# Controls on depositional history and architecture of the Oligocene–Miocene succession, northern North Sea Basin

Yngve Rundberg and Tor Eidvin

The tectonostratigraphic framework of the Oligocene–Miocene succession in the northern North Sea Basin (58–62°N) is closely linked to the large-scale structural evolution of the NW European passive margin. Fairly contemporaneous with the structural doming on the Mid-Norwegian margin uplift activity also affected the Shetland Platform and southern Fennoscandia, including the sedimentary basin of the northern North Sea. This uplift caused a gradual shallowing-upward trend of the northern North Sea Basin, which culminated in severe submarine and possibly also subaerial erosion during middle Miocene, creating a northward increasing stratigraphic break (20 million years in northernmost North Sea), which is visible as a distinct seismic unconformity. Uplift of the East Shetland Platform caused three major phases of sand influx to the basin (1) an early Oligocene phase, resulting in deposition of gravity flow sands in the northern Viking Graben (Statfjord–Tampen area); (2) an early Miocene phase, resulting in deposition of turbiditic sands (Skade Formation) in southern Viking Graben; and (3) a late Miocene–early Pliocene phase, resulting in deposition of shelfal sands (Utsira Formation). During the latter phase, the northern North Sea Basin formed a relatively shallow marine, shelfal strait between deeper marine settings to the north and south. The Utsira Formation sands accumulated in this narrow strait in a high-energy, possibly tidal-current controlled regime.

This chapter also presents an improved lithostratigraphic and chronostratigraphic subdivision of the Oligocene–Miocene including redefinitions of the Skade and Utsira formations. The Oligocene–Miocene succession in the northern North Sea has been subdivided into two megasequences, separated by a seismically distinct unconformity (mid-Miocene break). The age diagnostic *Bolboforma* assemblages, known from ODP/DSDP boreholes in the North Atlantic and on the Vøring Plateau, have aided in correlation between wells and have been important in resolving the basin history.

## Introduction

In this chapter, we present our latest understanding of the depositional history of the Oligocene–Miocene succession in northern North Sea. The main object has been to view the depositional history of this area in a larger-scale tectonic perspective. Focus has been on the depositional architecture, stratigraphical outline and the coarse clastic input to the basin, with special emphasis on the Utsira Formation. We also present an improved chronology of the Oligocene–Miocene, with more precise age constraints of the Skade and Utsira formations.

The study area embraces the northern North Sea between 58 and 62°N. Some results of the work carried out in the Møre and Faeroe–Shetland Basins are also presented. The erosive mid-Miocene surface forming the top of the Hordaland Group and its continuation to the south has been crucial to our work, and subdivides the strata described in this chapter into two distinct megasequences. Critical features that are preserved in the southern part of the basin are applicable to the interpretation of strata, farther north.

This work synthesizes several data sets and methods. The interpretations are results of detailed biostratigraphic works; integrated with $^{87}$Sr/$^{86}$Sr isotope stratigraphy, seismic and wireline log studies. A suite of regional 2-D lines from an extensive database has been interpreted. Six selected lines are presented in this chapter. An extensive well database has also been available for study. The well data include gamma ray, resistivity and sonic logs; in some wells the density and neutron logs were also available. Interpreted log data from

*Onshore–Offshore Relationships on the North Atlantic Margin*
edited by B. Wandas et al. NPF Special Publication 12, pp. 207–239,
Published by Elsevier B.V., Amsterdam

17 wells located along or close to the selected lines are shown in this chapter.

Biostratigraphic data were obtained from ditch-cuttings, sidewall cores and conventional cores from 17 selected wells. Main results from seven wells in the southern Viking Graben (wells 15/9-A-11, 15/9-A-23, 15/9-13, 15/12-3, 16/1-2, 16/1-4 and 24/12-1) are presented in two tables and also are shown in the log correlation diagrams. Detailed fossil descriptions from these wells and results from strontium isotope stratigraphy will be reported in a paper, to be submitted shortly. Results from well 15/12-3 are previously also presented in Eidvin et al. (1999) but samples from this well have been reanalysed and reinterpreted in the current study. Biostratigraphic data and results from strontium isotope analyses from 10 wells in northernmost North Sea have previously been presented in Eidvin and Rundberg (2001).

Much of the background of this work is based on the comprehensive study of the Cainozoic stratigraphy and basin evolution of Norwegian northern North Sea Basin, carried out by Rundberg (1989). Earlier works dealing with the litho- and seismic stratigraphy of the Oligocene–Miocene in the Norwegian Northern North Sea have been presented by Isaksen and Tonstad (1989), Rundberg (1989), Rundberg and Smalley (1989), Galloway et al. (1993), Gregersen et al. (1997), Jordt et al. (1995), Martinsen et al. (1999), Galloway (2002).

## Oligocene–Miocene palaeogeography and palaeotectonic evolution

The sea-floor spreading history of the Norwegian and Greenland Seas and its effects on the NW European passive margin have been addressed by a number of earlier studies (e.g. Talwani and Eldholm, 1977; Vogt et al., 1981; Eldholm et al., 1990; Doré and Lundin, 1996; Vågnes et al., 1998; Brekke, 2000; Lundin and Doré, 2002 and Mosar et al., 2002). At end Eocene times, major plate reorganisations initiated a compressive structural regime, which had dramatic effects on the geohistory of the NW European margin. In the Norwegian Sea (at about anomaly 13; 35 Ma), the plate movements were characterised by a 30° counterclockwise rotation (Lundin and Doré, 2002) and a westward jump in sea-floor spreading axis to the south of the Jan Mayen Fracture Zone (JMFZ; Fig. 1) which led to the formation of the Jan Mayen microcontinent (Fig. 1). Sea-floor spreading also commenced in the Greenland Sea, with shearing affecting the Spitsbergen Margin and gradually during Oligocene establishing a seaway link to the Arctic Sea (Fig. 1).

The structural activity of the margin was heavily controlled by compressional strain, developed as a response to movements along major fracture zones. Between Lofoten and the Faeroe Islands, three large fracture zones (Bivrost, Jan Mayen and Erlend; Fig. 1), broadly subdivide the margin into three compartments, each of which has undergone a different structural post-Eocene evolution. (1) The margin between the Jan Mayen and Bivrost Fracture Zones comprises the Vøring Basin and Vøring Marginal High. This area has undergone a complex structural evolution involving the growth of large domes (Helland Hansen and Modgunn Arches, Naglfar and Vema Domes; Figs. 1, 2) and also inversion structures (e.g. Fles Fault Complex). Southward, along the Helland Hansen structural trend, the Ormen Lange dome developed at the transition to the Møre Basin. (2) The area between the Jan Mayen and the Erlend Fracture Zones, comprising the Møre Basin and Møre Marginal High, underwent a totally different evolution. It is characterised by overall subsidence and the almost absence of compressional structures, apart from a slight uplift of the Møre Marginal High. These two contrasting segments of the passive margin could thus reflect a lower-plate origin for the Møre Basin and an upper-plate origin for the Vøring Basin (Rundberg, 1989 p. 235; Mosar et al., 2002). (3) The margin to the south of the Erlend Fracture Zone was affected by severe compressional folding which developed the strongly anticlinal Fugløy Ridge and the narrow Faeroe–Shetland Basin. Further to the south, a complex structural evolution took place involving formation of the Wyville Thompson, Ymir and Munkegrunnur Ridges (Boldreel and Andersen, 1993 and 1994). More distant from the ocean-continent boundary, and sub-parallel to the Fugløy Ridge, structural uplift also affected the Shetland Platform and southern Fennoscandia during Oligo-Miocene times, as shown in Figures 1 and 2.

Most of the anticlinal structures or domes along the margin show a multi-phase growth history with important phases in (1) Middle Eocene to Early Oligocene and (2) the Miocene (Doré and Lundin, 1996; Brekke, 2000; Lundin and Doré, 2002).

As a result of the mid-Cainozoic plate reorganisations, an important change in palaeogeography took place during Oligocene–Miocene. The semi-enclosed basin of the Norwegian and North Seas that existed during late Palaeocene–Eocene

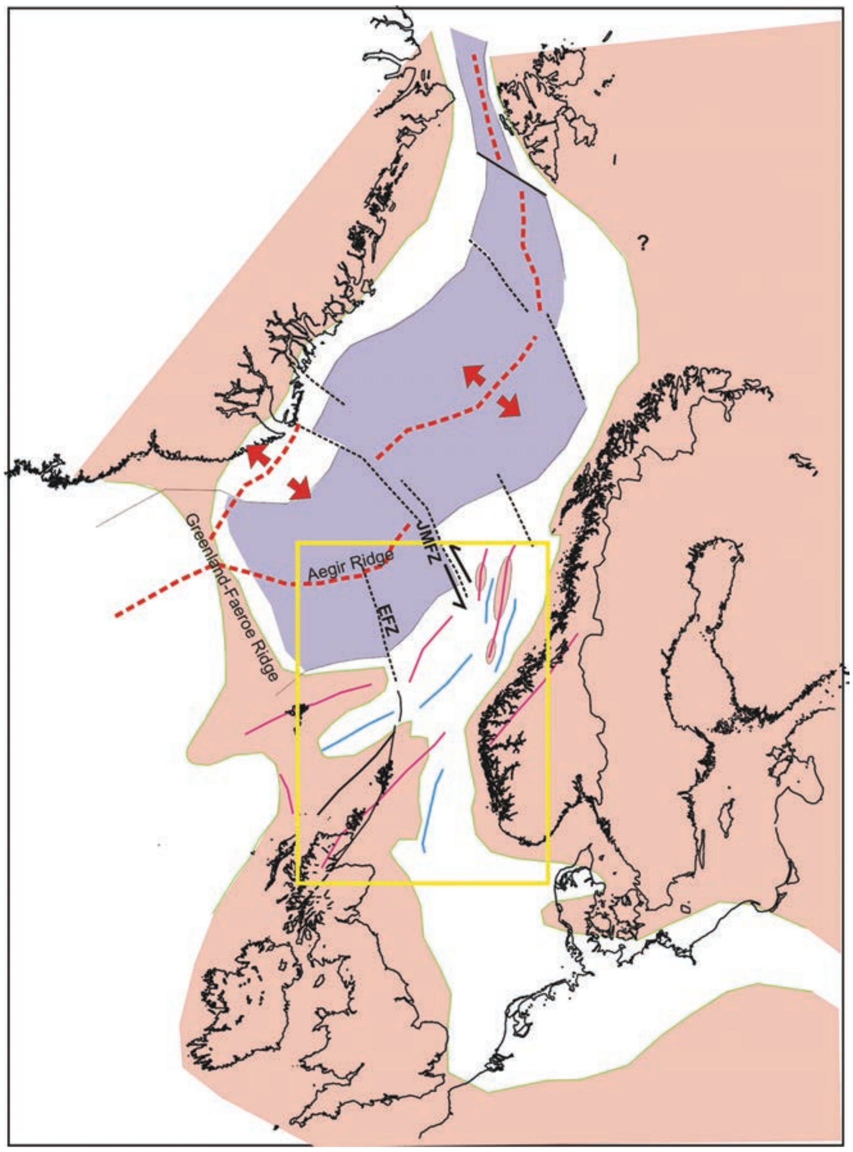

Fig. 1 Late Oligocene palaeogeography of NW Europe illustrating some key elements: (a) westward jump in spreading axis to the south of the Jan Mayen Fracture Zone (JMFZ), extinction of Aegir spreading axis and formation of the Jan Mayen microcontinent; (b) opening of a seaway to the Arctic Sea; (c) the mainly subaerially exposed Greenland–Faeroe Ridge and (d) the structurally affected margin between Faeroe and Lofoten Islands (modified from Rundberg, 1989). Red lines illustrate anticlinal areas or areas affected by uplift; blue lines illustrate synclinal areas. Yellow rectangle shows location of Fig. 2. It is uncertain whether the entire Barents Sea was exposed during this time, as indicated here.

(e.g. Rundberg, 1989) gradually changed during Oligocene into a more open basin with seaway connections to the Arctic Sea to the northeast (Fig. 1). The Greenland–Scotland Ridge acted as a barrier to the Atlantic, although surface water connections probably existed, via the Faeroe–Shetland Channel and the Denmark Strait (Eldholm and Thiede, 1980). Its subsidence history and the connection to the Atlantic have been discussed by a number of authors (e.g. Wold, 1994; Wright and Miller, 1996).

In the study area of the northern North Sea, the Eocene–Oligocene boundary probably represents one of the most important breaks within the Cainozoic. Rundberg (1989) suggested that the distinct changes in lithostratigraphy, mineralogy and biostratigraphy observed at this boundary are thought to be controlled by the large drop in global temperature at terminal Eocene time (Kennett, 1982; Ruddiman, 2000; Zachos et al., 2001), coupled with an increased oceanic circulation pattern and the rise of the passive margin at the intercept with the North Sea (Figs. 2 and 3). The latter was probably a result of the compressional regime, which also affected the northernmost North Sea.

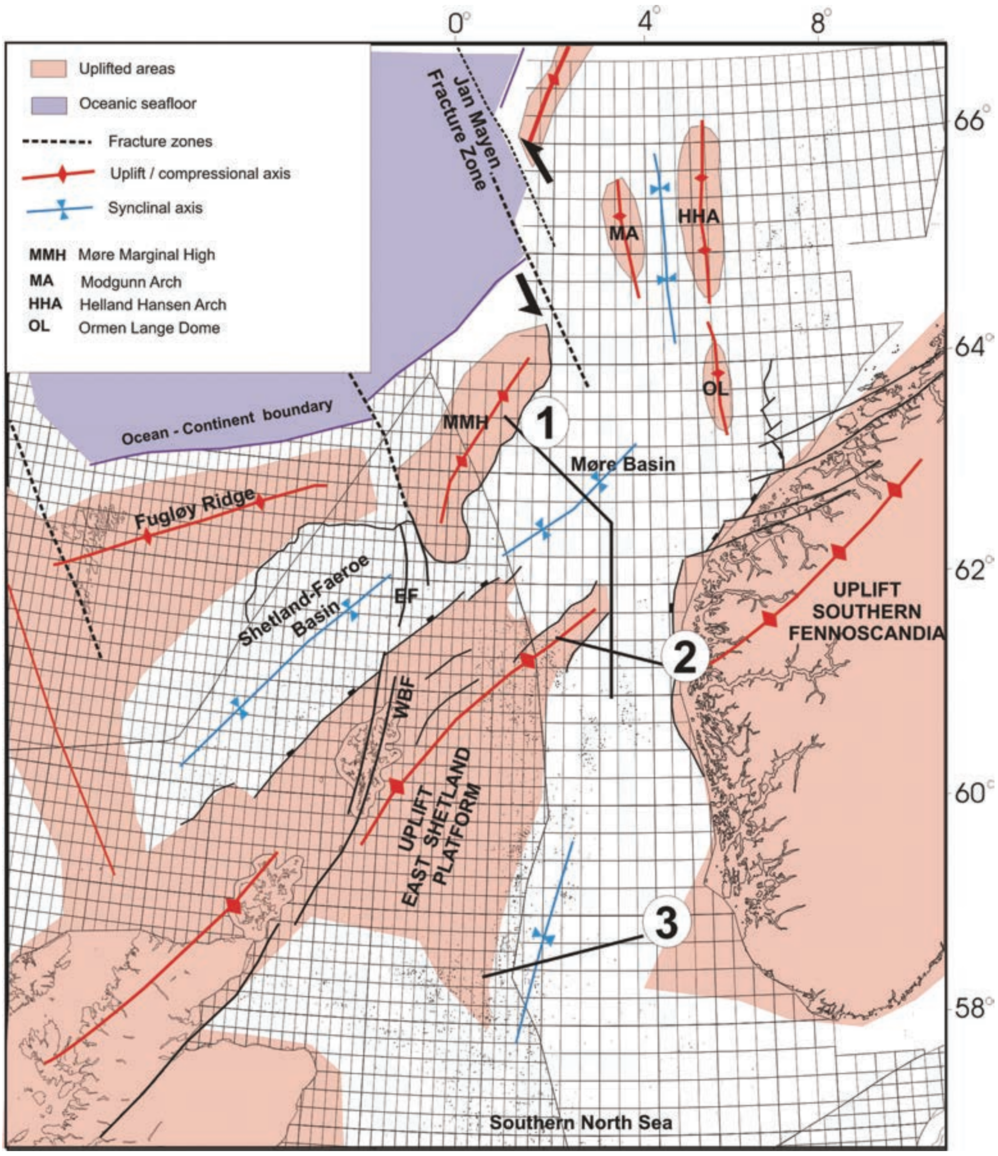

Fig. 2 Structural map of Oligocene–Miocene showing main areas affected by uplift, large structural domes (red lines). Note location of Erlend Fracture Zone and Erlend transfer Fault (EF) and its southern link with the Walls Boundary Fault (WBF) on the Shetland Platform. See insertion of map in Fig. 1 (yellow rectangle) for larger scale structural setting. Line 1, 2 and 3 refer to lines shown in Figs. 3, 4a and 4b, respectively.

During the Oligocene–Early Miocene, the northern North Sea progressively shallowed, and by the end of the period fairly shallow-marine conditions were established in the northernmost North Sea. The sediments are mainly fine-grained in nature and contain an abundance of diatoms and sponge spicules. The climatic conditions were still relatively warm and resulted in intense, locally lateritic weathering on the continents (Buchardt, 1978; Rundberg, 1989). Late Miocene paleogeographic reconstruction and sedimentary evolution of the northern sea are presented in a later section of this chapter (see Figs. 17, 18).

## Oligocene–Miocene stratigraphy

### *Present day depositional architecture*

A schematic north–south profile (Fig. 3) illustrates some key features of the present day architecture of the northern North Sea and Møre Basins. In the northern North Sea, a distinct northwards thinning of both Oligocene and Miocene strata is illustrated. A mirror image of this architecture is presented for the Møre Basin. Severe erosion is indicated at base Miocene in northernmost North Sea. This architecture

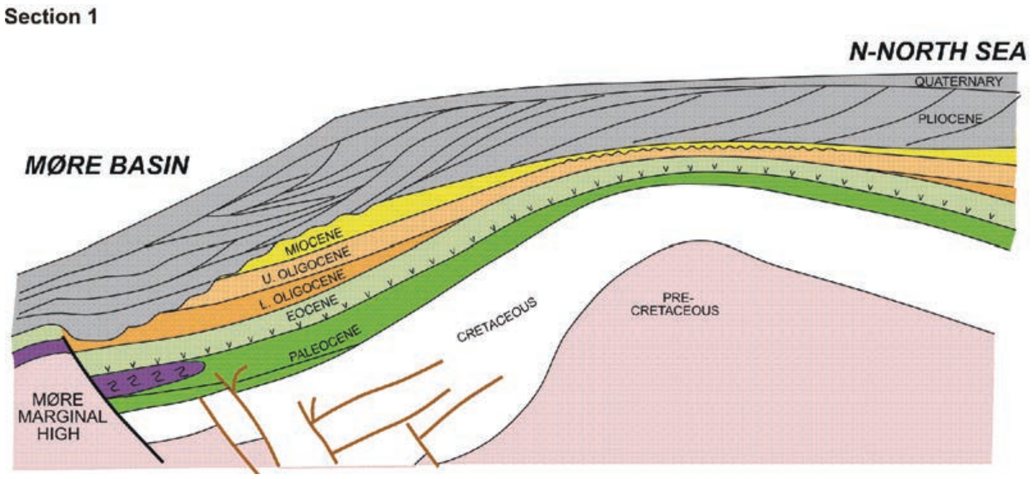

Fig. 3 Schematic illustration of the present day structural and sedimentary architecture of the Cainozoic along a N–S transect from the Møre Marginal High to the Viking Graben to the south. (Location of line shown in Fig. 2). Note the Oligocene–Miocene thinning of strata towards the Tampen Spur crest of the northernmost North Sea.

demonstrates that uplift has affected the northernmost North Sea during Oligocene–Miocene.

Two interpreted transects across the northern and southern Viking Grabens are presented in Figs. 4a and 4b, respectively. As seen, there are significant differences in the stratigraphical architectures of northern and southern Viking Grabens. The largest difference is linked to the stratal relationships just above and beneath the mid-Miocene unconformity. To the south (Fig. 4b), a very distinct infilling of sediments can be observed in the middle of the basin, above the mid-Miocene unconformity. To the north (Fig. 4a), strata below the mid-Miocene unconformity that are present to the south are either absent or heavily affected by erosion. Furthermore, the eastern flank of the basin has been heavily affected by Late Pliocene uplift, and a very characteristic thick, clinoformal system can be observed.

### *Lithostratigraphy*

The post-Eocene lithostratigraphy of the North Sea is poorly subdivided in the Norwegian sector. Deegan and Scull (1977) subdivided Eocene to Lower Miocene strata into the Hordaland Group and the early Miocene to Recent into the Nordland Group. The only formation defined by these authors within the post-Eocene was the sandy Utsira Formation at the base of the Nordland Group. Isaksen and Tonstad (1989) adopted this nomenclature, and also recognised two sandy formations in the Oligocene part of the Hordaland Group, which they termed, Skade and Vade Formations, present in the Viking Graben and central North Sea, respectively. In his work on the Tertiary sediments of the Norwegian North Sea (60–62°N), Rundberg (1989) subdivided the Hordaland and Nordland Groups into four lithostratigraphic associations and nine lithostratigraphic units. This subdivision was based on a detailed study of sediments from eleven wells along two transects in the eastern part of the northern North Sea.

In the UK part of the basin, Knox and Holloway (1992) established the Westray Group as a new lithostratigraphic unit. It formed the upper of the two groups which they had introduced to replace the Hordaland Group. They introduced the Lark Formation for the distal, mudstone-dominated facies of the Westray Group and used the Skade Formation for glauconitic sandstones and siltstones of shelf-facies. Recently, Fyfe et al. (2002) published an updated lithostratigraphy of the central and northern North Sea, based on Isaksen and Tonstad (1989), Knox and Holloway (1992) and recent dating by Eidvin et al. (1999) and Eidvin and Rundberg (2001).

We present in this work a revised lithostratigraphic and chronostratigraphic subdivision of the Oligocene–Miocene of the Norwegian northern North Sea. This subdivision is illustrated in Figure 5. The Skade Formation is in this work assigned to the Early Miocene, and not to Oligocene, as defined earlier by Isaksen and Tonstad (1989) and a more precise age assignment is given to the Utsira Formation. As shown in Fig. 5, a large hiatus separates the Hordaland and Nordland Groups, which is widespread in the Norwegian continental shelf and has been termed

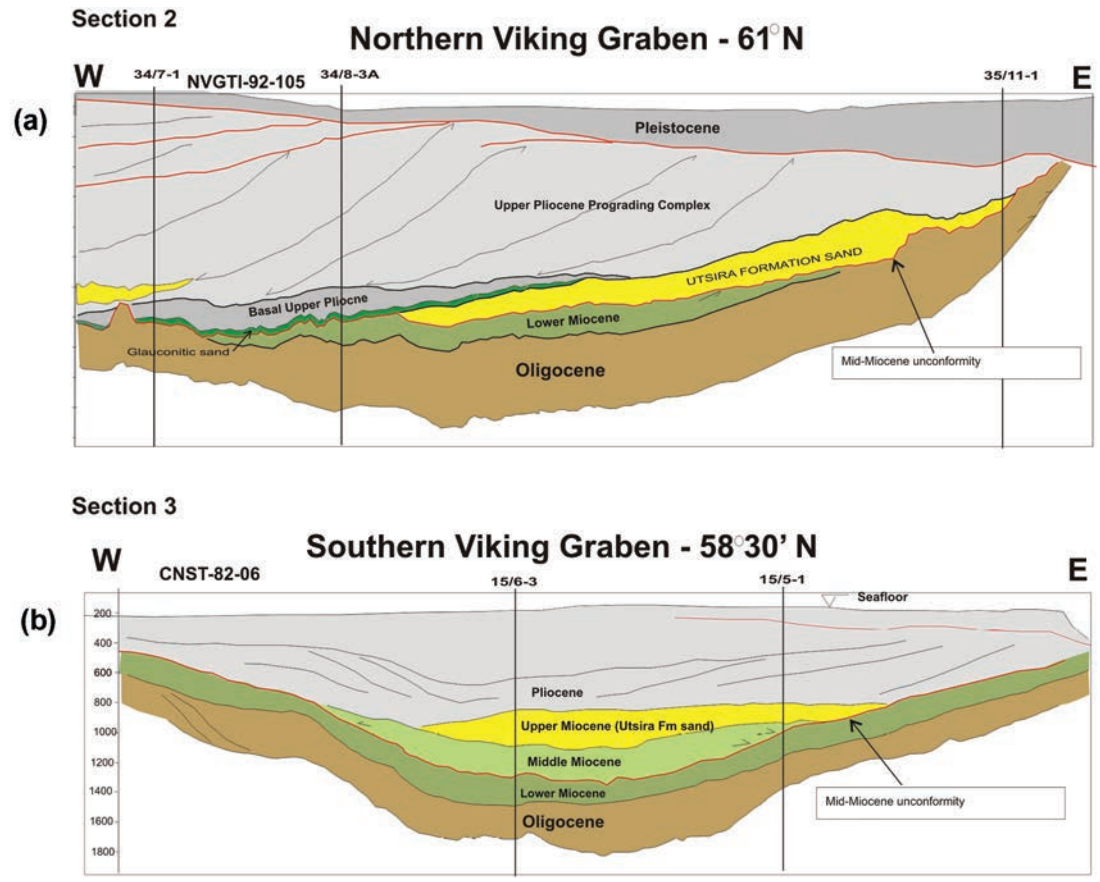

Fig. 4 (a) East–west transect of the northern North Sea at about 61°N illustrating main sequences and sedimentary architecture of the post-Eocene strata. Note the mid-Miocene unconformity (red line) and the seismic truncation of the Lower Miocene. See Fig. 2 for location of the line. (Modified from Eidvin and Rundberg, 2001). (b) East–west transect of the southern Viking Graben at about 58°30′N illustrating main sequences and sedimentary architecture of the post Eocene. Note the mid-Miocene unconformity and the infilling of the Middle Miocene sequence (this sequence is absent to the north). See Fig. 2 for location of the line.

the mid-Miocene hiatus by many workers. In the northern North Sea, it increases dramatically northwards, from almost no time-gap in the southern Viking Graben to about 15–20 million years, in the northernmost North Sea. The succession below the hiatus comprises sediments of Oligocene and early Miocene age. The Lower Oligocene sands are unnamed in the Norwegian sector.

Of particular notice is the recognition of an inconsistency in the definition of Skade and Utsira Formations. As presented in Figure 6, there is an overlap in definitions of the Utsira and Skade Formations in which the Skade Formation, as defined in type well 24/12-1, correlates to the lower part of the Utsira Formation as defined in type well 16/1-1. Using the type well boundaries for the Utsira, it would embrace sediments of almost the entire Miocene epoch and would also include the topmost part of the Hordaland Group. This is obviously in conflict with the definition and common usage of the Utsira Formation, being related in time and place to the Nordland Group.

### *Problems in seismic subdivision and biostratigraphic dating*

The Oligocene–Miocene succession of the northern North Sea has been described seismically by many workers (e.g. Rundberg, 1989; Rundberg and Smalley, 1989; Galloway et al., 1993; Jordt et al., 1995; Gregersen et al., 1997; Martinsen et al., 1999). Still, however, there are many problems with a detailed sequential understanding and mapping of these strata. The reasons for this are threefold.

Firstly, much of the Oligocene–Miocene strata display a poor seismic resolution due chaotic seismic reflection pattern in large parts of the basin. The chaotic reflections can be observed particularly within the Viking and the Sogn Grabens and within parts of the southern Møre Basin. Much of the chaotic pattern probably represents highly deformed strata resulting from severe gas leakage from the Jurassic source rocks. A discussion of the origin of the chaotic facies has recently been presented by Løseth et al. (2003).

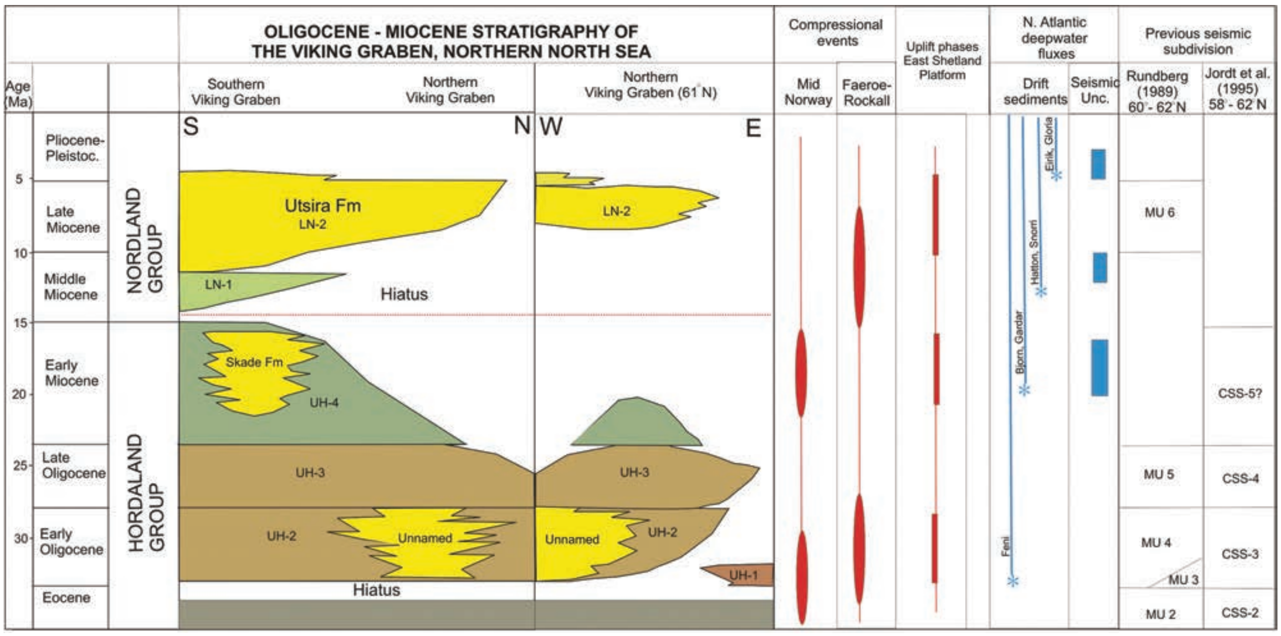

Fig. 5 Oligocene–Miocene stratigraphy of the Viking Graben, northern North Sea. Note the Middle Miocene sequence (new) and the chronology of the Skade Formation sands (new dating by Eidvin et al. 2002). North Atlantic deep-water fluxes showing periods of major drift accumulation to the south of the Greenland–Scotland Ridge (after Wold, 1994) and timing of seismic unconformities (after Wright and Miller, 1996). Compressional events of the Northwest European Atlantic margin after Lundin and Doré, 2002.

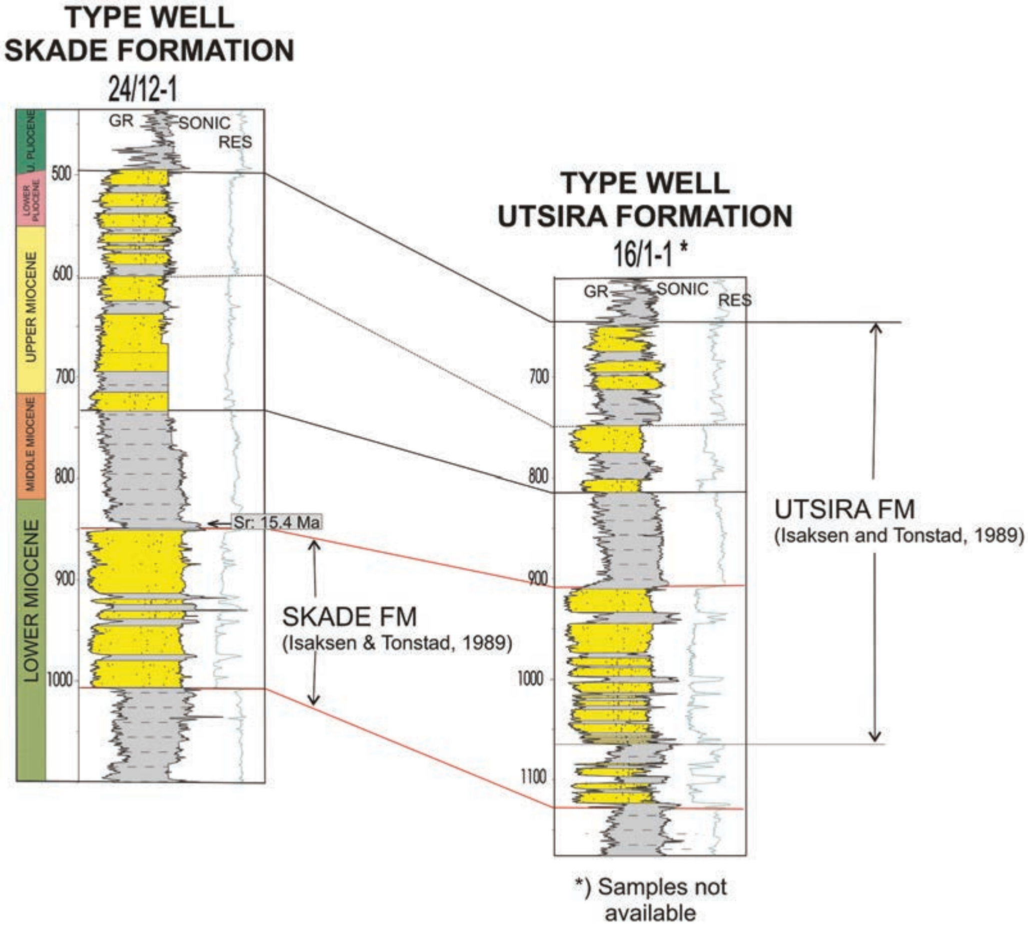

Fig. 6 Log correlation between well 24/12-1 (type well of the Skade Formation) and well 16/1-1 (type well of the Utsira Formation) illustrating conflict in previous definition of the Utsira Formation (see text for details). Left panel in well 24/12-1 shows results of biostratigraphic dating. Sr = Sr isotopic dating.

Secondly, there are often problems with the biostratigraphic dating of the Upper Oligocene and Lower Miocene sections, and the top Oligocene is a difficult boundary to assign using micropalaeontology. This is often seen in well completion logs from the northern North Sea. In many cases, the top Oligocene varies from well to well, and even between closely spaced wells. This is probably due to the fact that different biostratigraphic workers and consultants use different index fossils for the Oligocene/Miocene boundary, and due to severe reworking of fossil tests.

Thirdly, an inconsistency in the definition of Skade and Utsira Formations (see Fig. 6) has apparently caused much conflict for seismic workers in this part of the basin. Gregersen et al. (1997) for example, included Lower Miocene strata in their mapping of the Utsira in southern Viking Graben (e.g. their Fig. 6). This error probably results from the definition of the Utsira Formation in its type well 16/1-1. In their mapping of the Lower Miocene of the northern North Sea, Jordt et al. (1995) erroneously included included Upper Miocene strata (Utsira sands) in Unit CSS-5 (their Figs. 9 and 15).

### Depositional systems and seismic units

The Oligocene–Miocene succession of the northern North Sea can broadly be subdivided into two megasequences. The base of each megacycle is marked by an unconformity or a regional hiatus. The lower megasequence comprises the Lower Oligocene to Lower Miocene succession, or the upper part of the Hordaland Group. It consists of a compounded system of sequences, which are best defined towards the margins of the basin. In general, much of the Oligocene strata display a chaotic seismic reflection pattern, which make it difficult to map regionally. Locally, however, it is possible to map the Oligocene in a more detailed manner. The upper megasequence comprises the Middle Miocene to Lower Pliocene succession, or the lower part of the Nordland Group. This megasequence has been subdivided into two seismic units. All of these units will briefly be described here.

### Lower Oligocene–Lower Miocene megasequence

The Oligocene to Lower Miocene succession (upper part of Hordaland Group) has been subdivided into four seismic units (UH-1–UH-4; Fig. 5): (1) A wedge-shaped seismic unit (UH-1) confined to the eastern part of the basin, assigned to lowermost Oligocene; (2) a Lower Oligocene unit (UH-2) derived mainly from the west; (3) an Upper Oligocene unit (UH-3), and (4) a Lower Miocene unit (UH-4).

### Lower Oligocene wedge unit (UH-1)

This unit occurs parallel to the Norwegian coastline and can easily be mapped between ~60° and 61°30′N. The areal distribution of this unit is shown in Fig. 7a. It was termed map unit 3 (lithologic unit B3) by Rundberg (1989) and was described in detail in his work. It was not distinguished as a separate unit by Jordt et al. (1995), and is included in their sequence CSS-3.

Unit UH-1 has a distinct wedge-shaped geometry with a thickness in excess of 200 m, and rapidly pinches out basinwards, as illustrated in seismic sections (Figs. 8a, 8b, 9). Seismically, it displays a characteristic low-amplitude, occasionally transparent reflection pattern, which can be obviously related to a uniform lithology as expressed by well log data. Lithologically, the unit consists of a very uniform series of noncalcareous, dark brownish claystones, which become slightly coarser upwards. In well 31/3-1 (Fig. 8b), the clays grade upward into glauconitic, sandy siltstones. Rundberg and Smalley (1989) reported Early Oligocene Sr isotope ages of samples from well 31/3-1. Such ages have later been confirmed in the same well by Eidvin and Rundberg (2001) using the same dating methodology and biostratigraphical correlation, and by Sejrup et al. (1995) in a borehole, cored nearby.

### Lower Oligocene unit (UH-2)

The Lower Oligocene unit has been distinguished seismically in the northern part of the basin (between 60–61°N). It corresponds to seismic map unit 4 of Rundberg (1989) and to seismic sequence CSS-3 of Jordt et al. (1995). The outline of the Lower Oligocene unit is shown in Fig. 7a. It overlies Eocene strata and pinches out eastward, close to the western limit of the Lower Oligocene clastic wedge (UH-1; Figs. 8, 9).

Between 60–61°N the top of the unit is defined by a moderate to high-amplitude, semi-continuous seismic reflector in the eastern part of the basin (Figs. 8, 9). This reflector corresponds to an abrupt downward increase in sonic and particularly density levels, as illustrated in Figure 10. The top of unit UH-2 corresponds to a diagenetic horizon characterised by the transition from opal-A to

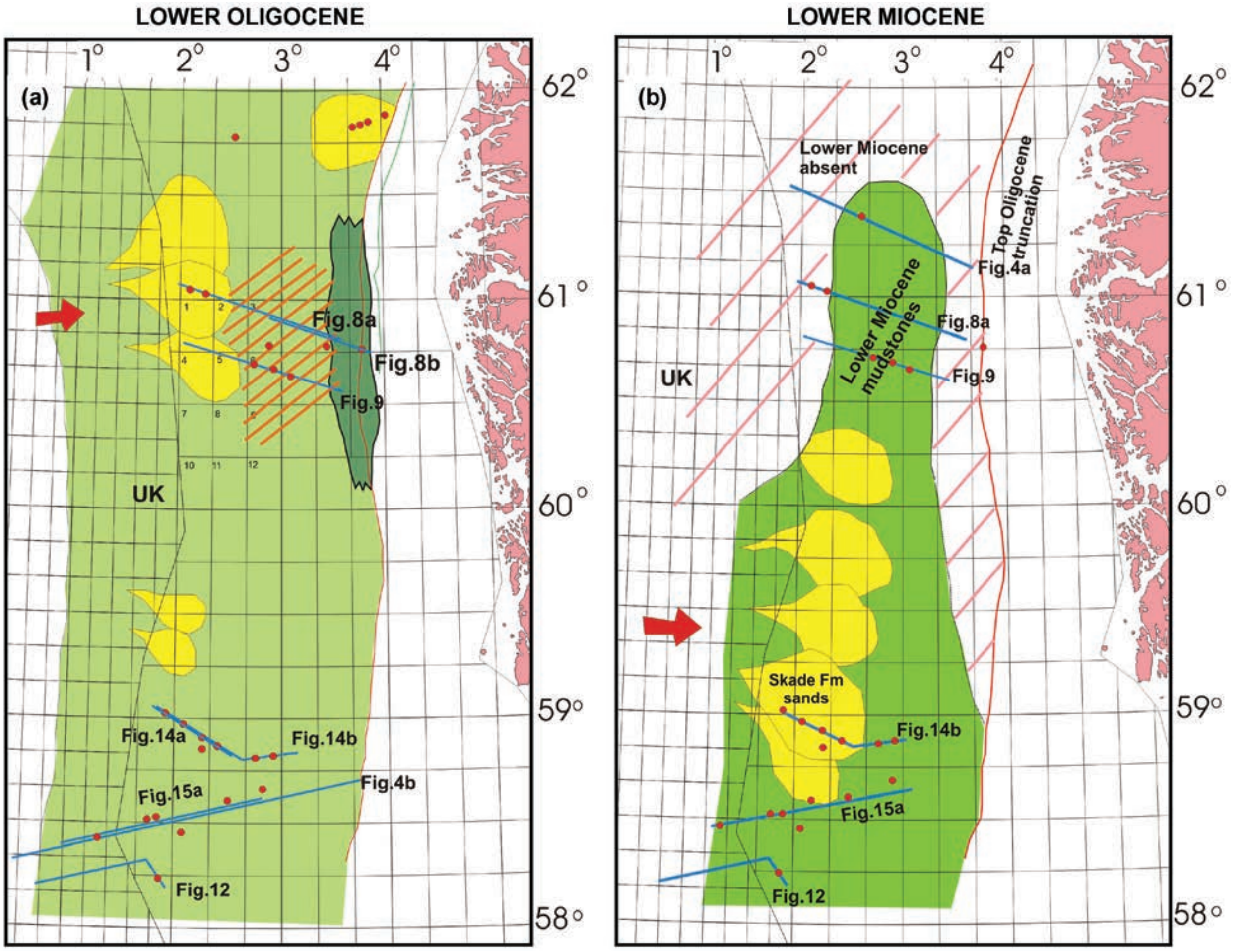

Fig. 7 (a) Distribution of Lower Oligocene sediments in northern North Sea; seismic units UH-1 (dark green) and UH-2 (light green). Approximate outlines of sands derived from west (Statfjord–Tampen area) and sands derived from east (Agat area). Hatched area shows approximate outline of siliceous-rich sediments (in the form of opal-CT). (b) Distribution of Lower Miocene sediments (seismic unit UH-4) in northern North Sea with approximate outline of the sandy Skade Formation. Hatched area shows erosion of Lower Miocene. (c) Distribution of Middle Miocene sediments (seismic unit LN-1) in northern North Sea. The northward extent is uncertain. Hatched area shows not deposited Middle Miocene strata. (d) Distribution of Utsira Formation sands (seismic unit LN-2) in northern North Sea. Yellow area shows outline of lower part (main Utsira sands, predominantly ?Late Miocene age), orange area shows outline of upper part of the Utsira Formation (Early Pliocene age). Green area to the north shows outline of thin glauconitic member extending beyond the main sand.

opal-CT rich mudstones (Fig. 11). Locally, at the top of the unit, it defines a flat seismic event cutting inclined reflectors. This siliceous-rich mudstone lithology is thought to be present locally within the northern North Sea, particularly between 60–61°N (see hatched area Fig. 7a), as interpreted from the seismic and wireline log data.

Westward, the Oligocene strata are severely affected by seismic disturbance, and it is difficult to map the top of the unit. It is probably best defined in the northern part, at about 60°45′–61°N, as illustrated in the two seismic sections, shown in Figs. 8a and 9. Along both of these profiles, the seismic reflector defining the top of the high-density zone can, with some degree of certainty, be correlated to discontinuous, high-amplitude seismic events further to the west. These events define the top of a thick sandy interval, which is penetrated in two wells (34/10-17 and 34/10-23) along the seismic profile, shown in Figure 8a. The sands make up a gross thickness of about 400 m in block 34/10 (Fig. 8c). They are clearly turbiditic in origin, and their areal extent is shown in Figure 7a. The Lower Oligocene sands are unnamed in the Norwegian sector.

Lower Oligocene sands are also present in the Agat area (block 35/3; Fig. 7a), as described by Rundberg (1989) and Rundberg and Smalley (1989). These sands (termed, subunit 3 in Rundberg, 1989) are distinguishable from the underlying sands (subunits 1 and 2) by their relatively high-content of glauconite, shell debris and lignites and by common calcite-cemented sandstone horizons. Rundberg (1989) interpreted subunits 1 and 2 to

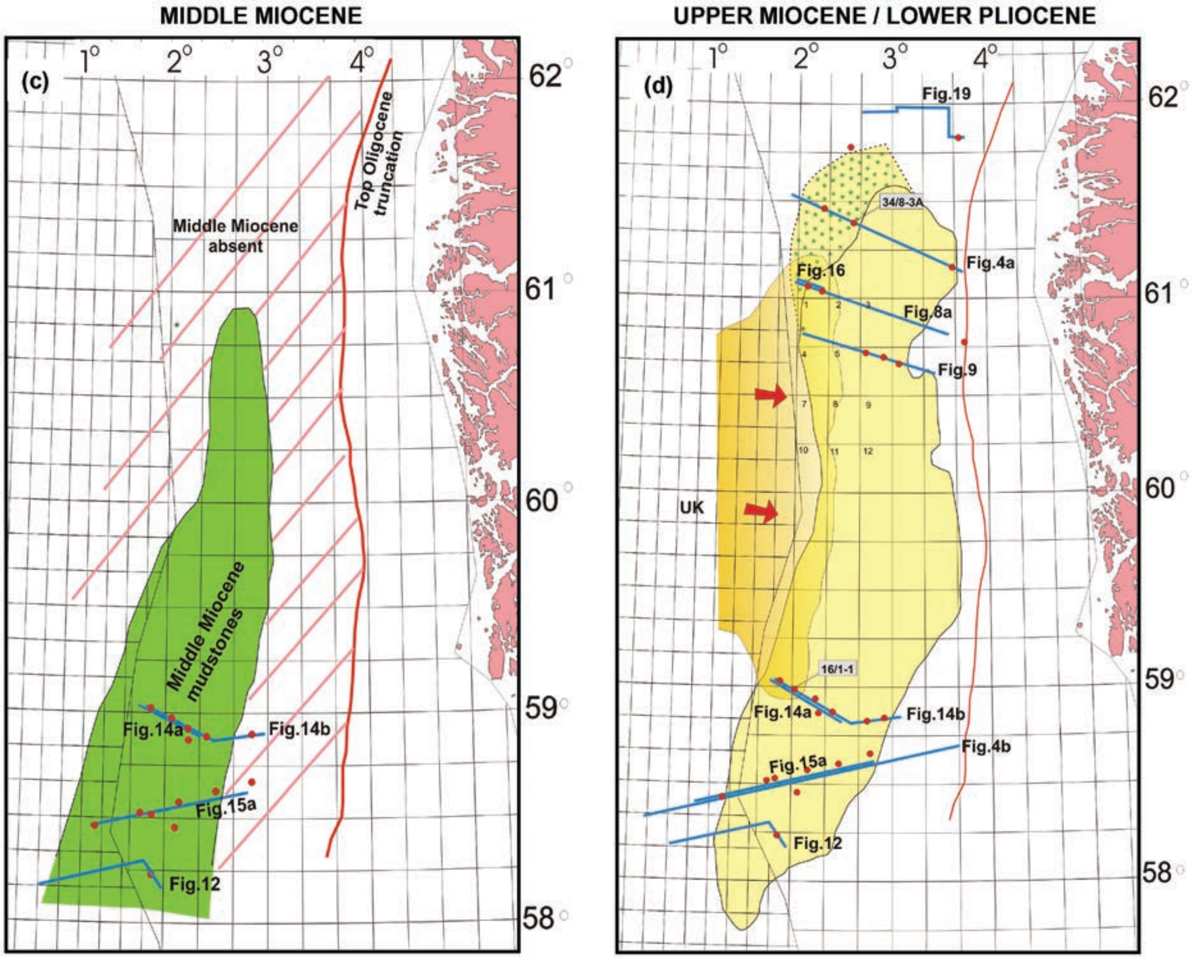

Fig. 7 Continued.

represent gravity-flow sands and interpreted a dramatic shallowing to take place with the incoming of subunit 3.

### *Upper Oligocene unit (UH-3)*

The top of the Oligocene is commonly difficult to pick biostratigraphically in wells in the basin centre, as described earlier. Also seismically, it may be difficult to distinguish from the conformably overlying Lower Miocene sediments. In addition, a chaotic seismic reflection pattern causes mapping problems over large parts of the basin. Earlier workers in the northern North Sea have therefore grouped all sediments of the upper part of the Hordaland Group in one compound unit (e.g. Map unit 5 of Rundberg, 1989; CSS-4 of Jordt et al., 1995).

The outline of the Upper Oligocene unit (UH3) is not presented here, but is largely similar to that of the Lower Oligocene unit UH2 (Fig. 7a). Toward the eastern margin (between 60–61°N), it clearly onlaps the underlying wedge-shaped unit UH-1 (Figs. 8, 9). To the north of 60°N, the top of the unit becomes eroded at both margins, as illustrated in Fig. 4a, and is here unconformably overlain by Upper Miocene and Pliocene sediments.

We have defined the top of the Oligocene by detailed biostratigraphic investigations in wells 15/9-13, 15/12-3, 16/1-4 and 24/12-1 in the southern Viking Graben. The Miocene–Oligocene boundary is mainly based on the last appearance datum (LAD) of Diatom sp. 3 (King, 1983) (Tab. 2). In wells 15/12-3 and 16/1-4, the biostratigraphic interpretations are confirmed by Sr isotope stratigraphy (see Figs. 12 and 13). Similarly, in the Tampen area in the northern North Sea, we defined the Miocene–Oligocene boundary in wells 34/8-1 and 34/8-3A by biostratigraphic correlation and Sr isotope stratigraphy (Eidvin and Rundberg, 2001).

In well 15/12-3 in southern Viking Graben, the top of the Oligocene corresponds to a low-amplitude seismic event (Fig. 12) which can be traced with relatively good precision to the south of about 58°30′N. In the Tampen area, the top of

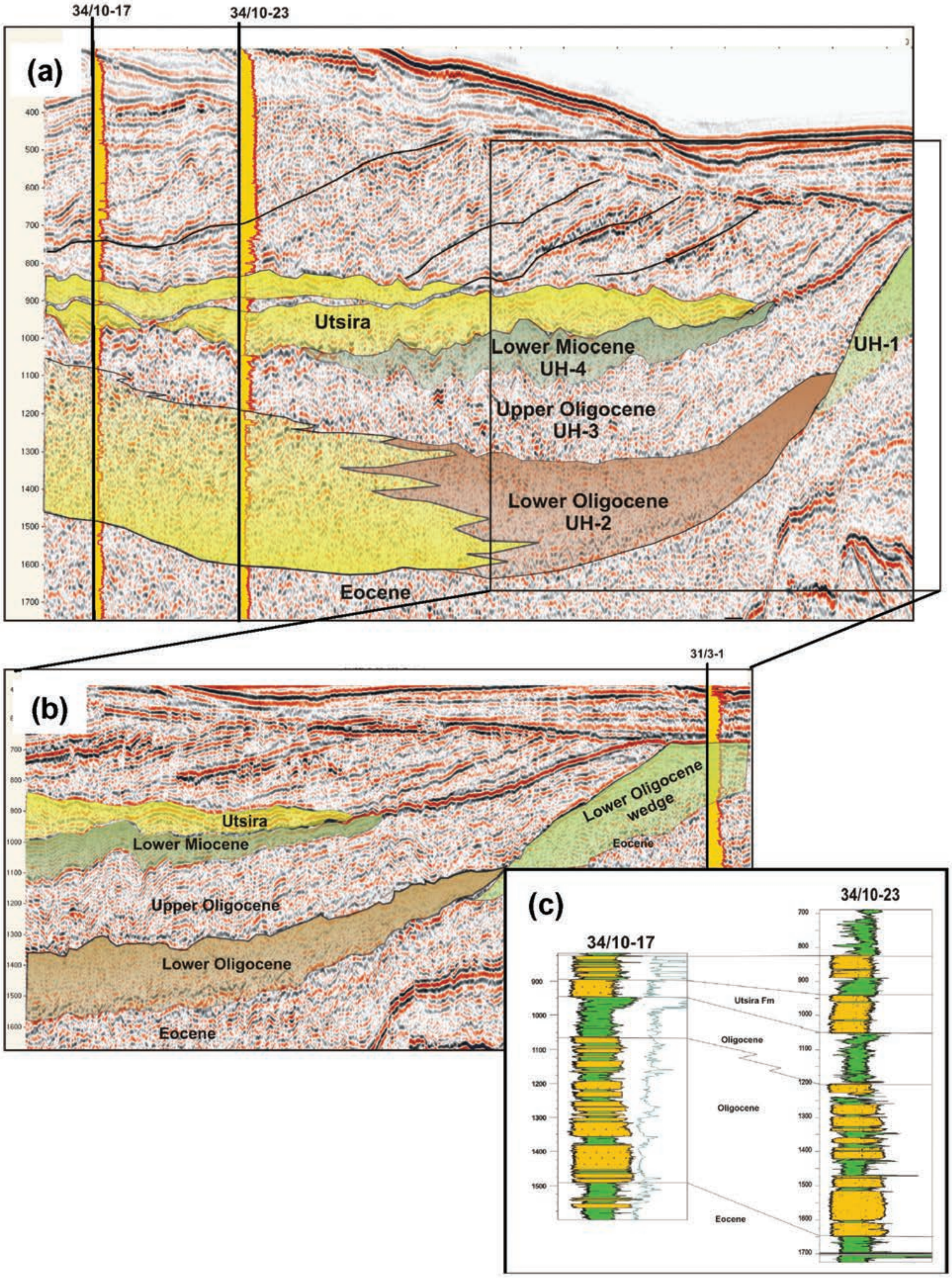

Fig. 8 (a) Seismic section (line NVGTI-92-208) across northern Viking Graben through wells 34/10-17 and 23 showing subdivision of Oligocene–Miocene strata at about 61°N. Note wedge-shaped Lower Oligocene seismic unit (UH-1) to the east; sand-rich wedge of sediments (seismic unit UH-2) pinching out to the east; lower Miocene strata (seismic unit UH-4) preserved in the middle of the basin. Location of line shown in Figs. 7a, 7b and 7d. (b) Seismic section (eastern part of NVGT-92-208) through well 31/3-1 illustrating stratal relationship between lower Oligocene units. Location of line shown in Fig. 7a. (c) Log correlation between wells 34/10-17 and 34/10-23 along seismic section shown in Fig. 8a.

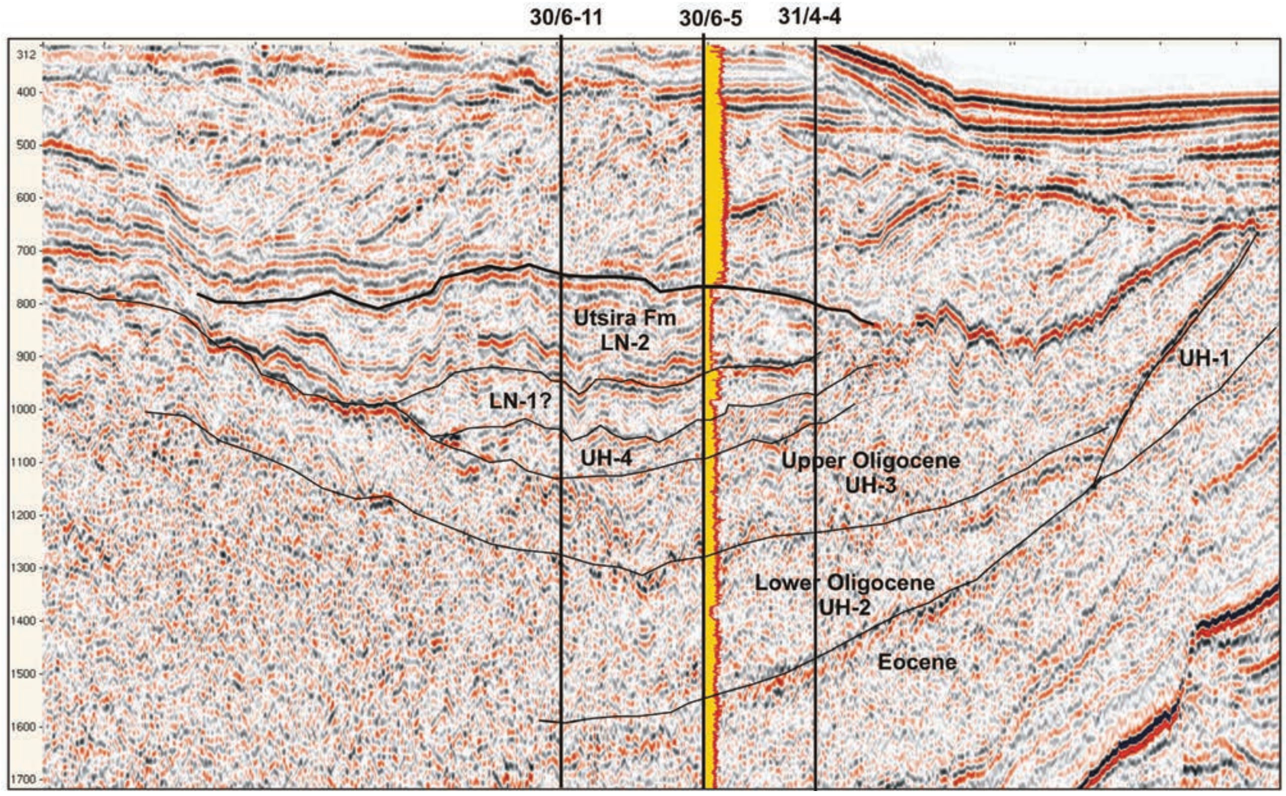

Fig. 9 Seismic section through wells 30/6-11, 30/6-5 and 30/6-4 illustrating seismic subdivision of the Oligocene–Miocene succession. Note main Utsira Formation sands (lower part) pinching out in westward direction and high-amplitude reflectors to the west (upper part of Utsira Formation) denoting influx of sands from the East Shetland Platform. Location of line shown in Figs. 7a–d.

the Oligocene also closely corresponds to a seismic reflector (well 34/8-3A), which allows a precise mapping in the northern part of the basin. Between 59–61°N, we have not executed new, biostratigraphical investigations, since the top of the Oligocene may be difficult to pick seismically. The mapping is also complicated by a chaotic seismic reflection pattern, which affects the Hordaland Group, over much of the central basin area.

Lithologically, the Upper Oligocene unit comprises dominantly; these are, mudstones however, only scattered with thin sands. Some sands are however noted in wells of block 30/2 and 30/3. In the northern part of the basin, the unit coarsens upward to silty sands and siltstones at the top (e.g. well 34/2-2, described by Rundberg, 1989). The siltstones are typically rich in sponge spicules and glauconite. In the Agat area, close to the eastern margin of the basin, the unit is represented by a progradational system with fine-grained, glauconitic sands at the top. The planktonic fossil assemblage is dominated by pyritised diatoms and radiolaria. Calcareous foraminifera dominate a moderately rich benthic fauna in most wells, but agglutinated forms are common in some areas (e.g. wells 15/12-3 and 15/9-13).

On wireline logs, the unit displays a slightly serrated, but otherwise stable, low gamma-log profile in wells to the north of 60°N (e.g. wells presented in Figs. 10 and 11). In the southern Viking Graben, the topmost part of the Oligocene shows an upward change to higher gamma-ray levels (e.g. well 15/12-3, Fig. 12). In the Statfjord area (block 34/10) for example, the very top of the Oligocene section displays characteristic high velocity and resistivity log values (Fig. 8c).

### *Lower Miocene unit (UH-4)*

This unit comprises the topmost part of the Hordaland Group. The outline of the unit is shown in Fig. 7b. In the southern Viking Graben, it conformably overlies Oligocene strata (Fig. 4b). It is overlain by Middle Miocene sediments in the centre of the basin and Pliocene sediments at the margins. To the north of 60°N, the Lower Miocene unit is only present in the central basin and absent at the margins to the west and east (Figs. 4a, 7b). On seismic sections, the top of the unit can be defined by erosional truncation, onlap or downlap reflection terminations, as schematically illustrated in Figures 4a and 4b. In the

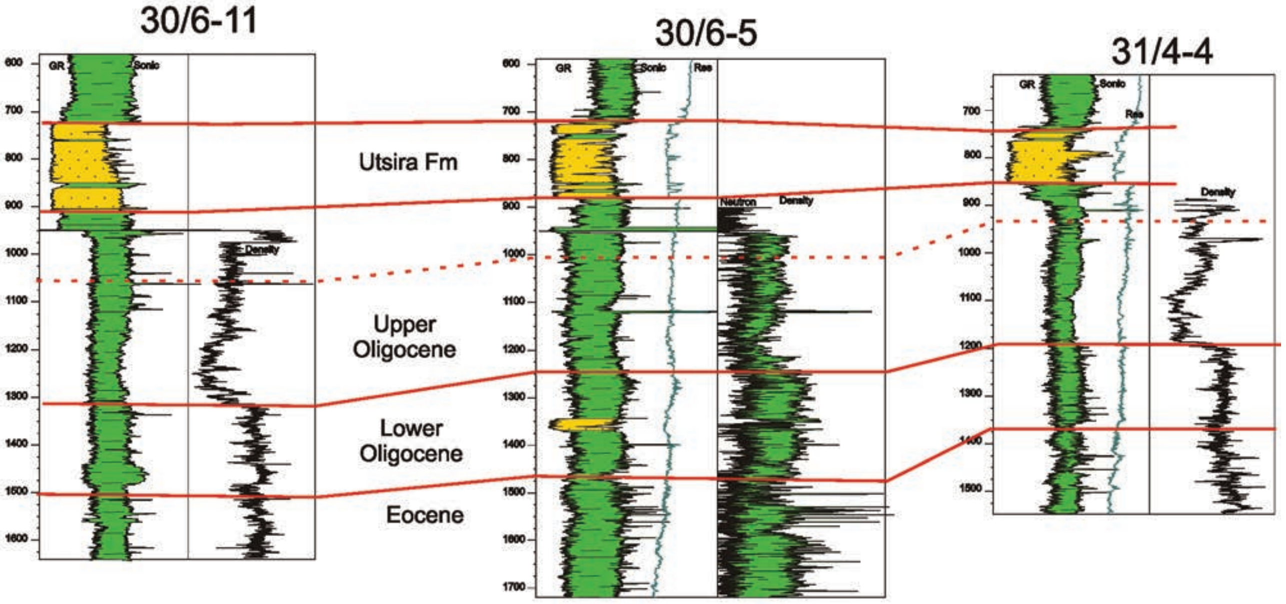

Fig. 10 Log correlation between wells 30/6-11, 30/6-5 and 31/4-4 along seismic section shown in Fig. 9 illustrating very abrupt downward density increase which marks the top of the lower Oligocene unit (UH-2). This boundary can be seen as a discontinuous, high-amplitude seismic response in Fig. 9.

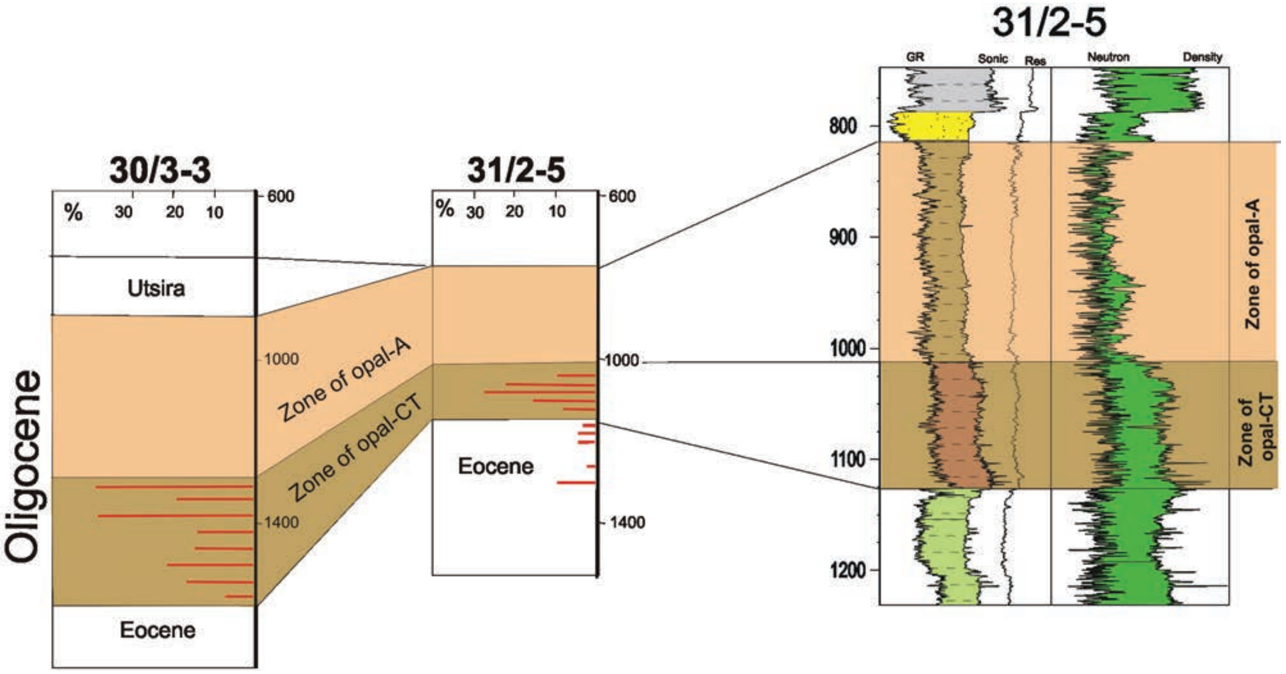

Fig. 11 Distribution of siliceous sediments (opal-CT) in wells 30/3-3 and 31/2-5. Note abrupt increase in opal-CT at the Eocene–Oligocene boundary. Top of opal-CT zone corresponds to abrupt downward density increase in well 31/2-5. This marks the top of seismic unit UH-2 (see Fig. 9). Modified from Rundberg (1989).

northernmost North Sea, between 61°30′ and 62°N, the unit has been completely eroded. This erosional period, termed mid-Miocene erosional event, is further dealt with in this chapter.

Unit UH-4 corresponds to the upper part of map unit 5 of Rundberg (1989) and to CSS-5 of Jordt et al. (1995). In the latter work, however, there are conflicts in the interpretation of the Miocene strata within the northern North Sea, in which Upper Miocene Utsira sands have been mistakenly included in CSS-5 (their Figs. 3, 9).

Lower Miocene strata have recently been described in the Tampen area by Eidvin and Rundberg (2001), and comprise mud-prone lithologies. In large parts of the Viking Graben, a sandy section makes up a great proportion of the Lower Miocene unit. These sands are referred to as the Skade Formation and reach a gross thickness up to

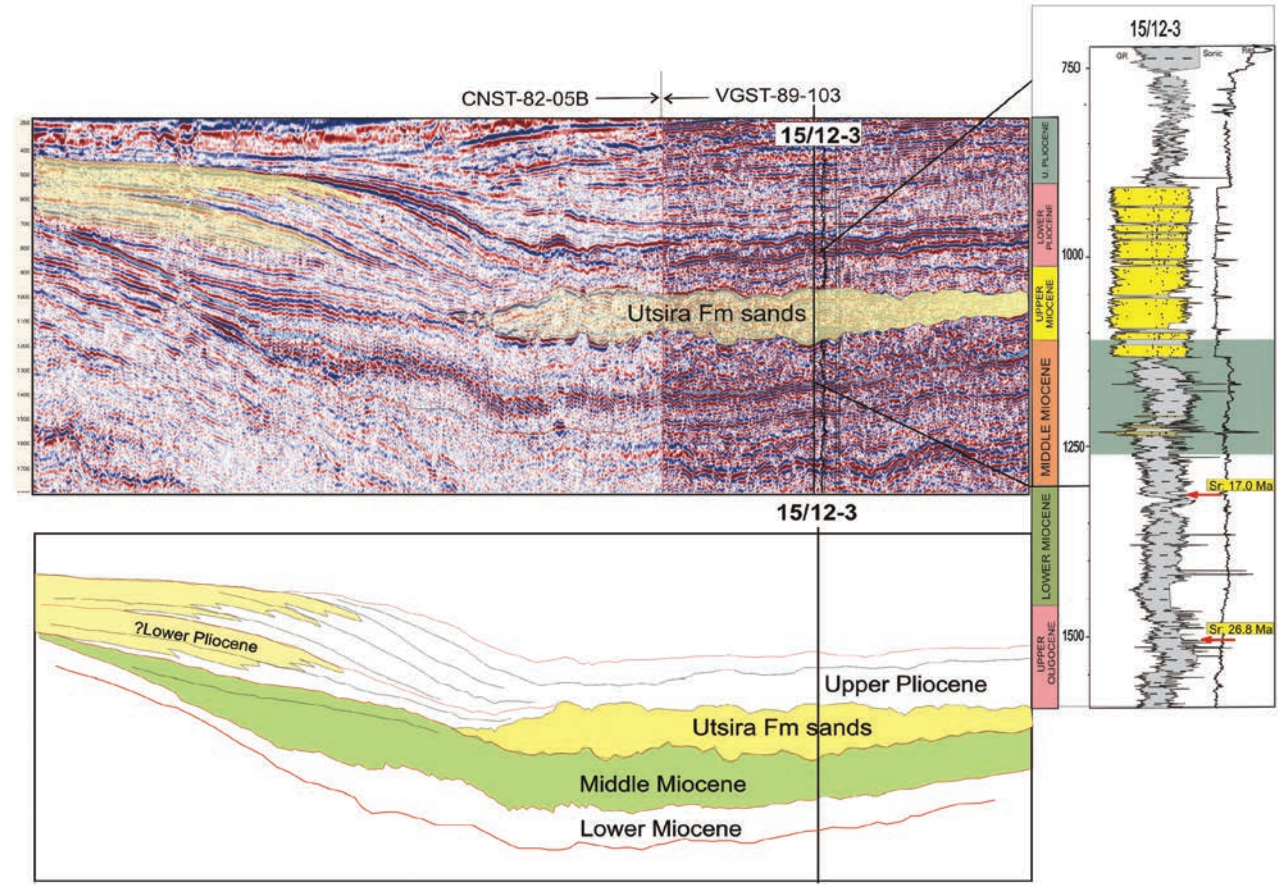

Fig. 12 Seismic profile across southern Viking Graben through wells 15/12-3 (well panel inserted) showing stratigraphical relationships of Miocene sediments. Location of line shown in Figs. 7a–d. Left panel of 15/12-3 shows results of biostratigraphic dating. Green-coloured part of log panel corresponds to the occurrence of the Middle Miocene *Bolboforma badenensis* and *B. reticulata* assemblages. See text for details.

300 m (well 16/1-4). The areal extent of the sands is shown in Fig. 7b. They comprise a sequence of amalgamated sands in alternation with thinner mudstones. Detailed biostratigraphic investigations of well 24/12-1 (type well of the Skade Formation) show that the sands are Early Miocene in age (Tables 1 and 2; Fig. 13) and not Late Oligocene, as suggested by Isaksen and Tonstad (1989).

A log correlation diagram between key wells in blocks 16/1 and 24/12 is presented in Fig. 13. As can be seen from this figure, the top of the Skade sands corresponds closely to the top of the Lower Miocene in wells with good biostratigraphic control. In well 24/12-1 (type well of the Skade Formation), the Early Miocene *Uvigerina tenuipustulata–Asterigerina guerichi staeschei* benthic foraminiferal assemblage and the Early Miocene *Globorotalia zealandica–Globigerina ciperoensis* planktonic foraminiferal assemblage have been identified for the intervals 820–1020 and 840–1040 m, respectively (Tables 1 and 2), both embracing the strata above and below the Skade Formation sands. The biostratigraphic data are supported by Sr isotope stratigraphy, which yield ages of about 15 Ma for samples just above the sands in wells 24/12-1 and 16/1-4 (see Fig. 13). A seismic section through all the three wells (plus wells 16/1-1 and 16/3-2) is shown in Fig. 14a. The Skade Formation sands are overlain by mudstones which clearly onlap the Middle Miocene surface to the east.

Further to the south, in blocks 15/6 and 16/7, the Lower Miocene unit has a maximum thickness of about 250 m. In Fig. 15a, is shown a seismic line through seven wells, close to the southern pinchout of the Skade sands (see Fig. 7b). Here, the Lower Miocene deposits comprise a stacked series of upward-coarsening subunits (up to 50 m thick), particularly well observed in wells 15/6-3 and 15/6-5. The top of the unit is taken at a very distinct high radioactive marker (defined in 15/12-3; Fig. 12), which can be identified in a number of wells in the southern Viking Graben (Fig. 15b). This marker defines the transition between the Hordaland and Nordland Groups, in this part of the basin.

The Lower Miocene section contains a rich planktonic assemblage including foraminifera, diatoms and radiolaria. Calcareous foraminifera

Table 1 Benthic Foraminiferal assemblages in southern Viking Graben wells.

| Benthic Foraminiferal assemblages | Age interpretation | 15/9-A-11 | 15/9-A-23 | 15/9-13 | 15/12-3 | 16/1-2 | 16/1-4 | 24/12-1 |
|---|---|---|---|---|---|---|---|---|
| *Elphidium excavatum–Haynesina orbiculare* | Early to Middle Pliocene | | | | 200–380 m | | | |
| *Elphidium excavatum–Cassidulina teretis* | Early Pleistocene | | | | 380–600 m | | 357.5–480.5 m | |
| *Cibicides grossus* | Late Pliocene to Early Pleistocene | 912. 4 m (one sample) | | | 600–900 m | 710–740 m | 480.5–760 m | 480–500 m |
| *Cibicidoides pachyderma* | Late Pliocene | 912.8–913.1 m | | | | | | |
| *Monspeliensina Pseudotepida* | Early Pliocene | | | | | 740–750 m | | 500–520 m |
| *Uvigerina venusta saxonica* | Late Miocene to Early Pliocene | | 1080 m (one sample) | | 900–1110 m | 750–870 m | 760–770 m | 520–720 m |
| *Uvigerina pygmea langeri–Uvigerina pygmea langenfeldensis* | Middle Miocene | | | 1110–1160 m | | 870–880 m | 860–912.5 m | 720–820 m |
| *Uvigerina pygmea langenfeldensis* | Middle Miocene | | | | 1110–1250 m | | | |
| *Asterigerina guerichi staeschei* | Middle Miocene | | | 1160–1190 m | 1250–1300 m | | | |
| *Uvigerina tenuipustulata–Asterigerina guerichi staeschei* | Early Miocene | | | | | | 912–1090 m | 820–1020 m |
| *Uvigerina tenuipustulata* | Early Miocene | | | 1190–1320 m | 1300–1340 m | | | |
| *Plectofrondicularia seminuda* | Early Miocene | | | 1320–1480 m | 1340–1460 m | | | 1020–1090 m |
| *Spirosigmoilinella compressa* | Latest Late Oligocene to Early Miocene | | | | | | 1090–1190 m | |
| *Turrilina alsatica* | Late Oligocene to Earliest Miocene | | | 1480–1550 m | | | 1190–1260 m | 1090–1240 m |
| *Annectina biedai–Turrilina alsatica* | Late Oligocene | | | | 1460–1520 m | | | |
| *Rotaliatina bulimoides* | Early Oligocene | | | | | | 1260–1400.5 m | |

Table 2 Planktonic fossil assemblages in southern Viking Graben wells.

| **Planktonic fossil assemblages** | **Age interpretation** | **15/9-13** | **15/9-A-11** | **15/9-A-23** | **15/12-3** | **16/1-2** | **16/1-4** | **24/12-1** |
|---|---|---|---|---|---|---|---|---|
| *Neogloboquadrina pachyderma* (dextral) | Late Pliocene | | | | 790–840 m | | 650–670 m | |
| Upper *Neogloboquadrina atlantica* (dextral) | Late Pliocene | | 913.1 m (one sample) | | 840–850 m | | 670–720 m | |
| *Globigerina bulloides* | Early to Late Pliocene | | | | 850–860 m | | | 480–510 m |
| *Neogloboquadrina atlantica* (sinistral) | Early to Late Pliocene | | | | 860–940 m | 710–740 m | 720–763.5 m | |
| *Globorotalia puncticulata* | Early Pliocene | | | 1080 m (one sample) | 940–1010 m | 740–780 m | 763.5–770 m | 510–550 m |
| Lower *Neogloboquadrina atlantica* (dextral) | Late Miocene | | | | | 780–870 m | | 550–700 m |
| *Neogloboquadrina atlantica* (dextral)–*Neogloboquadrina acostaensis* | Late Miocene | | | | 1010–1110 m | | | |
| *Bolboforma fragori* | Late Miocene | | | | | | | 700–720 m |
| *Bolboforma badenensis* | Middle Miocene | 1110–1140 m | | | | 870–880 m | | 720–790 m |
| *Bolboforma badenensis*–*Bolboforma reticulata* | Middle Miocene | | | | 1110–1260 m | | 860–912.5 m | |
| *Bolboforma reticulata* | Middle Miocene | 1140–1160 m | | | | | | 790–840 m |
| *Globigerina praebulloides* | Middle Miocene | | | | 1260–1300 m | | | |
| *Globigerina praebulloides*–*Globigerinoides quadrilobatus triloba* | Early- Middle Miocene | 1160–1200 m | | | | | | |
| *Globorotalia zealandica*–*Globigerina ciperoensis* | Early Miocene | 1200–1310 m | | | 1300–1340 m | | 912.5–950 m | 840–1040 m |
| Diatom sp.4 | Early Miocene | 1310–1480 m | | | 1340–1460 m | | 1030–1180 m | 1040–1130 m |
| Diatom sp.3 | Early Oligocene to Late Oligocene | 1480–1550 m | | | 1340–1460 m | | 1180–1400.5 m | 1130–1240 m |

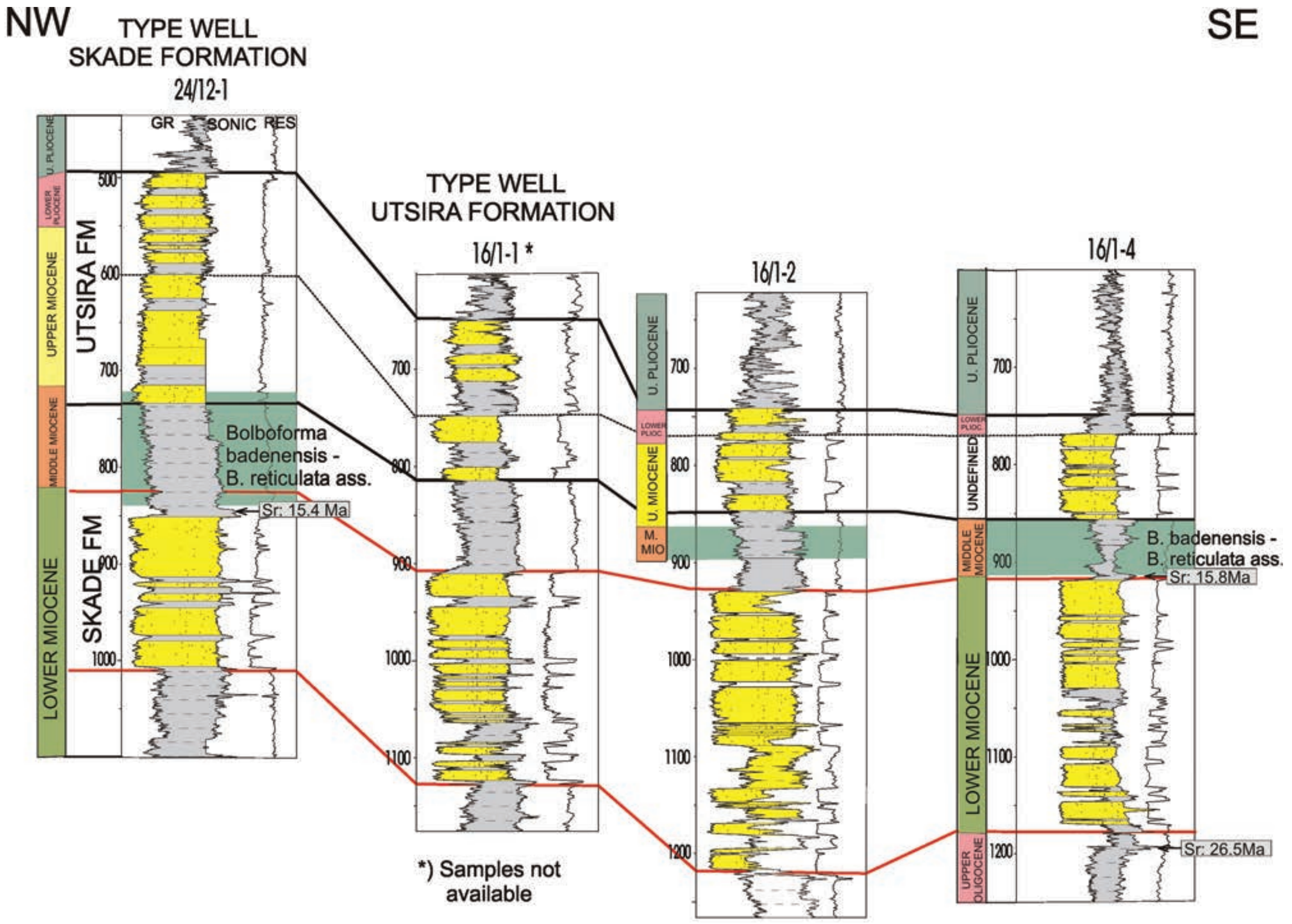

Fig. 13 Log correlation between wells 24/12-1, 16/1-1, 16/1-2 and 16/1-4 showing Skade Formation sands within the Lower Miocene section overlain by Middle Miocene mudstones characterised by the diagnostic *Bolboforma badenensis* and *B. reticulata* assemblages (interval marked in green) which again are overlain by Utsira Formation sands. Note lower main sands of the Utsira Formation yielding Late Miocene age and upper part yielding Early Pliocene age. Note also thick sands of the Utsira in well 24/12-1. See text for details. Location of wells shown in Figs. 7a–d.

dominate a moderately rich to sparse benthic fauna. Locally, agglutinating forms are numerous (e.g. 16/1-4 in the well).

## Lower Nordland megasequence (Middle Miocene–Lower Pliocene)

The lower Nordland megasequence has been subdivided into two seismic units; (1) a Middle Miocene unit of dominantly mudstones at the base, overlain by (2) an Upper Miocene–Lower Pliocene unit (Utsira Formation) comprising dominantly thick, blocky sands.

### Middle Miocene unit (LN-1)

Detailed biostratigraphic investigations of key wells in the southern Viking Graben have proved the existence of a distinct Middle Miocene unit in the northern North Sea. Sediments of this age have been identified in wells 24/12-1, 16/1-2 and 16/1-4 in southern Viking Graben (Tables 1 and 2). The biostratigraphic dating is summarised in the log correlation diagram (Fig. 13) and is also presented in Tables 1 and 2. The mudstone sequence overlying the Skade sands contains the diagnostic planktonic microfossil *Bolboforma badenensis* and *B. reticulata* assemblages. These assemblages that are known from the ODP/DSDP deep sea boreholes in the North Atlantic and the Vøring Plateau (Spiegler and Müller, 1992; Müller and Spiegler, 1993), suggest an age of approximately 14–12 Ma for this depositional unit. The presence of the *Bolboforma* assemblages is also indicated on the seismic section (Fig. 14a).

Farther to the south we have also identified the same *Bolboforma* assemblages in well 15/9-13 and 15/12-3 (Fig. 12). On the GR log from well 15/12-3, a very distinct high-radioactive marker occurs close to the boundary between the Lower and Middle Miocene strata. As can be seen from Figure 12, this

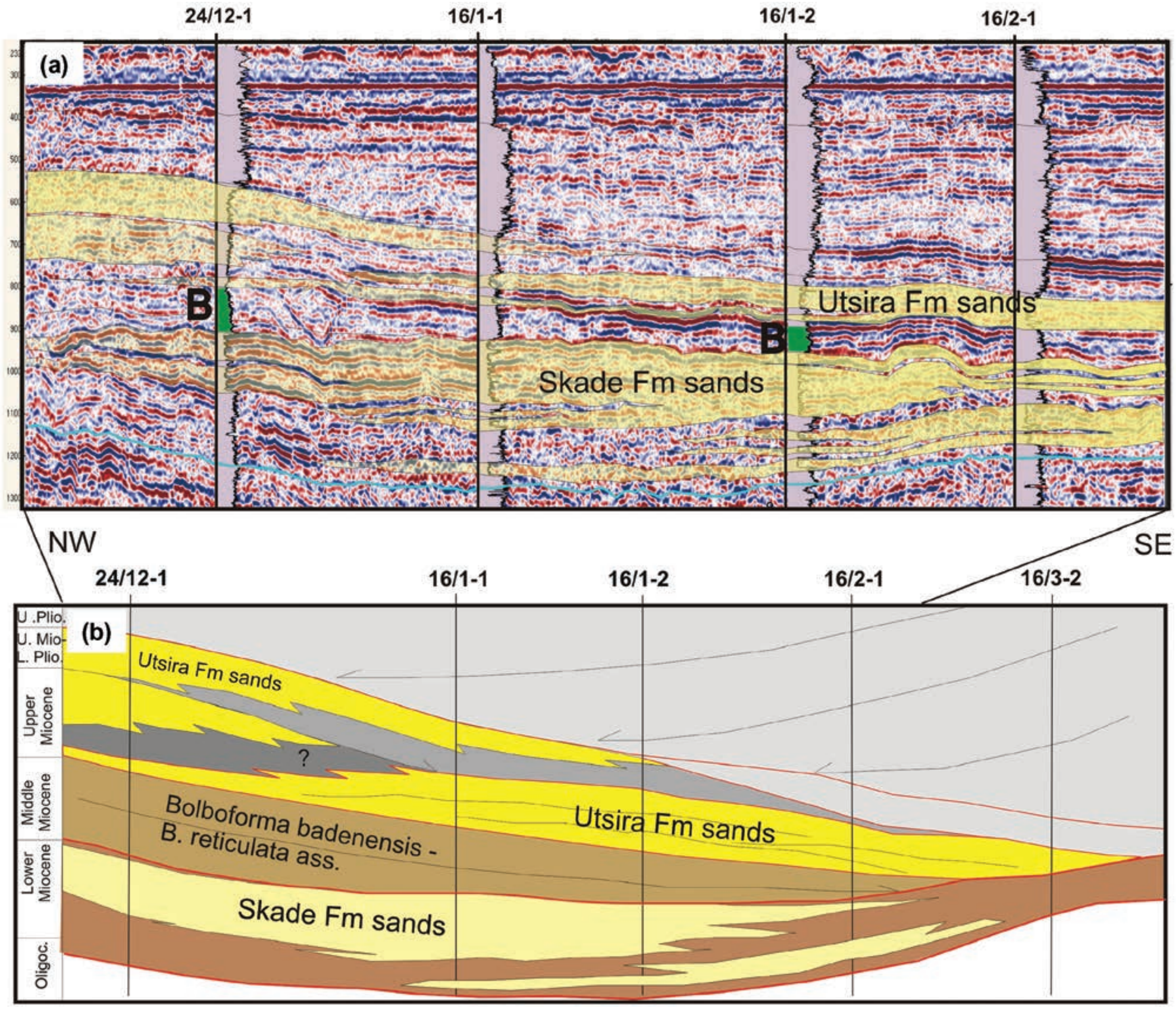

Fig. 14 (a) Seismic line through wells 24/12-1, 16/1-1, 16/1-2 and 16/2-1 across southern Viking Graben showing Skade and Utsira formations. (Well correlation between three of the wells is shown in Fig. 13). Green-coloured part of GR-logs denotes Middle Miocene *Bolboforma badenensis* and *B. reticulate* assemblages. (b) Interpretation of seismic line shown in Fig. 14a (extended towards east through well 16/3-2) illustrating Middle Miocene strata onlapping the top Lower Miocene surface (mid-Miocene unconformity) to the east, and interpretation of Utsira Formation (see text for details). Location of line shown in Figs. 7a–d.

marker can be tied closely to a high-amplitude seismic reflector, which to the east can be interpreted as a major sequence boundary. This high-amplitude reflector is also prominent on the seismic section presented in Fig. 15a. It ties very well to a high GR log marker in wells along this transect, as illustrated in the log correlation diagram (Fig. 15b). This GR marker also serves as a key for the definition of the base Middle Miocene sequence boundary in other wells that are located in the centre of the basin.

The Middle Miocene unit forms a basin infilling sequence which onlaps the underlying Lower Miocene. This is well-illustrated in seismic sections (Figs. 4b and 15a). It clearly postdates the mid-Miocene unconformity, thus forming the basal part of the Nordland Group. It comprises dominantly mudstones with only sparse thin sands present in some wells. The unit attains a maximum thickness of about 250 m in well 15/6-5 (Fig. 15b).

The northern extent of this sequence is difficult to map seismically due to chaotic reflections, but is thought to be present in the centre of the basin along the Viking Graben, as presented in Fig. 7c.

The seismic section (Fig. 15a) illustrates very clearly the sequential relationships and the geometry of the three Miocene units, and represents a key line to the understanding of the stratigraphic framework of the northern North Sea. This line is also schematically presented in its

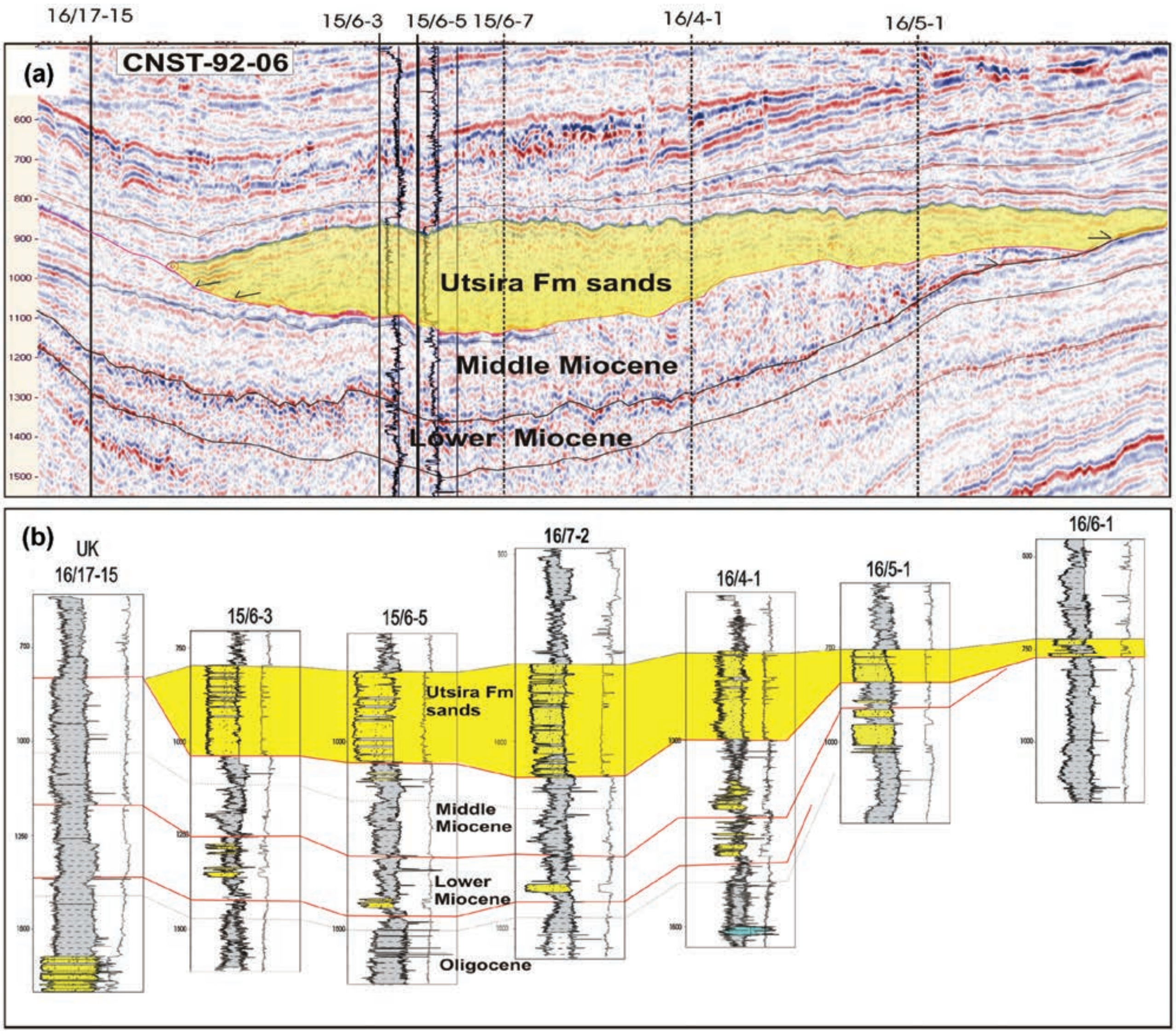

Fig. 15 (a) Seismic section (CNST-92-06) across southern Viking Graben through wells 16/17-15, 15/6-3 and 15/6-5 and close to wells 15/6-7, 16/4-1 and 16/5-1 showing Utsira Formation sands as a thick infilling unit in the basin centre. Note also the infilling nature of the Middle Miocene seismic unit above the mid-Miocene unconformity (see text for details). Location of line is shown in Figs. 7a–d. (b) Log correlation between wells shown in Fig. 15a (well 16/6-7 has been substituted with well 16/7-2). Note the overall blocky GR log profile of the Utsira Formation sands. Skade Formation sands penetrated in well 16/5-1. See text for details.

full length in Fig. 4b, illustrating the regional sequential architecture across the southern Viking Graben.

### *Upper Miocene–Lower Pliocene unit (LN-2)*

The Upper Miocene–Lower Pliocene unit comprises the Utsira Formation, encompassing a huge sandy system with subordinate intercalated thin mudstones. The sands overlie Lower Miocene and Oligocene strata to the north and Middle Miocene strata to the south (Figs. 4a and 4b).

The outline of the sandy Utsira system is shown in Fig. 7d. It forms an elongated sandbody about 450 km long and 90 km wide, mainly deposited in the centre of the northern North Sea basin. To the north, in the Tampen area, the Utsira Formation is represented by a thin glauconitic member overlying Oligocene strata and deposited close to the Miocene–Pliocene transition (Eidvin and Rundberg, 2001). This member is thought to cap the main Utsira Formation sands in the northern part of the basin. Similar glauconitic sands have been observed at the same position in many wells in the Viking Graben to the south (Rundberg, 1989).

The thickness of the sands reaches about 250–300 m at maximum. Previous reported thickness estimates of 400–600 m (Gregersen et al., 1997) are probably incorrect. We believe that these estimates result from an error in the definition of the Utsira and Skade Formations (Fig. 6).

The Utsira Formation displays a very complex depositional architecture, as recently described by Galloway (2002). We present the Utsira Formation along four transects in the northern North Sea; two from the southern Viking Graben and two from the northern Viking Graben.

The southernmost transect (Fig. 15a) shows the Utsira Formation in the southern Viking Graben, at about 58°30′N. In this part of the basin, the Utsira is developed as a giant mounded sand system, pinching out in both the eastward and the westward directions. A log correlation diagram (Fig. 15b) through seven wells along the seismic profile (Fig. 15a) shows a very characteristic, blocky GR log profile of the Utsira sands with only scattered thin mudstone intervals. A maximum thickness of about 300 m is recorded in well 16/7-2. The top of the sands is marked by an abrupt increase in the GR log values. As can be interpreted from Fig. 15a, the base of the sands clearly erodes into the underlying sequence. This may explain differences in the GR log profiles just beneath the sands (Fig. 15b), which in some wells define coarsening-upward and in other wells fining-upward motifs.

At about 59°N, a different development of the Utsira Formation appears. Along this transect (Fig. 14a; Utsira type well 16/1-1) the Utsira Formation sands are distinctly thinner (blocky sands, 25–100 m thick). Based on seismic and log data (Fig. 13), there is no sign of erosion into the underlying mudstone sequence. The Utsira Formation can here be subdivided into two subunits: (1) a lower subunit characterised by dominant blocky sands, forming the main sandbody (thickest developed to the east); and (2) an upper subunit displaying a clear coarsening-upward trend (see Fig. 13). This subunit clearly thins in the eastward direction and probably represents a progradational system which downlaps the underlying blocky sands. This is also illustrated in Fig. 14b, which shows a more basin-wide interpretation of the Utsira Formation sands, along this transect (depositional model of the Utsira Formation dealt with below). The westward extension of the main Utsira Formation sandbody (lower subunit) is not clearly resolved along this transect. It is thought to pinch out close to well 24/12-1. This boundary is difficult to map precisely between 59° and 61°N.

In the northern Viking Graben, at about 60°45′N, the Utsira Formation forms a large mounded sandbody with thickness of almost 200 m in the basin centre (Fig. 9). Along this transect, it is penetrated by wells 30/6-5 and 30/6-11 and 31/4-4 (Fig. 10). The sands display a blocky GR response with only subordinate thin mudstone intervals. The top of the sands is well-expressed by a relatively continuous moderate to high-amplitude reflector. To the west, the main sandbody apparently thins out. Notably in the western part of the transect, a number of high-amplitude reflectors apparently overlie (downlapping) the main Utsira Formation sandbody in a retrogradational pattern. There are no wells penetrating these reflectors in blocks 30/4 and 30/5, but they probably reflect a very sandy system shed from the East Shetland Platform. This sandy system is thought to represent a northern equivalent to Utsira Formation subunit 2, as defined in the transect at about 59°N (Figs. 13, 14a).

Further to the north, at about 61°N, a similar development of the Utsira Formation can be observed (Fig. 8a). Along this transect, the Utsira Formation sands are penetrated by wells 30/10-15 and 30/10-23, close the western pinchout of the main sandbody. A log correlation between these wells is shown in Fig. 8c. The upper part of the Utsira Formation probably represents westerly-derived strata equivalent to those observed in Fig. 9. This upper subunit of the Utsira Formation is further dealt with in the discussion part of this chapter.

Rundberg (1989) reported that the Utsira Formation sands in wells from the northern Viking Graben (blocks 30/3, 30/6) are extremely well-sorted, mainly coarse-grained and texturally mature (subordinate feldspar content). They are also rich in shell debris and glauconite. Intercalated siltstones from the lower part of the sands were rich in glauconite and sponge spicules.

The age of the Utsira Formation sands has been discussed previously by several authors (Rundberg and Smalley, 1989; Goll and Skarbø, 1990; Smalley and Rundberg, 1990; Eidvin and Rundberg, 2001). Eidvin and Rundberg (2001) concluded that the main deposition of this sand to took place between 12 and 5 Ma (based on biostratigraphic correlations and Sr isotopic dating). New investigations of the dinoflagellate flora (Piasecki et al., 2002) and the foraminiferal fauna (this work) in a cored section in well 15/9-A-23 (Tables 1 and 2) indicate an age as young as ca 4.5 Ma, for the upper part of the Utsira.

A moderately rich planktonic fossil assemblage of mainly foraminifera is recorded throughout the Utsira Formation. *Bolboforma* are also recorded in parts of the section, but many of these are probably reworked. Calcareous foraminifera dominate a rich benthic fauna. Mollusc and mollusc fragments are also common.

## Discussion

The data presented in this study permit a reconstruction of the sedimentary and tectonic history of the northern North Sea, whose general stratigraphic framework is schematically shown along two transects across the basin in Figs. 4a and 4b. We propose in this chapter that the stratigraphy and depositional history of the northern North Sea was heavily controlled by the major compressional tectonic regime that affected the Atlantic margin of northwest Europe during Oligocene–Miocene times. The northern transect (Fig. 4a) clearly demonstrates that the northern domains of the North Sea have been affected by severe erosion at mid-Miocene time. The southern transect (Fig. 4b) illustrates that a major drop in relative sea-level took place close to the Early-Middle Miocene transition. This drop in sea level probably resulted in subaerial exposure of much of the northern North Sea, particularly the flanks of the basin.

### *The Eocene–Oligocene transition: controls of lithostratigraphic changes*

Globally, the Eocene–Oligocene boundary marks the last major transition from greenhouse to icehouse condition (Zachos, 2001; Ivany et al., 2003). It is marked by a drop in bottom water temperatures of about 4–5°C, based on oxygen isotope signatures from deep-sea core microfossils. This transition coincides with the first build up of significant ice on Antarctica and appears to have been the onset of deep-sea thermohaline circulation, with an overall increase in ocean fertility (Zachos, 2001). Recent work has demonstrated a large global mass extinction at the E/O-boundary (Ivany et al., 2000), and remarkable faunal changes from the late Eocene to the early Oligocene (Ogasawara, 2002). Sequences from areas of the Antarctic margin show an increase in biogenic sedimentation, usually biogenic silica (diatoms) during the Early Oligocene, suggesting significant cool-water upwelling (Kennett and Barker, 1988; Shipboard Scientific Party, 2000). In the western part of the equatorial Atlantic, Mikkelsen and Barron (1997) reported a distinct increase in biogenic silica accumulation during the Early Oligocene, which they related to the global cooling.

As stated earlier, the Eocene–Oligocene boundary in the northern North Sea is probably one of the most important breaks within the Cainozoic. This break is documented in the work of Gradstein and Bäckström (1996) and also described by Martinsen et al. (1999). The boundary is characterised by the following (Rundberg, 1989): (1) It marks an end to the extremely fine-grained, greenish, smectite-rich depositional regime that had dominated since the Danian, (2) It marks the onset of a clastic regime characterised by brownish, progressively coarser mudstones; (3) It marks the re-appearance of calcareous benthic foraminifera in the study area and a strong increase in microfossil siliceous sedimentation, which includes the marked incoming of opal-CT (Fig. 11). The very marked lithostratigraphic changes observed at the Eocene–Oligocene boundary in the northern North Sea are also observed in sediments exposed in Denmark (Heilmann-Clausen, 1985) and in wells offshore Mid Norway (Haltenbanken and Vøring Basins).

The Eocene–Oligocene boundary in the northern North Sea records many similar characteristics that are described from the boundary in ODP sites of the world oceans. For example, Rundberg (1989) reported a conspicuous change in clay mineralogy characterised by a decrease in smectite at the expense of illite and kaolinite, similar to what has been described from the boundary in the Southern Hemisphere (e.g. Shipboard Scientific Party, 2002). In the northern North Sea, the clay mineral changes are accompanied by other distinctive changes of the mudrocks, such as coarser grain size and a change in dominantly olive-green to yellowish-brown mudrock colouration. Rundberg (1989) suggested that the clay mineral changes at this boundary were primarily controlled by the abrupt climatic deterioration and, for some wells, also controlled by uplift activity of the Norwegian margin. In NE Belgium, de Man et al. (2003a), based on a study on stable oxygen isotopes reported a main temperature drop just above the Eocene–Oligocene boundary. It is also interesting that de Man et al. (2003b), based on biofacies analysis of the shallow marine Rupelian section in Belgium and Germany, could suggest relatively cold-water conditions for the Rupelian and a return to warm-water conditions at the Rupelian–Chattian boundary, the latter coinciding with the widespread Chattian warming event (e.g. Zachos, 2001). Warm and humid Chattian conditions were also suggested by Rundberg (1989) from mineralogical data, in particular the occurrence of gibbsite, boehmite and the traces of goethite peloids in sands from Block 35/3 (Agat area).

We agree that the onset of siliceous-rich sedimentation in the northern North Sea was most likely related to the dramatic decrease in global temperature at the Eocene–Oligocene boundary, as suggested by Rundberg (1989). He further suggested that the siliceous sedimentation was related to more oceanic circulation in response to seafloor spreading between Greenland and Spitsbergen (Fig. 1) and upwelling conditions that developed by uplift of the northernmost North Sea, along the Tampen Spur extension. Thyberg et al. (1999) also pointed to upwelling conditions in their work on the diatomaceous Oligocene deposits of the northern North Sea, but suggested that such conditions developed by a northward-oriented marine current system. It is evident that the opening of the Fram Strait during Early Oligocene permitted at least surface-water exchange with the Arctic Sea, but was the abyssal circulation of the Norwegian Sea affected? Kaminski and Austin (1999), based on a study of deep-water agglutinated foraminifers at ODP Site 985, suggested that the Oligocene deep water of the Norwegian Sea was poorly oxygenated, advocating no particular change in the bottom-water circulation pattern. These workers suggested that the Norwegian Sea was strongly dysaerobic, in contrast to the more ventilated environment south of the Greenland–Scotland Ridge. If this view is correct, the siliceous sedimentation of the northern North Sea cannot be linked to the increased deep-water circulation. It should, however, be noted that other workers have indicated intensification of deep-water circulation at the Eocene/Oligocene transition; for example, Eldrett (2004), in order to explain the Upper Eocene hiatus, observed in many ODP holes (and also reported from the northern North Sea), and Hull (1995) in a study of radiolarians from ODP Leg 151.

It is, however, likely that the end Eocene global cooling, which caused the start of the glaciations of Antarctica, must have led to a change in global wind systems. Obviously, such an increase in wind energy must have caused an increase in surface-water circulation. Thus, if there was no particular change in deep-water circulation in the Norwegian Sea, as suggested by Kaminski and Austin (1999), the distinct increase in siliceous sedimentation in the northern North Sea (see Fig. 11) could also be controlled by local increase in productivity of diatoms in response to wind-induced upwelling.

## *Influence of Oligocene–Miocene compressional tectonics on the sedimentary and structural evolution of the northern North Sea*

We argue in this study that the compressive tectonic episode that affected the NW Atlantic margin also influenced the Shetland Platform, the northern North Sea Basin and southern Fennoscandia, as well (as shown in Fig. 2). The structural uplift of these areas corresponds broadly with the large-scale plate movements on the Atlantic margin (see Fig. 5). Such uplift may be difficult to envisage from seismic data alone, but is suggested from a series of observations and data, which make this statement more than mere guesswork:

(1) Two huge sandy depositional systems, with gross thickness in excess of 300 m, were sourced from the East Shetland Platform during the Early Oligocene and Early Miocene. These sands are most likely linked to uplift and erosion of the Platform (Fig. 5);
(2) The southern shift in depocentre for these sandy systems (from northern to southern Viking Graben) could be a result of change in basin physiography, in response to uplift of the northernmost North Sea (Tampen Spur area);
(3) The strong influx of sediments from southern Fennoscandia during early Oligocene time (wedge of mudstones between 60–61°N which northward passes into thick sands) indicates contemporaneous uplift of the eastern hinterland;
(4) The upward coarsening pattern in Oligocene mudstones for wells in northernmost North Sea indicates shallowing of the basin;
(5) The upward change from deeper marine, gravity flow to shallow marine facies in Oligocene sands, block 35/3 (Agat area) indicates rapid shallowing along the margin;
(6) The isopach of Oligocene strata between 60–62°N shows northward thinning (Rundberg, 1989);
(7) The distinct mid-Miocene unconformity and the northward increase in erosional hiatus (Fig. 5) are probably linked to uplift of the basin.

The mid-Miocene unconformity separates the Hordaland and Nordland Groups (Fig. 5). It is well-expressed from the stratal geometries of southern and northern Viking Grabens, as presented in Figs. 4a and 4b. In the southern Viking Graben, a very large fall in the relative sea level can be inferred from the architecture of the Lower and Middle Miocene seismic units (Fig. 4b). In the northern Viking Graben, the Lower Miocene strata are truncated at both margins, whereas Middle Miocene deposits are totally absent (Fig. 4a). As seen from Fig. 5, the mid-Miocene erosional unconformity records a hiatus in the order of 15–20 million years, and even more, in areas where the Utsira Formation is absent. This erosion period corresponds broadly with the last compressional phase activity along the mid-Norwegian margin (Lundin and Doré, 2002) and in the Faeroe–Rockall region (Boldreel and Andersen, 1993). Mid-Miocene unconformities are also a widespread phenomenon on the Norwegian Continental shelf (Eidvin et al., 2000; Gradstein and Bäckström, 1996, Brekke, 2000).

## Sedimentary response of uplift

As discussed in the previous sections, three major sandy systems were deposited in the Norwegian North Sea, during the Oligocene and Miocene. These systems were largely sourced from the East Shetland Platform, as shown in Figs. 7a, 7b and 7d. Coarse clastic influx from the east were also recorded, but to a much lesser extent.

### Lower Oligocene sandy system

The first major sandy influx to the northern North Sea Basin was deposited in the Statfjord–Tampen area during the Early Oligocene (Fig. 7a) and in our opinion represents marine gravity-flow facies. The thick pile of Oligocene sands (gross thickness of about 400 m, Fig. 8c) suggests that significant tectonic uplift of the Shetland Platform has taken place.

It is tempting to relate this uplift to compressive strain along the Erlend Transfer Zone separating the Møre and Shetland-Faeroe Basins (Figs. 1, 2). As can be seen in Fig. 2, movements along this transfer fault could be taken up along its southward extension, the Walls Boundary Fault. Erosional products from the uplifted areas of the East Shetland Platform have then been shed eastwards by river systems (~61°N), focussing delta progradation and gravity flow transport towards the Statfjord–Tampen area of the northern North Sea. This sandy system is illustrated by clear wedging of the Lower Oligocene strata, particularly well-observed along the seismic sections shown in Figures 8a and 9.

We suggest that the abrupt incoming of this depositional system marks the first signal of the uplift that affected the East Shetland area during Late Eocene–Early Oligocene time. It is broadly contemporaneous with a tectonic pulse that caused domal growth along the margin (Boldreel and Andersen, 1994; Doré and Lundin, 1996, Brekke, 2000; Lundin and Doré, 2002; see Fig. 5). We suggest that the sands are linked to this tectonic event, rather than to global eustasy.

Sands were also derived from an eastern source area during the Early Oligocene as recorded in block 30/3 (Agat area, Fig. 7a). In this part of the basin, thick sands of turbiditic origin are capped by sands of shallow marine facies (Rundberg, 1989). These sands are contemporaneous with sands of the Statfjord area and most likely represent Early Oligocene uplift of the Agat hinterland to the east. Further south towards the Troll area, a distinct wedge of organic-rich mudstones occurs parallel to the western coast of Norway (Fig. 7a). This wedge (seismic unit UH-1), termed map unit 3 of Rundberg (1989), was suggested to been an erosional product from the uplift of southern Fennoscandia at this time.

### Lower Miocene sandy system

The second phase of large sand input took place during Early Miocene. Sands belonging to the Skade Formation were deposited mainly in the southern Viking Graben, as shown in Fig. 7b. They represent a southern shift in coarse clastic influx to the basin, relative to Oligocene time, and are also clearly turbiditic in origin. The sands pinch out to the east and were sourced from the East Shetland Platform. This sandy system has a magnitude in the same order as the Lower Oligocene system, i.e. a maximum gross thickness in excess of 300 m. According to our dating, the sands were deposited during Early Miocene, between 20 and 15 Ma We infer that they are a result of new tectonic event of uplift of the East Shetland Platform, possibly associated with a renewed compressional tectonic phase along the northwest European margin.

Lundin and Doré (2002) reported a compressional phase during Early Miocene along the Mid-Norwegian margin, which affected a number of domes between the Jan Mayen and Bivrost Fracture zones. This phase corresponds favourably with the deposition of the Skade Formation sands, as shown in Figure 5. Boldreel and Andersen (1994) suggested that a compressional phase affected the Faeroe–Rockall area during Middle or Late Miocene times. As indicated by these authors, there is a lack of a detailed well control in the Neogene section, which, consequently, leads to less precise timing for the last compressional phase. If the timing is correct, this phase post-dates deposition of the Skade Formation sands but coincides better with deposition of the Utsira Formation sands (Fig. 5).

### *Upper Miocene–Lower Pliocene sandy systems*

The third phase of large sand input took place during Late Miocene–Early Pliocene time. This sand input, comprising the huge Utsira Formation, was the largest sandy influx to the North Sea Basin during the Cainozoic. It is dealt with in more detail later.

## *The mid-Miocene unconformity and the creation of a shallow seaway*

A question, which arises, is whether the North Sea could have been subaerially exposed during this Middle Miocene erosion period, as suggested by several authors (Jordt et al., 1995; Rundberg et al., 1995; Martinsen et al., 1999). In the wells examined, no clear subaerial signature of sediments immediately below the unconformity has been observed. There are, however, a number of features that indicate a shallowing of the basin during late Oligocene–Miocene:

(1) The overall architecture of the depositional sequences, in particular the change from Early Miocene to Middle Miocene deposition, clearly signifies a very dramatic relative sea-level fall which must have caused a rapid decrease in water depths;
(2) The uppermost preserved Oligocene strata in wells on the Tampen Spur (block 34/2) consist of glauconitic, spicule-rich siltstones (Rundberg, 1989) which most likely represent a marine shelf setting. Such sediments are also typical of the Lower Miocene in wells, farther to the south (Blocks 30/6 and 30/3);
(3) The top Oligocene surface reveals a strong character of subaerial erosion (incisional features) in much of quadrant 35, particularly in areas to the northeast of Utsira Formation sand extent (see Fig. 7d);
(4) At the base of the Utsira Formation, there are several erosional features (Gregersen et al., 1997; Galloway, 2002), which have been interpreted as tidal channel scours (Galloway, 2002);
(5) Shell beds within the Utsira Formation sands point to periods with shallow-water conditions.

The long channel feature extending from offshore Sognefjorden (block 35/8) to about 62°N (block 34/3) incising deeply into Oligocene strata has previously been interpreted to indicate subaerial erosion (Rundberg et al., 1995; Gregersen, 1998; Martinsen et al., 1999). Work carried out by Eidvin and Rundberg (2001), however, shows that this incision is Late Pliocene in age. It cannot, therefore, be linked to the formation of the mid-Miocene unconformity.

We consider that it is more likely that a major part of the mid-Miocene unconformity is a result of submarine erosion, which is a very common phenomenon. Such erosion has been reported from work in the North Atlantic waters to the south of the Greenland–Scotland Ridge (e.g. Wold, 1994; Wright and Miller, 1996). Three major erosional phases, that can be seismically identified as distinct unconformities (age estimates, shown in Fig. 5), were linked to the development of strong deep-water currents. These unconformities correspond with the development of prominent drift sediments (Bjorn and Gardar Drifts, Hatton and Snorri Drifts, Eirik and Gloria Drifts). The accumulation of the drift sediments and their link to deep-water fluxes and Greenland–Scotland Ridge overflow have been thoroughly discussed by Wold (1994) and Wright and Miller (1996). Stoker et al. (2002) interpreted the latest Oligocene/Early Miocene unconformity on the Faeroe–Shetland Channel as a result of major change in oceanic regime, linked to the establishment of deep-water exchange between the Arctic and North Atlantic oceans.

In accordance with these workers we suggest that the mid-Miocene unconformity could have developed as a result of increased marine circulation and vigorous current erosion, which affected the uplifted northernmost North Sea. The abrupt Middle Miocene climatic cooling at about 14 Ma (Zachos, 2001) may also have intensified oceanic circulation systems at this time. Another aspect which may be important in this discussion is related to the change in North Sea Basin physiography that developed during Middle and Late Miocene, in which the northernmost North Sea gradually became shallower due to the tectonic uplift. The resultant basin physiography of the North Sea with a shallow threshold to the north may be ideal for the formation of strong tidal current regimes. Such currents may therefore have swept across the Viking Strait and caused vigorous erosion of the uplifted sea floor. The tidal effect would probably increase as the strait became shallower. The fact that the hiatus is largest to the north and decreases in the southward direction, is in accordance with this model.

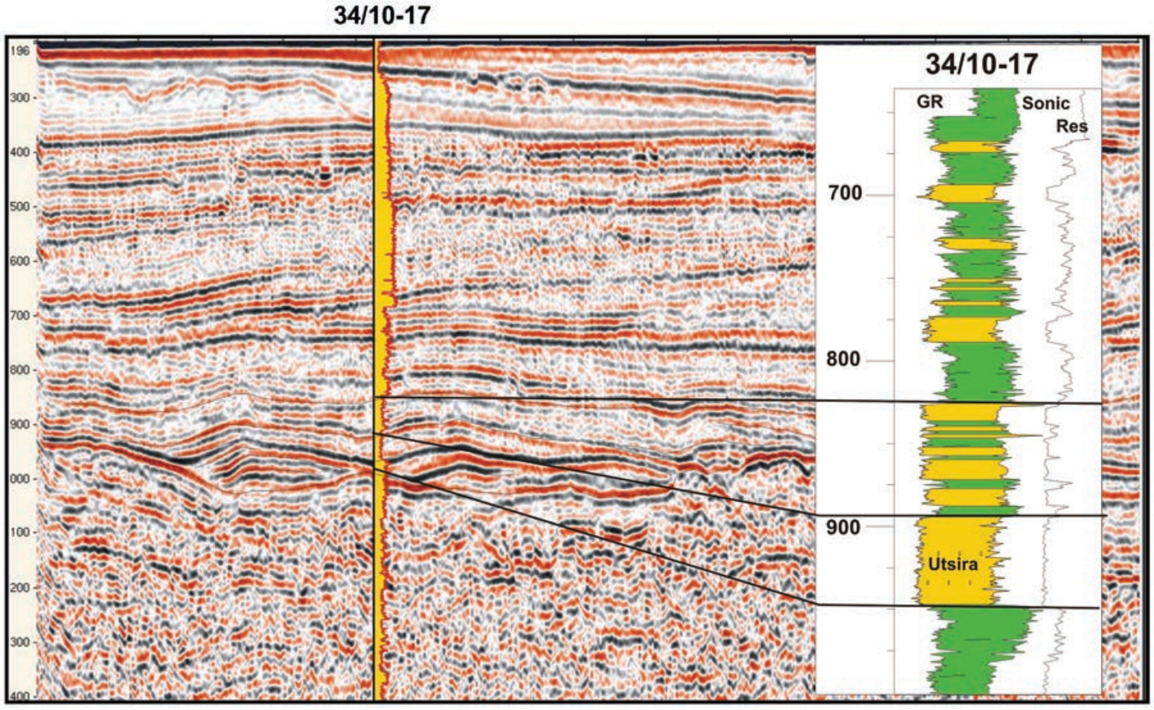

Fig. 16 Seismic section through well 34/10-17 (detail of line shown in Fig. 8a) showing erosive base of the Utsira Formation and infill with distinct westward migrating stacking pattern. The lower part of the Utsira Formation sands forms a mounded geometry whereas the upper part is more sheet-like.

The mid-Miocene (or top Hordaland) surface is locally very irregular forming diapirs, large ridges and troughs, as illustrated in Figs. 8a and 9. Some of these structures could have been formed as a result of instability and pore-pressure release of the underlying mudrocks in response to the sudden sea-level fall at mid-Miocene time. A number of incisional features are also observed at this surface below the Utsira Formation. One example is illustrated, close to well 34/10-17 in Fig. 16. This erosion may have developed as tidal channel scouring during late Miocene, marking the end of the erosional phase and the onset of a new clastic depositional regime.

## *Timing of the mid-Miocene tectonic and erosional events*

Based on our biostratigraphic and seismic work in the southern Viking Graben, we are now able to give more precise age constraints for the tectonic and erosional events. We suggest that the first response of the Miocene tectonic activity was felt by the incoming Skade sands. This sandy system was deposited during Early Miocene and abruptly ceased at about 15 Ma, as shown by Sr isotopic dating of carbonate foraminiferal tests from the top of the Skade Formation (15.5 and 15.1 Ma in wells 24/12-1 and 16/1-4, respectively). Such ages are supported by biostratigraphic data from the overlying mudstones, containing the diagnostic *Bolboforma badenensis* and *B. reticulata* assemblages. These assemblages suggest deposition at about 14–12 Ma years. Deposition of the Skade sands was followed by a large relative sea-level fall, which was probably associated with the end of the Mid-Norwegian compression event. We infer that the erosional activity in the northern North Sea started at this time, beginning first in the Tampen Spur area to the north and then successively working in a southward direction.

## *Late Miocene palaeogeography and deposition of the Utsira Formation*

As discussed earlier, we infer that the large-scale tectonic movements have exerted control on the basin evolution and depositional history of the northern North Sea. As a response to the structural uplift, the northern North Sea gradually changed into a shallow shelfal seaway between deeper waters in the Møre Basin to the north and central and southern North Sea to the south. The palaeogeographic reconstruction is illustrated in Figure 17.

When compared with the early Oligocene map (Fig. 1a), three interesting aspects can be observed: (1) Much of the Greenland–Faeroe-Scotland Ridge has subsided below sea level; (2) deep-water link is established to the Arctic Ocean, via the Fram Strait and to the Atlantic Ocean, via the

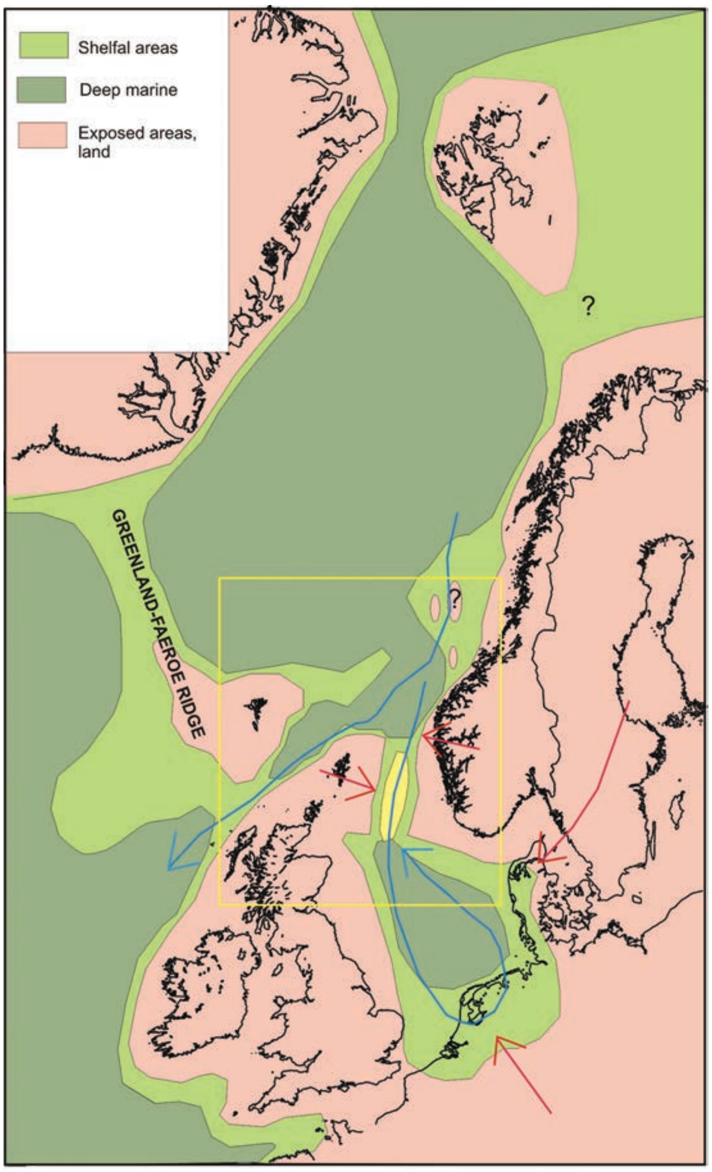

Fig. 17 Late Miocene palaeogeography of northwest Europe. The North Sea forms a semi-enclosed sea with deeper waters in central and southern North Sea and a narrow shallow strait in northern North Sea. The Greenland–Faeroe Ridge submerged during the Middle Miocene. Large amounts of coarse clastics were shed into the basin from the East Shetland Platform (northern North Sea), Fennoscandia (northern North Sea and Denmark) and the Alpine Region (Netherlands). Yellow rectangle shows location of map in Fig. 18.

Faeroe–Shetland Channel; and (3) the North Sea has changed into a semi-enclosed sea with a narrow shelfal passage to open marine waters to the north.

The Miocene submergence and the subsidence history of the Greenland–Scotland Ridge has been reported by many authors (e.g. Eldholm and Thiede, 1980; Wold, 1994; Wright and Miller, 1996). As mentioned earlier, the Faeroe–Shetland Channel probably operated as a conduit for deep-water passage from early Miocene time (Stoker et al., 2002). This gateway was characterised by vigorous deep-water circulation, which created severe erosion and subsequent deposition of drift sediments in the Rockall Trough.

The North Sea Basin progressively developed into a more or less landlocked or silled basin, with deeper waters in the central and southern North Sea and shallower waters in the northernmost North Sea. This situation is illustrated in the Late Miocene paleogeographic reconstruction (Fig. 17). The central North Sea formed a broader and deeper basin, which underwent subsidence during the entire Miocene. The shallow gateway of the northern North Sea or Viking Strait (term proposed by Galloway, 2002) persisted for a long period, probably from about 15 to 5 Ma. As mentioned above, an important consequence for this type of basin physiography is that it is ideal for the formation of large tidal cycles, which would create high-energy currents across the Viking Strait. It is under such conditions that the Utsira Formation sands probably were deposited.

## *Depositional model of the Utsira Formation sands*

Several authors have discussed the depositional model of the Utsira Formation sands. In his work on the sedimentary history and basin evolution of the northern North Sea, Rundberg (1989) inferred that the northern North Sea formed a shallow marine passage between deeper waters of the North Sea to the south and the Møre Basin to the north during deposition of the Utsira Formation, and that the Utsira Formation sands were deposited under fairly uniform high energy conditions in a relatively stable tectonic setting. Based on a number of factors, such as the palaeogeographic setting, the elongate morphology of the total sand body, the overall slow accumulation rate, the uniform log patterns and the extreme maturity of the sands, he pointed to a model where strong, shallow marine and possibly tidal currents flowed between the deeper seas to the north and south. These currents probably caused sands to accumulate in parallel, N–S linear ridges, which subsequently became moulded and amalgamated into elongate sheet sands, as the shelf periodically became shallower due to local? tectonic activity and/or slight fluctuations in sea level.

Galloway et al. (1993), in a study of the Cainozoic sediments from the northern North Sea, interpreted the Utsira Formation to consist of a sand-dominated contourite drift system throughout the Viking Trough, and that the sands were derived almost entirely from the Scandinavian Platform.

Gregersen et al. (1997) questioned Rundberg's (1989) depositional model of the Utsira Formation and suggested a turbiditic origin, largely because of its typical blocky GR log profile coupled with seismic mounded and bi-directional onlap. These authors also interpreted the sands as representing stacked lowstand fan deposits. A problem with their interpretation, however, is the fact that they, by mistake, have included sands of the Skade Formation into the Utsira Formation. Martinsen et al. (1999), on the other hand, favoured a shallow-marine origin within a high-energy current setting.

Recently, Galloway (2002) has presented a thorough discussion of the Utsira Formation sands. His new model involves sediment input through a prograding platform (Shetland), coast-to-shelf bypass, and regional basin-centred transport within an elongate seaway characterised by (1) high-energy marine regime, (2) very low rates of sediment supply, (3) high sediment reworking and (4) regional along-strike sediment transport. He suggested that the deposition was concentrated in a southern and northern shoal system, which could be explained by a combined current system, probably tidal in origin, characterised by inflow into the North Sea along the western margin and outflow along the eastern side of the strait.

We agree in much of Galloways (2002) model, which largely follows Rundberg's (1989) interpretations, although in much more detail. Galloway included time-equivalent sands, which are present over large areas in UK waters to the Utsira Formation. Earlier, these sands have been termed Hutton sands, and their relationship to the Utsira Formation sands in Norwegian waters, has been discussed by Gregersen et al. (1997). Galloway (2002) interpreted these sands to represent an eastward prograding strandplain, which provided a source of sediment to the Viking Strait (Fig. 7d).

Our work in the southern Viking Graben demonstrates that such a relationship probably exists. This can be seen in Figure 14b, which represents an interpretation of the Utsira Formation between key wells at about 59°N. In the westernmost well (24/12-1), the Utsira Formation is distinctly thicker than seen in wells to the east. By reference to Galloway's depositional model of the Utsira Formation (Fig. 10), well 24/12-1 would be located in the easternmost part of the Shetland strandplain. It represents, therefore, a different facies than the sediments penetrated in wells to the east. Consequently, this may explain the sudden change in thickness between wells 16/1-1 and 24/12-1.

The biostratigraphic dating for these wells also yields important accounts to the depositional history. The results of the dating (Fig. 13; Tables 1 and 2) indicate that the upper prograding subunit of the Utsira is Early Pliocene in age whereas the lower subunit is Late Miocene in age. Farther to the south, in well 15/12-3 (Fig. 12), where the Utsira Formation is developed as a 300 m-thick, uniform sand throughout, we have recorded Late Miocene age for the lower half of the Utsira Formation and Early Pliocene age for the upper half. In a short core from the upper part of the Utsira Formation sands in well 15/9-A-23 (Sleipner area), Piasecki et al. (2002) reported Early Pliocene dinoflagellate cysts. We have analysed the same core and have confirmed the Early Pliocene age using foraminiferal correlation (Tables 1 and 2) and Sr isotopic analyses. These findings suggest that a prominent part of Utsira Formation deposition in the southern Viking Graben took place during early Pliocene.

The western source of sediments is evident from seismic data (Fig. 9). Supply from the east is more difficult to assess from seismic data as much of the Neogene section has been eroded. Remnants of easterly derived clastics are, however, preserved locally, e.g. in block 35/11 (penetrated in well 35/11-1). Farther to the north, off the Møre Margin at about 62°N, a very pronounced Neogene progradational system comprising nine depositional sequences (N1–N9) is preserved (Fig. 18). The lower part of this system is penetrated in well 35/3-1. It consists of spicule-rich, glauconitic fine-grained sands of possibly Early Miocene age (Rundberg, unpublished data), which are overlain by coarse, yellowish, marginal marine sands (lithologic unit D2 of Rundberg, 1989).

The relationship between this progradational system and the Utsira Formation is not clear, but may be interpreted as follows. As seen from Figure 18, a very pronounced basinward shift in depocentre (or forced regression) took place at the end of sequence N4. If this progradational system represents continuous Miocene deposition, as outlined in the Wheeler diagram of Figure 18, the forced regression would start at about Middle Miocene time, estimated very close to 15 Ma. Such an age fits into our understanding of the structural evolution of the northern North Sea and, as noted earlier, would correspond to the timing of the large relative sea-level fall, based on data from the southern Viking Graben. The Utsira Formation may thus be equivalent to the upper part of this prograding system, most likely sequences N5–N7. The major incision to the west of sequence N7 represents the northernmost part of an incisional feature extending from off Sognefjorden to about 62°N (Rundberg et al., 1995). Eidvin and Rundberg (2001) assigned a late Pliocene age of this incision, based on data from well 34/2-2, penetrating strata to the west of the incision in Fig. 18.

Noteworthy also is that at maximum progradation of this Neogene system, during latest Miocene/earliest Pliocene, the shoreline was probably as far east as block 35/1. This also indicates a narrowing of Viking Strait during deposition of the Utsira Formation sands.

The overall depositional model and palaeogeographic setting of the giant sand system of the Utsira Formation is reconstructed for the Late Miocene time interval (Fig. 18). The sands were deposited within a shelfal seaway, probably by high-energy marine current systems. These currents also had strong erosive capacity and created large scouring features, which can be observed particularly to the north of 59°30′N, as exemplified in Figure 16. Water depths probably fluctuated between fairly deep shelf to shallow-marine conditions. The planktonic and benthic foraminifera indicate that intermediate (shelfal) water depths periodically must have existed. The abundance of glauconite suggests longer periods with non-deposition, probably related to transgressive phases and relatively deep shelf settings. The concentration of molluscs in parts of the Utsira Formation suggests that faunal colonization periodically was established, most likely, within shallow-marine waters. The sands were deposited largely in a southern and northern shoal system (Galloway, 2002), and their accumulation was interrupted by frequent periods with non-deposition followed by vigorous reworking and amalgamation.

We had argued earlier (Eidvin and Rundberg, 2001) that the Utsira Formation in some wells is directly overlain by Upper Pliocene sands that are difficult to distinguish from the Utsira Formation sands. Some of these sands are genetically different and represent turbiditic sands belonging to the huge Upper Pliocene prograding complex. The westerly-derived sands, however, which represent the Lower Pliocene sand system are genetically related to the underlying main Utsira Formation sand system, and should, therefore, be included in the proper Utsira Formation.

One of the key issues regarding the model of Utsira Formation sand deposition is the lack of ancient analogues. In much of the published literature, shelf sands only make up 10–30 m sequences with a clear coarsening-upward grain size profile (e.g. Johnson and Baldwin, 1996). Rundberg (1989) therefore proposed that the Utsira Formation sands were atypical of shelf settings, and pointed out that a unique depositional setting was required for the deposition of the sands. Galloway (2002) discussed many sedimentologists reluctance to interpret thick (30–100 m) aggradational sand units as products of shelf transport and deposition. As pointed out in his work, some modern shelves (in particular, the Mallaca Strait) have many similarities in geographic setting, sediment composition and sand morphologies as the Utsira Formation.

It appears, however, that ancient analogues to the Utsira sand system do exist. The Middle Jurassic Garn Formation sandstones off Mid Norway comprise an aggradational system of

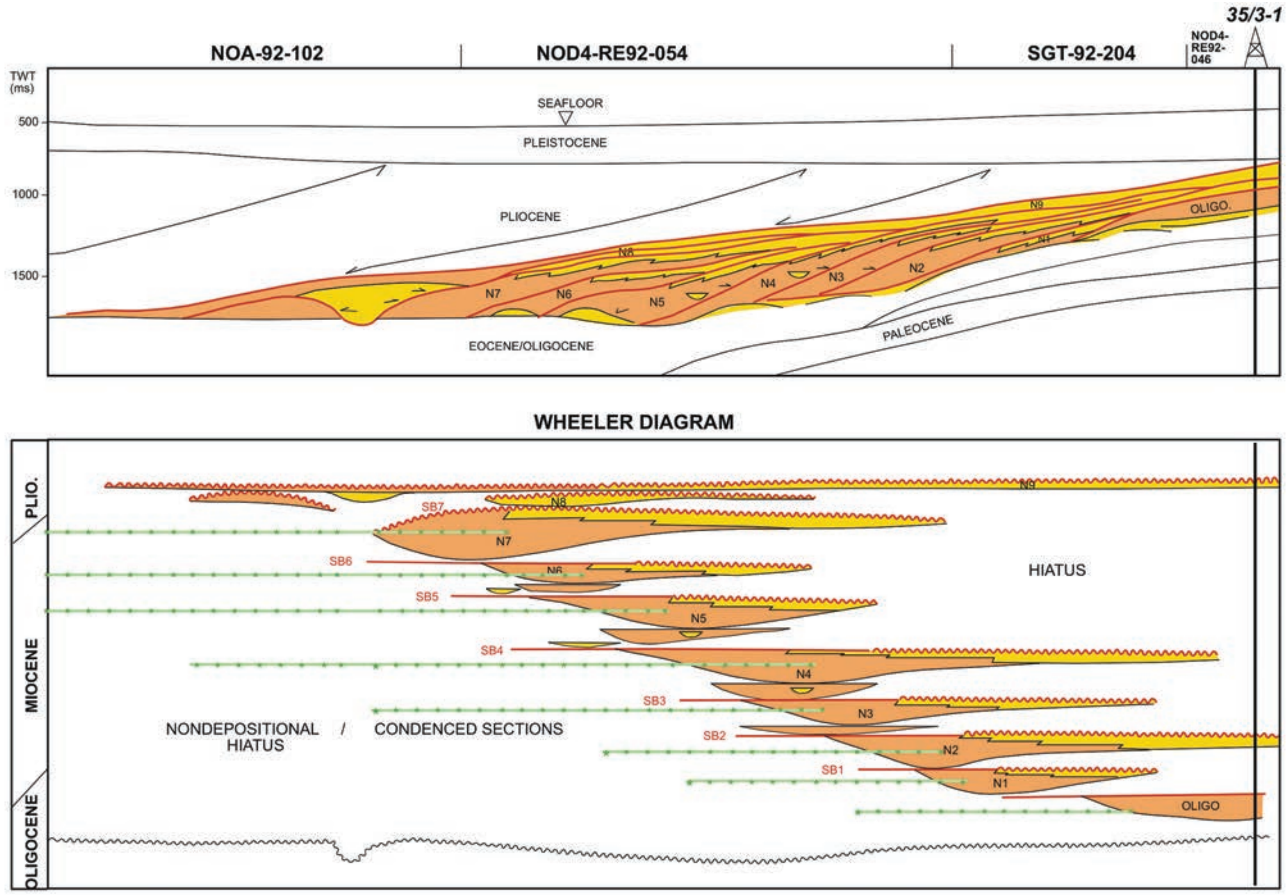

Fig. 18 (Above) Interpreted seismic composite section close to 62°N showing Neogene progradation from Møre Margin to the east into the southern Møre Basin, with tie to Agat well 35/3-1. This line shows the preservation of an almost complete post-Oligocene progradational system, which is absent further to the south due to uplift and erosion. Note stratigraphical position and dating of the large channel with incision into Oligocene strata. Location of line shown in Fig. 7d. (Below) Wheeler diagram of the composite section. Green lines illustrate glauconitic concentration at maximum flooding surfaces within each of the sequences.

blocky sands virtually without interbedding, reaching thickness in the order of 100–200 m. This sand has been variably interpreted as a fluvial to shelfal deposit, but its depositional environment remains relatively poorly constrained. In parts of the basin it is, however, interpreted as compounded tidal sandwaves, deposited in a high-energy current regime (Gjelberg et al., 1987; Corfield et al., 2001).

## Conclusions

An improved seismic-lithostratigraphic subdivision of post-Eocene to Lower Pliocene strata has been established for the Norwegian North Sea between 58 and 62°N. This succession has been subdivided into a lower megasequence (Upper Hordaland Group) and an upper megasequence (Lower Nordland Group) separated by a major hiatus.

The stratigraphic framework has been revised by assigning the Skade Formation to the Early Miocene (previously Late Oligocene) and by introducing a new mudstone unit of Middle Miocene age at the base of the Nordland Group. The base of the Utsira Formation has been redefined in its type well (16/1-1; Isaksen and Tonstad, 1989), as the previous definition obviously overlapped with the upper part of the Skade Formation. Based upon diagnostic *Bolboforma* assemblages in the underlying mudstone, we conclude that the base of the Utsira Formation is not older than 12 Ma.

We suggest that the major 'mid-Tertiary' compressional tectonic regime that affected the passive margin of northwest Europe had a major impact on the stratigraphic and depositional evolution of the northern North Sea Basin.

On a larger scale, the Early Oligocene plate reorganisations caused seaway link to the Arctic Ocean, introducing a change in oceanic and palaeogeographic conditions. In the northern North Sea Basin, these changes coupled with the global climatic deterioration resulted in (1) a marked lithostratigraphic change at the Eocene–Oligocene boundary; and (2) an increased ocean

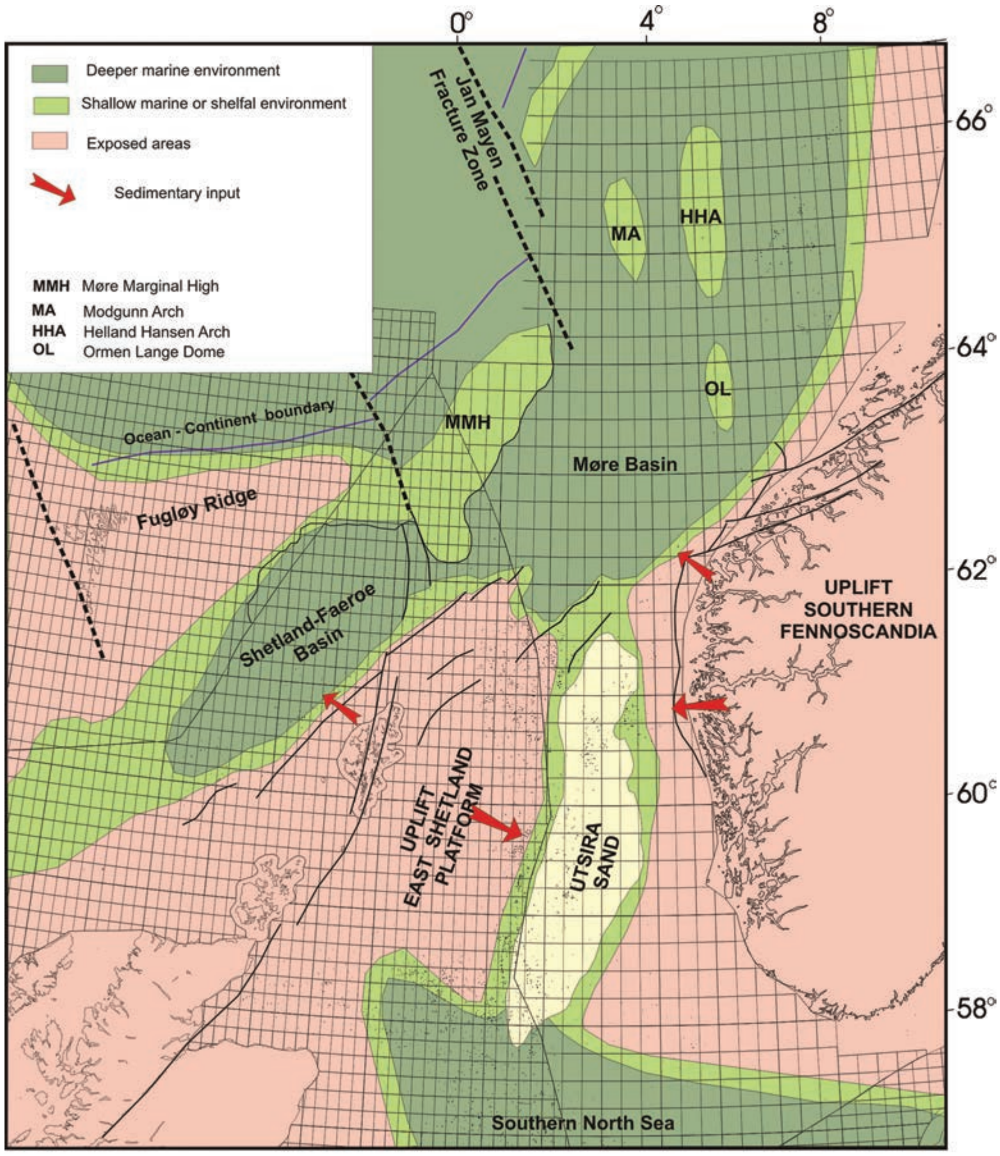

Fig. 19 Late Miocene palaeogeographic map of the northern North Sea and the Faeroe–Norwegian margin showing deposition of the Utsira sandbody in a narrow, shelfal strait within the Viking Graben of northern North Sea. The sands were deposited through a long time span (7–8 million years), and their accumulation was interrupted by frequent periods of non-deposition, followed by vigorous reworking and amalgamation. High-energy, (?tidal) marine currents probably operated across the narrow strait during the Late Miocene.

fertility, probably associated with upwelling conditions, leading to the marked increase in silica-rich deposition during Early Oligocene times.

The Oligocene–Miocene structural activity heavily affected the Shetland Platform and northernmost North Sea and was also felt in southern Fennoscandia (Fig. 5). We suggest that the East Shetland Platform underwent three significant phases of post-Eocene uplift, which resulted in deposition of major sandy systems into the northern North Sea Basin. The first sandy system was deposited during Early Oligocene (33–28 million years), the second input, during Early Miocene (20–15 million years) and third input, during Late Miocene/earliest Pliocene (12–4.5 million years). The first and the second sandy systems were deposited as turbiditic sands in the northern and southern Viking Graben, respectively, whereas the third sandy system was deposited in shallower marine settings as a consequence of uplift of the marine basin.

The progressive uplift of the northernmost North Sea during Oligocene–Miocene coupled with increased marine circulation led to vigorous current erosion and possibly also subaerial erosion in northernmost North Sea resulting in the formation of the mid-Miocene stratigraphic break. This erosional break is of 20 m.v. duration at maximum in northernmost North Sea to almost zero in southern Viking Graben. We suggest that this erosional event was associated with peak compression, beginning first, in the Tampen Spur area to the north and then successively working in the southward direction. Based on faunal and isotopic dating of samples from the southern Viking Graben, an age of about 15 Ma can be assigned for the transition between the Hordaland and Nordland Groups, at minimum stratigraphic break. Such an age also yields a timing of the uplift that affected the northern North Sea Basin, comparing closely to age estimates for the growth history of anticlinal structures and domes, along the passive margin.

During the Late Miocene to Early Pliocene, the northern North Sea formed a narrow seaway between deeper waters in the Møre Basin to the north and central North Sea to the south. This narrow strait received large amounts of coarse clastics from the East Shetland Platform and probably, also from southern Fennoscandia (although evidence for the latter is lacking due to later uplift and erosion of the Norwegian basin margin). The sands accumulated in a high-energy current regime, probably, first as elongated shelfal sand ridges which subsequently became moulded and amalgamated, and then as elongated sheet sands, as the shelf periodically became shallower due to local tectonic activity and/or fluctuations in sea level.

## Acknowledgements

We thank Felix Gradstein and Morten Smelror for their critical reviews, which increased the quality of this chapter. We also thank Norsk Hydro ASA and Norwegian Petroleum Directorate for funding the project and giving us the permission to publish. The authors acknowledge TGS-Nopec for permission to publish seismic lines.

## References

Boldreel, L.A. and Andersen, M.S., 1993. Late Palaeocene to Miocene compression in the Faeroe-Rockall area. In: J.R. Parker (Editor), Petroleum Geology of Northwest Europe. Proceedings of the 4th Conference. Geological Society, London, pp. 1025–1034.

Boldreel, L.A. and Andersen, M.S., 1994. Tertiary development of the Faeroe-Rockall Plateau based on reflection data. Bull. Geol. Soc. Den., 41: 162–180.

Brekke, T., 2000. The tectonic evolution of the Norwegian Sea continental margin with emphasis on the Vøring and Møre Basins. Geol. Soc., London, Spec. Publ., 167: 327–378.

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

Buchardt, B., 1981. Tertiary deposits of the Norwegian-Greenland Sea region (Svalbard, Northeast and East Greenland, Iceland, the Faeroe islands and the Norwegian-Greenland Sea) and their correlation to NW Europe. Can. Soc. Petr. Geol., Mem., 7: 585–610.

Corfield, S., Sharp, I., Häger, K.-O., Dreyer, T. and Underhill, J., 2001. An integrated study of the Garn and Melke formations (Middle to Upper Jurassic) of the Smørbukk area, Halten terrace, mid-Norway. In: Martinsen, O. and Dreyer, T. Sedimentary environments offshore Norway — Palaeozoic to Recent. Norwegian Petroleum Society (NPF), Special Publication 10, Elsevier, Amsterdam, pp. 199–210.

Deegan, C.E. and Scull, B. (Editors), 1977. A proposed standard lithostratigraphic nomenclature for the central and northern North Sea. Institute for Geological Sciences, London, Rep., 77 (25).

DeMan, E., Ivany, L. and Vanderberghe, N., 2003a. Stable isotope record of the Eocene-Oligocene transition in NE-Belgium. Symposium on the Paleogene Preparing for Modern Life and Climate, Leumen, Belgium (abs.)

DeMan, E., Van Simaeys, S., Vanderberghe, N. and Steurbaut, E., 2003b. The Rupelian/Chattian boundary in the North Sea Basin: New micropaleontological and geochemical data from the stratotype areas. Symposium on the Paleogene Preparing for Modern Life and Climate, Leumen, Belgium (abs.)

Doré, A.G. and Lundin, E.R., 1996. Cenozoic compressional structures on the NE Atlantic margin: Nature, origin and potential significance for hydrocarbon exploration. Petrol. Geosci., 2: 299–311.

Eidvin, T. and 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. Norsk Geol. Tidsskr., 81: 119–160.

Eidvin, T., Jansen, E., Rundberg, Y., Brekke, H. and 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. Petrol. Geol., 17: 579–600.

Eidvin, T., Riis, F. and Rundberg, Y., 1999. Upper Cainozoic stratigraphy in the central North Sea (Ekofisk and Sleipner fields). Norsk Geol. Tidsskr., 79: 98–129.

Eidvin, T., Rundberg, Y. and Smelror, M., 2002. Revised chronology of Neogene sands (Utsira and Skade formations) in the central North Sea. In: A. Hurst (Editor), Onshore-Offshore Relationships on the Nordic Atlantic Margin. NGF Abstracts and proceedings of the Norwegian Petroleum Society (NPF) and Norwegian Geological Society (NGF) Conference, 7–9th Oct. Trondheim, pp. 51–53.

Eldholm, O. and Thiede, J., 1980. Cenozoic continental separation between Europe and Greenland. Palaeogeogr., Palaeoclimat., Palaeoecol., 30: 243–259.

Eldholm, O., Skogseid, J., Sundvor, E. and Myhre, A.M., 1990. The Norwegian-Greenland Sea. In: Grantz, A., Johnson, L. and Sweeney, J.F. (Editors), The Geology of North America (Vol. L): The Arctic Ocean Region. Geol. Soc. Am., 351–364.

Eldrett, J.S., Harding, I.C., Firth, J.V. and Roberts, A.P., 2004. Magnetostratigraphic calibration of Eocene-Oligocene dinoflagellate cyst biostratigraphy from the Norwegian-Greenland Sea. Marine Geology, 204 (1–2), 91–127.

Fyfe, J.A., Gregersen, U., Jordt, H., Rundberg, Y., Eidvin, T., Evans, D., Stewart, D., Hovland, M. and Andresen, P., 2003. Chapter 16: Oligocene to Holocene. In: D. Evans, C. Graham, A. Armour and P. Bathurst (Editors), The Millennium Atlas: Petroleum geology of the Central and Northern North Sea. Geological Society, London, pp. 279–287.

Galloway, W.E., Garber, J.L., Liu, X., and Sloan, B.J., 1993. Sequence stratigraphic and depositional framework of the

Cenozoic fill, Central and Northern North Sea Basin. In: J.R. Parker (Editor), Petroleum Geology of Northwestern Europe: Proceedings of the 4th Conference. Geological Society, London, pp. 33–43.

Galloway, W.E., 2002. Paleogeographic setting and depositional architecture of a sand-dominated shelf depositional system, Miocene Utsira Formation, North Sea Basin. J. Sediment. Res., 72 (4): 477–490.

Gjelberg, J., Dreyer, T., Høie, A., Tjelland, T. and Lilleng, T., 1987. Late Triassic to Mid-Jurassic sandbody development on the Barents and Mid-Norwegian shelf. In: J. Brooks and K. Glennie (Editors), Petroleum Geology of North West Europe, Graham and Trotman, London, pp. 1105–1129.

Goll, R.M. and Skarbø, O., 1990. High resolution dating of Cenozoic sediments from the northern North Sea using 87Sr/86Sr isotope stratigraphy. Discussion. AAPG Bull., Discussion, 74: 1283–1286.

Gradstein, F. and Bäckström, S., 1996. Cainozoic Biostratigraphy and Paleobathymetry, northern North Sea and Haltenbanken. Norsk Geol. Tidsskr., 76: 3–32.

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

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

Hull, D.M., 1996. Paleogeography and biostratigraphy of Paleogene radiolarians from the Norwegian-Greenland Sea. In: Thiede, J., Myhre, A.M., Firth, J.V., Johnson, G.L., and Ruddiman, W.F. (Editors). Proc. ODP. Sci. Results, 151: College Station, TX (Ocean Drilling Program).

Isaksen, D. and Tonstad, K., 1989. A revised Cretaceous and Tertiary lithostratigraphic nomenclature for the Norwegian North Sea. NPD, Bull., 5: 59 pp.

Ivany, L.C., Patterson, W.P., and Lohmann, K.C., 2000. Cooler winters as a possible cause of mass extinctions at the Eocene-Oligocene boundary. Nature, 407: 887–890.

Ivany, L.C., Nesbitt, E.A., and Prothero, D.R., 2003. The marine Eocene-Oligocene transition: a synthesis. In: Prothero, D.R., Ivany, L.C., and Nesbitt, E.A. (Editors). From Greenhouse to Icehouse: The Marine Marine-Oligocene Transition. Columbia University Press, New York, pp. 522–534.

Johnson, H.D. and Baldwin, C.T., 1996. Shallow siliciclastic seas. In: H.G. Reading (Editor), Sedimentary environments, Processes, Facies and Stratigraphy. Oxford, Blackwell Science Ltd, pp. 232–280.

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

Kaminski, M. and Austin, W.E.N., 1999. Oligocene deep-water agglutinated foraminifers at Site 985, Norwegian Basin, southern Norwegian Sea. In: M.E. Raymo, E. Jansen, P. Blum and T.D. Herbert (Editors), Proceedings of the Ocean Drilling Program, Scientific Results, 162: 169–177.

Kennett, J.P., 1982. Marine Geology. Prentice-Hall, Inc., New Jersey, 813 pp.

Kennett, J.P. and Barker, P.F., 1990. Latest Cretaceous to Cenozoic climate and oceanographic developments in the Weddell Sea, Antarctica: an ocean-drilling perspective. In: Barker, P.F. and Kennett, J.P. et al. (Editors). Proc. ODP Sci. Results, 113: College Station, TX (Ocean Drilling Program), 937–960.

King, C., 1983. Cenozoic micropaleontological biostratigraphy of the North Sea. Institute for Geological Sciences, Rep., 82: 40 pp.

Kitchell, J.A. and Clark, D.L., 1982. Late Cretaceous-Paleogene paleogeography and paleocirculation: evidence of North Polar upwelling. Palaeogeogr., Palaeoclimat., Palaeoecol., 40: 135–165.

Knox, R.W.O'B. and Holloway, S., 1992. Paleogene of the central and northern North Sea. In: R.W.O'B. Knox and W.G. Cordey (Editors), Lithostratigraphic nomenclature of the UK North Sea. Nottingham, British Geological Survey.

Lundin, E. and Doré, A.G., 2002. Mid-Cenozoic post-breakup deformation in the 'passive' margins bordering the Norwegian-Greenland Sea. Mar. Petrol. Geol., 19: 79–93.

Løseth, H., Wensaas, L., Arntsen, B. and Hovland, M., 2003. Gas and fluid injection triggering shallow mud mobilization in the Hordaland Group, North Sea. In: P. van Rensbergen, R.R. Hillis, A.J. Maltman and C.K. Morley (Editors), Subsurface sediment mobilization. Geol. Soc., London, Spec. Publ., 216: 139–157.

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

Mikkelsen, N. and Barron, J.A., 1997. Early Oligocene diatoms on the Ceara Rise and the Cenozoic evolution of biogenic silica accumulation in the low-latitude Atlantic. In: N.J. Shackleton, W.B. Curry, C. Richter and T.C. Bralower (Editors), Proceedings of the Ocean Drilling Program, Scientific Results, 154.

Mosar, J., Lewis, G. and Torsvik, T.H., 2002. North Atlantic sea-floor spreading rates: implications for Tertiary development of inversion structures of the Norwegian-Greenland Sea. J. Geol. Soc., London, 159: 503–515.

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

Ogasawara, K., 2002. Responses of Japanese Cenozoic molluscus to Pacific gateway events. Revista Mexicana de Ciencias Geológicas, 19: 206–214.

Piasecki, S., Gregersen, U. and Johannessen, P., 2002. Lower Pliocene dinoflaggelate cysts from cored Utsira Formation in the Viking Graben, northern North Sea. Mar. Petrol. Geol., 19: 55–67.

Ruddiman, W.F., 2000. Earth's Climate, Past and Future. W.H. Freeman and Company, New York, 465 pp.

Rundberg, Y., 1989. Tertiary sedimentary history and basin evolution of the Norwegian North Sea between 60–62°N — An integrated approach. PhD thesis Univ Trondheim, (Reprinted 1991: NTH, Geol. Inst., Report Series, 25, 292 pp).

Rundberg, Y. and Smalley, P.C., 1989: High resolution dating of Cenozoic sediments from the northern North Sea using 87Sr/86Sr isotope stratigraphy. AAPG Bull., 73: 298–308.

Rundberg, Y., Olaussen, S. and Gradstein, F., 1995: Incision of Oligocene strata; evidence for northern North Sea Miocene uplift and key to the formation of the Utsira sands. Geonytt, 22: 62.

Sejrup, H.P., Haflidason, H., Løvlie, R., Bratten, Å., Tjøstheim, G., Forsberg, C.F. and Ellingsen, K.L., 1995. Quaternary of the Norwegian channel: glaciation history and palaeooceanography. Norsk Geol. Tidsskr., 75: 65–87.

Shipboard Scientific Party, 2000: Leg 189 Preliminary Report; The Tasmanian Seaway between Australia and Antarctica — Paleoclimate and Paleoceanography. ODP Prelim. Rpt, 89 (Online). Available from World Wide Web: (http://www-odp.tamu.edu/publications/prelim/189_prel/189PREL.PDF)

Smalley, P.C. and Rundberg, Y., 1990. High-resolution, dating of Cenozoic Sediments from northern North Sea using $^{87}$Sr/$^{86}$Sr Stratigraphy. AAPG Bulletin, 74. Reply to Discussion, 74: 1287–1290.

Shipboard Scientific Party, 2002: Leg 199 Preliminary Report; Paleogene Equatorial Transect. ODP Prelim. Rpt, 99 (Online). Available from World Wide Web: (http://www-odp.tamu.edu/publications/prelim/199_prel/199PREL.PDF)

Spiegler, D. and 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., 1997. Mid-to late Cenozoic sedimentation on the continental margin off NW Britain. J. Geol. Soc., London, 154: 509–515.

Stoker, M.S., Nielsen, T., van Weering, T.C.E. and Kuijpers, A., 2002. Towards an understanding of the Neogene framework of the NE Atlantic margin between Ireland and the Faeroe Islands. Mar. Geol., 188: 233–248.

Talwani, M. and Eldholm, O., 1977. Evolution of the Norwegian-Greenland Sea. Geol. Soc. Am. Bulletin, 88: 969–999.

Thyberg, B.I., Stabell, B., Faleide, J.I. and Bjørlykke, K., 1999. Upper Oligocene diatomaceous deposits in the northern North Sea — silica diagenesis and paleogeographic implications. Norsk Geol. Tidsskr., 79: 3–18.

Vogt, P.R., Perry, R.K., Feden, R.H., Fleming, H.S. and Cherkiz, N.Z., 1981. The Greenland-Norwegian Sea and the Iceland environment; geology and geophysics. In: A.E.M. Nairn, M. Churkin and F.G. Stehli (Editors), The ocean basins and margins, 5, The Arctic Ocean. Plenum Press, N.Y., pp. 493–598.

Vågnes, E., Gabrielsen, R.H. and Haremo, P., 1998. Late Cretaceous-Cenozoic intraplate contractional deformation at the Norwegian continental shelf: timing, magnitude and regional implications. Tectonophysics, 300: 29–46.

Wold, C.N., 1994. Cenozoic sediment accumulation on drifts in the northern North Atlantic. Paleoceanography, 9: 917–941.

Wright, J.D. and Miller, K.G., 1996. Control of North-Atlantic deep-water circulation by the Greenland-Scotland Ridge. Paleoceanography, 11: 157–170.

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