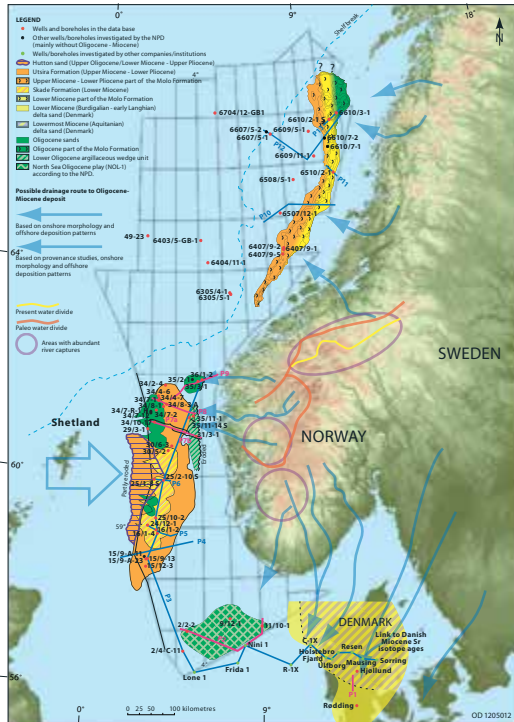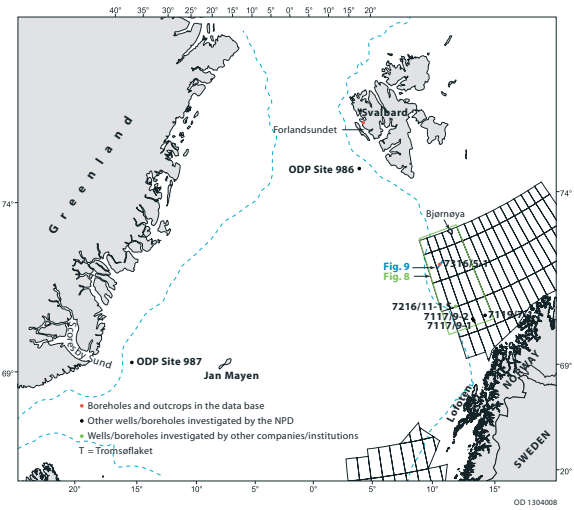# Investigation of Oligocene to Lower Pliocene deposits in the Nordic offshore area and onshore Denmark

(Including interactive maps and diagrams)

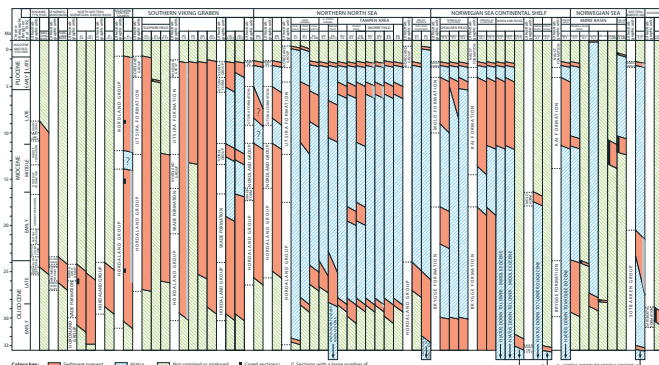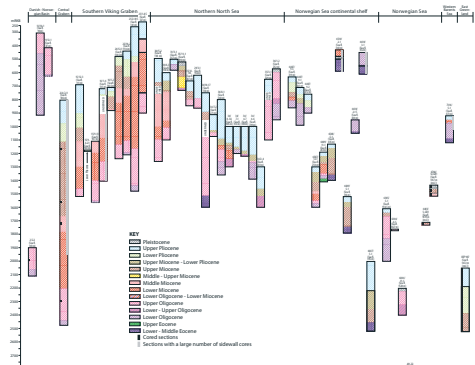Map 1

Map 2

Fig. 1

Fig. 2

T. Eidvin, F. Riis, E. S. Rasmussen & Y. Rundberg, 2013
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Frontpage

In the current publication, all the well, borehole and outcrop descriptions are hyperlinked to the numbers on Map 1, Map 2 and the numbers and columns on Fig. 1 and Fig. 2. Seismic profiles are linked to the profile numbers. The well, borehole and outcrop information includes figures and descriptions of lithology, gamma logs, lithostratigraphic units, fossil units, paleobathymetry, Sr isotope analyses and sample types. All microfossil assemblages and zones are described and included in the figures.

Contents

Investigation of Oligocene to Lower Pliocene deposits in the Nordic offshore area and onshore Denmark

Tor Eidvin[1], Fridtjof Riis[1], Erik S. Rasmussen[2] & Yngve Rundberg[3]

[1]Norwegian Petroleum Directorate (NPD), Professor Olav Hanssens vei 10, P. O. Box 600, N-4003 Stavanger, NORWAY. [2]Geological Survey of Denmark and Greenland (GEUS), Øster Voldgade 10, DK-1350 Copenhagen K, DENMARK. [3]Svenska Petroleum Exploration A/S, Strandveien 35, P. O. Box 153, N-0216 Oslo, NORWAY

Extended abstract

Regional seismic interpretation indicates that offshore West and Mid Norway and along the western Barents Sea margin, the Paleocene-Eocene sediment progradation was terminated in the period from the latest Eocene to the earliest Oligocene, and the Eocene clinoforms were onlapped by Oligocene shales. This occurred at the same time as there was a shift in the drainage divide of West Norway which caused transport of Oligocene coarser clastics southwards towards the Norwegian-Danish Basin. From now on prograding slope/deltaic systems developed in the Norwegian-Danish Basin (Vade Formation and Dufa Member). In the northern North Sea, gravity-flow sand was sourced from the Shetland Platform and to a lesser degree from Fennoscandia. Along the inner continental shelf of the Norwegian Sea, a pronounced out-building of coastal plains and deltas started (Molo Formation). Coarse clastic sediments were deposited in northwestern Svalbard, while argillaceous sedimentation prevailed elsewhere, except for the deep-water Norwegian Sea where mainly siliceous ooze accumulated. On the outer Vøring Plateou contourite growth prevailed. The climate was probably cold temperate during the Early to early Late Oligocene and warm temperate to subtropical during the latter part of Late Oligocene.

During Early Miocene, global climatic variations and major sea-level changes combined with uplift of the southern part of the Fennoscandian Shield led to increased sediment transport from the north (present-day Finland, Sweden and particularly Norway) towards present-day Denmark. Deltas (Ribe Group) covered large parts of the present-day Jutland area. In the western part of the Viking Graben in the North Sea, sand-rich gravity deposits of the Skade Formation were sourced from the Shetland Platform. To the east, in the central part of the basin north of 60ºN and in the Central Graben, fine-grained sedimentation occurred. The out-building of the Molo Formation along the inner Norwegian Sea continental shelf continued durin the Early Miocene. To the west, thin successions of fine-grained deposits are recorded on the Trøndelag Platform, and mainly pelagic ooze was laid down in the Norwegian Sea (Brygge Formation).

The uplift culminated at the Early to Middle Miocene transition, and the deposition of the Skade Formation sands was followed by a large fall in relative sea-level. In the Norwegian Sea, major compressional features, e.g. the Helland Hansen Arch, were formed. In the southern North Sea and Norwegian-Danish Basin subsidence continued. During the Middle Miocene, mainly fine-grained sediments were deposited in most parts of the Viking and Central Graben, and in parts of the Trøndelag Platform on the Norwegian Sea continental shelf. However, in the western part of the Viking Graben deposition of sand still prevailed. The southern North Sea and the Norwegian-Danish Basin subsided and record a complete Middle to early Late Miocene succession. In the southern Viking and Central Graben hiatuses are minor or absent. A local hiatus is present in the Middle Miocene in well 2/4-C-11

(Ekofisk Field) probably due to salt tectonics and polygonal faulting. Pelagic sedimentation and contourite growth continued uninterrupted in most of the Norwegian Sea and continued into the Late Miocene and Early Pliocene (Kai Formation). However, hiatuses are probably present on large dome structures. The Barents Sea margin was also uplifted, and a hiatus is recorded below the Middle Miocene in the Sørvestnaget Basin. In the Vestbakken Volcanic Province there is a break between the Upper Pliocene and Lower Miocene. The climate was probably warmtemperate during the Early Miocene and culminated with a subtropical climate in the early Middle Miocene.

In the Late Miocene, a marked relief of the Fennoscandian Shield, accompanied by continued uplift, a colder climate and a low global sea-level, resulted in a continued and pronounced out-building of the coastal plains and deltas along the inner Norwegian Sea continental shelf (Molo Formation). During the same period the northern North Sea formed a narrow seaway between deeper water in the Møre Basin and the central North Sea. The strait received a large amount of coarse clastics (Utsira Formation), mainly from the East Shetland Platform in the west but also from the Sognefjorden area in the east. Offshore West Norway farther to the south, only thin and shaly sections are recorded. Mainly fine-grained deposition continued towards Denmark and the Norwegian Sea, probably using the drainage systems which were established in the Oligocene and Early Miocene. This situation lasted through the Early Pliocene when the global temperature and sea level temporarily rose.

Investigation of the large sediment wedge off the Scoresby Sund fjord system has shown that the build-up of a substantial continental ice sheet on Greenland started in the Late Miocene at approximately 7.5 Ma.

Introduction

In this NPD Bulletin, the stratigraphy of Oligocene to Lower Pliocene deposits from Svalbard and East Greenland in the north to Denmark in the south is presented. To define the upper limit of the successions, we have also included the investigations of the Upper Pliocene in most wells. This publication includes a synthesis of data from 47 wells and boreholes from the entire Norwegian shelf, one outcrop from northwestern Svalbard, one ODP borehole off East Greenland and two stratigraphic boreholes from onshore Denmark (Map 1, Map 2, Fig. 1, Fig. 2, Fig. 3, Fig. 4 and Fig. 5). The descriptions are based on a number of papers and other publications which include biostratigraphic (mainly based on foraminifera and *Bolboforma*), lithostratigraphic and seismostratigraphic studies and Sr isotope analyses, including Eidvin (2009), Eidvin & Rundberg (2001 and 2007), Eidvin et al. (1993, 1998 a, b and c, 1999, 2000, 2007, 2010) and Rundberg & Eidvin (2005). Later, some wells were partly re-analysed or re-interpreted, and new data from a number of wells and stratigraphical boreholes are now included. Most biostratigraphic analyses of wells, boreholes and outcrops have been integrated with wire-line log and seismic data. The deposits of the Norwegian continental shelf and onshore Denmark are correlated to the deep-sea record.

A detailed understanding of the Oligocene to Pliocene stratigraphy is important in reconstructing the geological history of the North Sea Basin and the uplift and erosion of the Fennoscandian Shield. It can also be applied to petroleum exploration and CO_2 sequestration. For these purposes, in most areas, most emphasis has been placed on investigation of sandy deposits.

There has been no production of hydrocarbons from post-Eocene sediments on the Norwegian continental shelf. One medium-sized gas discovery in Pleistocene glacial sand deposits (upper part of the Nordland Group) was made in wells 35/2-1 and 35/2-2, several small gas discoveries have been reported from the Vade Formation (wells 2/2-1, 2/2-2 and 2/3-1), and the Utsira Formation (well 15/6-9 S). Oil has been discovered in the lower Nordland Group (well 1/5-3 S) and in a sandy section just below the Skade Formation in well 25/2-10 S. Shallow gas and oil shows are recorded in a number of wells, e.g. before placing the Gullfaks Field platform (northern North Sea, block 34/10) shallow gas was discovered in a number of wells in the Late Pliocene Nordland Group (NPD 2013). The high oil price in recent years has resulted in an increased focus on high-risk exploration targets, including post-Eocene sandy formations and units.

To meet Norway's commitment to the Kyoto agreement on reduction of greenhouse gas emissions, it has been suggested to separate and store CO_2 from large point sources. Depleted oil and gas fields could be used for CO_2 storage, but their capacity will be too small if carbon capture and storage (CCS) will be utilised as a major instrument to prevent global climate warming. There exists a very large potential storage capacity in post-Eocene saline aquifers on the Norwegian continental shelf, especially in the Utsira Formation in the North Sea. CCS has been implemented full scale at the Sleipner gas field (North Sea, block 15/12), where one million tons of CO_2 per year have been successfully injected into the Utsira Formation since 1996. Currently, the Utsira Formation has also been used in other fields for the production of water for injection, and the injection of produced water and other waste like drill cuttings and chemicals.

The post-Eocene deposits on the Norwegian continental shelf have been far less sampled and investigated than the older sediments, which have been the main target for hydrocarbon exploration. However, when drilling exploration wells the oil companies commonly sample the post-Eocene deposits with drill cuttings, except for the upper part of the Pleistocene. The sampling programme is usually considerably less dense than in the deeper section, e.g. every ten metres compared to every three metres in reservoir sections. A small number of wells have been sampled with sidewall cores and short conventional cores. The conventional cores are used mainly for geotechnical investigations. Contracted biostratigraphical consultants usually execute routine investigations, but the samples are often investigated with a large sample spacing and only limited effort is put into the analyses. Mistakes and inaccuracies in the biostratigraphical analysis and age interpretations have led to errors in completion logs, final well reports, regional seismic mapping and even in the stratigraphic nomenclature. Historically, this has led to considerable confusion in our understanding of the overall stratigraphy. Several scientific investigations have tried to improve this situation, including those of Gregersen (1998), Gregersen & Johannessen (2007), Gregersen et al. (1997), Henriksen et al. (2005), Jarsve et al. (work in progress), Jordt et al. (1995, 2000), Løseth & Henriksen (2005), Martinsen et al. (1999), Michelsen & Danielsen (1996), Michelsen et al. (1995) and Ryseth et al. (2003). Much of their work has focused on regional seismic interpretation, but some of their correlations have unfortunately been hampered by inaccurate/incorrect completion logs and final well reports. Biostratigraphic studies, including the present paper, dealing with re-dating of petroleum wells and boreholes may improve this situation. Regional seismic studies dealing with the outer shelf, continental slope and rise, including Laberg et al. (2001, 2005a and b), Stoker et al. (2005a and b) and Knies et al. (2009), are less affected by this problem since their seismic data, to a large extent, are calibrated with data from deep-sea ODP/DSDP boreholes.

In Jutland, Denmark, upper Paleogene and Neogene sediments occur below the glacial deposits over large areas. According to Dybkjær & Piasecki (2008), most of the water used in private households, in industry and for irrigation in Denmark comes from subsurface aquifers. Some of the most important aquifers in Jutland (Jylland in Danish), western Denmark, are sand layers deposited in the early Neogene (Early to Middle Miocene). Global climatic variations and major sea-level changes (Zachos et al. 2001), combined with uplift of the southern part of the Fennoscandian Shield, led to increased sediment transport from the north (present-day Finland, Sweden and particularly Norway, Map 1). This resulted in deposition of huge, fluvio-deltaic sand systems intercalated with marine clay (Rasmussen 2004). According to Rasmussen et al. (2004), the Geological Survey of Denmark and Greenland (GEUS) has executed a systematic study of these deposits, which includes detailed sedimentological descriptions of outcrops, sedimentological and log-interpretations of new stratigraphic boreholes and interpretation of high-resolution seismic data. More than 50 boreholes and outcrops (including some offshore boreholes) have been studied palynologically. These studies have resulted in a dinoflagellate cyst zonation scheme (Dybkjær & Piasecki 2008, 2010) and a regional, stratigraphic model. In many of these sites, thin-walled calcareous foraminifera have been dissolved due to a high concentration of humic acid in the pore water. However, based on examination of the foraminiferal contents in marine clay from 18 onshore boreholes (most from the North German Basin in the southern Jutland), Laursen & Kristoffersen (1999) have established a detailed foraminiferal biostratigraphy of the Miocene Ribe and Måde groups for these areas.

To facilitate correlation of the Danish onshore boreholes and outcrops (palynologically investigated by Dybkjær & Piasecki, 2008 and 2010) with the Norwegian wells and boreholes, a large number of the Danish samples containing molluscs and mollusc fragments have been analysed for Sr isotopes. The thick-walled tests of molluscs are far less prone to dissolution than the foraminiferal tests and are present in many samples where foraminifera are absent. The detailed results from this investigation will be published in Eidvin et al. (work in progress a and b), but the main results are shown here in Link to Danish Sr isotope ages.

In the present publication, all absolute ages are referred to Berggren et al. (1995). The main reason for this is that the Strontium Isotope Stratigraphy (SIS) Look-up table of Howard & McArthur (1997) has been used, and this is based on the time scale of Berggren et al. (1995). For the post-Eocene part, this time scale does not deviate to any great extent from the new time scale of the International Commission on Stratigraphy (ICS 2013). The most important difference is that the base Pleistocene has been moved from 1.85 Ma to 2.588 Ma (see Table 1). All depths are expressed as metres below the rig floor (m RKB) if not stated otherwise.

In the current publication, all the well, borehole and outcrop descriptions are hyperlinked to the numbers on Map 1, Map 2 and the numbers and columns on Fig. 1 and Fig. 2. Seismic profiles are linked to the profile numbers. The well, borehole and outcrop information includes figures and descriptions of lithology, gamma logs, lithostratigraphic units, fossil units, paleobathymetry, Sr isotope analyses and sample types. All microfossil assemblages and zones are described and included in the figures, but no fossil range charts are included. Many range charts of the most stratigraphically important taxa can be found in our cited papers. However, in the future we plan to make full range charts available on DVD on request. For a discussion of the interpretation of paleobathymetry, we refer the reader to our previous papers (see above). The definition of bathymetric zones is according to van Hinte (1978); inner neritic: 0-30 m, middle neritic: 30-100 m, outer neritic: 100-200 m and upper bathyal: 200-600 m.

Geological setting

The Oligocene and Miocene sediments investigated for this publication are sampled from wells, boreholes and outcrops which belong to six different provinces along the North Atlantic Margin. Prior to the Oligocene, the geological history of these provinces was influenced by several processes related to Paleocene and Eocene break-up, volcanism, rifting and strike-slip movements in the Atlantic domain. A significant change in the plate tectonic setting took place at the time of magnetic anomaly 13 when the rifting and spreading activity at the Kolbeinsey Ridge west of Jan Mayen was initiated. This event corresponds approximate to the Eocene-Oligocene boundary, e.g. Faleide et al. (1996) and Eidvin et al. (1998b). Following this plate tectonic rearrangement, strike-slip tectonic activity along the western Barents Sea and Spitsbergen margin ceased and gave way to sea-floor spreading in the Norwegian-Greenland Sea. In all the provinces described, deposition of Oligocene and Miocene sediments took place in a tectonically quiet passive-margin setting, although an event of Mid Miocene compression is recorded in the Norwegian Sea and southern North Sea. The geometries of the basins, the uplift of the hinterlands and the local climate were constrained by pre-Oligocene events. Several pulses of coarse clastic sedimentation are found in the Oligocene-Miocene sedimentary record. Such events can be interpreted as responses to tectonic uplift of the Scandinavian hinterland or the Shetland Platform, or, alternatively, as non-tectonic processes such as sedimentary progradation, rearrangement by ocean current circulation (Laberg et al. 2005b) as well as eustatic and/or climatic changes which thus influenced the clastic input to the basins. Good correlation between the wells in the region is important in order to understand the geological history, interpret the paleogeography and to map the distribution of economically important reservoir sands in the region.

East Greenland – Scoresby Sund. The Scoresby Sund Fan forms the largest accumulation of Neogene sediments along the entire East Greenland Margin (Profile P14 and ODP Site 987). It has a slope of about 2º beyond the shelf break with the total sediment volume estimated at $30\,000 \pm 10\,000$ km^3 (Dowdeswell et al. 1998, Butt et al. 2001). The fan occupies the Outer Liverpool Land Basin and is located at the mouth of the large drainage system of Scoresby Sund, which is bounded to the south by the Paleocene volcanic province of East Greenland and to the north by the Mesozoic sedimentary province of Liverpool Land. The hinterland area was strongly uplifted in the Cenozoic, and the stratigraphy of the fan is of interest for the timing and reconstruction of the geological development of the region.

The Liverpool Land Basin contains an approximately 10 km-thick sediment pile overlying oceanic/volcanic basement (Larsen 1990, Butt et al. 2001) and is located to the north of the Blosseville Kyst Basin in the shelf region in the vicinity of the Scoresby Sund Fjord complex. The Iceland Plateau and the Kolbeinsey Ridge form the eastern boundary of the basin. The evolution of the area has been strongly influenced by Cenozoic tectonic events, which principally consist of an early phase of rift basin formation and a later phase of sea-floor spreading (Larsen 1990, Butt et al. 2001).

The Forlandssundet basin. In Forlandssundet, West Spitsbergen, Cenozoic sediments are infilling an elongate, fault-bounded, basinal structure within the hinterland of the Spitsbergen orogen (see Map 2 and Forlandsundet). Offshore seismic data show that the basin belongs to a coast-parallel structure, about 30 km wide and 300 km long (Sigmond 1992). The Cenozoic regional deformation of Svalbard and formation of the West Spitsbergen Orogen is related to the opening of the Norwegian-Greenland Sea and dextral motion between Greenland and

Svalbard in the Paleocene and Eocene (Gabrielsen et al. 1992, Maher et al. 1997, Braathen et al. 1999, Bergh et al. 1999). The main transpressive/compressive tectonism of the orogen affected the Paleocene and Eocene sedimentary rocks outcropping in the thrust/fold belt in central parts of West Spitsbergen, whereas the sediments of Forlandsundet were deposited in a different tectonic setting where both normal faulting and strike-slip faulting prevailed.

In the literature, the age of the sedimentary fill of the Forlandsundet basin, based on foraminiferal and strontium isotope studies, has been considered to be Oligocene by Feyling-Hanssen & Ulleberg (1984) and Eidvin et al. (1998b), whereas Manum & Throndsen (1986) interpreted the sedimentation as Eocene based on palynological studies. Given an Eocene age for part of the fill, the basin would have formed partly coevally with contractional deformation in the thrust-belt to the east, thus indicating a complex regional strain partitioning. On the other hand, if all of the basin fill is Oligocene, the basin itself could post-date the West Spitsbergen orogeny. Consequently, a more reliable age determination of these sediments is important for the reconstruction of the last phases of the formation of the orogen and correlation with the plate tectonic events.

The Western Barents Sea margin. The present continental margin of the western Barents Sea and Svalbard (see Map 2, Profile P15 and Profile P15 map) extends for about 1000 km in a broadly north-northwesterly direction. It comprises three major structural segments, including a southern, sheared margin along the Senja Fracture Zone, a central volcanic rift segment (Vestbakken Volcanic Province), and a northern sheared and subsequently rifted margin along the Hornsund Fault (Ryseth et al. 2003). The evolution of the margin is closely linked to the opening of the Norwegian-Greenland Sea. In the Paleocene-Eocene, transcurrent movements prevailed, with the Vestbakken Volcanic Province opening as a pull-apart basin. From the Oligocene onwards, oceanic crust developed along the entire margin between Norway and Svalbard, leading to subsidence of a passive margin. Small amounts of Oligocene and Miocene sediments accumulated in local basins east of the main boundary fault between continental and oceanic crust. The biostratigraphic and Sr-isotope analyses of these sediments are important for the timing of the formation of these basins and their correlation with the main plate tectonic events. Post-Eocene sediments are generally not preserved on the Barents Sea shelf. Later, in the Pliocene to Pleistocene, a very thick, Neogene, sedimentary wedge accumulated as a result of glacial processes acting in Svalbard and on the Barents Sea shelf (Faleide et al. 1996, Ryseth et al. 2003 and Laberg et al. 2012).

The Norwegian Sea and its continental shelf represent different structural settings (Fig. 6). The Møre and Vøring basins are characterised by exceptionally thick Cretaceous successions and a complex Cretaceous and Cenozoic tectonic history (Blystad et al. 1995, Brekke 2000). The Utgard High forms the eastern flank of the Late Cretaceous Någrind Syncline, and the drilled wells reveal a complex and condensed Paleogene and a very thick post-Cenomanian Cretaceous succession. In Oligocene to Early Pliocene times, the Møre and Vøring Basins were located in a distal position relative to sediment supply from Scandinavia, and biogenic ooze makes up a significant part of the succession. Large compressional structures were formed during Mid Miocene tectonism. In the tectonically more stable, Late Jurassic/Early Cretaceous Trøndelag Platform, the pre-Cenozoic succession is characterised by a condensed Cretaceous sequence, whilst in the Paleocene, thick wedges prograded from the Scandinavian mainland towards the deeper parts of the Møre and northern Nordland sea areas. Towards the Fennoscandian Shield, the Cenozoic succession is deeply eroded (Blystad et al. 1995, Brekke 2000). In the Oligocene to Early Pliocene, there was a pronounced progradation of coastal plains along the inner Norwegian Sea continental shelf (the sandy Molo Formation). Farther

west, on the continental shelf, fine-grained clastic sedimentation, partly contouritic, prevailed (Laberg et al 2005b, Map 1, Profile P10, Profile P11, Profile P12 and Profile P13).

The North Sea Basin is an epicontinental basin, confined by the Scandinavian and British landmasses, with a marine connection in the north to the Norwegian-Greenland Sea. In the Norwegian sector, the basin comprises several major Mesozoic highs and grabens of which the Central Graben in its south-central region and the Viking Graben in the north are dominant (Fig. 6 and Fig. 7). These structures were formed during several periods of extensional tectonics during the Permian and the Mesozoic. This extension ceased in the Cretaceous and the basin was subjected to post-rift subsidence and filled by sediments derived from surrounding topographical highs. In the Paleocene-Eocene, the surrounding landmasses were uplifted and the North Sea Basin deepened. Deltaic sequences prograded into the deep basin from the Shetland Platform and West Norway. Progradation continued in the Oligocene and Miocene, but was more confined to depocentres which varied through time (Eidvin & Rundberg 2001 and 2007, Gregersen & Johannessen 2007, Rundberg & Eidvin 2005).

The Norwegian-Danish Basin is confined by the Fennoscandian Shield in the north and the Fennoscandian Border Zone, also known as the Sorgenfrei-Tornquist Zone, in the northeast. In the south, the Ringkøbing-Fyn High separates the Norwegian-Danish Basin and the North German Basin. The deepest part of the basin is located in the west towards the Central Graben (Fig. 7, Ziegler 1990, Rasmussen et al. 2005). The basin was formed during Permian tectonism and thick sections of salt were deposited (Ziegler 1982, 1990 and Berthelsen 1992). Reactivation of different structural elements took place in Triassic to Early Cretaceous times (Vejbæk & Andersen 1987, Berthelsen 1992, Thybo 2001). The depositional environment was characterised by progradation and retrogradation of a coastal plain resulting in alternating sand-rich shore face deposits and mud-dominated marine sediments (Nielsen 2003). Parts of the basin were inverted during the Late Cretaceous (Liboriusen et al. 1987, Mogensen & Korstgård 1993) and also in the Early Miocene (Rasmussen 2009). Furthermore, fission-track data and reactivation of salt structures indicate an Eocene–Oligocene tectonic phase. The Late Cretaceous–Paleogene period was dominated by a deep-marine depositional environment dominated by pelagic and hemi-pelagic deposits (Surlyk & Lykke-Andersen 2007, Heilmann-Clausen 1985). The tectonic phase at the Eocene-Olgocene transition was accompanied by progradation of Early-Late Oligocene deltas off southern Norway (Schiøler et al. 2007). The Early Miocene inversion resulted in widespread delta progradation from central Sweden and southern Norway, and major parts of the Norwegian-Danish Basin became a land area in the Early Miocene (Rasmussen 2004, 2009). Increased subsidence in the Mid Miocene resulted in flooding of the area and sedimentation of clay-dominated marine sediments. This was succeeded by progradation of the shoreline during both the latest Late Miocene and the Late Pliocene when the shoreline prograded towards the Central Graben. A distinct tilting of the Norwegian-Danish Basin commenced in the late Neogene (Jensen & Schmidt 1992, Japsen 1993, Japsen et al. 2010). This was succeeded by a marked erosion of the marginal areas of the Norwegian-Danish Basin. Well 2/2-2 is situated in the deep part of the basin, and wells 9/12-1 and 11/10-1 are situated in marginal parts.

The *Scandes mountains* is a name commonly used for the present mountainous belt of western Scandinavia, which is underlain mainly by Proterozoic to Devonian metamorphic rocks. The paleogeography of this mountain range is debated, but regional mapping and well data show that western Scandinavia has been an important sediment source for the Norwegian shelf since the Paleocene. The Scandes mountains have two major culminations, one in central South Norway and one in northern Nordland, Troms and northern Sweden

(Dehls et al., 2000). These culminations are referred to here as the southern and northern Scandes domes (Lidmar-Bergström 1999, Lidmar-Bergström & Näslund 2002).

Oligocene to Early Pliocene climate evolution in the Nordic area

Early Oligocene climate and environment

The long-term trend in the global δ^{18}O record, based on carbonate from deep-sea calcareous benthic foraminifera, shows that the Early Eocene Climatic Optimum was followed by a 17-My-long trend towards cooler conditions with most of the changes occurring during the Early-Middle Eocene (50-48 Ma), Late Eocene (40-36 Ma) and Early Oligocene (35-34 Ma, Fig. 5). This was a profound change in regime from a greenhouse climate, prevailing since the Mesozoic, to a modern ice-house climate (Zachos et al. 2001). A generally lowered, but fluctuating eustatic sea level was caused by growing and waning ice sheets primarily in Antarctica, but probably also in Greenland (see below). A δ^{18}O-record, based on carbonate from molluscs collected from strata in southern England, Holland, Germany, Denmark and southern Sweden, shows that the climate became much cooler also in Scandinavia (Buchardt 1978).

Eldrett et al. (2007) studied cores from ODP Site 913 in the Norwegian-Greenland Sea (Fig. 5). To test the shipboard interpretations, they undertook an investigation of the Eocene-Oligocene succession at Site 913B. The core observations revealed the presence of *in situ* macroscopic gneiss clasts up to 3.5 cm in length. According to Eldrett et al. (2007), their data demonstrate that ice rafting into the Norwegian-Greenland Sea occurred at least intermittently between 38 and 30 Ma at ODP Site 913, and they pointed to East Greenland as the likely source. Previously, the existence of Northern Hemisphere ice sheets had been demonstrated back to the Mid Miocene (approximately 15 Ma, Winkler et al. 2002, Helland & Holmes 1997), but these findings document the first occurrence of ice-rafted debris some 20 million years earlier in the Norwegian-Greenland Sea (Moran et al. 2006).

According to DeConto et al. (2008) and Pekar (2008), the findings of Eldrett et al. (2007) indicate that small, isolated sheets of glacial ice could have formed in the Northern Hemisphere during the cooler intervals of the Eocene and Oligocene, especially during periods when variations in the Earth's orbit produced relatively cold northern summers. However, they stressed that there is currently only scant evidence to suggest that large amounts of glacial ice existed in the Northern Hemisphere before the Late Miocene.

Erosion has removed any terrestrial, palynological evidence from the Oligocene to the Pliocene on and close to the Fennoscandian Shield area and the Barents Sea. However, Boulter & Manum (1996) have recorded organic assemblages (pollen, spores, dinoflagellate cysts, plant debris) in mid Oligocene sediments from the Hovgård Ridge (ODP Site 908, Fig. 8). The assemblages are dominantly of terrestrial origin, and their present position, in the middle of the Fram Strait (Greenland Sea), can be explained by a tectonic model for the origin of the ridge as a sliver rifted from the Svalbard Platform since anomaly 13 time. The dominance of pollen and plant-tissue fragments and the low proportion of dinoflagellate cysts indicate relatively short distances to a swampy, forested lowland with prolific humic productivity. The pollen flora in the Hovgård Ridge sediment presents a unique glimpse into previously unknown vegetation in high northern latitudes during mid Oligocene times. The pollen indicates forests of conifers related to *Pinus*, *Picea, Tsuga* and *Taxodium*, with a minor element of angiosperms but relatively common ferns. This is different from the well-known

Paleocene-Eocene floras on adjacent Spitsbergen that were also rich in conifers, but had a richer and more diverse angiosperm element and lacked *Tsuga* relatives.

Manum (1962) has also described the pollen found in Cenozoic deposits from Sarsbukta (Forlandsundet, Spitsbergen). Manum & Throndsen (1986) gave a Late Eocene age to these deposits based on dinoflagellate cysts, but Feyling-Hanssen & Ulleberg (1984) interpreted the deposits to be of mid Oligocene age. The last age interpretation was verified by Eidvin et al. (1994, 1998b) by means of Sr isotope analyses (latest Early Oligocene). Boulter & Manum (1996) supported an Oligocene age for the Sarsbukta deposits and considered the pollen flora to be very similar to that recorded on the Hovgård Ridge, with a pronounced but small angiosperm component.

Late Oligocene climate and environment
The global deep-sea $\delta^{18}O$ record shows that a cool climate prevailed early in the Late Oligocene, but a warming trend started in the late part of Late Oligocene (Fig. 5). The Antarctic continental ice-sheet that had built up during the Early Oligocene persisted until the later part of the Oligocene (27 to 26 Ma), when the warming trend reduced the extent of the Antarctic ice (the Northern Hemisphere ice sheets may have disappeared). From this time until the Mid Miocene (approximately 15 Ma), the global ice volume remained low and bottom-water temperatures trended slightly higher, with the exception of several brief periods of glaciation. This warm phase peaked in the late Mid Miocene climatic optimum (17-15 Ma, Zachos et al. 2001). The latest Oligocene warming trend is also seen in the $\delta^{18}O$ record of Buchardt (1978) from northern Europe, but it is considerable less distinct than the Mid Miocene optimum warming trend.

Early Miocene climate and environment
According to the global deep-sea $\delta^{18}O$ record, the warming trend that started in the late part of Late Oligocene levelled out in the Early Miocene, and cooled somewhat early in the period (Fig. 5, Zachos et al. 2001).

According to Larsson et al. (2010), two exposures in Jytland encompassing beds of latest Oligocene to earliest Miocene age yield well-preserved palynofloras. The assemblages indicate that Jutland was covered by Taxodiaceae swamp forests at the time. Besides a Taxodiaceae-Cupressaceae association, which was overwhelmingly dominant, other common plants in the habitat were *Alnus*, *Nyssa*, *Betula*, *Salix*, *Cyrilla* and *Myrica*. Most of the trees and shrubs are well adapted to swamps and thrive under more or less flooded conditions in modern, bald, cypress swamps of southeastern North America. Vegetation composition indicates that a warm-temperate climate prevailed in Denmark during the Oligocene-Miocene transition. According to calculations using the Coexistence Approach of Mosbrugger & Utescher (1997), the mean annual temperature during this time span ranged from 15.6 to 16.6 °C. An increase to 16.5-21.1°C is inferred from the palynoflora in the upper part of the section. The earlier, cooler period possibly reflects global cooling associated with the Mi-1 glaciation event at the Oligocene-Miocene boundary.

Larsson et al. (2006) performed a palynological analysis of a Lower Miocene (upper Aquitanian) section from Sønder Vium in southwestern Jytland, Denmark. Terrestrial pollen and spores dominated their samples, with lesser contents of dinoflagellates, indicating a substantial fluvial input into a marine setting. The pollen record suggests that swamp forests dominated the onshore region, which is consistent with previous results from central and northern Europe. The swamp forest also contained several angiosperm taxa. Elevated or better drained hinterland areas hosted a diverse mesophytic forest, which included evergreen

conifers and deciduous angiosperms. A decrease in the relative abundances of thermophilous elements in the middle part of the studied succession indicates a possible correlation with the Early Miocene climatic cooling. The composition of the palynological assemblages suggests a warm, frost-free, temperate climate during the Early Miocene, culminating with a subtropical climate in the latest part of the Early Miocene in Denmark (Friis 1975, Larsson et al. 2006).

Middle Miocene climate and environment
According to the global deep-sea $\delta^{18}O$ record, the warming trend which started in the late part of Late Oligocene peaked in the early Middle Miocene climatic optimum (17-15 Ma, Fig. 5, Zachos et al. 2001). This peak is also distinct in the $\delta^{18}O$ record of Buchardt (1978) from northern Europe.

Utescher et al. (2000) made a reconstruction of the continental paleoclimate evolution of Northwest Germany during Late Oligocene to Pliocene time. The paleoclimate data are derived from the paleobotanical record of twenty-six megafloras (fruits and seeds, leaves, wood) from the Lower Rhine Basin and neighbouring areas. The temperature curves show a comparatively cooler phase in the Late Oligocene, a warm interval in the Middle Miocene, and a cooling starting at 14 Ma.

Grimsson et al. (2007) described two Middle Miocene macrofloras (15 and 13.5 Ma) from plant-bearing sediments, sealed off by lava, in northwestern Iceland. In the case of the older flora, differences in environments are reflected in plants derived from high elevations and from lowland alluvial plains. The former flora is characterised by *Fagus*, and the latter by conifers inhabiting swamps and hummocks. The younger flora is poorer and more similar to the older high-elevation flora. Both floras suggest a humid warm temperate climate with a number of exotic elements.

Late Miocene to Early Pliocene climate and environment
According to the global deep-sea $\delta^{18}O$ record, the late Middle Miocene climatic optimum was followed by a gradual cooling and reestablishment of a major ice-sheet on Antarctica by 10 Ma. Mean $\delta^{18}O$ values then continued to rise gently through the Late Miocene until the Early Pliocene (6 Ma), indicating additional cooling and small-scale ice-sheet expansion on West Antarctica and in the Arctic. The Early Pliocene is marked by a subtle warming trend until approximately 3.2 Ma, when $\delta^{18}O$ again increased reflecting the onset of large-scale northern hemisphere glaciations (Fig. 5, Zachos et al. 2001). This trend is also quite distinct in the $\delta^{18}O$ record of Buchardt (1978) from northern Europe.

Frondval & Jansen (1996) studied continuous, late Neogene, sediment sections from ODP Site 907 on the Iceland Plateau and ODP Sites 642, 643 and 644 on the Vøring Plateau (Norwegian Sea) by using stable isotope stratigraphy and sedimentological methods. They described an overall increase in $\delta^{18}O$ values in benthic calcareous foraminifera from 12 to 1 Ma which documents a gradual cooling of the Iceland-Norwegian Sea deep water with major cooling events at approximately 11 and 6.4 Ma. The oldest ice-rafted debris detected is dated to approximately 12.6 Ma (an event also recorded in borehole 6704/12-GB1, see also Eidvin et al. 1998c). This coincides with a decrease in mean annual temperature at middle and high latitudes, an intensification of North Atlantic deep-water production, and a change in circulation patterns within the Iceland-Norwegian Sea, as indicated by a shift from extensive biogenic opal deposition to carbonate accumulation on the Vøring Plateau. IRD records from southeast Greenland (Larsen et al. 1994), the Iceland and the Vøring Plateau suggest further intensifications of the Northern Hemisphere glaciations at approximately 7-6 Ma

(Messinian). Between 6 and 3 Ma, small-scale ice sheets periodically existed around the Iceland-Norwegian Sea, interrupted by intervals with lesser local ice volumes as indicated by reduced ice rafting. The onset of the large-scale Northern Hemisphere glaciations is dated to 2.75 Ma on the Vøring Plateau and Svalbard/Barents Sea (Knies et al. in press) and 2.9 Ma at the Iceland Plateau.

Besides terrestrial, palynological evidence, at ODP Site 908 on the Hovgård Ridge (Fram Strait, Greenland Sea, Fig. 8) from the Oligocene, Boulter & Manum (1996) also reported such evidence from the Upper Miocene. They stated that in the Upper Miocene, all the pollen taxa present in the Oligocene sections continue to be present, which showed that the vegetational source was fundamentally similar over a hiatus of about 18-15 My. They suggested that the high Arctic (Spitsbergen area) would have served as a stagnant genetic pool with little evolutionary activity during the late Paleogene and early Neogene, quite different than in areas at lower latitudes.

Denk et al. (2005) studied a large number of plant macrofossils from several localities exposing Middle to Upper Miocene successions on Iceland. Their main finding is that the Miocene flora of Iceland belongs to a widespread, Neogene, northern hemispheric floral type whose representatives are restricted to East Asia, North America and western Eurasia at the present time. The type of vegetation in four plant-bearing sedimentary formations from the late Middle Miocene to Late Miocene, at respectively 12, 10, 9-8 and 7-6 Ma, corresponds to humid temperate broad-leaved (deciduous) to coniferous mixed forest. Compositional changes in the species in the sedimentary formations reflect a shift from warm temperate to cool temperate conditions from the late Mid Miocene to the latest Miocene.

From eastern Iceland, Mudie & Helgason (1983) have obtained palynological data from clastic units between lava formations. The data they obtained from the Holmatindur Tuff Formation records a floral spectrum ranging up-section from a strongly thermophilic swamp forest to cool temperate deciduous-boreal forest, then microthermal spruce forest, and finally, subarctic woodland. According to Mudie & Helgason (1983), this suggests the occurrence of a major climatic cooling event during the time interval from 10.3 and 9.5 Ma.

From an extensively karstified landscape at Pollnahallia, western Ireland, Coxon (2005) and Coxon et al. (2005) have obtained palynological data from a borehole in preglacial Pliocene lignite. The lignite is filling a limestone gorge, and is covered with silica-rich sand and lodgement till. The lignite contains a richly diverse pollen assemblage characteristic of the preglacial Pliocene including fir, maple, sweet chestnut, swamp cypress (abundant), hazel, beech, walnut, tulip tree, sweetgum, sourgum, pines, spruce, oak, Japanese umbrella pine, wingnut, oak, redwood, yew, hemlock and heather. This indicates a forested, swampy landscape on an undulating intensely karstified surface. The upper pollen assemblages in the lignite indicate a deterioration of the climate.

Material and methods

From the Norwegian continental shelf, Norwegian Sea, Svalbard, off Scoresby Sund (East-Greenland) and onshore Denmark, 1880 samples from 50 wells and boreholes and one outcrop have been investigated. In most of the studied wells, the biostratigraphic analyses were performed largely on ditch-cutting samples. Sidewall cores were available in wells 16/1-4, 2/4-C-11, 6510/2-1 and 6610/3-1. Short conventional cores were available from wells 6305/4-1, 15/9-A-23, 2/4-C-11 and 2/2-2, boreholes 6704/12-GB1and 6403/5-GB1, and the

gravity core 49-23. The ODP Site 987 drilling off Scoresby Sund was nearly continuously cored (Map 2). The ditch cuttings are usually sampled at 10 m intervals in the upper Cenozoic sections, and most of the available samples have been analysed. However, some of the samples stored at the NPD contain so little material that they could not be released for analyses. The Rødding and Hjøllund boreholes from onshore Denmark were sampled at one metre intervals for parts of sections, but with larger intervals in other parts.

Biostratigraphy
Micropalaeontological investigations were based on analyses of planktonic and benthic foraminifera and *Bolboforma*. Pyritised diatoms were also used to establish the stratigraphy in Lower Miocene and Oligocene deposits. In some wells, palynological investigations were also performed.

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

In this study, the fossil assemblages are correlated with the biozonation of King (1983, 1989), who outlined a micropalaeontological zonation for Cenozoic sediments in the North Sea. According to King (in prep.) some of the taxa names used in King (1983, 1989) have been revised. These are listed in Table 2. Gradstein & Bäckström's (1996) faunal zonation from the North Sea and Haltenbanken is also used. In addition, a number of articles describing benthic foraminifera from onshore basins in the area surrounding central and southern North Sea are utilised. The zonations of planktonic foraminifera (Weaver 1987, Weaver & Clement 1986 and 1987, Spiegler & Jansen 1989) and *Bolboforma* (Spiegler & Müller 1992, Müller & Spiegler 1993, Spiegler 1999) from ODP and DSDP drillings in the Norwegian Sea and the North Atlantic are very important for the dating of the sediments. Correlation with these zones yields the most accurate age determinations, because the zones are calibrated with both nannoplankton and palaeomagnetic data.

Lithological analyses
The lithological analyses are based on visual examination of the samples prior to treatment, and of the washed, sieved and fractionated material after preparation.

Sr isotope analyses
Strontium isotope stratigraphy is used as an additional control for the biostratigraphic correlations. The $^{87}Sr/^{86}Sr$ ratio of seawater is very uniform on a global scale, which is a reflection of the long oceanic residence time of strontium (2-4 My), combined with a relatively short (≤ 2000 years) oceanic mixing time. This is an effective method particularly for the dating of Miocene and Oligocene sections. The method has best resolution in sediments older than 15 Ma. The reason for this is that the Sr isotopic composition of seawater changed rapidly with time during this period (e.g. Howard & McArthur 1997). For samples with ages younger than 8 Ma, the Sr isotope ages have to be treated with more caution. This is due to less variation in the Sr isotopic composition and a relatively flat curve between 2.5 and 4.5 Ma and also to some extent between 5.5 and 8 Ma (Hodell et al. 1991, Farrell et al. 1995).

In total, 825 samples were analysed for Sr isotopic composition. The analyses were carried out mainly on tests of calcareous foraminifera and fragments of molluscs (especially in sandy sections). In some samples, *Bolboforma*, fish teeth and *Bryozoa* fragments were also used.

Ninety of these samples were taken from the Danish onshore boreholes and outcrops investigated palynologically by Dybkjær & Piasecki (2008, 2010, see Map 1 and Link to Danish Sr isotope ages). These analyses were based mainly on molluscs and mollusc fragments, but a few also on foraminiferal tests and shark teeth. The analytical work was conducted mainly at the Mass Spectrometry Laboratory, University of Bergen, Norway. The earliest analyses were performed at the Institute for Energy Technology (IFE) at Kjeller, Norway. All Sr isotopic ratios were normalised to $^{86}Sr/^{88}Sr = 0.1194$ and to National Institute for Standard and Technology (NIST) 987 = 0.710248. Strontium values were converted to age estimates using the Strontium Isotope Stratigraphy (SIS) Look-up table of Howard & McArthur (1997); see McArthur et al. (2001) and Eidvin & Rundberg (2001, 2007) for more details about the method.

Seismic analyses
Seismic studies are based on a large number of regional 2-D lines and 3-D cubes from an extensive database covering most of the Norwegian continental margin and the Danish continental shelf. In addition, more than 1000 km of high-resolution, land-seismic data have been acquired across Jutland (Denmark) for the study of the Miocene deltas. Sequence boundaries identified on seismic data are tied to wells and boreholes by well velocity surveys carried out on the respective offshore wells (see profiles P1 to P13 in Map 1 and Map 2). Onshore boreholes in Denmark have been tied with seismic sections using a standard velocity of c. 1900 m/s. In the offshore areas, velocities are in the range of 1900 to 2100 m/s, except for the low-velocity deep-marine ooze. The principles of seismic stratigraphy of Brown & Fisher (1977) and concepts of sequence stratigraphy of Posamentier et al. (1988) and Hunt & Tucker (1992, 1995) have been applied.

Biostratigraphical and Sr isotope correlations

Lower Oligocene deposits (Fig. 1 and Fig. 2) are recorded at Forlandsundet (outcrop), in wells 7316/5-1, 6305/5-1, 6610/3-1, 6610/2-1 S, 6609/11-1, 6507/12-1, 6407/9-2, 6407/9-1, 6407/9-5, 36/1-2, 34/4-6, 34/7-1, 34/8-1, 31/3-1, 25/2-10 S, 25/10-2, 16/1-4, 15/9-13, 2/4-C-11, 9/12-1, 2/2-2 and 11/10-1. King (1989) described a *Rotaliatina bulimoides* Zone (NSB7b) from the Lower Oligocene of the North Sea. *Gyroidina soldanii mamillata* is also common in this zone, and both species have their last appearance datums (LADs) close to the Lower/Upper Oligocene boundary. In most of the wells/outcrops we have investigated, from the northwestern Norwegian-Danish Basin in the south to the Forlandsundet (northwestern Svalbard) in the north (Map 1), we have used *R. bulimoides* or *G. soldanii mamillata* as index fossils for the Lower Oligocene. The Early Oligocene age is also supported by Sr isotope analyses in most of the wells and outcrops. The exceptions include wells 7316/5-1 and 6609/11-1 where the identification of the Lower Oligocene is based on palynological evidence and Sr isotope analyses, and wells 6610/3-1 and 36/1-2 where the occurrence of the Lower Oligocene is based on a number of Sr analyses. It is probably due to environmental factors that neither *R. bulimoides* nor *G. soldanii mamillata* occur in these deposits. In wells 6610/2-1 S and 6407/9-1 the occurrence of *R. bulimoides* and *G. soldanii mamillata* does not reach to the top of the Lower Oligocene units (also probably due to environmental factors), and the top is based solely on palynological evidence. In both of these wells, Sr isotope analyses support the Early Oligocene age.

Upper Oligocene deposits (including Lower-Upper Oligocene deposits, Fig. 1 and Fig. 2) are recorded in wells 6404/11-1, 6305/4-1, 6305/5-1, 49-23 (core), 6609/11-1, 6507/12-1, 36/1-2,

35/3-1, 34/2-4, 34/4-6, 34/4-7, 34/8-3A, 34/8-1, 34/7-2, 35/11-1, 35/11-14 S, 34/10-17, 30/5-2, 30/6-3, 25/1-8 S, 25/2-10 S, 25/10-2, 24/12-1, 16/1-4, 15/9-13, 15/12-3, 2/4-C-11, 9/12-1, 2/2-2, 11/10-1 and in the Hjøllund and Rødding boreholes (Denmark). In the North Sea area, the LAD of Diatom sp. 3 is close to the Late Oligocene/Early Miocene boundary according to King (1989, the top of Zone NSP 10). The LADs of the calcareous benthic foraminifera *Turrilina alsatica, Gyroidina soldanii girardana* and *Almaena osnabrugensis* are also close to this boundary according to King (1989). In CaCO$_3$-poor deposits, the LAD of the agglutinated foraminifera *Ammodiscus* sp. B is a reliable marker for an event close to the Late Oligocene/Early Miocene boundary, according to King (1989).

In most of the wells and boreholes from the northern Central Graben in the North Sea to the Trøndelag Platform (Norwegian Sea continental shelf, Fig. 6 and Fig. 7) we have used the LAD of Diatom sp. 3 as a marker for top Upper Oligocene. In many of these wells, the LADs of *T. alsatica* and *G. soldanii girardana* occur at or close to the same level. In a few wells, where Diatom sp. 3 is scarce or missing, we have used the LADs of *T. alsatica* and/or *G. soldanii girardana* as markers for the top of the Upper Oligocene. The Late Oligocene age is also supported by Sr isotope analyses in many of these wells (usually based on analyses of tests of *T. alsatica* and/or *G. soldanii girardana*). In well 25/1-8 S, the LAD of *A. osnabrugensis* is used. In well 2/2-2, the Upper Oligocene is scarce in calcareous foraminifera, and in this well the top Oligocene is based on the LAD of *Ammodiscus* sp. B. In wells 34/7-2 and 35/11-14 S, Diatom sp. 3 does not reach to the top of the Upper Oligocene unit, but similar pyritised diatoms are common towards the top of the unit. Seismic correlation also indicates that these units are of Late Oligocene age. In the Hjøllund and Rødding boreholes from onshore southern Denmark (Map 1), the foraminiferal fauna has a more shallow-marine affinity than in most North Sea wells. In these boreholes the top of the Upper Oligocene is based on LAD of *Pararotalia canui,* which is also close to the Late Oligocene/Early Miocene boundary according to King (1989). Some of the index fossils used in wells from the North Sea area are absent in these boreholes. However, *T. alsatica* and Diatom sp. 3 are recorded somewhat lower in the unit in the Hjøllund borehole. In most of the wells the biostratigraphical correlations are supported by Sr isotope analyses. In well 7316/5-1, a section was given an unspecified Late Oligocene to Early Miocene age based mainly on palynological evidence (see Eidvin et al. 1998b). In well 29/3-1, we have not recorded any Upper Oligocene index fossils, but the general fossil assemblage and seismic correlation indicate a Late Oligocene age.

Onshore Denmark (Map 1), Upper Oligocene deposits of the Brejning Formation (Rasmussen et al. 2010) are recorded from several boreholes and outcrops. In some of these we have supported the palynological datings of Dybkjær & Piasecki (2008, 2010) with strontium isotope datings of mollusc tests (Eidvin et al. work in progress a and b, Link to Danish Sr isotope ages).

Lower Miocene sediments (Fig. 1 and Fig. 2) are recorded in wells 7316/5-1, 6510/2-1, 6609/11-1, 6507/12-1, 6407/9-5, 34/8-3A, 34/8-1, 30/5-2, 30/6-3, 25/1-8 S, 25/2-10 S, 25/10-2, 24/12-1, 16/1-4, 15/9-13, 15/12-3, 2/4-C-11 and in the Rødding borehole (Denmark). In the North Sea area, the LADs of the calcareous benthic foraminifera *Uvigerina tenuipustulata* and the planktonic foraminifera *Globorotalia zealandica* and *Globorotalia praescitula* are close to the Lower/Middle Miocene boundary (the top of Zone NSB 10 and Zone NSP 11, respectively, according to King 1983, 1989). In some wells, also the LADs of *Globigerina angustiumbilica* and/or *Globigerina ciperoensis* are close to the Lower/Middle Miocene boundary. As marker fossils for the lower part of the Lower Miocene, King (1983, 1989)

used the LAD of the calcareous benthic foraminifera *Plectofrondicularia seminuda* (Zone NSB 10), the LAD of the agglutinated foraminifera *Spirosigmoilinella* sp. A (synonymous with *Spirosigmoilinella compressa*, Zone NSA 10) and the LADs of the Diatom sp. 4 and sp. 5 (Zone NSP 10).

The registration of the lower part of Lower Miocene in the wells from the Trøndelag Platform (Norwegian Sea continental shelf) and the Tampen area (northern North Sea) is mainly based on the occurrence of Diatom sp. 4 and sp. 5. The registration of the top of the Lower Miocene is based on the LAD of *U. tenuipustulata* in almost all of the wells from the southern Viking Graben (Fig. 6 and Fig. 7). In addition, the LADs of *G. zealandica* and/or *G. praescitula* are also used in most of the wells. The exception is well 25/1-8 S and 25/2-10 S where the LADs of *G. angustiumbilica* and *G. ciperoensis* are used. The recording of the lower part of Lower Miocene in wells 25/10-2, 24/12-1, 15/9-13 and 15/12-3 is based on the occurrence of Diatom sp. 4 and *P. seminuda,* only *P. seminuda* in well 25/2-10S and Diatom sp. 4 and *S. compressa* in well 16/1-4. In nearly all the wells from the southern Viking Graben (Fig. 7) the biostratigraphical correlations are supported by a large number of Sr isotope analyses. The benthic index foraminifera *U. tenuipustulata* is missing in the shallow-marine deposits in the Molo Formation in well 6510/2-1 and in the Rødding borehole (Denmark). However, the shallow-marine dwelling *Asterigerina guerichi stashei* is recorded, and this species is known from the Lower Miocene and the lowermost Middle Miocene in the North Sea (King 1989). According to King (1983) and Eidvin & Rundberg (2007), the LADs of *A. guerichi stashei* and *U. tenuipustulata* are approximately coincident in some areas of the North Sea. The obtained ^{87}Sr/^{86}Sr ratios from a number of Sr isotope analyses support an Early Miocene age.

Onshore Denmark, Lower Miocene deposits of the Ribe Group are recorded from a number of boreholes and outcrops. In many of these we have supported the palynological datings of Dybkjær & Piasecki (2008, 2010) with strontium isotope datings of mollusc tests (Map 1 and Link to Danish Sr isotope ages).

Middle Miocene sediments (Fig. 1 and Fig. 2) are recorded in boreholes 6704/12-GB1 and 6403/5-GB1, wells 6507/12-1, 30/5-2, 30/6-3, 25/1-8 S, 25/2-10 S, 25/10-2, 24/12-1, 16/1-2, 16/1-4, 15/9-13, 15/12-3, 2/4-C-11 and in the Rødding borehole (Denmark). The planktonic fossils of genus *Bolboforma* are very reliable index fossils for the Middle Miocene. Spiegler & Müller (1992) described a *Bolboforma reticulata* Zone from deposits with an age slightly older than 14 to 12.3 Ma, a very short *Bolboforma danielsi* Zone from around 12.3 Ma and a *Bolboforma badenensis* Zone from 12.3-11.7 Ma from the North Atlantic. On the Vøring Plateau, *B. reticulata* and *B. badenensis* occur together in the same samples in a *B. badenensis – B. reticulata* Zone (Müller & Spiegler 1993). As marker fossils for the lower part of the Middle Miocene, King (1983, 1989) use the LAD of the calcareous benthic foraminifera *A. guerichi stashei* (Zone NSB 11) and the LADs of the planktonic foraminifera *Sphaeroidinellopsis disjuncta* and *Globigerinoides quadrilobatus triloba* (Zone NSP 12) for the North Sea area. In some areas in the North Sea, Zone NSB 11 is not easily recognisable, and may be very condensed or absent, and in these areas the LADs of *A. guerichi stashei* and *U. tenuipustulata* are approximately coincident (King 1983, Eidvin & Rundberg 2007). In such areas the planktonic foraminiferal Zone NSP 11 and NSP 12 also seem to merge (Eidvin & Rundberg 2007).

B. badenensis was used as index fossil for the upper part of the Middle Miocene (younger than 12.3 Ma) in borehole 6704/12-GB1. A *Bolboforma reticulata* assemblage and a *B. badenensis* or a *B. badenensis – B. reticulata* assemblage are recorded in borehole 6403/5-

GB1, wells 6507/12-1, 30/5-2, 30/6-3 (northern Viking Graben, Fig. 7) and all of the wells from the southern Viking Graben (except 25/1-8 S) and in the Rødding borehole onshore Denmark (Map 1). In well 2/4-C-11, neither *B. badenensis* nor *B. reticulata* is recorded, indicating that some of the Middle Miocene is missing. However, this is probably a local hiatus due to salt tectonics and polygonal faulting. Benthic and planktonic foraminiferal assemblages corresponding to Zone NSB 11 and Zone NSP 12 (King 1983, 1989), respectively, are present, indicating that at least the lower the part of the Middle Miocene is present. Neither *B. badenensis* nor *B. reticulata* is recorded in the shallow-marine sandy deposits in well 25/1-8 S, even though Sr analyses indicate an age of approximately 15 to 12 Ma for the sediments. However, the occurrence of *G. quadrilobatus triloba* indicates the presence of Zone NSP 12 (King 1989). Benthic and planktonic foraminiferal assemblages corresponding to Zone NSB 11 and Zone NSP 12 are also present in well 15/12-3, benthic foraminifera corresponding to Zone NSB 11 are present in well 25/10-2 and planktonic foraminifera corresponding to Zone NSP 12 are present in well 25/2-10 S. In boreholes 6704/12-GB1 and 6403/5-GB11 and wells 30/5-2, 30/6-3, 25/2-10 S, 15/12-3, 15/9-13 and 2/4-C-11 the Middle Miocene age is supported by Sr isotope analyses.

Upper Miocene deposits (Fig. 1 and Fig. 2) are recorded in boreholes ODP Site 987 (off Scoresby Sund, East Greenland, Map 2), 6704/12-GB1, 6403/5-GB1, wells 6305/5-1, 6609/5-1, 6508/5-1, 6609/11-1, 6507/12-1, 6407/9-5, 34/8-3A, 35/11-1, 35/11-14 S, 34/10-17, 30/5-2, 30/6-3, 25/10-2, 24/12-1, 16/1-2, 15/12-3, 2/4-C-11, and in the Rødding borehole (Denmark). First and foremost we have used several planktonic fossils as index fossils for the Upper Miocene. For the lowermost part of the Upper Miocene we have used *Bolboforma fragori* and *Bolboforma subfragori*. A *B. fragori/B. subfragori* Zone is described from deposits with an age of 11.7-10.3 Ma from the North Atlantic and the Vøring Plateau (Spiegler & Müller 1992, Müller & Spiegler 1993). According to Berggren et al. (1995), the Middle/Late Miocene boundary is at 11.2 Ma, consequently the oldest part of this unit is within the Middle Miocene. *Bolboforma metzmacheri* is also used as an index fossil for the lower part of Upper Miocene. A *B. metzmacheri* Zone is recorded from sediments with an age of 10.0-8.7 Ma from the North Atlantic and the Vøring Plateau (Spiegler & Müller 1992, Müller & Spiegler 1993). We have also used the LAD of *Neogloboquadrina atlantica* (dextral). Spiegler & Jansen (1989) described a lower *N. atlantica* (dextral) Zone from Upper Miocene sediments on the Vøring Plateau, and Weaver (1987) and Weaver & Clement (1987) recorded a *Neogloboquadrina atlantica* (dextral)/*Neogloboquadrina acostaensis* Zone from Upper Miocene sediments in the North Atlantic. However, Spiegler & Jansen (1989) also described an upper *N. atlantica* (dextral) Zone from the Upper Pliocene and, consequently, caved specimens of *N. atlantica* (dextral) can be recorded in the Lower Pliocene and Upper Miocene.

The calcareous benthic foraminifera *Globocassidulina subglobosa, Ehrenberina variabilis, Sphaeroidina bulloides, Florilus boueanus, Eponides pygmeus, Cibicides telegdi* and *Martinottiella communis* (agglutinated) are common in Upper Miocene and Lower Pliocene deposits in the North Sea, on the Norwegian Sea continental shelf and in the Netherlands. However, these species also occur, though less numerous, in the lower Neogene and upper Paleogene, and *E. pygmeus* and probably *C. telegdi* also in the Upper Pliocene (see below, Doppert 1980, King 1983 and 1989, Skarbø & Verdenius 1986, Stratlab 1988, Gradstein & Bäckström 1996, Eidvin & Rundberg 2007, Eidvin et al. 2007).

Either a *B. fragori - B. subfragori* assemblage, a *B. fragori* assemblage or a *B. subfragori* assemblage is recorded in the lower part of Upper Miocene in borehole 6704/12-GB1, wells

6607/5-1, 6609/5-1, 6508/5-1, 6609/11-1, 6507/12-1, 34/8-3A, 35/11-1, 30/6-3, 25/10-2, 24/12-1 and 2/4-C-11. A *B. metzmacheri* assemblage is recorded in wells 6607/5-1, 6609/5-1, 6508/5-1, 6407/9-5, 30/5-2, 25/10-2, 2/4-C-11 and Rødding borehole onshore Denmark. In borehole 6403/5-GB1 we have recorded a *Bolboforma pseudohystrix - Bolboforma compressibadenensis* assemblage and a *Bolboforma clodiusi* assemblage and these forms are known from, respectively, Middle to Upper Miocene sediments and Upper Miocene deposits on the Vøring Plateau and in the North Atlantic. In well 6507/12-1 and the Rødding borehole we have described a *Bolboforma laevis* assemblage, and this species is known from the Upper Miocene in the same areas (Qvale & Spiegler 1989, Spiegler & Müller 1992, Müller & Spiegler 1993). A *N. atlantica* (dextral) assemblage is recorded in wells 6507/12-1, 34/10-17, 25/10-2, 24/12-1, 16/1-2, 15/12-3, 2/4-C-11, and a *N. atlantica* (dextral)- *N. acostaensis* assemblage in well 15/12-3. A large number of Sr isotope analyses based on calcareous foraminifera, *Bolboforma* and mollusc fragments support the biostratigraphical correlations.

The uppermost part of the Upper Miocene in well 6508/5-1 is defined on basis of the common occurrence of the calcareous benthic foraminifera *Uvigerina venusta saxonica* and Sr isotope analyses of tests of this species.

In borehole ODP Site 987 off Scoresby Sund (East Greenland, Map 2), thorough magneto-stratigraphic investigations of continuous cores have resulted in a very good stratigraphic resolution (Channell et al. 1999). The magneto-stratigraphic data give an age of approximately 7.43 Ma to the base of the borehole. The Upper Miocene section is nearly barren of planktonic foraminifera, but contains a sparse but continuous calcareous benthic foraminiferal fauna which we denoted as the *Globocassidulina subglobosa - Ehrenbergina variabilis - Cibicides dutemplei* assemblage. The assemblage is very similar to calcareous benthic foraminiferal assemblages which we have recorded in the North Sea (e.g. in the Utsira Formation) and on the Norwegian Sea continental shelf (e.g. in the Kai Formation). Unfortunately, the samples do not contain sufficient numbers of calcareous index fossils to give reliable Sr isotope ages. The Upper Miocene unit in well 35/11-14 S (coarse sand) is barren of microfossils. However, mollusc fragments were recorded at four levels, and the nine Sr isotope analyses all gave Late Miocene ages.

Sediments of a general **Late Miocene-Early Pliocene** age and **Early Pliocene** age (Fig. 1 and Fig. 2) are recorded at ODP Site 987 (off Scoresby Sund, East Greenland) and in wells 6609/5-1, 6508/5-1, 6609/11-1, 6507/12-1, 6407/9-2, 6407/9-1, 6407/9-5, 34/2-4, 34/4-6, 34/4-7, 34/7-1, 34/8-3A, 34/8-1, 34/7-2, 35/11-1, 30/6-3, 25/2-10 S, 25/10-2, 24/12-1, 16/1-2, 16/1-4, 15/9-A-23, 15/12-3 and 2/4-C-11. An exact definition of the Lower Pliocene is usually difficult in the areas we have investigated, since there are no planktonic or benthic foraminifera which have a range limited to the Lower Pliocene. The use of Sr isotope stratigraphy is also problematic for the interval 4.5-2.5 Ma. The Sr isotope seawater curves of Hodell et al. (1991), Farrell et al. (1995) and Howarth & McArthur (1997) are relatively flat in this interval due to small variations in the Sr composition. The LAD of *N. atlantica* (dextral) indicates the top of the Upper Miocene, but this species is sometimes absent due to environmental factors, and in several wells there are no Lower Pliocene deposits overlying the Upper Miocene. The benthic calcareous foraminiferid *Monspeliensina pseudotepida* is an easily recognisable and reliable index fossil for the Early Pliocene and the early Late Pliocene (before the start of extensive glaciations), but this species is a shallow-marine form and consequently has a limited geographic range (King 1983, 1989). When *M. pseudotepida* occurs together with some of the calcareous benthic foraminifera *G. subglobosa, E. variabilis, S. bulloides, F. boueanus, E. pygmeus* and *C. telegdi,* which are typical for both

Upper Miocene and Lower Pliocene deposits, a Late Pliocene age is unlikely. However, in the North Sea, tests of *E. pygmeus* and *C. telegdi* are also recorded in basal Upper Pliocene deposits (Stratlab 1988, Eidvin & Rundberg 2007). Micropalaeontologists working with deposits from the Norwegian shelf have discussed if the occurrences in the Upper Pliocene represent *in situ* or reworked tests. The tests are very small and are probably easily re-worked. Their small sizes had made it difficult to collect enough tests for Sr analyses which could have solved the problem. Recently, we were able to collect enough tests for two analyses from one sediment sample, each based on more than 100 tests of *E. pygmeus*, in a cored section of the Upper Pliocene in well 34/8-A-33 H (Tampen area, northern North Sea). The grain sorting mechanism of turbidite currents has probably concentrated this species in this sample. The Sr analyses gave ages of 2.52 and 1.84 Ma and showed that at least *E. pygmeus* lived in the Late Pliocene (T. Eidvin, unpublished data). However, in areas on the Norwegian continental shelf where *E. pygmeus* occurs in both the Lower and the Upper Pliocene, there is a clear unconformity between the units visible both on seismic, wire line log data and lithology (see the chapter "The base of the Upper Pliocene and important Upper Pliocene foraminifera" below).

Neogloboquadrina atlantica (sinistral), *Globigerina bulloides* and *Globorotalia puncticulata* are the most common planktonic foraminifera in Lower Pliocene deposits. *N. atlantica* (sinistral) and *G. bulloides* occur through the Upper Miocene and Lower Pliocene and into the Upper Pliocene, and *G. puncticulata* occurs through the Lower Pliocene and into the Upper Pliocene (Weaver 1987, Weaver & Clement 1987, Spiegler & Jansen 1989). However, according to Eidvin & Rundberg (2007) *G. puncticulata* seems to disappear from the southern Viking Graben area close to the Early/Late Pliocene boundary. This observation is based on co-occurrence with the calcareous benthic foraminifera listed above and on Sr isotope analyses.

A general Late Miocene-Early Pliocene age is based on the occurrence of an *E. variabilis – G. subglobosa* assemblage and *C. telegdi – E. pygmeus assemblage* in well 6607/5-1, a *G. subglobosa* assemblage in well 6609/5-1, an *E. pygmeus - C. telegdi* assemblage and *E. pygmeus* assemblage in well 6508/5-1, an *E. pygmeus - G. subglobosa* assemblage and *C. telegdi* assemblage in well 6609/11-1, an *E. pygmeus - C. telegdi* assemblage and *E. pygmeus* asseblage in well 6507/12-1, a dinoflagellate *Achomosphaera* sp. 1 Zone in well 6407/9-1, an *E. variabilis* assemblage in wells 34/2-4, 34/4-7, 34/8-3A and 34/8-1, the upper part of a *S. bulloides* assemblage in well 35/11-1 and a *F. boueanus* assemblage in well 30/6-3. In wells 34/2-4, 34/4-6, 34/4-7, 34/7-2 and 34/8-1, Sr isotope analyses based on tests of some of these foraminifera gave ages of about 5 Ma and an indication of ages near the Late Miocene/Early Pliocene boundary (5.32 Ma).

An Early Pliocene age is based on the occurrence of a *Monspeliensina pseudotepida* assemblage capped by an *E. pygmeus* assemblage in wells 6407/9-2 and 6407/9-5, a dinoflagellate *Reticulatosphaera actinocoronata* Zone and an *E. pygmeus - S. bulloides* assemblage in well 6407/9-1, the upper part of a benthic *U. venusta saxonica* assemblage and *G. subglobosa* assemblage and a planktonic *G. puncticulata* assemblage in well 25/10-2, a *F. boueanus - S. bulloides* assemblage, *E. pygmeus - C. telegdi* assemblage and *G. puncticulata* assemblage in well 25/2-10 S and the upper part of an *U. venusta saxonica* assemblage, *M. pseudotepida* assemblage and *G. puncticulata* assemblage in wells 24/12-1, 16/1-2, 15/12-3, an *U. venusta saxonica* assemblage and *G. puncticulata* assemblage in wells 16/1-4, 15/9-A-23 and 15/12-3 and the upper part of an *U. venusta saxonica* assemblage and lower part of a *Cibicides limbatosuturalis* assemblage in well 2/4-C-11. In some of these wells an Early Pliocene age is supported by Sr isotope analyses.

In borehole ODP Site 987, an Early Pliocene age is based on magneto-stratigraphy. The lower part of the Lower Pliocene is nearly barren of benthic calcareous and planktonic foraminifera. In the upper part we defined a benthic *Cassidulina teretis - Nonion affine - Elphidium excavatum* assemblage and a planktonic *N. atlantica* (sinistral) - *G. bulloides* assemblage. All these taxa are common throughout most of the upper Neogene on the Norwegian continental shelf. It is noteworthy that the FAD of *Cibicides grossus* is very close to the Early/Late Pliocene boundary.

The base of the Upper Pliocene and important Upper Pliocene foraminifera

Seismic profiles of the Upper Pliocene show that these sediments prograded from the east (Scandes mountains) with distinct, shallow-angled clinoforms forming several hundred metre -thick accumulations (up to 3000 m thick in the Bjørnøya fan (Eidvin et al. 1993, Faleide et al. 1996, Map 2). Regional seismic mapping indicates that the Upper Pliocene changes character towards the north. North of approximately 58ºN, the succession is thicker and exhibits a more distinct progradation from land with a depocentre developed closer to the Norwegian mainland (Eidvin et al. 1998a and 2000). It has also been noted that in the western part of the Viking Graben, Late Pliocene progradation occurred from the Shetland Platform, so that parts of the lowermost sandy Upper Pliocene section in this area may be derived from the west.

The base of the Upper Pliocene succession usually coincides with a distinct seismic reflector. In the wells we have investigated in the Tampen area in the northern North Sea, on the Norwegian Sea continental shelf and in the western Barents Sea we have recorded ice-rafted pebbles of crystalline rocks down to the base of the Upper Pliocene. Sidewall core samples in wells 34/4-7 and 34/7-1 (Tampen area, Eidvin & Rundberg 2001, Ottesen et al. 2009), 34/7-12 (Tampen area, Eidvin 2009), 6610/7-2 (Nordland Ridge, Eidvin et al. 1998a, Ottesen et al. 2009) and 7316/5-1 (western Barents Sea, Eidvin et al. 1998b) verify that the ice-rafted pebbles are *in situ*. Conventional cores taken from the base of the Upper Pliocene unit in wells 34/8-9 S and 34/8-A-1 H (Tampen area) contain gravity flow deposits with a glacio-marine imprint (Eidvin et al. 1998a, Ottesen et al. in 2009). Since the large input of ice-rafted material in the Norwegian Sea did not started before about 2.75 Ma (recorded from ODP boreholes by Frondval & Jansen 1996), it seems that most of the lower part of the Upper Pliocene is missing in these areas (e.g. deposits with an age of about 3.5-2.75 Ma). However, planktonic foraminiferal correlations show that the base of the succession is older than 2.4 Ma (Eidvin et al. 2000, Ottesen et al. 2009). We suggest that at about 2.75 Ma, expanding glaciers started loading large volumes of material off the coastal areas which probably triggered the extensive submarine mass flowing and erosion.

In the wells we have investigated from the southern part of the Viking Graben and northern part of Central Graben (Fig. 7), the Upper Pliocene is more fine grained and contains fewer ice-rafted pebbles. In the Viking Graben the lower part of the Upper Pliocene is very condensed. In well 15/9-A-11 in the Sleipner Field (southern Viking Graben), a short conventional core was obtained from the base of the Upper Pliocene at about 20-25 m above the Lower Pliocene part of the Utsira Formation (Head et al. 2004). The core was dated to 2.4-1.9 Ma, but contained no ice-rafted pebbles. The seismic data show that the uppermost sandy units of the Utsira Formation interfinger with the lowermost units of the mudstone drape. This indicates that the Utsira sand and the mudstone drape formed a depositional continuum in this area (Chadwick et al. 2004, Head et al. 2004). However, a small hiatus may be present locally.

Of the wells that we have studied, the foraminiferal correlations show that it is only in well 2/4-C-11 from the northern Central Graben (Fig. 7) that the lower part of the Upper Pliocene is well developed (see also King 1989 and Eidvin et al. 1999). According to the new time scale of the International Commission on Stratigraphy (ICS 2013), where the base Pleistocene is moved back in time to 2.588 Ma, it is just in this area that Upper Pliocene deposits are present. According to that time scale, Pleistocene sediments lie unconformably on Lower Pliocene or older deposits in the other investigated areas of the Norwegian continental shelf.

In wells and seismic data it is commonly observed that the base of the Upper Pliocene represents an erosional surface. Below the western Barents Sea wedge, such erosion is evident in several wells including 7117/9-1, 7117/9-2 and 7316/5-1. In the northernmost North Sea, an irregular erosional surface can be mapped in the Viking Graben. The surface cuts into the pre-existing mud diapirs and has probably locally removed the Miocene section.

With the exception of *C. grossus* and *Elphidiella hannai*, all the *in situ* benthic foraminifera recorded in the Upper Pliocene units are extant. According to King (1989) *C. grossus* is recorded in the northern North Sea in Upper Pliocene to Lower Pleistocene (based on the time scale of Berggren et al. 1995). In the southern parts of the North Sea it becomes extinct somewhat earlier, close to the Pliocene/Pleistocene boundary. The FAD of *C. grossus*, in the southern parts of the North Sea, is observed somewhat above the Lower/Upper Pliocene boundary. King (1989) established the time for the LAD of *C. grossus* in the northern North Sea by registering its LAD above the FAD of *Neogloboquadrina pachyderma* (sinistral, encrusted). A similar range is described for *E. hannai*. However, according to Skarbø & Verdenius (1986) and King (1989), *E. hannai* inhabited shallow water, whereas *C. grossus* was a deep- to shallow-water form. The FAD of *N. pachyderma* (sinistral, encrusted) at about 1.8 Ma (Spiegler & Jansen 1989) is a good marker for top Upper Pliocene in cored ODP/DSDP boreholes on the Vøring Plateau, but this biostratigraphic event is difficult to detect in drill cuttings in wells on the continental shelf due to caving.

Spiegler & Jansen (1989) also described a *N. atlantica* (sinistral) Zone from the Vøring Plateau (Norwegian Sea) from Upper Miocene to Upper Pliocene deposits. The LAD of *N. atlantica* (sinistral) in that area is approximately 2.4 Ma. A *G. bulloides* Zone is described from the North Atlantic (DSDP Leg 94) in Pliocene sediments as young as 2.2 Ma (Weaver & Clement 1986). On the Vøring Plateau *G. bulloides* is common in Pliocene deposits older than 2.4 Ma (Spiegler & Jansen 1989). *G. bulloides* is also common in the warmest interglacials of the last 0.5 Ma in the North Atlantic (Kellogg 1977). An upper *N. atlantica* (dextral) Zone is described from the Vøring Plateau in Upper Pliocene deposits, and is dated to 2.4-1.9 Ma (Spiegler & Jansen 1989). A latest Pliocene *Neogloboquadrina pachyderma* (dextral) Zone is described by King (1989) for the North Sea, by Weaver (1987) and Weaver & Clement (1986) from the North Atlantic and by Spiegler & Jansen (1989) from the Vøring Plateau. On the Vøring Plateau the zone is dated to 1.9-1.8 Ma. Several of these biostratigraphical events are also recorded in the Upper Pliocene units in the wells that we have studied on the continental shelf.

Regional synthesis

Introduction
Within the study area, three main depocentres have been identified where sandy sediments accumulated throughout the Oligocene to Early Pliocene period. The depocentre in the

Norwegian-Danish Basin and Jutland received sediments from the southern Scandes mountains, with a general progradation from north to south during the studied period. The depocentre in the basinal areas of the UK and Norwegian sectors of the North Sea north of 58°N received sediments from the Scotland-Shetland area. Because of the sedimentary infilling there was a gradual shallowing of the northern North Sea basin in the Oligocene and Miocene. A smaller depocentre is identified offshore northern Nordland between Ranafjorden (approximately 66°N) and Vesterålen (approximately 68°N, Map 1), where the northern Scandes mountains were the source of the Oligocene to Early Pliocene sediments. In other local depocentres along the west coast of Norway, sandy sedimentation occurred during only parts of the period. Shifts in local depocentres are indicative of changes in the paleogeography.

In the Barents Sea and south to approximately 68°N, the Oligocene to Early Pliocene section is eroded except for distal fine-grained and biogenic deposits along the western margin and on the oceanic crust. This margin was undergoing deformation in a strike-slip regime until the Eocene-Oligocene transition. The Early Oligocene dated sediments in the Vestbakken Volcanic Province and the Forlandssundet basin represent the termination of this strike-slip regime.

The change in the plate tectonic regime at the Eocene-Oligocene transition affected mainly the northern part of the study area, and was followed by a quiet tectonic period until the Mid Miocene, when large compressional dome and basin structures were formed in the Norwegian Sea and a large delta developed in the Viking Graben (Frigg area). The Mid Miocene event is correlated with a relative fall in sea level in the main depocentres in the North Sea, and uplift of the North and South Scandes domes. In the Jutland area, the Sorgenfrei-Tornquist Zone was reactivated in the Early Miocene, possibly causing a shift in the deltaic progradation towards the east. A Late Pliocene relative rise in sea level resulted in low sedimentation rates in the main depositional areas until the onset of glaciations at about 2.7 Ma, when the Scandes mountains were strongly eroded and became a major source of sediments for the Norwegian shelf, whilst the Frigg delta prograded farther to the northwest.

Lower Oligocene

Forlandsundet, Svalbard
The Forlandssundet basin is a partly fault-bounded structure trending north-south along the west coast of Spitsbergen. The western border fault of the Forlandsundet basin is exposed on Prins Karls Forland (Map 2), and consists of graben-parallel normal faults stepping down into the interior of the basin. Adjacent Cenozoic fanglomerates locally rest unconformably on basement rocks. The syntectonic Cenozoic fill is deformed by both extensional and oblique-contractional structures. The eastern fault margin of the Forlandsundet graben is intermittently exposed at the base of Sarstangen and Kaffiøyra. This boundary lies along the northern strike continuation of the Svartfjella-Eidembukta-Daumannsodden Lineament (SEDL), a major fault zone of Carboniferous rocks intensely deformed during a complex history of Cenozoic motion (Gabrielsen et al. 1992, Kleinsphen & Teyssier 1992, Lepvrier 1992, Bergh et al. 1999).

According to Bergh et al. (1999), there are two Cenozoic units of very different character and likely different age exposed on Sarstangen at Forlandsundet; an eastern unit exposed mainly along the interior moraine margin, and a western unit that is exposed mainly along the southern shore of Sarstangen. The differences in coloration, lithification, grain size and

proximity to source, and deformation history are consistent with two units of different age. Large clasts of the eastern unit are found in the western succession, clearly indicating that the western unit is younger. A greater degree of lithification and structural complexity of the eastern complex is also consistent with it being the older one. Slip-linear data and other structural observations are consistent with a history beginning with sinistral, then dextral motions along the easternmost border faults, followed by orogen-perpendicular extension. Such a history likely records the change from transpressional to transtensional plate motions between northeast Greenland and Svalbard (Bergh et al., 1999).

This age relationship, however, is opposite to that interpreted by Gabrielsen et al. (1992). Considering the geological setting and the plate history and limited paleontological data, Bergh et al. (1999) concluded that the older unit might well be Eocene and the younger Oligocene.

An exploration well drilled at Sarstangen in 1974 penetrated about 1000 m of Cenozoic rocks and terminated in crystalline basement (total length 1135.5 m, Harland 1997, Skotte 2007, Brugmans 2008). Reports and samples from this drillhole were not available for this study. The thickness of the Cenozoic section recorded implies that the lowermost Cenozoic rocks in the basin may not be represented by the outcrop samples.

Feyling-Hanssen & Ulleberg (1984) described two outcrops of Oligocene deposits in Balanusviken, Sarsbukta, on the east side of Forlandsundet (western sequence according to Berg et al. 1999). At Balanuspynten, in the southern end of Balanusviken, they described an 8 m-thick section of micaceous claystone. At Konglomeratodden, in the northern end of Balanusviken, they recorded a 7 m-thick section with beds of varying lithology including different kinds of conglomerates, sandstone and sandy clay. The micaceous clay was not found at Konglomeratodden (see figure 1 under Forlandsundet).

On the basis of benthic, calcareous, foraminiferal assemblages in nine samples, these authors divided the sections into two zones: the overlying *Asterigerina guerichi* Zone and the underlying *Bolivina* cf. *antiqua* Zone. Feyling-Hanssen & Ulleberg (1984) assigned a transitional Early to Late Oligocene age to this entire section, and indicated an age equivalent to Subzones NSB 7a to NSB 8a according to King (1989). However, Manum & Throndsen (1986) proposed an age not younger than Late Eocene for the Balanusviken (Forlandsundet) sections based on dinoflagellate cysts. Eidvin et al. (1998b) performed Sr isotope analyses on foraminiferal tests from four of these samples and new dinoflagellate cyst analyses in two samples. These gave ages close to and slightly younger than the Early/Late Oligocene boundary (based on the time scale of Berggren et al. 1995) for the western sequence. In this study, that result has now been revised to slightly older ages of latest Early Oligocene by use of the look-up table presented by Howard & McArthur (1997, see figure 2 under Forlandsundet). Eidvin et al. (1998b) concluded that most of the recorded dinoflagellates identified by Manum & Throndsen (1986) are older Paleogene forms reworked into Oligocene strata.

Vestbakken Volcanic Province, western Barents Sea
Well 7316/5-1 (Map 2, Profile 15 and Profile 15 Map) penetrates the western margin of a local fault bounded terrace which subsided in the Oligocene and Miocene due to movements on the Knølegga Fault zone which bounds the terrace to the east. A thick wedge of glacigenic sediments overlies the Oligocene-Miocene section with an erosional contact.

Based on analyses of benthic foraminifera, dinoflagellate cysts and Sr isotopes, a 108 m-thick unit of Lower Oligocene sediments and 22 m of Lower Oligocene to Lower Miocene deposits

were recorded in well 7316/5-1. The Lower Oligocene consists of silty clay. Upper Middle Eocene and Upper Eocene sediments are absent in the well. East of the well location, the hiatus is expressed as an angular unconformity truncating older Middle Eocene units (Fig. 1 and Profile 15). The unconformity was a result of uplift and rotation of the terrace due to movement along the boundary faults. The sediments in the drilled structure were consequently raised above the wave base, resulting in a period of mild erosion and non-deposition. This appears to have occurred in the period between 45 and 34 Ma, to some extent pre-dating, but also overlapping, the supposed initiation of the northwesterly direction of relative plate motion in the Norwegian – Greenland Sea (Anomaly 13 time, 37-36 Ma, Eidvin et al. 1998b). Regional mapping indicates that along the western Barents Sea margin, a seismic sequence boundary of approximately this age can be defined, where the overlying Lower Oligocene succession is onlapping the underlying, more strongly faulted and folded Eocene sequence. The Oligocene onlap was described by Ryseth et al. (2003) in well 7216/11-1S in the Sørvestsnaget Basin (Map 2). Movements of this age have also been recorded in the Vøring Basin (Brekke 2000), suggesting that the shift in direction of the plate motion was reflected in the sedimentary record over a large region.

Norwegian Sea and its continental shelf
Along the inner continental shelf of the Norwegian Sea north of 66°N, progradation of sandy coastal plains and deltas started in the Early Oligocene (Molo Formation, Map 1). This unit has been analysed in well 6610/3-1 and contains coarse, rust-stained sand with pebbles in the upper part and mica-rich, medium sand in the lower part (see also Profile P12 and Profile P13). Farther west, in the shelf areas, the Lower Oligocene sediments are generally thin. In places, the section is below seismic resolution, or is totally missing (Henriksen et al. 2005), such as in the wells 6508/5-1 and 6609/5-1 on the Nordland Ridge and well 6607/5-1 on the Utgard High (Fig. 6, Map 1, Fig. 1 and Fig. 2). The Lower Oligocene is present in the DSDP Site 336 and ODP Site 643 in the Vøring Basin (Talwani et al. 1976, Eldholm et al. 1989), in wells 6305/5-1 and 6404/11-1 in the Møre Basin, in well 6407/9-1, 6407/9-2, 6407/9-5, 6507/12-1 and 6609/11-1 on the Trøndelag Platform and in wells 6610/2-1 S on the Nordland Ridge (Fig. 6, Map 1). The top is eroded in wells 6407/9-1, 6407/9-2, 6407/9-5 (Draugen Field, Trøndelag Platform), 6610/2-1 S (Nordland Ridge) and 6404/11-1 (Storegga slide area, Møre Basin, Fig. 1, Fig. 2 and Fig. 6). These sections are overall fine-grained and are characterised by semi-transparent and parallel seismic facies patterns (Henriksen et al., 2005). In the outher part of the Vøring Plateau, the sediments were rearranged by countouritic currents (Laberg et al. 2005b). Biostratigraphical, lithological and seismic data suggest a quite deep-marine depositional environment dominated by hemipelagic sedimentation on the shelf areas and pelagic biogenic sedimentation in the Møre and Vøring basins. The base of the Lower Oligocene has been investigated only in well 6610/2-1 S, and lies unconformably on the Middle Eocene. The sandy, deltaic, Lower Oligocene section in well 6610/3-1 can be tied to its distal equivalent in 6610/2-1 S by 3D seismic data (Profile P13).

North Sea

In the Norwegian sector of the North Sea, the Lower Oligocene sediments that were derived from the Shetland Platform in the west are predominantly fine grained and located in a distal setting. Progradation from the Scandes mountains continued offshore West Norway, but sandy sediments have been recorded locally only in the northernmost part. The Early Oligocene marks the onset of large-scale progradation of sediments southwards from the Scandes into the Norwegian-Danish basin (Jarsve et al. work in progress).

Northern North Sea

Based on well log correlation, Rundberg & Eidvin (2005) presented an outline of the Lower Oligocene of the northern North Sea in their figure 7a (unit UH-1 and UH-2). However, our new investigation of wells 34/10-17, 35/3-1, 36/1-2 and 31/3-1 (Map 1, Profile 8 and Profile 9) shows that only unit UH-1 and the proximal, eastern part of unit UH-2 (recorded in well 36/1-2, Fig. 1, Fig. 2 and Profile 9) are of Early Oligocene age. The Lower Oligocene part of UH-2 in well 36/1-2 (Agat Discovery area) includes a very coarse sand. The lower half of the Lower Oligocene sandy section is rich in rounded, sub-rounded and sub-angular pebbles and mollusc fragments. There is a break below the Lower Oligocene in well 36/1-2. Gradstein et al. (1992) recorded a break between the Lower Oligocene and Middle Eocene in wells 34/8-1 (Tampen area) and 16/1-1 (southern Viking Graben).

Most parts of the Lower Oligocene sandy section in the Agat Discovery area were interpreted to be of turbiditic origin by Rundberg (1989), but the lower part probably also contains some debris flow and/or shallow-marine deposits (Profile 9). It is likely that the deposits are erosional products derived from the western part of the Fennoscandian Shield in the present - day Nordfjord area. Farther south towards the Troll Field area, a distinct wedge of organic-rich mudstones strikes parallel to the western coast of Norway (Map 1). This wedge has a slightly older Early Oligocene age than 36/1-2 (investigated in well 31/3-1, Fig. 1 and Profile 7). In seismic sections, the seismic unit UH-1 wedge appears to represent the last stage of regional progradation of Paleogene sediments from the Fennoscandian Shield. It is onlapped by a younger Oligocene sequence, and the whole section was slightly rotated during later tectonic events.

Central North Sea, Northern Central Graben

There is no well-defined seismic reflector and no obvious lithological change close to the Lower/Upper Oligocene boundary. The Oligocene in well 2/4-C-11 comprises mostly clay with some components of silt and sand. The Central Graben was located in a distal position relative to the Oligocene progradation from Scandinavia. According to Eidvin et al. (1995) the Lower Oligocene lies unconformably on the Lower Eocene.

Norwegian-Danish Basin

The Lower Oligocene of the Norwegian-Danish Basin was investigated in well 2/2-2 from the deep central part of the basin and in wells 11/10-1 and 9/12-1 from the marginal part (Map 1, Fig. 1, Profile 2, Jarsve et al. work in progress). The base of the Lower Oligocene was not studied in these wells, but was investigated in the well Nini-1 (Danish sector) by Sliwinska et al. (2010, Map 1 and Profile 2). In the marginal, northeastern part of the basin, the Lower Oligocene succession is locally very thick, approximately 800 m. The succession is dominated by fine-grained sediments of the Hordaland Group except for the uppermost part of well 11/10-1 which is quite sandy. This sandy section constitutes the lower part of the Vade Formation, and can be interpreted as the beginning of transport of coarser clastics into the Norwegian-Danish Basin. The main part of the sandy Vade Formation was deposited during the Late Oligocene (Fig. 1 and Jarsve et al. work in progress). This was also the case for the Oligocene sandy sections in the northern North Sea (off Nordfjord). Our data imply that the sediment progradation from Scandinavia was directed mainly to the west and northwest until the Early Oligocene and towards the south and southwest later in the Oligocene and Miocene (Map 1).

Upper Oligocene

Vestbakken Volcanic Province, western Barents Sea
In well 7316/5-1, a fine-grained section is given an unspecified Late Oligocene to Early Miocene age, but Upper Oligocene sediments have not been proved by biostratigraphy. There is no distinct hiatus or unconformity recorded locally on seismic data at this level. Seismic data show that the thickness increases towards Knølegga Fault, and it is suggested that the succession is eroded and/or condensed due to tectonic movements along the structure. It is likely that an expanded succession of Oligocene and Lower Miocene sediments was deposited and is now preserved in the basin between the drilled structure and the Knølegga Fault (Map 2, Profile 15, Profile 15 Map and Eidvin et al. 1998b). Expanded sections are also expected towards the oceanic crust in the west. At this time, sea-floor spreading activity was established to the west of the well area, promoting sedimentation in locally developed open marine basins formed between highs generated by the continuing structural readjustments to the new tectonic regime. A global eustatic lowering of sea level as a result of the initiation of the Antarctic glaciations (Vågnes et al. 1992, Zachos et al. 2001) may also have exerted an influence on the Oligocene successions, although it is not possible to quantify the relative magnitude of these events (Eidvin et al. 1998b).

Norwegian Sea and its continental shelf
Seismic data indicate that the progradation of the Molo Formation along the inner continental shelf of the Norwegian Sea (Map 1) continued in the Late Oligocene, but no well has so far been drilled in a position where Upper Oligocene sediments from the Molo Formation could be identified. Upper Oligocene sediments are recorded in thin shaly sections in distal positions in wells 6507/12-1 and 6609/11-1 (Fig. 1 and Fig. 2). In the Møre Basin the Upper Oligocene was investigated in well 6305/5-1, and the lower part of the Upper Oligocene in wells 6305/4-1and 6404/11-1 and the gravity core 49-23 (Fig. 6). In the Vøring Basin, the Upper Oligocene is present at DSDP Sites 336 and 338 and ODP Site 643 according to Talwani et al. (1976) and Eldholm et al. (1989). Biostratigraphical, lithological and seismic data of the Upper Oligocene successions suggest a continuation of the Early Oligocene setting with a fairly deep-marine depositional environment dominated by hemipelagic sedimentation on the central shelf areas and pelagic sedimentation (biogenic ooze) in the Møre and Vøring basins.

North Sea

In the Late Oligocene, there was a large input of sandy sediments from the Shetland Platform into the northern North Sea. Most sediments were laid down in the southern Tampen area (Map. 1). Farther south, Upper Oligocene sandy deposits are recorded below the Skade Formation in the Frigg Field area, i.e., within the area of the Hutton sand according to Gregersen & Johannessen (2007, Map 1). Sediment transport from the Scandes in this period was directed mainly towards the Norwegian-Danish Basin, where the sandy Vade Formation was deposited. The progradation of sediments towards the west ceased at the Early/Late Oligocene transition, except in the northernmost Nordfjord area (Map 1).

Northern North Sea
The western sands (quadrants 30, 34 and 25) shale out to the east and are sourced from the Shetland Platform (Profile P6 and Profile P7), while the eastern sands (blocks 35/3 and 36/1) appear to be sourced from the Nordfjord area, West Norway (Profile P9). In this study, the sandy section has been analysed in wells 34/10-17, 35/3-1, 36/1-2 and 25/1-8 S. Due to intense sand injections and mud diapirism, it is difficult to study the lithostratigraphy and

depositional environment of the western sands in seismic data. Mud diapirs in the Oligocene-Miocene section cover a large area in the Viking Graben (Løseth et al. 2003), and the distribution of massive diapirism seems to coincide with the central and outer parts of the Oligocene and Miocene sandy systems (NPD, 2011).

Several mechanisms have been proposed to explain the sand injection activity and diapirism (Løseth et al. 2003), but will not be discussed further here. However, some observations based on interpretation of regional 3D seismic data are of importance in understanding the distribution of the Oligocene and Miocene sediments. Our observations are compatible with the observations of Løseth et al. (2003).

Mud diapirs typically contain sand intrusions which can commonly be recognised in seismic data as V-shaped reflections ("V-brights", Løseth et al. 2003). Care must be taken in the biostratigraphic analysis to avoid misinterpretation of intrusive sands as *in situ*. Mud diapirism has taken place in different phases, which are interpreted in seismic data by correlation of the sediments between diapirs and sediments deformed by diapirism. Within the diapir area, there are local basins where a full Miocene section is preserved, implying that the deposition of Miocene sediments in the northern North Sea was partly controlled by a pre-existing topography created by diapirism. Later diapirism and erosion took place in the Miocene and Late Pliocene and will be discussed below.

Between 60º and 61ºN east of well 34/10-17, the top of the Upper Oligocene (unit UH-2 of Rundberg & Eidvin 2005) is defined by a moderate- to high-amplitude, semi-continuous seismic reflector in the eastern part of the basin (Map 1 and Profile 7). The top of the unit also corresponds to a diagenetic horizon characterised by the transition from opal-A to opal-CT-rich mudstones. This siliceous mudstone is thought to be present locally within the northern North Sea, particularly between 60º and 61ºN, according to Rundberg & Eidvin (2005). In the basin centre, the exact position of the top of the Oligocene is sometimes difficult to detect seismically since there is no depositional break between the uppermost Upper Oligocene (unit UH-3 of Rundberg & Eidvin 2005) and the Lower Miocene (unit UH-4 of Rundberg & Eidvin 2005).

Farther west, unit UH-2 is strongly disturbed by diapirism, and it is difficult to map the top. It is probably best defined at about 60º45'-61ºN, as illustrated in Profile 7. Along this profile, the seismic reflector defining the top of the high-density zone can probably be correlated to discontinuous, high-amplitude seismic events farther to the west. These events define the top of a thick sandy interval, which is penetrated in wells 34/10-17 and 34/10-23 (not analysed for this study). The sands make up a gross thickness of about 400 m in block 34/10 (Profile 7). In well 34/10-17, the fossil data confirm that the sands belong to the sequence and have not been injected. The Lower-Upper Oligocene sands are unnamed in the Norwegian sector of the northern North Sea (Fig. 3).

The thick sandy interval in block 34/10 shows that there must have been a significant input of sand from the Shetland Platform. Erosional products from the uplifted areas of the East Shetland Platform have probably been transported eastwards by river systems, with delta progradation and gravity flow transport towards the Statfjord Field-Tampen area and the Frigg area. In seismic sections, this sandy system is illustrated by wedging of the Oligocene strata, Profile 6 and Profile 7.

Sands continued to be derived from an easterly source (Nordfjord), during the Late Oligocene, in the Agat Discovery area (Map 1 and Profile 9). Most of these sands are contemporaneous with sands of the Statfjord Field and Frigg Field areas (Fig. 1).

In wells in the northern Tampen area the Upper Oligocene consists of silty mudstones. In the well 25/10-2, from the southern Viking Graben, the Upper Oligocene is dominated by clay, but thin sand beds are quite common throughout. In the other wells from the southern Viking Graben (Map 1), the unit contains mainly fine-grained material (see also Eidvin & Rundberg 2001 and 2007, Rundberg & Eidvin 2005).

Northern Central Graben

In the northern Central Graben there is no well-defined seismic reflector close to the Oligocene-Miocene boundary; this is similar to the situation in the southern Viking Graben. However, a number of seismic reflectors are visible on seismic profiles and if guided by a tie from the Danish sector and key wells it is possible to map the boundary. In well 2/4-C-11 the Upper Oligocene comprises mostly clay with intercalations of silt, sand and some limestone stringers (see also Eidvin et al. 1999 and 2000). These deposits were laid down in a deep-marine setting beyond the deltaic slope.

Norwegian-Danish Basin

Transport of coarser clastics from Fennoscandia into the Norwegian-Danish Basin continued in the early Late Oligocene (Vade Formation). In well 2/2-2 (Map 1, Profile P2, Jarsve et al. work in progress), in the deepest part of the basin, sand (glauconitic, biotitic and quartzose) is common but not dominant. The sands were probably transported by gravity flows. The sediments of the Vade Formation in well 11/10-1, from the marginal part of the basin, are dominated by quartzose sand. The sand is rich in mollusc fragments and was probably deposited in a shallow shelfal environment. It is coarsening upwards and the uppermost part is coarse. Corresponding sediments of the Hordaland Group in well 9/12-1, also from the marginal part of the basin, are rich in mollusc fragments and lignite (Map 1, Jarsve et al. work in progress), and this unit was also probably deposited in a shallow shelfal environment. Sand is not frequent in the lower, main part, but glauconitic sand is quite common in the upper part. The uppermost part of the Upper Oligocene has been reported from the well Nini-1 in the Danish sector by Sliwinska et al. (2010, Map 1 and Profile P2). In the central and eastern Norwegian-Danish Basin, mud characterises the Branden Formation which shows a coarsening-upward trend containing slightly more sand in the upper part. The formation was deposited in deep water in front of a southward prograding slope system. An unconformity separates the Branden Formation from the overlying, latest Late Oligocene, Brejning Formation (Rasmussen et al. 2010). The Brejning Formation is composed of glauconitic clay in the lower part, but is more sand-rich in the upper part. Locally, the Brejning Formation displays thin, commonly bioturbated, sand layers. Cross-bedding has been recognised in this formation in the easternmost part of Denmark. The Brejning Formation was deposited mainly in a water depth of more than 200 m, but the cross-bedded sand and microfauna indicate shallow-water conditions locally on the Ringkøbing-Fyn High at the end of the Oligocene.

Lower Miocene

Barents Sea

The Miocene section of the Barents Sea shelf has been preserved only along the western margin in local basins formed by tectonism along the Senja Fracture Zone. Possible Lower Miocene has only been recorded in well 7316/5-1 (Map 2), which penetrated an Oligocene – Lower Miocene section below the base Upper Pliocene erosional surface. In well 7216/11-1S, there is a hiatus below the Mid Miocene unconformity (Ryseth et al. 2003, Map 2). In the

Senja Ridge, in wells 7117/9-1 and 7117/9-2, the Upper Pliocene sediments rest on Eocene sediments with an erosional boundary (see also the discussion section).

Norwegian Sea and its continental shelf
The progradation of the Molo Formation along the inner continental shelf of the Norwegian Sea continued into the Early Miocene, and extended farther south than in the Oligocene. The formation is investigated in well 6510/2-1 (Map 1) and consists of glauconitic (dominant) and quartzose sand of late Burdigalian age. It is not clear if there is a hiatus or continuous deposition between the Lower Oligocene and Lower Miocene part of the formation (Fig. 5). In the wells 6407/9-5 and 6407/9-3 (not investigated) in the Draugen Field (Map 1) there is an up to 22 m-thick, fine-grained, hemipelagic section of Lower Miocene sediments. It is wedge shaped and overlies a well defined erosional unconformity (see figure 4 in Eidvin et al. 2007). The stratigraphic gap in well 6407/9-5 ranges from the Lower Oligocene to the Lower Miocene below the wedge, and from the Lower to the Upper Miocene above (Fig. 1). About 50 km northeast of the Draugen Field another wedge with the same stratigraphic position and appearance has been observed. It has not been investigated in any well, but from its geometry it might be considered to be similar to the one in the Draugen Field (see figure 5 in Eidvin et al. 2007). Stratigraphically and agewise, the wedge belongs to the Brygge Formation. The unconformity below the wedge seems to represent more active erosion than at the time of the Mid Miocene unconformity on top. There are few signs of erosional products related to any of the two hiati, which indicates that the Mid Miocene unconformity in this area is more related to non-deposition rather than representing a major episode of erosion (Bugge et al. 2004, Eidvin et al. 2007). Lower Miocene pelagic sediments are also present at several DSDP and ODP sites in the Vøring and Møre basins (Talwani et al. 1976, Eldholm et al. 1989).

North Sea

In the North Sea, the Oligocene – Lower Miocene boundary is marked by major shifts in sedimentation, with onset of sand deposition in the Viking Graben and Jutland (Map 1).

Northern North Sea
The Lower Miocene (unit UH-4 of Rundberg & Eidvin 2005) comprises the topmost part of the Hordaland Group. In the southern Viking Graben, it conformably overlies Oligocene strata. It is overlain by Middle Miocene sediments in the centre of the basin and Pliocene sediments at the margins (Profile 4). Just south of 61ºN and northwards, the Lower Miocene unit is only present in the central basin and absent at the margins to the west and east (Fig. 10). It may be present locally in depressions between diapirs. On seismic sections, the top of the unit can be defined by erosional truncation, as illustrated schematically in Profile 4. In the northernmost North Sea, between 61º30' and 62ºN, the unit has been completely eroded (Rundberg & Eidvin 2005).

In the Tampen area the Lower Miocene strata comprise mud-prone lithologies. In large parts of the Viking Graben, a sandy section, sourced from the East Shetland Platform, makes up a great proportion of the Lower Miocene unit. These sands are referred to as the Skade Formation and reach a gross thickness of up to 300 m (well 16/1-4). The areal extent and thickness of the sands are shown in Fig. 10. They comprise a succession of amalgamated sands alternating with thinner mudstones.

The deposition of the Skade Formation represents a southern shift in coarse clastic influx to the basin from the East Shetland Platform, relative to Oligocene time (Map 1). In most parts, the deposits are turbiditic in origin and were probably deposited in quite deep parts of the shelf. The Skade sections in wells 25/2-10 S and 25/1-8 S contain common mollusc fragments and lignite, and have probably been deposited in shallower water close to, or as parts of, a delta. According to the mapping of Gregersen & Johannessen (2007), these wells are situated in the distal part of the Hutton sand area (Fig. 10). Hutton sand is an informal term used in the UK sector by several oil companies to describe all sands above the Lower Eocene Balder Formation in the Northern North Sea (British Geological Survey 2000). As seen in Fig. 10, the Hutton sand as defined by Gregersen & Johannessen (2007) extends into the Norwegian sector and continues into the Skade Formation, However, we recommend using the established Norwegian stratigraphy in Norwegian waters.

The Skade sands pinch out to the east. According to our investigations, the sands were deposited between approximately 24 and 15.5 Ma and they represent a huge sand volume comparable to the Utsira Formation. It has been suggested that they are a result of a new tectonic uplift event affecting the East Shetland Platform, possibly associated with a renewed compressional tectonic phase along the northwest European margin (Lundin & Dore 2002, Boldreel & Andersen 1994).

Northern Central Graben
In well 2/4-C-11 the Lower Miocene consists mainly of clay, but small components of silt and fine-grained sand are also recorded (Eidvin et al. 1999 and 2000). The sand-rich units can be correlated to the Miocene delta of the Norwegian-Danish Basin, and the best developed sand unit correlates with sequence D of Rasmussen (2004).

Norwegian–Danish Basin
In the Norwegian-Danish Basin, Lower Miocene sediments rest unconformably on Oligocene deposits. In Jutland, they are characterised by coarse-grained, dominantly sand-rich, deltaic deposits (Profile P3, Larsen & Dinesen 1959, Friis et al. 1998, Hansen & Rasmussen 2008, Rasmussen & Dybkjær 2005, Rasmussen et al. 2010, Map 1 and Link to Danish Miocene Sr isotope ages). The delta was sourced from the southern Scandes in Norway and central Sweden and prograded towards the south and southwest. The deltaic succession of the Ribe Group is composed of three discrete units referred to sequences B, C and D of Rasmussen (2004, Profile P1). The delta succession is about 200 m thick with a gross thickness of sand up to 150 m. The abrupt incursion of sand in the southern part of the Norwegian-Danish Basin is interpreted to be the result of an Early Miocene inversion of the basin and coincident uplift of the source area. Towards the Central Graben area the deltaic unit is wedging out and is dominated there by clay-rich deposits (Profile P3).

Middle Miocene

Distribution of sediments and Mid Miocene tectonism
The Middle Miocene is represented by a hiatus in many of the studied wells, and the distribution of sediments from this period is strongly related to effects of tectonic movements. The large compressional domes in the Norwegian Sea had their main phase of growth in the Middle Miocene, and there is seismic evidence indicating that other major structures such as the Nordland Ridge (Løseth & Henriksen 2005) and the Lofoten-Vesterålen area (Rise et al. in press) were reactivated at this time. Along the western Barents Sea margin well data are sparse, but there are indications of a hiatus in well 7216/11-1S (Map 2, see discussion

section). In the North Sea, seismic data indicate uplift and erosion of the area bounding the west coast of Norway, and reactivation of major faults. In the Central Graben and Norwegian-Danish Basin, the Middle Miocene is characterised by deposition of hemipelagic clays and formation of glauconite. Reactivation of some major structural elements and salt structures occurred and minor unconformities are present.

Norwegian Sea and its continental shelf
After the Middle Miocene tectonism, fine-grained pelagic and hemipelagic sediments of the Kai Formation were deposited on the outer and middle parts of the margin. So far, no wells have sampled Middle Miocene sediments from the Molo Formation, and consequently it is not clear if the Middle Miocene is represented by a hiatus or if the progradation was continuous into the Late Miocene (Map 1, Fig. 5).

The upper part of the Middle Miocene is recorded only in well 6507/12-1 on the Trøndelag Platform, borehole 6403/5-GB1 in the Møre Basin and borehole 6704/12-GB1 on the Gjallar Ridge (Map. 1, Fig. 1 and Fig. 2). Middle Miocene sediments are absent in well 6305/5-1 on the compressional, Ormen Lange, elongated dome structure. Seismic data reveal the presence of an angular unconformity below the Upper Miocene sediments on the top of the dome.

Northern North Sea
Middle Miocene sediments in the northern North Sea represent the basal part of the Nordland Group and occur as an infilling unit within the Viking Graben. South of the Viking Graben, these are mainly fine-grained sediments. Middle Miocene units in the wells 15/9-13, 25/1-8 S, 25/2-10 S (southern Viking Graben) and 30/5-2 and 30/6-3 in the northern Viking Graben are sandy and microfossils indicate an inner to middle shelf environment (Fig. 12). The Middle Miocene section in well 25/1-8 S was probably deposited at a very shallow-marine site. In the wells, it may be difficult to distinguish these sands from sands of Utsira above and Skade below, and they are believed to act as a single aquifer system (NPD 2011). Seismic data show that in the Middle Miocene, a well defined delta system was developed in the Frigg area and prograded rapidly to the east. Well 25/1-8 S penetrated the sandy deposits in the delta clinoforms (Fig. 12, Profile P6). A thick depocentre of Middle Miocene sands was developed east and north of the Frigg area in a more distal shelf environment (sands penetrated in wells 30/5-2 and 30/6-3, Fig. 12). The Middle Miocene sandy sections appear to form mappable units which are clearly younger than the Skade Formation and older than the Utsira Formation in the Viking Graben, and we introduce the name Eir Formation, after an Æsir ("god") in Norse mythology, for these units in the Norwegian sector as a new formation in the Nordland Group (see chapter "Suggestions to an update of the lithostratigraphic nomenclature for the post-Eocene succession").

In the eastern part of the northern North Sea, the Middle Miocene sediments wedge out into an angular unconformity. In the northernmost North Sea, Middle Miocene sediments are mainly absent, but may be locally present in the depressions between diapiric structures penetrated by injectites. In this northern area, an erosional surface of probable Mid Miocene age was described by Løseth & Henriksen 2005. The surface is overlain by a condensed glauconitic bed deposited close to the Late Miocene/Early Pliocene boundary (Profile P8).

Northern Central Graben
The Middle Miocene in the Central Graben consists of fine-grained deposits. A local hiatus is present in the Middle Miocene in well 2/4-C-11 (Ekofisk Field, Map 1 and Profile 3), and the upper part of the Middle Miocene is missing. This is possibly due to salt tectonics and polygonal faulting.

Norwegian-Danish Basin
The Middle Miocene deposits onshore Denmark are characterised by a major transgression (Profile 3). The depositional environment was dominated by clay sedimentation and in the late Serravallian the sedimentation rate was very low, thus permitting widespread formation of glauconite (Rasmussen et al. 2010). Despite the global climatic deterioration, water depth increased in this part of the North Sea Basin.

Upper Miocene to Lower Pliocene

East Greenland, off Scoresby Sund
The lithology at ODP Site 987 (Map 2) principally consists of silty clay with varying amounts of ice-rafted clasts and stones. The succession is seen to consist of three dominantly hemipelagic sections with varying input from ice rafting (Units I, III and IV in Butt et al. 2001) and two debris flow units (Units II and IV in Butt et al. 2001). We have not investigated samples from Units I and II. The existence of ice on continental Greenland is indicated since approximately 7.5 Ma (Unit V), but the depositional environments at this time were dominantly hemipelagic. The first major advance across the Scoresby Sund took place at approximately 5 Ma (Unit IV). A return to a dominantly hemipelagic environment took place at around 4.5 Ma (Unit III). Another major glacial advance across the shelf at 2.58 Ma is represented by another debris flow unit (Unit II). This phase is related to the onset of major Northern Hemisphere glaciations at approximately 2.6 Ma (Butt et al. 2001, Laberg et al. in press).

Larsen (1990) identified 12 seismic sequences along line GGU 82-12 where the deposits reach a thickness of over 3 km on the outer shelf (see Profile P14). The earliest sedimentation was dated to Eocene to Early Oligocene (sequences 1-2) and the major sedimentation phase (sequences 3-8) to Miocene. The uppermost units 9-12 were interpreted as representing Plio-Pleistocene deposition. Site ODP 987 was drilled on the eastern extremity of the GGU 82-12 line (Profile 14). The age model for Site 987 suggests that although sedimentation may have started during Late Miocene times, the section is dominated by Plio-Pleistocene deposits (ODP Site 987, Fig. 1, Channel et al. 1999, Butt et al. 2001).

Barents Sea – Svalbard
In the Barents Sea shelf, Upper Miocene sediments are only preserved in a distal position in local basins along the western margin (well 7216/11-1 S, Ryseth et al. 2003). In northern Spitsbergen, a sequence of volcanic rocks overlying crystalline basement and Devonian sediments has been tentatively dated to Late Miocene (Vågnes & Amundsen 1993).

Norwegian Sea and its continental shelf
A marked relief of the Fennoscandian Shield, accompanied by continued uplift, colder climate (Fig. 5) and a low global sea-level, resulted in a continued and pronounced out-building of the coastal plains and deltas along the inner continental shelf (Molo Formation). Upper Miocene to Lower Pliocene deposits are recorded from the Molo Formation in well 6407/9-5, 6407/9-1 and 6407/9-2 in the Draugen Field in its southwestern part (Map 1, Fig. 1). In these wells the Molo Formation contains glauconitic sand. There is not sufficient data to determine whether there is a hiatus between the Lower Miocene and the Upper Miocene-Lower Pliocene part of the formation (Fig. 5).

Sediments belonging to the Kai Formation were deposited on the outer and middle parts of the margin. On the outer shelf and slope down to the deeper Møre and Vøring basins, the Kai

Formation is overall clayey (e.g. wells 6607/5-1, 6609/5-1, 6508/5-1, 6609/11-1 and 6507/12-1) with ooze in the basinal part (e.g. boreholes 6704/12-GB1 and 6403/5-GB1 and well 6305/5-1, Map 1, see also figure 9c in Henriksen et al. 2005). It has a similar polygonal fault pattern as the Brygge Formation, although in detail there are differences in seismic facies between the two units (Bugge et al. 2004, Eidvin et al. 2007). According to Laberg et al. (2005a, 2005b) and Henriksen et al. (2005), in the Norwegian Sea the sediments of the Kai Formation have to a large extent been redistributed by contour currents. At this time, the sea-floor bathymetry was controlled by large domes and depressions formed by the Mid Miocene compressional tectonic phase. Seismic data indicate that redistribution of fine-grained sediments commonly took place along the flanks of the domes. Fig. 13 shows the redistribution of Miocene sediments in a section through the Sør High, a part of the Nordland Ridge which underwent Mid Miocene compression.

Northern and central North Sea
During the Late Miocene to Early Pliocene, the northern North Sea formed a narrow seaway between deeper water in the Møre Basin and the central North Sea. The strait received large amounts of coarse sand (Utsira Formation). The Utsira Formation represents a huge sedimentary depositional system in the northern North Sea (about 450 km long and 90 km wide, Fig. 11) comprising one large sandy depocentre (250-300 m in the southern Viking Graben) and an area with 80-100 m-thick sandy deposits in the northern Viking Graben. The western central area comprises a large deltaic system which prograded eastwards in the Early and Mid Miocene, but where Upper Miocene to Lower Pliocene sediments of the Utsira Formation are thin or absent (Fig. 3). Apparently, the progradation of the delta stopped in the Mid/Late Miocene, and the sediments were transported to the delta slope and the shallow shelf beyond the delta, suggesting a relative fall in sea level. To the north, in the Tampen area, the Utsira Formation is represented by a thin glauconitic unit dated to close to the Late Miocene/Early Pliocene boundary and overlying the Oligocene and Lower Miocene. This member is thought to cap the main Utsira Formation sands in the northeastern part of the basin (Fig. 11, Profile P8, Rundberg & Eidvin 2005, Eidvin & Rundberg 2001 and 2007). Within the Tampen area, the glauconitic member is locally absent and Upper Pliocene deposits lie unconformably on Oligocene sediments, e.g. in the Tordis Field area (Eidvin 2009 and Eidvin & Øverland 2009). In the western part of the Norwegian sector in quadrants 30 and 25, the Utsira Formation merges with parts of the Hutton sand (see Profile P6). Offshore West Norway, a sandy deltaic system was developed north of the Troll Field, probably fed by the Sognefjorden paleovalley (Map 1, Profile P8). Farther to the south, only thin and shaly sections are recorded.

Northern Central Graben
In the Ekofisk area, the Upper Miocene to Lower Pliocene succession has been investigated in well 2/4-C-11 (Map 1) and contains mostly clay. Seismic data show a parallel to sub-parallel, rather continuous, reflection pattern. The section thickens into the Central Graben depocentre, but there are no clear indications of any direction of progradation. At its base, a faint onlap has been observed along the lower boundary at the Mid Miocene reflector. In the Ekofisk area, the section may be tentatively divided into a lower part with more continuous internal reflections and an upper part with less continuity. This change takes place within the Upper Miocene. The upper part seems to onlap the lower section towards the north (Eidvin et al. 1999). The Lower Pliocene succession is characterised by a low-angle, northward-dipping, clinoformal reflection pattern. Locally, pockmarks characterise the Pliocene succession (Knutz 2010).

At the lower boundary of the interval, the base Upper Miocene reflector is well defined by a conspicuous change in internal deformation, the underlying unit being strongly polygonally faulted. From regional mapping, it is known that the base Upper Miocene reflector commonly defines the top of gas chimneys and that it coincides with the latest phase of major salt movement in the Central Graben. Pressure build-up above hydrostatic is commonly encountered below the reflector/unconformity. Above the big, chalk, oil and gas fields, gas chimneys and undercompacted clays are also encountered in the Upper Miocene and Lower Pliocene succession (Eidvin et al. 1999).

Norwegian-Danish Basin
Onshore Denmark, the base of the Upper Miocene is characterised by a regional oxidation of glauconite minerals to goethite (Map 1 and Link to Danish Miocene Sr isotope ages). This reflects a relative sea-level fall in the area (Rasmussen 2004). The sedimentation during the Late Miocene was dominated by deposition of clay-rich sediments with an increasing incursion of sand in the upper part. The thin sand beds were deposited as storm sand layers, but show a clear tidal influence, i.e. with double clay drapes. In the latest Late Miocene, shoreface deposits were laid down in the Danish area and the shoreline prograded as far as the Central Graben at the end of the Late Miocene (Rasmussen 2005, Møller et al. 2009).

Discussion

Implications for the development of the North Sea and the southern Scandes Mountains
In Map 1 it is possible to correlate the locations of the described Oligocene to Lower Pliocene depocentres with the topography and present drainage of Scandinavia. In the topographic map in Map 1, the shift from greenish to brownish colour takes place at about 800 m elevation. The highest peaks of the South Scandes Dome exceed 2000 m. Here, red lines show generalised water divides, separating major drainage systems. Extensive river capturing has taken place, in particular in the northern part of the dome where the present water divide has moved to the southeast (yellow line, Map 1). It is believed that the paleo-drainage which had developed in the crystalline basement rocks would, to a large extent, have controlled the present drainage, and one hypothesis for a rapid significant movement of the water involved in tectonic movements of the South Scandes Dome.

Our compilation shows that the Oligocene sediments in the northern North Sea were sourced from the western part of the South Scandes Dome (blue broken arrows, Map 1). Offshore West Norway, the sedimentation continued from the Eocene and terminated in the Early Oligocene. In the northernmost North Sea, sedimentation continued throughout the Oligocene. In the Late Oligocene, a much larger volume of clastic sediments was transported to the Norwegian-Danish Basin. This depositional pattern is consistent with a water divide located far to the northwest and west on the South Scandes Dome. At the transition to the Early Miocene, there was a shift in depocentres and nearly all the clastic sediment transport was now apparently directed towards the south (blue unbroken arrows in Southeast Norway and Sweden, Map 1). This situation continued to the Late Miocene, when the paleo-Sognefjorden valley was probably sourcing the sandy deltaic deposits that are found in well 35/11-1 north of the Troll Field (Map 1, Profile P8 and Fig. 11). Compared with the Utsira Formation, the volumes are negligible. Large-scale erosion and sediment progradation from the western part of the South Scandes Dome did not take place until the onset of glaciations in the Late Pliocene. The Mid Miocene angular unconformity appearing in the seismic data

offshore West Norway suggest a rotation of the inner shelf which could be related to tectonic uplift of the South Scandes Dome.

Throughout the Oligocene and Miocene, the water depth in the Viking Graben was gradually shallowing, probably because of the high sedimentation rates and deltaic progradation in the Frigg area. In the huge delta system of the Frigg area, sedimentation was affected by changes in relative sea level, but there is no direct evidence of Mid Miocene tectonism in our data. Løseth & Henriksen (2005) interpreted the erosional surface in the northernmost North Sea to indicate subaerial erosion caused by Mid Miocene uplift. However, our new data presented above indicate that the area where the erosion surface occurs was located in a distal position relative to the Middle Miocene delta and the corresponding shelfal depocentre penetrated by wells 30/5-2 and 30/6-3. This depocentre postdates the Mid Miocene compressional tectonism. We suggest as an alternative explanation that the erosional event may have been caused by an increased marine circulation and vigorous current erosion due to the subsidence of the Greenland-Scotland Ridge (Laberg et al. 2005b). The abrupt Mid Miocene climatic cooling at approximately 14 Ma (Fig. 5, Zachos 2001) may have intensified the oceanic circulation system.

Another aspect which is important is the change in the North Sea Basin physiography that developed during Mid and Late Miocene time, in which the northern North Sea gradually became shallower and narrower due to Oligocene sedimentary infilling and Miocene tectonic uplift of the south Scandes Dome. The resultant basin physiography of the North Sea with a shallow threshold to the north may have been ideal for the formation of strong tidal current regimes. Such currents may have swept across the uplifted Viking Strait (term proposed in Galloway 2002) and caused vigorous erosion of the relatively shallow sea floor. The tidal effect would probably have increased as the strait became shallower. The fact that the hiatus is largest to the north and decreases southwards is in accordance with this model (Rundberg & Eidvin 2005). It should also be taken into account that the Lower and Middle Miocene sections, which were deposited in the western part of the northernmost North Sea, were so thin that even a small amount of erosion could have created a large stratigraphic hiatus.

A major transgression in the Early Pliocene created accommodation space for huge volumes of glacigenic sediments sourced by the Scandes Mountains. In the Late Pliocene, in the Frigg area, there was a new phase of sandy deltaic aggradation. The shallowest, Upper Pliocene, sand sequence of the Frigg delta is in direct communication with the Utsira-Skade aquifer system (NPD 2011).

The Utsira Formation and the western (youngest) part of the Molo Formation (Map. 1, Profile P10 and Profile P12) postdate the Mid Miocene tectonism in the North Atlantic. The Molo Formation was derived from the central part of the Scandes Mountains, where the present drainage system seems to be controlled by longitudinal valleys and by Mesozoic fault blocks and fractures.

The age and depositional environments of the Kai, Utsira and Molo formations
Mid Miocene compression formed large anticlines, synclines and elongated domes in the deep Norwegian Sea and the outer part of the shelf. The age of this event is constrained to Middle Miocene by seismic evidence from the wells on the Ormen Lange dome.

Based on an assumption that the Molo Formation is everywhere younger than the Middle Miocene, Løseth & Henriksen (2005) argued that a compression phase caused a major regression along the Norwegian margin between 62º and 69ºN during the Mid to Late Miocene. This interpreted regression forced the coastline of the syn-tectonic Kai Formation

50-150 km seaward of the present coastline. The regression should also have lifted the many intra-basin highs in the Norwegian Sea above sea level. Their idealised palaeogeography for the Late Miocene (figure 15 in Løseth & Henriksen 2005) shows a situation where most of the Norwegian Sea continental shelf, northern North Sea including the Viking Graben area and large parts of the compressional dome structures in the Norwegian Sea were dry land. Furthermore, they suggested that a stress reduction at the end of the Miocene resulted in a subsidence of approximately 400 m near the coast. Subsequently, the sandy Molo Formation and its assumed southern equivalent, the sandy Utsira Formation, were built out (their figure 16). Løseth & Henriksen (2005) assigned a late Mid to Late Miocene age to the Kai Formation and an Early Pliocene age to the Molo and Utsira formations. Their model implies that a postulated major regression should have caused the development of shallow-marine deltas and sand-rich fans in Mid to Late Miocene time. The existence of such deposits, older than the Molo and Utsira formations, has not yet been proven.

Based on biostratigraphy and seismic correlation, Eidvin et al. (2007) interpreted the Kai, Molo and Utsira formations to have been deposited mainly contemporaneously during the Late Miocene and Early Pliocene. They showed, however, that the oldest part of the Kai Formation (late Middle Miocene) is slightly older than the oldest part of the Utsira Formation (see also Rundberg & Eidvin 2005 and Eidvin & Rundberg 2007). Additional investigations of wells and boreholes in the present publication support the latter findings. The most important correlative tool for this interpretation is that of the *Bolboforma* assemblages. We recorded *Bolboforma* assemblages in the Kai, Molo and Utsira formations that enabled us to correlate shelfal fossil assemblages with short-range, deep-ocean *Bolboforma* zones which are calibrated with nannoplankton and paleomagnetic data. However, no *Bolboforma* were recorded in the Utsira Formation in the northwestern part of the North Sea (wells 34/4-7, 34/7-1 and 34/7-2). In this area, only the youngest part of the Utsira Formation is present, consisting of a thin glauconitic sand bed which probably drapes over the main Utsira Formation towards the east (Profile P8).

According to the deep-sea record, Spiegler & Müller (1992) and Müller & Spiegler (1993) described a *B. fragori/B. subfragori* Zone from sediments with an age of 11.7-10.3 Ma (earliest Late Miocene). We recorded *B. fragori* or *B. subfragori* assemblages at the base or in the lower part of the Utsira Formation in wells 34/8-3A (Tampen area), 35/11-1 (Sogn Graben), 25/10-2 (Viking Graben) and 24/12-1 (Viking Graben). The same assemblages were recorded at the base or near the base of the Kai Formation in wells 6508/5-1, 6609/5-1, 6609/11-1, 6507/12-1 (Trøndelag Platform), 6305/5-1 (Møre basin) and in the cored borehole 6704/12-GB1 (Gjallar Ridge).

According to the deep-sea record, Spiegler & Müller (1992) and Müller & Spiegler (1993) described a *B. badenensis/B. reticulata* Zone from deposits with an age slightly older than 14 to 11.7 Ma (Middle Miocene). In the southern Viking Graben, we recorded a *B. badenensis/B.reticulata* assemblage in a number of wells in the fine-grained deposits at the base of the Nordland Group, just below the Utsira Formation and just above a distinct base Middle Miocene seismic reflector. However, in wells 24/12-1 and 15/12-3 the uppermost part of the *B. badenensis/B.reticulata* assemblage is within the lowermost part of the Utsira Formation. On the Norwegian Sea continental shelf, we recorded the same assemblage at the base of the Kai Formation in well 6507/12-1. In the distal part of the Kai Formation we recorded the *B. badenensis/B.reticulata* assemblage in borehole 6403/5-GB1 (Møre Basin) and a *Bolboforma compressispinosa-B. badenensis* assemblage in borehole 6704/12-GB1 (Møre Basin). The ages indicated by the *Bolboforma* correlations are confirmed by Sr analyses in a number of wells and boreholes, especially from the southern Viking Graben, but

also from the Norwegian Sea (see also Eidvin et al. 2013c). Unfortunately, except for a few samples, the *Bolboforma* tests are usually too small and too few to provide sufficient $CaCO_3$ for Sr isotope analyses. Consequently, calcareous foraminifera, and in sandy sections mollusc fragments, are used for Sr analysis.

Eidvin et al. (1998a) investigated sidewall cores of the Molo Formation in well 6610/3-1 (in its northern part, Map 1) and gave an Early Oligocene age for the unit based on benthic foraminiferal and dinoflagellate cyst correlations and strontium isotope analyses. Later, T. Eidvin and M. Smelror investigated sidewall cores of the same formation in well 6510/2-1 (in the middle part of the formation, Map 1). Based on the same kind of analyses they suggested an Early Miocene age for the formation in that well. Eidvin et al. (2007) investigated ditch cutting samples of the Molo Formation in wells 6407/9-5, 6407/9-2 and 6407/9-1 (in its southern part, Map 1) and based on the same kind of analyses they interpreted a Late Miocene to Early Pliocene age for the unit in those particular wells. Eidvin et al. (2007) interpreted the Oligocene fossils in well 6610/3-1 and the Early Miocene fossils in well 6510/2-1 to be reworked and suggested a post-Mid Miocene age for the whole of the Molo Formation. They interpreted the Molo Formation to be the proximal equivalent to the deeper marine Kai Formation. However, interpretation of the new seismic data and correlation with the well 6610/2-1 S, for the current publication, support the view the northern proximal part of the Molo Formation is as old as Early Oligocene and that the formation contains younger sediments towards the west and south. We now believe that the recorded index fossils in wells 6610/3-1 and 6510/2-1 are not reworked, and that the Molo Formation is the proximal equivalent of both the Brygge and the Kai formations (Map 1, Profile P10, Profile P11, Profile P12 and Profile P13, see also Eidvin & Riis 2013).

Profile 13 shows that there is a good seismic correlation between the proximal sandy Lower Oligocene sediments in well 6610/3-1 and their fine-grained distal equivalent in 6610/2-1 S. Map 1 and Profile P13 also show that the Molo progradation in this area covers a more than 20 km-wide, coast-parallel belt where at least three different stages of progradation can be defined seismically. Farther south in well 6510/2-1 and towards the Draugen area, the Molo progradational belt is much narrower and its seismic character can be correlated with the younger, western part of the 6610/3-1 profile (Profile P13). These seismic observations are compatible with the biostratigraphic analysis. The oldest part of the Molo Formation is located offshore from the northern Scandes dome and could have been sourced through a paleo-drainage in Vestfjorden.

The Mid to Late Miocene regression model of Løseth & Henriksen (2005) implies that large parts of the Kai Formation on the continental shelf of the Norwegian Sea should have been deposited in shallow water depths in an inner to middle shelf environment. Also, on at the intra-basin highs in the Norwegian Sea, a shallow-water depositional environment should have prevailed during deposition of the Kai Formation (see their figures 15 and 16). However, our biostratigraphical record contradicts such a model. Even in the most marginal wells, where we have investigated the Kai Formation, including 6609/11-1 and 6507/12-1 (Trøndelag Platform), we recorded a fine-grained sediment rich in pelagic microfossils including planktonic foraminifera, *Bolboforma*, radiolaria and diatoms immediately above the Mid Miocene unconformity. No inner-shelf benthic foraminifera are recorded. In well 6305/5-1, situated on the Ormen Lange dome in the Møre Basin (Map 1, Fig. 6), we recorded an approximately 30 m-thick section of Upper Miocene Kai Formation lying unconformably on Upper Oligocene Brygge Formation. The Kai Formation in this well contains mainly pelagic ooze, and all of the recorded microfossils indicated deposition in deep water. There is no indication that this intra-basin high could have been close to the sea surface. It should be

noted that these sediments were deposited on a structural dome which formed a positive relief on the sea floor.

Regional seismic mapping on the Trøndelag Platform is consistent with the biostratigraphic interpretation, and provides some additional information about the paleogeography. The thickness of the Kai Formation is greatest in the central part of the Trøndelag Platform and decreases towards the Molo Formation to the east and towards the Nordland Ridge to the west. In particular, the central part of the Nordland Ridge (the Sør High) was affected by Miocene compression and formed a dome structure which is onlapped by the Kai Formation. The central Trøndelag Platform can be regarded as a very wide and shallow syncline between the Nordland Ridge and the central Scandes Mountains. West of, and restricted to, the Sør High, there are conspicuous internal structures within the Miocene succession which can be interpreted as reworking by contourites (Fig. 13).

In summary, our interpretation is that most of the Kai Formation is a distal equivalent to the youngest, western part of the Molo Formation in the Norwegian Sea continental shelf and the Utsira Formation in the Møre Basin. We believe that only the eastern part of the Norwegian continental shelf was submerged during the Late Miocene and that the paleo-coastline is marked by the Molo Formation. Since no shallow-marine fossil assemblages were recorded in the lower part of the Kai Formation, immediately above the Mid Miocene unconformity, the observed erosional features probably occurred in quite deep water. In their seismic investigation of the Kai Formation in the Norwegian Sea, Laberg et al. (2005ab) showed that the sediments have been redistributed by contour currents. Intra Kai Formation prograding clinoforms were interpreted as parts of deltas by Løseth & Henriksen (2005), but similar seismic signatures are also made by along-slope flowing currents according to Laberg et al. (2005ab). The structures west of the Sør High are a good example. If these structures should be interpreted as deltaic, they would imply a sedimentary transport from west to east. Such an interpretation is incompatible with the deep-water ooze deposits in the Kai Formation in the deep Norwegian Sea. Contour currents, compressional structures and deposition of thick ooze layers in the deep sea may be important factors to explain the thinning and local pinching-out of the Kai Formation towards the distal part of the Molo Formation. It should also be remembered that the Mid Miocene compression resulted in the formation of large anticlines and synclines rather than just regional uplift.

The erosional features observed in the northernmost North Sea towards the Møre Basin were interpreted by Løseth & Henriksen (2005) as subaerial erosion, whereas the biostratigrapic analysis presented here is consistent with submarine erosion since no shallow-water assemblages were found in the relevant wells. Seismic mapping shows no indications of any regional tectonic structures which could have uplifted the area north of the Utsira Formation delta by several hundred metres in the Mid Miocene and then have subsided rapidly in the Late Miocene. Considering that the whole development of the Utsira Formation delta from the Oligocene to the Late Pliocene is consistent with a quiet tectonic regime, such inferred uplift and subsidence affecting its northern part is regarded as unlikely.

Oligocene to Pliocene along the Barent Sea margin
From the Sørvestsnaget Basin on the Barents Sea margin, Ryseth et al. (2003) recorded Middle and Upper Miocene deposits in well 7216/11-1S (Map 2), and stated that uppermost Middle Miocene deposits lie unconformably on the Upper Oligocene in that well. They also reported a small break between the Upper Eocene and the Lower Oligocene (their figure 3). The Oligocene to Miocene stratigraphy in well 7216/11-1S is based mainly on analyses of dinoflagellate cysts since no Oligocene calcareous benthic index foraminifera are recorded, as

in well 7316/5-1, and the recorded agglutinated foraminifera are of long-range forms (Ryseth et al. 2003, T. Eidvin personal investigation).

The stratigraphical and regional interpretations of Ryseth et al. (2003) deviate somewhat from ours in that they indicate an absence of any Miocene deposits in the Vestbakken Volcanic Province and in well 7316/5-1 (Map 2). In their figure 11 they show that Miocene deposits pinch out on a high in the Knølegga Fault Zone south of the Vestbakken Volcanic Province. Also, they extend the Oligocene deposits, recorded in the Vestbakken Volcanic Province and the Sørvestsnaget Basin, towards the southwest and onto the Senja Ridge. They interpreted the interval 1180-1020 m in well 7117/9-1 and 1120-960 m in well 7117/9-2 to be of Oligocene age (their figure 10). A similar age for these intervals was also given by different biostratigraphical industry consultants soon after the wells were drilled in 1982 to 1983. This led several authors of published literature to conclude that the lower boundary of the large sedimentary fan along the Barents Sea margin is of Oligocene to Miocene age. However, a re-dating of these wells was performed at the Norwegian Petroleum Directorate in 1988, which concluded that these sections are Late Pliocene glacial deposits (Eidvin & Riis 1989, Eidvin et al. 1993). This result was later supported by different authors, working in several independent disciplines, including Mørk & Duncan (1993), Sættem et al. (1992, 1994) and Faleide et al. (1996). It appears that Ryseth et al. (2003) have used the original age interpretations, carried out by the industry consultants, in their regional interpretations, since no new re-dating of these wells is referred to in their paper. A profile through the Senja Ridge based on a seismic section (Fig. 14) shows the erosional contact between the Eocene ooze sediments and the glacigenic section.

Summary and conclusions

Based on an extensive study of biostratigraphic and strontium data from 47 wells and boreholes from the entire Norwegian continental shelf, one outcrop from northwestern Svalbard, one ODP borehole off Scoresby Sund (East Greenland), two stratigraphic boreholes from onshore Denmark, and both published and new data from a number of other boreholes and outcrops from Denmark, we have presented an improved chronology of Oligocene to Lower Pliocene strata. Emphasis has been placed on sandy deposits. The deposits of the Norwegian continental shelf and onshore Denmark are correlated to the deep-sea record. Most wells and boreholes have been integrated with wire-line log and seismic data.

Our findings show that during late Early to Late Oligocene time, sediments in the northernmost part of the North Sea Basin were sourced from the northwestern part of the South Scandes Dome, which was topographically high throughout the Paleogene. In the northeastern part of the northern North Sea off Nordfjord, sandy gravity-flow sediments were deposited. Farther south off Hordaland and Sogn and Fjordane, a distinct wedge of organic-rich mudstones was formed along the coast (Early Oligocene). Deltaic complexes prograded southwards into the Norwegian-Danish Basin (Vade Formation and the sand-rich part of the Lark Formation, Dufa and Freja members). In the Late Oligocene there is a large input of sandy sediments from the Shetland Platform into the northern North Sea. Most of the sediments were laid down in the southern Tampen area. Farther south, Upper Oligocene deposits are recorded below the Skade Formation in the Frigg Field area, i.e. within the area belonging to the Hutton sand according to Gregersen & Johannessen (2007). Along the inner continental shelf of the Norwegian Sea a pronounced progradation of coastal plains and deltas from the Northern Scandes Dome started in the Early Oligocene north of 66°N (Molo

Formation). Mainly argillaceous sediments were deposited elsewhere in the central and northern North Sea, on the Norwegian Sea continental shelf and on the Barents Sea margin. Mainly pelagic ooze was deposited in the Norwegian Sea. Conglomerates, sandstones and sandy clay were deposited in the Forlandsundet basin in northwestern Svalbard. Climate was probably cold temperate during the Early to early Late Oligocene and warm temperate to subtropical during the latter part of Late Oligocene.

At the end of the Oligocene, prominent polar ice caps built up primarily in Antarctica which resulted in a global sea-level fall. Contemporaneous with this event, tectonism occurred along the Sorgenfrei-Tornquist Zone and on former graben structures in the southern North Sea. Associated with this, deltas (Ribe Group) prograded southwards during the Early Miocene, and covered large parts of the present-day Jutland area in Denmark. In the northern North Sea, there was a marked shift in depocentres. The thick Oligocene depocentre in the Tampen area was abandoned, and sand-rich sediments of the Lower Miocene Skade Formation were deposited in the Viking Graben. North of 60ºN, in the North Sea, fine-grained Lower Miocene sediments are present only in the central basin and absent at the margins to the west and east. The Skade Formation thus represents a southern shift in coarse clastic influx to the basin from the East Shetland Platform, relative to Oligocene time. These deposits are turbiditic in origin and were probably deposited in quite deep parts of the shelf. The Skade sections in blocks 25/1 and 25/2 contain common mollusc fragments and lignite, and have probably been deposited in shallower water close to, or as parts of, a delta. According to the mapping of Gregersen & Johannessen (2007), these wells are situated in the distal part of the Hutton sand area. Farther east, fine-grained, distal sediments were deposited. The out-building of the Molo Formation along the inner continental shelf of the Norwegian Sea continued in the Early Miocene over a larger area than in the Oligocene, possibly as far south as to 64ºN. A distal, fine-grained, thin Lower Miocene wedge is recorded on the Trøndelag Platform. Mainly pelagic ooze was laid down in the Norwegian Sea.

Tectonic movements in the Norwegian Sea culminated at the Early to Middle Miocene transition, and the deposition of the Skade Formation sands was followed by progradation of a large delta in the Frigg area. In the Norwegian Sea, major compressional structures were formed.

Middle Miocene sediments in the northern North Sea represent the basal part of the Nordland Group. Seismic data show that in the Mid Miocene a significant delta structure was formed in the Frigg Field area, and throughout the Middle Miocene the delta-front prograded to the east. Middle Miocene units in block 25/2 (southern Viking Graben) and in the depocentre in blocks 30/5 and 30/6 in the northern Viking Graben are sandy and microfossils indicate an inner to middle shelf environment. South of the Viking Graben, the Middle Miocene sediments are mainly fine-grained. Fine-grained sediments were deposited in parts of the Trøndelag Platform on the Norwegian Sea continental shelf. No data exist for the Mid Miocene development of the Molo Formation. Hiatuses are either minor or absent in the Viking Graben, but the youngest part of the Middle Miocene may be missing in the Ekofisk Field in the Central Graben. Pelagic sedimentation continued uninterrupted in most of the Norwegian Sea. However, hiatuses are present on large dome structures. On the Ormen Lange Dome, for example, a hiatus occurs below the Upper Miocene. Along the western Barents Sea margin there was renewed tectonic activity, and a hiatus is recorded below the Middle Miocene in the Sørvestnaget Basin (Ryseth et al. 2003). In well 7316/5-1 in the Vestbakken Volcanic Province there is an erosional boundary between the Lower Miocene and Upper Pliocene. The climate was probably warm temperate during the Early Miocene and culminated with a subtropical climate in the early Middle Miocene.

In the Late Miocene, a considerable climatic deterioration and a low global sea level resulted in continued out-building of coastal plains and deltas of the Molo Formation along the inner continental shelf of the Norwegian Sea. To the west, clayey and hemipelagic sediments were laid down on the shelf and pelagic ooze on the slope and rise (Kai Formation). During the same period, the northern North Sea formed a narrow seaway between the deeper water of the Møre Basin and the central North Sea. This strait received a large amount of coarse clastic sediments from the East Shetland Platform in the west (Utsira Formation) and locally from the Fennoscandian Shield in the northeast. The Utsira Formation represents a huge sedimentary depositional system in the northern North Sea comparable in volume to the Skade Formation. The Utsira Formation comprises one large sandy depocentre in the southern Viking Graben and a much smaller one in the northern Viking Graben. In the deltaic system of the Frigg Field area, the Utsira Formation is thin or absent due to the fall in sea level. In the northern North Sea Tampen area, the Utsira Formation is represented by a thin glauconitic unit deposited close to the Miocene-Pliocene transition and overlying an erosional surface which cuts into Oligocene and Lower Miocene strata. This glauconitic member is thought to cap the main Utsira Formation sands in the northeastern part of the basin. In late Early Pliocene the climate temporarily improved, and this coincided with a temporary rise in sea level.

The deep-sea record from the Norwegian-Greenland Sea reveals small quantities of ice-rafted material during the Late Eocene to Early Oligocene and the late Mid to early Late Miocene. East Greenland is the likely source of this material. However, the investigation of the large sediment wedge off the Scoresby Sund fjord system shows that the build up of substantial continental ice on Greenland started late in the Late Miocene at approximately 7.5 Ma. There is no evidence for the existence of glaciers on the eastern seaboard of the Norwegian-Greenland Sea before 2.75 Ma.

Suggestions for an update of the lithostratigraphic nomenclature for the post-Eocene succession

The lithostratigraphy of the post-Eocene succession in the Norwegian North Sea was established by Isaksen & Tonstad (1989). Within the Hordaland (upper part) and Nordland groups, only two major sandy sections have been defined (Skade and Utsira formations) whereas the remaining lithologies have remained undifferentiated. Eidvin & Rundberg (2007) suggested some changes to this, and we have amended and developed this further and extended the area to the successions offshore Mid and North Norway (nomenclature of Dalland et al. 1988).

Central and northern North Sea, Hordaland Group
Eidvin & Rundberg (2007) suggested using the name Lark Formation, introduced by Knox & Halloway (1992), for mudstones of Oligocene to early Mid Miocene age (upper part of the Hordaland Group). The Lark Formation has already been used informally by industry consultants and stratigraphic workers in the Norwegian North Sea. In accordance with international lithostratigraphic rules and recommendations (Nystuen 1986, Salvador 1994), formation names which already have been defined in parts of the basin should also be used for equivalent strata across national borders. We therefore also propose to extend the usage of the term Lark Formation into Norwegian waters. Its original type section will remain unchanged, but we suggest the use of the well 2/4-C-11 succession from 2789 to 1664.7 m as the well reference section in Norwegian waters. Below 2789 m there is a hiatus down to

Lower-Middle Eocene. A description of the interval from 2472 to 1664.7 m is available under the hyperlink to well 2/4-C-11. The lower part has been investigated by Eidvin et al. (1995, unpublished report).

Eidvin & Rundberg (2007) suggested that, in the northern North Sea, the Lark Formation should comprise the Skade Member (downgraded from formation) and an unnamed member (see their figure 27). We suggest that we do not downgrade the Skade Formation and at the same time keep the Vade Formation, in the central and eastern North Sea. For the unnamed sandstone unit in the northern Viking Graben, we suggest using the name Ull Formation after an *Æsir* ("god") in Norse mythology (Fig. 9).

Skade Formation
Isaksen & Tonstad (1989) introduced the term Skade Formation for sands that were thought to be Oligocene in age. Eidvin & Rundberg (2007), however, showed that these sands are dominantly Early Miocene (Fig. 3 and Fig. 9). Knox & Halloway (1992) adopted the term Skade Formation but used it for shallow-marine sands in the UK sector. Isaksen & Tonstad (1989) suggested that the sands were deposited in deeper marine settings in Norwegian waters. Eidvin & Rundberg (2007) interpreted the Skade Formation sands to be deposited by gravity processes (turbidites) mainly in upper bathyal water depths in the area they studied in the southern Viking Graben. The Skade sections in wells 25/2-10 S and 25/1-8 S (analysed for the current publication) contain common mollusc fragments and lignite, and have been deposited in shallower water close to, or parts of, a delta. According to the mapping of Gregersen & Johannessen (2007), these wells are situated in the distal part of the Hutton sand (see Fig. 10 and Profile P6). Hutton sand is an informal term used in British sector by several oil companies to describe all sands above the Lower Eocene Balder Formation in the Northern North Sea (British Geological Survey 2000). According to Bater (2003) and Gregersen & Johannessen (2007), the Hutton sand constitutes the entire sediment succession from the Upper Oligocene/Lower Miocene to Upper Pliocene and reaches eastwards into quadrants 30 and 25 in the Norwegian sector (see figure 5 in Gregersen & Johannessen 2007, Fig. 10 and Eidvin et al. 2013a). In some areas, parts of the Hutton sand continue into the Skade Formation, but we prefer not to use the term Hutton sand in Norwegian waters. More work need to be done on this relationship.

According to Isaksen & Tonstad (1989) the well type section for the Skade Formation is in well 24/12-1 from 1007 to 851 m, and the well reference section is 15/9-13 from 1224 to 1143 m. These wells were investigated by Eidvin & Rundberg (2007), and they found that the sandy unit in well 15/9-13 was younger than the Skade Formation in the other wells that they had studied, and dated the unit to Mid Miocene and belonging to the base of the Nordland Group. For the current publication we have recorded sandy sections of Mid Miocene age in four other wells and here suggest a name for this unit (see the Nordland Group below). We suggest well 16/1-4 from 1170 to 916 m as the new well reference section for the Skade Formation.

Vade Formation
Isaksen & Tonstad (1989) introduced the term Vade Formation for sands that were suggested to be Late Oligocene in age. We have investigated the distal part of these sandy sections in well 2/2-2 and the proximal part in well 11/10-1. We found that in well 2/2-2 the unit is of early Late Oligocene age and that the unit in well 11/10-1 is of late Early to early Late Oligocene age (the top was not seen). According to Isaksen & Tonstad (1989) the well type section is 2/2-1 from 2172 to 2100 m and the well reference section is the nearby 2/3-2 from 1855 to 1795 m. They interpreted the sand in the wells to be deposited in a shallow-marine

environment. Our interpretation of the fossil assemblages and the sediments of the Vade unit in the nearby well 2/2-2 indicate deposition by gravity processes in upper bathyal to outer neritic water depths. It is also obvious from seismic interpretation that wells 2/2-1, 2/2-2 and 2/3-2 are all situated central in the basin containing distal deposits (Profile P2, Jarsve et al. work in progress). On the contrary, the Vade unit in well 11/10-1 contains much coarser sand than in 2/2-2, mollusc fragments and a foraminiferal fauna with a more shallow-water affinity. We interpret the Vade unit in well 11/10-1 to have been deposited in middle to inner neritic water depths (see also Profile P2 and Jarsve et al. work in progress). Since wells 2/2-2 and 11/10-1 have both been investigated thoroughly by lithological, micropalaeontological and strontium isotope analyses, we suggest using 2/2-2 from 2060 to 1950 m as the new well type section (representing distal deposits) and 11/10-1 from 500 to 304.8 m as the well reference section (representing proximal deposits).

Ull Formation
We would here like to introduce the Ull Formation as a new formation in the Hordaland Group. The Ull Formation represents erosional products from uplifted areas of the western part of the Fennoscandian Shield, i.e. the area close to the present day Nordfjord and the East Shetland Platform (Map 1 and Fig. 9) during Early to Late Oligocene. We have investigated these sandy sections in wells 34/10-17, 35/3-1 and 36/1-2. Well 34/10-17 contains deposits shed from the East Shetland Platform and wells 35/3-1 and 36/1-2 contain, respectively, distal and proximal deposits shed from the Fennoscandian Shield. The Lower Oligocene is recorded only in well 36/1-2, and this part contains a very coarse-grained sand-rich succession characterised by rounded, sub-rounded and sub-angular pebbles and mollusc fragments. The succession was probably deposited as debris-flow and/or shallow- marine sediments. The successions in wells 34/10-17, 35/3-1 and the upper part of 36/1-2 are dominated of medium- to fine-grained sand with variable clay and silt content. These sediments are probably all of turbiditic origin and were laid down during the Late Oligocene. We suggest well 36/1-2 from 940 to 620 m as the well type section (representing proximal deposits) and 35/3-1 from 1100 to 740 m as the well reference section (representing distal deposits).

Nordland Group
According to Isaksen & Tonstad (1989), the term Nordland Group was introduced by Deegen & Scull (1977) for Middle Miocene to recent claystones in the North Sea Cenozoic Basin. According to their definition, the Nordland Group contains only one formation, namely the sandy Utsira Formation in the Viking Graben area.

Utsira Formation
The Utsira Formation represents a huge sedimentary depositional system in the northern North Sea (about 450 km long and 90 km wide) comprising one large sandy depocentre (250-300 m thick in the southern Viking Graben) and one much smaller centre (80-100 m thick in the northern Viking Graben). These areas are separated by a central area (Frigg area) where the unit is very thin and contains only Early Pliocene deposits (well 25/2-10 S and Fig. 11). Just to the west of this well the Utsira Formation pinches out (see Profile P6). To the north, in the Tampen area, the Utsira Formation is represented by a thin glauconitic unit overlying Oligocene and Lower Miocene strata deposited close to the Miocene-Pliocene transition (Eidvin & Rundberg 2001, Eidvin 2009, see Fig. 3, Fig. 11 and figures 4a and 7d in Rundberg & Eidvin 2005). We suggest subdividing the Utsira Formation into three members, viz. Southern Utsira Member, Northern Utsira Member and a Glauconitic Utsira Member in the northernmost part (Fig. 3, Fig. 9 and Fig. 11). In the same way as the Skade Formation, in the western part of quadrants 30 and 25 in the Norwegian sector, the Utsira Formation merges

with parts of the Hutton sand (see figures 5 and 6A-C in Gregersen & Johannessen 2007, Fig. 11, Profile P6 and Eidvin et al. 2013c).

Rundberg & Eidvin (2005) pointed out an obvious correlation conflict between the Utsira and Skade formations in the type wells of Isaksen & Tonstad (1989, see figure 6 in Rundberg & Eidvin 2005) and showed the need for a revision of the base of the Utsira Formation. Eidvin & Rundberg (2007) suggested an adjustment of the base of the Utsira in the type well 16/1-1 from 1064 to 815 m, and noted also that after such a revision the well 16/1-1 is no longer the appropriate choice as the type well for the sandy system. It penetrates only thin sand and does not represent a typical succession of the sandstones of the Utsira Formation. Consequently, we suggest well 24/12-1 from 730 to 495 m as the new well type section (Profile 5, also the well reference section for the Southern Utsira Member). We suggest well 30/6-3 from 750 to 680 m as the well reference section for the Northern Utsira Member and 34/4-6 from 1250 to 1210 m as the well reference section for the Glauconitic Utsira Member.

Eir Formation
According to Eidvin & Rundberg (2007), a revision of the base of the Utsira Formation might lead to some uncertainty about the dominantly fine-grained section above the Mid Miocene unconformity and below the Utsira sands. These sediments represent the basal part of the Nordland Group and occur as an infilling unit within the southern Viking Graben. They contain a *Bolboforma* assemblage with the important index fossils *B. badenensis* and *B. reticulata* which show that the age is slightly more than 14 to about 11.7 Ma (Middle Miocene, also vertified by Sr analyses). Except for a part of the Middle Miocene section in well 15/9-13, Eidvin & Rundberg (2007) recorded mainly fine-grained sediments in the wells they investigated in quadrants 15 and 24 in the southern Viking Graben (see wells 25/10-2, 24/12-1, 16/1-2, 16/1-4 and 15/12-3). They suggested that this basal section of the Nordland Group in the Viking Graben should be given the status of a formation, but did not suggest a name (see their figure 27). For the current publication, we have investigated this unit in wells 30/5-2 and 30/6-3 in the northern Viking Graben and 25/1-8 S and 25/2-10 S in the southern Viking Graben (Fig. 12). In wells 30/5-2, 30/6-3 and 25/2-10 S, the Middle Miocene contains mainly sandy sediments. The age is to a large extent based on the occurrence of the index fossils *B. badenensis* and *B. reticulata*. Sand also dominates the Middle Miocene section in well 25/1-8 S, but this was probably at a very shallow-marine site and oceanic forms such as *Bolboforma* did not enter the area. In this well the age is based mainly on correlation of benthic and planktonic foraminifera and a number of Sr analyses. It may be difficult to distinguish these sands from the sands of Utsira above and Skade below. However, since these sandy sections are clearly younger than the Skade Formation and older than the Utsira Formation in the type section areas in quadrants 16 and 24, we here introduce the name Eir Formation, after an Æsir ("god") in Norse mythology, for these units in the Norwegian sector as a new formation in the Nordland Group (Fig. 9). We suggest well 25/2-10 S from 630 to 520 m as the well type section and 30/5-2 from 920 to 760 m as the well reference section. In the same way as the Skade and Utsira, this unit also merges with parts of the Hutton sand in the western part of quadrant 25. As mentioned above, wells 25/1-8 S and 25/2-10 S are situated in the distal part of the Hutton sand area according to Gregersen & Johannessen (2007, Fig. 12 and Eidvin et al. 2013b). However, we suggest using the term Eir Formation for this unit in Norwegian waters.

Naust Formation
The very conspicuous Upper Pliocene prograding complex and the overlying Pleistocene deposits constitute the uppermost part of the Nordland Group of Isaksen & Tonstad (1989). These sediments consist mainly of clay-rich glacial diamictons. In the lower part of the

succession gravity sands that were deposited in front of the oblique clinoforms are common (Eidvin & Rundberg 2001). Løseth et al. (2012) interpret some of these units to be extrusive sands sourced from Paleocene-Eocene turbidites. The sands may be difficult to distinguish from the Utsira sands below (informally called Tampen Spur sandstones by Robertson Resarch 1996 and Eidvin & Rundberg 2001, see also Eidvin 2009 and Eidvin & Øverland 2009). The uppermost part of the Nordland Group also includes the large Peon gas discovery in the basal Pleistocene sands of block 35/2 (Carsten 2005, Eidvin 2005). Dalland et al. (1988) introduced the name Naust Formation for the Upper Pliocene, including the Pleistocene section. As these sediments are similar in genetic origin, reflecting the glaciation history and the main uplift of Fennoscandia, it could be appropriate to extend the usage of the term Naust Formation to the North Sea; this has in fact been a common practice by industry consultants and stratigraphic workers for a long time. Eidvin & Rundberg (2007) argued against this, but we consider that the usage has been so common that an extension of the term to the North Sea will be most convenient and appropriate. We suggest that the original type section on the Norwegian Sea shelf should remain unchanged, but we suggest the use of well 15/12-3 from 900 to 200 m as the well reference section for the North Sea (see figure 9a in Eidvin & Rundberg 2007). We also suggest regarding the Tampen Spur and Peon sandy sections as formal members within the Naust Formation in the northern North Sea. We suggest well 34/4-7 from 1090 to 1050 m as the well type section for the Tampen Spur Member (see also figure 11b in Eidvin & Rundberg 2001) and well 34/4-6 from 1150 to 1130 m as the well reference section (see also figure 10 in Eidvin & Rundberg 2001). We suggest the use of 35/2-1 from 618 to 573 m as the well type section for the Peon Member (Eidvin 2005) and 35/2-2 from 609 to 581 m as the well reference section.

Offshore Mid Norway, Hordaland Group and Brygge Formation
The lithostratigraphy of the post-Eocene succession offshore Mid Norway was introduced by Dalland et al. (1998). As for the North Sea, according to Isaksen & Tonstad (1989) the terms Hordaland Group and Nordland Group, introduced by Deegan & Scull (1977), were also used for offshore areas outside Mid Norway. Dalland et al. (1998) introduced the Brygge Formation for fine-grained deposits of Early Eocene to Early Miocene age within the Hordland Group. We suggest no changes for the well type section of the Brygge Formation.

Nordland Group, Naust, Molo and Kai formations
Within the Nordland Group, Dalland et al. (1998) defined the Kai Formation for fine-grained sediments of Middle to Late Pliocene age, and the Naust Formation for the uppermost Late Pliocene to Pleistocene succession containing mainly glacial diamictons. We suggest no changes for the well type section of the Naust Formation.

The Molo Formation is a sand-dominated unit on the middle/inner part of the shelf extending from the coast off Møre (63°15'N) to Lofoten (67°50'N, Map. 1, Profile P10, P11, P12, P13 and Eidvin & Riis (2013). It has a unique seismic signature, and represents a prograding system comprising fairly steep clinoforms (Eidvin et al. 2007). Eidvin et al. (1998a) investigated sidewall cores of the Molo Formation in well 6610/3-1 (in its northern part) and gave an Early Oligocene age for the unit based on benthic foraminiferal and dinoflagellate cyst correlations and strontium isotope analyses. Later, T. Eidvin and M. Smelror investigated sidewall cores of the same formation in well 6510/2-1 (in middle part of the formation, Map 1). Based on the same kind of analyses they suggested an Early Miocene age for the formation in that well. Eidvin et al. (2007) investigated ditch-cutting samples of the Molo Formation in wells 6407/9-5, 6407/9-2 and 6407/9-1 (in its southern part, Map 1) and based on the same kind of analyses they suggested a Late Miocene to Early Pliocene age for the unit in those wells.

Eidvin et al. (2007) interpreted the Oligocene fossils in well 6610/3-1 and the Early Miocene fossils in well 6510/2-1 to be reworked and suggested a post Mid Miocene age for the whole of the Molo Formation. They interpreted the Molo Formation to be the proximal equivalent to the deeper marine Kai Formation. However, interpretation of new seismic data for the current paper indicates that the northern proximal part of the Molo Formation is as old as Early Oligocene and that the formation contains younger sediments towards the west and south (Map 1, Profile P10, P11, P12 and P13). We now believe that the recorded index fossils in wells 6610/3-1 and 6510/2-1 are not reworked, and that the Molo Formation is the proximal equivalent to both the Brygge and the Kai formations (Fig. 4 and Fig. 5). Eidvin et al. (2007) suggested well 6610/3-1 from 555 to approximately 349 m (the upper part was not sampled or logged) as the well type section and 6407/9-5 from 787 to 670 m as the well reference section. For the current publication we suggest well 6510/2-1 from 480 to 441 m (the upper part was not sampled or logged) also as the well reference section.

Eidvin et al. (2007) investigated also the Kai Formation, by use of lithological, micropalaeontological and strontium isotope analyses, in a number of wells, and several more were investigated for the current publication (Map 1 and Fig. 4). As a result of this new, thorough investigation we think it is appropriate to choose new type and reference sections among these wells. We suggest well 6507/12-1 from 1495 to 1340 m as the new well type section and well 6508/5-1 from 1358 to 1165 m as the new well reference section.

Barents Sea, Sotbakken Group and Torsk Formation
For the Trømsøflaket offshore northern Norway, Dalland et al. (1998) introduced the term Sotbakken Group and Torsk Formation for sediments of Late Paleocene to Oligocene age and chose well 7119/12-1 from 810 to 465 m as the type well section and 7120/12-1 from 725 to 462 m as the well reference section. In our inspection of the biostratigraphic reports for these wells, we could not find evidence of any Oligocene sediments. Reliable evidence of Oligocene and Miocene deposits, in any Barents Sea well, were first recorded in well 7316/5-1 (Lower Oligocene and Lower Miocene, see also Eidvin et al. 1994, 1998b) from the Vestbakken Volcanic Province on the western margin of the Barents Sea (Map 2, Profile P15 and Fig. 5). Ryseth et al. (2003) described a more complete post-Eocene succession in well 7216/11-1S, with Upper Oligocene, Middle and Upper Miocene sediments, in the Sørvestsnaget Basin on the southwestern Barents Sea Margin (Map 2 and Fig. 5). A thin succession of Lower Miocene sediments was also recorded in the shallow stratigraphic borehole 7316/06-U-01 (Map 2, Vestbakken Volcanic Province, Sættem et al. 1994). It is natural to choose new well type and reference sections for the Sotbakken Group and Torsk Formation from these two wells. We suggest 7216/11-1S from 4215 to 2346 m as the new type section and 7316/5-1 from 3751.5 to 948 m for the well reference section (only the description of the Middle Eocene to Lower Miocene part is available under the hyperlink to this well).

Nordland Group
Dalland et al. (1988) used the term Nordland Group (introduced by Deegan & Scull (1977) for the North Sea) for sediments of Late Pliocene to Pleistocene/Holocene age and chose well 7119/12-1 from 465 to 225 m as well reference section. However, in our inspection of the biostratigraphic reports for this well, we could not find any evidence of Upper Pliocene sediments, but only Pleistocene. Reliable evidence of Upper Pliocene deposits, in any Barents Sea well, was first recorded in wells 7117/9-1 and 7117/9-2 on the Senja Ridge (Map 2), and documented in Eidvin & Riis (1989) and Eidvin et al. (1993). Wells 7316/5-1, 7216/11-1S, the shallow stratigraphic borehole 7316/03-U-01 (Vestbakken Volcanic Province, Sættem et al. 1992, Mørk & Duncan 1993) and ODP Hole 986D (southwestern Svalbard margin, Eidvin

& Nagy 1999, Smelror 1999) are the only other wells/boreholes with well documented evidence of Upper Pliocene deposits in the Barents Sea. Since well 7216/11-1S also contains thin sections of both Middle and Upper Miocene deposits (Ryseth et al. 2003), we suggest the interval from 2346 to 361 m as the new reference section for the Nordland Group (see also Knies et al. 2009).

Naust Formation
We suggest extending the usage of the term Naust Formation within the Nordland Group also to the Barents Sea. These sediments are very similar in both genetic origin and age to equivalent sediments in the northern North Sea and on Norwegian Sea shelf. We suggest well 7117/9-1 from 1180 to 550 m as the well reference section for the Naust Formation in the Barents Sea area (Eidvin & Riis 1989, Eidvin et al. 1993).

Acknowledgements

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