossils in the upper part of the investigated interval of well 6607/5-1. M RKB = meters below rig floor, m MSL = meters below mean sea level. (b). Range chart of the most important index fossils in the lower part of the investigated interval of well 6607/5-1.

Depth range: 2020–2211 m.

Age: Late Miocene.

Lithostratigraphic formation: Kai Formation.

Equivalent zones: Lower *N. atlantica* (dextral) zone of Spiegler & Jansen (1989) and probably lower part of *Melonis–Trifaria* zone of Stratlab (1988).

Assemblage: There are significantly fewer foraminifera in this interval than in the overlying zones. In addition, specimens of sponge spicules (rod-shaped and the round *Geodia* sp.) are common in this zone. Benthonic calcareous species include: *C. telegdi*, *E. pygmeus*, *C. reniforme*, *B. marginata*, *C. teretis*, *C. scaldisiensis*, *N. affine* and *Pullenia bulloides*. *C. grossus* is registered in the upper part of the zone (Fig. 8b).

Planktonic foraminifera include: *N. atlantica* (sinistral) and *N. atlantica* (dextral). *N. atlantica* (sinistral) is common in the upper part of the interval and *N. atlantica* (dextral) in the lower part. Other important species are *G. bulloides*, *N. pachyderma* (sinistral) and *N. acostaensis* (lower part). A small number of *N. pachyderma* (dextral), *T. quinqueloba* and *G. inflata* are also found.

Remarks: Most of the registered benthonic specimens are known from sediments covering almost the entire Neogene. However, *C. telegdi* and *E. pygmeus* are described from the Upper Oligocene and older deposits in Denmark and Germany (Grossheide & Trunko 1965; Hausmann 1964; Kummerle 1963, Ulleberg 1974). These species are recorded in the Upper Miocene sediments in the northern North Sea and on the Mid-Norwegian continental shelf (Eidvin & Riis 1992; Stratlab 1988), showing that these species have a time-transgressive LAD from south to north. Spiegler & Jansen (1989) describe a lower *N. atlantica* (dextral) zone from Upper Miocene sediments on the Vøring Plateau. The occurrence of *N. atlantica* (dextral) is probably *in situ* and indicates that this interval is of Late Miocene age. *N. acostaensis* is reported from deposits of Late to Middle Miocene age on the Vøring Plateau (Spiegler & Jansen 1989).

In the upper part of the interval a few specimens of *C. grossus* are recorded. These are probably caved. Other caved material is also observed.

EHRENBERGINA VARIABILIS–GLOBOCASSIDULINA SUBGLOBOSA – N. ATLANTICA (DEXTRAL) ZONE

Category: Informal partial range zone.

Designation: M–I.

Depth range: 2211–2337 m.

Informal boundary criteria: The top of the zone is taken at the highest occurrences of *E. variabilis* and *G. subglobosa.* The base of the zone is marked by the highest occurrence of *Bolboforma metzmacheri.*

Age: Late Miocene.

Lithostratigraphic formation: Kai Formation.

Equivalent zones: Lower *N. atlantica* (dextral) zone of Spiegler & Jansen (1989) and *G. subglobosa–E. variabilis* zone of Stratlab (1988).

Assemblage: In this zone the benthonic faunas include calcareous foraminifera and sponge spicules. Sponge spicules (rod-shaped and *Geodia* sp.) are significantly more common than foraminifera. Benthonic foraminifera include: *G. subglobosa*, *C. teretis*, *N. affine*, *A. fluens*, *P. bulloides*, *E. pygmeus* and *E. variabilis* (Fig. 8b).

Planktonic foraminifera include: *G. bulloides* (common), *N. atlantica* (sinistral; common), *N. atlantica* (dextral), *N. acostaensis*, *N. pachyderma* (sinistral; unencrusted; few) and *N. pachyderma* (dextral; few).

Remarks: Most of the benthonic foraminifera are known from almost the entire Neogene. Some of these are probably caved. *E. variabilis* is described from the Upper Oligocene to Lower Miocene of Germany (Grossheide & Trunco 1965; Spiegler 1974), from the Upper Oligocene to Lower Pliocene on the Norwegian continental shelf (Skarbø & Verdenius 1986) and from the Upper Miocene on the Mid-Norwegian continental shelf (Stratlab 1988). This species also seems to have a south to north time-transgressive appearance. *G. subglobosa* is described from the Middle to Upper Miocene of Belgium (Doppert 1980) and from the Upper Oligocene to Upper Miocene of Germany (Spiegler 1974). These forms are also described from the Upper Miocene of the northern North Sea (Eidvin & Riis 1992). *N. atlantica* (dextral) and *N. acostaensis* also indicate a Late Miocene age for this interval (Jansen & Spiegler 1989).

BOLBOFORMA METZMACHERI ZONE

Category: Informal partial range zone.

Designation: M–J.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *B. metzmacheri.* The base of the zone is marked by the highest occurrence of *B. subfragori.*

Depth range: 2337–2382 m.

Age: Late Miocene.

Lithostratigraphic formation: Kai Formation.

Equivalent zones: *B. metzmacheri* zone of Spiegler & Müller (1992) and Müller & Spiegler (1993), Zone NSR 10 of Gradstein & Bäckström (1996), Subzone NSP 14b of King (1989) and *B. metzmacheri* zone of Stratlab (1988).

Assemblage: The greater proportion of the fossils in this sequence are sponge spicules. Considerably fewer foraminifera are registered. A small number of *B. metzmacheri* are also registered. Both calcareous benthonic foraminifera and agglutinated taxa are present, calcareous species being dominant. Important calcareous species are: *C. teretis*, *N. affine*, *P. bulloides*, *E. pygmeus* and *G. subglobosa.* The most important agglutinated species is: *Martinottiella communis.* The most important planktonic foraminifera are: *G. bulloides*, *N. atlantica* (dextral), *N. atlantica* (sinistral) and *N. acostaensis* (Fig. 8b).

Remarks: *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. metzmacheri* is described from deposits with an age of 9.2–7.9 Ma from the North Atlantic and the Vøring Plateau (Spiegler & Müller 1992; Müller & Spiegler 1993).

BOLBOFORMA SUBFRAGORI–BOLBOFORMA FRAGORI ZONE

Category: Informal partial range zone.

Designation: M–K.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *B. subfragori.* The base of the zone is marked by the highest consistent occurrence of *Cenosphaera* sp.

Depth range: 2382–2448 m.

Age: Middle Miocene.

Lithostratigraphic formation: Kai Formation.

Equivalent zones: *B. fragori/B. subfragori* zone of Spiegler & Müller (1992) and Müller & Spiegler (1993), Subzone NSP 14a of King (1989) and *B. spiralis* zone of Stratlab (1988).

Assemblage: Sponge spicules (rod-shaped and *Geodia* sp.) and *Bolboforma* are dominant in this interval, with foraminifera being subordinate. *B. subfragori* occurs frequently throughout the sequence. *B. metzmacheri*, *B. laevis*, *B. reticulata*, *B. clodiusi*, *B. fragori*, *B. voeringensis*, *B. pseudohystrix*, *B. compressibadensis* and *B. spinosa* are recorded in the upper part of the interval. Both calcareous benthonic foraminifera and agglutinated taxa are present. Important calcareous species are: *P. bulloides*, *G. subglobosa* and *E. variabilis*. *M. communis* is the only agglutinated form recorded. The most important planktonic foraminifera are: *G. bulloides*, *N. atlantica* (sinistral) and *N. atlantica* (dextral) (Fig. 8b).

Remarks: The known stratigraphic ranges of the important benthonic and planktonic foraminifera registered in this interval are discussed above under the descriptions of Zones M–I and M–J. A *B. fragori/B. subfragori* zone is described from deposits with an age of slightly less than 12–9.6 Ma from the North Atlantic and the Vøring Plateau (Spiegler & Müller 1992 and Müller & Spiegler 1993).

CENOSPHAERA SP. ZONE

Category: Informal partial range zone.

Designation: M–N.

Informal boundary criteria: The top of the zone is taken at the highest consistent occurrence of *Cenosphaera* sp. The base of the zone is undefined.

Depth range: 2448–2520 m.

Age: Early to Middle Eocene.

Lithostratigraphic formation: Brygge Formation.

Equivalent zones: Zone NSP 6 of King (1989).

Assemblage: The fauna of this sequence is almost completely dominated by radiolarians, mostly *Cenosphaera* sp. In addition, some sponge spicules and a few foraminifera are recorded (Fig. 8b).

Remarks: *A Cenosphaera* sp. acme is known from the Lower to Middle Eocene of the North Sea (King 1989). The foraminifera found in this interval are probably caved. The deposits immediately below this interval are assigned to an age of Late to Middle Campanian based on dinoflagellates (Robert Williams, pers. comm., 1991).

WELL 6607/5-2 (66°41′N, 7°21′E)

CIBICIDES GROSSUS–GLOBIGERINA BULLOIDES–NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ZONE

Category: Informal partial range zone.

Designation: M–C.

Informal boundary criteria: The top of the zone extends above the uppermost investigated sample (2290 m). The base of the zone is marked by the lowest abundant occurrence of *Cenosphaera* sp.

Depth range: 2290 (uppermost investigated sample) – 2320 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzones NSB 15a and b of King (1989), *C. grossa* zone of Stratlab (1988) and *N. atlantica* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This interval contains a rich benthonic fauna of mainly calcareous foraminifera. *E. excavatum* and *C. grossus* occur frequently throughout the zone. Other important species are: *N. affine*, *B. marginata*, *C. teretis*, *Elphidium subarcticum* and *C. scaldisiensis* (Fig. 9).

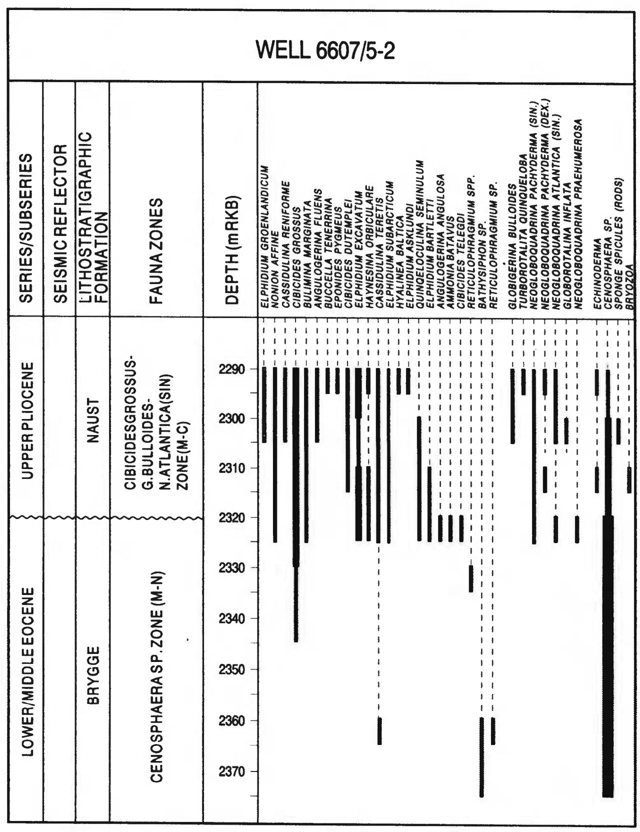


Fig. 9. Range chart of the most important index fossils in the investigated interval of well 6607/5-2. M RKB = meters below rig floor, m MSL = meters below mean sea level.

Planktonic foraminifera are less frequent than calcareous benthonic taxa. *N. pachyderma* (sinistral, unencrusted) and *N. atlantica* (sinistral) are dominant. Other important species are: *G. bulloides*, *N. pachyderma* (dextral) and *G. inflata*.

Remarks: The occurrence of *C. grossus*, *N. atlantica* (sinistral) and *G. bulloides* indicates that this interval is of Late Pliocene age, but older than 2.3 Ma (King 1989; Spiegler & Jansen 1989).

The common occurrence of the radiolarian *Cenosphaera* sp. indicates redeposition of Lower to Middle Eocene sediments. The benthonic calcareous foraminifera *E. pygmeus* and *C. telegdi* are reworked Oligocene–Miocene taxa. The base of Zone M–C coincides with a regional seismic reflector which represents a depositional hiatus.

CENOSPHAERA SP. ZONE

Category: Informal partial range zone.

Designation: M–N.

Informal boundary criteria: The top of the zone is taken at the highest abundant occurrence of *Cenosphaera* sp. The base of the zone is undefined.

Depth range: 2320–2370 m (lowest sample analyzed).

Age: Early to Middle Eocene.

Lithostratigraphic formation: Brygge Formation.

Equivalent zones: Zone NSP 6 of King (1989).

Assemblage: The fauna in this interval is dominated by the radiolarian *Cenosphaera* sp. Some sponge spicules and foraminifera are also recorded (Fig. 9).

Remarks: *A Cenosphaera* sp. acme is known from the Lower to Middle Eocene of the North Sea (King 1989). This zone is coeval with the M–N zone in well 6607/5-1. Most of the foraminifera are found in the uppermost sample, and are caved from the above interval.

WELL 6506/12-4 (65°12′N, 6°43′E)

NEOGLOBOQUADRINA PACHYDERMA (SINISTRAL)–*NONION LABRADORICUM* ZONE

Category: Informal partial range zone.

Designation: M–A.

Informal boundary criteria: The top of the zone extends above the uppermost investigated sample (370 m) and probably to near the sea floor. The base of the zone is marked by the highest occurrence of *C. grossus* and the highest consistent occurrence of *N. atlantica* (sinistral).

Depth range: 370 (uppermost investigated sample) – 660 m.

Age: Pleistocene.

Lithostratigraphic formation: Naust Formation.

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

Assemblage: This interval contains a rich benthonic fauna consisting mainly of calcareous foraminifera, of which *E. excavatum* is the most common. *C. reniforme* and *B. marginata* are also common. Other characteristic forms are: *N. labradoricum*, *V. loeblichi*, *B. tenerrima*, *C. teretis*, *C. scaldisiensis*, *N. affine* and *U. peregrina* (Fig. 10a).

Planktonic foraminifera are also quite common, but less frequent than the calcareous benthonic taxa. *N. pachyderma* (both encrusted and unencrusted varieties of the sinistrally coiled individuals) is dominant. Other important species are: *N. pachyderma* (dextral), *G. bulloides* and *T. quinqueloba*.

Remarks: The occurrence of *N. pachyderma* (sinistral, encrusted) and *N. labradoricum* indicates that this zone is of Pleistocene age (King 1989; Spiegler & Jansen 1989).

The base of this interval coincides with a regional seismic reflector which is interpreted to represent a depositional hiatus.

CIBICIDES GROSSUS–GLOBIGERINA BULLOIDES–N. ATLANTICA (SINISTRAL) ZONE

Category: Informal partial range zone.

Designation: M–C.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *C. grossus* and the highest consistent occurrence of *N. atlantica* (sinistral). The base of the zone is marked by the highest occurrence of *E. hannai*.

Depth range: 660–1040 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzones NSB 15a and b of King (1989), *C. grossa* zone of Stratlab (1988) and *N. atlantica* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This interval contains a rich benthonic fauna of mainly calcareous foraminifera. *E. excavatum*, *B. marginata*, *C. teretis* and *C. grossus* all occur frequently throughout. Other important species are: *N. affine*, *C. lobatulus*, *E. albiumbilicatum*, *C. pachyderma* and *B. tenerrima* (Fig. 10a).

Planktonic foraminifera are less frequent than calcareous benthonic taxa. *N. atlantica* (sinistral), *G. bulloides* and *N. pachyderma* (sinistral; both encrusted and unencrusted varieties) are dominant. The encrusted variety of *N. pachyderma* (sinistral) is common in the upper part of the interval. The unencrusted variety is common in the lower part. Other species are: *N. pachyderma* (dextral) and *N. atlantica* (dextral).

Remarks: The occurrence of *C. grossus*, *N. atlantica* (sinistral) and *G. bulloides* indicates that this interval is of Late Pliocene age, but older than 2.3 Ma (King 1989; Spiegler & Jansen 1989). The youngest part of the Late Pliocene is not therefore recorded in well 6506/12-4. This is supported by the fact that Zone M–B is not present.

N. atlantica (dextral) is recorded once in the Upper Pliocene (2.3–2.0 Ma) and once in the Upper Miocene on the Vøring Plateau (Spiegler & Jansen 1989). This indicates either that *N. atlantica* has a somewhat different range in this area than on the Vøring Plateau, or that the recorded specimens are reworked from Upper Miocene deposits. *N. pachyderma* (sinistral, encrusted) is caved from Zone M–A.

CIBICIDES GROSSUS–ELPHIDIELLA HANNAI–GLOBIGERINA BULLOIDES–N. ATLANTICA (SINISTRAL) ZONE

Category: Informal assemblage zone.

Designation: M–D.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *E. hannai*. The base of the zone is marked by highest consistent occurrence of *N. atlantica* (dextral).

Depth range: 1040–1480 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzones NSB 15a and b of King (1989), *C. grossa* zone of Stratlab (1988) and *N. atlantica* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: The assemblage in this zone is very similar to that in Zone M–C, the main difference being the presence of *E. hannai* (Figs. 10a, b).

Remarks: The occurrence of *C. grossus*, *E. hannai*, *G. bulloides* and *N. atlantica* (sinistral) indicates that this zone is of Late Pliocene age (King 1989; Spiegler & Jansen 1989). The occurrence of *E. hannai* indicates that the sediments are of a more shallow marine origin than in Zone M–C (Feyling-Hanssen 1986; Skarbø & Verdenius 1986).

In this zone and in the M–A and M–C zones reworked agglutinated foraminifera are recorded from the Lower Cenozoic, benthonic and planktonic calcareous foraminifera from the Upper Cretaceous and *Inoceramus* prisms from the Upper Cretaceous. The base of the M–D zone coincides with a regional seismic reflector which is interpreted to represent a depositional hiatus.

NONION AFFINE–N. ATLANTICA (DEXTRAL) ZONE

Category: Informal partial range zone.

Designation: M–G.

Informal boundary criteria: The top of the zone is taken at the highest consistent occurrence of *N. atlantica* (dextral). The base of the zone is marked by the highest occurrence of *C. telegdi.*

Depth range: 1480–1660 m.

Age: Late Miocene.

Lithostratigraphic formation: Kai Formation.

Equivalent zones: Lower *N. atlantica* (dextral) zone of Spiegler & Jansen (1989) and probably Melonis–Trifarina zone of Stratlab (1988).

Assemblage: This zone contains a medium-rich benthonic fauna of mainly calcareous foraminifera. Sponge spicules (rod-shaped and *Geodia* sp.) are also recorded in this zone. The benthonic calcareous foraminifera include *N. affine* and *C. teretis*, which are the most common species, and which occur throughout the zone. Other characteristic species are: *C. lobatulus*, *I. islandica*, *B. marginata* and *A. fluens.*

Planktonic foraminifera are less frequent than calcareous benthonic taxa. *N. atlantica* (sinistral), *G. bulloides*, *N. atlantica* (dextral) and *T. quinqueloba are dominant*. Other species are: *N. pachyderma* (sinistral, unencrusted), *N. pachyderma* (dextral), *G. inflata* and *G. puncticulata* (Fig. 10b).

Remarks: The consistent appearance of *N. atlantica* (dextral) indicates that these specimens are *in situ*, and that the zone represents the lower *N. atlantica* (dextral) zone seen on the Vøring Plateau. Spiegler & Jansen (1989) have described the lower *N. atlantica* (dextral) zone from Upper Miocene sediments in that area. This is the uppermost zone of the Kai Formation, and was not encountered in well 6607/5-1.

CIBICIDES TELEGDI–EPONIDES PYGMEUS–N. ATLANTICA (DEXTRAL) ZONE

Category: Informal partial range zone.

Designation: M–H.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *C. telegdi*. The base of the zone is marked by the highest occurrence of *E. variabilis* and *G. subglobosa*.

Depth range: 1660–1770 m.

Age: Late Miocene.

Lithostratigraphic formation: Kai Formation.

Equivalent zones: Lower *N. atlantica* (dextral) zone of Spiegler & Jansen (1989) and probably the lower part of Melonis–Trifarina zone of Stratlab (1988).

Assemblage: This interval contains a medium-rich benthonic fauna of calcareous foraminifera. Sponge spicules (rod-shaped and *Geodia* sp.) are also recorded in this zone. The benthonic calcareous foraminifera include: *N. affine* and *C. teretis*, which are the most common species.

Other important species are: *C. telegdi*, *E. pygmeus*, *C. reniforme*, *A. fluens*, *B. marginata* and *Epistominella* sp. (Fig. 10b).

Planktonic foraminifera are less frequent than calcareous benthonic taxa. *N. atlantica* (dextral), *N. atlantica* (sinistral), *G. bulloides* and *T. quinqueloba* are dominant. Other species are: *N. acostaensis*, *N. pachyderma* (sinistral, unencrusted) and *N. pachyderma* (dextral).

Remarks: This zone is coeval with the M–H zone in well 6607/5-1, and both intervals are of Late Miocene age.

EHRENBERGINA VARIABILIS–GLOBOCASSIDULINA SUBGLOBOSA–N. ATLANTICA (DEXTRAL) ZONE

Category: Informal partial range zone.

Designation: M–I.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *E. variabilis* and *G. subglobosa*. The base of the zone is marked by the highest occurrence of Diatom sp. 3.

Depth range: 1770–1920 m.

Age: Late Miocene.

Lithostratigraphic formation: Kai Formation.

Equivalent zones: Lower *N. atlantica* (dextral) zone of Spiegler & Jansen (1989), and *G. subglobosa– E. variabilis* zone of Stratlab (1988).

Assemblage: The benthonic fauna within this interval includes calcareous foraminifera and sponge spicules. Sponge spicules (rod-shaped and *Geodia* sp.) are significantly more common than foraminifera. Benthonic calcareous foraminifera include: *N. affine* and *C. teretis*, which are the most common species and which occur throughout the zone. Other important species are: *G. subglobosa*, *E. variabilis*, *C. telegdi*, *E. pygmeus*, *A. fluens* and *B. marginata* (Fig. 10b).

Planktonic foraminifera are less frequent than calcareous benthonic taxa. *N. atlantica* (dextral), *N. atlantica* (sinistral), *G. bulloides* and *T. quinqueloba* are dominant. Other species are: *N. acostaensis*, *N. pachyderma* (sinistral, unencrusted) and *N. pachyderma* (dextral).

Remarks: This zone is coeval with the M–I zone in well 6607/5-1 and both intervals are of Late Miocene age. The base of this interval coincides with a regional seismic reflector which is interpreted to represent a depositional hiatus.

DIATOM SP. 3 ZONE

Category: Informal partial range zone.

Designation: M–L.

Depth range: 1920–1960 m.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of Diatom sp. 3. The base of the zone is marked by the highest consistent occurrence of *Cenosphaera* sp.

Age: Late Oligocene to Early Miocene.

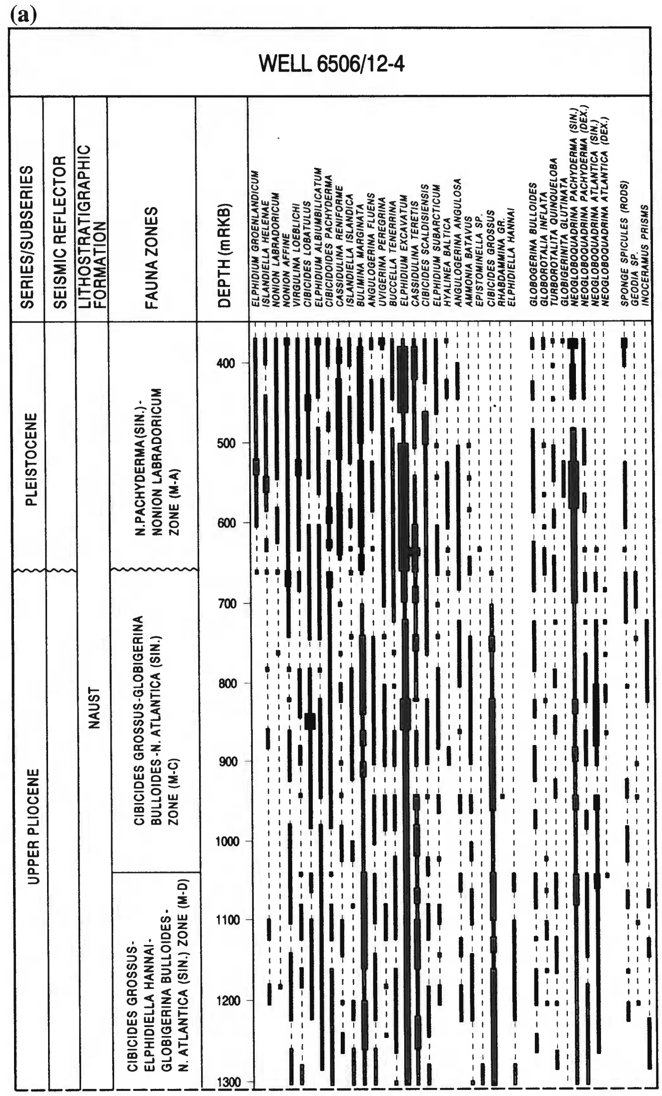
Lithostratigraphic formation: Brygge Formation.

Equivalent zones: Subzone NSP 9c of King (1989) and Diatom sp. 3 zone of Stratlab (1988).

Assemblage: Most fossils in this interval are radiolarian. Considerably fewer diatoms, sponge spicules and benthonic and planktonic foraminifera are recorded. Some of the diatoms are Diatom sp. 3 (King 1983) (Fig. 10b).

Remarks: King (1989) employs Diatom sp. 3 as the nominate taxon for the Late Oligocene–Early Miocene Subzone NSP 9c of the North Sea. Most of the foraminifers found in this interval are probably caved.

(a)



Water depth: 256 M (MSL)

Fig. 10(a). (Legend overleaf).

(b)

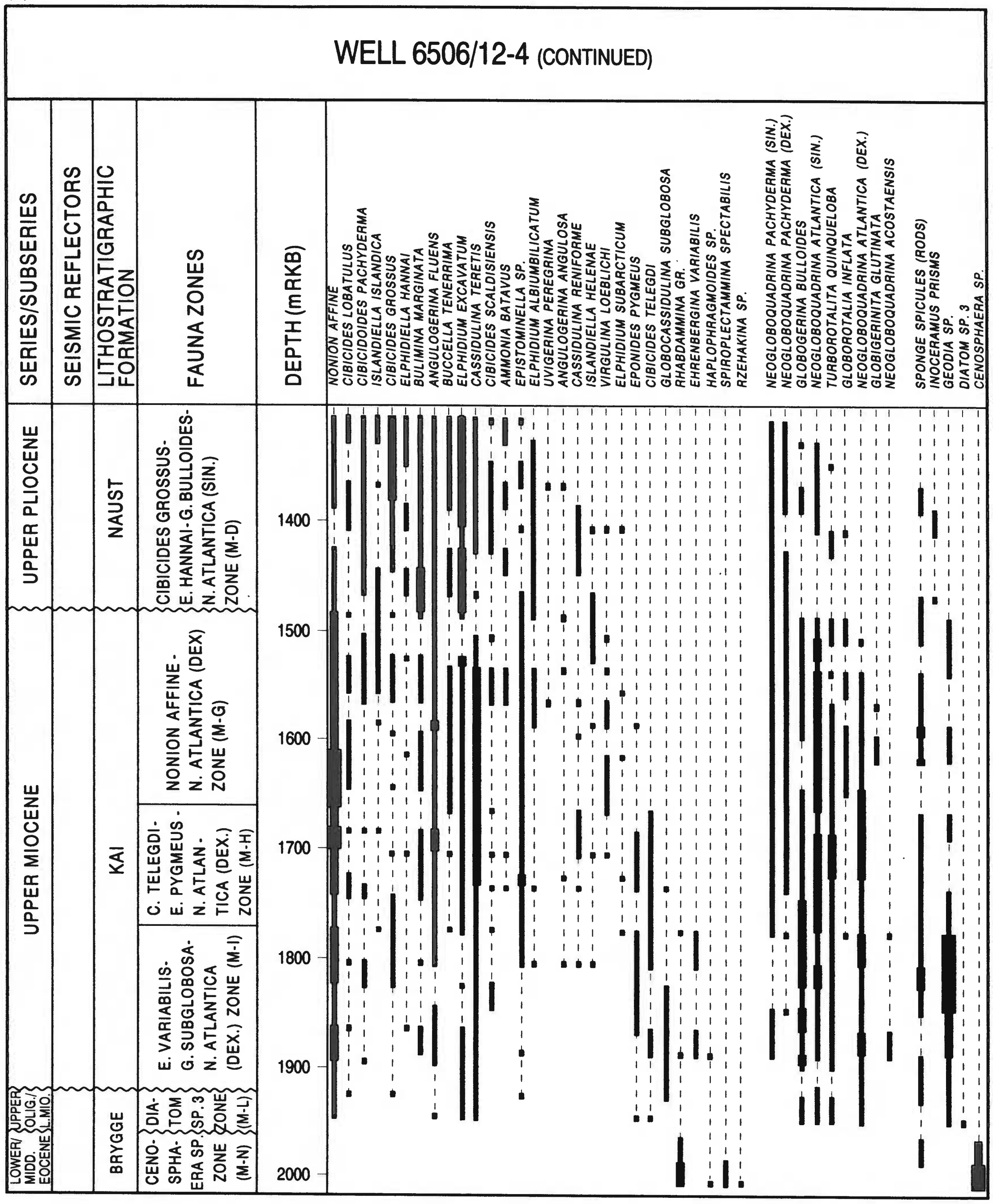


Fig. 10. (a) Range chart of the most important index fossils in the upper part of the investigated interval of well 6506/12-4. M RKB = meters below rig floor, m MSL = meters below mean sea level. (b). Range chart of the most important index fossils in the lower part of the investigated interval of well 6506/12-4.

CENOSPHAERA SP. ZONE

Category: Informal partial range zone.

Designation: M–N.

Informal boundary criteria: The top of the zone is taken at the highest consistent occurrence of *Cenosphaera* sp. The base of the zone is undefined.

Depth range: 1960–2000 m (lowest sample analyzed).

Age: Early to Middle Eocene.

Lithostratigraphic formation: Brygge formation.

Equivalent zones: Zone NSP 6 of King (1989).

Assemblage: The fauna in this interval is dominated by the radiolarian *Cenosphaera* sp. In addition, agglutinated foraminifera and sponge spicules are recorded. The agglutinated foraminifera include the *Rhabdammina* group, which is the most common. Other species are *Spiroplectammina spectabilis*, *Haplophragmoides* sp. and *Rzehakina* sp. (Fig. 10b).

Remarks: *S. spectabilis* and a *Cenosphaera* sp. acme is known from the Lower to Middle Eocene of the North Sea (King 1989). This zone is coeval with the M–N zones in the wells 6607/5-1 and /5-2.

WELL 6610/7-2 (66°27′N, 10°10′E)

NEOGLOBOQUADRINA PACHYDERMA (SINISTRAL) – *NONION LABRADORICUM* ZONE

Category: Informal partial range zone.

Designation: M–A.

Informal boundary criteria: The top of the zone extends above the uppermost investigated sample (330 m) and probably to near the sea floor. The base of the zone is taken at the highest occurrence of *E. hannai*, *N. atlantica* (sinistral) and *G. bulloides* and the highest consistent occurrence of *C. grossus*.

Depth range: 330 (uppermost investigated sample) – 410 m.

Age: Pleistocene.

Lithostratigraphic formation: Naust formation.

Equivalent zones: Subzone NSB 16x of King (1989), Zone NSR 13 of Gradstein & Bäckström (1996) and the *N. pachyderma* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This interval contains a rich benthonic fauna of calcareous foraminifera. *E. excavatum*, *C. lobatulus*,. *C. reniforme* and *B. marginata* occur most frequently. Other important species are: *N. labradoricum*, *Islandiella islandica*, *Islandiella helenae*, *C. teretis*, *N. affine* and *B. tenerrima* (Fig. 11).

The planktonic foraminifera are considerably less frequent than benthonic taxa and include: *N. pachyderma* (both encrusted and unencrusted varieties of sinistrally coiled individuals), *N. pachyderma* (dextral) and *T. quinqueloba*.

Remarks: The occurrence of *N. pachyderma* (sinistral, encrusted) and *N. labradoricum* indicates that this zone is of Pleistocene age (King 1989; Spiegler & Jansen 1989).

CIBICIDES GROSSUS–ELPHIDIELLA HANNAI–GLOBIGERINA BULLOIDES–N. ATLANTICA (SINISTRAL) ZONE

Category: Informal partial range zone.

Designation: M–D.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *E. hannai*, *N. atlantica* (sinistral) and *G. bulloides* and the highest consistent occurrence of *C. grossus*. The base of the zone is marked by the highest consistent occurrence of *Coscinodiscus* sp. 1.

Depth range: 410–1002 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzones NSB 15a and b of King (1989), *C. grossa* zone of Stratlab (1988) and *N. atlantica* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This zone contains a rich benthonic fauna of calcareous foraminifera. *E. excavatum*, *C. teretis*, *C. lobatulus*, *E. albiumbilicatum*, *C. grossus* and *E. hannai* all occur frequently throughout (Fig. 11).

Planktonic foraminifera are less frequent than benthonic taxa. *G. bulloides* and *N. atlantica* (sinistral) are the most common species. *N. pachyderma* (sinistral) and *N. pachyderma* (dextral) are recorded in the upper part of the interval.

Remarks: In addition to analyses of drill cuttings, the investigation of this zone is based on analyses of seven sidewall cores from the interval between 712 m and 1002 m.

The occurrence of *C. grossus*, *E. hannai*, *G. bulloides* and *N. atlantica* (sinistral) indicates that this interval is of Late Pliocene age, but older than 2.3 Ma (King 1989; Spiegler & Jansen 1989). The youngest part of the Late Pliocene is therefore not recorded in well 6610/7-2. The zone is coeval with the M–C and M–D zones in wells 6506/12-4, 6607/5-1 and /5-2. The base of Zone M–D coincides with a regional seismic reflector which is interpreted to represent a depositional hiatus.

COSCINODISCUS SP. 1 ZONE

Category: Informal partial range zone.

Designation: M–O.

Depth range: 1002–1100 m (lowest sample analyzed).

Informal boundary criteria: The top of the zone is taken at the highest consistent occurrence of *Coscinodiscus* sp. 1. The base of the zone is undefined.

Age: Late Paleocene to Early Eocene.

Lithostratigraphic formation: Tare Formation.

Equivalent zones: Zone NSP 4 of King (1989), Zone NSR 3 of Gradstein & Bäckström (1996) and *Coscinodiscus* sp. 1 zone of Stratlab (1988).

Assemblage: The greater proportion of the fossils from this interval are diatoms. Sponge spicules and radiolaria are also recorded. The diatoms include *Coscinodiscus* sp. 1 (common), *Triceratium* sp. 1 and *Coscinodiscus* sp. 2 (Fig. 11).

Remarks: King (1989) employs *Coscinodiscus* sp. 1 as the nominate taxon for the Upper Paleocene – Lower Eocene Zone NSP 4 of the North Sea.

WELL 6610/7-1 (66°17′N, 10°16′E)

CIBICIDES GROSSUS–ELPHIDIELLA HANNAI ZONE

Category: Informal partial range zone.

Designation: M–E.

Informal boundary criteria: The top of the zone extends above the uppermost investigated sample (710 m). The base of the zone is marked by the lowest occurrence of *C. grossus*.

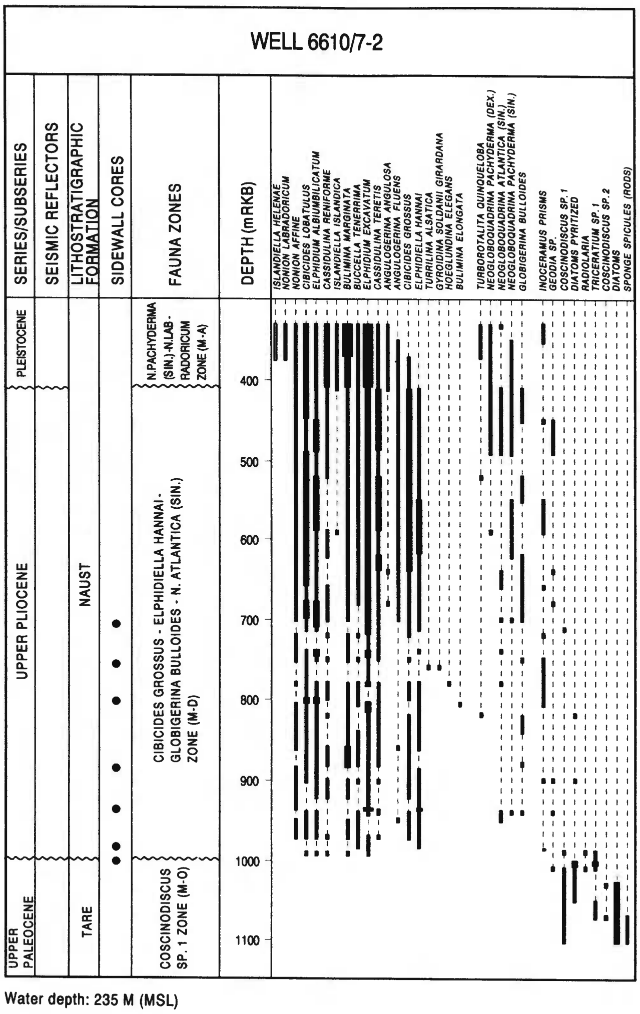


Fig. 11. Range chart of the most important index fossils in the investigated interval of well 6610/7-2. M RKB = meters below rig floor, m MSL = meters below mean sea level.

Depth range: 710 (uppermost investigated sample) – 830 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzones NSB 15a and b of King (1989), *C. grossa* zone of Stratlab (1988) and *N. atlantica* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This zone contains a medium-rich benthonic fauna of calcareous foraminifers. *B. marginata*, *C. teretis* and *E. excavatum* occur most frequently. Other important species are: *C. grossus*, *E. hannai*, *N. affine*, *C. lobatulus*, *E. albiubilicatum*, *C. reniforme* and *A. fluens*. *G. bulloides*, *N. atlantica* (sinistral) and *T. quinqueloba* are sporadic planktonic representatives (Fig. 12).

Remarks: The occurrence of *C. grossus*, *E. hannai*, *G. bulloides* and *N. atlantica* (sinistral) indicates that this zone is of Late Pliocene age, but older than 2.3 Ma (King 1989; Spiegler & Jansen 1989). This zone is coeval with the M–C and M–D zones in wells 6607/5-1, 6607/5-2, 6506/12-4 and 6610/7-2.

EPHIDIELLA HANNAI ZONE

Category: Informal partial range zone.

Designation: M–F.

Informal boundary criteria: The top of the zone is taken at the lowest occurrence of *C. grossus*. The base of the zone is marked by the lowest occurrence of *E. hannai*.

Depth range: 830–890 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzones NSB 15a and b of King (1989), the *C. grossa* zone of Stratlab (1988) and the *N. atlantica* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This interval contains a moderately rich benthonic fauna of calcareous foraminifers; these are less frequent than in Zone M–E. No planktonic foraminifera have been recorded. *E. excavatum* is dominant. Other important species include: *E. hannai*, *B. marginata*, *B. tenerrima*, *N. affine*, *C. lobatulus*, *E. albiumbilicatum* and *H. orbiculare* (Fig. 12).

Remarks: The presence of *E. hannai* indicates that this interval is of Late Pliocene age (King 1989). This zone is coeval with the M–D zones in wells 6506/12-4 and 6610/7-2. The base of Zone M–F coincides with a regional seismic reflector which is interpreted to represent a depositional hiatus.

UNZONED INTERVAL

Depth range: 890–970 m.

Age: Early Oligocene.

Lithostratigraphic formation: Frøyrygg Formation (informal) or Molo Formation (informal).

Assemblage: A few calcareous benthonic foraminifera are registered in the upper part of this interval, and a few radiolaria and sponge spicules are recorded in the lower part. The palynoflora has also been investigated in this interval. The sample at 900 m is dominated by spores and pollen thought to be of Griesbachian–Late Permian age together with a small number of dinoflagellates. Otherwise, poorly preserved and impoverished dinoflagellate associations have been observed down to 960 m. The sample at 920 m contains *Alisocysta margarita*, while that at 960 m contains *Deflandrea oebisfeldensis*.

Remarks: The calcareous benthonics recorded from this interval are Upper Pliocene/Pleistocene forms and are probably caved. The radiolaria and sponge spicules are most likely reworked. The dinoflagellate *A. margarita* is thought to be reworked from the Paleocene while *D. oebisfeldensis* is reworked from the Lower Eocene–

Paleocene. Other recorded species range from Pliocene to Eocene.

The sediment in this interval is the same coarse, rust-stained sand as found in the upper part of Zone M–M in well 6610/3-1. Zone M–M has been dated to Early Oligocene, and correlation to seismic data indicates that these intervals are the same.

CENOSPHAERA SP. ZONE

Category: Informal partial range zone.

Designation: M–N.

Informal boundary criteria: The top of the zone is taken at the highest consistent occurrence of *Cenosphaera* sp. The base of the zone is undefined.

Depth range: 970–1090 m (lowest sample analyzed).

Age: Early to Middle Eocene.

Lithostratigraphic formation: Brygge Formation.

Equivalent zones: Zone NSP 6 of King (1989).

Assemblage: The fauna in this interval is dominated by the radiolarian *Cenosphaera* sp. Some agglutinated foraminifera and sponge spicules are also recorded. The agglutinated foraminifera include *S. spectabilis*, which are the most common. Other species are *Reticulophragmium* sp. *Trochammina* sp. and the *Rhabdammina* group (Fig. 12).

Remarks: *S. spectabilis* and a *Cenosharera* sp. acme are known from the Lower to Middle Eocene of the North Sea (King 1989). This zone is coeval with the M–N zones in wells 6607/5-1, 6607/5-2 and 6506/12-4.

WELL 6610/3-1 (66°55′N, 10°54′E)

GYROIDINA SOLDANII GIRARDANA–BOLIVINA CF. *ANTIQUA* ZONE

Category: Informal assemblage zone.

Designation: M–M.

Informal boundary criteria: The top of the zone extends above the uppermost investigated sample (460 m). The base of the zone is undefined.

Depth range: 460–555 m.

Age: Early Oligocene.

Lithostratigraphic formation: Frøyrygg Formation (informal) or Molo Formation (informal).

Equivalent zones: Zone NSB 7 of King (1989) and Zone NSR 7A or NSR 7B of Gradstein & Bäckström (1996).

Assemblage: The biostratigraphic analyses of this well are based on five sidewall cores only. The three uppermost samples contain only a few calcareous benthonic foraminifera. The two lowermost samples contain a rich calcareous benthonic fauna. *Gyroidina soldanii girardana*, *P. bulloides*, *C. telegdi*, *Nodosaria* sp. and *Cibicides dutemplei* appear throughout the sequence. *Cibicides aknerianus*, *Alabamina tangentialis*, *G. subglobosa*, *Hoeglundina elegans*, *Alabamina wolterstorfi*, *Stilostomella adolphina*, *Guttulina problema*, *Cibicides dobergensis*, *Turrilina alsatica* and *Bolivina* cf. *antiqua* are all encountered in the two lowermost samples (Fig. 13).

The palynoflora has also been investigated from this interval. One feature of the assemblages is the high frequency and diversity within the genus *Phthanoperidinium*. In addition, there are large numbers of *Cribroperidinium* (reticulate forms) and an abundance of *Areosphaeridium arcuatum* at 555 m. *Areosphaeridium diktyoplokus* is recorded in variable numbers throughout the interval.

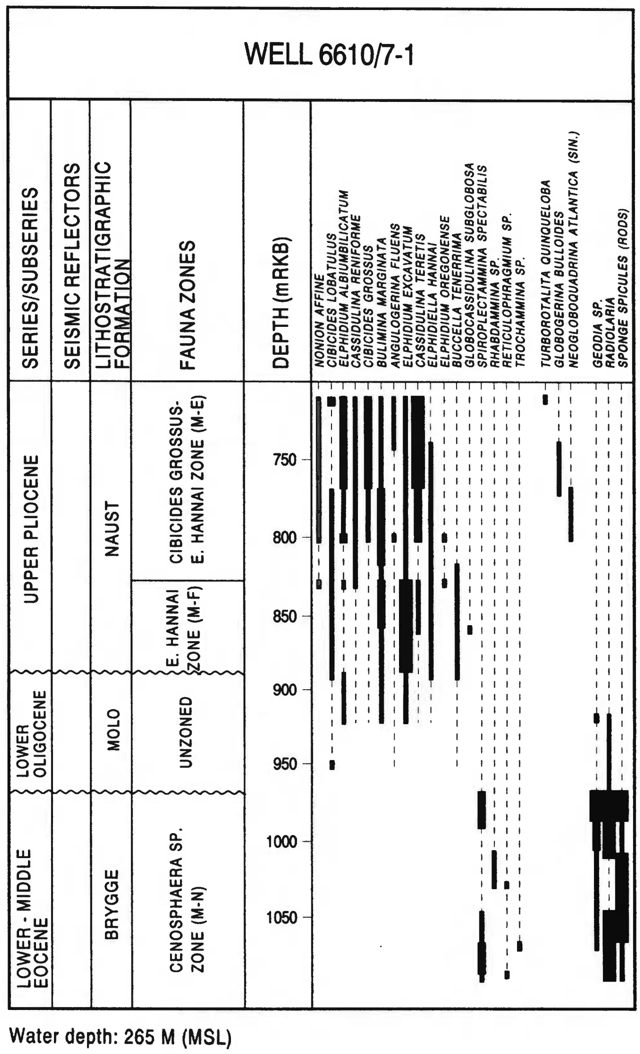


Fig. 12. Range chart of the most important index fossils in the investigated interval of well 6610/7-1. M RKB = meters below rig floor, m MSL = meters below mean sea level.

Remarks: The sediment in the three uppermost samples in this interval comprises the same coarse, rust-stained sand as encountered in the 'unzoned' interval in well 6610/7-1. The two lowermost samples contain a grey, unoxidized, mica-rich sand.

The foraminfera found in this interval are all described from the Lower Oligocene to Upper Miocene deposits in the North Sea area (Batjes 1958; Christensen & Ulleberg 1974; Ulleberg 1985; Nuglish & Spiegler 1974; King 1989). *Bolivina* cf. *antiqua* is restricted to the Upper Oligocene to lowermost Miocene sediments of the North Sea (King 1989).

Strontium-isotope analyses of tests in the sample at 525 m give an $^{87}Sr/^{86}Sr$ ratio of 0.707781 ± 11. The sample at 555 m gives an $^{87}Sr/^{86}Sr$ ratio of 0.707720 ± 9. These ratios indicate respective ages of about 35.9 and 39.8 Ma according to DePaolo & Ingram (1985), Hess et al. (1986), Koepnick et al. (1985), Palmer & Elderfield (1985) and Rundberg (pers. comm. 1995). The lowermost sample is possibly contaminated, so the uppermost analysis is probably the most reliable. The presence of the foraminifera *Bolivina* cf. *antiqua* indicates a Late Oligocene age for this unit, but since correlation of benthonic foraminifera over long distances is not always reliable, the Sr-isotope age of 35.9 Ma (Early Oligocene) is preferred.

One major characteristic of the samples analyzed for palynology between 460 and 555 m is the variety of reworking present, which is derived from all levels between the Jurassic and Upper Eocene. However, based on overall assemblage composition an Early Eocene age may be assigned to most of the samples. The dinoflagellate assemblage observed in the sample at 555 m which includes abundant *A. arcuatum* suggests an age close to the Eocene/Oligocene boundary equivalent to zone O1 as illustrated in Mudge & Bujak (1994, Fig. 3). The frequency of *A. diktyoplokus*, which has a LAD at the top of the Eocene, is highly variable (in some cases the abundance levels are more typical of the Middle Eocene). In this case a Late Eocene age equivalent to Zone E8b (Bujak & Mudge 1994) is possible, though questionable due to the degree of reworking of associated Eocene palynofloras. An Early Oligocene age is also in agreement with the micropaleontological data.

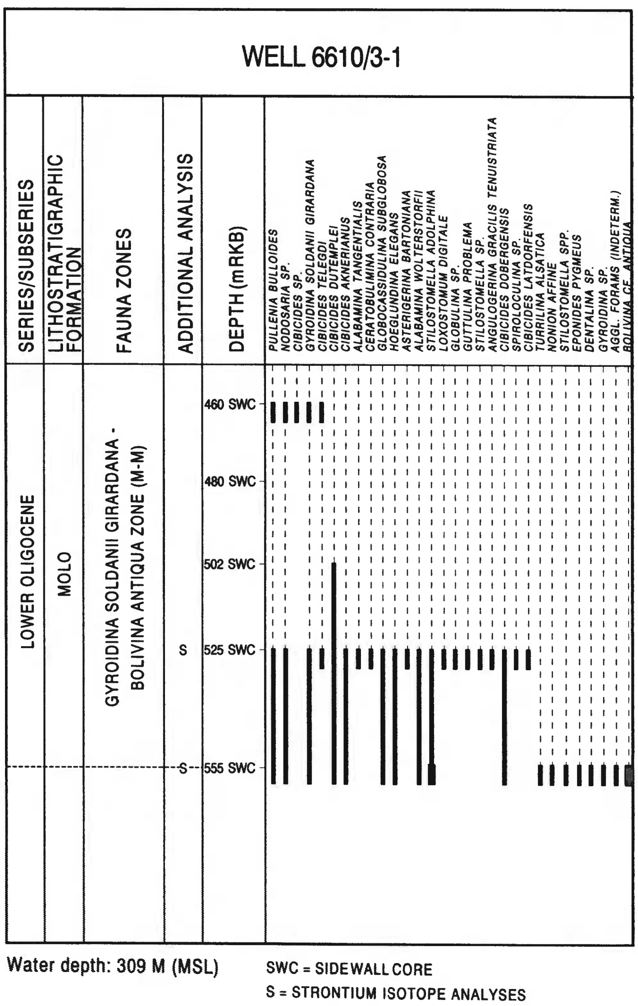


Fig. 13. Range chart of the most important index fossils in the investigated interval of well 6610/3-1. M RKB = meters below rig floor, m MSL = meters below mean sea level.

Paleoenvironments

Pleistocene to Upper Pliocene

A high content of glacigenic material and polar benthonic foraminifera such as *E. excavatum*, *C. reniforme* and several forms of the genus *Elphidium* indicate cold water conditions during most of the Late Pliocene and Pleistocene. In addition, the Pleistocene sections contain several more polar forms of the genus *Islandiella*, while containing several boreal forms such as: *U. peregrina*, *A. angulosa* and *H. balthica*. This reflects the larger variation between the glacial and the interglacial periods that existed during the Pleistocene, compared with the variation that existed during Late Pliocene time, described from ODP drillings in the Norwegian Sea (Jansen & Sjøholm 1991; Berger & Jansen 1994).

In wells 6607/5-1 and /5-2, Upper Pliocene and Pleistocene deposits correspond to Fauna Zones M–A, M–C and M–D (well 6607/5-2 contains only Zone M–C). These sections are rich in planktonic foraminifera, and a large proportion of planktonic foraminifera in coastal areas indicates open marine and fairly deep water conditions. A large content of *N. affine* also indicates fairly deep water (Mackensen et al. 1985). These units were probably deposited in an outer shelf environment.

In well 6506/12-4 the Upper Pliocene and Pleistocene correspond to Fauna Zones M–A, M–C and M–D. Zone M–A has a moderately rich planktonic foraminifera fauna. Zone M–C contains a smaller number,

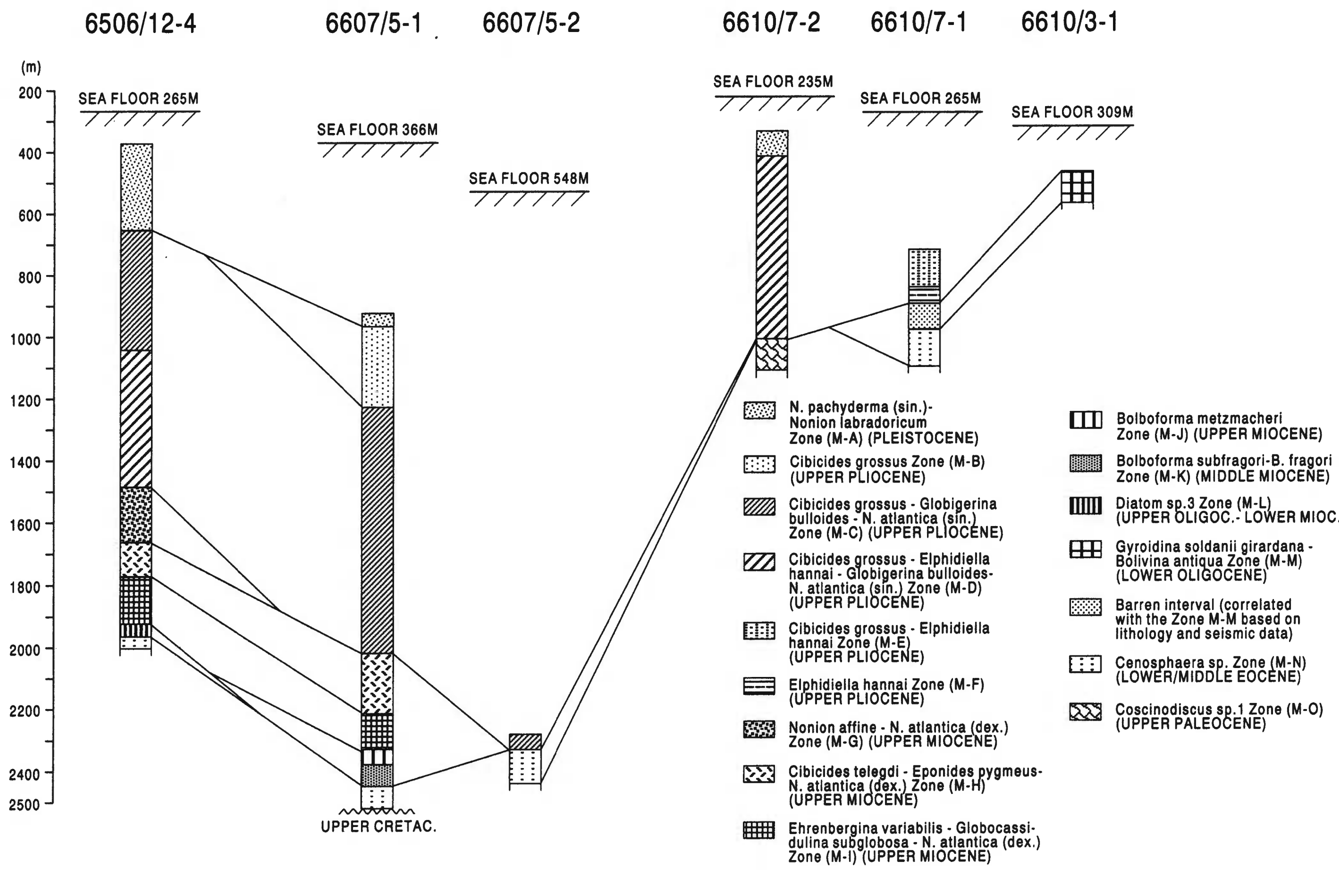


Fig. 14. Correlation of the faunal zones between the wells studied. Vertical axis is meters below rig floor.

while in Zone M–D there are few planktonic foraminifera. In Zone M–A there is a consistent occurrence of the deep-water form *N. affine*. This taxon decreases in numbers in Zone M–C, and in Zone M–D *N. affine* occurs only sporadically. In Zone M–D there is also a consistent occurrence of the shallow-water indicator *E. hannai* (Feyling-Hanssen 1986; Skarbø & Verdenius 1986). This indicates that Zone M–A was deposited in an outer shelf environment, Zone M–C in an outer to middle shelf environment and Zone M–D was probably deposited in a middle shelf environment.

In well 6610/7-2, the Upper Pliocene and Pleistocene correspond to Zones M–A and M–D. In Zone M–A there is a rare but consistent occurrence of planktonic foraminifera. This is also the case for the upper part of Zone M–D, but in the lower part of this zone there is only a sporadical occurrence. *N. affine* occurs rarely but consistently in Zone M–A and in upper part of Zone M–D. In the lower part of Zone M–D, this form occurs more sporadically. The shallow water dwelling *E. hannai* occurs consistently through Zone M–D. In this well these observations indicate that Zone M–A and the upper part of Zone M–D were deposited in a middle shelf environment, and the lower part of Zone M–D in a middle to inner shelf environment.

In well 6610/7-1 only the lower part of the Upper Pliocene is investigated, corresponding to Zones M–E and M–F. In Zone M–E there is only a sporadical occurrence of planktonic foraminifera. In Zone M–F no planktonic species are registered. There is a rare occurrence of *N. affine* in Zone M–E. *E. hannai* occurs consistently throughout both zones. This indicates that Zone M–E was deposited in an inner to middle shelf environment, and Zone M–F in an inner shelf environment.

Upper to Middle Miocene

Upper to Middle Miocene deposits (Zones M–G to M–K) are found in wells 6607/5-1 and 6506/12-4. Zone M–G is registered in well 6506/12-4 only. This zone contains a rich planktonic foraminifer fauna. Few polar and shallow-water forms have been registered, but the deep-water dwelling form *N. affine* is common throughout the zone. Zone M–G was probably deposited in an outer shelf environment.

Zones M-H and M-I are registered in both wells 6607/5-1 and 6506/12-4. Common occurrence of planktonic foraminifera, the consistent occurrence of *N.*

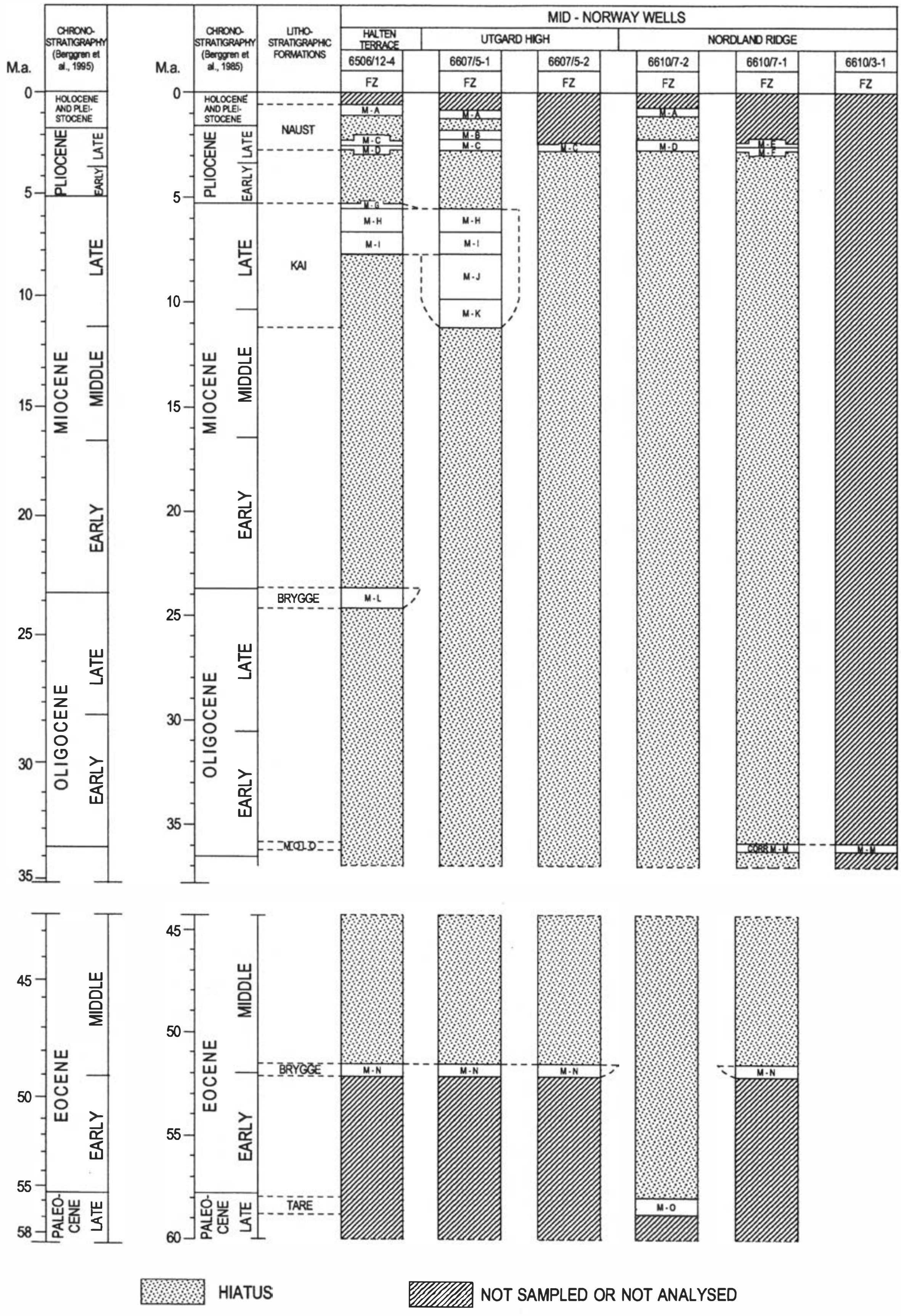


Fig. 15. Correlation of the faunal zones between the well studied. Vertical axis is Ma. Note that the ages of the Eocene and Paleocene fauna zones are less accurate than the younger fauna zones. Time scales of Berggren et al. (1985 and 1995) are presented. FZ = fauna zones.

affine and the occurrence of *P. bulloides* indicate deposition in an outer shelf environment (Mackensen et al., 1985).

Zones M-J and M-K are only registered in well 6607/5-1. Zone M-J represents the lowermost part of the Upper Miocene, and Zone M-K represents the uppermost part of the Middle Miocene. A large proportion of the microfossils in these zones are planktonic organisms (*Bolboforma* and planktonic foraminifera), indicating deep water. Registration of the benthonic forms *P. bulloides* and *M. communis* also indicate fairly deep water (Mackensen et al., 1985; Skarbø & Verdenius, 1986). Zones M-J and M-K were probably deposited in an outer shelf environment.

Base Lower Miocene to Upper Oligocene

Base Lower Miocene to Upper Oligocene deposits (Zone M–L) are only registered in well 6506/12-4. A large part of the microfossils in this section are planktonic organisms. Both radiolaria and diatoms are common, which indicates deposition in an outer to middle shelf environment.

Lower Oligocene

Zone M–M is registered in well 6610/3-1, which is situated furthest northeast in the investigated area. This zone corresponds to the sandy coastal deposits described below. Zone M–M contains only calcareous benthonic foraminifera. No planktonic species are registered. Most of the foraminifera are shallow water dwelling forms (Skarbø & Verdenius 1986). Both fossils and the lithology indicate that Zone M–M was deposited in an inner shelf environment. The unzoned interval in well 6610/7-1 contains no *in situ* fossils, but seismic correlation indicates that these sections are identical.

Middle to Lower Eocene

Middle to Lower Eocene deposits (Zone M–N) are found in wells 6607/5-1, 6607/5-2, 6506/12-4 and 6610/7-1. A large population of radiolarians, which is generally associated with normal marine conditions, indicates deposition in open marine, relatively deep environments (probably middle to outer shelf).

Upper Paleocene

Upper Paleocene deposits (Zone M–O) are only registered in well 6610/7-2. Pyritized diatoms dominate the fossil assemblage. No foraminifera are registered. The absence of calcareous fossils is probably due to carbonate dissolution. This section was probably deposited in a deep basin with restricted vertical circulation and low oxic to anoxic bottom conditions.

Lithology and lithostratigraphy

The Pleistocene and Upper Pliocene correspond to the Naust Formation. These sections consist of clay-rich diamicton interbeded with unconsolidated coarse- to medium-grained sand. Subangular to angular pebbles of mostly crystalline and some sedimentary rocks occur throughout these sections.

The glaciomarine sediments of the Vøring Plateau have been studied by Jansen (1991, 1993, 1995) and Jansen & Sjøholm (1991), and the results of these investigations provide the best inferences concerning the maximum age of the Naust Formation in these wells. There are traces of ice-dropped material in sediments as old as nearly 12 Ma on the Vøring Plateau. The frequency of such ice-rafted material increases during the period 6.5 to 5.5 Ma, which correlates with the Messinian Stage. The frequency of ice-dropped material remains relatively low, between 5.5 Ma and 2.6 Ma, but the great increase in the supply of ice-dropped material after about 2.6 Ma reflects the marked expansion of northern European glaciers (Fig. 16). This age is considered the maximum age of the Naust Formation in the investigated wells.

The Upper to Middle Miocene corresponds to the Kai Formation. The sediments of this formation are more consolidated than the sediments of the Naust Formation. The sections consist primarily of claystone with small portions of sand and silt. A few crystalline pebbles are found in the upper part of the sections, but these are probably caved.

The Lower Oligocene sections contain mostly sand and pebbles. In the section in well 6610/7-1 and in the upper part of the section in well 6610/3-1 the sand and pebble grains are rust-stained. The lower part of the section in well 6610/3-1 is not oxidized and contains a grey, mica-rich sand. These sections form a part of extensive deposits which extend along the mid-Norwegian coast from Møre to Lofoten (Rokoengen et al. 1995). These deposits are mapped and described by Bugge (1980), Bugge et al. (1984), Askvik & Rokoengen (1985), Rokoengen et al. (1988; 1995), Gustavson & Bugge (1995) and Henriksen & Vorren (1996). The deposits have been given the informal names Frøyrygg Formation (Askvik & Rokoengen 1985) and Molo Formation (Gustavson & Bugge 1995), and according to Rokoengen et al. (1995) classified as delta-like coastal deposits, probably formed in a wave-dominated environment with extensive long-shore drift.

The Middle to Lower Eocene corresponds to the Brygge Formation. These sections consist primarily of claystone. In well 6607/5-1 there are also some limestone beds.

The Upper Paleocene corresponds to the Tare Formation. This section consists primarily of claystone with smaller portions consisting of volcanic tuff.

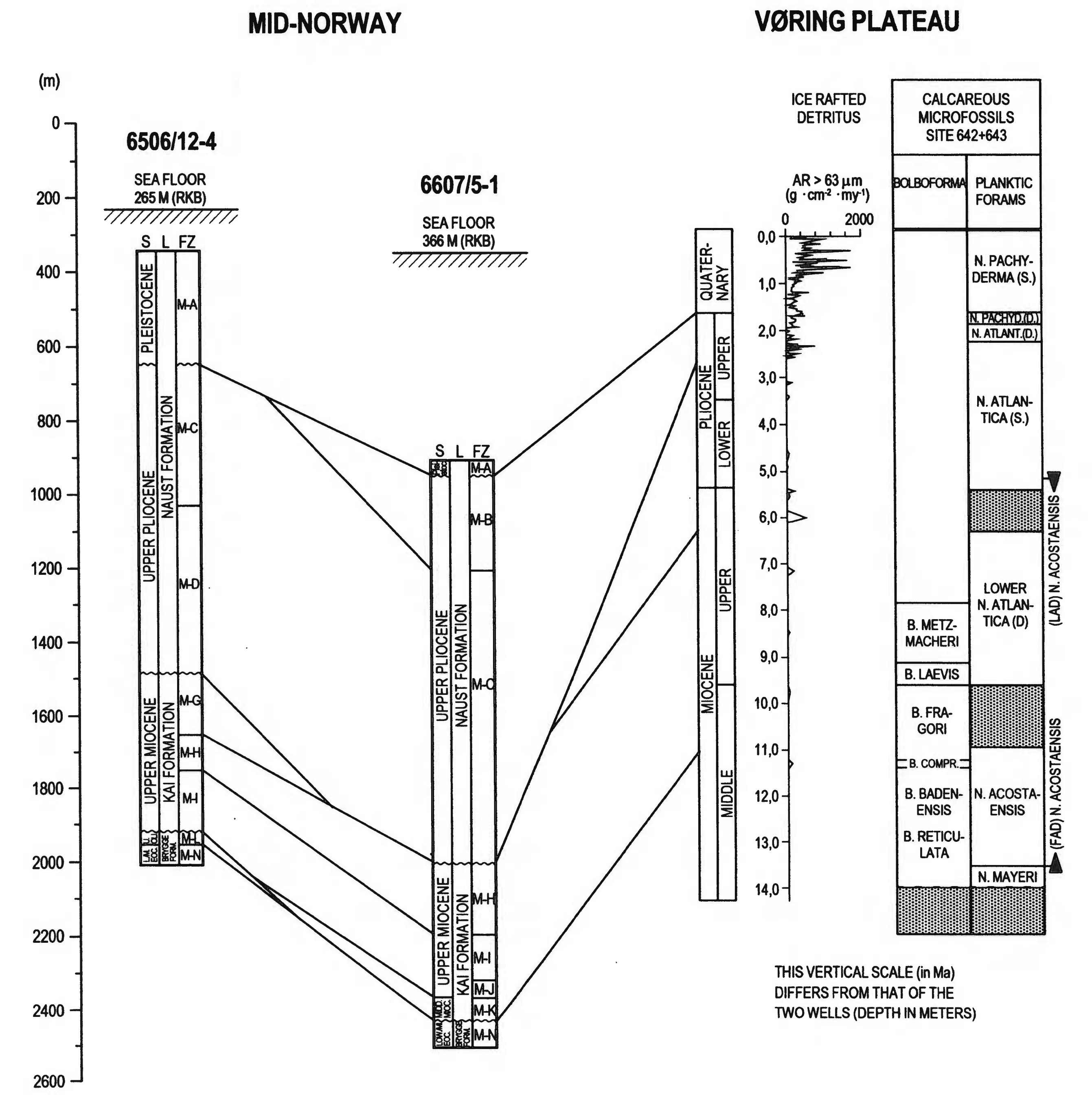


Fig. 16. Correlation of Vøring Plateau ODP sites and the stratigraphy of wells 6506/12-4 and 6607/5-1. The IRD curve is after Jansen & Sjøholm (1991) and Jansen (1995). The fossils zones of the ODP sites are after Spiegler & Jansen (1989) and Müller & Spiegler (1993). S = series/subseries, L = lithostratigraphic formations, FZ = fauna zones, AR = accumulation rate, m RKB = meters below rig floor.

Summary and discussion

During the Late Pliocene, thick, glacially derived deposits prograding from the east were laid down on the continental margin off Mid-Norway. In most areas, a hiatus is present between the Upper Pliocene and the Pleistocene. This hiatus is visible on seismic sections as a distinct reflector. Parallel and discontinuous reflectors in the Pleistocene truncate the prograding Upper Pliocene reflectors. Far west on the continental margin the base Pleistocene reflector becomes less distinct, and a truncation is not visible. In well 6607/5-1 on the Utgard High there is only a small hiatus between Upper Pliocene and Pleistocene.

Differences in Pliocene and Pleistocene deposition patterns are probably the result of changes in glaciation cycles. During the glacial period prior to 1 Ma, glacial cycles had durations spanning approximately 41 k.y. After approximately 1 Ma, 100 k.y. cycles were dominant. Both glacials and interglacials were more intense during the last period (Prell 1982, Ruddiman et al. 1986 and Berger & Jansen, 1994). During the period prior to approximately 1 Ma, the ice cap which covered Fennoscandia probably extended down to the coast in most areas. During the period subsequent to approximately 1 Ma, glaciers extended at times over the continental shelf and transported sediments over greater distances. Erosion between the Upper Pliocene and the Pleistocene was probably caused by either the advance of the glacial front or glacial-isostatic drop in sea-level. The advance of the glacial front is probably the most important transport mechanism for material from the land areas to the continental shelf, and the parallel and discontinuous reflectors seen in the Pleistocene section probably correspond to sediments laid down by glaciers.

In wells 6506/12-4 (Halten Terrace) and 6607/5-1 (Utgard High) Upper Pliocene deposits lie unconformably on the Upper Miocene. The lowermost Upper Pliocene and Lower Pliocene are absent in all of the investigated wells. In wells 6610/7-1 and /7-2 (Nordland Ridge) and 6607/5-2 (Utgard High) Upper Pliocene deposits rest unconformably on Paleogene sediments. In the northern North Sea the deposits from the lowermost Upper Pliocene to uppermost Upper Miocene are also absent (Eidvin & Riis 1992). In the western Barents Sea the Upper Pliocene lies unconformably on Lower Tertiary deposits (Eidvin et al. 1993a, 1994). In the central North Sea most of the Neogene and Upper Paleogene sections are present (Eidvin et al. 1993b). Vail & Hardenbol (1979) describe an extensive drop in global sea levels during the period 4.2–2.8 Ma. This regression appears to have caused an erosion of most of the Norwegian continental shelf, with the exception of the deeper areas in the Central and Viking Graben.

In well 6506/12-4 the Upper Miocene rests unconformably on Upper Oligocene-Lower Miocene deposits. In well 6607/5-1 Upper Miocene and uppermost Middle Miocene deposits lie unconformably on Lower to Middle Eocene deposits. Miocene sediments are not present in any of the wells on the Nordland Ridge. In well 6610/7-2 deposits younger than Late Paleocene and older than Late Pliocene are absent. In wells 6610/7-1 and 6610/3-1 coastal Lower Oligocene deposits are present. These deposits extend almost as far west as well 6610/7-2 (Fig. 6).

In connection with the seismic mapping of the eastern part of the mid-Norwegian continental shelf, IKU Petroleum Research cored the coastal deposits with a vibracorer. The vibracoring disturbed the sediments during the sampling, producing a blend of Holocene and late Weichselian foraminifera (dominant) and Oligocene and Eocene dinoflagellates. However, the Oligocene dinoflagellates were thought to be *in situ* fossils (Skarbø et al. 1983). Subsequently, it has been suggested that the coastal deposits correspond to the most proximal and oldest part of the Upper Pliocene sedimentary wedge.

Seismic profiles through this area show that Upper Pliocene prograding deposits onlap the Lower Oligocene coastal deposits (Figs. 6, 7). The coastal deposits probably represent erosional remnants. It is reasonable to assume that the these deposits have extended further east and probably have been eroded in three main phases: (1) During a regression caused by a drop in sea level at about 29 Ma (Vail & Hardenbol 1979). (2) During a regression in mid-Middle Miocene caused by regional uplift (Riis 1996). This phase is represented by a hiatus between the Upper Miocene and Upper Oligocene in well 6506/12-4, and in wells in the northern North Sea as a hiatus between the Upper and Lower Miocene (Eidvin & Riis 1992). In wells in the central North Sea this phase is represented by a seismic reflector with no discernible or only a small hiatus present. This reflector is accurately dated to 12.5 Ma (Eidvin et al. 1993b). (3) During the Late Pliocene and Pleistocene; first during the period with a drop in sea level between 4.2 and 2.8 Ma (Vail & Hardenbol 1979), later during glacial phases in the Late Pliocene and Pleistocene. Many rust-stained pebbles, which probably come from the Oligocene coastal sediments, are registered in the Upper Pliocene deposits in wells 6610/7-1 and /7-2.

Below the coastal deposits in well 6610/7-1 there are deposits of Early to Middle Eocene age.

Haflidason et al. (1991) investigated a cored geotechnical borehole from the Draugen Field (Haltenbanken). This borehole extends through the base Pleistocene angular unconformity and penetrates a seismic reflector in the prograding sequence below. The cores from this borehole were subjected to paleomagnetic, amino acid and foraminiferal analyses. The base of the borehole is dated to 1.1 Ma. However, following the dated reflector at the base of the borehole westwards, it is obvious that much of the Upper Pliocene wedge is situated above this reflector (Rise et al. 1988; Rokoengen et al. 1995). These Upper Pliocene deposits correspond to sediments which have been dated to 2.6–2.3 Ma in our investigations.

Sejrup et al. (1995) investigated a similar cored borehole from the Troll Field in the northern North Sea. This borehole only just penetrates the base Pleistocene angular unconformity in this area. The same investigations have been performed on the cored material from this borehole as on the Draugen Field. The base of this borehole is also dated as 1.1 Ma. In this area Pleistocene deposits rest unconformably on Upper Oligocene deposits, and in the west on prograding deposits of the Upper Pliocene. A comparison between the situation on the mid-Norwegian shelf after Haflidason et al. (1991) and the situation in the northern North Sea after Sejrup et al. (1995), would indicate that the Pliocene/Pleistocene sedimentary wedges are much younger on the mid-Norwegian continental shelf than in the northern North Sea. Seismic mapping over these areas indicates that this is not the case (F. Riis; pers. comm.) This suggests that the dating of the Draugen borehole is incorrect, or that the dated material is not from the anticipated seismic reflector.

Based on biostratigraphical investigations and oxygen isotope measurements of wells 6507/10-1 and 6407/1-2 on the Halten Terrace and well 6610/7-1 on the Nordland Ridge, Poole & Vorren (1993) suggest that the oldest parts of the sedimentary wedges are older than

Late Pliocene. They suggest that most of the wedges are of Middle Pliocene age. They state that the oldest part of the wedge system is found in well 6610/7-1, and this is given an Early Miocene to Early Pliocene age. This interval corresponds to two fossil-barren intervals designated 'Barren Zones 1 and 2'. Our investigations of the same well show that 'Barren Zone 2' corresponds to our 'unzoned' interval, which by seismic correlation is dated as Lower Oligocene. 'Barren Zone 1' corresponds to the base of the Upper Pliocene wedge. Our investigation of 'Barren Zone 1' shows that this interval contains a moderately rich Upper Pliocene foraminiferal fauna, and that the sediments are of glaciomarine origin. These observations are supported by results from the neighboring well 6610/7-2 where this section has sidewall core coverage.

According to Poole & Vorren (1993) there is a sequence below 'Barren Zone 2' in well 6610/7-1 containing Early Miocene fossils. We have examined this interval in detail, and have not found any of the described foraminifera. However, below this interval we have recorded a rich fauna of Lower–Middle Eocene radiolarian and agglutinated foraminifera (Zone M–N). We were unable to find any Miocene fossils in well 6610/7-2, either. If an Early Pliocene/Miocene age is correct, the foraminifers found in well 6610/3-1 are reworked. Reworking cannot be ruled out, but none of the analyzed tests showed any sign of wear, thus indicating that reworking is unlikely. Some of the palynomorphs are reworked, but these are much smaller and more buoyant and consequently more readily transported.

The theory of Poole & Vorren (1993), that the younger parts of the Pliocene wedge are of Middle Pliocene age, is based on the occurrence of the foraminifers *Florilus boueanus*, *Cibicidoides limbatosuturalis* and *Cancris auriculus* in well 6407/1-2. *F. boueanus and C. auriculus* are known from the Upper Oligocene to Lower Pliocene in the North Sea (King 1989), and *C. limbatosuturalis* is known from Upper Miocene to lower Upper Pliocene in the same area (King 1989). None of these foraminifers were recorded in our investigation of sediments of the same age. Therefore, if these forms are present in other parts of the Pliocene wedge, it must be the result of reworking.

Henriksen & Vorren (1996) have given the coastal deposits, which 'Barren Zone 2' after Pool & Vorren (1993) is a part of, two alternative ages: (1) An Early Oligocene age based on a lecture and personal observations comprising preliminary results from this work; and (2) an Early Pliocene/Miocene age based on Poole & Vorren (1993).

The youngest part of the Kai Formation is represented by Zone M–G in well 6506/12-4. In Eidvin & Riis (1991) this zone was given an uncertain Late Miocene to Early Pliocene age. The re-examination of the planktonic foraminifera shows the presence of the lower *N. atlantica* (dextral) zone of Spiegler & Jansen (1989), confirming a Late Miocene age.

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