Marine and Petroleum Geology 56 (2014) 184–221

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Oligocene to Lower Pliocene deposits of the Norwegian continental shelf, Norwegian Sea, Svalbard, Denmark and their relation to the uplift of Fennoscandia: A synthesis

Tor Eidvin [a,*], Fridtjof Riis [a], Erik S. Rasmussen [b]

[a] *Norwegian Petroleum Directorate (NPD), Professor Olav Hanssens vei 10, P. O. Box 600, N-4003 Stavanger, Norway*
[b] *Geological Survey of Denmark and Greenland (GEUS), Øster Voldgade 10, DK-1350 Copenhagen K, Denmark*

ARTICLE INFO

Article history:
Received 21 August 2013
Received in revised form
11 April 2014
Accepted 17 April 2014
Available online 9 May 2014

Keywords:
Oligocene to Lower Pliocene
Deposits
Norwegian continental shelf
Norwegian Sea
Uplift

ABSTRACT

This study provides the results of the first integrated study of Oligocene–Pliocene basins around Norway.

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 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) 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 in only parts of the period. Shifts in local depocentres are indicative of changes in the paleogeography in the source areas.

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 sediments dated 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 Middle Miocene, when large compressional dome and basin structures were formed in the Norwegian Sea. The Middle Miocene event is correlated with a relative fall in sea level in the main depocentres in the North Sea, formation of a large delta in the Viking Graben (Frigg area) and uplift of the North and South Scandes domes. In the Norwegian–Danish Basin, 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 northeast.

© 2014 Norwegian Petroleum Directorate (NPD). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/3.0/).

1. Introduction

In this paper, the stratigraphy of Oligocene to Lower Pliocene deposits from Svalbard in the north to Denmark in the south is presented. To define the upper limit of the successions, the Upper Pliocene has been investigated in most wells. The paper is based on Eidvin et al. (2013d) which synthesises data from 47 wells and boreholes from the entire Norwegian shelf, one outcrop from northwestern Svalbard and two stratigraphic boreholes from onshore Denmark (Figs. 1–6). The purpose of the paper is to present a regional synthesis of our findings. For more detailed documentation of the biostratigraphical, lithological and strontium isotope data and interpretations the reader is referred to Eidvin et al. (2013d).

---

* Corresponding author. Tel.: +47 518 764 73.
E-mail addresses: tor.eidvin@lyse.net, tor.eidvin@npd.no (T. Eidvin).

http://dx.doi.org/10.1016/j.marpetgeo.2014.04.006
0264-8172/© 2014 Norwegian Petroleum Directorate (NPD). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/3.0/).

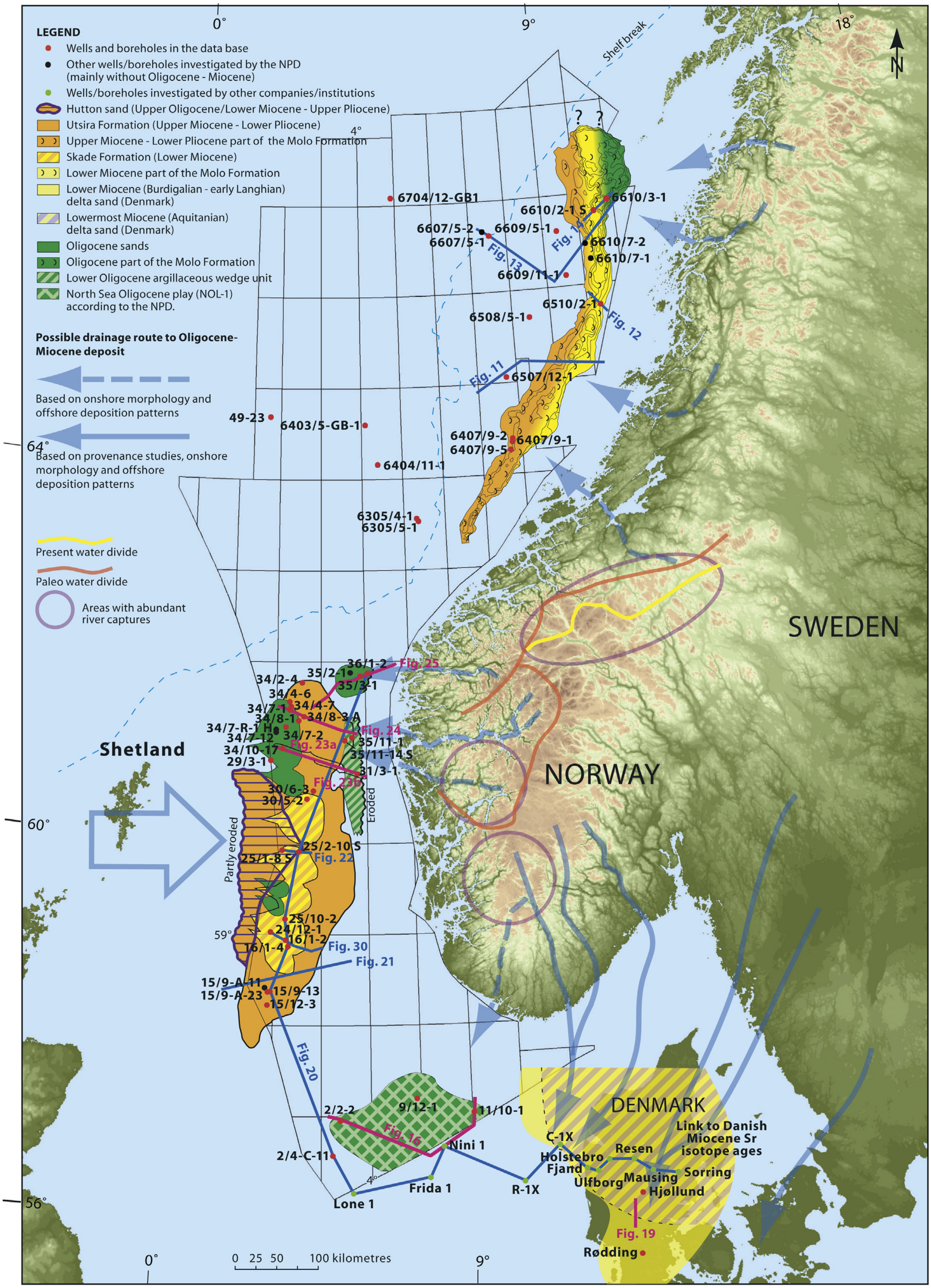


Figure 1. Oligocene to Pliocene well and borehole database, seismic profiles and Oligocene to Lower Pliocene sandy deposits in the North Sea, Norwegian Sea and on the continental shelf of the Norwegian Sea. The extent of the Oligocene sands and wedge unit and the Utsira and Skade formations is according to Rundberg and Eidvin (2005). The extent of the Molo Formation is according to Bullimore et al. (2005). The extent of the North Sea Oligocene play (NOL-1) is according to the Norwegian Petroleum Directorate web page (www.npd.no). The provenance study is after Olivarius (2009) and the topographic map is after Olesen et al. (2010). The extent of the Hutton sand (Upper Oligocene/Lower Miocene-Upper Pliocene, informal) is modified after Gregersen and Johannessen (2007). In the British sector, the Lower Miocene part of the Hutton sand probably corresponds to the Skade Formation in the Norwegian sector, and the Upper Miocene – Lower Pliocene part of the Hutton sand probably corresponds to the Utsira Formation in the Norwegian sector.

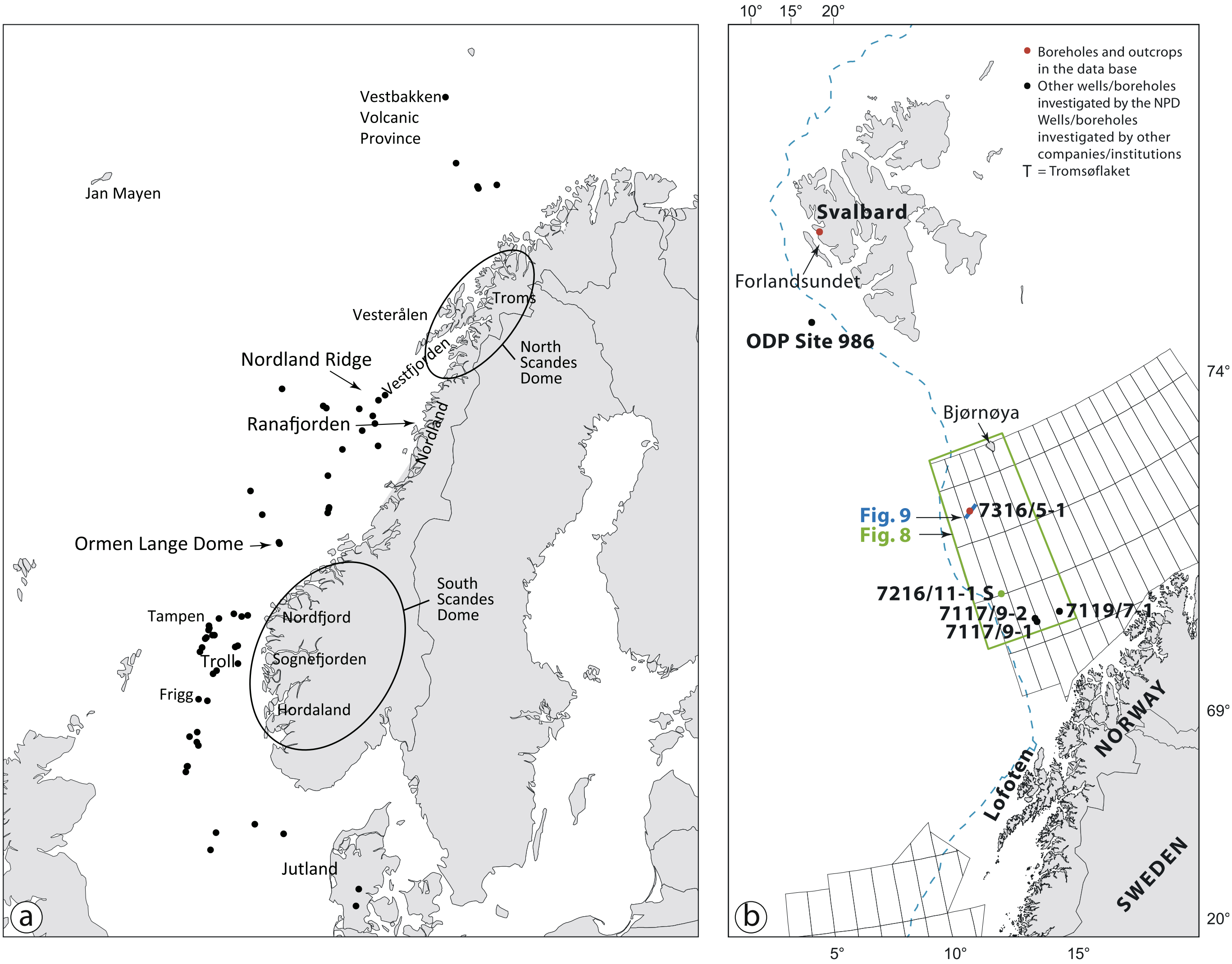


Figure 2. **a**) Location map. Studied wells in the Norwegian sector are shown by black dots. The North and South Scandes domes are outlined, N = Nordland Ridge, R = Ranafjorden, OLD = Ormen Lange Dome. **b**) Oligocene to Pliocene well, borehole and outcrop database and seismic profiles in the western Barents Sea and Svalbard.

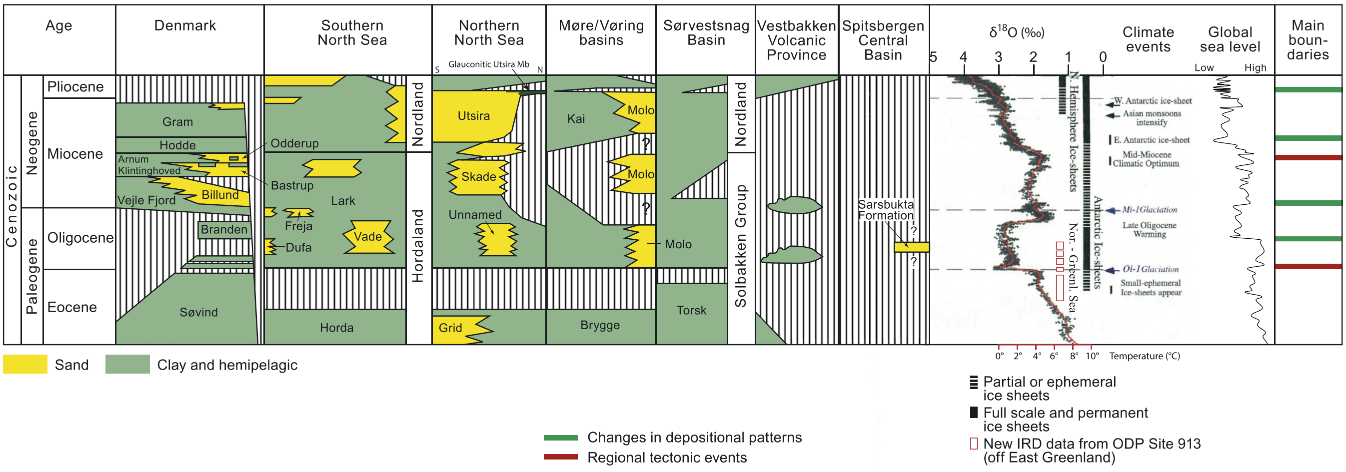
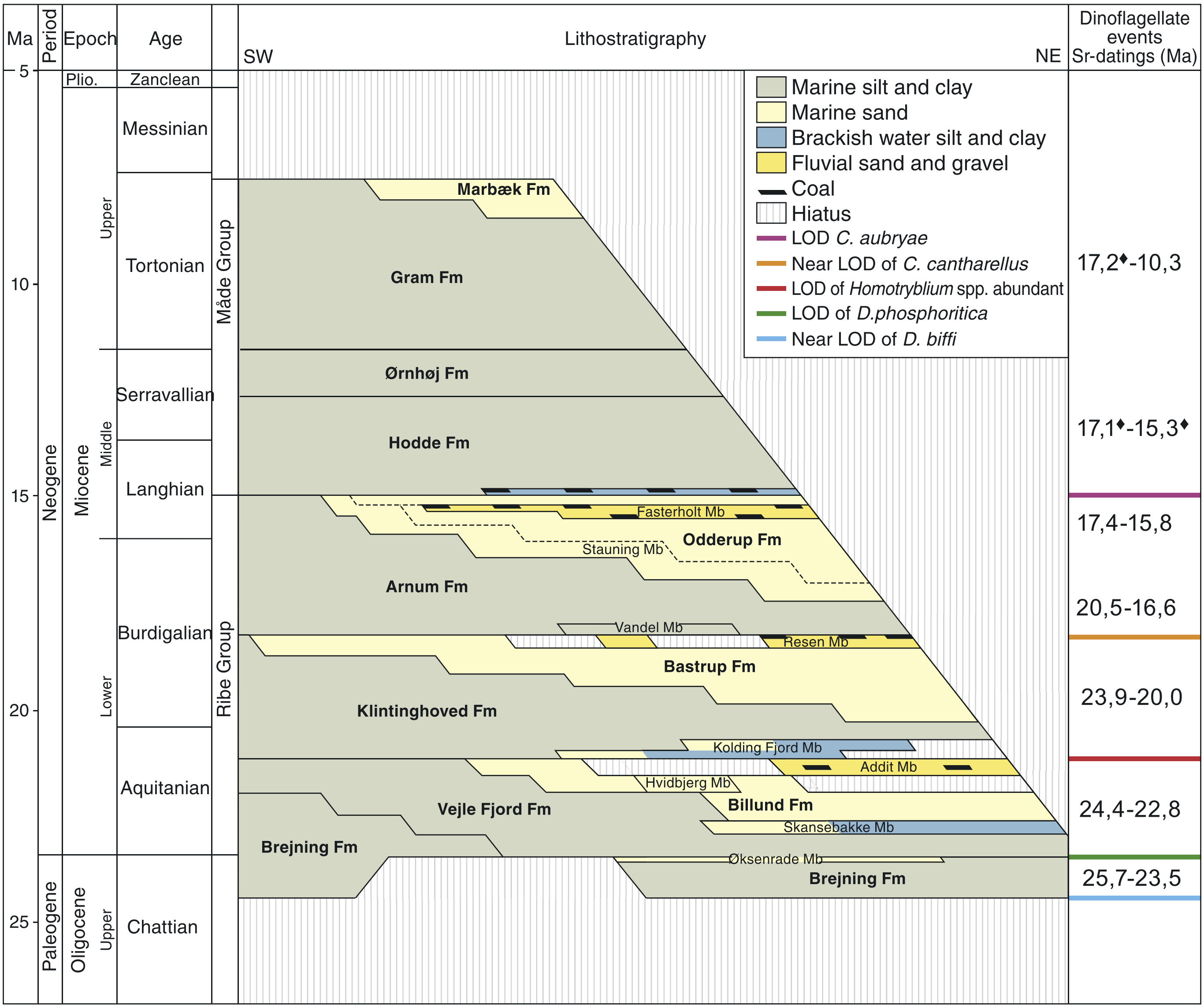


Figure 3. General view of the Late Paleogene and Neogene lithostratigraphy in the investigated areas modified after Rundberg and Eidvin (2005), Rasmussen et al. (2008), and Eidvin et al. (2010, 2013d). On the right-hand side of the diagram there are some paleoclimatic data including a global deep-sea oxygen curve and periods with ice-sheets in the Antarctica and northern hemisphere (after Zachos et al., 2001), and a global sea-level curve after Hardenbol et al. (1998). Periods with deposition of IRD at ODP Site 913 (off East Greenland; Eldrett et al., 2007) and changes in depositional patterns and tectonic events referred to in the text are also indicated.



♦ = These ages are considerably older than the ages obtained from dinocyst correlations according to Eidvin et al. (submitted).

Figure 4. Lithostratigraphy of the Danish Miocene and latest Oligocene (from Rasmussen et al., 2010). The column to the right shows the palynological stratigraphy of Dybkjær and Piasecki (2008, 2010) and the main results of the strontium isotope datings of mollusc tests from outcrop and borehole samples to facilitate a correlation with Norwegian wells and boreholes (modified after Eidvin et al., 2010). LOD = Last occurrence datum.

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.

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 the stratigraphical understanding. Several scientific investigations have tried to improve this situation, including those of Gregersen (1998), Gregersen and Johannessen (2007), Gregersen et al. (1997), Henriksen et al. (2005), Jarsve et al. (submitted), Jordt et al. (1995, 2000), Løseth and Henriksen (2005), Martinsen et al. (1999), Michelsen and 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

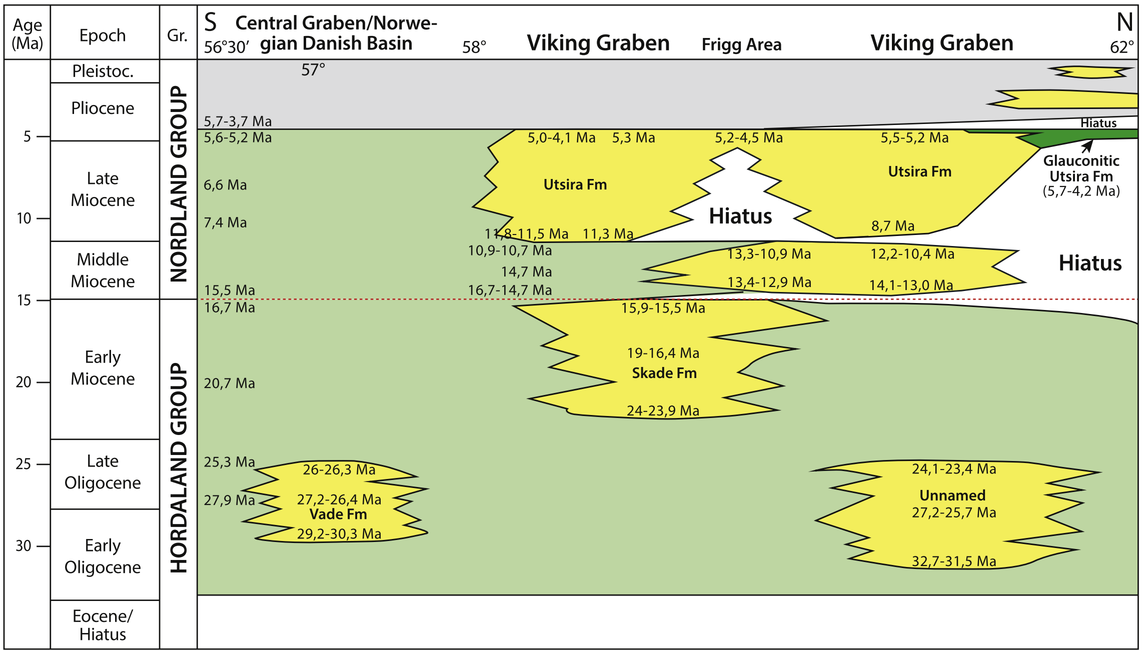


Figure 5. Post-Eocene lithostratigraphy of the Norwegian North Sea including the main results of the strontium isotope analyses based on fossil tests interpreted to be *in situ* (after Eidvin et al., 2013d).

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, 2005ab) and Stoker et al. (2005ab), are less affected by this problem since their seismic data, to a large extent, are calibrated with data from deep-sea ODP/DSDP boreholes.

Based on the revised and new biostratigraphic data, Eidvin et al. (2013d) presented a suggestion for an update of the lithostratigraphic nomenclature for the post-Eocene succession on the Norwegian continental shelf, and suggestions for new type- and reference wells. These suggestions will not be discussed here.

In Jutland, Denmark (Jylland in Danish, Figs. 1 and 2a), upper Paleogene and Neogene sediments occur below the glacial deposits over large areas. 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 cysts zonation scheme (Dybkjær and 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 and 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 and Piasecki, 2008, 2010) to 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. (submitted), but the main results are shown here in Figure 4.

In the present paper, 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 Howarth and 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), except that the base Pleistocene has been moved from 1.85 Ma to 2.588 Ma. All depths are expressed as metres below the rig floor (m RKB) if not stated otherwise.

2. Geological setting

The Oligocene and Miocene sediments investigated for this paper are sampled from wells, boreholes and outcrops which belong to six different provinces along the North Atlantic Margin and the North Sea described below. 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 (Fig. 2a) was initiated. This event corresponds to the approximate Eocene–Oligocene boundary, e.g. Faleide et al. (1996) and Eidvin et al. (1998b; Fig. 3). 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,

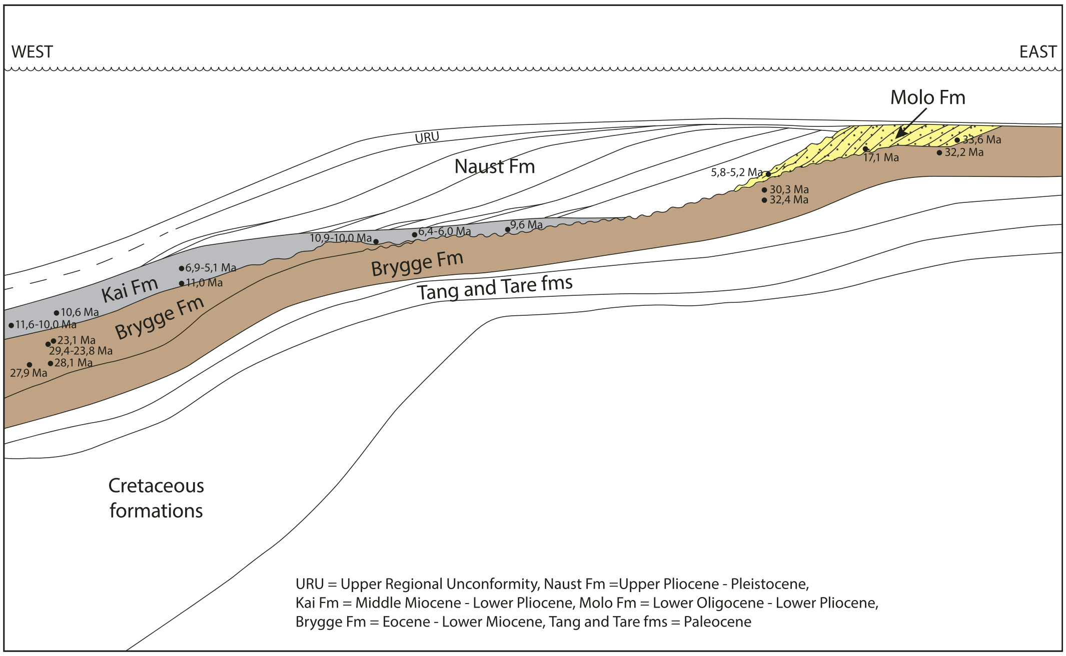


Figure 6. Schematic and generalised cross-section of the Norwegian Sea shelf (modified after Henriksen et al., 2005) including main results of the strontium isotope analyses based on fossil tests interpreted to be *in situ* (after Eidvin and Riis, 2013).

passive-margin setting, although an event of Middle Miocene compression is recorded in the Norwegian Sea and southern North Sea (Fig. 3). 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 (Laberg et al., 2005b) or eustatic and/or climatic changes which thus influenced the clastic input to the basins.

The Forlandssundet Basin. In Forlandssundet, West Spitsbergen, Cenozoic sediments are infilling an elongate, fault-bounded, basinal structure within the hinterland of the Spitsbergen orogen (Figs. 2b and 7). 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 the 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 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 and Ulleberg (1984) and Eidvin et al. (1998b), whereas Manum and Throndsen (1986) interpreted the sediments as Eocene based on palynological studies.

The Western Barents Sea margin. The present continental margin of the western Barents Sea and Svalbard (Figs. 2b, 8 and 9) 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. Since the Oligocene, 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. Post-Eocene sediments are generally not preserved in the Barents Sea shelf. 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).

The Norwegian Sea and its continental shelf contain various structural elements (Fig. 10). 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). 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 Middle Miocene tectonism. The Trøndelag Platform was tectonically stable since the Triassic. 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, typically 100–200 m thick). Farther west on the present continental shelf, fine-grained clastic sedimentation, partly contouritic, prevailed (Laberg et al., 2005b, Fig. 1, 11–14).

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

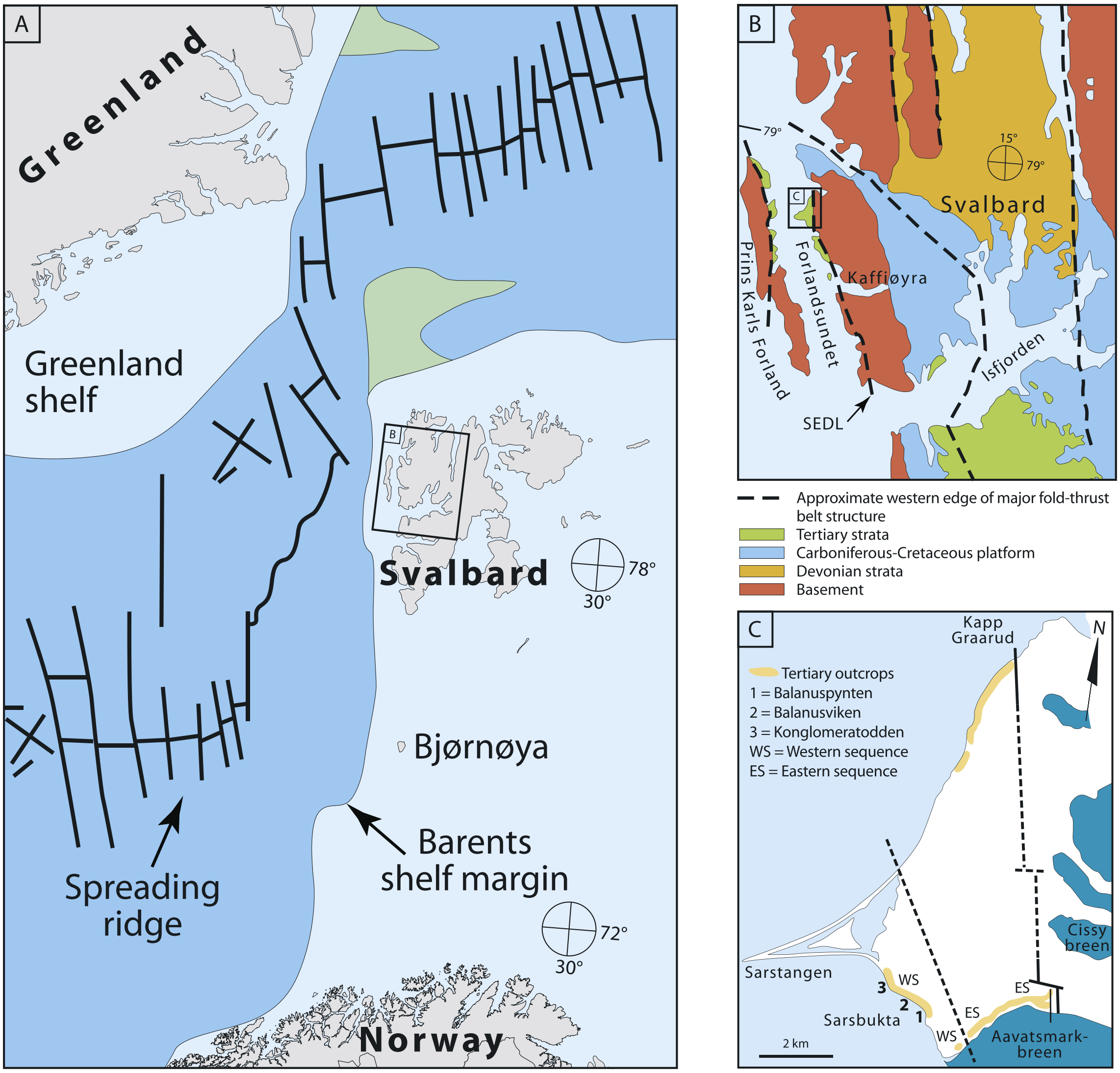


Figure 7. Location of the Forlandsundet graben and Cenozoic outcrops at Sarstangen (modified after Mahler et al., 1997; Bergh et al., 1999).

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 (Figs. 10 and 15). Tectonism 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 and Rundberg, 2001, 2007; Gregersen and Johannessen, 2007; Rundberg and Eidvin, 2005). The depocentres typically contain 200–600 m of Oligocene to Lower Pliocene sands.

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. 15; Ziegler, 1990; Rasmussen, 2005). The basin was formed associated with Permian tectonism and thick sections of salt were deposited (Ziegler, 1982, 1990; Berthelsen, 1992). Parts of the basin were inverted during the Late Cretaceous (Liboriusen et al., 1987; Mogensen and 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 hemipelagic deposits (Surlyk and Lykke-Andersen, 2007; Heilmann-Clausen et al., 1985). The tectonic phase at the Eocene–Oligocene transition was accompanied by progradation of Early – Late Oligocene deltas off southern Norway (Schiøler et al., 2007). The thickness of the sandy sections is typically in the order of tens of metres. 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). According to Dybkjær and Piasecki (2008), some of the most important aquifers in Jutland, western Denmark (Fig. 2a), are sand layers deposited in the Early to Middle Miocene. The Miocene section is in order of 2–300 m thick.

Increased subsidence in the Middle Miocene resulted in flooding of the area and sedimentation of clay-dominated marine

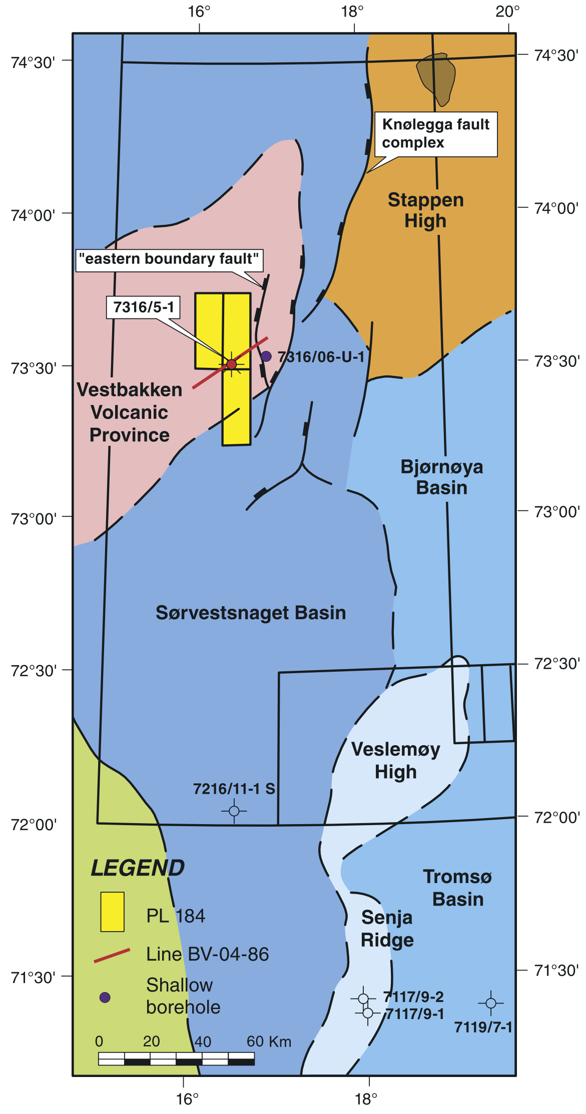


Figure 8. Location of the regional seismic line NPD BV-04-86 and well 7316/5-1. Main structural features and location of other wells and shallow boreholes referred to in the text are also shown (modified after Eidvin et al., 1998b). See Fig. 2b for a larger regional location.

sediments. This was succeeded by progradation of the shoreline during both the latest Late Miocene and Late Pliocene when the shoreline prograded towards the Central Graben. A distinct tilting of the Norwegian–Danish Basin commenced in the late Neogene (Jensen and 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 its marginal parts (Figs. 1 and 16).

The Scandes Mountains is a descriptive name commonly used for the western Scandinavia highlands, which are 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 and Näslund, 2002).

3. Material and methods

From the Norwegian continental shelf, Norwegian Sea, Svalbard and onshore Denmark, 1700 samples from 49 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 four wells, and conventional cores were available from four wells and two boreholes. One gravity core was also analysed (see Figs. 17 and 18).

3.1. 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).

The fossil assemblages are correlated with the micropalaeontological zonation for Cenozoic sediments of King (1983, 1989). Gradstein and 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 and Clement, 1986, 1987; Spiegler and Jansen, 1989) and *Bolboforma* (Spiegler and Müller, 1992; Müller and 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.

3.2. Lithological analyses

The lithological analyses are based on visual examination of the samples prior to treatment, and the dissolved and fractionated material after preparation (Eidvin et al., 2013d).

3.3. Sr isotope analyses

Strontium isotope stratigraphy is used as an additional control for the biostratigraphic correlations. 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 (Howarth and 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 used. One shark tooth was also used (Eidvin et al., 2013d). 129 of these samples were taken from the Danish onshore boreholes and outcrops investigated palynologically by Dybkjær and Piasecki (2008, 2010). 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

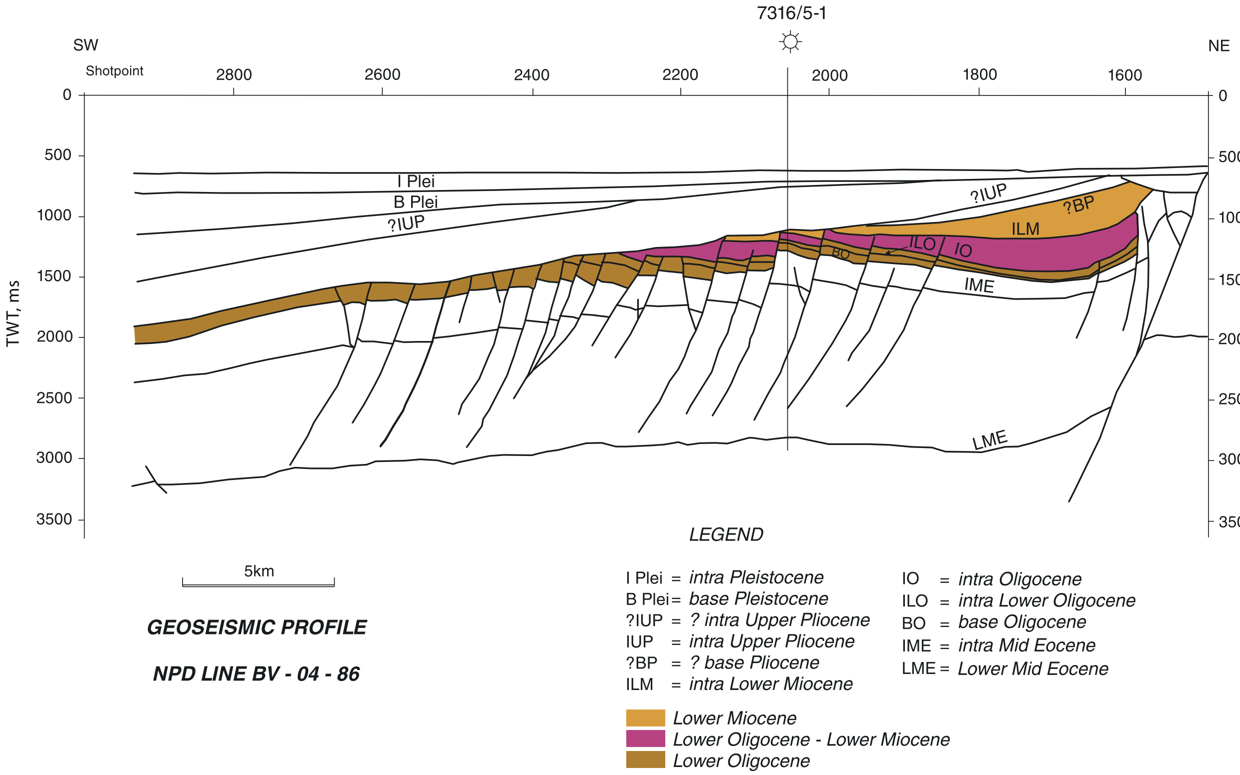


Figure 9. Digitised seismic line NPD BV-04-86 (modified after Eidvin et al., 1998b).

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 Howarth and McArthur (1997); see McArthur et al. (2001), Eidvin and Rundberg (2001, 2007) and Eidvin et al. (2013d) for more details about the method.

3.4. *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; Fig 2a) 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 Figs. 1, 2b, 9, 11–14, 16, 19–25 and 30). 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 1800–2100 m/s. The principles of seismic stratigraphy of Brown and Fisher (1977) and concepts of sequence stratigraphy of Posamentier et al. (1988) and Hunt and Tucker (1992, 1995) have been applied.

4. Lower Oligocene

Lower Oligocene deposits are recorded in outcrop at Forlandsundet (Spitsbergen), and in 23 wells on the Norwegian continental shelf and in the Norwegian Sea (see Figs. 17 and 18; Eidvin et al., 2013d).

4.1. *Regional synthesis*

4.1.1. *Forlandsundet, Svalbard*

Forlandssundet Basin is a partly fault-bounded structure trending north–south along the west coast of Spitsbergen (Figs. 2b and 7). The western border fault of the Forlandssundet Basin is exposed on Prins Karls Forland (Fig. 7), 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 syn-tectonic Cenozoic fill is deformed by both extensional and oblique-contractional structures (Gabrielsen et al., 1992; Kleinspehn and Teyssier, 1992; Lepvrier, 1992; Bergh et al., 1999).

Feyling-Hanssen and Ulleberg (1984) described two outcrops of Oligocene deposits at Balanusviken, Sarsbukta, on the east side of Forlandsundet (western sequence according to Berg et al., 1999). On the basis of benthic calcareous foraminiferal assemblages in nine samples, these authors divided the sections into two zones: the overlying *Astigerina guerichi* Zone and the underlying *Bolivina* cf. *antique* Zone. Feyling-Hanssen and 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 and 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 Eidvin et al. (2013d), that result has been revised to slightly older ages of latest Early Oligocene by use of the Sr look-up table presented by Howarth and McArthur (1997). Eidvin et al. (1998b) concluded that most of the

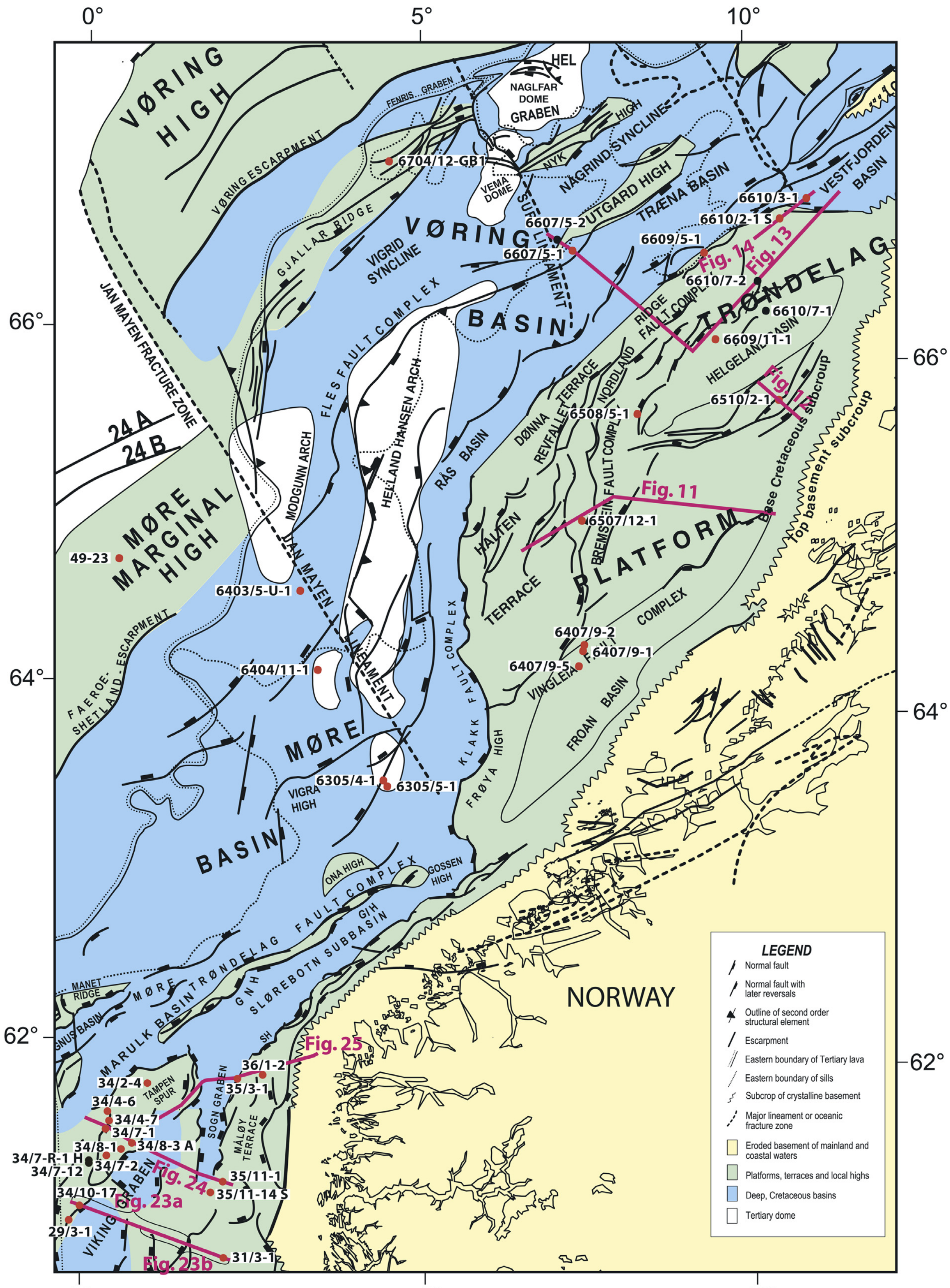


Figure 10. Map showing structural elements and seismic lines in the Norwegian Sea and its continental shelf, and in the northernmost part of the North Sea (modified after Brekke, 2000). Red dots are investigated wells and boreholes, black dots are wells and boreholes referred to, and magenta lines are locations of seismic profiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

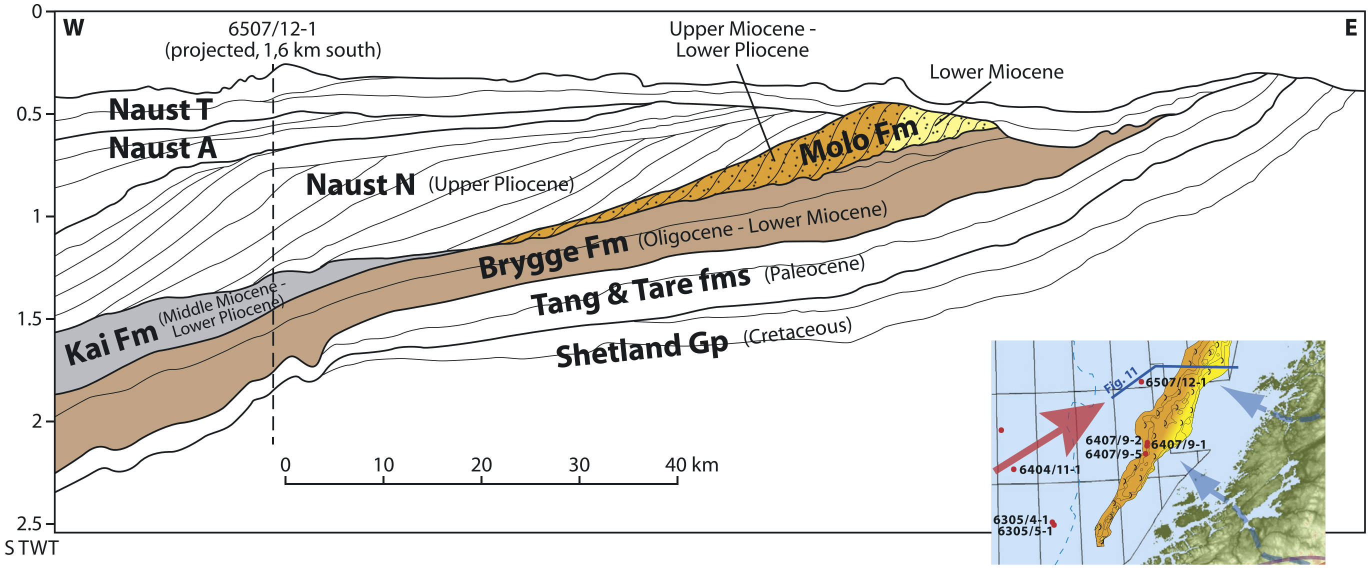


Figure 11. Geoseismic section showing the Middle part of the Molo Formation (see also Fig. 1 for location; modified after Eidvin et al., 2007). The boundary between the Lower Miocene and Upper Miocene – Lower Pliocene parts of the Molo Formation is tentative (after Eidvin and Riis, 2013).

recorded dinoflagellates identified by Manum and Throndsen (1986) are older Paleogene forms reworked into Oligocene strata.

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. This age relationship, however, is opposite to that interpreted by Gabrielsen et al. (1992). 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).

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 are not available for this study. The thickness of the Cenozoic section recorded implies that the lowermost Cenozoic rocks in the basin may not have been dated in the outcrop samples.

4.1.2. *Vestbakken Volcanic Province, western Barents Sea*

According to Eidvin et al. (1998b, 2013d), well 7316/5-1 (Figs. 2b, 8 and 9) 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 (Fig. 18; Eidvin et al., 2013d). 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 (Figs. 9 and 17). 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 (Fig. 2b). 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.

4.1.3. *Norwegian Sea and its continental shelf*

According to Eidvin and Riis (2013) and Eidvin et al. (1998a, 2007, 2013d), 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; Fig. 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 (Eidvin et al., 1998a, 2007, 2013d, Figs. 13 and 14). 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 6508/5-1,6609/5-1 and 6607/5-1 (Figs. 1, 10, 17 and 18). 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 wells 6407/9-1, 6407/9-2, 6407/9-5, 6507/12-1 and 6609/11-1 on the Trøndelag Platform

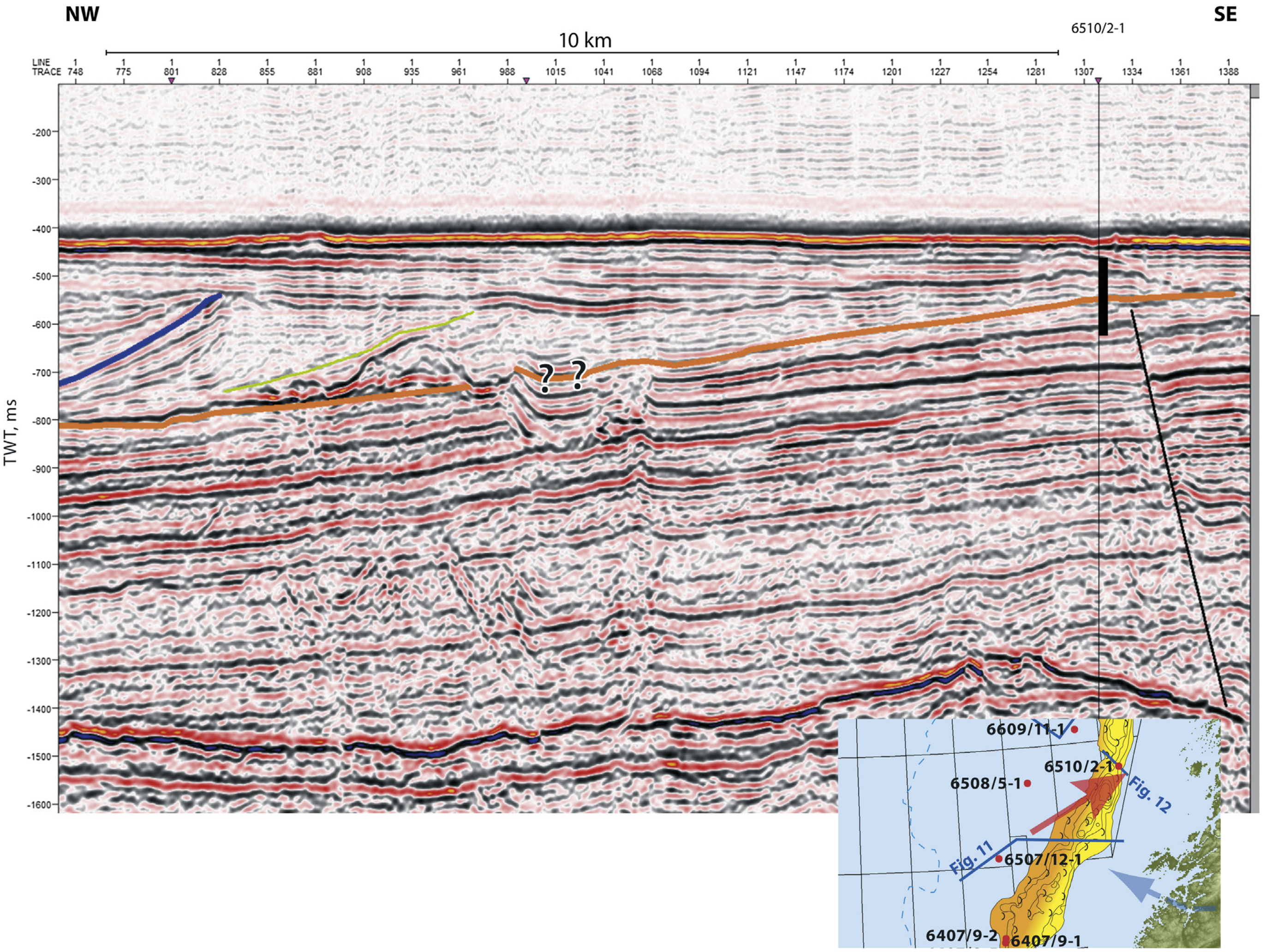


Figure 12. Seismic 2D line SH9601-409 showing the development of the Molo Formation in a profile through exploration well 6510/2-1 on the Vega High. The black rectangle shows the studied interval, dated to Eocene in the lower part and Early Miocene in the upper part. The Miocene section (above the orange line) consists of a glauconite-rich, quartzose sand deposited in a neritic environment. In this area, only the outer parts of the Molo sand system, believed to be of a Late Miocene and Early Pliocene age, show a distinct progradation indicated by green and blue lines (after Eidvin and Riis, 2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and in well 6610/2-1 S on the Nordland Ridge. 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; Figs. 10, 17 and 18). These sections are overall fine-grained and are recognised by semi-transparent and parallel, seismic facies patterns (Henriksen et al., 2005). In the outer 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 only been investigated in well 6610/2-1 S, and the age of the lowermost part, which lies unconformably on the Middle Eocene (Fig. 17), is slightly younger than Late Eocene. The sandy, deltaic, Lower Oligocene section in well 6610/3-1 can be tied to its distal equivalent in 6610/2-1 S in 3D seismic data (Fig. 14).

4.1.4. North Sea

In the Norwegian sector of the North Sea, the Lower Oligocene sediments 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 from the Scandes southwards into the Norwegian–Danish Basin (Eidvin et al., 2013d; Jarsve et al., submitted).

4.1.4.1. Northern North Sea. Based on well log correlation, Rundberg and 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, according to Eidvin et al. (2013d) wells 34/10-17, 35/3-1, 36/1-2 and 31/3-1 show that only unit UH-1 and the lowermost part of unit UH-2 (recorded in well 36/1-2 and probably 34/10-17) are of Early Oligocene age (Figs. 1, 17, 18, 23 and 25). The Lower Oligocene part of UH-2 in well 36/1-2 (Agat Discovery area) contains 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 (Fig. 17). Gradstein et al. (1992) recorded a break between the Lower Oligocene and Middle Eocene in wells 34/8-1 (Tampen area, Figs. 2a and 15) and 16/1-1 (southern Viking Graben, Fig. 15).

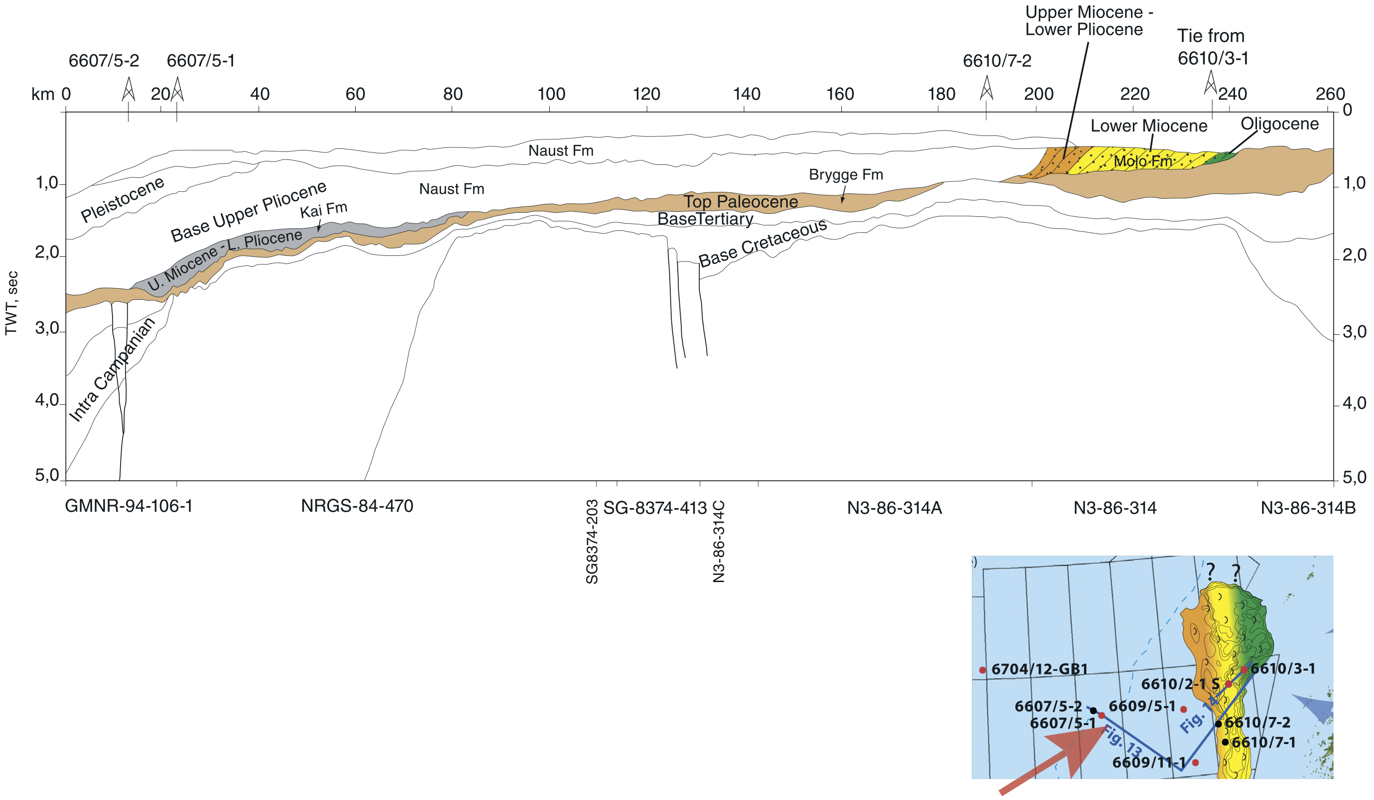


Figure 13. Regional geoseismic line across the Utgaard High and along the Nordland Ridge through wells 6607/5-1 and 6607/7-2. The boundaries between the Oligocene, Lower Miocene and Upper Miocene – Lower Pliocene parts of the Molo Formation are tentative (after Eidvin and Riis, 2013).

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 (Fig. 25). It is likely that the deposits are erosional products derived from the western part of the Fennoscandian Shield in the present-day Nordfjord area (Fig. 2a). Farther south towards the Troll Field area (Fig. 2a), a distinct wedge of organic-rich mudstones strikes parallel to the western coast of Norway (Fig. 1). This wedge has a slightly older Early Oligocene age than 36/1-2 (investigated in well 31/3-1; Figs. 17 and 23). 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.

4.1.4.2. Central North Sea, northern Central Graben. The Oligocene in well 2/4-C-11 (Figs. 1, 17 and 20), comprises mostly clay with some components of silt and sand (Eidvin et al., 2013d). 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 in 2/4-C-11.

4.1.4.3. 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 (Figs. 1, 16 and 17; see also Jarsve et al., submitted). 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; Figs. 1 and 16). In the marginal, north-eastern 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.

4.2. 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. 3). 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 onshore strata, 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 (Figs. 3 and 26). 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 (Fig. 26), and they pointed to East Greenland as the likely source. Previously, the existence of Northern Hemisphere ice sheets had been demonstrated back to the Middle Miocene

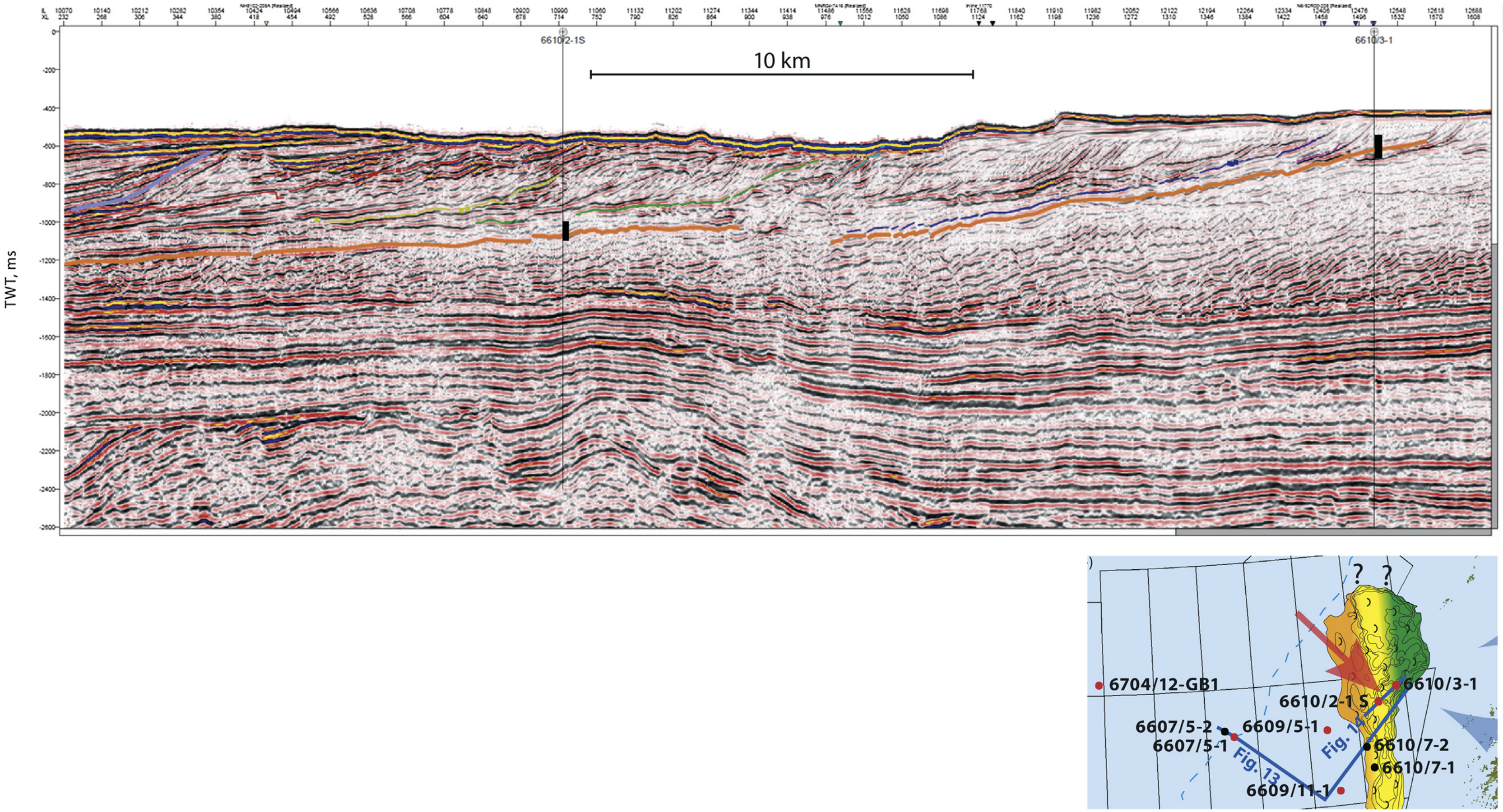


Figure 14. Seismic 3D line generated from the ST9404 cube, showing the development of the northern part of the Molo Formation in a profile through exploration wells 6610/2-1 S and 6610/3-1. The seismic data are consistent with the biostratigraphy indicating that Early Oligocene sediments are distal and fine-grained in 6610/2-1 S whereas they belong to a sandy progradational unit in 6610/3-1. In both profiles, the orange horizon marks the base of the Oligocene whereas the blue horizon indicates the boundary between the Molo and the Naust formations. Some undated internal boundaries (green lines) within the Molo progradation have also been marked. Black rectangles show the studied, Eocene and Early Oligocene intervals (after Eidvin and Riis, 2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

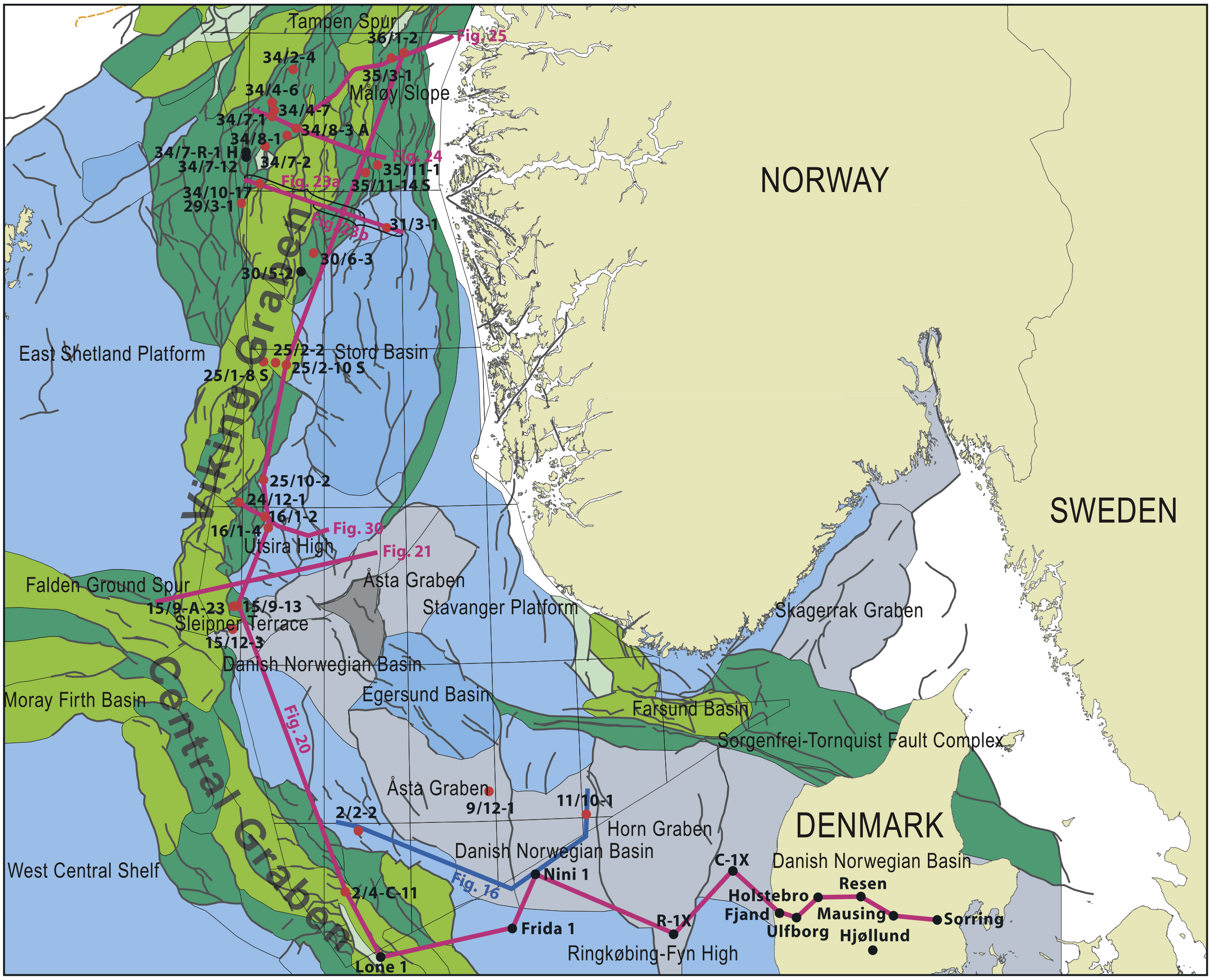


Figure 15. Map showing structural elements and seismic lines in the North Sea and Norwegian–Danish Basin. Red dots are investigated wells and boreholes, black dots are wells and boreholes referred to, and magenta and blue lines are locations of seismic profiles. The map is taken from the Norwegian Petroleum Directorate web page (www.npd.no). See Fig. 10 for legend. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(approximately 15 Ma; Winkler et al., 2002; Helland and 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 and Manum (1996) have recorded organic assemblages (pollen, spores, dinoflagellate cysts and plant debris) of mid Oligocene sediments from the Hovgård Ridge (ODP Site 908, Fig. 26). The assemblages are dominantly of terrestrial origin, and their present position, in the middle of the Fram Strait (Greenland Sea), can be explained with 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 sediments present 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; Fig. 2b). Boulter and 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.

5. Upper Oligocene

Upper Oligocene deposits (including Lower–Upper Oligocene deposits) are recorded in 28 wells and one gravity core on the

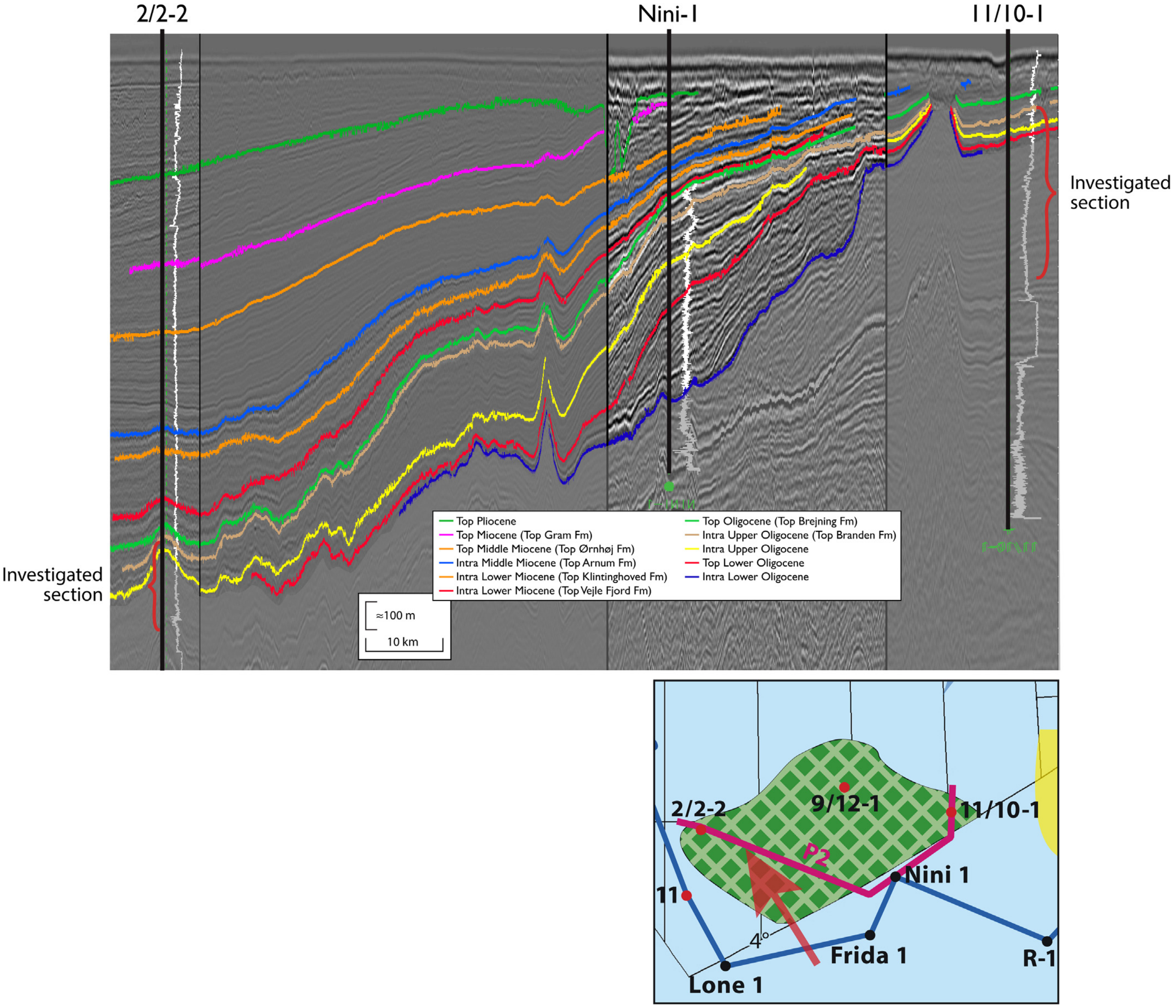


Figure 16. Seismic line tying the well 11/10-1, Nini-1 (Danish sector) and well 2/2-2 (gamma ray logs are included for all wells). The profile shows the Oligocene–Miocene progradational shelf-slope system. Note especially the huge Oligocene system where 11/10-1 and 2/2-2 represent the shelf and basin floor, respectively. The investigated sections in 11/10-1 and 2/2-2 are marked by brackets. The datings of the Miocene seismic reflectors and partly the Oligocene are based on the investigation of well Nini-1 (after Sliwinska et al., 2010; see also Fig. 1 for location).

Norwegian continental shelf and the Norwegian Sea and in two borehole onshore Denmark (Figs. 17 and 18; Eidvin et al., 2013d).

5.1. Regional synthesis

5.1.1. 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 regional distinct hiatus or unconformity recorded 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 (Figs. 2b, 8 and 9; Eidvin et al., 1998b, 2013d). Expanded sections are also expected towards the oceanic crust in the west. 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, 2013d).

5.1.2. 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 (Fig. 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. In the Møre Basin, the Upper Oligocene was investigated in well 6305/5-1, and the lower part of the Upper Oligocene in wells 6305/4-1, 6404/11-1 and the gravity core 49-29

(Figs. 1, 10 and 18). In the Vøring Basin, the Upper Oligocene is present at DSDP Site 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.

5.1.3. *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 (Figs. 1 and 2a). Farther south, Upper Oligocene sandy deposits are recorded below the Skade Formation in the Frigg Field area (Fig. 2a), i.e., within the area belonging to the Hutton sand according to Gregersen and Johannessen (2007; Figs. 1 and 22). The Lower – Upper Oligocene sands are unnamed in the Norwegian sector of the northern North Sea (Fig. 5). 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 (Figs. 1 and 2a).

5.1.4. *Northern North Sea*

We have analysed the sandy section in wells 34/10-17, 35/3-1, 36/1-2 and 25/1-8 S (Eidvin et al., 2013d). The western sands (quadrants 30, 34 and 25) shale out to the east and are sourced from the Shetland Platform (Figs. 1, 22 and 23), while the eastern sands (blocks 35/3 and 36/1) appear to be sourced from the Nordfjord area, West Norway (Figs. 2a and 25). 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, 2013), and the distribution of massive diapirism seems to coincide with the central and outer parts of the Oligocene and Miocene sandy systems (NPD, 2011).

Mud diapirs typically contain sand intrusions which can commonly be recognised in seismic data as V-shaped reflections (Løseth et al., 2003, 2013). Care must be taken in the biostratigraphic analysis to avoid misinterpretation of intrusive sands as *in situ*. Seismic data indicates that mud diapirism has taken place in different phases. Within the diapir areas, 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.

Between 60° and 61°N east of well 34/10-17, the top of the Upper Oligocene (unit UH-2 of Rundberg and Eidvin, 2005) is defined by a moderate- to high-amplitude, semi-continuous seismic reflector in the eastern part of the basin (Figs. 1 and 23). 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 60° and 61°N according to Rundberg and 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 and Eidvin, 2005) and the Lower Miocene (unit UH-4 of Rundberg and Eidvin, 2005).

Farther west, the unit UH-2 is strongly disturbed by diapirism, and it is difficult to map the top. It is probably best defined at about 60°45′–61°N, as illustrated in Figure 23. 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 the thick sandy interval, which is penetrated in wells 34/10-17 and 34/10-23. The sands make up a gross thickness of about 400 m in block 34/10 (Fig. 23). In well 34/10-17, the fossil data confirm that the sands belong to the sequence and have not been injected (Eidvin et al., 2013d).

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, classified as part of the Hutton sand in the UK sector, 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 (Figs. 1 and 2a). In seismic sections, this sandy system is illustrated by wedging of the Oligocene strata (Figs. 22 and 23).

Sands continued to be derived from an easterly source (Nordfjord) during the Late Oligocene in the Agat Discovery area (Figs. 1, 2a and 25). Most of these sands are contemporaneous with sands of the Statfjord Field and Frigg Field areas (Figs. 2a and 17).

In wells in the northern Tampen area the Upper Oligocene consists of silty mudstones. In 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 (Fig. 1), the unit contains mainly fine-grained material (Eidvin and Rundberg, 2001, 2007; Rundberg and Eidvin, 2005; Eidvin et al., 2013d).

5.1.5. *Northern Central Graben*

In well 2/4-C-11 (Fig. 1), the Upper Oligocene comprises mostly clay with intercalations of silt, sand and some limestone stringers (Eidvin et al., 1999, 2000, 2013d). These deposits were laid down in a deep-marine setting beyond the deltaic slope.

5.1.6. *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 (Figs. 1 and 16; Eidvin et al., 2013d; Jarsve et al., submitted), 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 coal (Fig. 1; Eidvin et al., 2013d; Jarsve et al., submitted), 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; Figs. 1 and 16). 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 the easternmost part of Denmark. The Brejning Formation was deposited mainly in a water depth of more than 200 m,

Geochronology of studied wells, boreholes and outcrops

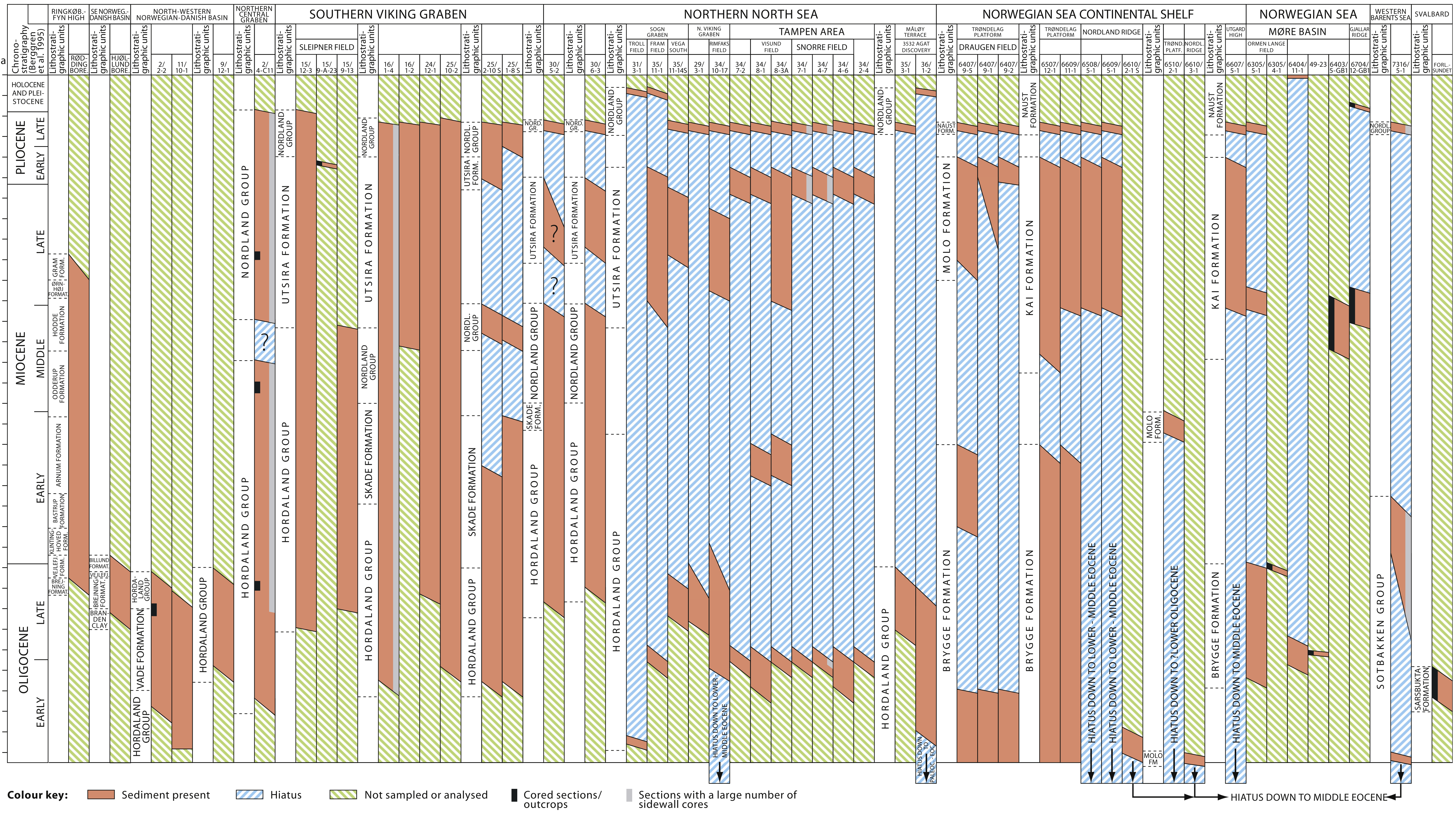


Figure 17. Geochronology of studied wells, boreholes and outcrops. Vertical axis is in Ma.

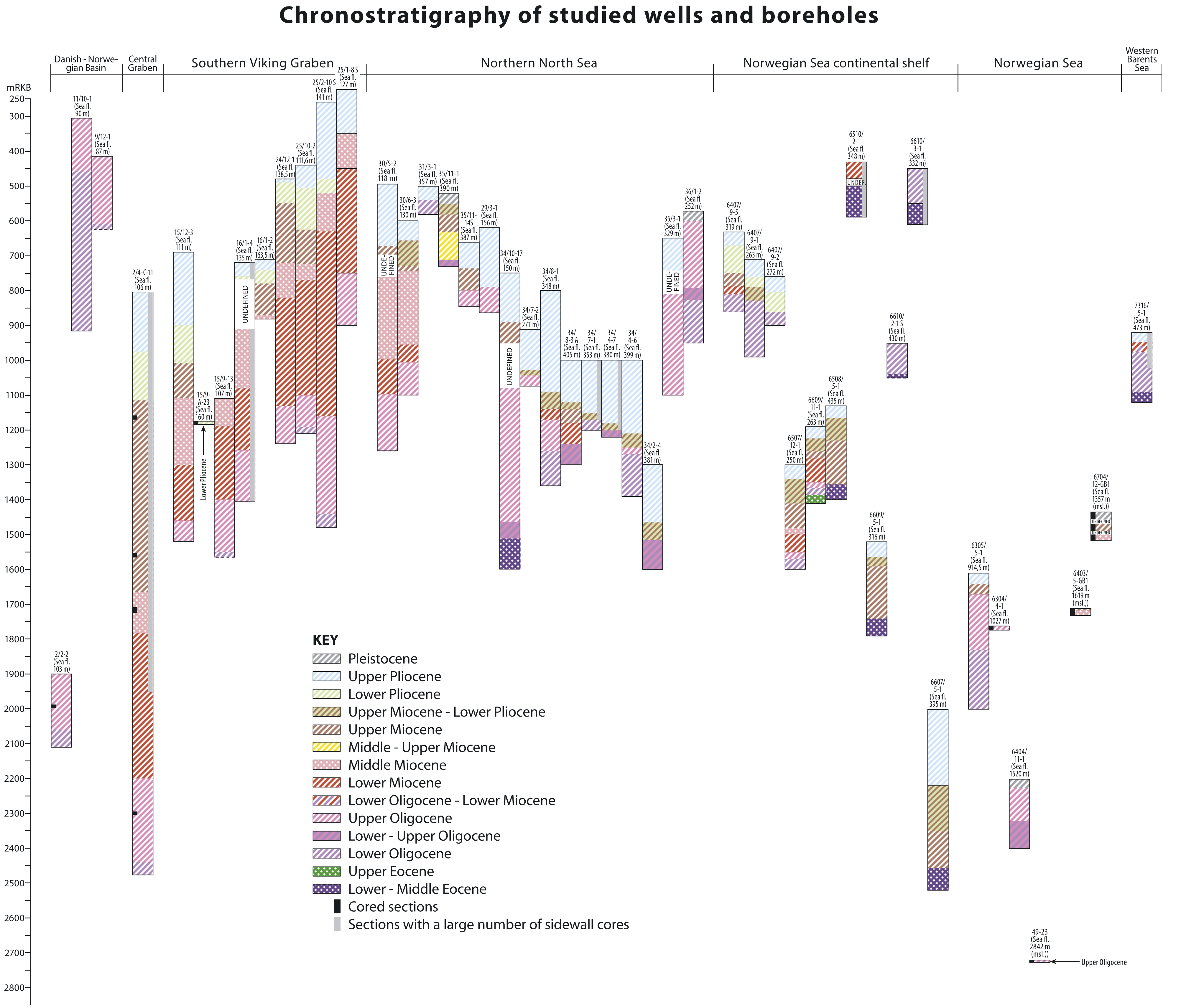


Figure 18. Chronostratigraphy of studied wells and boreholes. All depths are in metres below rig floor, except for the boreholes 6704/12-GB1 and 6403/5-GB1 and the core 49-23 which are in metres below mean sea level. The onshore Hjøllund and Rødding boreholes and the outcrop at Sarsbukta (Forlandsundet, Spitsbergen) are not included in the figure.

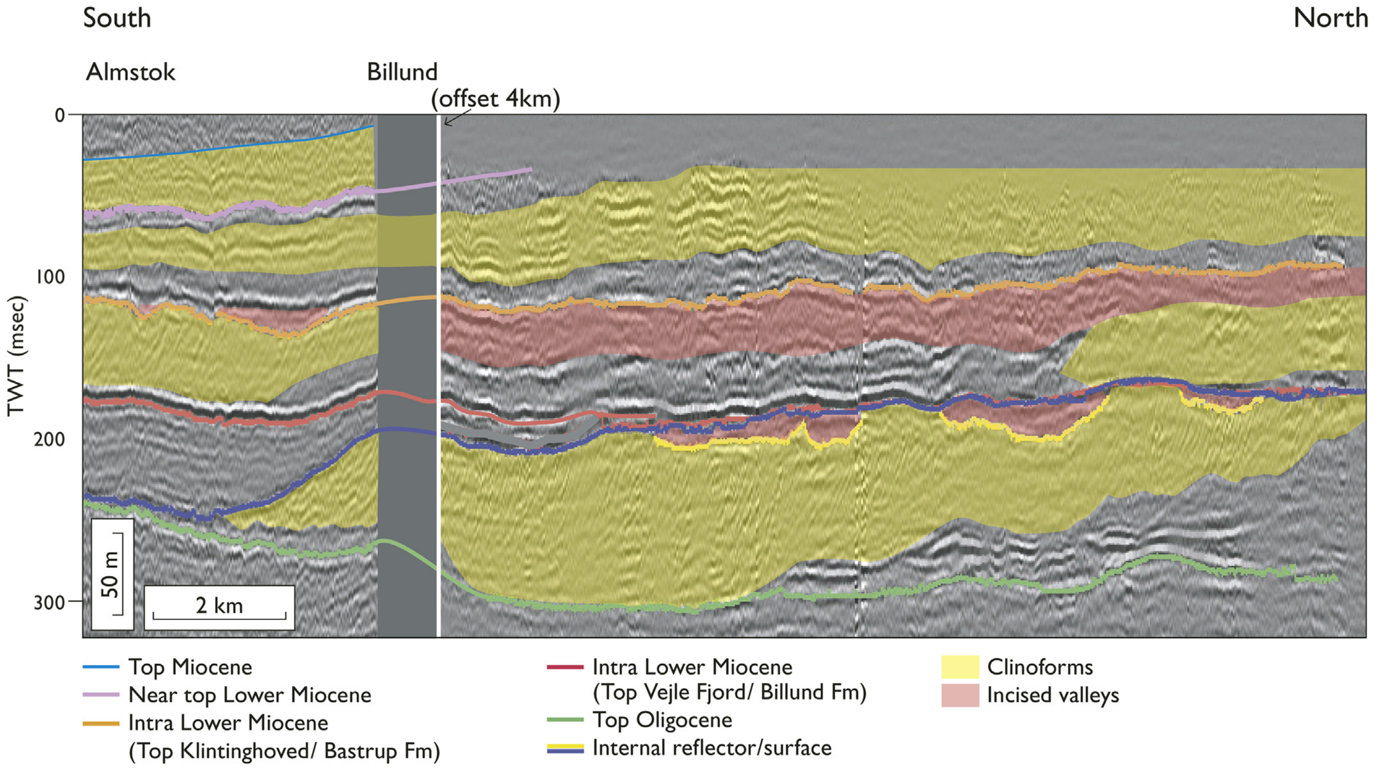


Figure 19. North-south trending seismic section from central Jytland, Denmark showing alternating delta progradation and marine deposits. Note the sand-rich delta lobe deposits indicated in yellow. Fluvial incised valley fill is shown in orange. Note the incised valley north of the Billund well. The southern wall is not imaged on the seismic section due to the offset of 4 km between the two seismic sections. It means that, South of Billund, the shown valley forms a small branch at the fringe of the main incised valley that was located west of the seismic section. This pattern characterised the Norwegian–Danish Basin during the Early Miocene. The Middle – Late Miocene was dominated by marine shelf deposits (see Fig. 1 for location; modified after Eidvin et al., 2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

but the cross-bedded sand and microfossil fauna indicate shallow-water conditions locally on the Ringkøbing-Fyn High at the end of the Oligocene.

5.2. *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. 3). The Antarctic continental ice-sheet that built up during the Early Oligocene persisted until the later part of the Oligocene (27–26 Ma), when the warming trend reduced the extent of Antarctic ice (the Northern Hemisphere ice sheets may have disappeared). From this time until the Middle 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 Middle 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 considerably less distinct than the Middle Miocene optimum warming trend.

6. Lower Miocene

Lower Miocene sediments were studied in 17 wells on the Norwegian continental shelf and in one borehole onshore Denmark (Figs. 17 and 18; Eidvin et al., 2013d).

6.1. *Regional synthesis*

6.1.1. *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 (Fig. 2b), which penetrated an Oligocene – Lower Miocene section below the base Upper Pliocene erosional surface (Fig. 17; Eidvin et al., 2013d). In well 7216/11-1S, there is a hiatus below the Middle Miocene unconformity (Ryseth et al., 2003, Figs. 2b and 3). 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 (Fig. 17; see also the discussion section).

6.1.2. *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 (Figs. 1, 17 and 18) and consists of glauconitic (dominant) and quartzose sand of late Burdigalian age (Eidvin and Riis, 2013; Eidvin et al., 2013d). It is not clear if there is a hiatus or continuous deposition between the Lower Oligocene and Lower Miocene part of the formation (Fig. 3). In the wells 6407/9-5 and 6407/9-3 on the Draugen Field (Fig. 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 Fig. 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. 17). Stratigraphically and age wise, the wedge belongs to the Brygge Formation. The unconformity below the wedge seems to represent more active erosion than the Middle Miocene unconformity on top. There are few signs of erosional products related to any of the two hiati, which indicates that the Middle Miocene Unconformity in this area is more related to non-

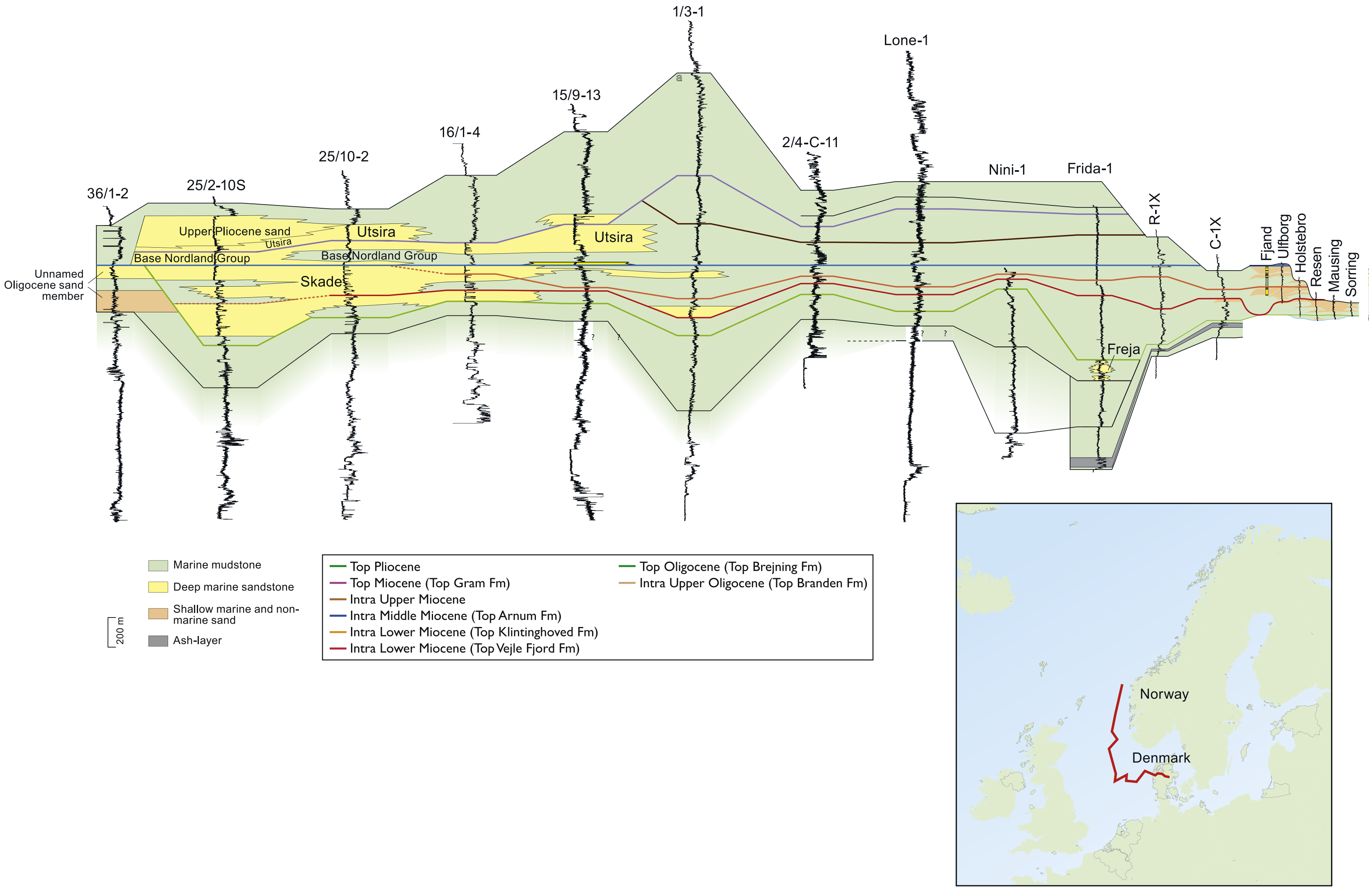


Figure 20. Correlation panel of the Oligocene to Pliocene succession from central Jytland, Denmark, into the North Sea and northward to near Stadt, West Norway. The datum (dark blue line) is the Middle Miocene unconformity (see also Fig. 1 for location; modified after Eidvin et al., 2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

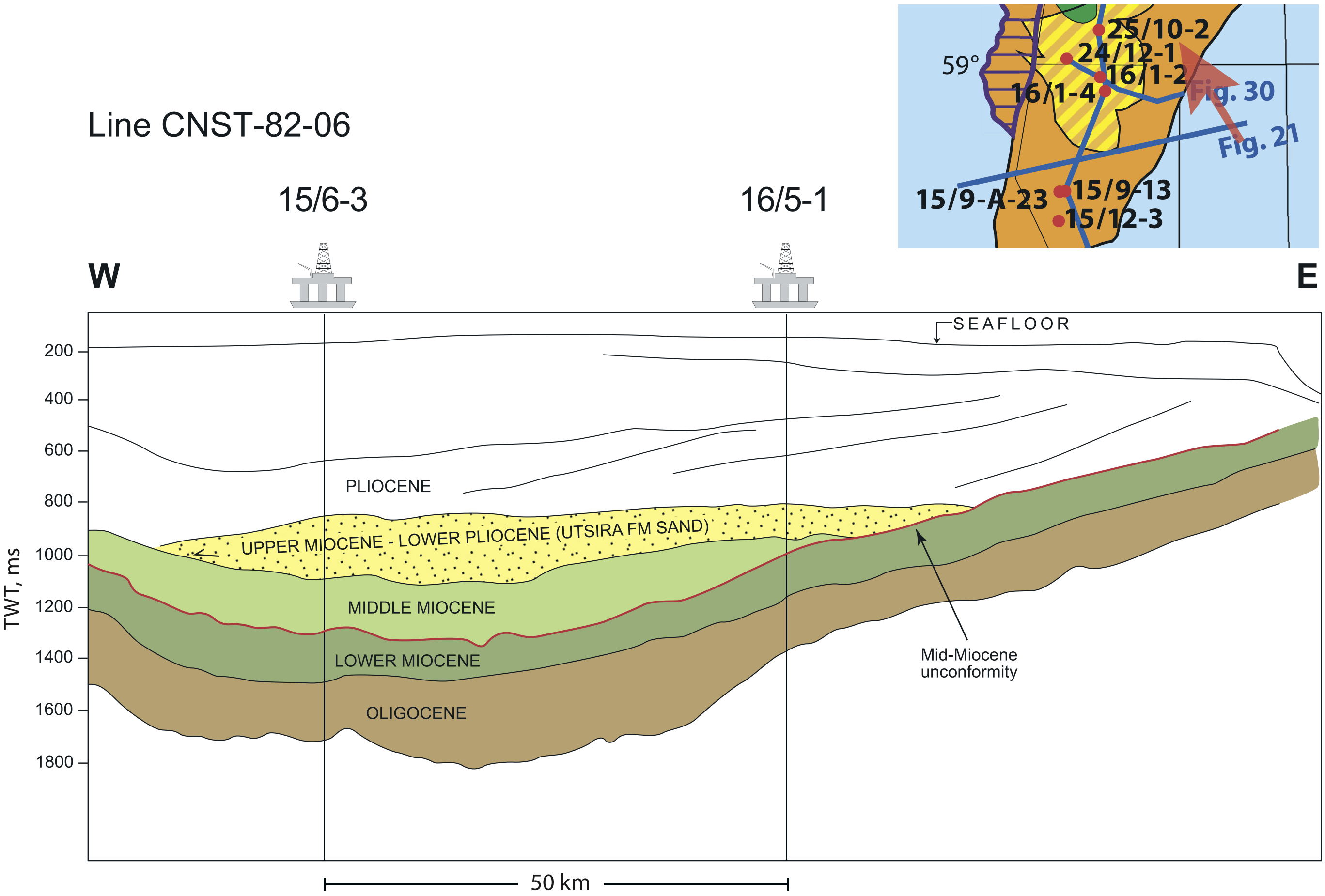


Figure 21. East-west geoprofile of the southern Viking Graben at about 58°30′N illustrating the main sequences and sedimentary architecture of post-Eocene strata (see also Fig. 1 for location; modified after Rundberg and Eidvin, 2005).

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).

6.1.3. 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 (Figs. 2a and 15) .

6.1.4. Northern North Sea

The Lower Miocene (unit UH-4 of Rundberg and 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 (Figs. 1 and 21).

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 is shown in Figure 27. They comprise a succession of amalgamated sands in alternation 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 (Fig. 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 coal, and have probably been deposited in shallower water close to, or as parts of, a delta (Eidvin et al., 2013a and d). According to the mapping of Gregersen and Johannessen (2007), these wells are situated in the distal part of the Hutton sand area (Figs. 1 and 27). 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 Figures 1 and 22, the Hutton sand as defined by Gregersen and Johannessen (2007) extends into the Norwegian sector and continues into the Skade Formation, However, we recommend using the established Norwegian stratigraphy in Norwegian waters.

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, possible associated with a renewed compressional tectonic phase along the northwest European margin (Rundberg and Eidvin, 2005).

The Skade sands pinch out to the east and north. In the Tampen area, the Lower Miocene strata comprise mainly mud-prone lithologies in a distal setting. Just south of 61°N and northwards, the Lower Miocene unit is only present in the central basin and absent at the margins to the west and east (Fig. 27). It may be present locally in depressions between diapirs. On seismic sections, the top

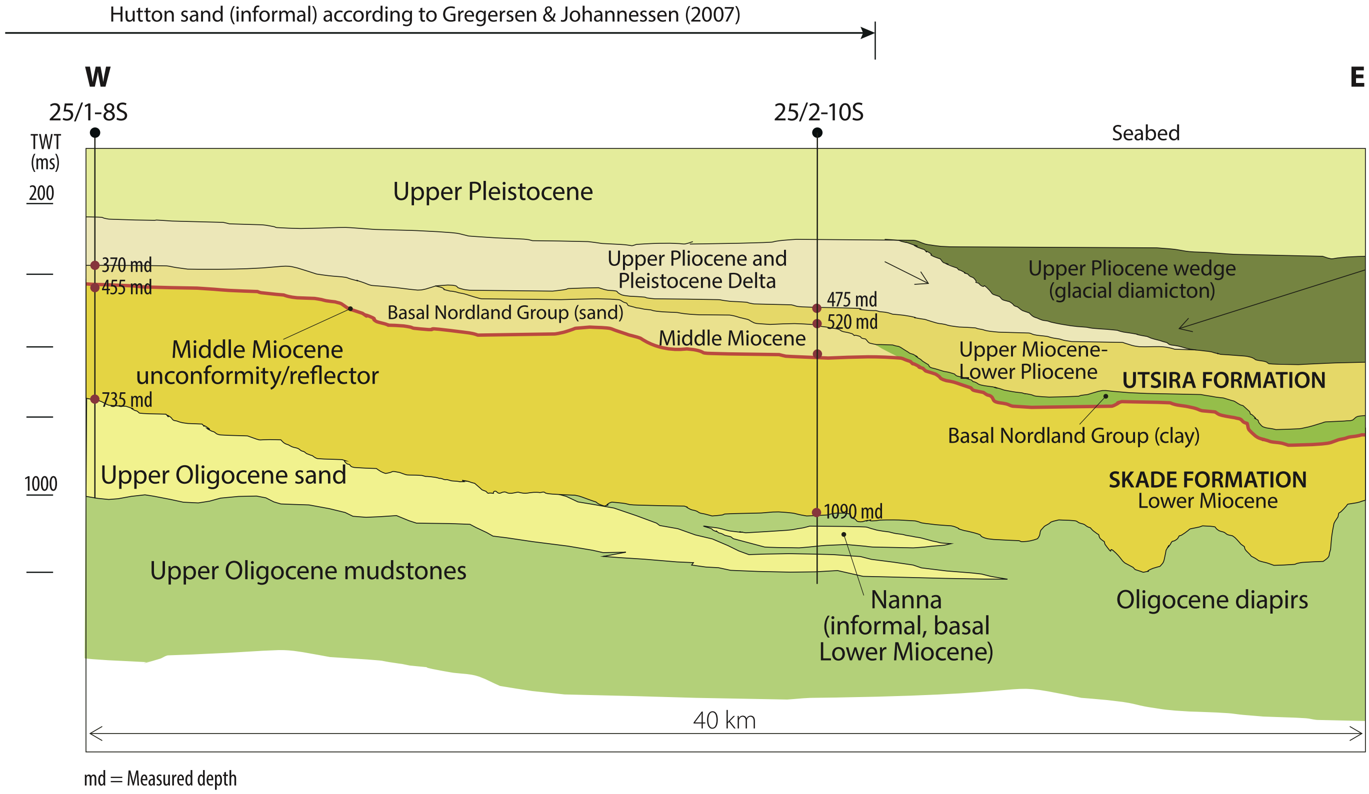


Figure 22. Geo-section illustrating how four different delta sands, which constitute the outer delta front of the Hutton sand system (informal name used only in UK waters), are considered to have been deposited. In Norwegian waters the Lower Miocene Skade Formation is turbitic in origin and overlies Oligocene mudstones. The Utsira Formation overlies a mud prone, distal, Middle Miocene unit and thins out westwards from the delta front towards the area of well 25/1-8 S. An Upper Pliocene delta was built out on top of the Utsira Formation in the area of well 25/2-10 S (modified after Gjeldvik et al., 2011).

of the unit can be defined by erosional truncation, as illustrated schematically in Figure 21. In the northernmost North Sea, between 61°30′ and 62°N, the unit has been completely eroded (Rundberg and Eidvin, 2005).

6.1.5. *Northern Central Graben*

In well 2/4-C-11 (Fig. 1) the Lower Miocene contains mostly clay, but small components of silt and fine-grained sand are also recorded (Eidvin et al., 1999, 2000, 2013d). 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).

6.1.6. *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 (Figs. 1, 2a, 4 and 20; Larsen and Dinesen, 1959; Friis et al., 1998; Hansen and Rasmussen, 2008; Rasmussen and Dybkjær, 2005; Rasmussen et al., 2010). 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; Fig. 19). 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 (Fig. 20).

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, Fig. 1). This resulted in deposition of huge, fluvio-deltaic sand systems intercalated with marine clay (Rasmussen, 2004).

6.2. *Early 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 levelled out in the Early Miocene, and cooled somewhat early in the period (Fig. 3; Zachos et al., 2001).

According to Larsson et al. (2010), two exposures in Jutland (Fig. 2a), encompassing beds of latest Oligocene to earliest Miocene age, yield well-preserved palynofloras. The 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 and 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 Jutland (Fig. 2a). Terrestrial pollen and spores dominated their samples, with lesser contents of dinoflagellates, indicating a substantial fluvial input into a marine setting.

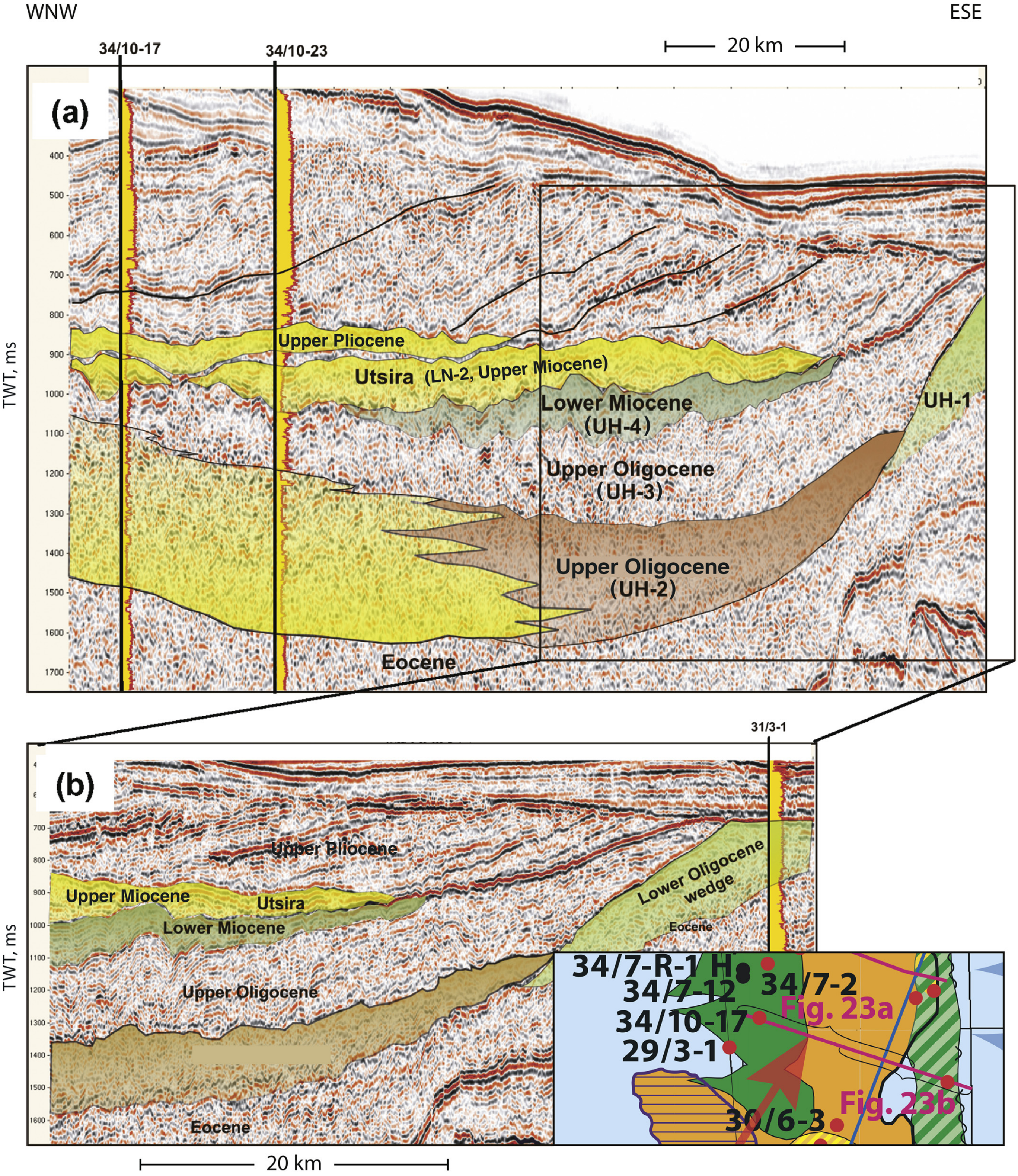


Figure 23. (a) Seismic section (line NVGTI-92-208) across the northern Viking Graben through wells 34/10-17 and 34/10-23 (not investigated) showing subdivision of Oligocene – Miocene strata at about 61°N, including the seismic units of Rundberg and Eidvin (2005). (b) Seismic section (eastern part of NVGT-92-2008) through well 31/3-1 (see also Fig. 1 for location; modified after Rundberg and Eidvin, 2005).

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. A decrease in the relative abundances of thermophilous elements in the middle part of the studied succession indicates a possible correlation to the Early Miocene climatic cooling (Friis, 1975; Larsson et al., 2006).

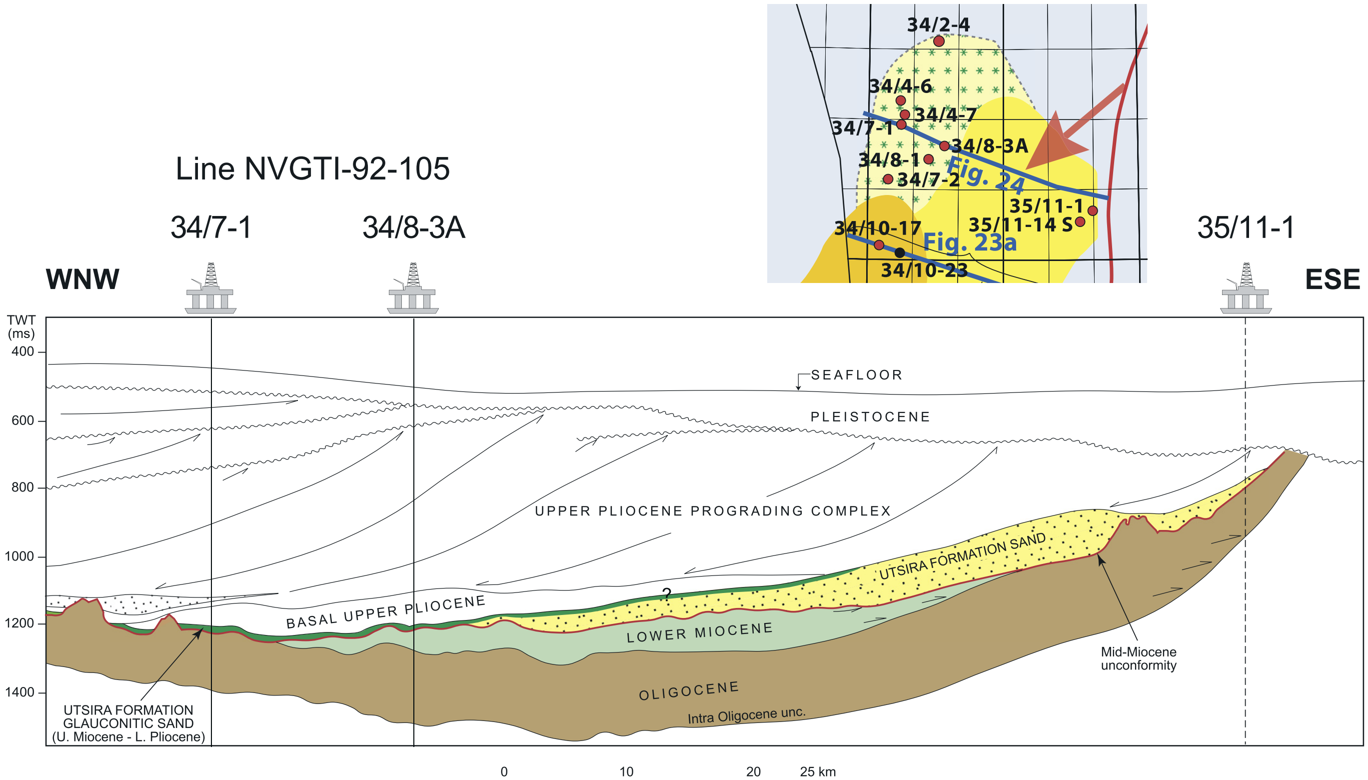


Figure 24. East-west transect of the northern North Sea at about 61°N illustrating the main sequences and sedimentary architecture of the post-Eocene strata. Note the Middle Miocene unconformity (red line) and the seismic truncation of the Lower Miocene (see also Fig. 1 for location; modified after Eidvin and Rundberg, 2001; Rundberg and Eidvin, 2005). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

7. Middle Miocene

Middle Miocene sediments are recorded in twelve boreholes and wells on the Norwegian continental shelf and in the Norwegian Sea and in one borehole onshore Denmark (Figs. 17 and 18; Eidvin et al., 2013d).

7.1. *Regional synthesis*

7.1.1. *Distribution of sediments and Middle 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 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 and Henriksen, 2005) and the Lofoten–Vesterålen area (Fig. 2a; Rise et al., 2013) 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 (Sørvestnaget Basin; Figs. 2b and 3; see discussion section). In the North Sea, seismic data indicate uplift and erosion of the area bounding the west coast of Norway, and slight 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.

7.1.2. *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 (Figs. 1 and 3).

The upper part of the Middle Miocene is only recorded 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 (Figs. 1, 17 and 18). Middle Miocene sediments are absent in well 6305/5-1 on the compressional, Ormen Lange, elongated dome structure (Figs. 2a and 17). Seismic data reveal the presence of an angular unconformity below the Upper Miocene sediments on the top of the dome.

7.1.3. *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. Seismic data show that in the Middle Miocene, a well-defined delta system was developed in the Frigg area (Fig. 2a) and prograded rapidly to the east. Well 25/1-8 S penetrated the sandy deposits in the delta clinoforms (Figs. 22 and 28). Microfossils indicate that the Middle Miocene section in well 25/1-8 S was deposited at a very shallow-marine site. 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 well 30/5-2 and 30/6-3; Fig. 28). 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 tentatively introduce the name Eir Formation, after an Æsir in Norse mythology, for these units in the Norwegian sector as a new formation in the Nordland Group (see Eidvin et al., 2013b and d).

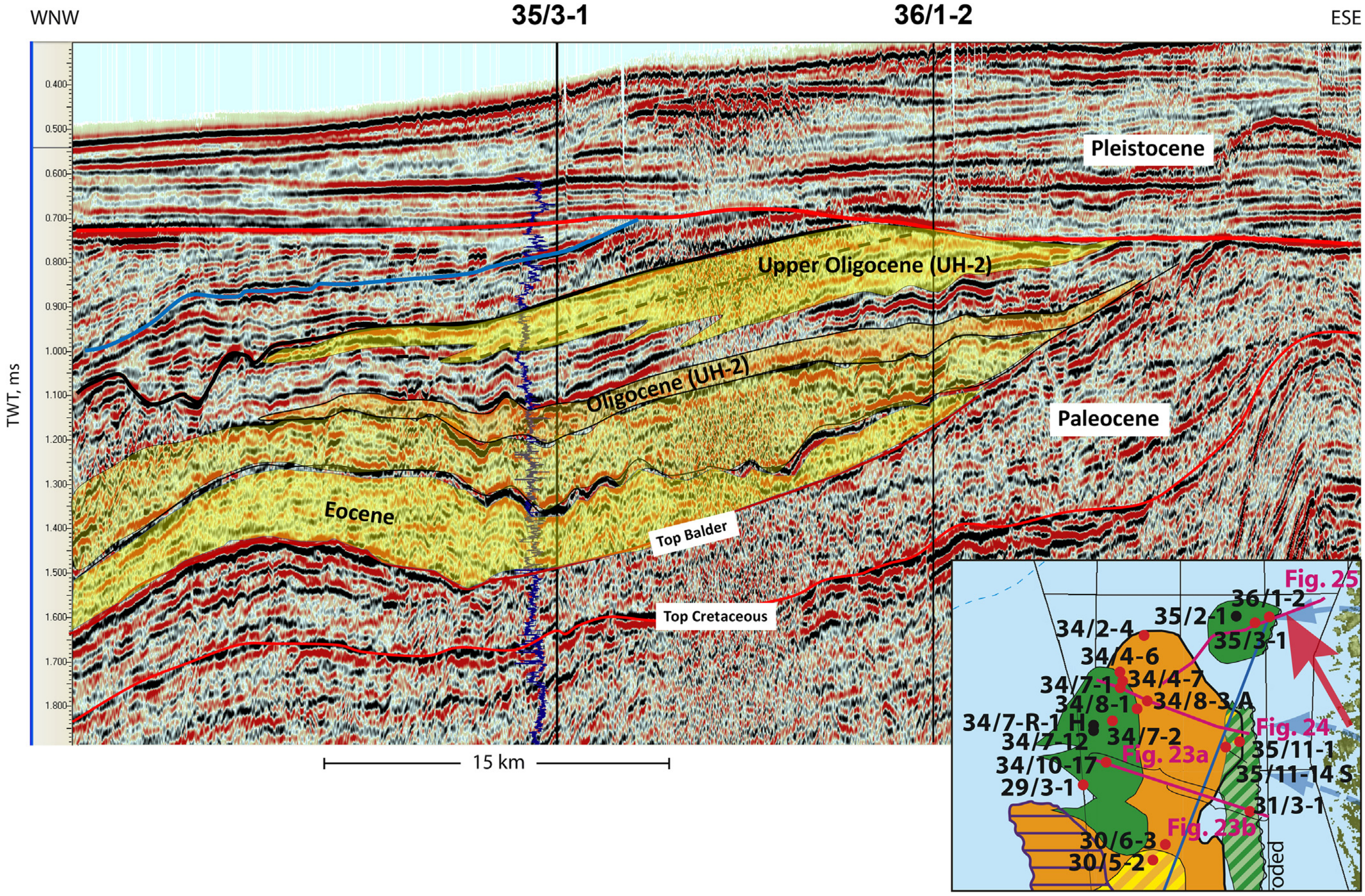


Figure 25. NNE-SSW geoseismic line through well 35/3-1 (with gamma log) and 36/1-2 (Agat Field, Måløy Terrace), including the seismic units of Rundberg and Eidvin (2005; see also Fig. 1 for location; after Eidvin et al., 2010).

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 (Eidvin et al., 2013b, d; Fig. 28). In the well logs, it may be difficult to distinguish these sands from sands of Utsira above and Skade below, and they are believed to act as one aquifer system (NPD, 2011; Eidvin et al., 2013d).

In the eastern part of the northern North Sea, the Middle Miocene sediments wedge out towards 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.

In this northern area, an erosional surface of probable Middle Miocene age was described by Løseth and Henriksen (2005) and Løseth et al., 2013. The surface is overlain by a condensed glauconitic bed deposited close to the Late Miocene/Early Pliocene boundary (Fig. 24).

7.1.4. 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; Figs. 1, 17 and 20), and the upper part of the Middle Miocene is missing. This is possibly due to salt tectonics and polygonal faulting.

7.1.5. Norwegian–Danish Basin

The Middle Miocene deposits onshore Denmark are characterised by a major transgression (Fig. 20). The depositional environment was dominated by clay sedimentation and in the late Serravallian the sedimentation rate was very low permitting widespread formation of glauconite (Rasmussen et al., 2010).

7.2. 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. 3; 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. Both floras suggest a humid warm temperate climate with a number of exotic elements.

8. Upper Miocene to Lower Pliocene

Upper Miocene deposits are studied in 19 boreholes and wells from the Norwegian continental shelf and Norwegian Sea and in

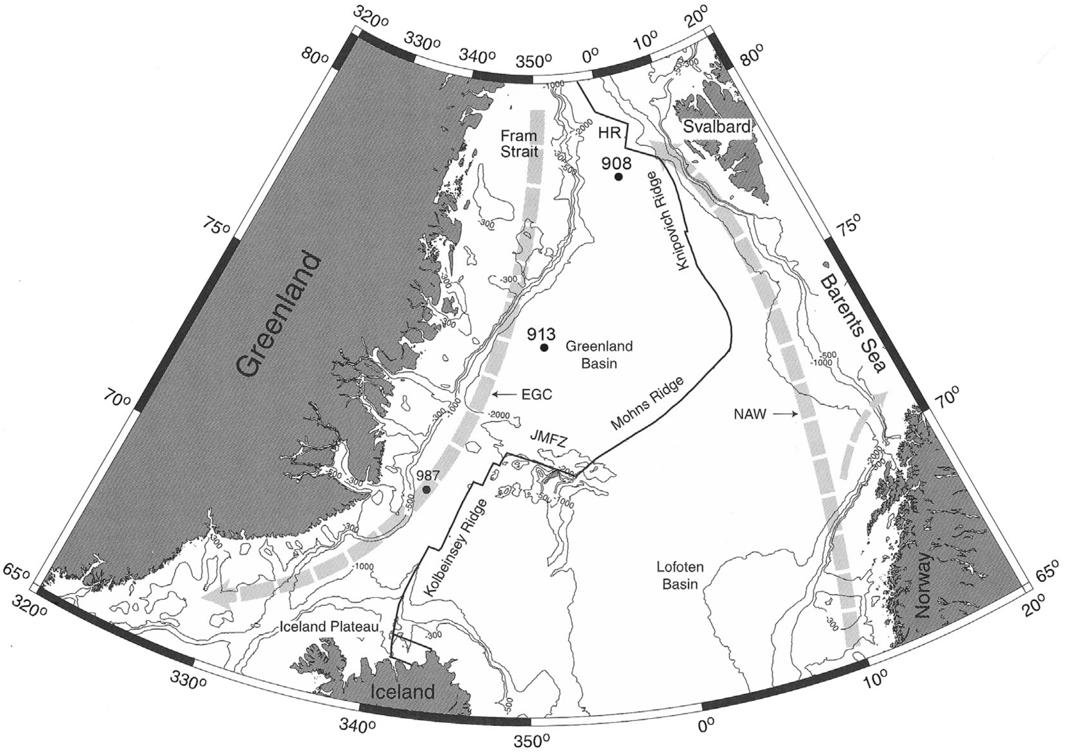


Figure 26. Map of the Polar North Atlantic region with locations of the ODP Site 987, 913 and 908. The bathymetry of the shelf and slope is indicated. HR = Hovgård Ridge, EGC = East Greenland Current, JMFZ = Jan Mayen Fracture Zone, NAW = North Atlantic Water (modified after Butt et al., 2001).

one borehole from onshore Denmark (Figs. 17 and 18; Eidvin et al., 2013d).

Sediments of a general Late Miocene – Early Pliocene age and definite Early Pliocene age are studied in 23 wells from the Norwegian continental shelf (Figs. 17 and 18; Eidvin et al., 2013d).

8.1. *Regional synthesis*

8.1.1. *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 7216/11-1S; Fig. 2b; 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 and Amundsen, 1993).

8.1.2. *Norwegian Sea and its continental shelf*

A marked relief of the Fennoscandian Shield, accompanied by continued uplift, colder climate and a low global sea-level (Fig. 3), 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 wells 6407/9-5, 6407/9-1 and 6407/9-2 in the Draugen Field in its southwestern part (Figs. 1 and 17). In these wells, the Molo Formation contains glauconitic sand (Eidvin et al., 2007, 2013d). 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. 3).

Sediments belonging to the Kai Formation were deposited on the outer and middle part 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; Fig. 1). 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, 2013d). 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 Middle Miocene compressional tectonic phase. Seismic data indicate that redistribution of fine-grained sediments commonly took place along the flanks of the domes (Eidvin et al., 2013d).

8.1.3. *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 clean 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. 29) comprising one large sandy depocentre (250–300 m thick in the southern Viking Graben; Fig. 30) and an area with 80–100 m-thick sandy deposits in the northern Viking Graben. The western central area between the depocentres comprises a large deltaic system which prograded eastwards in the Early and Middle Miocene, but where Upper Miocene to Lower Pliocene sediments of the Utsira Formation are thin or absent (Fig. 5). Apparently, the progradation of the delta stopped in the Middle/Late Miocene, and the sediments of the Utsira Formation 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 (Figs. 2a and 15), 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 unit is thought to cap the main Utsira

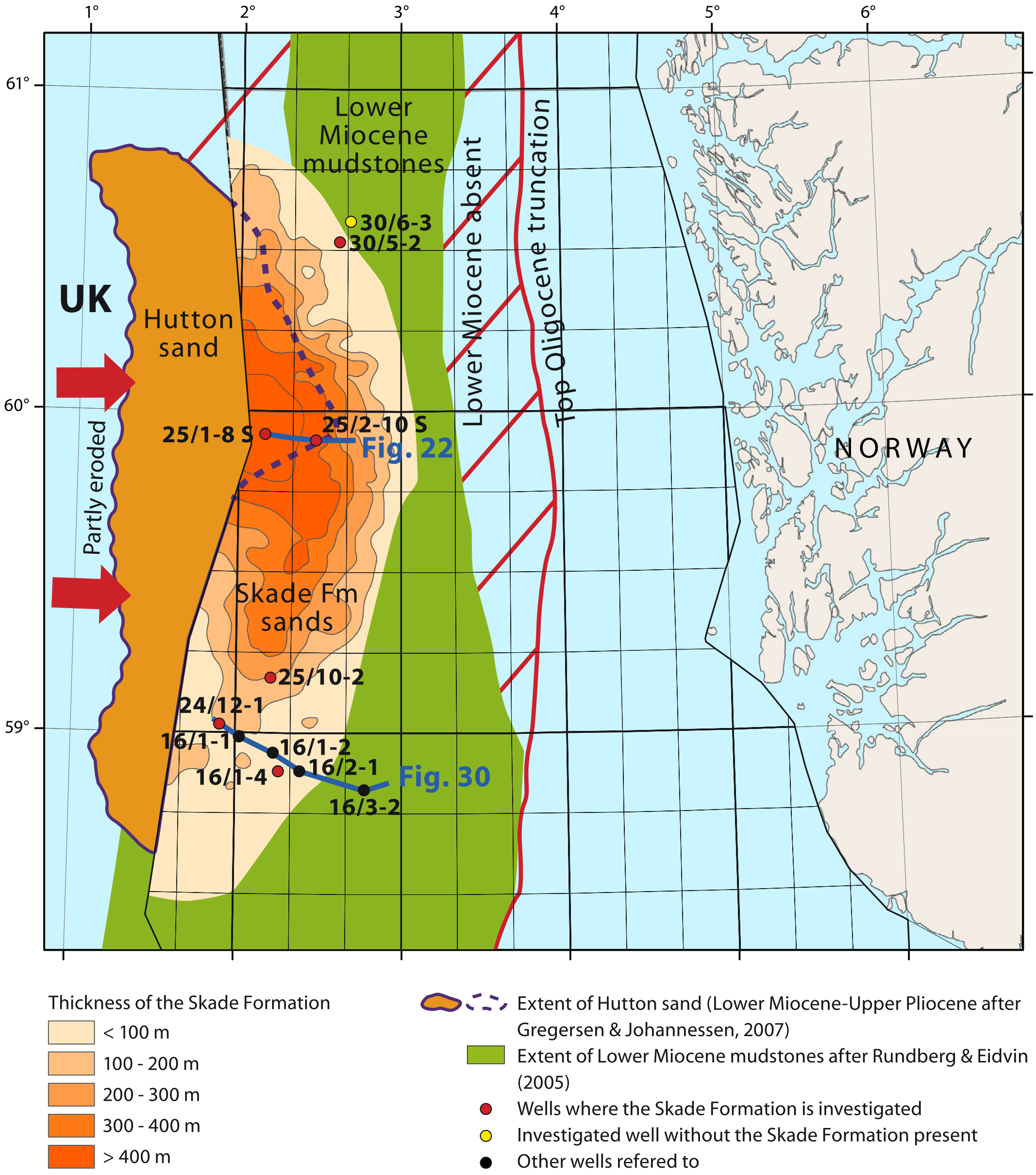


Figure 27. Distribution of Lower Miocene sediments in the northern North Sea with a thickness map of the Skade Formation according to NPD (2011), outline of the Upper Oligocene/Lower Miocene – Upper Pliocene Hutton sand according to Gregersen and Johannessen (2007), and outline of Lower Miocene mudstones according to Rundberg and Eidvin (2005). After Eidvin et al. (2013a).

Formation sands in the northeastern part of the basin (Figs. 24 and 29; Rundberg and Eidvin, 2005; Eidvin and Rundberg, 2001, 2007; Eidvin et al., 2013c and d). 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; Eidvin and Øverland, 2009). In the western part of the Norwegian sector block 30 and 25, the Utsira Formation merges with parts of the Hutton sand (see Fig. 22). Offshore West Norway, a sandy deltaic system was developed north of the Troll Field, probably fed by the Sognefjorden paleovalley (Figs. 1, 2a and 24). Farther to the south, only thin and shaly sections are recorded.

8.1.4. Northern Central Graben

In the Ekofisk area, the Upper Miocene to Lower Pliocene succession has been investigated in well 2/4-C-11 (Fig. 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 Middle Miocene reflector (Eidvin et al., 1999). The underlying seismic unit is strongly polygonally faulted suggesting a change in initial water content and possible lithological change in the clays from the Lower/Middle to the Upper Miocene section.

8.1.5. Norwegian–Danish Basin

Onshore Denmark, the base of the Upper Miocene is characterised by a regional oxidation of glauconite minerals to goethite (Figs. 1 and 4). 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 increasing incursion of sand in the upper part. The thin sand layers

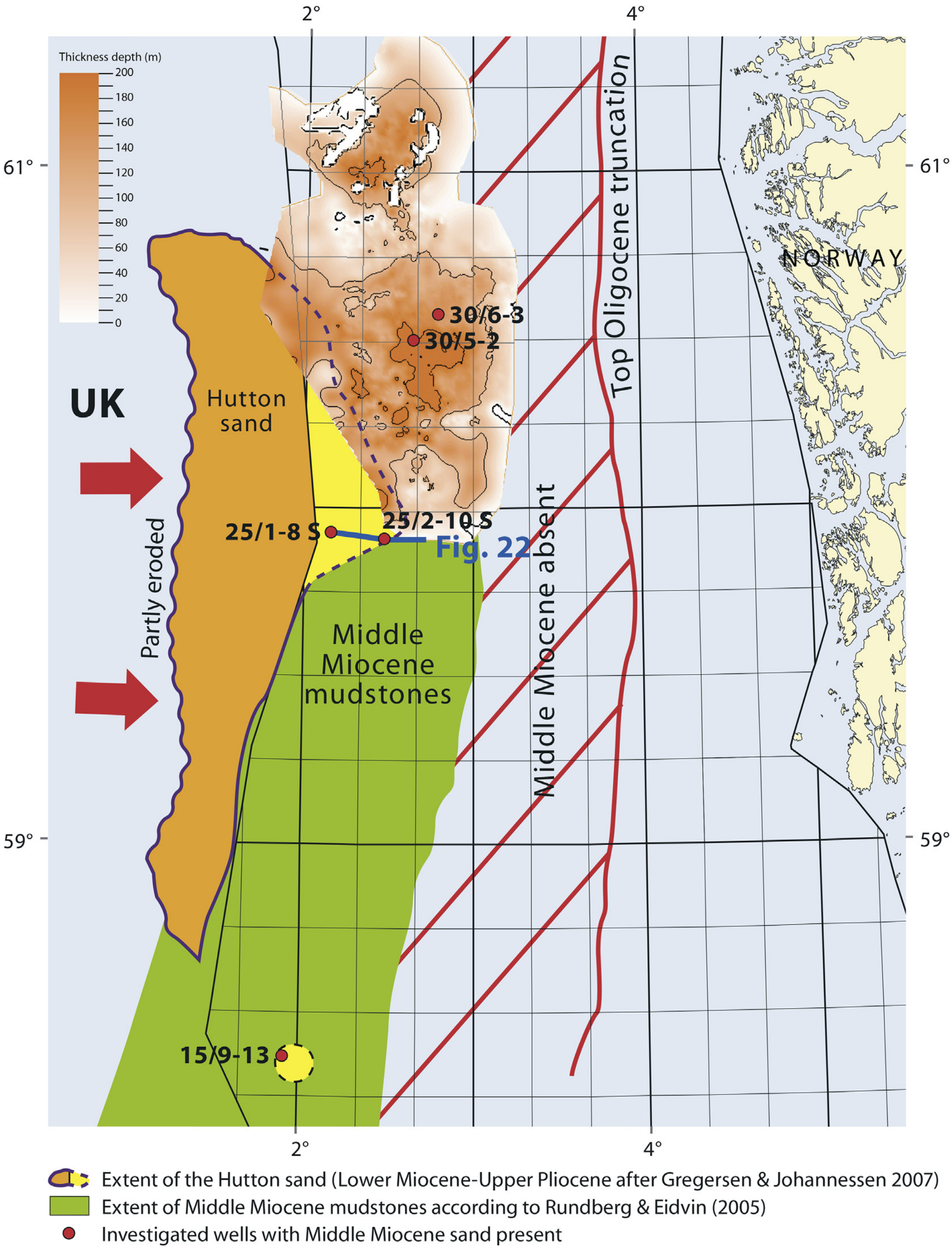


Figure 28. Thickness of the Middle Miocene in the northern North Sea consisting mainly of sandy deposits (after Eidvin et al., 2013b). The Extent of the Hutton sand is according to Gregersen and Johannessen (2007), and the extent of the Middle Miocene mudstones is according to Rundberg and Eidvin (2005).

were deposited as storm sand layers, but show a clear tidal influence, i.e. 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).

8.2. Late Miocene to Early Pliocene climate and environment

According to the global deep-sea δ^{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 δ^{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 δ^{18}O again increased reflecting the onset of the large-scale northern hemisphere glaciations (Fig. 3; Zachos et al., 2001). This trend is also quite distinct in the δ^{18}O record of Buchardt (1978) from northern Europe.

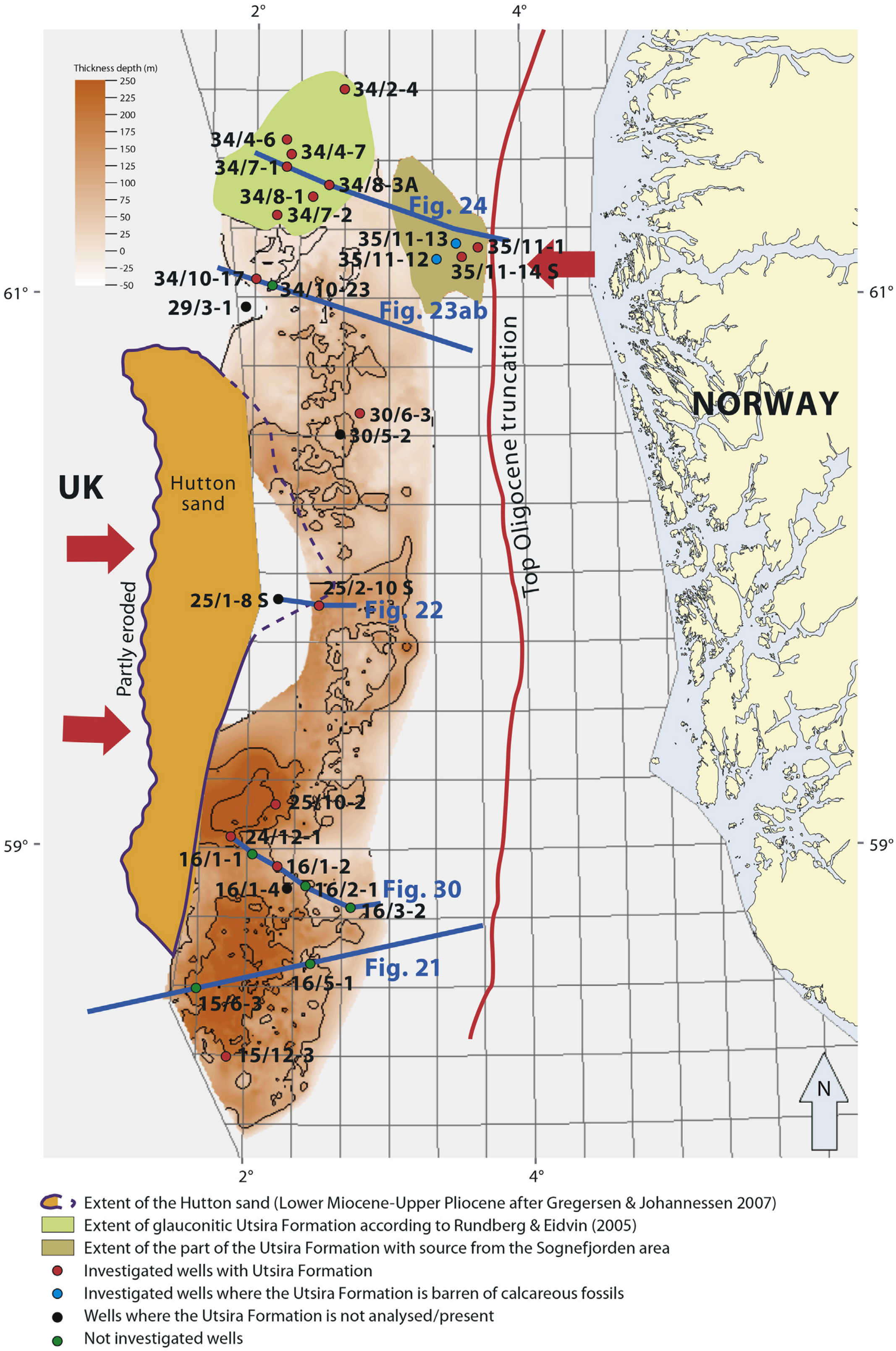


Figure 29. Thickness of the Upper Miocene – Lower Pliocene Utsira Formation in the northern North Sea (modified after NPD, 2011; see also Eidvin et al., 2013c). The outline of the Upper Oligocene/Lower Miocene – Upper Pliocene Hutton sand is after Gregersen and Johannessen (2007). The extent of the area with glauconitic sand is taken from Eidvin and Rundberg (2001) and Rundberg and Eidvin (2005).

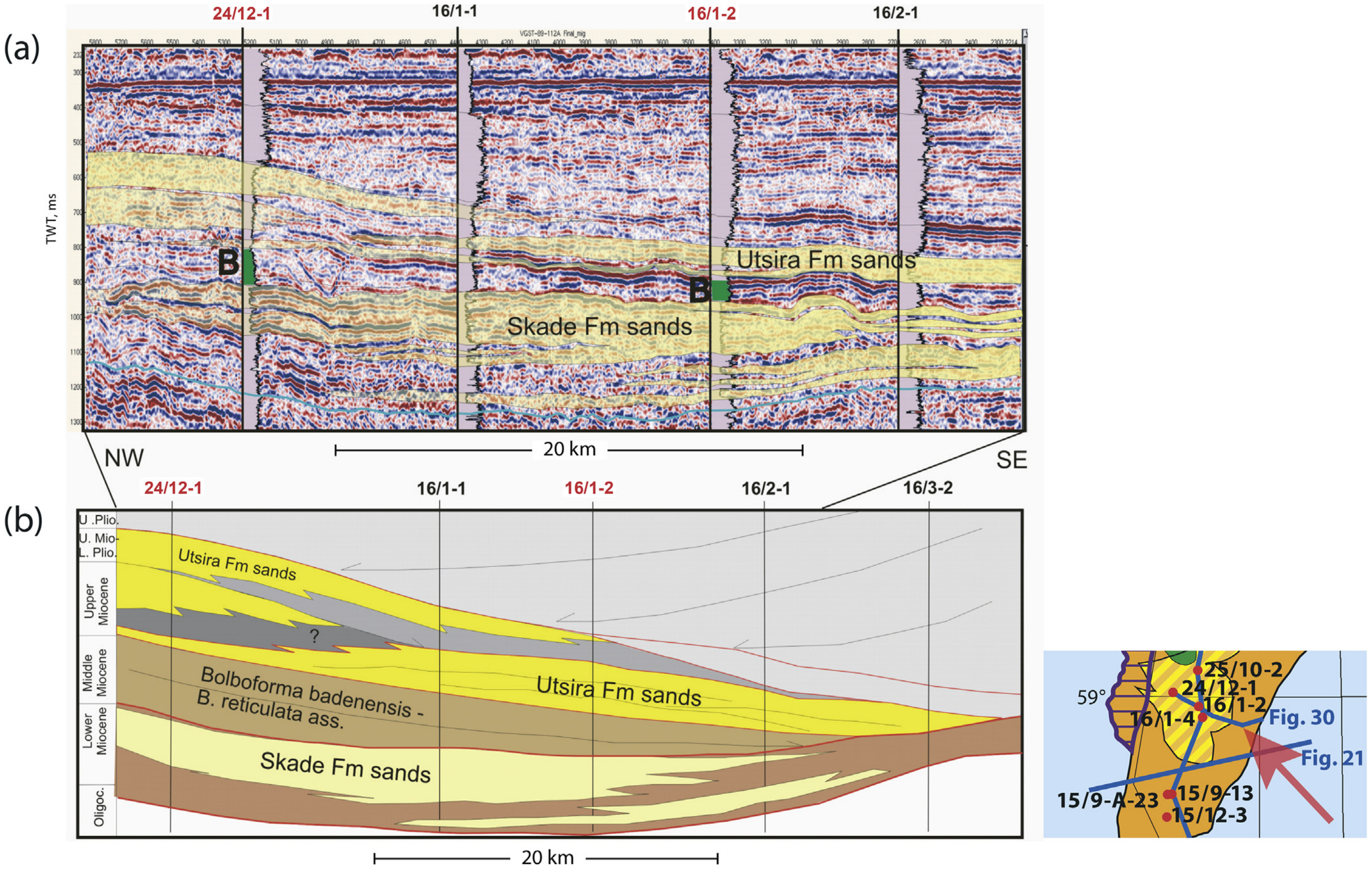


Figure 30. (a) Seismic line through wells 24/12-1, 16/1-1, 16/1-2 and 16/2-1 across the southern Viking Graben showing the Skade and Utsira formations. The green-coloured part of the gamma ray logs denotes Middle Miocene *Bolboforma badenensis* and *Bolboforma reticulata* assemblages. (b) Interpretation of seismic line shown in Fig. 30 (a) (extended towards east through well 16/3-2 (not investigated)) illustrating Middle Miocene strata onlapping the top Lower Miocene surface (Middle Miocene unconformity) to the east (see also Fig. 1 for location; after Rundberg and Eidvin, 2005). The investigated wells 24/12-1 and 16/1-2 have red numbers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fronval and 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; Fig. 1; see Eidvin et al., 1998c, 2013d). 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 at 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 on the Iceland Plateau.

Besides terrestrial, palynological evidence, at ODP Site 908 on the Hovgård Ridge (Fram Strait, Greenland Sea; Fig. 26) from the Oligocene, Boulter and Manum (1996) also reported such evidence from the Upper Miocene. They stated that in the Late 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 Ma. 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 was 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 to 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 Middle Miocene to the latest Miocene.

From eastern Iceland, Mudie and Helgason (1983) have obtained palynological data from clastic units between lava formations. The data suggest the occurrence of a major climatic cooling event during the time interval from 10.3 to 9.5 Ma.

From an extensively karstified landscape at Pollnahallia, western Ireland, Coxon (2005) and Coxon et al. (1998) have obtained palynological data from a borehole in preglacial Pliocene lignite. The data indicate a forested, swampy landscape on an undulating intensely karstified surface. The upper pollen assemblages in the lignite indicate a deterioration of the climate.

9. Discussion

9.1. Implications for the development of the North Sea and the southern Scandes Mountains

The locations of the described Oligocene to Early Pliocene depocentres can be correlated with the topography and present drainage of Scandinavia. In the topographic map in Figure 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; Fig. 1). It is believed that the paleo-drainage developed in crystalline basement rocks to a large extent will control the present drainage, and one hypothesis for a rapid significant movement of the water divide would involve tectonic movements of the South Scandes Dome.

The Paleocene and Eocene progradation of sediments from the South Scandes Dome towards the offshore West Norway terminated in the Early Oligocene, except that in the northernmost North Sea (Nordfjord area, Fig. 2a), sedimentation continued throughout the Oligocene. In the Late Oligocene, a much larger volume of clastic sediments was transported to the Norwegian–Danish Basin. The main part of the sandy Vade Formation was deposited during the Late Oligocene (Fig. 17; Eidvin et al., 2013d; Jarsve et al., submitted). 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 (Fig. 1) 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; Fig. 1). Offshore West Norway, the progradation of sediments continued from the Eocene and terminated in the Early Oligocene.

This depositional pattern is consistent with a Late Oligocene and Miocene water divide located far to the northwest and west on the South Scandes Dome. The transition from the Oligocene to the Early Miocene was marked by a new shift in depocentres both in the central North Sea and in the Norwegian–Danish Basin and Jutland (Figs. 1 and 2a). Nearly all the clastic sediment transport from the South Scandes Dome was now apparently directed towards the south (blue unbroken arrows in Southeast Norway and Sweden; Fig. 1).

Middle Miocene tectonism apparently changed the paleogeography again. The middle Miocene angular unconformity interpreted in the seismic data offshore West Norway is defined by truncation of Oligocene to Middle Miocene reflectors and implies a rotation of the inner shelf which could be related to tectonic uplift of the South Scandes Dome. The Late Miocene deltaic deposits in well 35/11-1 north of the Troll Field (Figs. 1, 2a, 24 and 29) overlie the unconformity and represent a renewed progradation of sandy sediments to the west. The deltaic system can be geographically correlated with the paleo-Sognefjorden valley (Fig. 2a). Compared with the main part of the Utsira Formation, the sand volumes are negligible, but the deposit is significant because it indicates a reactivation of the South Scandes Dome and is a precursor to the large-scale erosion and sediment progradation from the western part of the South Scandes Dome beginning at the onset of glaciations in the Late Pliocene.

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 from the west. In the huge delta system of the Frigg area (Figs. 1 and 2a), sedimentation was affected by changes in relative sea level, but there is no direct evidence of Middle Miocene tectonism in our data. Løseth and Henriksen (2005) interpreted the erosional surface below the Upper Miocene glauconite layer in the northernmost North Sea to indicate subaerial erosion caused by mid Miocene uplift. However, our new data presented above and in Eidvin et al. (2013d) 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. An alternative explanation could be that the erosional event may have been caused by an increased marine circulation and vigorous current erosion due to subsidence of the Greenland–Scotland Ridge (Laberg et al., 2005b). The abrupt mid Miocene climatic cooling at approximately 14 Ma (Fig. 3; Zachos et al., 2001) may have intensified the oceanic circulation system. However, based on the morphology of escarpments and the eroded surface, Løseth et al. (2013) argue that this explanation is not likely.

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 (Fig. 2a), there was a new phase of sandy deltaic aggradation sourced from the Shetland Platform. The shallowest, Upper Pliocene, sand sequence of the Frigg delta is directly overlying Middle Miocene sands and communicates with the Utsira-Skade aquifer system (NPD, 2011).

The Utsira Formation and the western (youngest) part of the Molo Formation (Figs. 1, 11 and 13) postdate the Middle 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.

9.2. The age and depositional environments for the Kai, Utsira and Molo formations

Middle 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 correlated to the wells on the Ormen Lange Dome (Fig. 2a).

Based on an assumption that the Molo Formation is everywhere younger than the Middle Miocene, Løseth and Henriksen et al. (2005) argued that a compression phase caused a major regression along the Norwegian margin between 62° and 69°N during the Middle to Late Miocene. This interpreted regression would have forced the coastline of the syntectonic Kai Formation 50–150 km seaward of the present coastline. The regression should also have lifted the many intra-basinal highs in the Norwegian Sea above sea-level. Their idealised palaeogeography for the Late Miocene (Fig. 15 in Løseth and 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 (see their

Fig. 16). They assigned a late Middle 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 Middle 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 in the Norwegian Sea south of Lofoten, 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 and Eidvin, 2005; Eidvin and Rundberg, 2007). Additional investigations of wells and boreholes documented by Eidvin et al. (2013d) and in the present paper 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.

According to the deep-sea record, Spiegler and Müller (1992) and Müller and Spiegler (1993) described a *Bolboforma metzmacheri* Zone from sediments with an age of 10.0–8.7 Ma (Late Miocene; North Atlantic and Vøring Plateau, Norwegian Sea). The same authors recorded a *Bolboforma fragori*/*Bolboforma subfragori* Zone from sediments with an age of 11.7–10.3 Ma (earliest Late Miocene) and a *Bolboforma badenensis*/*Bolboforma reticulata* Zone from deposits with an age slightly older than 14 to 11.7 Ma (Middle Miocene) from the same areas.

We have recorded *B. metzmacheri* assemblages in the lower part of the Molo Formation in its southwestern, youngest part (Fig. 1) and in the middle parts of the Kai and Utsira formations. *B. fragori*/*B. subfragori* assemblages were found in the lower parts of the Kai and Utsira formations, and *B. badenensis*/*B. reticulata* assemblages were recorded in 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, in the southern Viking Graben. In some wells the uppermost part of the *B. badenensis*/*B. reticulata* assemblage is recorded within the lowermost part of the Utsira Formation. *B. badenensis*/*B. reticulata* assemblages are also recorded from sandy Middle Miocene deposits in the northern part of the Viking Graben and in basal parts of the Kai Formation in the Norwegian Sea and in one well on the Norwegian Sea shelf (see Eidvin et al., 2013d).

Eidvin et al. (1998a) investigated sidewall cores of the Molo Formation in well 6610/3-1 (in its northeastern part, Fig. 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; Fig. 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 southwestern part; Fig. 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-Middle 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 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. 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 (Fig. 1, 11–14; see also Eidvin and Riis, 2013; Eidvin et al., 2013d).

Figure 14 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. Figures 1 and 14 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 (Fig. 14). These seismic observations are compatible with the biostratigraphic analysis. The oldest part of the Molo Formation is located offshore from the central part of the Northern Scandes Dome and could have been sourced through a paleo-drainage in Vestfjorden (Fig. 2a).

The Middle to Late Miocene regression model of Løseth and Henriksen (2005) implies that large parts of the Kai Formation, on the Norwegian Sea continental shelf, should have been deposited at shallow water depths in an inner to middle shelf environment. Also, on the intra-basin highs in the Norwegian Sea, a shallow water depth depositional environment should have prevailed during deposition of the Kai Formation (see their Figs. 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 Middle Miocene unconformity. No inner-shelf benthic foraminifera are recorded (Eidvin et al., 2013d). In well 6305/5-1, situated on the Ormen Lange Dome in the Møre Basin (Figs. 1, 2a and 10), we recorded an approximately 30 m-thick section of Upper Miocene Kai Formation lying unconformably on Upper Oligocene Brygge Formation (Figs. 17 and 18). The Kai Formation in this well contains mainly pelagic ooze, and all of the recorded microfossils indicated deposition in deep water (Eidvin et al., 2013d). 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 of the sea floor.

Regional seismic mapping in 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 are interpreted as reworking by contourites implying that western part of this local high was surrounded by deep water (see Fig. 13 in Eidvin et al., 2013d). Løseth and Henriksen (2005) also interpret these internal structures as contourites, but they argue that a small feature at the foot of slope of the Sør High could be deltaic. Other data examples in Løseth and Henriksen (2005) interpreted as prograding clinoforms related to coastal progradation also seem to be located at the foot of slope of lineaments which were reactivated in the Middle Miocene at the time of deposition of the Kai Formation. Considering the biostratigraphic evidence, we suggest these tectonically created basins were infilled by ooze-rich sediments in a relatively deep sea environment and that alternative explanations should be investigated for the formation of the clinoforms.

In summary, our interpretation is that most of the Kai Formation south of Lofoten 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 Middle Miocene unconformity, erosional features observed probably occurred in quite deep water (Eidvin et al., 2013d). 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. 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 considered that the Middle Miocene compression resulted in the formation of large anticlines and synclines rather than major regional uplift.

The erosional features observed in the northernmost North Sea towards the Møre Basin were interpreted by Løseth and Henriksen (2005) as subaerial erosion, whereas the biostratigraphic analysis presented in Eidvin et al. (2013d) 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 Middle Miocene and then have subsided rapidly in the Late Miocene. Considering that the whole development of the Frigg area delta system (Figs. 1 and 2a) 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. It should be pointed out, however, that the interpretation by Løseth et al. (2013) of the (mid? Miocene) erosional surface is valid, and that there is a need for an explanation which can integrate the well data and the seismic interpretation in the northernmost North Sea.

9.3. *Oligocene to Pliocene along the Barents 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 (Fig. 2b), 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 Fig. 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 (Fig. 2b), 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. 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 intervals 1180–1020 m in well 7117/9-1 and 1120–960 m in well 7117/9-2 (Fig. 2b) to be of Oligocene age (their Fig. 10). A similar age for these intervals was also given by different biostratigraphical industry consultants soon after the wells were drilled in 1982–1983. 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 concluded that these sections are Late Pliocene glacial deposits (Eidvin et al., 1993). This result was supported by different authors, working in several independent disciplines, including Mørk and Duncan (1993), Sættem et al. (1992, 1994) and Faleide et al. (1996). No new redating of these wells is referred to by Ryseth et al. (2003). Seismic data shows an erosional contact between the Eocene ooze sediments and the glacigenic section (Fig. 14 in Eidvin et al., 2013d).

10. Summary and conclusions

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 (Fig. 2a), sandy gravity-flow sediments were deposited. Farther south off Hordaland and Sogn and Fjordane (Fig 2a), 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 latest Early to Late Oligocene there was 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 (Figs. 1 and 2a), i.e. within the area belonging to the Hutton sand according to Gregersen and Johannessen (2007). Along the inner continental shelf of the Norwegian Sea, a pronounced progradation of coastal plains and deltas from the North 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 north-western Svalbard. Climate was probably cold temperate during the Early to early Late Oligocene and warm temperate to subtropical during the later 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 (Figs. 1 and 2a). 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 60°N, 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 coal, and have probably been deposited in shallower water close to, or as parts of, a delta.

According to the mapping of Gregersen and 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 64°N. 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 (Figs. 2a and 27). 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 Middle 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 the block 25/2 (southern Viking Graben) and the depocentre in the northern Viking Graben blocks 30/5 and 30/6 are sandy and microfossils indicate an inner to middle shelf environment (Figs. 2a and 28). 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 Middle 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 on 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 (Fig. 2a), 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 the Vestbakken Volcanic Province well 7316/5-1 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 Fennoscandia 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 depo-centre 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.

Acknowledgements

The authors extend their thanks to Jan Allan Eide, Svein Finnestad, Birgitte Madland, Oddbjørn Nevestveit and Alf B. Stensøy for their important technical assistance and to Dag Bering, Karen Dybkjær (Geological Survey of Denmark and Greenland), Ine T. Gjeldvik, Dag Helliksen, Wenche Tjelta Johansen, Jan Sverre Laberg (University of Tromsø), Christian Magnus, Atle Mørk (SINTEF Petroleum Research), Stephan Piasecki (Geological Survey of Denmark and Greenland), Robert Williams and Jon Arne Øverland for important discussions. Special thanks go to Rune Goa who has drawn most of the figures, Dag Ottesen (Exploro AS) for helpful comments on an earlier version of the manuscript, Tone M. Tjelta Hansen and Inger M. Rovik who have prepared most of the fossil samples, David Roberts (Geological Survey of Norway) who has improved the language, Yuval Ronen (University of Bergen) who has executed most of the strontium isotope analyses and to Statoil ASA for supplying sidewall cores. If not stated otherwise the supporters are employed at the Norwegian Petroleum Directorate. We acknowledge Tom Bugge (det norske oljeselskap ASA) and Tony Doré (Statoil (UK) Ltd) for reviewing the manuscript and providing valuable comments and suggestions and the Norwegian Petroleum Directorate and the Geological Survey of Denmark and Greenland for permission to publish.

References

Berggren, W.A., Kent, D.V., Swisher III, C.C., Aubry, M.-P., 1995. A revised cenozoic Geochronology and Chronostratigraphy. In: Berggren, W.A., et al. (Eds.), Geochronology Time Scale and Global Stratigraphic Correlation, 54. Society for Sedimentary Geology Special Pulication, pp. 129–212.

Bergh, S., Braathen, A., Karlson, F., Maher, H., 1999. Fault Motion along the Eastern Margin of the Forlandsundet graben, Sarstangen, Svalbard (Field Report). Available from the Internet: http://maps.unomaha.edu/maher/svalbard/sarstangen/default.html (accessed 14.02.14.).

Berthelsen, A., 1992. Mobil Europe. In: Blundell, D.J., Mueller, St., Freeman, R. (Eds.), A Continent Revealed: the Eropean Geotraverse Project. Cambridge University Press, Cambridge, pp. 153–164.

Blystad, P., Brekke, H., Færseth, R.B., Larsen, B.T., Skogseid, J., Tørudbakken, B., 1995. Structural elements of the Norwegian continental shelf, Part II: the Norwegian Sea Region. NPD-Bulletin 8.

Boulter, M.C., Manum, S.B., 1996. Oligocene and Miocene vegetation in high latitudes of the North Atlantic: Palynological evidence from the Hovgård Ridge in the Greenland Sea (Site 908). In: Thiede, J., Myhre, A.M., Firth, J.V., Johnson, G.L., Ruddiman, W.F. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 151, pp. 289–296.

Braathen, A., Bergh, S.G., Mahler Jr., H.D., 1999. Application of a critical wedge taper model to the Tertiary transpressional fold-thrust belt on Spitsbergen, Svalbard. Geol. Soc. Am. Bull. 111, 1468–1485.

Brekke, H., 2000. The tectonic evolution of the Norwegian Sea Continental Margin with emphasis on the Vøring and Møre Basins. In: Nøttvedt, A., et al. (Eds.), Dynamics of the Norwegian Margin, Geological Society, London, Special Publications, vol. 167, pp. 327–378.

British Geological Survey, 2000. Saline Aquifer CO_2 Storage (SACS), Final Report: Work Area 1 (Geology). Available from the Internet: http://www.sintef.no/project/IK23430000%20SACS/Formal%20Reports/SACS2_WA1_Rep_Dec00.pdf (accessed 14.02.14.).

Brown, L.F., Fisher, W.L., 1977. Seismic stratigraphic interpretation of depositional systems: examples from Brazilian rift and pull-apart basins. In: Payton, C.E. (Ed.), Seismic Stratigraphy – Applications to Hydrocarbon Exploration, Memoir 26. American Association of Petroleum Geologists, pp. 213–238.

Brugmans, P.J., 2008. Store Norske Spitsbergen Kulkompani Aktieselskap, Oljeleting på Svalbard, En glemt del av norsk oljehistorie. Store Nor. Longyearbyen –Svea 349.

Buchardt, B., 1978. Oxygen isotope palaeotemperatures from the Tertiary period in the North Sea area. Nature 275, 121–123.

Bugge, T., Eidvin, T., Smelror, M., Ayers, S., Ottesen, D., Rise, L., Andersen, E.S., Dahlgreen, T., Evans, D., Henriksen, S., 2004. The middle and Upper Cenozoic depositional system on the Mid-Norwegian continental margin. In: Martinsen, O. (Ed.), Deep-water Sedimentary System of Arctic and North Atlantic Margins, NGF Abstract and Proceedings, Number 3, pp. 14–15.

Bullimore, S., Henriksen, S., Liestøl, F.M., Helland-Hansen, W., 2005. Clinoform stacking patterns, shelf-edge trajectories and facies associations in Tertiary coastal deltas, offshore Norway: Implications for the predictions of lithology in prograding systems. Norwegian Journal of Geology 85, 169–187.

Butt, F.A., Elverhøi, A., Forsberg, C.F., Solheim, A., 2001. Evolution of the Scoresby Sund fan, central east Greenland - evidence from ODP site 987. Nor. J. Geol. 81, 3–15.

Coxon, P., 2005. The late Tertiary landscapes of western Ireland. Ir. Geogr. 38 (2), 111–127.

Coxon, P., McMorrow, S., Coxon, C.E., Nolan, T., 1998. Site 2.3. Pollnahallia: a tertiary palaeosurface and a glimpse of Ireland's pre-Pleistocene landscape. In: Coxon, P. (Ed.), The Quaternary of Central Western Ireland: Field Guide. Quaternary Research Association, London, pp. 79–100.

DeConto, R.M., Pollard, D., Wilson, P.A., Pälike, H., Lear, C.H., Pagani, M., October 2 2008. Thresholds for Cenozoic bipolar glaciations. Nature 455 (7213), 652–656.

Dehls, J.F., Olesen, O., Bungum, H., Hicks, E.C., Lindholm, C.D., Riis, F., 2000. Neotectonic Map: Norway and Adjacent Areas, Scale 1:3 Million, Geological Survey of Norway.

Dybkjær, K., Piasecki, S., 2008. A new Neogene biostratigraphy for Denmark. Geol. Surv. Den. Greenl. Bull. 15, 29–32.

Dybkjær, K., Piasecki, S., 2010. Neogene dinocyst zonation in the eastern North Sea Basin, Denmark. Rev. Palaeobot. Palynol. 161, 1–29.

Eidvin, T., 2009. A Biostratigraphic, Strontium Isotopic and Lithostratigraphic Study of the Upper Part of Hordaland Group and Lower Part of Nordland Group in Well 34/7-2, 34/7–12 and 34/7-R-1 H from the Tordis Field in the Tampen Area (Northern North Sea). Available from the Internet: http://www.npd.no/Global/Norsk/3%20-%20Publikasjoner/Forskningsartikler/Tordis-biostr-rapp.pdf (accessed 14.02.14.).

Eidvin, T., Riis, F., 2013. The lower oligocene – lower Pliocene Molo Formation on the inner Norwegian Sea continental shelf (Extent and thickness, age from fossil and Sr isotope correlations, lithology, paleobathymetry and regional correlation). NGF Abstr. Proc. no 1 (2013), 31. Poster available from the Internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Presentasjoner/NGF-Vinterkonferanse-2013/Poster-4-til-NGF-vintermotet-nett.pdf (accessed 14.02.14.).

Eidvin, T., Rundberg, Y., 2001. Late Cainozoic stratigraphy of the Tampen area (Snorre and Visund fields) in the northern North Sea, with emphasis on the chronology of early Neogene sands. Nor. Geol. Tidsskr. 81, 119–160. Available from the Internet: http://www.npd.no/Global/Norsk/3%20-%20Publikasjoner/Forskningsartikler/Eidvin_and_Rundberg_2001.pdf (accessed 14.02.14.).

Eidvin, T., Rundberg, Y., 2007. Post-Eocene strata of the southern Viking Graben, northern North Sea; intergrated biostratigraphic, strontium isotopic and lithostratigraphic study. Nor. J. Geol. 87, 391–450. Available from the Internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Forskningsartikler/Eidvin_and_Rundberg_2007.pdf (accessed 14.02.14.).

Eidvin, T., Øverland, J.A., 2009. Faulty geology halts project. Nor. Cont. Shelf, no. 2, 35–36. Available from the Internet: http://www.npd.no/global/engelsk/3%20-%20publications/norwegian%20continental%20shelf/pdf/10%20faulty%20geology.pdf (accessed 14.02.14.).

Eidvin, T., Brekke, H., Riis, F., Renshaw, D.K., 1998a. Cenozoic Stratigraphy of the Norwegian Sea continental shelf, 64° N–68° N. Nor. Geol. Tidskr. 78, 125–151. Available from: the Internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Forskningsartikler/Eidvin-et-al.,-1998a.pdf (accessed 14.02.14.).

Eidvin, T., Bugge, T., Smelror, M., 2007. The Molo Formation, deposited by coastal progradation on the inner Mid-Norwegian continental shelf, coeval with the Kai Formation to the west and the Utsira Formation in the North Sea. Nor. J. Geol. 87, 75–142. Available from the Internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Forskningsartikler/Eidvin_et_al_2007.pdf (accessed 14.02.14.).

Eidvin, T., Goll, R.M., Grogan, P., Smelror, M., Ulleberg, K., 1998b. The Pleistocene to Middle Eocene stratigraphy and geological evolution of the western Barents Sea continental margin at well site 7316/5-1 (Bjørnøya West area). Nor. Geol. Tidsskr. 78, 99–123. Available from the Internet: http://www.npd.no/Global/Norsk/3%20-%20Publikasjoner/Forskningsartikler/Eidvin_et_al_1998b.pdf (accessed 14.02.14.).

Eidvin, T., Goll, R.M., Smelror, M., 1995. Et multidisiplinært biostratigrafisk studie av paleogene sedimenter i brønn 2/4-C-11 på Ekofiskfeltet i sentrale Nordsjøen. Nor. Pet. Dir. Intern. Rep. OD-95-33.

Eidvin, T., Jansen, E., Riis, F., 1993. Chronology of Tertiary fan deposits of the western Barents Sea: implications for the uplift and erosional history of the Barents Shelf. Mar. Geol. 112, 109–131.

Eidvin, T., Jansen, E., Rundberg, Y., Brekke, H., Grogan, P., 2000. The upper Cainozoic of the Norwegian continental shelf correlated with the deep sea record of the Norwegian Sea and North Atlantic. Mar. Pet. Geol. 17, 579–600.

Eidvin, T., Koç, N., Smelror, M., Jansen, E., 1998c. Biostratigraphical Investigations of Borehole 6704/12–GB1 from the Gjallar Ridge on the Vøring Plateau, Report for the Seabed Project. OD-98-22. Available from the Internet: http://www.npd.no/engelsk/cwi/pbl/wdss_old/3759_01_Investigation_6704-12-GB1.pdf (accessed 14.02.14.).

Eidvin, T., Rasmussen, E.S., Riis, F., Rundberg, Y., 2010. Oligocene to Lower Pliocene deposits of the Norwegian continental shelf, with correlation to the Norwegian Sea, Greenland, Svalbard, Denmark and their relation to the uplift of Fennoscandia (poster). In: NGF Abstracts and proceedings of the 29th Nordic Geological Winter Meeting, 11–13 January. Oslo, pp. 43–44. Available from the Internet: http://www.npd.no/Global/Engelsk/3%20-%20Publications/Presentations/NGF-2010-Poster.pdf (accessed 14.02.14.).

Eidvin, T., Riis, F., Gjeldvik, I.T., 2013a. The Lower Miocene Skade Formation in the northern North Sea (Extent and thickness, age from fossil and Sr isotope correlations, lithology, paleobathymetry and regional correlation). NGF Abstr. Proc. no 1 (2013), 28–29. Poster available from the Internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Presentasjoner/NGF-Vinterkonferanse-2013/Poster-1-til-NGF-vintermotet-nett.pdf (accessed 14.02.14.).

Eidvin, T., Riis, F., Gjeldvik, I.T., 2013b. Middle Miocene sandy deposits of the Nordland Group, northern North Sea (Suggested called Eir Formation, extent and thickness, age from fossil and Sr isotope correlations, lithology, paleobathymetry and regional correlation). NGF Abstr. Proc. no 1 (2013), 30–31. Poster available from the Internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Presentasjoner/NGF-Vinterkonferanse-2013/Poster-2-til-NGF-vintermotet-nett.pdf (accessed 14.02.14.).

Eidvin, T., Riis, F., Gjeldvik, I.T., 2013c. The Upper Miocene – Lower Pliocene Utsira Formation in the northern North Sea (Extent and thickness, age from fossil and Sr isotope correlations, lithology, paleobathymetry and regional correlation). NGF Abstr. Proc. no 1 (2013), 29–30. Poster available from the Internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Presentasjoner/NGF-Vinterkonferanse-2013/Poster-3-til-NGF-vintermotet-nett.pdf (accessed 14.02.14.).

Eidvin, T., Riis, F., Rasmussen, E.S., Rundberg, Y., 2013d. Investigation of Oligocene to Lower Pliocene deposits in the Nordic area. NPD Bull. No 10. Available from the Internet: http://www.npd.no/engelsk/cwi/pbl/NPD_papers/Hyperlink-NPD-Bulletin-10.pdf (accessed 14.01.14.).

Eidvin, T., Riis, F., Rundberg, Y., 1999. Upper Cainozoic stratigraphy in the central North Sea (Ekofisk and Sleipner fields). Nor. Geol. Tidsskr. 79, 97–127. Available from the Internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Forskningsartikler/Eidvin-et-al-1999-(2).pdf (accessed 14.02.14.).

Eidvin, T., Ullmann, C.V., Dybkjær, K., Rasmussen, E.S., Piasecki, S., 2014. Strontium isotope stratigraphy of the Danish Upper Oligocene – Miocene succession; ^{87}Sr/^{86}Sr-ages of calcareous marine fossils compared to dinoflagellate stratigraphy. Palaeogeogr. Palaeoclimatol. Palaeoecol. (submitted for publication).

Eldrett, J.S., Harding, I.C., Wilson, P.A., Butler, E., Roberts, A.P., 2007. Continental ice in Greenland during the Eocene and Oligocene. Nature 446, 176–179.

Eldholm, O., Thiede, J., Taylor, E., 1989. In: Proceedings of the Ocean Drilling Program, Scientific Results, vol. 104. (Ocean Drilling Program), TX, College Station.

Faleide, J.I., Solheim, A., Fielder, A., Hjelstuen, B.O., Andersen, E.S., Vanneste, K., 1996. Late Cenozoic evolution of the western Barents Sea-Svalbard continental margin. In: Solheim, A., et al. (Eds.), Impact of glaciations on basin evolution: data and models from the Norwegian margin and adjacent areas. Global Planet. Change 12, 53–74.

Farrell, J., Clemens, S.C., Gromet, L.P., 1995. Improved chronostratigraphic reference curve of late Neogene seawater ^{87}Sr/^{86}Sr. Geology 23, 403–406.

Feyling-Hanssen, R.W., Ulleberg, K., 1984. Tertiary – Quaternary section at sarsbukta, spitsbergen. Polar Res. 2, 77–106.

Friis, E.M., 1975. Climatic implications of microcarpological analyses of the Miocene Fasterholt flora. Bull. Geol. Soc. Den. 24, 179–191.

Fronval, T., Jansen, E., 1996. Late Neogene Paleoclimates and paleoceanography in the Iceland-Norwegian Sea: evidence from the Iceland and Vøring Plateaus. In: Thiede, J., Myhre, A.M., Firth, J.V., John, G.L., Ruddiman, W.F. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 151, pp. 455–468. College Station, TX (Ocean Drilling Program).

Gabrielsen, R.H., Kløvjan, O.S., Haugsbø, H., Midbøe, P.S., Nødtvedt, A., Rasmussen, E., Skott, P.H., 1992. A structural outline of Forlandsundet Graben, Prins Karls Forland, Svalbard. Nor. Geol. Tidsskr. 72, 105–120.

Gjeldvik, I.T., Eidvin, T., Riis, F., 2011. Neogene Delta Systems In The North-Western North Sea. In: Poster shown at Sustainable Earth Sciences Conference and Exibition, Valencia, Spain, 8–10 November 2011. Available from the Internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Presentasjoner/Plakat.pdf (accessed 14.02.14.).

Gradstein, F., Bäckström, S., 1996. Cainozoic biostratigraphy and paleobathymetry, northern North sea and haltenbanken. Nor. Geol. Tidsskr. 76, 3–32.

Gradstein, F.M., Kristiansen, I.L., Loemo, L., Kaminski, M.A., 1992. Cenozoic foraminiferal and dinoflagellate cyst biostratigraphy of the central North Sea. Micropaleontology 38 (2), 101–137.

Gregersen, U., 1998. Upper Cenozoic channels and fans on 3D seismic data in the northern Norwegian North Sea. Geoscience 4, 67–80.

Gregersen, U., Johannessen, P.N., 2007. Distribution of the Neogene Utsira Sand and Hutton Sand, and the succeeding deposits in the Viking Graben area, North Sea. Mar. Pet. Geol. 24, 591–606.

Gregersen, U., Michelsen, O., Sørensen, J.C., 1997. Stratigraphy and facies distribution of the Utsira Formation and the Pliocene sequences in the northern North Sea. Mar. Pet. Geol. 14 (7/8), 893–914.

Grimsson, F., Denk, T., Simonarson, L.A., 2007. Middle Miocene floras of Iceland – the early colonization of an island? Rev. Palaeobot. Palynol. 144, 181–219.

Hansen, J.P.V., Rasmussen, E.S., 2008. Distribusjon and thicknesses of reservoir sands in a wave-dominated delta, Billund delta, eastern Danish North Sea and Jylland. Sediment. Res. 78, 130–146.

Hardenbol, J., Thierry, J., Farley, M.B., Jacquin, Th, de Graciansky, P.-C., Vail, P.R., 1998. Mesozoic and Cenozoic sequence chronostratigraphic Framework of European Basins. SEPM Spec. Publ. No. 60.

Harland, W.B., 1997. The Geology of Svalbard. In: Geological Society Memoir No 17, 525. Geological Society Publication House, Bath BAI 3JN, UK.

Heilmann-Clausen, C., Nielsen, O.B., Gersner, F., 1985. Lithostratigraphy and depositional environments in the Upper Paleocene and Eocene of Denmark. Geol. Soc. Den. Bull. 33, 287–323.

Helland, P.E., Holmes, M.A., 1997. Surface textural analysis of quartz sand grains from ODP Site 918 off the southeast coast of Greenland suggests glaciations of southern Greenland at 11 Ma. Palaeogeogr. Palaeoclimatol. Palaeoecol. 135, 109–121.

Henriksen, S., Ficher, C., Grønlie, A., Henningsen, T., Laursen, I., Løseth, H., Ottesen, D., Prince, I., 2005. The Norwegian Sea during the Cenozoic. In: Wandaas, B.T.G., et al. (Eds.), Onshore-offshore Relationships on the North Atlantic Margin, NPF Special Publication, vol. 12, pp. 111–133.

Hodell, D.A., Mueller, P.A., Garrido, J.R., 1991. Variations in the strontium isotopic composition of seawater during the Neogene. Geology 19, 24–27.

Howarth, R.J., McArthur, J.M., 1997. Statistics for strontium isotope stratigraphy: a robust lowess fit to marine Sr-isotope curve for 0 to 206 Ma, with look-up table for derivation of numeric age. J. Geol. 105, 441–456.

Hunt, D., Tucker, M.E., 1992. Stranded parasequences and the forced regressive wedge system tract: deposition during base-level fall. Sediment. Geol. 81, 1–9.

Hunt, D., Tucker, M.E., 1995. Stranded parasequences and the forced regressive wedge system tract: deposition during base-level fall. Sediment. Geol. 95, 147–160.

International Commission on Stratigraphy (ICS), 2013. International Stratigraphic Chart (2013). Available from the Internet: http://www.stratigraphy.org/ICSchart/ChronostratChart2013-01.jpg (accessed 14.02.14.).

Japsen, P., 1993. Influence of lithology and Neogene uplift on seismic velocities in Denmark: Implications for depth conversion of maps. Bull. Am. Assoc. Pet. Geol. 77, 194–211.

Japsen, P., Green, P.F., Bonow, J.M., Rasmussen, E.S., Chalmers, J.A., Kjennerud, T., 2010. Episodic uplift and exhumation along North Atlantic passive margins: implications for hydrocarbon prospectivity. In: Vining, B.A., Pickering, S.C. (Eds.), Petroleum Geology: from Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference, pp. 979–1004.

Jarsve, E.M., Eidvin, T., Nystuen, J.P., Faleide, J.I., Gabrielsen, R.H., Thyberg, B.I., 2014. The Oligocene succession in the eastern North Sea – control mechanisms of basin development and depositional systems. Geol. Mag. (submitted for publication).

Jensen, L.N., Schmidt, B.J., 1992. Late tertiary uplift and erosion in the Skagerrak area: magnitude and consequences. Nor. Geol. Tidsskr. 72, 275–279.

Jordt, H., Faleide, J.I., Bjørlykke, K., Ibrahim, M.T., 1995. Cenozoic sequence stratigraphy of the central and northern North Sea Basin: tectonic development, sediment distribution and provenance areas. Mar. Pet. Geol. 12 (8), 845–879.

Jordt, H., Thyberg, B.I., Nøttvedt, A., 2000. Cenozoic evolution of the central and northern North Sea with focus on differential vertical movements of the basin floor and surrounding clastic source areas. Geol. Soc. Lond. Spec. Publ. 167, 219–243.

King, C., 1983. Cenozoic micropaleontological biostratigraphy of the North Sea. Rep. Inst. Geol. Sci. 82, 40pp.

King, C., 1989. Cenozoic of the North Sea. In: Jenkins, D.G., Murray, J.W. (Eds.), Stratigraphical Atlas of Fossils Foraminifera. Ellis Horwood Ltd., Chichester, pp. 418–489.

Kleinspehn, K.L., Teyssier, C., 1992. Tectonics of the Palaeogene Forlandsundet Basin, Spitsbergen: a preliminary report. Nor. Geol. Tidsskr. 72, 93–104.

Knies, J., Mattingsdal, R., Fabian, K., Grøsfjeld, K., Barawal, S., Husum, K., De Schepper, S., Vogt, C., Andersen, N., Matthiessen, J., Andreassen, K., Jokat, W., Nam, S.-I., Gaina, C., 2014. Effect of early Pliocene uplift of late Pliocene cooling in the Artic-Atlantic gateway. Planet. Sci. Lett. (in press).

Laberg, J.S., Dahlgren, T., Vorren, T.O., Haflidason, H., Bryn, P., 2001. Seismic analyses of Cenozoic contourite drift development in the Northern Norwegian Sea. Mar. Geophys. Res. 22, 401–416.

Laberg, J.S., Dahlgren, K.I.T., Vorren, T.O., 2005a. The Eocene-late Pliocene paleoenvironment in the Vøring Plateau area, Norwegian Sea-paleoceanographic implications. Mar. Geol. 214, 269–285.

Laberg, J.S., Stoker, M.S., Dahlgren, K.I.T., de Haas, H., Haflidason, H., Hjelstuen, B.O., Nielsen, T., Shannon, P.M., Vorren, T.O., van Weering, T.C.E., Ceramicola, S., 2005b. Cenozoic alongslope processes and sedimentation on the NW European Atlantic margin. Mar. Pet. Geol. 22, 1069–1088.

Larsen, G., Dinesen, A., 1959. Vejle Fjord formation ved Brejning: Sedimenterne og foraminiferfaunaen (oligocæn – miocæ. Danmarks Geol. Unders. II; Række 82, 114.

Larsen, H.C., Saunders, A.D., Clift, P.D., Beget, J., Wei, W., Spezzaferri, S., ODP Leg 152 Scientific Party, 1994. Seven million years of glaciation in Greenland. Science 264, 952–955.

Larsson, L.M., Vajda, V., Rasmussen, E.S., 2006. Early Miocene pollen and spores from western Jylland, Denmark-environmental and climatic implications. GFF 128, 261–272.

Larsson, L.M., Vajda, V., Dybkjær, K., 2010. Vegetation and climate in the latest Oligocene-earliest Miocene in Jylland, Denmark. Rev. Palaeobot. Palynol. 159 (3–4), 166–176.

Laursen, G.V., Kristoffersen, F.N., 1999. Detailed foraminiferal biostratigraphy of Miocene formations in Denmark. Contrib. Tert. Quat. Geol. 36 (1–4), 73–107.

Lepvrier, C., 1992. Early tertiary palaeostress distribution on Spitsbergen: implications for the tectonic development of the western fold-and thrust belt. Nor. Geol. Tidsskr. 72, 129–135.

Liboriussen, J., Aston, P., Tygesen, T., 1987. The tectonic evolution of the Fennoscandian Border Zone in Denmark. Tectonophysics 137, 21–29.

Lidmar-Bergström, K., 1999. Uplift histories revealed by landforms of the Scandinavian domes. In: Smith, B.J., Whalley, W.B., Warke, P.A. (Eds.), Uplift, erosion and stability, London, Geological Society. Special publication, vol. 162, pp. 1–7.

Lidmar-Bergström, K., Näslund, J.O., 2002. Landforms and uplift in Scandinavia. In: Geological Society of London, Special Publication, vol. 196, pp. 103–116.

Løseth, H., Henriksen, S., 2005. . A Middle to Late Miocene compression phase along the Norwegian passive margin. In: Doré, A.G., Vining, B.A. (Eds.), Petroleum Geology: North-West Europe and Global Perspectives-proceedings of the 6th Petroleum Geology Conference, pp. 845–859.

Løseth, H., Raulline, B., Nygård, A., 2013. Late Cenozoic geological evolution of the northern North Sea: development of a Miocene unconformity reshaped by large-scale Pleistocene sand intrusion. J. Geol. Soc. Lond. 170, 133–145.

Løseth, H., Wensaas, L., Arntsen, B., Hovland, M., 2003. Gas and fluid injection triggering shallow mud mobilization in the Hordaland Group, North Sea. In: van Rensbergen, P., Hillis, R.R., Maltman, A.J., Morley, C.K. (Eds.), Surface Sediment Mobilization, Geological Society, London, Special Publication, vol. 216, pp. 139–157.

Maher Jr., H.D., Bergh, S., Braathen, A., Ohta, Y., 1997. Svartfjella, Eidembukta, and Daumansodden lineament: tertiary orogen-parallel motion in the crystalline hinterland of Spitsbergen's fold-thrust belt. Tectonics 1 (1), 88–106.

Manum, S.B., 1962. Studies in the Tertiary flora of Spitsbergen, with notes on Tertiary floras of Ellesmere Island, Greenland, and Iceland. Nor. Polarinst. Skr. 125, 1–127.

Manum, S.B., Throndsen, T., 1986. Age of Tertiary Formations on Spitsbergen. Polar Research 4 n.s., 103–131. In: Thiede, J., Myhre, A.M., Firth, J.V., John, G.L., Ruddiman, W.F. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 151. TX (Ocean Drilling Program), College Station, pp. 289–296.

Martinsen, O.J., Bøen, F., Charnock, M., Mangerud, G., Nøttvedt, A., 1999. Cenozoic development of the Norwegian margin 60 – 64°N: sequences and sedimentary response to variable basin physiography and tectonic setting. In: Fleet, A.J., Boldy, S.A. (Eds.), Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference. Geological Society, London, pp. 293–304.

McArthur, J.M., Howarth, R.J., Bailey, T.R., 2001. Strontium isotope stratigraphy: LOWESS version 3: best fit to the marine Sr-isotope curve for 0-509 ma and accompanying look-up table for deriving numerical age. J. Geol. 109, 155–170.

Michelsen, O., Danielsen, M., 1996. Sequence and system tract interpretation of epicontinental Oligocene deposits in the Danish North Sea. Geol. Soc. Lond. Spec. Publ. 117, 1–13.

Michelsen, O., Danielsen, M., Heilmann-Clausen, C., Jordt, H., Laursen, G.V., Thomsen, E., 1995. Occurrence of Major sequence stratigraphic boundaries in relation to basin development in the Cenozoic deposits of the southeastern North Sea. In: Steel, R.J. (Ed.), Sequence Stratigraphy of the Northwestern European Margin. Norwegian Petroleum Society (NPF), pp. 415–427.

Mogensen, T.E., Korstgård, J., 1993. Structural development and trap formation along the Børglum Fault, Tornquist Zone, Denmark, and a comparison with the Painted Canyon Fault, San Andreas Zone, USA. In: Spencer, A.M. (Ed.), Generation, Accumulation and Production of Europe's Hydrocarbons III. Springer Verlag, Berlin, pp. 89–97.

Moran, K., Backman, J., Brinkhuis, H., et al., 2006. The cenozoic palaeoenvironment of the Arctic ocean. Nature 441, 601–605.

Mosbrugger, V., Utescher, T., 1997. The coexistence approach – a method for quantitative reconstructions of tertiary terrestrial palaeoclimate data using plant fossils. Palaeogeogr. Palaeoclimatol. Palaeoecol. 134, 61–86.

Mudie, P.J., Helgason, J., 1983. Palynological evidence for Miocene climatic cooling in eastern Iceland about 9.8 Myr ago. Nature 303, 689–692.

Müller, C., Spiegler, D., 1993. Revision of the Late/Middle Miocene boundary on the Voering Plateau (ODP Leg 104). Newsl. Stratigr. 28 (2/3), 171–178.

Møller, L.K., Rasmussen, E.S., Clausen, O.R., 2009. Clinoform migration patterns of a Late Miocene delta complex in the Central Graben; implications for relative sea-level changes. In: Henriksen, S., Hampson, G.J., Helland-Hansen, W., Johannessen, E.P., Steel, R.J. (Eds.), Trajectory Analysis in Stratigraphy, Basin Research, vol. 21, pp. 704–720.

Mørk, M.B.E., Duncan, R.A., 1993. Late Pliocene volcanism on the western barents shelf margin-implications from petrology ^{40}Ar-^{39}Ar dating of volcanic-clastic debris from a shallow drill-core. Nor. Geol. Tidsskr. 73, 209–225.

NPD, 2011. CO_2 Atlas, Norwegian North Sea. Available from the Internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Rapporter/PDF/CO2-ATLAS-lav.pdf (accessed 14.02.14.).

Olesen, O., Gellin, J., Gernigon, L., Kihle, O., Koziel, J., Lauritsen, T., Mogaard, J.O., Myklebust, R., Skilbrei, J.R., Usov, S., 2010. Magnetic Anomaly Map, Norway and Adjacent Areas, Scale 1:3 Millions. Geological Surway of Norway.

Pekar, S.F., October 2 2008. Climate Change: When Did the Icehouse Cometh?. In: Comment on Nature, vol. 455(7213), pp. 652–656. Available from the Internet: http://www.nature.com/climate/2008/0811/full/455602a.html (accessed 14.02.14.).

Posamentier, H.W., Jervey, M.T., Vail, P.R., 1988. Eustatic controls on clastic deposition I — conceptual framework. In: Wilgus, C.K., Hastings, B.S., Kendall, C. G. St. C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea-Level Changes: an integrated approach, vol. 42. Society of Economic Paleontologists and Mineralogists Special Publications, pp. 109–124.

Rasmussen, E.S., 2004. The interplay between true eustatic sea-level changes, tectonics, and climate changes: what is the dominating factor in sequence formation of the Upper Oligocene-Miocene succession in the eastern North Sea Basin, Denmark? Global Planet. Change 41, 15–30.

Rasmussen, E.S., 2005. The geology of the upper Middle – upper Miocene Gram Formation in the Danish area. Paleontos 7, 5–18.

Rasmussen, E.S., 2009. Neogene inversion of the north-eastern North Sea. Tectonophysic 465, 84–97.

Rasmussen, E.S., Dybkjær, K., 2005. Sequence stratigraphy of the Upper Oligocene – lower Miocene of eastern Jylland, Denmark: role of structural relief and variable sediment supply in controlling sequence development. Sedimentology 52, 25–63.

Rasmussen, E.S., Dybkjær, K., Piasecki, S., 2004. The Billund delta: a possible new giant aquifer in central and western Jutland. Geol. Surv. Den. Greenl. Bull. 4, 21–24.

Rasmussen, E.S., Dybkjær, K., Piasecki, S., 2010. Lithostratigraphy of the Upper Oligocene – Miocene Succession of Denmark. Geological Survey of Denmark and Greenland Bulletin 22, pp. 92 + 9 plates.

Rasmussen, E.S., Heilmann-Clausen, Waagstein, R., Eidvin, T., 2008. The Tertiary of Norden. Episones 21 (1), 66–72. Available from the Internet: http://www.npd.no/Global/Norsk/3%20-%20Publikasjoner/Forskningsartikler/Rasmussen_et_al_2007.pdf (accessed 14.02.14.).

Rise, L., Bøe, R., Riis, F., Bellec, V.K., Laberg, J.S., Eidvin, T., Elvenes, S., Thorsnes, T., 2013. The Lofoten-Vesterålen continental margin, North Norway: canyons and mass-movement activity. Mar. Pet. Geol. 45, 134–149.

Rundberg, Y., 1989. Tertiary sedimentary history and Basin Evolution of the Norwegian North Sea between 60°–62°N – an Integrated Approach. (Dr. ing. thesis) University of Trondheim, Norway, 308 pp, (reprinted in 1991 in Report 25 Institute for geology and rock Mechanics, University of Trondheim).

Rundberg, Y., Eidvin, T., 2005. Controls on depositional history and architecture of the Oligocene–Miocene succession, northern North Sea Basin. In: Wandaas, B.T.G., et al. (Eds.), Onshore–offshore Relationships on the North Atlantic Margin, NPF Special Publication, vol. 12, pp. 207–239.

Ryseth, A., Augustson, J.H., Charnock, M., Haugerud, O., Knudsen, S.-M., Midbøe, P.S., Opsal, J.G., Sundsbø, G., 2003. Cenozoic stratigraphy and evolution of the Sørvestnaget Basin, southwestern Barents Sea. Nor. J. Geology 83, 107–130.

Sigmond, E.M.O., 1992. Berggrunnskart Norge med havområder. Målestokk 1:3 millioner. Norges Geologiske Undersøkelse.

Schiøler, P., Andsbjerg, J., Clausen, O.R., Dam, G., Dybkjær, K., Hamberg, L., Heilmann-Clausen, C., Johannessen, E.P., Kristensen, L.E., Prince, I., Rasmussen, J.A., 2007. Lithostratigraphy of the Palaeogene – Lower Neogene succession of the Danish North Sea. Geol. Surv. Den. Greenl. Bull. 12, 77.

Skotte, A., 2007. Norwegian Petroleum Group ASA, 20 år. Norwegian Petroleum Group ASA. ISBN 13 978-827424-006-03, 140 pp.

Sliwinska, K.K., Clausen, O.R., Heilmann-Clausen, C., 2010. A mid-Oligocene cooling (Oi-2b) reflected in the dinoflagellate record and in depositional sequence architecture. An integrated study from the eastern North Sea Basin. Mar. Pet. Geol. 27 (7), 1424–1430.

Spiegler, D., 1999. *Bolboforma* biostratigraphy from the Hatton-Rockall Basin (North Atlantic). In: Raymo, M.E., Jansen, E., Blum, P., Herbert, T.D. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 162. TX (Ocean Drilling Program), College Station, pp. 35–49.

Spiegler, D., Jansen, E., 1989. Planktonic Foraminifer Biostratigraphy of Norwegian Sea Sediments: ODP Leg 104. In: Eldholm, O., Thiede, J., Tayler, E., et al. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 104. TX (Ocean Drilling Program), College Station, pp. 681–696.

Spiegler, D., Müller, C., 1992. Correlation of *Bolboforma* zonation and nannoplankton stratigraphy in the Neogene of the North Atlantic: DSDP sites 12-116, 49-408, 81-555 and 94-608. Mar. Micropaleontol. 20, 45–58.

Stoker, M.S., Hoult, R.J., Nielsen, T., Hjelstuen, B.O., Laberg, J.S., Shannon, P.M., Praeg, D., Mathiesen, A., van Weering, T.C.E., McDonnell, A., 2005a. Sedimentary and oceanographic respons to early Neogene compression on the NW European margin. Mar. Pet. Geol. 22, 1031–1044.

Stoker, M.S., Praeg, D., Hjelstuen, B.O., Laberg, J.S., Nielsen, T., Shannon, P.M., 2005b. Neogene stratigraphy and the sedimentary and oceanographic development of the NW European Atlantic margin. Mar. Pet. Geol. 22, 997–1005.

Surlyk, F., Lykke-Andersen, H., 2007. Contourite drifts, moats and channels in the Upper Cretaceous chalk of the Danish Basin. Sedimentology 54, 405–422.

Sættem, J., Bugge, T., Fanavoll, S., Goll, R.M., Mørk, A., Mørk, M.B.E., Smelror, M., Verdenius, J.G., 1994. Cenozoic margin development and erosion of the Barents Sea: core evidence from southwest of Bjørnøya. Mar. Geol. 118, 257–281.

Sættem, J., Poole, D.A.R., Ellingsen, L., Sejrup, H.P., 1992. Glacial geology of outer Bjørnøyrenna, soutwestern Barents Sea. Mar. Geol. 103, 15–51.

Talwani, M., Udintsev, G., et al., 1976. In: Proceedings of the Deep Sea Drilling Program, initial Reports, vol. 38. U.S. Government Printing Office, Washington.

Utescher, T., Mosbrugger, V., Ashraf, A.R., 2000. Terrestrial climate evolution in Northwest Germany over the last 25 million years. Palaios 15, 430–449.

Vågnes, G.L., Amundsen, H.E.F., 1993. Late Cenozoic uplift and volcanism on Spitsbergen: caused by mantle convection? Geology 21, 251–254.

Vågnes, G.L., Faleide, J.I., Gudlaugsson, S.T., 1992. Glacial erosion and tectonic uplift in the Barents Sea. Nor. Geol. Tidsskr. 72, 251–254.

Weaver, P.P.E., 1987. Late Miocene to Recent planktonic foraminifers from the North Atlantic: deep sea drilling project Leg 94. Initial Reports Deep Sea Drill. Proj. 94, 703–727.

Weaver, P.P.E., Clement, B.M., 1986. Synchronicity of Pliocene planktonic foraminiferid datums in the North Atlantic. Mar. Micropalaeontol. 10, 295–307.

Weaver, P.P.E., Clement, B.M., 1987. Magnetobiostratigraphy of planktonic foraminiferal datums: Deep Sea Drilling Project Leg 94, North Atlantic. In: Ruddiman, W.F., Kidd, R.B., Thomas, E., et al. (Eds.), Initial Reports Deep Sea Drill. Proj. 94, 815–829.

Winkler, A., Wolf-Welling, T.C.W., Stattegger, K., Thiede, J., 2002. Claymineral sedimentation in high northern latitude deep-sea basins since the Middle Miocene (ODP Leg 151, NAAG). Int. J. Earth Sci. 91, 133–148.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 ma to present. Science 292, 686–693.

Ziegler, P.A., 1982. Geological Atlas of Western and Central Europe. Elsevier, Amsterdam, 130 pp.

Ziegler, P.A., 1990. Geological Atlas of Western and Central Europe. Geological Society, London.

These publications may also be of interest:

NPD Bulletin no. 10 (including interactive maps and diagrams)

The Lower Miocene Skade Formation in the northern North Sea

Middle Miocene sandy deposits of the Nordland Group, northern North Sea

The Upper Miocene - Lower Pliocene Utsira Formation in the northern North Sea