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A new Miocene biostratigraphy for the northeastern North Atlantic: an integrated foraminiferal, bolboformid, dinoflagellate and diatom zonation

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With 9 figures and 2 tables

Abstract. This study presents a new Miocene biostratigraphic synthesis for the high-latitude northeastern North Atlantic region. Via correlations to the bio-magnetostratigraphy and oxygen isotope records of Ocean Drilling Program and Deep Sea Drilling Project Sites, the ages of shallower North Sea deposits have been better constrained. The result has been an improved precision and documentation of the age designations of the existing North Sea foraminiferal zonal boundaries of King (1989) and Gradstein and Bäckström (1996). All calibrations have been updated to the Astronomically Tuned Neogene Time Scale (ATNTS) of Lourens et al. (2004).

This improved Miocene biozonation has been achieved through: the updating of age calibrations for key microfossil bioevents, identification of new events, and integration of new biostratigraphic data from a foraminiferal analysis of commercial wells in the North Sea and Norwegian Sea. The new zonation has been successfully applied to two commercial wells and an onshore research borehole.

At these high latitudes, where standard zonal markers are often absent, integration of microfossil groups significantly improves temporal resolution. The new zonation comprises 11 Nordic Miocene (NM) Zones with an average duration of 1 to 2 million years. This multi-group combination of a total of 92 bioevents (70 foraminifers and bolboformids; 16 dinoflagellate cysts and acritarchs; 6 marine diatoms) facilitates zonal identification throughout the Nordic Atlantic region. With the highest proportion of events being of calcareous walled microfossils, this zonation is primarily suited to micropaleontologists.

A correlation of this Miocene biostratigraphy with a re-calibrated oxygen isotope record for DSDP Site 608 suggests a strong correlation between Miocene planktonic microfossil turnover rates and the inferred paleoclimatic trends. Benthic foraminifera zonal boundaries appear to often coincide with Miocene global sequence boundaries. The biostratigraphic record is punctuated by four main stratigraphic hiati which show variation in their geographic and temporal extent. These are related to the following regional unconformities: basal Neogene, Lower/Middle Miocene ("mid-Miocene unconformity"), basal Upper Miocene and basal Messinian unconformities. Further coring of Neogene sections in the North Sea and Norwegian Sea may better constrain their extent and their effect on the biostratigraphic record.

Key words. North Sea, Norwegian Sea, Foraminifera, *Bolboforma*, Dinocyst, Miocene, Neogene

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1. Introduction

This study aims to improve the temporal resolution and accuracy of the established Miocene (23.0 to 5.3 Ma) marine biostratigraphy of the north-eastern North Atlantic region, with a special emphasis on the North Sea and Norwegian continental margin. To understand the possible biotic and abiotic factors leading to this biostratigraphic record, a paleoclimatic and tectonic framework is necessary.

On the basis of paleoclimatic interpretations the Miocene can be divided broadly into three distinct intervals: 1) Early Miocene warming; 2) early Middle Miocene climatic optimum; 3) late Middle Miocene to end Miocene cooling (Thunell and Belyea 1982, Iaccarino et al. 2007). Miocene global cooling intervals have been linked to the expansion of the East Antarctic Ice Sheet and related increase in Antarctic Bottom Water (Miller et al. 2008 and references therein). Following the earliest Oligocene global cooling and shift from a greenhouse to an icehouse climatic regime, the Oligocene to middle Miocene was a period of waxing and waning of Antarctic ice sheets. This is expressed through the series of Mi-glacial intervals in the deep-sea oxygen isotope record. From mid-Langhian through Serravallian time a major shift occurred towards a cooler global climate, with the establishment of a permanent (at least through the Miocene) East Antarctic Ice Sheet (Miller et al. 2008).

In the North and Norwegian seas the tectonic history of the late Cenozoic was characterised by periods of basin subsidence and margin uplift, overprinting the paleoclimatic trends. The Late Eocene–Oligocene was a period of major basin subsistence so that by Early Oligocene time, deep-water basins had formed on either side of the Greenland Scotland Ridge complex. This established the paleoceanographic context for the Neogene (Stoker et al. 2005). In the Early Miocene compressional doming resulted in the uplift of the East Shetland Platform and Mid-Norwegian shelf. This uplift led to a pronounced basin margin unconformity at the base of the Neogene. In the North Sea this resulted in deposition of Lower Miocene turbiditic sands (Skade sands) in the southern Viking Graben (Rundberg and Eidvin 2005). Further doming led to the creation of a mid-Miocene unconformity, especially pronounced along the basin margins, including the Norwegian continental shelf (Stoker et al. 2005, Rundberg and Eidvin 2005). Along structural highs the basal Neogene and mid-Miocene unconformities may merge into a composite unconformity (Stoker et al. 2005). Following this, deep-water sedimentation from the Mid-Miocene indicates an expansion of contourite sediment drifts above submarine unconformities on both sides of the Greenland – Scotland Ridge (Kaminski et al 1989, Stoker et al. 2005). In the North Sea this is represented by the Utsira contourite sands of Late Miocene to Early Pliocene age (Galloway 2002). On the continental shelf of Mid-Norway the coeval deltaic deposits of the Molo sands are present (Eidvin et al. 2007). The Stauning sands of the Odderup Formation in Denmark may also have been deposited in response to this uplift. The next major tectonic event occurred in the Pliocene with the large-scale tilting of the Norwegian margin and major basinward progradation of shelf-slope sediment wedges with deposition of the Naust Formation (Cloetingh et al. 1990, Ottesen 2006).

2. Regional setting and biostratigraphy

The 'Nordic Atlantic region' is shown in its geographical and oceanographic context in Fig. 1. It stretches from just south of the Greenland-Scotland Ridge (GSR) northwards across the North Sea and Nordic Seas (Iceland Sea, Norwegian Sea, Greenland Sea), to the Arctic Ocean Gateway. In this region the Neogene biostratigraphy is based primarily upon foraminifers, calcareous nannoplankton and dinoflagellate cysts, with foraminifers and dinoflagellate cysts preferred by the petroleum industry. Marine diatoms and bolboformid calcareous algae add paleontological age-control for discrete time intervals, especially in lowermost Miocene sediments and across the Miocene-Pliocene transition.

The existing North Sea foraminiferal zonations of King (1989), Gradstein & Bäckström (1996) and Laursen and Kristoffersen (1999) have their zonal boundary ages based primarily on correlations with Deep Sea Drilling Project (DSDP) Leg 94 in the northern North Atlantic and Ocean Drilling Program (ODP) Leg 104 in the Norwegian Sea. With the limited availability of high-resolution deep sea drilling cores at the time and with generally poor sample quality, correlations to the then standard geologic time scales (Berggren et al. 1985, 1995) were poorly constrained.

The dinoflagellate cyst zonations of Manum et al. (1989), Mudie (1987, 1989) and Munsterman and Brinkhuis (2004) for the the Norwegian and North Seas, utilised recent ocean drilling and onshore bore-

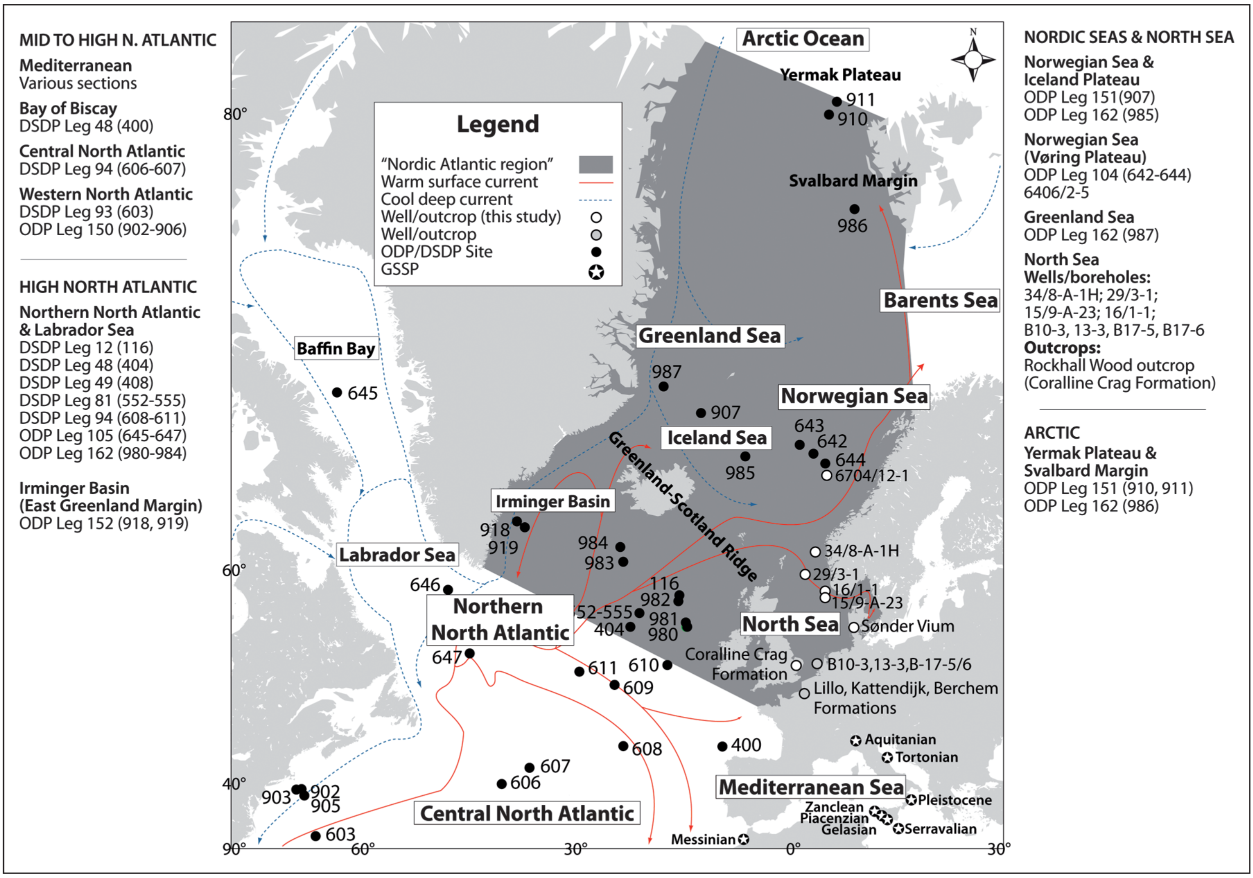


Fig. 1. Location of calibration sites used in constraining the ages of Nordic Miocene microfossil markers. The 'Nordic Atlantic Region' is highlighted.

hole data, but with age calibrations still based on the Berggren et al. (1995) biochronology. The foraminiferal, bolboformid and dinoflagellate cyst biostratigraphy of the Norwegian Sea and the Mid-Norwegian shelf has been documented extensively in the reports of Eidvin and colleagues (Eidvin and Riis 1995, Eidvin et al. 1998, Eidvin et al. 2000, Eidvin et al. 2007). The biostratigraphic age interpretations of these reports are based on the existing North Sea foraminiferal zonations, with limited addition of new ocean drilling findings. With a heavy focus on the benthic foraminiferal component, these studies have clearly proven many of the North Sea benthic events to be strongly diachronous at the deeper (middle bathyal) paleo-water depths of Mid-Norway. Instead of quantifying this diachrony in a unified zonation scheme for offshore Mid-Norway, Eidvin and colleagues chose to define a large number of separate assemblage sequences for each sub-basin. In addition to the poorly constrained benthic foraminiferal ages, these many assemblages have often proved difficult to correlate. This study aims to improve correlation based on an improved planktonic foraminiferal biostratigraphy as a framework for the regional benthic foraminiferal record.

Since the publication of the North Sea zonations a number of new ocean drilling sites have greatly improved knowledge of the regional stratigraphy of the north-eastern North Atlantic (Fig. 1). The resulting studies have produced a range of integrated high-resolution stratigraphic data-sets. These were obtained through high-resolution sampling strategies, combined biostratigraphic analysis of multiple microfossil groups and onsite geomagnetic calibration to the Astronomically Tuned Neogene Time Scale (ATNTS). It is via these deep-sea high-resolution data-sets that the ages of the shallower deposits of the North Sea can be better resolved.

3. Materials and Methods

3.1 Mid- to high-latitude regional correlations and calibrations

The location of Nordic ocean drilling sites together with selected commercial wells/boreholes analysed for their foraminiferal contents is shown in Fig. 1. To obtain a new calibrated framework of biostratigraphic events for the Nordic Atlantic region, a four-step method was followed:

1. Identification of bioevents: Calcareous, organic-walled and siliceous microfossil bioevents for the Miocene were identified primarily in the Ocean Drilling Program and Deep Sea Drilling Project publications of the North Atlantic region. These were either published as is, or identified as new events in their respective publications. In addition to the standard first and last appearances (lowest and highest occurrences respectively) routinely reported in these publications, a number of quantitative abundance changes have been identified as possible correlation tools. These include primarily acmes/paracmes, influxes, disappearances and reappearances of planktonic foraminifera and bolboformids (see results Ch. 4.1).

2. Updating original age models: The astronomically tuned geomagnetic polarity time scale together with selected planktonic foraminiferal and calcareous nannofossil events of Lourens et al. (2004) was used to update the original ODP/DSDP site age-models to the latest time scale. The oxygen isotope records of DSDP Site 608 and ODP Site 982 offered a secondary means for bioevent age calibration. The oxygen isotope record for Site 982 was generated from a composite of the following studies: 5.3–8.9 Ma = Hodell et al. (2001) + Hilgen et al. (2007); 8.2–11.6 = Anderson and Jansen (2003). The raw oxygen isotope data for DSDP Site 608 is a composite of Miller et al. (1987, 1991) and Wright et al. (1992). The resulting oxygen isotope data-set for DSDP Site 608, based on the time scale of Berggren et al. (1985), has been re-calibrated to the time scale of Lourens et al. (2004), see Figure 2. The ages of the oxygen isotope "Mi" cooling events have also been updated to the latest time scale, via their calibrations in Miller et al. (1998) and Westerhold et al. (2005). The warm to cold (red to purple) paleoclimate record (Fig. 3) is an

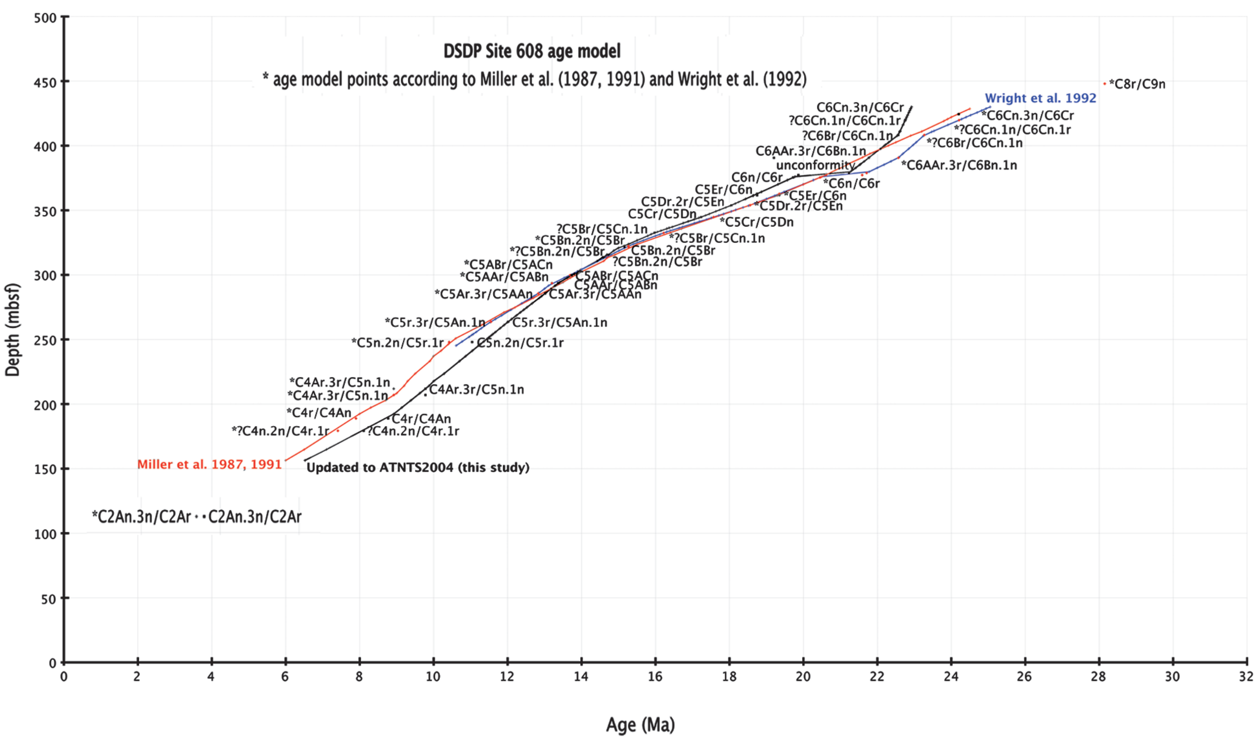


Fig. 2. Age model of DSDP Site 608 showing original magnetic reversal tie points of Miller et al. (1987, 1991) and Wright et al. (1992), together with an updated re-calibration to the astronomically tuned Neogene geomagnetic polarity time scale of Lourens et al. (2004).

interpretation based on comparison with the oxygen isotope record, the paleoclimatic/paleoceanographic findings of various authors, and the record of planktonic foraminiferal acmes on the Rockall Plateau (ODP Site 982 in Flower 1999) and in the Irminger Basin (ODP Site 918 in Spezzaferri 1998). The well calibrated planktonic foraminiferal record was then used to calibrate the shallower benthic foraminiferal record of the North Sea. The main source for the calibrated ages is first-order magnetostratigraphic control at the respective sites (Bleil 1989, Canninga et al. 1987, Channell et al. 1999a, Channell and Lehman 1999, Channell et al. 1999b, Clement and Robinson 1986, Clement et al. 1989, Hailwood 1979, Krumsiek and Roberts 1984, Shipboard Scientific Party 1995). Ages have been updated to the Astronomically Tuned Neogene Time Scale (ATNTS) of Lourens et al. 2004.

3. Calculation of calibrated bioevent ages: The true depth of a bioevent as reported in the ODP/DSDP data archives could theoretically fall between two sample depths due to non-continuous sampling. For each bioevent a depth range was therefore determined based on the sample depth reported for the fossil's highest or lowest occurrence and then the immediately overlying or underlying sample respectively. Bioevent ages have been calculated via linear interpolation from updated age models. Interpolated ages have been calculated based on their relative positions between bracketing levels (or age model tie-points). These bracketing levels are magnetosubzone boundaries and/or standard nannofossil zonal boundaries. For details to depths and ages derived per calibrated bioevent, see Appendix 1b (The appendices are available under http://doi.pangaea.de/10.1594/PANGAEA.789399).

4. Regional comparison of calibrated ages: So as to identify possible latitudinal trends, the resulting calibrated ages were arranged according to latitudinal regions defined roughly as: 35°–50° N mid- to high-latitude North Atlantic; 50°–63° N high-latitude North Atlantic; 63°–70° N Nordic Seas and North Sea; 70°–80° N Arctic. The entire area discussed in this study (Fig. 1) has the Mediterranean at its southern limit and the Arctic Ocean at its northern limit. The choice of these latitudinal regions was based on the Late Miocene planktonic foraminiferal provinces of Thunell and Belyea (1982), being the time of steepest latitudinal temperature gradient in the Miocene. They are as follows: 35°–50° N = Mediterranean latitude and southernmost calibration sites to the northernmost dominance of the "Tropical-Subtropical Zone"; 50°–63° N = northernmost dominance of the "Tropical-Subtropical Zone" northwards to the northernmost dominance of the "Transitional Zone"; 63°–70° N = northernmost dominance of the "Transitional Zone" northwards to the southernmost junction between the Norwegian Sea and Barents Sea; 70°–80° N = Barents Sea to Yermak Plateau (Arctic Ocean). The resulting 145 calibrated bioevent ages were then averaged on a per region basis, taking into account possible reworking and contamination signals (Appendix 1b). Where contrasting ages exist for an event in a single region, the most reliable calibration was used (see below).

5. Sources of error: For the majority of events the age has been calculated at the depth originally quoted in the respective ODP publications, taking into account any non-continuous sampling. Biostratigraphic sampling resolution can account for the greatest uncertainty in the stratigraphic position of an event. Interpolation uncertainty arises due to uncertainty in the depths and/or ages of the bracketing age model tie-points (e.g. magnetic reversal boundaries). The 'interpolation interval' used to calculate a bioevent age is the stratigraphic spacing in depth and time between the bracketing age model tie-points. The smaller the interpolation interval, the more reliable the interpolation. This is due to the calculation of average sedimentation rate over a shorter interval being more precise than over a longer interval. Therefore, assuming the effects of biological and mechanical reworking of the fossil record to be minimal, the most reliable calibration site for a bioevent is the one with the highest biostratigraphic sampling resolution and the smallest interpolation interval. Due to this inherent uncertainty, individual bioevent age calibrations have been expressed as ranges. Where a bioevent age is given to one decimal place only, the intention is to account for either very low sample resolution, large age/depth uncertainties of bracketing intervals, or the often numerous occurrences of barren bracketing intervals.

The resulting bioevent ages, their calibration points and sites are summarised in Appendix 1a.

For details of individual event calibrations and depths by site, see Appendix 1a and Appendix 1b.

3.2 Nordic high-latitude local correlations (North Sea)

In order to to test the application of the new zonation and to better constrain the existing North Sea – Norwegian Sea benthic foraminiferal zonations, three in-

Table 1 North Sea and Norwegian Sea wells samples analysed for foraminiferal content in this study. Lithostratigraphy follows Eidvin and Rundberg (2007) and the updated Norwegian Lithostratigraphic Lexicon (NORLEX), available at http://www.nhm2.uio.no/norlex.

Well/Outcrop	Coordinates	Lithostratigraphic unit	Depth (m below KB)	Sample type
6704/12-1-GB	67° 07′ 25.00″ N 4° 42′ 44.70″	E Kai and Brygge Formations	1482–1964	remote vehicle core-catcher
29/3-1	60° 57′ 50.24″ N 1° 56′ 13.25″	E Lark Formation	683–1633	ditch cuttings
Sønder Vium BH (DK)	55° 81′ 98.15″ N 8° 41′ 42.74″	E Hodde, Gram, Arnum Fm's	24.08–286.69	conventional cores/cuttings

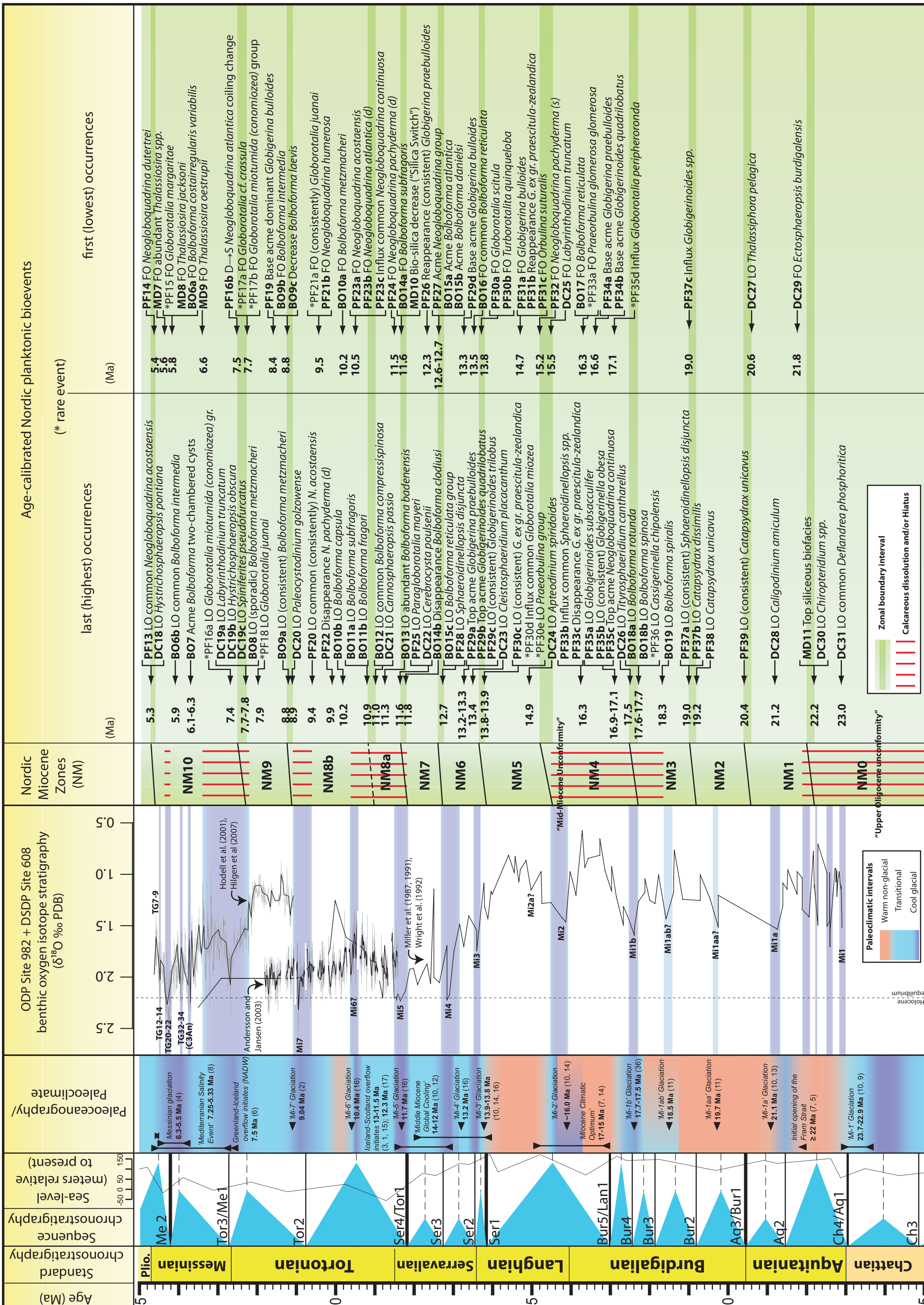
dustrial wells were analysed for their foraminiferal components (Table 1).

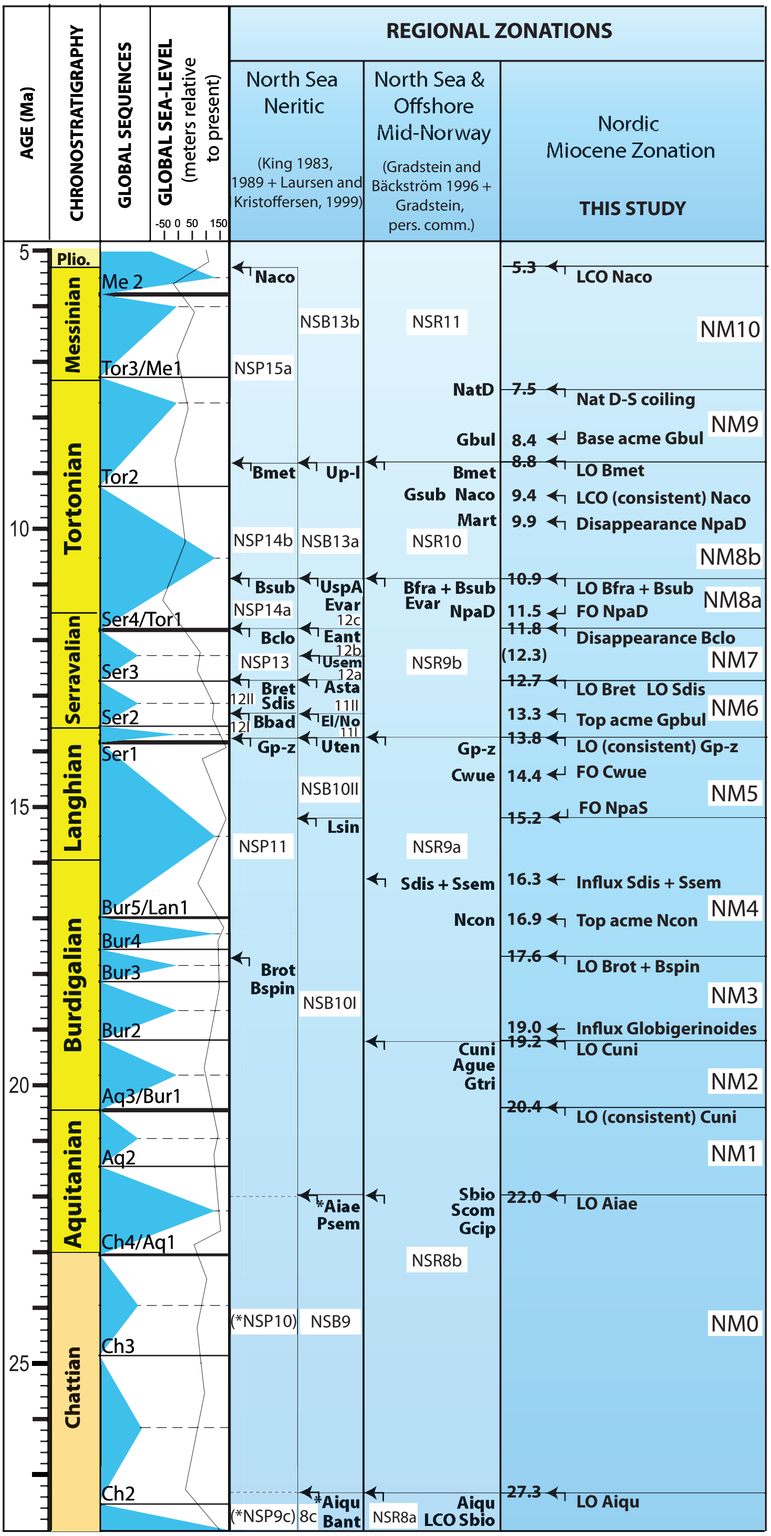
The southernmost well, Sønder Vium research borehole, is located in the circum-North Sea area of onshore Denmark near the town of Sønder Vium. It was drilled as part of the ongoing research effort by the Geological Survey of Denmark and Greenland (GEUS) to map the extent of Neogene aquifers for groundwater consumption. The dinoflagellate cyst study of Piasecki et al. (2004) allows for direct comparison between the calcareous and organic-walled microfossil biostratigraphy. For the northern North Sea, industrial well 29/3-1 was chosen due to its rich foraminiferal assemblage contents. The northernmost industrial well 6704/12-GB1 was drilled as a geotechnical well on the Gjallar Ridge of offshore Mid-Norway. Previous investigations of the younger post-Miocene section were conducted by Eidvin et al. (1998). The choice of this well is based partly on the integrated multi-group biostratigraphy of these authors and partly on the wells proximity to the ODP Leg 104 sites on the Vøring Plateau (Fig. 1). Sample types analysed include ditch cuttings, conventional cores and remote vehicle samples (Table 1).

Standard micropaleontological preparation techniques were used, with a mesh size of 63 microns. The procedures involved boiling of samples in a solution of water and sodium hexa-metaphosphate, wet sieving through a 63 micron mesh, followed by oven drying.

Microscope analysis involved identification and counting, where possible, of approximately 300 benthic and planktonic foraminiferal individuals per sample. Benthic foraminiferal taxonomy is according to Loeblich and Tappan (1987) and Van Morkhoven et al. (1986). Planktonic foraminiferal taxonomy is according to Iaccarino et al. (2007). Bolboformid taxonomy is according to Spiegler and Jansen (1989) and Spiegler (1999). The main micropaleontological results are shown in Figure 4 together with published palynological findings from the same sections according to Piasecki et al. (2004) and Eidvin et al. (1998). For

Fig. 3. A new multi-group Nordic Miocene Zonation for the northeastern North Atlantic region. Standard chronostratigraphy follows the time scale of Gradstein et al. (2004). Sequence chronostratigraphy is according to Hardenbol et al. (1998) with the updated ages of Ogg and Lugowski (2008). The global sea-level curve is according to the software 'TimeScale Creator Pro'. The raw oxygen isotope data for ODP Site 982 is a composite of the following studies: 5.3–8.9 Ma = Hodell et al. (2001) + Hilgen et al. (2007); 8.2–11.6 = Anderson and Jansen (2003). The raw oxygen isotope data for DSDP Site 608 is a composite of Miller et al. (1987, 1991) and Wright et al. (1992). The resulting oxygen isotope data-set for DSDP Site 608 has been re-calibrated to the time scale of Lourens et al. (2004). The ages of the Miocene oxygen isotope "Mi" events have also been updated to the latest time scale, via their calibrations in Miller et al. (1998) and Westerhold et al. (2005). The warm to cold (red to purple) paleoclimate record is an interpretation based on comparison with the oxygen isotope record, and the record of planktonic foraminiferal acmes on the Rockall Plateau (ODP Site 982) and in the Irminger Basin (ODP Site 918). Correlation of bioevents to the marine oxygen isotope record and paleoceanographic/paleoclimatic trends is based on the new and updated age calibrations in this study. bioevent codes: CN = Calcareous Nannofossil; PF = Planktonic Foraminifera; BF = Benthic Foraminifera; BO = Bolboformid alga; DC = Dinoflagellate cyst or acritarch. Paleoceanography and paleoclimate according to: 1. Ali and Vandamme (1998), 2. Andersson and Jansen (2003), 3. Bohrmann et al. (1990), 4. Hilgen et al. (2007), 5. Hull et al. (1996), 6. Kaminski et al. (1989), 7. Kaminski et al. (2005), 8. Krijgsman et al. (1999), 9. Lear et al. (2004) and Pälike et al. (2006), 10. Miller et al. (1991), 11. Miller et al. (1998) + Lourens et al. (2004), 12. Moran et al. (2006), 13. Paul et al. (2000), 14. Shevenell et al. (2008), 15. Wei and Peleo-Alampay (1997), 16. Westerhold et al. (2005), 17. Wright and Miller (1996).


Age (Ma)
Standard chronostratigraphy
Sequence chronostratigraphy
Sea-level (meters relative to present)
Paleoceanography/ Paleoclimate
ODP Site 982 + DSDP Site 608 benthic oxygen isotope stratigraphy ($\delta^{18}O$ ‰ PDB)
Nordic Miocene Zones (NM)
Age-calibrated Nordic planktonic bioevents
(* rare event)
last (highest) occurrences
first (lowest) occurrences
(Ma)
Plio.
Messinian
Tortonian
Serravalian
Langhian
Burdigalian
Aquitanian
Chattian
Me 2
Tor3/Me1
Tor2
Ser4/Tor1
Ser3
Ser2
Ser1
Bur5/Lan1
Bur4
Bur3
Bur2
Aq3/Bur1
Aq2
Ch4/Aq1
Ch3
Messinian glaciation 6.3-5.5 Ma (4)
'Mediterranean Salinity Event' 7.25-5.33 Ma (8)
Greenland-Iceland overflow initiates (NADW) 7.5 Ma (6)
'Mi-7' Glaciation 9.04 Ma (2)
'Mi-6' Glaciation 10.4 Ma (16)
Iceland-Scotland overflow initiates 13-11.5 Ma (3, 1, 15); 12.3 Ma (17)
'Mi-5' Glaciation 11.7 Ma (16)
'Middle Miocene Global Cooling' 14-12 Ma (10, 12)
'Mi-4' Glaciation 13.2 Ma (16)
'Mi-3' Glaciation 13.9-13.8 Ma (10, 14, 16)
'Mi-2' Glaciation ~16.0 Ma (10, 14)
'Miocene Climatic Optimum' 17-15 Ma (7, 14)
'Mi-1b' Glaciation 17.7-17.5 Ma (36)
'Mi-1ab' Glaciation 18.5 Ma (11)
'Mi-1aa' Glaciation 19.7 Ma (11)
'Mi-1a' Glaciation 21.1 Ma (10, 13)
Initial opening of the Fram Strait ≥ 22 Ma (7, 5)
'Mi-1' Glaciation 23.7-22.9 Ma (10, 9)
TG7-9
TG12-14
TG20-22
TG32-34 (C3An)
Hodell et al. (2001), Hilgen et al (2007)
Andersson and Jansen (2003)
Miller et al. (1987, 1991), Wright et al. (1992)
Mi7
Mi6?
Mi5
Mi4
Mi3
Mi2a?
Mi2
Mi1b
Mi1ab?
Mi1aa?
Mi1a
Mi1
Holocene equilibrium
Paleoclimatic intervals
Warm non-glacial
Transitional
Cool glacial
"Mid-Miocene Unconformity"
"Upper Oligocene unconformity"
NM10
NM9
NM8b
NM8a
NM7
NM6
NM5
NM4
NM3
NM2
NM1
NM0
Zonal boundary interval
Calcareous dissolution and/or Hiatus
5.3 PF13 LO common Neogloboquadrina acostaensis
DC18 LO Hystrichosphaeropsis pontiana
5.9 BO6b LO common Bolboforma intermedia
6.1-6.3 BO7 Acme Bolboforma two-chambered cysts
*PF16a LO Globorotalia miotumida (conomiozea) gr.
7.4 DC19a LO Labyrinthodinium truncatum
7.7-7.8 DC19b LO Hystrichosphaeropsis obscura
DC19c LO Spiniferites pseudofurcatus
7.9 BO8 LO (sporadic) Bolboforma metzmacheri
*PF18 LO Globorotalia juanai
8.8 BO9a LO (consistent) Bolboforma metzmacheri
8.9 DC20 LO Paleocystodinium golzowense
9.4 PF20 LO common (consistently) N. acostaensis
9.9 PF22 Disappearance N. pachyderma (d)
10.2 BO10b LO Bolboforma capsula
BO11a LO Bolboforma subfragoris
10.9 BO11b LO Bolboforma fragori
11.0 BO12 LO common Bolboforma compressispinosa
11.3 DC21 LO Cannosphaeropsis passio
11.6 BO13 LO abundant Bolboforma badenensis
11.8 PF25 LO Paragloborotalia mayeri
DC22 LO Cerebrocysta poulsenii
BO14b Disappearance Bolboforma clodiusi
12.7 BO15c LO Bolboforma reticulata group
13.2-13.3 PF28 LO Sphaeroidinellopsis disjuncta
13.4 PF29a Top acme Globigerina praebulloides
13.8-13.9 PF29b Top acme Globigerinoides quadrilobatus
PF29c LO (consistent) Globigerinoides trilobus
DC23 LO Cleistosphaeridium placacanthum
14.9 PF30c LO (consistent) G. ex gr. praescitula-zealandica
*PF30d Influx common Globorotalia miozea
*PF30e LO Praeorbulina group
DC24 LO Apteodinium spiridoides
PF33b Influx common Sphaeroidinellopsis spp.
16.3 PF33c Disappearance G. ex gr. praescitula-zealandica
PF35a LO Globigerinoides subsacculifer
16.9-17.1 PF35b LO (consistent) Globigerinella obesa
PF35c Top acme Neogloboquadrina continuosa
17.5 DC26 LO Tityrosphaeridium cantharellus
17.6-17.7 BO18a LO Bolboforma rotunda
BO18b LO Bolboforma spinosa
18.3 *PF36 LO Cassigerinella chipolensis
BO19 LO Bolboforma spiralis
19.0 PF37a LO (consistent) Sphaeroidinellopsis disjuncta
19.2 PF37b LO Catapsydrax dissimilis
PF38 LO Catapsydrax unicavus
20.4 PF39 LO (consistent) Catapsydrax unicavus
21.2 DC28 LO Caligodinium amiculum
22.2 MD11 Top siliceous biofacies
DC30 LO Chiropteridium spp.
23.0 DC31 LO common Deflandrea phosphoritica
5.4 PF14 FO Neogloboquadrina dutertrei
5.6 MD7 FO abundant Thalassiosira spp.
5.8 *PF15 FO Globorotalia margaritae
MD8 FO Thalassiosira jacksoni
BO6a FO Bolboforma costairregularis variabilis
6.6 MD9 FO Thalassiosira oestrupii
7.5 PF16b D→S Neogloboquadrina atlantica coiling change
7.7 *PF17a FO Globorotalia cf. crassula
*PF17b FO Globorotalia miotumida (conomiozea) group
8.4 PF19 Base acme dominant Globigerina bulloides
8.8 BO9b FO Bolboforma intermedia
BO9c Decrease Bolboforma laevis
9.5 *PF21a FO (consistently) Globorotalia juanai
PF21b FO Neogloboquadrina humerosa
10.2 BO10a FO Bolboforma metzmacheri
10.5 PF23a FO Neogloboquadrina acostaensis
PF23b FO Neogloboquadrina atlantica (d)
11.5 PF23c Influx common Neogloboquadrina continuosa
11.6 PF24 FO Neogloboquadrina pachyderma (d)
BO14a FO Bolboforma subfragoris
12.3 MD10 Bio-silica decrease ("Silica Switch")
12.6-12.7 PF26 Reappearance (consistent) Globigerina praebulloides
PF27 Acme Neogloboquadrina group
13.3 BO15a Acme Bolboforma atlantica
13.5 BO15b Acme Bolboforma danielsi
13.8 PF29d Base acme Globigerina bulloides
BO16 FO common Bolboforma reticulata
PF30a FO Globorotalia scitula
14.7 PF30b FO Turborotalita quinqueloba
15.2 PF31a FO Globigerina bulloides
15.5 PF31b Reappearance G. ex gr. praescitula-zealandica
PF31c FO Orbulina suturalis
PF32 FO Neogloboquadrina pachyderma (s)
DC25 FO Labyrinthodinium truncatum
16.3 BO17 FO Bolboforma reticulata
16.6 *PF33a FO Praeorbulina glomerosa glomerosa
17.1 PF34a Base acme Globigerina praebulloides
PF34b Base acme Globigerinoides quadrilobatus
*PF35d Influx Globorotalia peripheroronda
19.0 PF37c Influx Globigerinoides spp.
20.6 DC27 LO Thalassiphora pelagica
21.8 DC29 FO Ectosphaeropsis burdigalensis



GROUPS:
BF = benthic foraminifer
PF = planktonic foraminifer
BO = bolboformid algal cyst
MD = marine diatom

ABBRE.	CODE	TAXON
Ague	BF16	Asterigerina guerichi
Aiae	MD12	Aulacodiscus insignis aemulans
Aiqu	MD13	Aulacodiscus insignis quadrata
Asta	BF11	Asterigerina staeschei
Bant	BF19	Bolivina antiqua
Bbad	(BO13)	Bolboforma badenensis
Bclo	BO14b	Bolboforma clodiusi
Bfra	BO11b	Bolboforma fragori
Bmet	BO9a	Bolboforma metzmacheri
Bret	BO15c	Bolboforma reticulata
Brot	BO18a	Bolboforma rotunda
Bspin	BO18b	Bolboforma spinosa
Bsub	BO11a	Bolboforma subfragoris
Cuni	PF38/39	Catapsydrax unicavus
Cwue	BF14	Cibicidoides wuellerstorfi
Eant	BF9	Elphidium antoninum
El/No	BF12	Elphidiid/Nonionid fauna
Evar	BF8b	Ehrenbergina variabilis
Gbul	PF19/29d	Globigerina bulloides
Gcip	PF	Globoturborotalita ciperoensis
Gp-z	PF30c	Globorotalia ex gr. praescitula-zealandica
Gpbul	PF29a	Globigerina praebulloides
Gsub	BF6	Globocassidulina subglobosa
Gtri	PF37c	Globigerinoides trilobus
Lsin	BF15	Loxostomum sinuosum
Mart	BF7	Martinottiella spp.
Naco	PF13/20	Neogloboquadrina acostaensis
NatD	PF16b/24	Neogloboquadrina atlantica (dextral)
NatS	PF16b	Neogloboquadrina atlantica (sinistral)
Ncon	PF35c	Neogloboquadrina continuosa
NpaD	PF22/24	Neogloboquadrina pachyderma (dextral)
NpaS	PF32	Neogloboquadrina pachyderma (sinistral)
Psem	BF17	Plectofrondicularia seminuda
Sbio	MD11	Siliceous biofacies
Scom	BF18	Spirosigmoilinella compressa
Sdis	PF33b	Sphaeroidinella disjuncta
Ssem	PF33b	Sphaeroidinellopsis seminulina
Up-l	BF5	Uvigerina pygmea langeri
Usem	BF10	Uvigerina semiornata group
UspA	BF8a	Uvigerina sp. A of King (1983)
Uten	BF13	Uvigerina tenuipustulata

Fig. 4. Correlation of the main foraminiferal zonations of the North Sea and offshore Mid-Norway. Zonal boundary ages have been updated to correspond with the calibrated Nordic events(far right column). Ages is parentheses are only tentative. * Note: *Aulacodiscus insignis var quadrata* (= "Diatom sp. 3" of King 1983) and LO *Aulacodiscus insignis* var. *aemulans* (= "*Diatom* sp. 4" of King 1983) were benthic organisms according to Mitlehner (1994). Their usage as markers for the North Sea Planktonic (NSP) foraminiferal zones of King (1983, 1989) and Laursen & Kristoffersen (1999) is here revised to reflect this.

detailed quantitative foraminiferal and bolboformid counts see Appendix 2.

Definition of the relevant chronostratigraphic units follows Ogg et al. (2008). This is in addition to the publications defining the Miocene global stage boundaries with a Global boundary Stratotype Section and Point (GSSP): Hilgen et al. (2000) – base Messinian Stage; Hilgen et al. (2005) – base Tortonian Stage, Hilgen et al. (2008, unpubl.) – base Serravallian Stage, Steininger et al. (1997) – base Aquitanian Stage. The GSSP's for the Langhian and Burdigalian stages have not yet been ratified and follow the current working definitions on the International Commission on Stratigraphy website (http://www.stratigraphy.org). The orbitally tuned time scale in this study is that of Lourens et al. (2004), who also re-calibrated the Berggren et al. (1995) biochronology.

4. Results

4.1 A new Nordic Miocene Zonation

Based on the results of the age-calibrations presented in Appendix 1a and Appendix 1b, the new multi-group microfossil zonation currently represents the most refined and well-constrained biostratigraphic framework for the Miocene of the Nordic Atlantic region.

The Nordic Miocene (NM) Zones presented here are essentially all assemblage zones (Fig. 3). Last (highest) occurrence events have been generally favoured over first occurrences, especially in industrial wellbore samples where downhole contamination can lead to artificially older first occurrences. First occurrences are, however, utilised to a greater degree in this Miocene biostratigraphy than in the Pliocene and Pleistocene schemes for the Nordic Atlantic (see Anthonissen 2008, Anthonissen 2009). This is due to the higher evolutionary inception rates in the Miocene as compared with the later pre-glacial and glacial Plio-Pleistocene world (Wei and Kennett 1986). This is probably related to the pronounced warmer climate of the Miocene, with average oxygen isotope ratios significantly lower than during the Holocene (Fig. 3).

Unlike traditional single-group zonations, this multi-group combination of a total of 92 bioevents (70 foraminifers and bolboformids; 16 dinoflagellate cysts and acritarchs; 6 marine diatoms) facilitates zonal identification throughout the Nordic Atlantic region. With the highest proportion of events being of calcareous walled microfossils, this zonation is primarily suited to micropaleontologists. While every effort was made to increase the resolution of the dinoflagellate cyst element, the record of Miocene dinoflagellates has proved mostly too sparse and with evidence of diachroneity. The exception is across the Oligocene-Miocene transition, where an absence of calcite preservation leaves the dinoflagellate cysts as the most important markers. For many of the planktonic foraminiferal events, identification of additional quantitative assemblage changes and acme/paracme intervals facilitates bioevent identification (Fig. 3). This additional parameter for event identification is especially useful north of the Greenland-Scotland Ridge (e.g. northern North Sea and offshore Mid-Norway), where much lower diversity planktonic foraminiferal assemblages occur (Eidvin et al. 2000, Spiegler and Jansen 1989).

The definition of zonal boundaries as coinciding with multiple marker events results in the ages of most boundaries appearing to be stratigraphically uncertain. However, this deliberate boundary interval, averaging between 100,000 to 200,000 years duration, allows for a much greater range of zonal markers, thus significantly increasing usability. While these boundary intervals might pose a problem in defining zonal boundaries in extremely high-resolution integrated data-sets, they significantly increase the utility of this zonation in the more readily available petroleum industry sections. In addition, the bioevents marking these boundary intervals often appear to belong to the same faunal province and occur in similar biofacies (i.e. subtropical, warm temperate and cool temperate faunas and floras). They have been grouped into 'boundary event clusters' according to their most reliable age-calibrations (Appendix 1a). Zonal duration ranges on average from 1 to 2 million years. Ages of zonal boundaries follow that of the 'boundary event clusters' in Appendix 1a.

Bioevent numbering continues on from the Nordic Pliocene Zonation in Anthonissen (2009). First time occurrences (uphole) are abbreviated to "FO" and last time occurrences (uphole) to "LO", following common petroleum industry practice. The quantitative events refer to uphole abundance changes. An "acme" is here a readily identifiable abundance increase, following on from a relatively consistent occurrence. An acme differs from an "influx" which is considered here to be a sudden abundance pulse without a foregoing consistent occurrence. "Disappearance" and "Reappearance" events brackets intervals of temporary absence of a taxon, but may correlate with local extinctions elsewhere in the region. Global sequence boundaries are according to Hardenbol et al. (1998), with updated ages according to Ogg and Lugowski (2008). The oxygen isotope "Mi" glacial intervals are according to the definitions of Miller et al. (1998), with ages updated to the Neogene astronomically tuned geomagnetic polarity time scale of Lourens et al. (2004).

Nordic Miocene Zone NM0

Age: 27.3–22.2/22.0 Ma (Chattian to early Aquitanian)
Lower boundary (27.3 Ma): This level is marked by marine diatom event MD13 (LO *Aulacodiscus insignes quadrata* and the last common occurrence of siliceous biofacies). Additional markers are the dinoflagellate cyst event DC32 (LO *Distatodinium biffii*). This level may correlate to the Ch2 global sequence boundary.
Upper boundary (22.2–22.0 Ma): The dinoflagellate cyst event DC30 (LO *Chiropteridium* spp. including *C. galea*) occurs at this level. In the North and Norwegian seas the upper boundary may be identified by the marine diatom event MD12 (LO *Aulacodiscus insignes aemulans*) and the benthic foraminiferal event BF18 (LO *Spirosigmoilinella compressa*). Additional events are the last occurrence of siliceous biofacies (MD11) including the LO *Aulacodiscus allorgei*. This level may correlate to a glacial interval between oxygen isotope events Mi1 and Mi1a.
Intrazonal events: The planktonic foraminiferal last occurrence of *Globigerina ciperoensis* occurs within this zone.

Nordic Miocene Zone NM1

Age: 22.2/22.0–20.4/20.6 Ma (early-late Aquitanian)
Lower boundary (22.2–22.0 Ma): Equivalent to the top of Zone NM0.
Upper boundary (20.6–20.4 Ma): This level is marked by the planktonic foraminiferal event PF39 (LO (consistent) *Catapsydrax unicavus*) and by the dinoflagellate cyst event DC27 (LO *Thalassiphora pelagica*). This boundary correlates to the Aq3/Bur1 major global sequence boundary and probably occurs between oxygen isotope events Mi1 and Mi1a.
Intrazonal events: The dinoflagellate cyst events DC28 (LO *Caligodinium amiculum*) and DC29 (LO *Ectosphaeropsis burdigalensis*) occur within this zone.

Nordic Miocene Zone NM2

Age: 20.6/20.4–19.2/19.0 Ma (late Aquitanian to early Burdigalian)
Lower boundary (20.6–20.4 Ma): Equivalent to the top of Zone NM1.
Upper boundary (19.2–19.0 Ma): This boundary is marked by the planktonic foraminiferal events: PF38 (LO *Catapsydrax unicavus*), PF37a (LO (consistent) *Sphaeroidinellopsis disjuncta*), PF37b (LO *Catapsydrax dissimilis*) and PF37c (Influx *Globigerinoides* spp.). Additional markers in the the North Sea are the benthic foraminiferal event BF16 (LO *Asterigerina guerichi*).
Intrazonal events: None were identified.

Nordic Miocene Zone NM3

Age: 19.2/19.0–17.7/17.5 Ma (early to mid-Burdigalian)
Lower boundary (19.2–19.0 Ma): Equivalent to the top of Zone NM2.
Upper boundary (17.7–17.5 Ma): This level is marked by the bolboformid events BO18a (LO *Bolboforma rotunda*) and BO18b (LO *Bolboforma spinosa*). The planktonic foraminiferal event PF36 (LO *Cassigerinella chipolensis*) is an additional marker. The dinoflagellate cyst event DC26 (LO *Tityrosphaeridium cantharellus*) is a good marker for this level. This boundary corresponds to the oxygen isotope Mi1b glacial interval and to the Bur4 global sequence boundary.
Intrazonal events: The bolboformid event BO19 (LO *Bolboforma spiralis*) occurs within this zone.

Nordic Miocene Zone NM4

Age: 17.7/17.5–15.5/15.2 Ma (late Burdigalian to early Langhian)
Lower boundary (17.7–17.5 Ma): Equivalent to the top of Zone NM3.
Upper boundary (15.5–15.2 Ma): This level is marked by the planktonic foraminiferal event PF32 (FO *Neogloboquadrina pachyderma* (sinistral)) and by the dinoflagellate cyst event DC25 (FO *Labyrinthodinium truncatum*). In the North Sea the benthic foraminiferal event BF15 (LO *Loxostomum sinuosum*) probably corresponds to this level. This boundary level closely post-dates the oxygen isotope Mi2 glacial event and the upper limit of the "Mid-Miocene hiatus".
Intrazonal events: Occurring within this zone are the following planktonic foraminiferal events in ascending order: PF35d (Influx *Globorotalia peripheroronda* – rare event), PF35c (Top acme *Neogloboquadrina continuosa*), PF35b (LO (consistent) *Globigerinella obesa*), PF35a (LO *Globigerinoides subsacculifer*), PF34a (Base acme *Globigerina praebulloides*), PF34b (Base acme *Globigerinoides quadrilobatus*), PF33a (Disappearance of *Globorotalia ex gr. praescitula*-

zealandica) and PF33b (Influx common *Sphaeroidinellopsis* spp.). Also occurring within this zone is the bolboformid event BO17 (FO *Bolboforma reticulata*). With the occurrence of a widespread regional unconformity underlying this level, Zone NM4 is often absent. The resulting hiatus is especially marked in the shallow deposits of the northern North Sea where it can reach a maximum extent of 15–20 million years duration (Rundberg and Eidvin 2005).

Nordic Miocene Zone NM5

Age: 15.5/15.2–13.9/13.8 Ma (early to late Langhian)
Lower boundary (15.5–15.2 Ma): Equivalent to the top of Zone NM4.
Upper boundary (13.9–13.8 Ma): This level is marked by the planktonic foraminiferal events PF30c (LO (consistent) *Globorotalia ex gr. praescitula-zealandica*), PF30b (FO *Turborotalita quinqueloba*), PF30a (FO *Globorotalia scitula*), PF30d (Influx common *Globorotalia miozea* – rare event), PF30e (LO *Praeorbulina* group – rare event). In the North Sea the benthic foraminiferal event BF13 (LO *Uvigerina tenuipustulata*) is a marker. This boundary may correspond to the oxygen isotope Mi3 glacial event, or be slightly older. It probably correlates to the Ser1 global sequence boundary.
Intrazonal events: Occurring within this zone are the planktonic foraminiferal events PF31a (FO *Globigerina bulloides*), PF31b (Reappearance *Globorotalia ex gr. praescitula-zealandica*) and PF31c (FO *Orbulina suturalis*). The dinoflagellate event DC24 (LO *Apteodinium spiridoides*) also occurs within this zone. The benthic foraminiferal event BF14 (FO *Cibicidoides wuellerstorfi*) is an intrazonal event.

Nordic Miocene Zone NM6

Age: 13.9/13.8–12.7/12.6 Ma (late Langhian to early Serravallian)
Lower boundary (13.9–13.8 Ma): Equivalent to the top of Zone NM5.
Upper boundary (12.7–12.6 Ma): This level is marked by the the planktonic foraminiferal events PF28 (LO *Sphaeroidinellopsis disjuncta*), followed by PF27 (Acme of the *Neogloboquadrina* group). Bolboformid events defining the boundary are BO15c (LO *Bolboforma reticulata* group), followed by the acme events BO15b (Acme *Bolboforma danielsi*) and BO15a (Acme *Bolboforma atlantica*). In the North Sea the benthic foraminiferal event BF11 (LO *Asterigerina staeschei*) marks this boundary. This boundary corresponds to, or slightly postdates, the Mi4 oxygen isotope glacial event and the Ser3 global sequence boundary.
Intrazonal events: The dinoflagellate cyst event DC23 (LO *Cleistosphaeridium placacanthum*) occurs within this zone. Intrazonal planktonic foraminiferal events are: PF29a (Top acme *Globigerina praebulloides*), PF29b (Top acme *Globigerinoides quadrilobatus*), PF29c (LO (consistent) *Globigerinoides trilobus*) and PF29d (Base acme *Globigerina bulloides*). The bolboformid event BO16 (FO common *Bolboforma reticulata*) occurs within this zone. In the North Sea the intrazonal benthic foraminiferal event BO12 (LO *Elphidiid/Nonionid* fauna) occurs at the same level as the last occurrence of *Bolboforma badenensis*. The latter is clearly diachronous, occurring elsewhere in the Nordic Atlantic region approximately two million years later as BO13 (LO abundant *Bolboforma badenensis*).

Nordic Miocene Zone NM7

Age: 12.7/12.6–11.8/11.6 Ma (late Serravallian)
Lower boundary (12.7–12.6 Ma): Equivalent to the top of Zone NM6.
Upper boundary (11.8–11.6 Ma): The planktonic foraminiferal event PF25 (LO *Paragloborotalia mayeri*) and the dinoflagellate cyst event DC22 (LO *Cerebrocysta poulsenii*) marks marks this boundary. Additionally, the bolboformid events BO14b (Disappearance *Bolboforma clodiusi*) and BO14a (FO *Bolboforma subfragoris*) are important markers. In the neritic North Sea this level corresponds to the benthic foraminiferal event BF9 (LO *Elphidium antoninum*). An additional marker is a significant decrease in the biosiliceous sediment component at this level. This boundary corresponds to the oxygen isotope Mi5 glacial event and the major Ser4/Tor1 global sequence boundary. This level marks the base of a calcareous dissolution interval and/or erosional hiatus corresponding to the standard planktonic foraminiferal Zone N15 of Blow (1969) or M12 of Wade et al. (2011).
Intrazonal events: The planktonic foraminiferal event PF26 (Reappearance (consistent) *Globigerina praebulloides* occurs within this zone. In the North Sea the benthic foraminiferal event BF10 (LO *Uvigerina semiornata* group) has an intrazonal occurrence.

Nordic Miocene Zone NM8, Subzone NM8a

Age: 11.8/11.6–11.0/10.9 Ma (earliest Tortonian)
Lower boundary (11.8–11.6 Ma): Equivalent to the top of Zone NM7.

Upper boundary (11.0–10.9 Ma): The principal markers defining this subzonal boundary are the bolboformid events BO11a (LO *Bolboforma subfragoris*) and BO11b (LO *Bolboforma fragori*). Additional events are the bolboformid event BO12 (LO common *Bolboforma compressispinosa*) and the dinoflagellate cyst event DC21 (LO *Cannosphaeropsis passio*). In the North Sea and offshore of Mid-Norway, the benthic foraminiferal events BF8a (LO *Uvigerina* sp. A of King (1983)) and BF8b (LO *Ehrenbergina variabilis*) are secondary markers. This level marks the top of a calcareous dissolution interval and/or erosional hiatus corresponding to the standard planktonic foraminiferal Zone N15 of Blow (1969) or M12 of Wade et al. (2011). This boundary may correspond to the Tor1 sea-level highstand.
Intrazonal events: Intra-subzonal markers include the bolboformid event BO13 (LO abundant *Bolboforma* badenensis) and the planktonic foraminiferal event PF24 (FO *Neogloboquadrina pachyderma* (dextral)). Depending on the extent of calcite dissolution, this subzone may be absent.

Nordic Miocene Zone NM8, Subzone NM8b

Age: 11.0/10.9–8.9/8.8 Ma (early to mid-Tortonian)
Lower boundary (11.0–10.9 Ma): Equivalent to the top of Subzone NM8a.
Upper boundary (8.9–8.8 Ma): The principal markers for this zonal boundary are the bolboformid event BO9a (LO (consistent) *Bolboforma metzmacheri*) and the dinoflagellate cyst event DC20 (LO *Palaeocystodinium golzowense*). Additional markers are the bolboformid events BO9b (FO *Bolboforma intermedia*) and BO9c (Decrease in *Bolboforma laevis*). Slightly younger than this level is the planktonic foraminiferal event PF19 (base of an acme of dominant *Globigerina bulloides*). In the North Sea the benthic foraminiferal event BF5 (LO *Uvigerina pygmea langeri*) serves as a secondary marker. This boundary corresponds to the oxygen isotope Mi7 glacial event and may correspond to the Tor2 global sequence boundary.
Intrazonal events: The following planktonic foraminiferal events occur within this subzone: PF23a (FO *Neogloboquadrina acostaensis*), PF23b (FO *Neogloboquadrina atlantica* (dextral)), PF23c (Influx common *Neogloboquadrina continuosa*), PF22 (Disappearance *Neogloboquadrina pachyderma* (dextral)), PF21a (FO (consistent) *Globorotalia juanai* – rare event), PF21b (FO *Neogloboquadrina humerosa*), PF22 (Disappearance *Neogloboquadrina pachyderma* (dextral)) and PF20 (LO consistently common *Neogloboquadrina acostaensis*). The bolboformid events BO10b (LO *Bolboforma capsula*) and BO10a (FO *Bolboforma metzmacheri*) occur within this subzone. In the North Sea and offshore Mid-Norway the benthic foraminiferal events BF7 (LO *Martinottiella* spp.) and BF6 (Disappearance of *Globocassidulina subglobosa*) occur within this zone.

Nordic Miocene Zone NM9

Age: 8.9/8.8–7.7/7.5 Ma (late Tortonian)
Lower boundary (8.9–8.8 Ma): Equivalent to the top of the Zone NM8 and subzone NM8b.
Upper boundary (7.7–7.5 Ma): This level is marked by the dextral to sinistral coiling change in the planktonic foraminifer *Neogloboquadrina atlantica* (PF16b). The dinoflagellate cyst events marking the boundary are: DC19a (LO *Labyrinthodinium truncatum*), DC19b (LO *Hystrichosphaeropsis obscura*) and DC19c (LO *Spiniferites pseudofurcatus*). Secondary, rare markers are the planktonic foraminiferal events PF17a (FO *Globorotalia cf. crassula*) and PF17b (FO *Globorotalia miotumida (conomiozea)* group) and the bolboformid event BO8 (LO (sporadic) *Bolboforma metzmacheri*). Occurring near to the boundary is the planktonic foraminiferal event PF16a (LO *Globorotalia miotumida (conomiozea)* group – rare). This level corresponds to a major shift towards heavier oxygen isotope ratios, suggesting a pronounced cooling event with associated calcite dissolution. It may also correspond to the Tor3/Me1 global sequence boundary.
Intrazonal events: Intrazonal planktonic foraminiferal events include PF19 (Base of acme with dominant *Globigerina bulloides*) and the rare PF18 (LO *Globorotalia juanai*).

Nordic Miocene Zone NM10

Age: 7.7/7.5–5.4/5.3 Ma (latest Tortonian to end Messinian)
Lower boundary (7.7–7.5 Ma): Equivalent to the top of the Zone NM9.
Upper boundary (5.4–5.3 Ma): This level coincides with the base of Nordic Pliocene Zone NP0 of Anthonissen (2009). The boundary is marked by the planktonic foraminiferal events PF13 (LO common *Neogloboquadrina acostaensis*) and PF14 (FO *Neogloboquadrina dutertrei*), together with the dinoflagellate cyst event DC18 (LO *Hystrichosphaeropsis pontiana*).
Intrazonal events: Bolboformids and marine diatoms dominate this zone with the following intrazonal

Table 2 Global boundary Stratotype and Point (GSSP) correlative markers for the Miocene stages showing best biostratigraphic approximations in the Nordic Atlantic. The most easily recognized events are highlighted in bold. Nordic Miocene Zones are indicated.

Low- to mid-latitudes			High-latitudes	
Age (Ma)	Stage/Subseries base	GSSP correlative markers	Nordic Atlantic approximations	Nordic Zone
7.246	Messinian	FO (consistent) *Globorotalia conomiozea* group (PF)	**D → S *Neogloboquadrina atlantica* coiling change (PF)** LO Globorotalia miotumida (conomiozea) group (PF)	NM10
11.608	Tortonian	LO common *Discoaster kugleri* (CN) LO common *Globigerinoides subquadratus* (PF)	**LO *Cerebrocysta poulsenii* (DC)** **Disappearance of *Bolboforma clodiusi* (BO)** LO *Uvigerina semiornata saprophila* (BF) LO *Paragloborotalia mayeri* (PF) FO *Bolboforma subfragoris* (BO) LO *Elphidium antoninum* (BF)	NM7/NM8b
13.82	Serravalian	FO *Sphenolithus heteromorphus* (PF)	**LO (consistent) *Globorotalia ex gr. praescitula zealandica* (PF)** LO *Uvigerina tenuipustulata* (BF) FO *Turborotalita quinqueloba* FO *Globorotalia scitula* (PF)	NM5/NM6
15.97	Langhian	FO *Praeorbulina glomerosa* (PF)	**FO *Praeorbulina glomerosa* (PF) Influx common *Sphaeroidinellopsis disjuncta* (PF)** FO *Bolboforma reticulata* (BO) Disappearance G. ex gr. *praescitula-zealandica* (PF)	NM4
20.43	Burdigalian	FO *Globigerinoides altiaperturus* (PF)	**LO (consistent) *Catapsydrax unicavus* (PF)** **LO *Thalassiphora pelagica* (DC)**	NM1/NM2
23.03	Aquitanian	FO *Paragloborotalia kugleri* (PF)	**LO common *Deflandrea phosphoritica* (DC)** LO *Reticulofenestra bisecta* (CN)	NM0

events: MD9 (FO *Thalassiosira oestrupiii*), MD8 (FO *Thalassiosira jacksoni*), MD7 (FO abundant *Thalassiosira* spp.), BO6a (FO *Bolboforma costairregularis variabilis*), BO6b (LO common *Bolboforma intermedia*) and BO7 (Acme *Bolboforma* two-chambered cysts). The rare planktonic foraminiferal events PF16a (LO *Globorotalia miotumida (conomiozea)* and PF15 (FO *Globorotalia margaritae*) occur within this zone.

The best Nordic biostratigraphic approximations to the standard Neogene stage boundaries are shown in Table 2. Of these identified events, only the base of the Langhian can be identified by its primary correlative marker, the FO Praeorbulina glomerosa. This is, however, not a practical marker for industrial well studies due to the problem of downhole contamination.

4.2 Constraining the age of shallower deposits of the North Sea and Norwegian Sea

The relationship between the new Nordic Miocene Zonation with the established foraminiferal zonations of the North Sea-Norwegian Sea is shown in Fig. 4.

The results of micropaleontological analysis of three Miocene wells in the North Sea and Norwegian Sea is presented in Figures 5, 6 and 7. A relatively good sample recovery, especially in the Sønder Vium borehole, has allowed for a high degree of stratigraphic certainty. Biostratigraphic resolution has been increased by the integration of both micropaleontological and palynological results. Located in the circum-North Sea, northern North Sea, and in the Vøring Basin (Norwegian Sea) these sections offer a general stratigraphic and paleoenvironmental perspective of the basin during Miocene time.

The application of the new Miocene biozonation to these wells, allowed for testing the applicability of this scheme in deposits of shallower depth than that of the ocean drilling sites. The sections investigated have been dated biostratigraphically through identification of the new and updated bioevents of this study.

For the southernmost section, Sønder Vium research borehole, four zonal boundaries and at least five Nordic Miocene zones were identified, spanning the time interval 13.3–8.8 Ma (Fig. 5). This corresponds to the Upper Arnum, Hodde and Gram Formations. The highest biostratigraphic resolution and richest planktonic fossil assemblages were obtained in the Hodde Formation. This is consistent with the Hodde representing a highstand systems tract with a possible maximum flooding surface at its lower boundary. Below this, only two tentative boundary placements were possible, due to extensive intervals barren of foraminifers. The palynology is similarly well resolved for the upper part of the borehole, while becoming progressively sparse at lower levels. The explanation for this is the presence of fluvial and deltaic brackish water deposits observed at various Danish locations at similar depths (Dybkjær 2004). This lack of marker events has proved a particular challenge for the identification of the lowermost lithological unit, tentatively assigned to the Klintinghoved Formation (Piasecki et al. 2004). Further palynology analysis by Dybkjær and colleagues may help to resolve this correlation problem.

The northern North Sea exploration well 29/3-1 was drilled in 1986 in the Norwegian sector near the maritime border between the UK and Norway. The extensive Pliocene record of well 29/3-1 was investigated in detail in Anthonissen (2008). This study includes the Miocene section with an associated lithostratigraphic interpretation based on available wireline logs (Fig. 6). While almost all Pliocene Nordic Zones (NP) were identified in this well, only four Nordic Miocene Zones (NM) were determined. In addition, absence of NM0-NM3 and NP0 suggests the presence of two unconformities. The lower hiatus may represent an amalgamation of the basal Neogene unconformity and the mid-Miocene unconformity. The upper hiatus corresponds to the time of the Messinian glaciation with increased bottom-water turbulence and associated erosion and/or calcite dissolution. It should be noted that the lithostratigraphic boundary for the top of the Utsira sands is according to the Norwegian Petroleum Directorate database. If this level can be supported by a seismic tie, then on the basis of this biostratigraphy the top of the sandy Utsira "Member" (demoted from formation to member in Gradstein et al. 2010) must be at least as young as the Gelasian in the south Viking Graben. This would contradict the Early Pliocene age designation of Rundberg and Eidvin (2005).

The most northerly well investigated, 6704/12-GB1, was drilled in connection with the Seabed Project with an integrated foraminiferal-dinoflagellate-diatom biostratigraphy produced for the upper ca. 100 metres (Eidvin et al. 1998). The present study extends the foraminiferal biostratigraphic record from and including the Upper Miocene down into Oligocene sediments. Despite its relatively deep water location (1357 m water depth) and close proximity to the ODP Leg 104 sites, fairly low abundance and non-distinctive results were obtained. The subzonal boundary

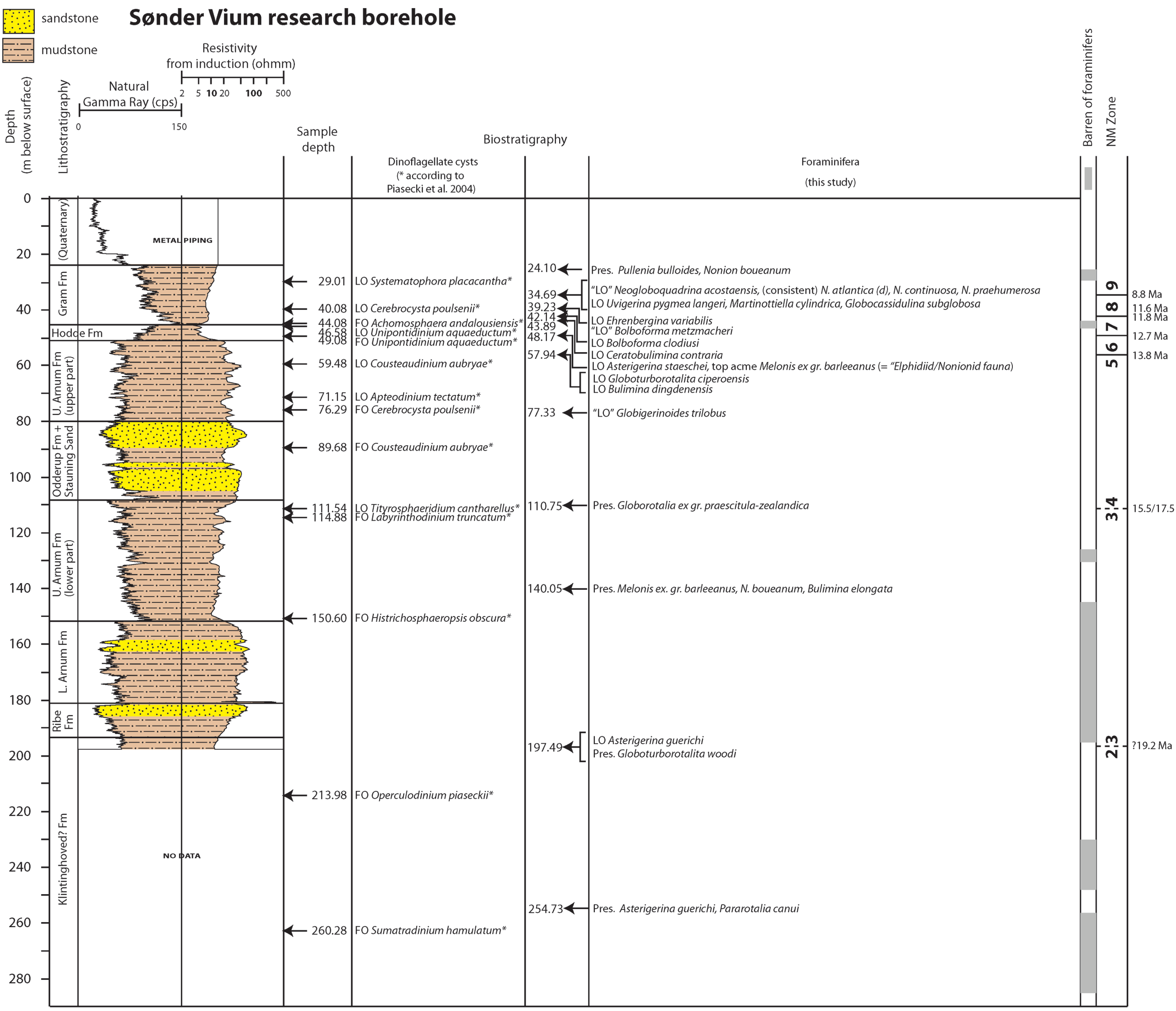


Fig. 5. Circum North Sea application: litho-biostratigraphy of the Sønder Vium research borehole, onshore southern Denmark. Age-constraining calcareous bioevents (planktonic foraminifera and bolboformids) are according to microscope observations in this study. Palynological bioevents, lithostratigraphy and wireline logs are according to Piasecki et al. (2004).

NM8b/8a was identified with the LO common *Bolboforma compressispinosa*. Zones NM4 and 6 were tentatively assigned, but the zonal boundaries were not identified. A hiatus has been interpreted at ca. 1745 m between a Middle Miocene and an Oligocene foraminiferal assemblage. This is based on the designation of the benthic foraminifer *Gyroidina soldanii mamillata* to the Oligocene according to King (1989). The exact depth of this unconformity has been placed at the uphole transition in gamma-log response to lower API values suggesting a coarsening upwards trend. The possible location of a sequence boundary is difficult to identify in such a mudstone sequence. The temporal extent of the hiatus conforms to the same composite basal Neogene unconformity + Mid-Miocene unconformity observed in the northern North Sea well 29/3-1. Additional sedimentary evidence of an unconformity is the low benthic foraminiferal diversity underlying this level, possibly due to erosional reworking. The 3D seismic study of the Gjallar Ridge by Hansen et al. (2005) reported a distinct seismic reflector surface at this same level. The authors attributed it to a diagenetic boundary marked by opal A to CT conversion.

For comparison with the studied well intervals, especially well 6704/12-GB1, the bio-magnetostratigra-

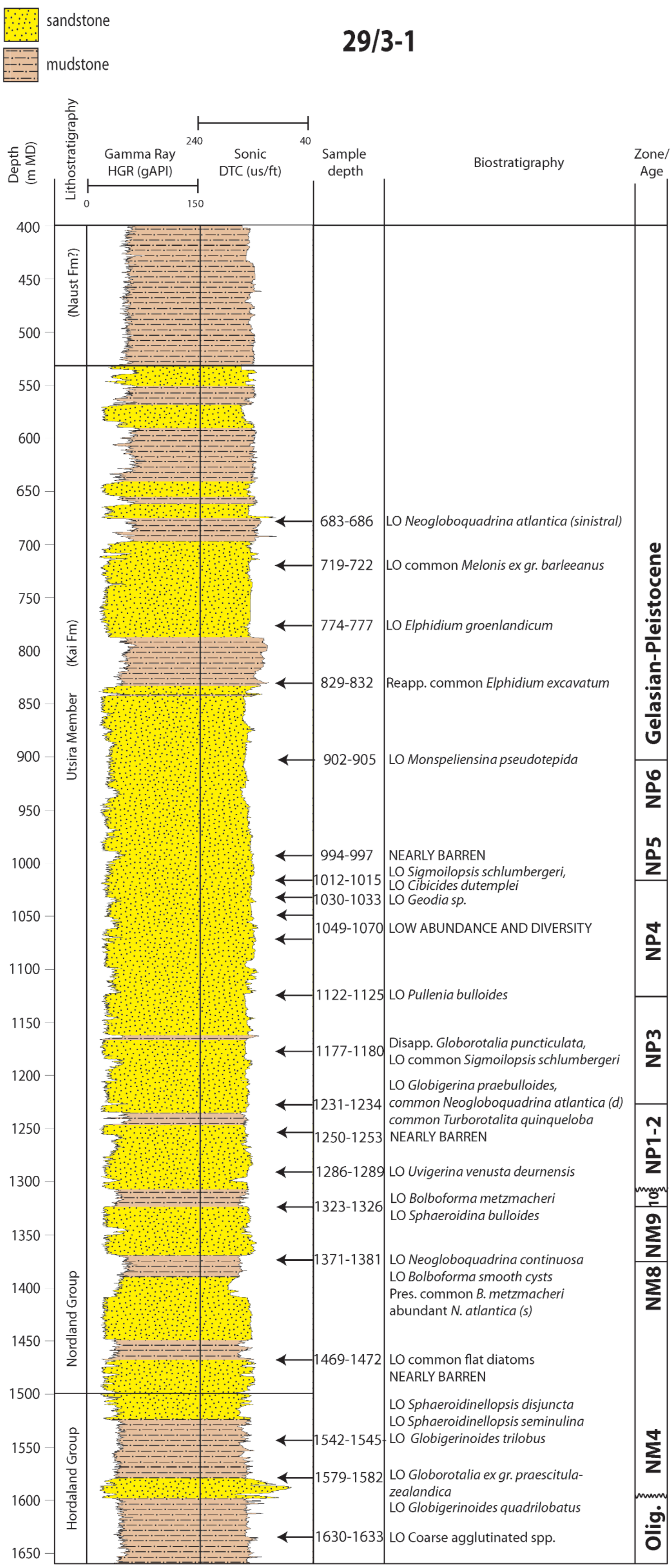


Fig. 6. Northern North Sea application: litho-biostratigraphy of exploration well 29/3-1, south Viking Graben. Biostratigraphy and lithological interpretation are according to this study. Wireline logs are according to the Norwegian Petroleum Directorate (http://www.npd.no/engelsk/cwi/pbl/en/index.htm).

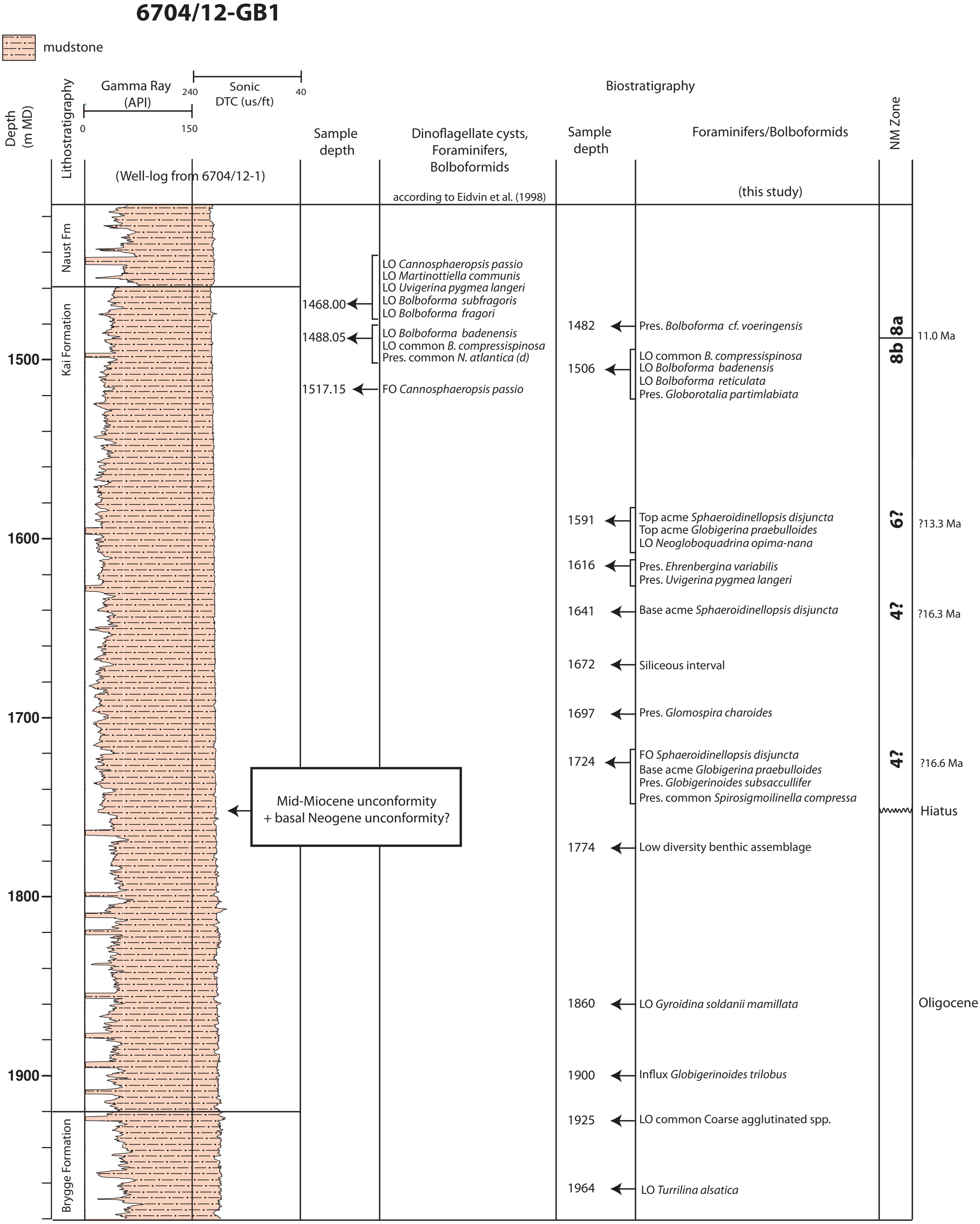


Fig. 7. Offshore Mid-Norway application: litho-biostratigraphy of geotechnical well 6704/12-GB1, Gjallar Ridge. Foraminiferal and bolboformid biostratigraphy according to his study in addition to comparison with the results of Eidvin et al. (1998). Wireline logs and lithostratigraphy from well 6704/12-1 are according to the Norwegian Petroleum Directorate (http://www.npd.no/engelsk/cwi/pbl/en/index.htm).

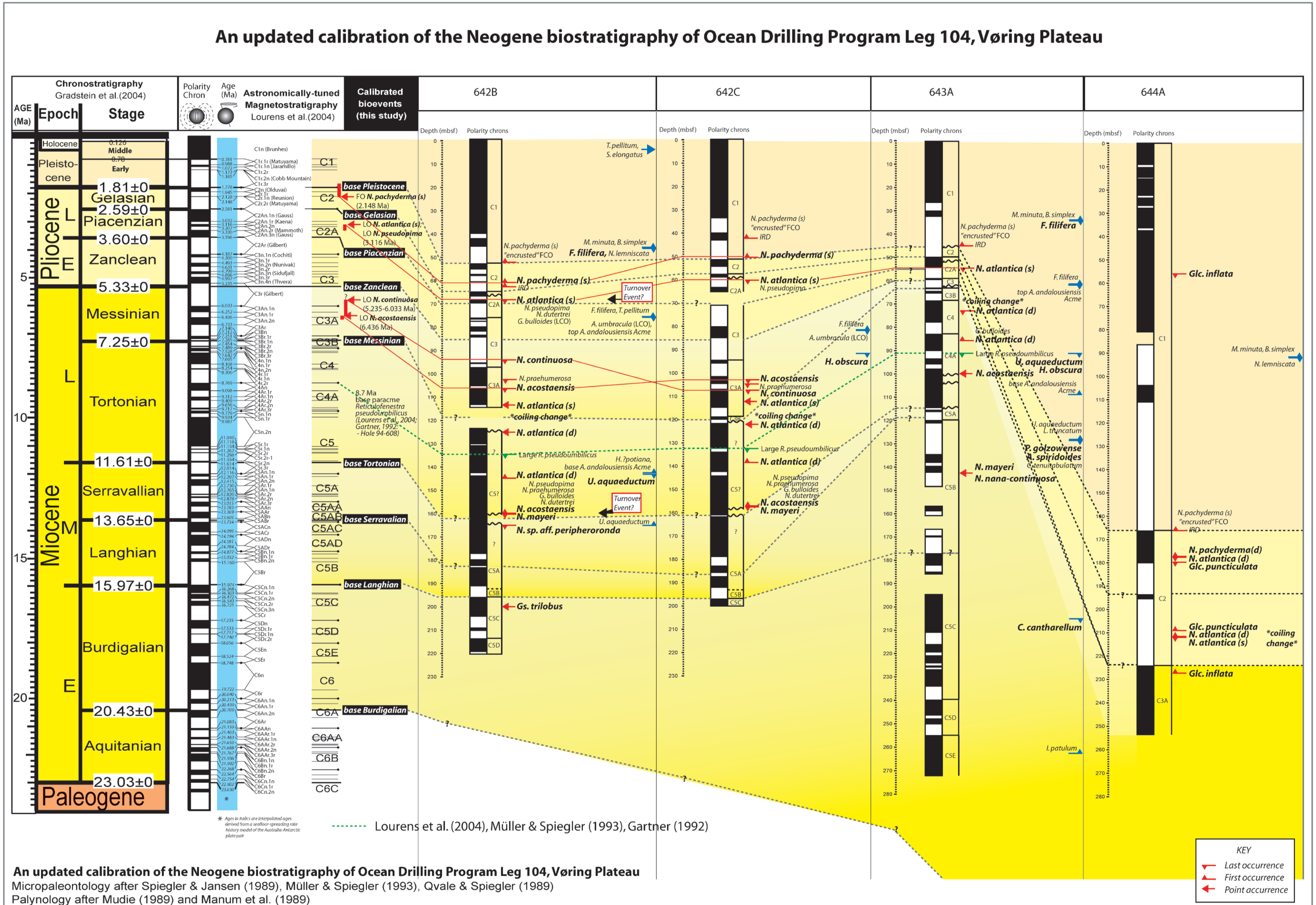


Fig. 8. A re-calibrated bio-magnetostratigraphy for Vøring Plateau ODP Leg 104, based on the astronomically tuned geomagnetic polarity time scale of Lourens et al. (2004). See figure for original site references.

phy of ODP Leg 104 sites has been re-calibrated to the time scale of Lourens et al. (2004), see Fig. 8. While affording a useful reference for the Norwegian Sea, without seismic control it was not possible to directly tie these results to that of well 6704/12-GB1.

5. Paleoceanography, paleoclimate and global sequences

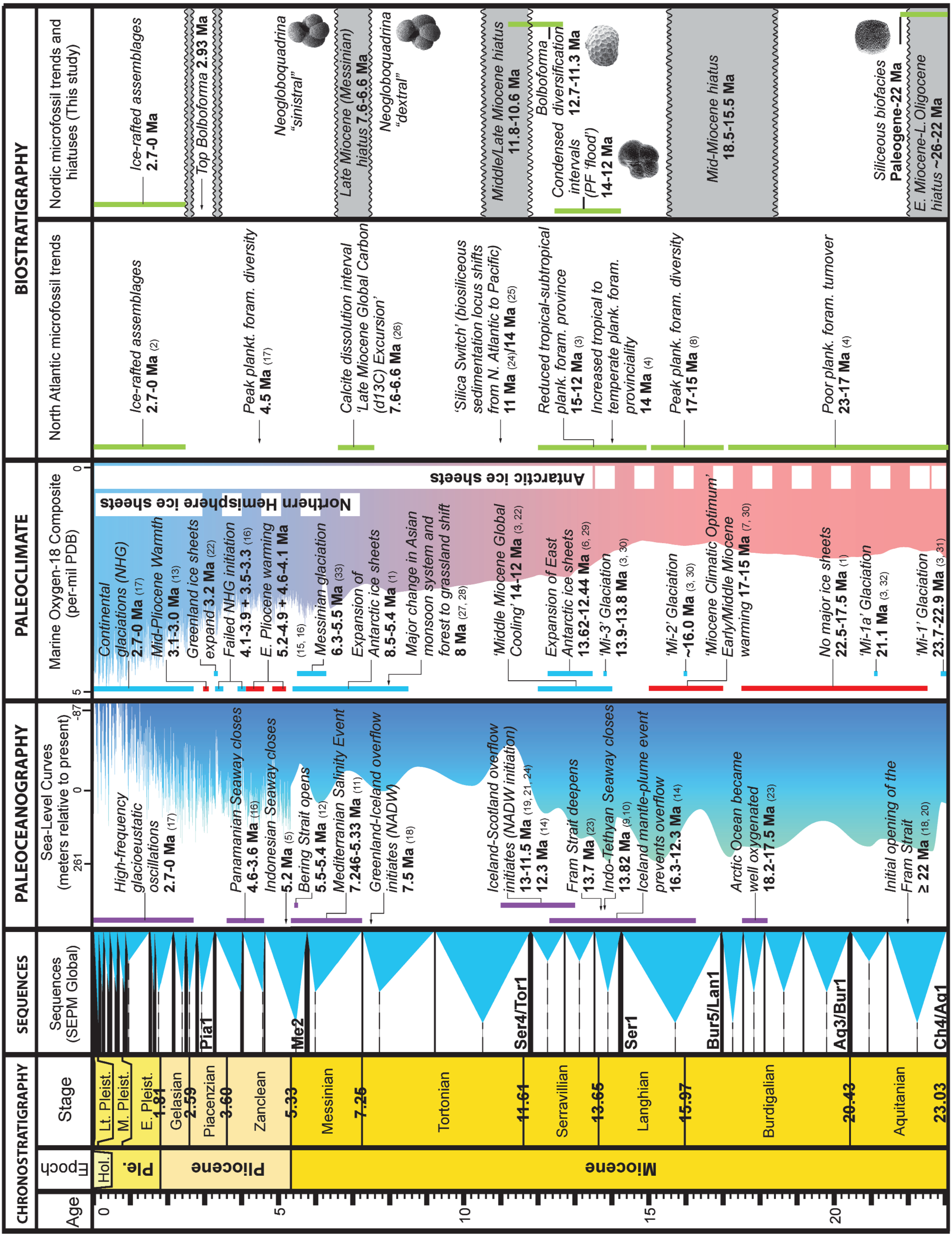
Correlation of the Nordic Miocene Zonation with the oxygen isotope records of DSDP Site 608 and ODP Site 982 suggests a causal relationship between planktonic microfossil turnover rates and North Atlantic Miocene climate (Fig. 3). The same appears to be true for correlation with the global eustatic sequences of Hardenbol et al. (1998), especially in the case of the shallower benthic foraminiferal record (Fig. 4).

The results of this study, (together with those of Anthonissen 2008, 2009) have allowed for indirect correlation between the major paleoceanographic and paleoclimatic episodes of the Neogene with the Nordic microfossil record. An overview of the main paleoceanographic, paleoclimatic and biostratigraphic events for the Neogene of the Nordic Atlantic is presented in Fig. 9.

The following is a summary of the main Miocene trends. The Mi1 glaciation marks the base of the Miocene. This coincides with a global sea level fall at the Ch4/Aq1 sequence boundary and may be entirely absent in the form of an Upper Oligocene – Lower Miocene hiatus. The oldest extent of this hiatus is in Upper Oligocene (basal Chattian equivalent) sediments, in the expanded section of the central North Sea (Schiøler 2005). The youngest extent of this hiatus occurs only slightly older than the last occurrence of the "siliceous biofacies" (a diatom-dominated calcite poor interval). This hiatus could coincide with the initial opening of the Fram Strait Arctic Ocean Gateway at, or older than, ca. 22 Ma (Kaminski et al. 2005). Following the brief Mi1a glacial event, the Early Miocene (until late Burdigalian time) was a period of relatively stable 'greenhouse' climate with poor planktonic foraminiferal turnover in the Mediterranean Sea and Atlantic Ocean (Thunell and Belyea 1982). With the low density of bioevents in Nordic Zones NM1 and NM2, this holds true for all microfossil groups investigated in this study.

A peak in planktonic foraminiferal diversity occurred across the boundary between the Early and Middle Miocene (Flower and Kennett 1994), coinciding with the Miocene Climatic Optimum (Zachos et al. 2001, Shevenell et al. 2008). This diversity peak was observed in the northeastern North Atlantic (Irminger Basin) ODP Site 918D (Spezzaferri 1998). This period of global warmth is characterised in the Nordic Atlantic region by the presence of a subtropical foraminiferal asemblage. Markers include a distinctive acme of *Globigerinoides quadrilobatus*, together with the rare FO *Praeorbulina glomerosa* and rare influx of *Globorotalia peripheroronda*. This interval is, however, often not preserved in the more marginal records of the Nordic Atlantic where the Mid-Miocene unconformity is most developed. This hiatus is probably bracketed by the Mi1b and Mi2 cooling episodes, with associated increased bottom water turbidity and corrosiveness. Increased turbidity at these high-latitudes is supported by findings that the Arctic Ocean became well oxygenated during mid-Burdigalian time (Jakobsson et al. 2007). The age of the mid-Miocene unconformity also falls within the estimate for the age of an Iceland mantle plume event according to Wright and Miller (1996). These authors concluded that accelerated uplift of the Greenland-Scotland Ridge between 16.3–12.3 Ma would have prevented deep water overflow from the Nordic Seas to the North Atlantic. This circulation change may have in turn resulted in increased bottom water turbidity in the Nordic Seas. The eustatic sea-level fall at the global Bur5/Lan1 sequence boundary may have also been responsible for the observed erosion (Rundberg and Eidvin 2005).

The early Langhian heralded a time of renewed 'greenhouse' conditions with increased diversity in planktonic foraminifers (Spezzaferri 1998). The reappearance of a subtropical to warm temperate foraminiferal fauna at Nordic high latitudes is marked by the first occurrence of *Orbulina suturalis* and the reappearance of *Globorotalia ex gr. praescitula-zealandica*. Around late Langhian time a major shift in global climate began, as evidenced by the dramatic shift in the oxygen isotope curve of DSDP Site 608 values towards heavier values (Mi3 glacial). This Middle Miocene global cooling continued until the late Serravallian, returning global climate to an icehouse regime (Miller et al. 1991, 1996, Moran et al. 2006). A rapid transition from obliquity to eccentricity orbital cyclicity is believed to have resulted in a major expansion of East Antarctic ice sheets with associated Antarctic Bottom Water (AABW) production leading to further cooling (Holbourn et al. 2005, Lewis et al. 2007). The timing of tectonic events including the closure of the Indo-Tethyan Seaway and the deepening of


CHRONOSTRATIGRAPHY
Age
Epoch
Stage
SEQUENCES
Sequences (SEPM Global)
PALEOCEANOGRAPHY
Sea-Level Curves (meters relative to present)
PALEOCLIMATE
Marine Oxygen-18 Composite (per-mil PDB)
BIOSTRATIGRAPHY
North Atlantic microfossil trends
Nordic microfossil trends and hiatuses (This study)
Hol.
Ple.
Pliocene
Miocene
Lt. Pleist.
M. Pleist.
E. Pleist.
1.81
Gelasian
2.59
Piacenzian
3.60
Zanclean
5.33
Messinian
7.25
Tortonian
11.61
Serravillian
13.65
Langhian
15.97
Burdigalian
20.43
Aquitanian
23.03
Pia1
Me2
Ser4/Tor1
Ser1
Bur5/Lan1
Aq3/Bur1
Ch4/Aq1
High-frequency glacioeustatic oscillations 2.7-0 Ma (17)
Panamanian Seaway closes 4.6-3.6 Ma (16)
Indonesian Seaway closes 5.2 Ma (5)
Bering Strait opens 5.5-5.4 Ma (12)
Mediterranian Salinity Event 7.246-5.33 Ma (11)
Greenland-Iceland overflow initiates (NADW) 7.5 Ma (18)
Iceland-Scotland overflow initiates (NADW initiation) 13-11.5 Ma (19, 21, 24) 12.3 Ma (14)
Fram Strait deepens 13.7 Ma (23)
Indo-Tethyan Seaway closes 13.82 Ma (9,10)
Iceland mantle-plume event prevents overflow 16.3-12.3 Ma (14)
Arctic Ocean became well oxygenated 18.2-17.5 Ma (23)
Initial opening of the Fram Strait ≥ 22 Ma (18, 20)
Northern Hemisphere ice sheets
Antarctic ice sheets
Continental glaciations (NHG) 2.7-0 Ma (17)
Mid-Pliocene Warmth 3.1-3.0 Ma (13)
Greenland ice sheets expand 3.2 Ma (22)
Failed NHG initiation 4.1-3.9 + 3.5-3.3 (16)
E. Pliocene warming 5.2-4.9 + 4.6-4.1 Ma (15, 16)
Messinian glaciation 6.3-5.5 Ma (33)
Expansion of Antarctic ice sheets 8.5-5.4 Ma (1)
Major change in Asian monsoon system and forest to grassland shift 8 Ma (27, 28)
'Middle Miocene Global Cooling' 14-12 Ma (3, 22)
Expansion of East Antarctic ice sheets 13.62-12.44 Ma (6, 29)
'Mi-3' Glaciation 13.9-13.8 Ma (3, 30)
'Mi-2' Glaciation ~16.0 Ma (3, 30)
'Miocene Climatic Optimum' Early/Middle Miocene warming 17-15 Ma (7, 30)
No major ice sheets 22.5-17.5 Ma (1)
'Mi-1a' Glaciation 21.1 Ma (3, 32)
'Mi-1' Glaciation 23.7-22.9 Ma (3, 31)
Ice-rafted assemblages 2.7-0 Ma (2)
Peak plankt. foram. diversity 4.5 Ma (17)
Calcite dissolution interval 'Late Miocene Global Carbon (d13C) Excursion' 7.6-6.6 Ma (26)
'Silica Switch' (biosiliceous sedimentation locus shifts from N. Atlantic to Pacific) 11 Ma (24)/14 Ma (25)
Reduced tropical-subtropical plank. foram. province 15-12 Ma (3)
Increased tropical to temperate plank. foram. provinciality 14 Ma (4)
Peak plank. foram. diversity 17-15 Ma (8)
Poor plank. foram. turnover 23-17 Ma (4)
Ice-rafted assemblages 2.7-0 Ma
Top Bolboforma 2.93 Ma
Neogloboquadrina "sinistral"
Late Miocene (Messinian) hiatus 7.6-6.6 Ma
Neogloboquadrina "dextral"
Middle/Late Miocene hiatus 11.8-10.6 Ma
Bolboforma diversification 12.7-11.3 Ma
Condensed intervals (PF 'flood') 14-12 Ma
Mid-Miocene hiatus 18.5-15.5 Ma
Siliceous biofacies Paleogene-22 Ma
E. Miocene-L. Oligocene hiatus ~26-22 Ma

the Fram Strait occurred around this time. The planktonic foraminiferal response to cooling at ca. 14 Ma was increased tropical to temperate provinciality in the Atlantic and Mediterranean (Thunell and Belyea 1982). At this time the Atlantic saw a contraction of the planktonic foraminiferal tropical-subtropical province of Thunell and Belyea (1982) in favour of an expanded transitional province. This signal is also observed in the Nordic Atlantic region with the first occurrence of the modern cool temperate-subpolar planktonic foraminiferal fauna in Zone NM5 (i.e. FO *Globigerina bulloides*, *Turborotalita quinqueloba*, *Globorotalia scitula*). The increased frequency of sea level fluctuation during the Serravallian, as evidenced from the global sequences, resulted in deposition of relatively closely spaced maximum flooding horizons in a condensed section. This is often expressed as a series of planktonic foraminiferal floods or acmes in the Nordic Miocene Zones NM6 and 7. During the colder Serravallian Mi3, Mi4 and Mi5 glacial intervals, acmes of *Bolboforma* occur together with the cold-adapted *Neogloboquadrina* group. This is also a level of increased bolboformid diversity (Spiegler 1999).

The Middle/Late Miocene boundary in the Nordic Atlantic region is typically marked by an unconformity. The juxtaposition of the planktonic foraminiferal LO *Paragloborotalia mayeri/siakensis* group with the FO *Neogloboquadrina acostaensis* has been observed at a number of North Atlantic sites, and may suggest a widespread hiatus or diachrony. This conclusion is based on the temperate North Atlantic age of 11.40 Ma for the LO *Paragloborotalia mayeri/siakensis* group, as reported in Berggren et al. (1995a), calibrated to the magnetostratigraphy of DSDP Site 563. The much younger age of the extinction of *Paragloborotalia mayeri/siakensis* group in the South Atlantic at 10.53 Ma as per Chaisson and Pearson (1997) suggests significant latitudinal diachrony for this bioevent. More study is necessary to ascertain the true stratigraphic range of these two important marker species globally.

At high latitude ODP Site 918D in the Irminger Basin, a hiatus was inferred based on the observed absence of standard planktonic foraminiferal Zone N15 of Blow (1969) or M12 of Wade et al. (2011). This is equivalent to Nordic Miocene Zone NM8b. At the same site a glauconitic hardground was identified at this level, suggesting an unconformity (Wei and Paleo-Alampay 1997). This appears to correlate with the major Ser4/Tor1 global sequence boundary of Hardenbol et al. (1998). This horizon also coincided with a significant biosiliceous decrease (Table 4 in Spezzaferri 1998). The age of this level at ca. 11.8 Ma corresponds roughly with the "Silica Switch" or shift in the locus of biosiliceous sedimentation from the North Atlantic to the Pacific (Cortese et al. 2004, Wei and Peleo-Alampay 1997). Occurring around this time (estimates from 13 to 11.5 Ma) was the initiation of Iceland-Scotland deep-water overflow (Ali and Vandamme 1998, Bohrmann et al. 1990, Wei and Peleo-Alampay 1997, Wright and Miller 1996). This initiation of North Atlantic Deep Water (NADW) flow into the North Atlantic was a major paleoceanographic event which probably affected the global thermohaline circulation.

Continued cooling through Tortonian time, especially across the Mi7 glacial interval, resulted in a number of calcite barren intervals, possibly due to increased bottom water corrosiveness. Enhanced dissolution in the North Atlantic, between 7.6–6.6 Ma, was correlated with the "Late Miocene carbon shift" at ODP Site 982 (Diester-Haass et al. 2005). The Late Miocene in the Nordic Atlantic region is therefore dominated by the thick-walled, dissolution-resistant *Neogloboquadrina* group of planktonic foraminifers, together with *Bolboforma* algal cysts. In the late Tortonian, at ca. 7.5 Ma, the initiation of Greenland-Scotland overflow led to a strengthening of NADW with a

Fig. 9. A summary of the main published paleoceanographic, paleoclimatic and tectonic episodes affecting the Neogene biostratigraphic expression of the Nordic Atlantic region. Chronostratigraphy according to Gradstein et al. (2004). Global sequences according to Hardenbol et al. (1998) with updated ages from Ogg and Lugowski (2008). Global sea level curve according to Haq et al. (1987). an Paleoceanography and paleoclimate according to: 1. Thunell and Belyea (1982), 2. Shackleton et al. (1984), 3. Miller et al. (1991, 1996), 4. Iaccarino et al. (2007), 5. Srinivasan and Sinha (1998), 6. Holbourn et al. (2005), 7. Zachos et al. (2001), 8. Flower and Kennett (1994), 9. Abels et al. (2005), 10. Holbourn et al. (2005), 11. Krijgsman et al. (1999), 12. Gladenkov et al. (2002), 13. Knies et al. (2002), 14. Wright and Miller (1996), 15. Diester-Haass et al. (2005), 16. Haug and Tiedemann (1998), 17. Flower (1999), 18. Kaminski et al. (1989), 19. Bohrmann et al. (1990), 20. Hull et al. (1996), 21. Ali and Vandamme (1998), 22. Moran et al. (2006), 23. Jakobsson et al. (2007), 24. Wei and Peleo-Alampay (1997), 25. Cortese et al. (2004), 26. Diester-Haass et al. (2005), 27. Behrensmeyer et al. (2007), 28. Clift et al. (2008), 29. Lewis et al. (2007), 30. Shevenell et al. (2008), 31. Lear et al. (2004), 32. Paul et al. (2000), 33. Hilgen et al. 2007, 34. Andersson and Jansen (2003), 35. Westerhold et al. (2005), 36. Miller et al. (1998) + Lourens et al. (2004).

migration of Norwegian Sea benthic foraminifera into the Labrador Sea (Kaminski et al. 1989). This is coincident with an increase in oxygen isotope ratios at Rockall Plateau Site 982 (Hilgen et al. 2007, Hodell et al. 2001) and the Nordic Atlantic coiling change in *Neogloboquadrina atlantica* from a dominant dextral morphotype to the sinistral one (D-S *Neogloboquadrina atlantica*). Slightly earlier is the last occurrence of a range of dinoflagellate taxa marking the NM9/NM10 boundary. Finally, near the end of the Miocene, the Messinian glaciation period (Hilgen et al. 2007) characterised by high abundances of marine diatoms of the *Thalissiosira* genus, together with *Bolboforma* cysts. In agreement with the observations of Hilgen et al. (2007), deglaciation following this interval is marked by the first occurrence of *Neogloboquadrina dutertrei*. This occurs, together with the last common occurrence of *N. acostaensis* and the dinocyst event LO *Hystrichosphaeropsis pontiana* at the boundary between the Nordic Miocene Zonation and the Nordic Pliocene Zonation of Anthonissen (2008).

6. Conclusions

A new multifossil zonation for the Miocene of the Nordic Atlantic has been constructed, based mainly on Ocean Drilling data. Micropaleontological analysis of selected Miocene commercial well intervals in the North Sea and Norwegian Sea has tested the applicability of the zonation. Improved planktonic event calibrations have allowed for better age constraints on existing benthic foraminiferal zonations of the North Sea. All but one of the standard Miocene GSSP correlative markers are present in Nordic high latitudes. For the Nordic Atlantic region this zonation allows for easier identification of the standard global stage boundaries of the Miocene.

There appears to be a causal relationship between planktonic microfossil turnover rates and North Atlantic climate during the Miocene, together with a correlation with the global sequences of Hardenbol et al. (1998). The latter is especially true in the case of the shallower benthic foraminiferal record of the North Sea. Acmes and diversification levels of *Bolboforma* appear to correlate well with heavy oxygen isotope intervals. While their first and last occurrences show large diachrony across the Nordic Atlantic region, it appears that an increased abundance of the *Bolboforma* microfossil group is a good indicator for cold climatic intervals during the Neogene of the high-latitudes.

It is only with further study and coring activity in the Nordic Seas that the chronostratigraphic significance of Miocene markers can be better resolved.

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Supporting data is available as Appendix 1b (Miocene event calibrations) and Appendix 2a–c (Miocene foraminiferal and bolboformid fossil counts) from http://doi.pangea.de/10.1594/PANGAEA.789399 or by contacting the author directly.

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Note

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Appendix 1a. Summary of Nordic Miocene Zones (NM) and bioevent calibrations for the Nordic Atlantic region. bioevent ages are organised from south to north according to latitudinal region. Ages are according to the calibrations in this study, except for the low-latitude ages in the "Time scale" column which are according to the Astronomically Tuned Neogene Time Scale (ATNTS04) of Lourens et al. 2004. bioevent codes: CN = Calcareous Nannofossil; PF = Planktonic Foraminifera; BF = Benthic Foraminifera; BO = Bolboformid; DC = Dinoflagellate cyst or acritarch. For details of individual age calibrations per ODP/DSDP hole, see Appendix 1b.

Appendix 1b. Details of individual Miocene age calibrations according to ODP/DSDP hole occurrence. Calibrations are organised according to the latitudinal regions described in the "Material and Methods" chapter. The most reliable calibrations and age estimations are highlighted in bold. These were then averaged on a per region basis. Appendix 1a shows the calibrations considered most reliable for the bioevents discussed in this paper.

Appendix 2a. Foraminiferal and bolboformid distribution charts for the Sønder Vium research borehole.
Appendix 2b. Detailed foraminiferal and bolboformid distribution charts for the northern North Sea commercial well 29/3-1.
Appendix 2c. Foraminiferal and bolboformid distribution charts for the offshore mid-Norway well 6704/12-GB1.