

Distribution of the Neogene Utsira Sand and the succeeding deposits in the Viking Graben area, North Sea

U. Gregersen*, P.N. Johannessen

Geological Survey of Denmark and Greenland (GEUS), Geus, Oste Voldgade 10, DK-1350 Copenhagen, Denmark

Received 13 June 2006; received in revised form 27 March 2007; accepted 30 August 2007

Abstract

The sandy quartzose parts of the Utsira Formation, the Middle Miocene to mid Pliocene Utsira Sand, extends north–south along the Viking Graben near the UK/Norwegian median line for more than 450 km and 75–130 km east–west. The Utsira Sand is located in basin-restricted seismic depocentres, east of and below prograding sandy units from the Shetland Platform area with Hutton Sands. The Utsira Sand reaches thicknesses up to ca. 300 m in the southern depocentre and 200 m in the two northern depocentres with sedimentation rates up to 2–4 cm/ka. Succeeding Plio–Pleistocene is divided into seismic units, including Base Upper Pliocene, Shale Drape, Prograding Complex and Pleistocene. The units mainly consist of clay, but locally minor sands occur, especially at toes of prograding clinoforms (bottom-set sands) and in the Pleistocene parts, and the total thickness covering the Utsira Sand is in most places more than 800 m, but thins towards the margins.

© 2007 Elsevier Ltd. All rights reserved.

Keywords: Utsira Sand; Neogene; Northern North Sea

1. Introduction

This paper presents regional studies of Neogene stratigraphy of the Viking Graben area. The objectives of this paper are, on a regional scale, to describe location, character and the relations of the Neogene sandy units, with focus on the Utsira Sand in the Viking Graben area (Fig. 1), and to contribute to the discussion of the stratigraphy of the Neogene succession of the northern North Sea region.

The paper is based on work mainly performed by the Geological Survey of Denmark and Greenland (GEUS) and the British Geological Survey (BGS) under the Saline Aquifer CO₂ Storage (SACS) project, in which a part of it was to map mainly the sands of the Utsira Formation on regional scale with focus on the southern Viking Graben area. The SACS project had several other sub-projects, and it was a field-scale demonstration project, which aimed to describe, monitor and predict geological and geochemical aspects related to injection of CO₂ at the Norwegian

Sleipner Field. To avoid letting out CO₂ in the atmosphere, the natural content of CO₂ in the Sleipner Field is separated on the Sleipner A platform, and has been treated and injected as fluid into the Utsira Formation sands since 1996 (Baklid et al., 1996; Eiken et al., 2000). The SACS project was carried out by European research and oil/energy companies in cooperation from 1998 to 2002, and included several sub-projects with geological, geophysical, and geochemical investigations (Chadwick et al., 2000, 2004; Gale et al., 2001). The industry partners comprise Statoil (Coordinator), BP, ExxonMobil, Norsk Hydro, Saga Petroleum, TotalFinaElf, Vattenfall. In addition to the partners the following organisations were active involved: GEUS, BGS, SINTEF Petroleum Research, TNO, BRGM, IFP, the Nansen ERS Centre and the IEA Greenhouse Gas R&D Programme (Gale et al., 2001). The demonstration project resulted in scientific results and a best practice manual (Holloway et al., 2003). Parts of its activities were continued in the EU-cofunded CO₂STORE project.

Mapping of the Neogene succession in the present sub-project was based on the interpretation of 2D seismic reflection and well data, including well-logs and well-completion

*Corresponding author. Tel.: +45 38142000; fax: +45 38142050.

E-mail address: ug@geus.dk (U. Gregersen).

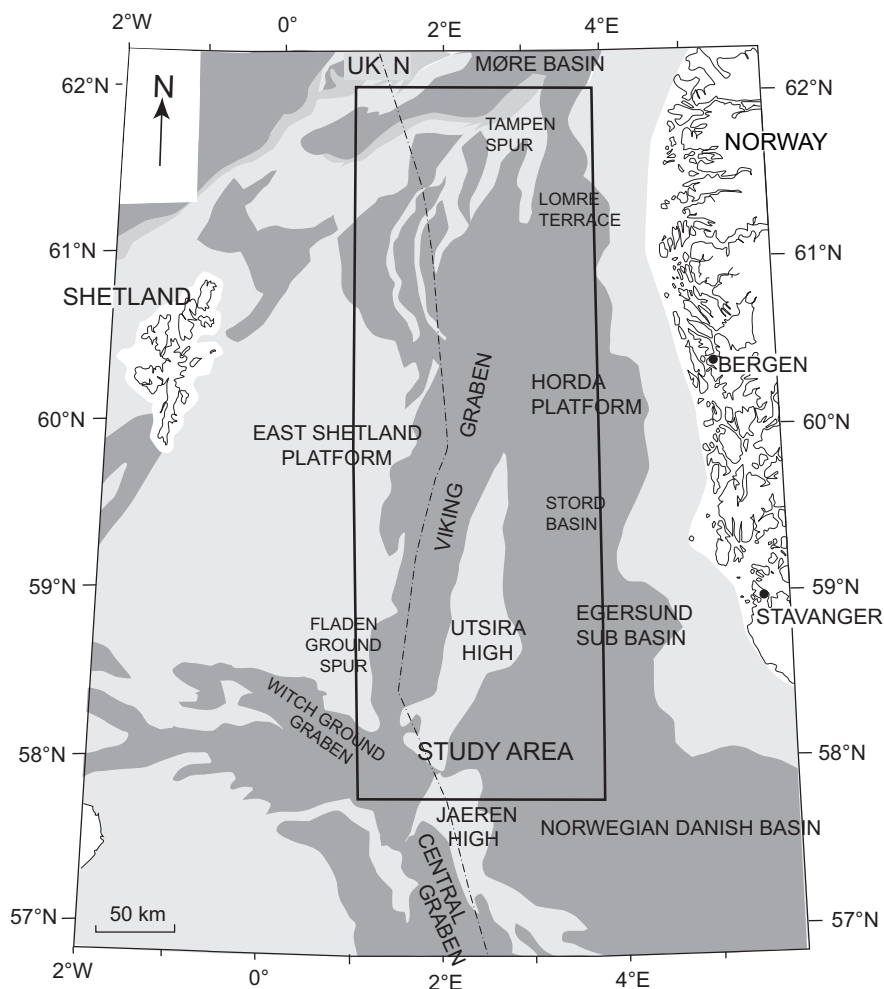


Fig. 1. Regional structural map of the Viking Graben area with the outline of the study area shown.

information (Fig. 2). Data was chosen in order to perform regional scale interpretation. Other SACS sub-project has performed detailed 3D seismic studies at the CO₂ injection site (Arts et al., 2000, 2004; Eiken et al., 2000; Zweigel et al., 2000, 2001). 2D seismic data available to the project comprised a number of regional 2D surveys (CNST82RE, NNST84, NVGT88) that cover much of the northern North Sea basin and extend to more than 10,000 line kilometres. More than 300 wells were available for the study of which most had geophysical log data, including gamma ray and sonic logs and well velocity surveys. Most wells with logs used are shown in Fig. 2. Seismic stratigraphic methods were employed, concentrating on the boundary relationships between different units. This information was integrated with lithology information from wells, i.e. from well completion descriptions, Norwegian Petroleum Directorate (NPD) papers and core and cutting analyses from the SACS project.

2. Regional geological setting

During Cenozoic times, the North Sea area was an epicontinental basin, bounded by higher areas of southern

Scandinavia, the British Isles and Central Europe. Up to more than 1500 m sediments were deposited from Miocene to Recent times in the central and northernmost part of the North Sea (Rundberg, 1989; Jordt et al., 1995).

The development of the late Cenozoic depositional systems was partly controlled by regional basin subsidence in the Viking Graben area (Fig. 1) and episodic marginal uplift (Rundberg, 1989; Jordt et al., 1995; Gregersen et al., 1997; Fyfe et al., 2003).

During the Neogene, the northern North Sea connected the deeper central North Sea and the Norwegian–Greenland basins. Deposition during the early Miocene was dominated by slow argillaceous sedimentation. A sedimentation break occurred during the early to mid-Miocene with erosion of underlying Oligocene and Miocene deposits (Rundberg et al., 1995). Uplift of the North Sea margins locally by more than 400 m (Rohrman et al., 1995; Hansen, 1996; Japsen, 1998) and tilting of the Horda Platform (Ghazi, 1992) affected the region during mid-Miocene and later during the Neogene, and an extensive unconformity was formed. Denudation of the margins of the central to northern North Sea basin resulted in deposition of mainly quartz-rich fine-to-medium grained sand with thin

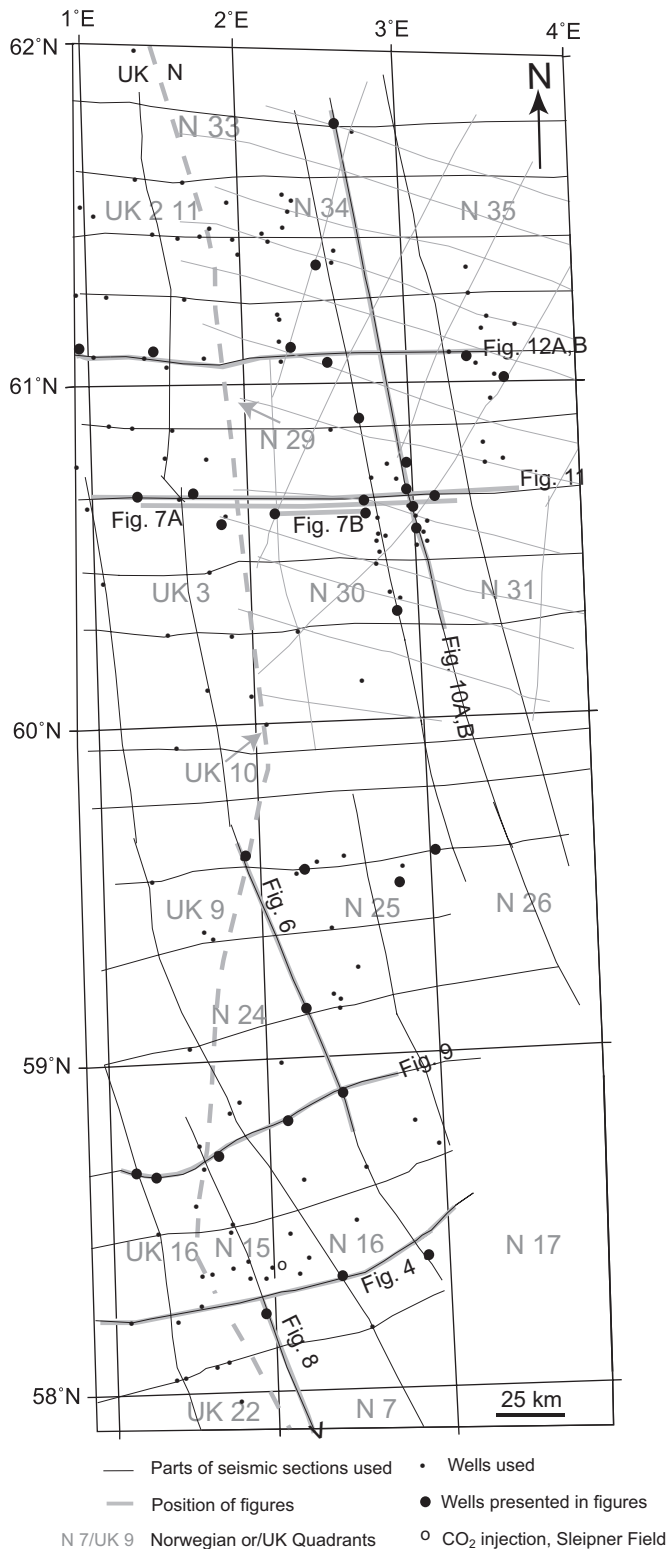


Fig. 2. Map showing the study area with seismic lines and wells used in this study. Locations of figures with geological sections are shown.

interbedded clay layers, comprising the sandy part of the Utsira Formation—which basin-restricted parts is here termed the Utsira Sand. The sands were transported into the basin areas and mixed with glauconite, which was locally concentrated in beds, e.g. towards the north. Shell

fragments often occur and locally lignite is seen. Along the eastern margin of the East Shetland Platform a depositional system included sands, prograded eastward and was deposited during late Cenozoic time. A variety of transportation mechanisms have acted on the distribution and deposition of the sand/silts including local outbuilding of basin marginal deltas at the East Shetland Platform and the Norwegian margin (Gregersen et al., 1997), and basin-axial marine and tidal currents (Galloway, 2002). The sandy deposits were formally described as belonging to the Utsira Formation, that constitutes the basal part of the Nordland Group (Isaksen and Tonstad, 1989), and more recently mapped as the informal Utsira Sand (Chadwick et al., 2000). Argillaceous deposition followed during Pliocene times and increased rates of subsidence during the Late Miocene to Early Pliocene may have caused a relative sea-level rise (Kyrkjebø et al., 2000).

A marked increase in the δO_{18} of seawater (Buchardt, 1978; Miller et al., 1987) during the Pliocene was probably caused by global cooling and icecap growth, which may have caused a general glacio-eustatic sea-level lowering (Haq et al., 1988). Ice sheet movements at the western Norwegian inner shelf have been proposed as a cause for late Pliocene shelf-margin progradation (Henriksen and Vorren, 1996). Uplift also lead to erosion of the basin marginal areas, and increased the sediment influx and probably also contributed to late Neogene progradation of systems.

Pleistocene glaciations resulted in erosional unconformities and removed the upper parts of the prograding Pliocene deposits. Later phases of glaciations/deglaciations resulted in deposition of tills interbedded with shallow-marine clays (Sejrup et al., 1991). Post-glacial isostatic rebound contributed to the continued elevation of the North Sea margins (Riis and Fjeldskaar, 1992).

3. The Utsira Sand

The Utsira Formation of the Nordland Group is lithostratigraphically defined by Deegan and Scull (1977) and later Isaksen and Tonstad (1989). The Utsira Sand as it is defined here, is interpreted in the present study mainly as basin-restricted sands, sometimes separated by interbedded clays, along the entire Viking Graben area (Figs. 3–10). The approximately gross sand thickness of the sandy units of the Utsira Sand is mapped (Fig. 5).

Lower sandy parts of the Utsira Formation in the Type well N16/1-1 of the Utsira Formation defined by Isaksen and Tonstad (1989) and time-equivalent thick sands nearby have recently been redefined and redated (Rundberg and Eidvin, 2005) as Skade Formation sands of Lower Miocene age, based on log- and seismic correlation and mainly by new Sr-isotope datings and biostratigraphic work. Rundberg and Eidvin (2005) separates the Utsira Formation from the Skade Formation below by a Middle Miocene mudstone interval with Strontium ages (e.g. 15.4 Ma) above Skade Fm sands in its Type well 24/12-1 and by correlation of the Middle Miocene *Bolboforma badenensis*–*Bolboforma reticulata*

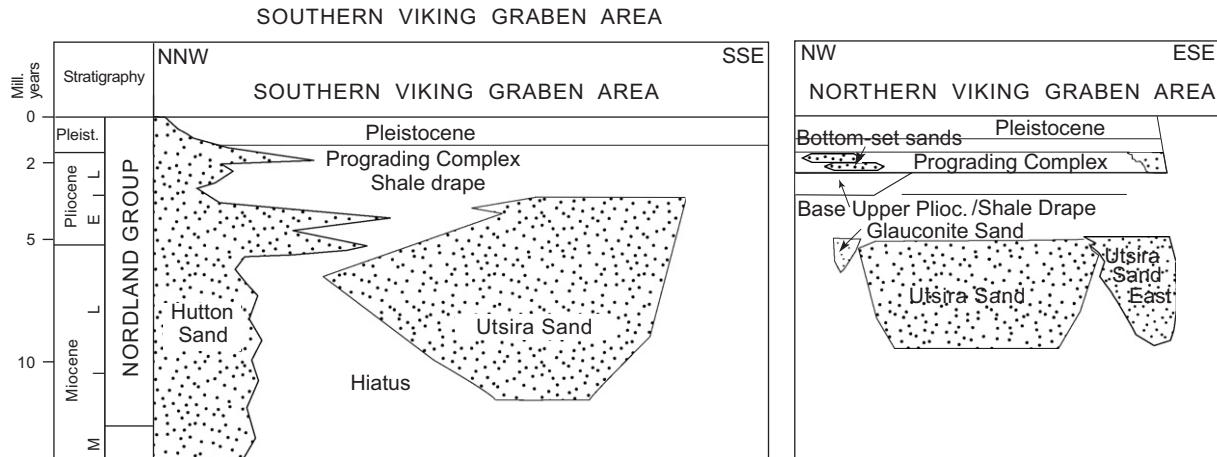


Fig. 3. Generalised stratigraphic scheme of the Neogene units from northwest to southeast in the southern and in the northern Viking Graben areas. In the southern Viking Graben area, the main Utsira Sand is up to 300 m thick. Eastward prograding Neogene clinoforms. The Hutton Sand seismic unit is located at the margin of the East Shetland Platform. The major Utsira Sand unit extends into the northern Viking Graben area (Fig. 5), and east of it occurs the partly time-equivalent Utsira Sand East unit. At the northwest limit of the quartzose Utsira Sand, a glauconitic sand unit succeeded by a Basal Upper Pliocene unit occur North of the Shale Drape unit. There are three units succeeding the Utsira Sand further south: a Shale Drape seismic unit, a Prograding Complex seismic unit dominated by prograding clinoforms with local bottom-set sands, and a mainly Pleistocene unit with a regional unconformity at its base.

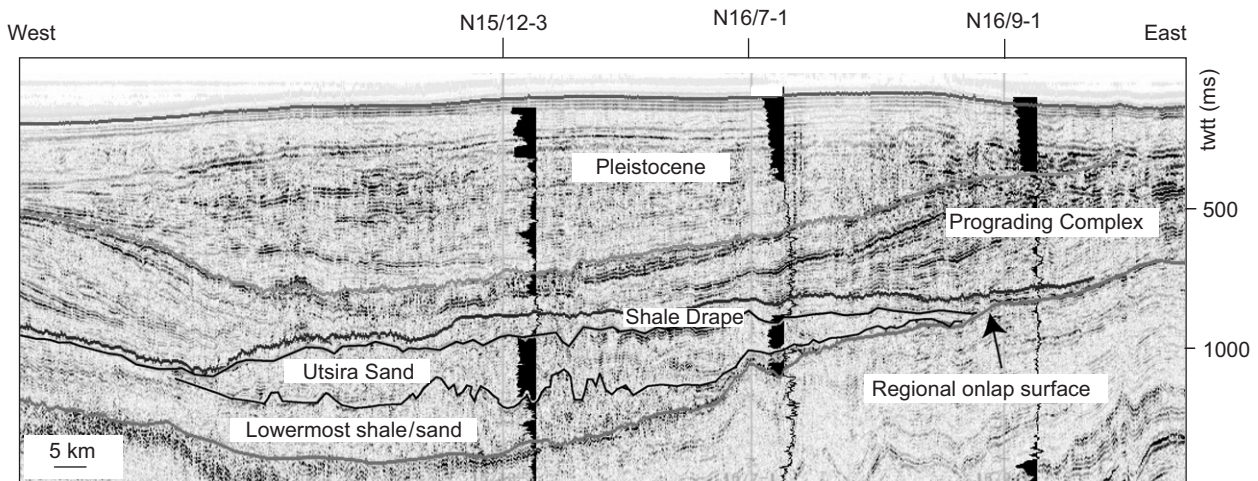


Fig. 4. Seismic section (CNST82-05) from west to east across the southern Viking Graben area, showing the stacked reflection mounds of the Utsira Sand unit, the Lowermost shale/sand unit, the Shale Drape unit, and the Prograding Complex unit, truncated by the unconformity at the base of the Pleistocene unit. Well profiles show gamma-log traces. Location is shown in Fig. 2.

assemblage in well N16/1-4, N16/1-2 and N24/12-1. This new stratigraphy changes a major part of the Miocene sands previously being interpreted as Utsira Formation of a mid- to Late Miocene age, such as in well 16/1-1 of Isaksen and Tonstad (1989) and in some of the Norwegian Petroleum Directorate papers with wells from this area (e.g. NPD Paper no. 8), and also in work partly based on their well stratigraphy and the type well, e.g. in Gregersen et al. (1997). The main area with the Skade Formation sands seems according to Rundberg and Eidvin (2005) to be located mainly from an area south of 59°N to north of 60°N in mainly the Norwegian sector blocks 16 (northern parts), 24 and 25. Seismic interpretation also indicates (Fig. 6) that reflections of the Utsira Sand succeed the seismic interval with the newly redefined Skade Formation.

3.1. Lithology and reservoir properties

Macroscopic and microscopic analysis of core and cuttings samples of the Utsira Sand (Chadwick et al., 2004) show that it consists mainly of fine-grained sand, with occasional medium and coarse grains. The sand grains are predominantly angular to sub-angular and consist primarily of quartz with some feldspar and shell fragments. Glauconite rarely occurs in the southernmost depocentre, but is more common towards the central and northern parts. The sand grains are almost completely uncemented. Sheet silicates are present in small amounts (a few percent). A core through the Utsira Sand from the well N15/9-A23 shows no visible layering or preferred orientation of minerals. Shell fragments are common and seem to be

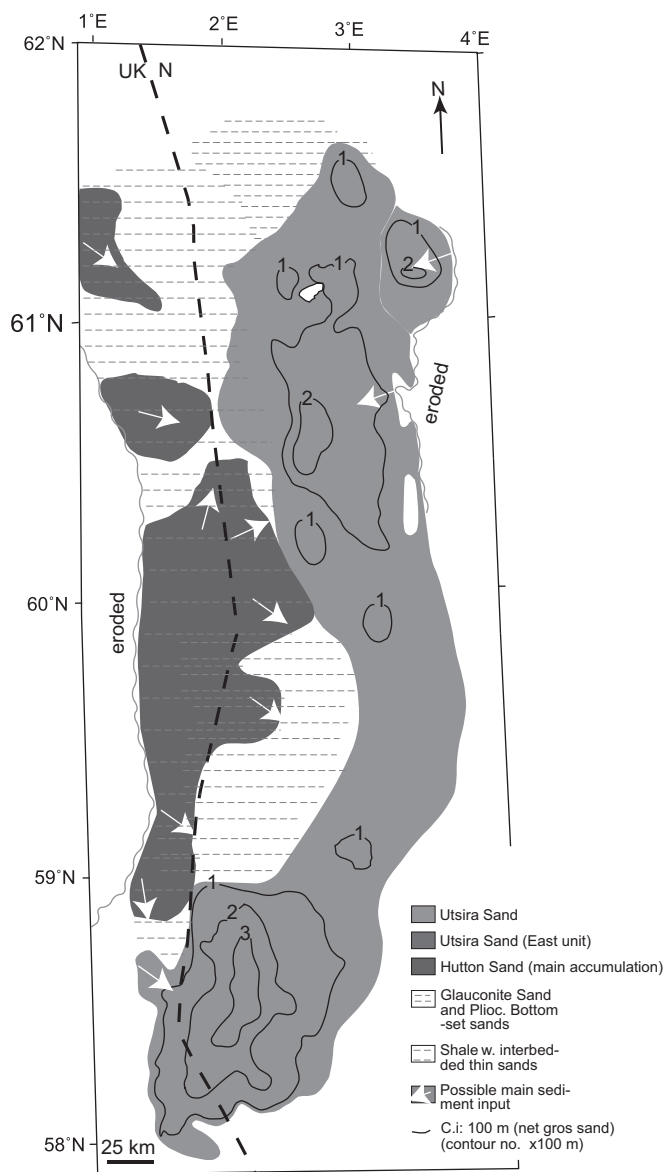


Fig. 5. Isopach map (100 m contour interval) of Neogene sandy units and sediment input directions. The quartzose Utsira Sand seismic unit occurs along the Viking Graben area, and the Hutton Sand seismic unit (Mio–Pliocene part) occurs to the west along the east Shetland Platform margin, from where the depositional system progrades eastward. From the northern limit of the Utsira Sand, an area with a Glaucanite Sand interval and succeeding bottom-set sands of the Pliocene Prograding Complex occurs. The Utsira Sand has a main depocentre with up to ca. 300 m in the southern Viking Graben/Utsira High area and two depocentres with up to ca. 200 m in the northern Viking Graben area—one in the main Utsira Sand and one in the Utsira Sand East unit. The distribution of the thicker part of the Hutton Sand supposed to be nearly time equivalent to the Utsira deposition is also shown, with direction of progradation indicated.

randomly oriented. This lack of layering might be due to high-energy deposition or bioturbation, or simply destruction of primary sedimentary structures during the coring process. Silts have been described from cuttings, and local high gamma ray readings indicate minor clay layers in the Utsira Sand. Well completion descriptions show that some lignite and glauconite occurs locally in the Utsira Sand.

Just north of the quartzose Utsira Sand, a glauconite-rich sand interval of Late Miocene to earliest Early Pliocene age up to ca. 50 m thick occurs in wells of the Tampen Spur area (Visund–Snorre fields) described by Eidvin and Rundberg (1999, 2001). They suggest it to be a part of the Utsira Formation, succeeding (may be interfingering) the quartzose formation sand.

The porosity of the Utsira Sand core determined by microscopic modal analysis of thin sections ranges generally from 27% to 31%, but reaches values as high as 42% (Pearce et al., 2000; Chadwick et al., 2004). However, these measurements were made from thin sections of a sample of frozen loose sand. As a guide to regional reservoir properties they may therefore be less reliable than porosities derived from wireline logs. A study of regional porosity variation in the Utsira Sand, based on density and sonic logs was carried out, and overall, the log-derived porosities mostly were quite uniform, in the range 35–40% over much of the sand (Chadwick et al., 2004). Only locally in the far north values appear to fall below 35%, and here well control is very sparse.

3.2. Geophysical log characteristics

The Utsira Sand is clearly identifiable on geophysical well logs (Figs. 9–12), being characterised by ‘blocky’ log pattern, low gamma ray values, and low sonic velocity and resistivity. Its top and base are generally sharply defined, particularly on the gamma ray logs (Fig. 4). Occasional high gamma ray readings/peaks in the sand dominated intervals are mainly interpreted as thin beds of clay or claystone on the basis of well completion descriptions, although some gamma ray peaks locally may be due to the presence of glauconite. Locally, glauconite is concentrated in beds (Eidvin and Rundberg, 2001) such as north of the main Utsira Sand (Fig. 10A).

3.3. Regional structure and seismic stratigraphy

The Utsira Sand forms clearly defined basin-restricted seismic units east of the East Shetland Platform, pinching out to the east and west, and seismically distinct from overlying and underlying strata. This is readily seen in its southernmost deposition area (Fig. 4). Regional cross-sections (Figs. 6 and 8) demonstrate the basin-restricted nature of the Utsira Sand, with internal stacked, mounded features. The Utsira Sand occurs all along the Viking Graben near the UK/Norwegian median line for more than 450 km south–north, between 58°N and 61°40'N, and 75–130 km east–west between 1°E and 3°50'E (Fig. 5).

The downlap surface below the Utsira Sand (Fig. 4) is locally very irregular and disturbed by shale deformation, and has been discussed by Heggland (1997), Gregersen et al. (1997) and Zweigel et al. (2000). At its northern limit, the Utsira Sand narrows and deepens to below 950 m (b.msl) (Fig. 10A) and is succeeded or perhaps partly interfingers with a glauconitic interval (Glaucanite Sand;

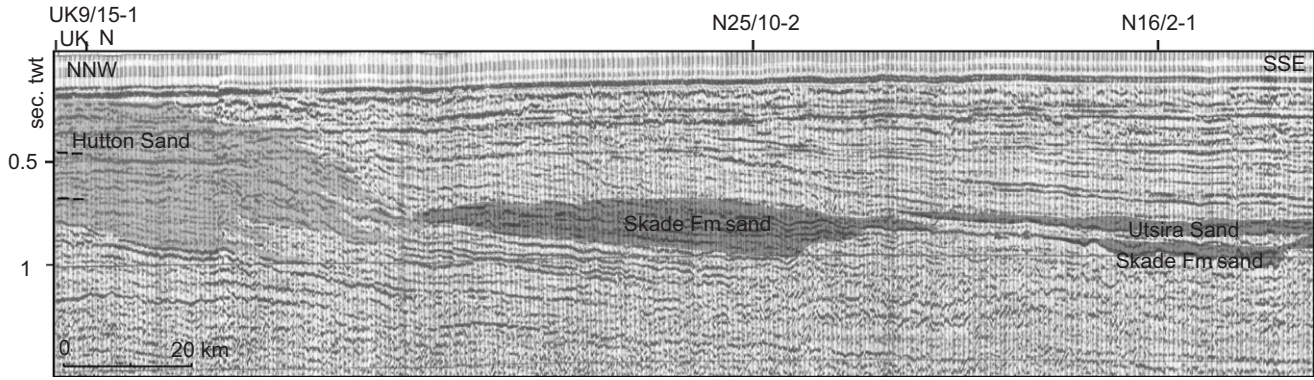


Fig. 6. Seismic section (CNST82-20) from NNW to SSE through the Hutton Sand, Skade Formation sand and the Utsira Sand based on seismic and well data. Seismic interpretation shows that the Utsira Sand is located in a distinct depocentre unit and overlies the sands of the Skade Formation. The location of the eastern limit of the Hutton Sand is uncertain and without well control.

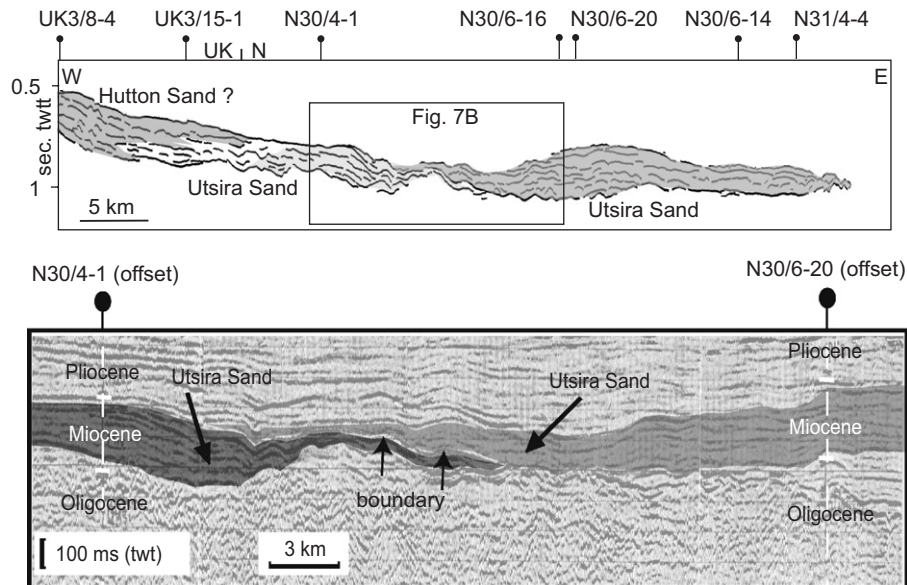


Fig. 7. (A) Redrawn reflections from seismic line and interpretation of well-logs (seismic line NNST84-05 (log profile in Fig. 11)) and stretch west to east from the Shetland Platform margin into the Viking Graben area. The profile shows eastward prograding-aggrading reflections of the Hutton Sand unit and its updip marginal position in relation to the basinal-located, mounded, stacked Utsira Sand reflections to the east. In the Northwest Viking Graben area local Utsira Sand accumulations overlap each other. Locally at the easternmost limit of the main Utsira Sand, a few subtle progradational reflections are locally found. Location of the profile is shown in Fig. 2. (B) Seismic section (NNST84-05) with projected wells, showing two local accumulations of the Utsira Sand which are partly overlapping each other in the Northwest Viking Graben area. Location is shown in Figs. 2 and 7A.

Figs. 3 and 5). At the northeast limit of the Utsira Sand a long, branching, deep channel/canyon-like feature occurs (Gregersen, 1998; Eidvin and Rundberg, 2001).

Depths to the base of the Utsira Sand vary from 600 to 1300 m, but mostly lie between 700 and 1100 m (b.msl). On seismic sections the base can be distinguished as a downlap surface (Fig. 7B) often separating mounded reflections above from more concordant or sometimes disturbed reflections below. The shape of the base Utsira Sand surface is generally more complex than that of the top Utsira Sand (Fig. 4), due to a combination of loading and shale deformation. Deformation areas are typically about 100 m high and in map view constitute isolated, ellipsoid domes often 1–3 km in diameter or irregular, elongate

bodies up to 10 km long with varying orientations. Correlation of the seismic defined domes with well data (e.g. N34/11-1; Fig. 12B) indicates that such domes may consist of mainly claystones and shales (Hordaland Group) of Late Oligocene to Early Miocene age, below the Utsira Sand. Locally, at the western or eastern limits of the Utsira Sand, incised channel-like features on seismic data have been interpreted (Gregersen, 1998) at the base of the Utsira Sand (Utsira Formation) level, approximately perpendicular to the basin axis, and could have been entry for some of the sand transport into the basin.

The depth of the top Utsira Sand surface ranges between 550 and 1100 m (b.msl), but is mostly at depths of 700 to 1000 m. The top of the Utsira Sand on seismic sections is

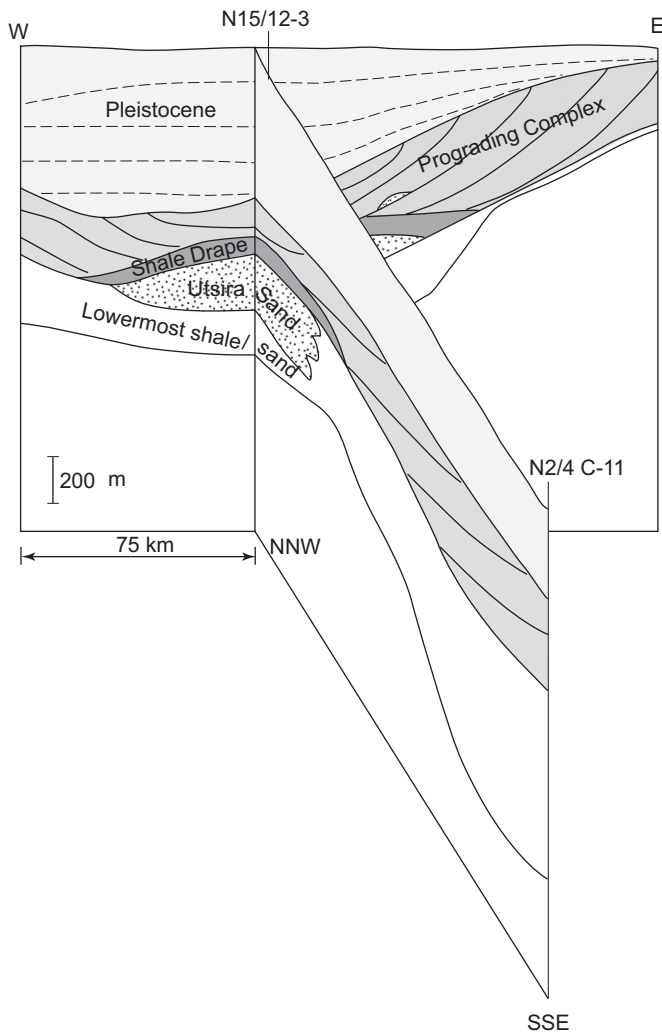


Fig. 8. Geo-section from seismic lines (CNST82-05 (W–E) (Fig. 4) and CNST82-18 + CGT81-12 (N–S)) and well data interpretations, showing the southernmost part of the main Utsira Sand unit and succeeding units, from the Central Graben area to the southern Viking Graben area, where it merges with the east–west crossing section. The Prograding Complex seems to prograde from west and east, but also from southeast towards central parts of the southern Viking Graben area. Location is shown in Fig. 2.

often an irregular surface succeeded by concordant draping reflections (Shale Drape unit), below a regional downlap surface (Fig. 4). Well-logs sometimes show upward increasing gamma readings/peaks in the Shale Drape, with maximum peaks at the seismic downlap surface (Fig. 4). Locally, at the northeast margin of the Utsira Sand, this level seems truncated and 3-D surveys indicate the presence of subtle, slightly meandering channels at this level (top of Utsira Formation in the northern Viking Graben area), e.g. in the Norwegian blocks 35/11 and 35/8 (Gregersen, 1998).

The thick Hutton Sand (sand dominated) succession was deposited through much of the Cenozoic era along parts of the eastern Shetland Platform (Figs. 5 and 6). In this context, only the Neogene part supposed to be approximately time equivalent to the Utsira Sand (Figs. 6 and 11) is described, referred to and mapped (Fig. 5) as the Hutton

Sand. In the northern study area, the Hutton Sand seems to pass laterally west to northeast from mostly thick sands and partly into basinal clayey facies with isolated sands (Fig. 5). Further south the Hutton Sand may be in contact with the Utsira Sand, where it prograded southeast into the basinal areas as indicated by clinofolds (Figs. 6 and 7A) with relief of up to 200–300 m (Fig. 11). The main prograding directions are indicated by arrows and local thicks by a dark colour in Fig. 5.

Integrated interpretation of wells and seismic sections (Figs. 6, 7B and 11) shows that the main Utsira Sand has two main sand depocentres, one depocentre in the southern and one depocentre in the northern study area (Fig. 5) described below.

3.4. Main Utsira Sand

The main Utsira Sand unit extends for more than 450 km north–south (58°N–61°40'N) along the Viking Graben/Utsira High area, and 70–130 km east–west (1°E–3°40'E), covering an area of more than 26,100 km² (Fig. 5). The mapping of the Utsira Sand along the Viking Graben (Chadwick et al., 2000; Gregersen et al., 2000) has been continued here. The eastern and western limits of the Utsira Sand are mainly defined by stratigraphic layout. The southern and the northern limits are defined by a lateral transition into shaly sediments. Locally, particularly in the north but also in the southernmost area, depositional patterns are quite complex with deformation at the base (Fig. 12B) and a few areas of probable non-deposition or removed deposits.

The Utsira Sand is mostly 50–150 m thick, but ranges up to 200–300 m in the depocentre. There are two main depocentre; the principal one is in the south (Fig. 5) at the Sleipner field, where injection of CO₂ takes place (Chadwick et al., 2000). Here, thicknesses range up to ca. 300 m in a generally irregular pattern, although locally there is a significant north–south trend. The second depocentre lies some 200 km to the north, at the Oseberg Field area. Here the thickness of the Utsira Sand locally reaches 200 m. A 70–90 km broad saddle, where the Utsira Sand generally thins below 100 m, separates these two depocentres. Some isolated miocene sands with more than 40 m net thickness is present to the northwest (Fig. 5).

Deposition of the upper part of the Utsira Sand seems to have continued into Pliocene times (Eidvin et al., 1999, 2000; Piasecki et al., 2002; Head et al., 2004) in its southern depocentre. Deposition may have lasted for shorter time towards north and/or parts may have been removed by erosion suggested by a hiatus at its top (Eidvin et al., 2000) (Fig. 3).

The westward extension of the Utsira Sands and exact connection with the sands of the Hutton Sand along the margin of the East Shetland Platform is uncertain due to poor coverage of available seismic lines and well data at the unit limits. However, at some locations the often irregular,

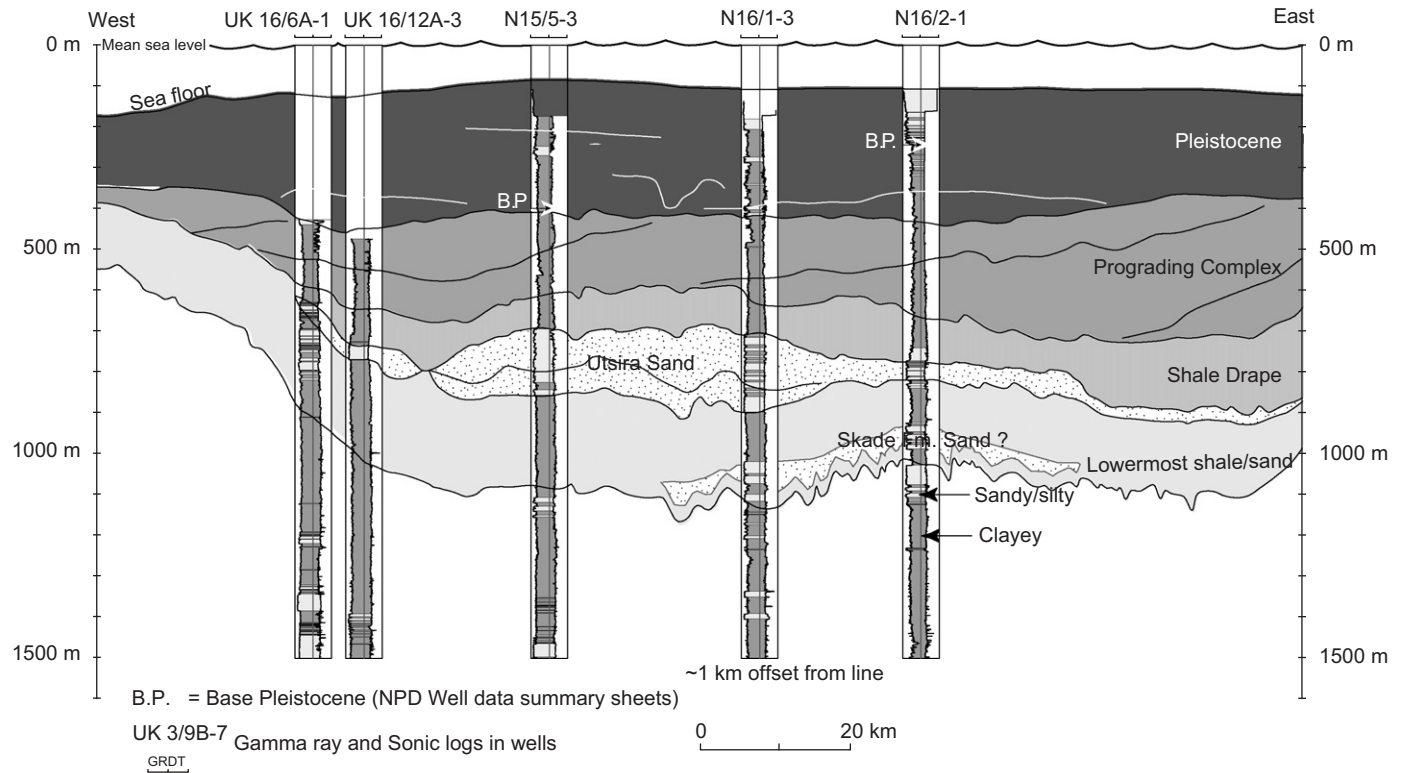


Fig. 9. Geo-section based on an interpreted, depth converted, seismic section (CNST82-07) and well-logs, showing the Utsira Sand and succeeding units from west to east across the southern Viking Graben area. The Utsira Sand is concentrated as thick stacked sands in the southern Viking Graben–Utsira High area and seismic reflections seem to separate lower central parts from upper more extensive parts. Location is shown in Fig. 2.

mounded, discontinuous appearance of seismic reflections and sand drilled nearby, may indicate that local sands occur at the lapout or overlap zones, e.g. between the Utsira Sand and the Hutton Sand (Fig. 11).

Towards the south in the Norwegian sector, Utsira Sand passes into a more basinal clay facies and is absent south of ca. 57°50'N (Figs. 5 and 8) towards the Central Graben area, minor and isolated sands occur, such as the late Oligocene Vade Formation (Norwegian blocks 2/2 and 2/3), and some minor Pliocene sands in the central North Sea. Further to the east, towards the coasts of southern Norway and Denmark, there are more significant Oligocene, Miocene and Pliocene sands. The Shale Drape succeeds the Utsira Sand (Figs. 8–12A) in most places, except in northernmost parts (Figs. 3 and 10A), where the Shale Drape is replaced by a thin glauconitic Sand unit, followed by a Basal Upper Pliocene unit (Eidvin and Rundberg, 2001).

3.5. Utsira Sand East unit

The Utsira Sand East unit occurs as a sand wedge northeast of the main Utsira Sand (Figs. 5 and 12A), in Norwegian Quadrant 35 (blocks 35/7, -8, -10, -11), where it extends ca. 60 km from south to north and ca. 40 km east–west. It is locally more than 200 m thick in the depocentre in block 35/11 (Fig. 5). It is succeeded by the

Shale Drape. Analyses of the unit (well completions and Eidvin et al. (1999)) suggest a Middle to Late Miocene age, and its westernmost late parts downlap onto/or may interfinger with the main Utsira Sand, and is possibly time equivalent to the main Utsira Sand unit (Fig. 3). It has also been suggested to be younger than the main Utsira Sand (Martinsen et al., 1999).

3.6. Biostratigraphy and depositional environment

Completions log from the Utsira Sand mainly suggest Middle to Late Miocene ages. Biostratigraphical analyses (Wilkinson, 1999; Piasecki et al., 2002; Head et al., 2004) from core samples from the southern part of the main Utsira Sand unit indicate ages in the range of early Late Miocene to Late Pliocene. Other analyses of ditch cuttings from this area (Well N15/12-3) indicate ages from late Middle Miocene to earliest Late Pliocene (Eidvin et al., 1999). This suggests that Utsira Sand may have been deposited in periods extending from late Middle Miocene to mid Pliocene times.

In the northernmost North Sea, Eidvin et al. (2000) and Eidvin and Rundberg (2001) suggested that the Utsira Formation, including the Glauconite Sand, has hiatus both at the base and top, and has a mid Late Miocene to earliest Early Pliocene age, with the quartzose formation sand not being younger than latest Miocene.

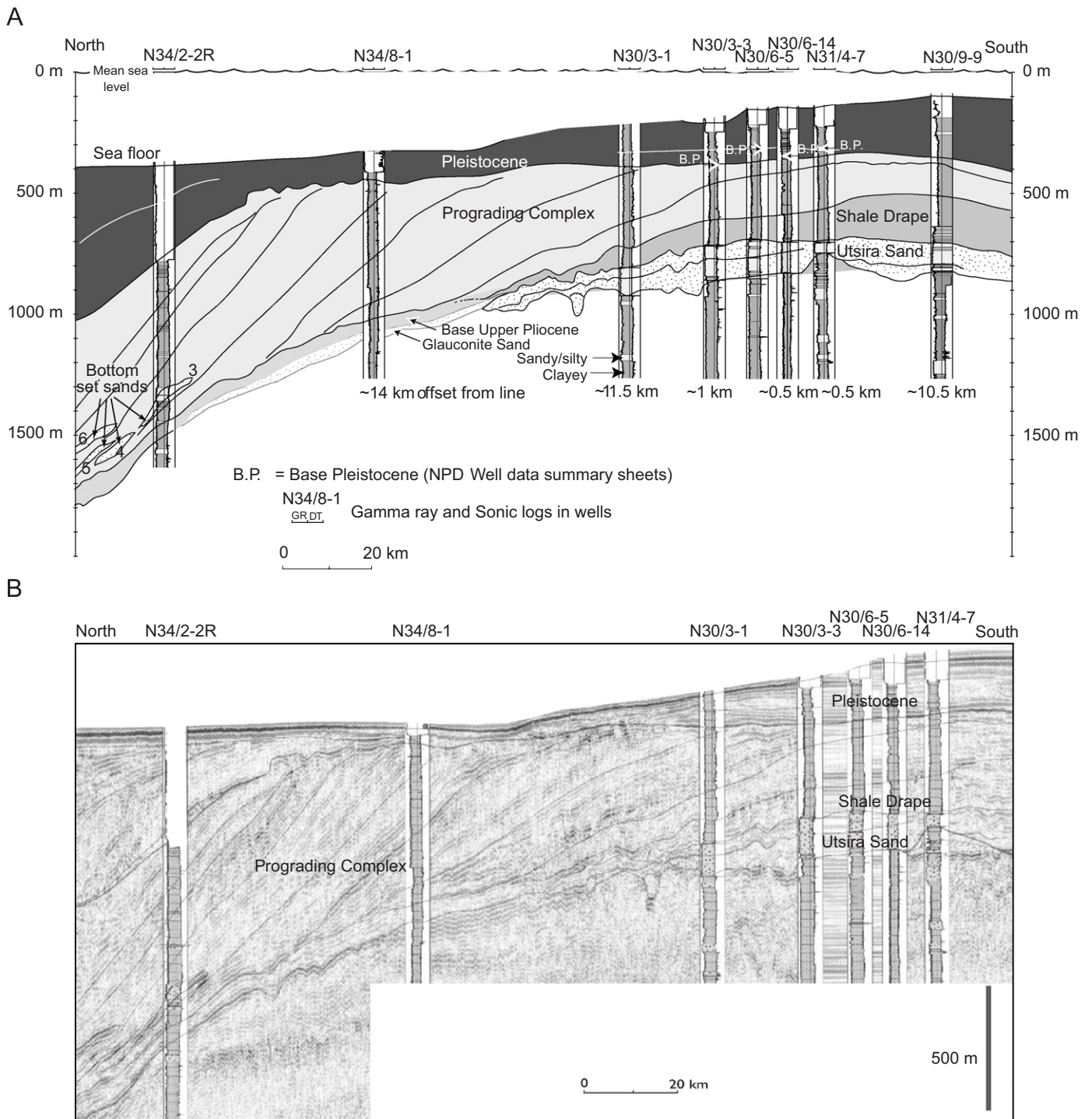


Fig. 10. (A) Geo-section (from depth converted seismic line NNST84-17 and well-logs) with the Utsira Sand, the bottom-set sands of the Prograding Complex unit, and other Neogene units, along the northern Viking Graben area. A glauconite-rich sand interval (Glauconite Sand) and a Basal Upper Pliocene unit of Eidvin and Rundberg (2001) are located at the northern limit of the quartzose Utsira Sand. Fig. 10A is based on interpretation of the seismic line and some of the well-logs shown in Fig. 10B. Interpreted seismic line (NNST84-17) is shown in Fig. 10B. Location is shown in Fig. 2. (B) Depth-converted seismic line NNST84-17 with well-logs, and with interpreted horizons. The Utsira Sand wedges out towards the north and succeeding unit (Prograding Complex) contains further to the north bottom set sands. Interpretation of units along the same profile is shown in Fig. 10A. High amplitudes of the bottom set sands are correlated to well N34/2-2R. Location is shown in Fig. 2.

This indicates that the most complete preserved Utsira Sand occurs in the southern deposition area (e.g. at the Sleipner field) and Utsira Sand deposition may be restricted towards the north by a hiatus.

The lowermost part of Upper Pliocene is probably missing throughout most of the Norwegian Viking Graben area (Eidvin et al., 1999). The total period of deposition of the quartzose Utsira Sand seems to cover a period of ca.

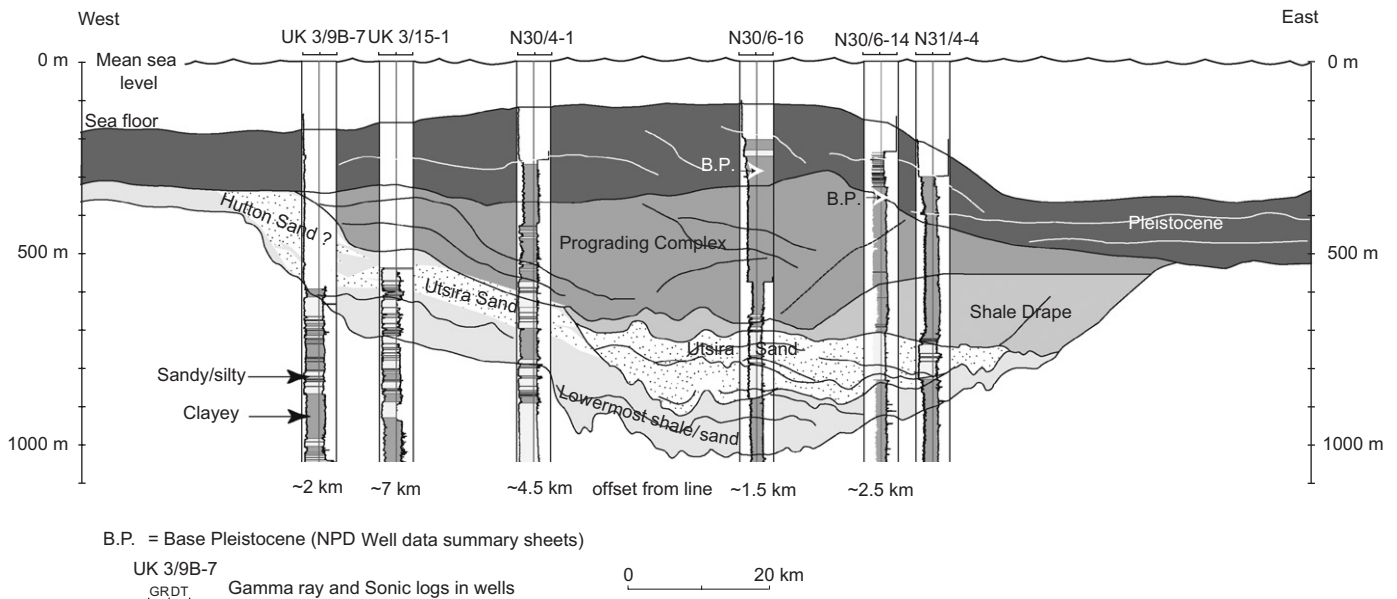


Fig. 11. Geo-section (from depth converted seismic line NNST84-05 and well-logs) from west to east through the northern Viking Graben area with the Utsira Sand and succeeding units. A part of the prograding Hutton Sand unit could possibly be located west of and updip of the Utsira Sand, as also indicated in Fig. 7A. Location is shown in Fig. 2.

8–9 my, from late Middle Miocene to mid Pliocene (Fig. 3). Given the average sand thickness of about 100–150 m, an average sedimentation rate was about 1–2 cm per thousand years, with up to 2–4 cm per thousand years in the 2–300 m thick depocentres.

Analysis of foraminifera and dinoflagellates (Wilkinson, 1999; Eidvin et al., 1999; Piasecki et al., 2002) indicates a marine, neritic environment, possibly with oceanic influence during deposition, with water depths characteristic of middle to outer shelf environments, i.e. around 100–200 m water depth.

A regional hiatus in the Middle Miocene and in places Late Miocene times is found in the northern North Sea area (Eidvin et al., 2000). Analyses of foraminiferal faunas by Eidvin et al. (1999) in the southern depocentre area suggest there was a gradual relative shallowing from outer to middle neritic conditions during Utsira Sand deposition in Miocene to mid Pliocene times. The local deposition of the Utsira Sand East unit suggests a period, especially during Late Miocene, of regression and sand supply from the Norwegian margin before relative sea-level rise in mainly Early Pliocene (Eidvin et al., 2000), and deposition of the Shale Drape clays. The occurrence of a thick Early Pliocene glauconite-rich sand (Eidvin et al., 2000; Eidvin and Rundberg, 2001) succeeding or partly time equivalent to the upper part of the Utsira Sand at its northern limits, may indicate less sediment input and deeper marine conditions in Early Pliocene. In the Late Pliocene a period of regression occurred (Eidvin et al., 2000) causing regional erosion (hiatus), and was followed by major Upper Pliocene progradation. Succeeding clinofolds of the

Prograding Complex seem to have built out at a level several hundred metres above the Utsira Sand.

The mixed content of terrestrial (lignite fragments) and marine (bivalve shell fragments, glauconite, and dinoflagellates) indicators, and the subangular and mature quartz sediments (Chadwick et al., 2000; Pearce et al., 2000), are consistent with deposition in an environment with some energy. The tabular to mounded morphology of the sand bodies, corresponding to blocky low gamma-ray values, separated by thin shale layers, indicates several events of high-energy deposition, separated by calmer conditions where clay was deposited. The sharp-based, mounded nature of the sand bodies deposited with mixed near-shore and more open-marine indicators in the deepest central part of the Viking Graben area may suggest high-energy reworking (Gregersen et al., 1997; Eidvin et al., 1999). A recent analyse by Galloway (2002) of the seismic reflector configuration and orientation of subtle units with analogue to modern tidal environments, suggest a tidal environment with southern main flow to the west in the Utsira Strait and a northern flow direction to the East. The depositional environment has been classified as a strand-plain to banner bank-shoal system, with coherent eastward-prograding Shetland platform and mounded basal shoal (Galloway, 2002). Core analyses (Chadwick et al., 2000) show massive sand with no clear trends in sedimentological variation, distinct bedding or gradual grain size changes to characterize the latest active depositional processes, and marine conditions with some energy/reworking seem to be likely. Regional comparison (Galloway, 2002) of grain sizes of Miocene sands from well

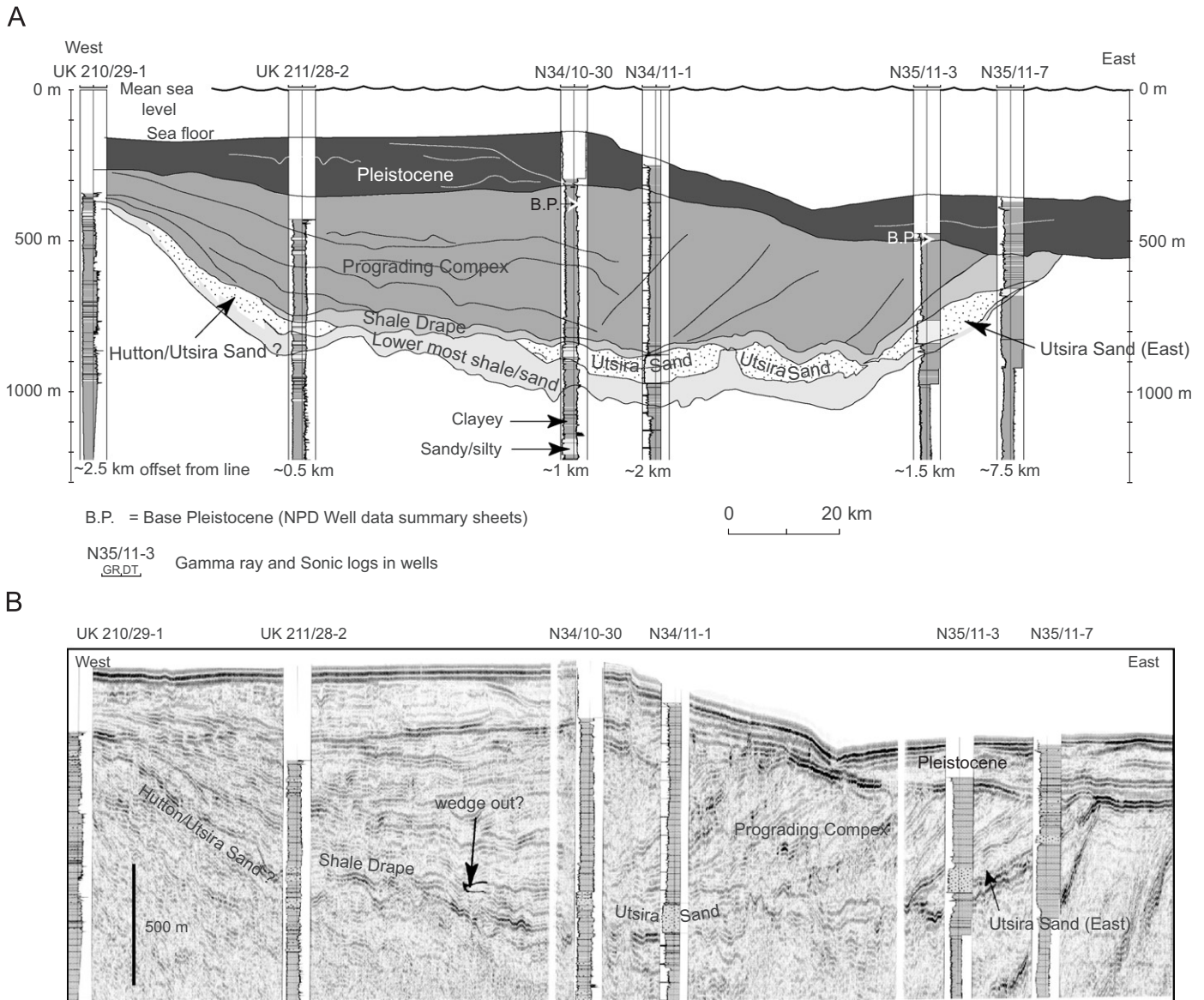


Fig. 12. (A) Geo-section (from depth converted seismic line NNST84-07 and well-logs) from west to east through the northern Viking Graben area with the Utsira Sand and succeeding units. The Utsira Sand East unit downlaps onto the easternmost part of the main Utsira Sand. Location is shown in Fig. 2. (B) Depth-converted seismic line NNST84-07 with well-logs west to east through the northern Viking Graben area. The interpretation with units of the section is shown in Fig. 12A. Location is shown in Fig. 2.

completion descriptions indicates a general grain size decrease southwards, suggesting sediment transport to the basin marginal areas, followed by southward transport and grain size sorting. Lignite beds have been found in Miocene sands at the East Shetland Platform area (Galloway, 2002). High sand content, lignite beds and east to southeastward prograding seismic clinoforms may suggest a Neogene prograding system at the East Shetland Platform supplying sands into the basinal parts of the same overall sequence along the Viking Graben area. This east-to southeastward prograding system (Figs. 5 and 6) has also been described by Galloway (2002), who termed it the Shetland Strandplain and inferred it to be of latest Miocene age, and sands in eastern parts are included by Rundberg and Eidvin (2005) in the Utsira Formation. Thus, the

depositional system at the East Shetland Platform seems to include a major deltaic system containing sands and lignite, which prograded towards the east and southeast and supplied sands into the marine, outer to middle Neritic Viking Graben area, where marine tidal currents probably reworked and redistributed the sands into elongated bodies and thick depocentre units of the Utsira Sand.

Lignite fragments are also present in the Utsira Sand (Utsira Formation) in the basinal areas (e.g. Norwegian Quadrant 30) to the east marginal uppermost parts of the Utsira Sand (e.g. Norwegian Quadrant 31), where lignite/coal is locally associated with fining upward log trends. Indications that sand supply to the Utsira Sand derive from Norwegian marginal areas, may be suggested by the concentration of thick stacked sands of the Utsira Sand

East unit, erosive northwest running channels (Gregersen et al., 1997) and subtle westward progradation at the easternmost basin margin. The eastern part of the basin margin was probably uplifted in Miocene and Pliocene phases (Rundberg, 1989) and consequently Miocene–Pliocene deposits have been eroded and only a few indications of westward progradation have been preserved.

The main depositional mechanism of the Utsira Sands may have been marine tidal currents as suggested by Galloway (2002) and Rundberg (1989). Channels at the margins and the Neogene progradation from west may indicate that sediments initially could have been supplied and entered the basin by various processes, such as deltaic-related distribution, erosive currents or other mechanisms, and were subsequently redistributed by marine currents/processes. The eastward dipping reflections in parts of Utsira Sand and the general eastward overlap by the upper parts may also indicate migration and an eastward component affecting the final deposition of the sands.

4. Younger Neogene units

The succession overlying the Utsira Sand is rather variable, principally comprising basinal shales and prograding clinoforms of Pliocene age, overlain by Pleistocene deposits (Figs. 10A and B). Lithologically the succession consists mainly of clays, with local minor sands (Figs. 9–12). The deposits succeeding the Utsira Sand have been divided into five seismic units, here termed the Shale Drape, the Glauconite Sand, the Base Upper Pliocene unit, the Prograding Complex and the Pleistocene unit. Samples from the basinal shales succeeding the Utsira Sand, mainly from the Shale Drape, comprises grey clay silts or silty clays and petrographic analysis suggests that most of the samples are massive although some present evidence (SEM) of a weak sedimentary lamination with preferred orientation (Chadwick et al., 2004). XRD analysis from cuttings show the samples to be typically composed of quartz (30%), undifferentiated mica (30%), kaolinite (14%), baryte, calcite, smectite, albite, and minor contents of other minerals, together with traces of drilling mud contamination (Chadwick et al., 2004).

4.1. The Shale Drape

In the southern study area, the lowermost part of the succession draping the Utsira Sand, the Shale Drape unit, is a well-defined seismic unit. It has the form of a tabular, basin-restricted unit, some 50–150 m thick, lying immediately above the Utsira Sand and overlapping it to the east and west (Fig. 9). The Shale Drape pinches out against the regional onlap surface and is bounded at the top by a regional downlap surface, beneath the Prograding Complex unit. Drill cuttings from the Sleipner area indicate a grey mudstone with a high content of clay minerals, supported by log analysis that indicates a high shale volume (Chadwick et al., 2004). This unit appears to be of

Late Pliocene age in the southern part of the Viking Graben area (Eidvin et al., 1999; Head et al., 2004). A middle to outer Neritic environment (ca. up to 200 m water depth) for the unit has been proposed (Eidvin et al., 1999) in the southern study area.

The Shale Drape unit can be mapped over much of the southern depocentre of the Utsira Sand. South of the Sleipner area it is less clearly identifiable, as the Utsira Sand itself shales out rendering the lithological contrast less clear (Fig. 8). Over much of the northern Utsira depocentre the unit has a dominantly draping geometry, with an upper bounding regional downlap surface, but towards the north this upper boundary locally cannot be identified as a downlap surface (Fig. 10B). The basinal parts of it were probably subject to marine condensation prior to the progradation of the succeeding Prograding Complex. Condensed deposits have been described from the lowermost Upper Pliocene in the northern Viking Graben area (Tongban et al., 1999), as well as a regional late Early Pliocene to early Late Pliocene hiatus (Tongban et al., 1999; Eidvin et al., 1999).

In the Sleipner field area the stratigraphy of the Shale Drape is complicated by the presence of a thin sand-wedge unit (Zweigel et al., 2000) (not included in figures here). It is separated from the main Utsira Sand unit by a shale about 5 m thick and has a wedge-like form, thickening eastwards and pinching out to the west in the central part of the Sleipner field area. The greatest thickness proved by wells around Sleipner is about 25 m, but it thickens locally eastwards.

4.2. Glauconite Sand and base Upper Pliocene unit

In the northern study area (Norwegian blocks 34/2–8), a Glauconite Sand interval and a succeeding basal Upper Pliocene unit (Fig. 3) have been described by Eidvin and Rundberg (2001). These units partly interfingers with or replace the Shale Drape unit towards the north and the Prograding Complex unit succeeds both the Shale Drape and the basal Upper Pliocene unit (Figs. 3 and 10A). Silty–sandy gravity flow deposits and ice-rafted debris have been found in cores (Eidvin and Rundberg, 2001) in the basal Upper Pliocene unit.

4.3. The Prograding Complex

The Prograding Complex is characterised by inclined reflections, indicating progradation from both east and west (Figs. 4 and 8), progradation towards the north is also seen (Figs. 8 and 10B). The basal bottom-set beds of the Prograding Complex downlap on to the Shale Drape unit (Fig. 4), and its upper parts are truncated mainly towards east by the erosive Pleistocene unit (Figs. 11 and 12). The variations in thickness and dip of the internal clinoforms are limited and indicate mainly balanced rates between sediment supply and creation of accommodation space, though internal erosional surfaces, interpreted as sequence

boundaries (Gregersen et al., 1997), indicate breaks in the overall progradation. The main part of it has also been termed the Upper Pliocene Prograding Complex by Eidvin and Rundberg (2001) and is dated (e.g. Tongban et al., 1999; Eidvin et al., 1999; Eidvin and Rundberg, 2001; well completion) as mainly Late Pliocene and Early Pleistocene age.

Cuttings descriptions from NPD papers and well logs show mainly clay lithologies, but minor sands do occur locally. High amplitude reflections, which onlap the toe-sets of the prograding clinofolds, may be interpreted as more sandy beds (bottom-set sands), perhaps deposited as massflow processes/turbidites (Fig. 10B). Such high amplitude reflections correlate with sandy intervals in wells north of the Utsira Sand and these are termed the bottom-set sands (Figs. 10A and B). Six such sand bodies have been mapped and they are up to 60 m thick, irregular in form and typically 10–20 km across (Fig. 13). The stratigraphical position of the sands at the slope-toes or bottom-sets of the prograding clinofolds suggests that they probably represent mass-flow deposits.

The major clinofolds of the Prograding Complex generally dip away from platforms or shallow areas at the east and west marginal parts of the northern North Sea Basin area towards the central deeper basinal parts, but they also occur filling in the basin in the northern part and south of the study area by progradation towards the north (Figs. 8 and 10B). The prograding nature of the Prograding Complex attests to an ensuing period of high sediment supply, with steady and possibly falling relative sea level, with basinward dip in seismic trajectory in the late

sequences. A middle Neritic environment (ca. 30–100 m water depth) has been proposed (Eidvin et al., 1999) in the southern study area (Well N15/12-3) for this unit. The present height of the clinofolds ranges mainly between 100 and 300 m (Figs. 4, 7B and 8) (not compensated for compaction/subsidence). Huge amounts of upper Pliocene sediments were deposited by major possibly deltaic systems, first mainly from the east and west or southwest (Fig. 4), presumably due to relative uplift of southern Scandinavia and Scotland/Shetland, and later more dominantly from southern directions (Fig. 8) (Gregersen et al., 1997). Pleistocene strata beneath the Norwegian Channel, parallel to the Norwegian coast, may have truncated some upper parts of the clinofolds to the East (in Norwegian Quadrants 31 and 35) of the basin margin (east part of Fig. 12B), indicating late Cenozoic uplift and deep glacial erosion. The main cause for progradation has been related to glaciation of the Norwegian shelf further north (Rokoengen et al., 1995; Henriksen and Vorren, 1996). Neogene tectonic uplift of Norway and its adjacent shelf areas, with uplift calculated to more than 400 m (Hansen, 1996; Japsen, 1998), must also be considered as an important factor. On a regional scale, this uplift of the southern Norwegian margin probably forced the Miocene to Pliocene depositional systems further to the south changing the direction of progradation gradually clockwise from southwest, then mainly towards the west and finally in Pliocene times towards the northwest, both in the northern North Sea (Gregersen et al., 1997) and in the south and central North Sea (Sørensen et al., 1997; Clausen et al., 1999).

Substantial eustatic sea level fall associated with glaciation in NW Europe followed and resulted in the formation of the basal unconformity to the Pleistocene unit recorded in wells and indicated by truncation on seismic sections (e.g. Figs. 9–12), including the Norwegian Channel itself (Fig. 11). A basal Pleistocene hiatus is described in the northern Viking Graben area (e.g. Tongban et al., 1999; Martinsen et al., 1999).

4.4. The Pleistocene unit

This unit, of mainly Pleistocene age, is here defined as the uppermost seismic unit between a basal regional Pleistocene (and locally Upper Pliocene) unconformity above the Prograding Complex and the sea floor (Figs. 3 and 4). The unit cannot be mapped everywhere with confidence; where it is shallow the seabed multiple obscures interpretation. In many places there are troughs or valleys (up to ca. 50–100 m deep and wide) in the unit (Figs. 9 and 12A, B). Beneath the Norwegian Channel the unit is almost concordantly stratified and onlaps dipping parts of the basal unconformity, while shallower strata prograde towards the east and downlap onto the lower concordant part (Fig. 12B). It has been suggested that the cause of the basal unconformity in the Norwegian Channel may be a grounding ice sheet, and that the northern North Sea was

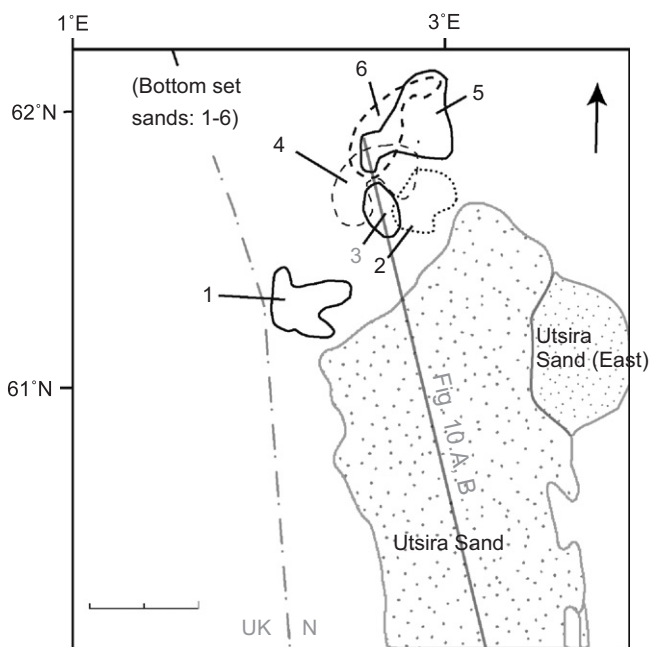


Fig. 13. Map from the northern Viking Graben area with location of the Utsira Sand and the approximately depositional areas of six of the early bottom-set sands of the Prograding Complex (Fig. 10B). The progradation of the unit is reflected in the northward displacement of the sands—see also the Fig. 10 profile through the area.

glaciated ca 850 ka. (Sejrup et al., 1991) or even 1200 ka. (Sejrup et al., 1995). Core information from southwest of the investigated area and also in the central part of the Norwegian Channel, prove glacio-marine clays, deposited under shallow-marine, boreal-arctic to arctic conditions and glacial tills (Sejrup et al., 1991). An inner Neritic environment (ca. 0–30 m water) has been suggested (Eidvin et al., 1999) in the Pleistocene unit of the southern study area (Well N15/12-3). Scattered high amplitude seismic anomalies may indicate locally sandy lithologies. Deposition of the Pleistocene unit has taken place in a variety of environments ranging from glacial (Sejrup et al., 1991) to fluvial.

5. Conclusion

The Utsira Sand and adjacent Neogene stratigraphic units in the Viking Graben area have been mapped. The Utsira Sand extends along the Viking Graben area near the UK/Norwegian median line, and covers an area more than 450 km long north–south (between 58°N and 61°40'N) and 75–130 km wide east–west area (between 1°E and 3°50'E). The Utsira Sand is distributed in two main depositional areas, with thicknesses up to nearly 300 m in the southern and 200 m in the northern area. To the northeast of the main Utsira Sand, a minor Utsira unit (Utsira Sand East unit) also reaches ca. 200 m in thickness. The Utsira Sand seems to have been deposited in a period ranging from late Middle Miocene to mid Pliocene, a period of at least ca. 8–9 my. Given the average sand thickness of about 100–150 m, the average sedimentation rate was about 1–2 cm per thousand years, up to 2–4 cm per thousand years in the depocentre.

The Utsira Sand was supplied both from the East Shetland Platform area and from the southwest Norwegian margin. At the East Shetland Platform Hutton Sand accumulated and a major system containing sands and with lignite prograde eastward, and supplied sands into the shallow marine, outer to middle Neritic Viking Graben area, where marine currents probably reworked and redistributed the sands into elongated bodies of the thick Utsira Sand units. Northwest trending marginal channels, a thick local depocentre (Utsira Sand East unit), subtle westward progradation and lignite indicate sand supply also from the Norwegian margin, possibly initially through deltaic distribution and other processes to be later redistributed by marine tidal currents in the basin.

Locally the overlying clayey deposits of the Pliocene Shale Drape and Prograding Complex contain minor sands. The 50–150 m thick Shale Drape succeeds and drapes the Utsira Sand. The Prograding Complex unit progrades from the basin margins into the basin from east and west, and also in the basin towards the north. Towards the north the Shale Drape is replaced by a Glauconite Sand and a Basal Upper Pliocene unit. A regional unconformity truncates the Prograding Complex and is succeeded by the Pleistocene unit with incised valleys. The mainly clayey

Plio–Pleistocene deposits reach thickness locally of more than 800 m, but thin towards the basin margins, partly due to erosion related to glacial influence.

Acknowledgments

We acknowledge funding of the work by the SACS Consortium (Statoil, BP, ExxonMobil, Norsk Hydro, Saga, TotalFinaElf, Vattenfall, GEUS, BGS, SINTEF, IFP, TNO, BRGM) and by the European Union (Thermie programme). Statoil is thanked for providing seismic data, TGS-NOPEC and partners is thanked for allowing reproduction of seismic data, and Statoil and BP for providing well-log data. We acknowledge the good cooperation on the regional geological interpretation in the SACS project with Gary Kirby, Andy Chadwick and Sam Holloway (BGS) and the review of the paper by Gary Kirby. We acknowledge the constructive comments from the referees. This paper is published with permission of Statoil (SACS Steering Committee) and the Geological Survey of Denmark and Greenland (GEUS).

References

- Arts, R., Brevik, I., Eiken, O., Sollie, R., Causse, E., Van Der Meer, B., 2000. Geophysical methods for monitoring marine aquifer CO₂ storage—Sleipner experiences. In: Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies (GHGT-5). CSIRO Publishing, Cairns, Australia.
- Arts, R., Eiken, O., Chadwick, A., Zweigel, P., Van Der Meer, B., Zinszner, B., 2004. Monitoring of CO₂ injected at Sleipner using time-lapse seismic data. *Energy* 29, 1383–1392.
- Baklid, A., Korbøl, R., Owren, G., 1996. Sleipner Vest CO₂ disposal, CO₂ injection into a shallow underground aquifer. In: Paper Presented on the 1996 SPE Annual Technical Conference and Exhibition, Denver, Colorado, USA, SPE Paper 36600, pp. 1–9.
- Buchardt, B., 1978. Oxygen isotope palaeotemperatures from the tertiary period in the North Sea area. *Nature* 275, 121–123.
- Chadwick, R.A., Holloway, S., Kirby, G.A., Gregersen, U., Johannessen, P.N., 2000. The Utsira Sand, Central North Sea—an assessment of its potential for regional CO₂ disposal. In: Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies (GHGT-5). CSIRO Publishing, Cairns, Australia, pp. 349–354.
- Chadwick, R.A., Zweigel, P., Gregersen, U., Kirby, G.A., Holloway, S., Johannessen, P.N., 2004. Geological reservoir characterization of a CO₂ storage site: the Utsira Sand, Sleipner, northern North Sea. *Energy* 29, 1371–1381.
- Clausen, O.R., Gregersen, U., Michelsen, O., Sørensen, J.C., 1999. Factors controlling the Cenozoic sequence development in the eastern parts of the North Sea. *Journal of the Geological Society, London* 156 (4), 809–816.
- Deegan, C.E., Scull, B.J., 1977. A standard lithostratigraphic nomenclature for the central and northern North Sea. Institute of Geological Sciences Report 77/25, NPD-Bulletin 1, 35pp.
- Eidvin, T., Rundberg, Y., 1999. A new chronology for the “Utsira Formation” in the northern North Sea (Snorre and Visund Fields). Norsk Geologisk Forenings Vintermøte, Stavanger, January 1999, Abstract Volume 43.
- Eidvin, T., Rundberg, Y., 2001. Late Cainozoic stratigraphy of the Tampen area (Snorre and Visund fields) in the northern North Sea, with emphasis on the chronology of early Neogene sands. *Norsk Geologisk Tidsskrift* 81, 119–160.

- Eidvin, T., Riis, F., Rundberg, Y., 1999. Upper Cainozoic stratigraphy in the central North Sea (Ekofisk and Sleipner fields). *Norsk Geologisk Tidsskrift* 79, 97–128.
- Eidvin, T., Jansen, E., Rundberg, Y., Brekke, H., Grogan, P., 2000. The upper Cainozoic of the Norwegian continental shelf correlated with the deep sea record of the Norwegian Sea and the North Atlantic. *Marine and Petroleum Geology* 17, 579–600.
- Eiken, O., Brevik, I., Arts, R., Lindeberg, E., Fagervik, K., 2000. Seismic monitoring of CO₂ injected into a marine aquifer. In: SEG Calgary 2000 International Conference and 70th Annual Meeting, Calgary.
- Fyfe, J.A., Gregersen, U., Jordt, H., Rundberg, Y., Eidvin, T., Evans, D., Stewart, D., Hovland, M., Andresen, P., 2003. Oligocene to Holocene. In: Evans, D., Graham, C., Armour, A., Bathurst, P. (Eds. and coordinators), *The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea*. The Geological Society of London, London, pp. 279–287.
- Gale, J., Christensen, N.P., Cutler, A., Torp, T.A., 2001. Demonstrating the potential for geological storage of CO₂: the Sleipner and GESTCO projects. *Environmental Geosciences* 8 (3), 160–165.
- Galloway, W.E., 2002. Paleogeographic setting and depositional architecture of a sand-dominated shelf depositional system, Miocene Utsira Formation, North Sea Basin. *Journal of Sedimentary Research* 72, 476–490.
- Ghazi, S.A., 1992. Cenozoic uplift in the Stord Basin area and its consequences for exploration. *Norsk Geologisk Tidsskrift* 72, 285–290.
- Gregersen, U., 1998. Upper Cenozoic channels and fans on 3D seismic data in the northern Norwegian North Sea. *Petroleum Geoscience* 4, 67–80.
- Gregersen, U., Michelsen, O., Sørensen, J.C., 1997. Stratigraphy and facies distribution of the Utsira Formation and the Pliocene sequences in the northern North Sea. *Marine and Petroleum geology* 14, 893–914.
- Gregersen, U., Johannessen, P.N., Chadwick, R.A., Holloway, S., Kirby, G.A., 2000. Regional study of the Neogene deposits in the southern Viking Graben area—a site for potential CO₂ storage. In: 62nd EAGE Meeting, Paper B-19, Glasgow.
- Hansen, S., 1996. Quantification of net uplift and erosion on the Norwegian Shelf south of 66N from sonic transit times of shale. *Norsk Geologisk Tidsskrift* 76, 245–252.
- Haq, B.U., Hardenbol, J., Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: Wilgus, C.K., Posamentier, H., Hastings, B.S., Van Wagoner, J., Roos, C.A., Kendall, C.G.St.C. (Eds.), *Sea-Level Changes: An Integrated Approach*, vol. 42. SEPM Special Publication, Tulsa, Oklahoma, pp. 71–108.
- Head, M.J., Riding, J.B., Eidvin, T., Chadwick, R.A., 2004. Palynological and foraminiferal biostratigraphy of (Upper Pliocene) Nordland Group mudstones at Sleipner, northern North Sea. *Marine and Petroleum Geology* 21, 277–297.
- Heggland, R., 1997. Detection of gas migration from a deep source by use of exploration 3D seismic data. *Marine Geology* 137, 41–47.
- Henriksen, S., Vorren, T.O., 1996. Late Cenozoic sedimentation and uplift history on the mid-Norwegian continental shelf. *Global and Planetary Change* 12, 171–199.
- Holloway, S., Chadwick, A., Lindeberg, E., Czernichowski-Lauriol, I., Arts, R. (Eds.), 2003. Best Practice Manual from SACS—Saline Aquifer CO₂ Storage Project (online available at <http://www.co2store.org>), IEA Greenhouse Gas R&D Programme, Report PH4/21, 53pp.
- Isaksen, D., Tonstad, K., 1989. A revised Cretaceous and Tertiary lithostratigraphic nomenclature for the Norwegian North Sea, NPD Bulletin 5, Oljedirektoratet, Norway.
- Japsen, P., 1998. Regional velocity–depth anomalies, North Sea Chalk: a record of overpressure and Neogene uplift and erosion. *AAPG Bulletin* 82 (11), 2031–2074.
- Jordt, H., Faleide, J.I., Bjørlykke, K., Ibrahim, M.T., 1995. Cenozoic sequence stratigraphy of the central and northern North Sea Basin: tectonic development, sediment distribution and provenance areas. *Marine and Petroleum Geology* 12, 845–879.
- Kyrkjebø, R., Hamborg, H., Faleide, J.I., Jordt, H., Christiansson, P., 2000. Cenozoic tectonic subsidence from 2D depositional simulations of a regional transect in the northern North Sea basin. In: Nøttvedt, A. (Ed.), *Dynamics of the Norwegian Margin*: Geological Society of London, Special Publication, vol. 167, pp. 273–294.
- Martinsen, O.J., Bøen, F., Charnock, M.A., Mangerud, G., Nøttvedt, A., 1999. Cenozoic development of the Norwegian margin 60–64°N: sequences and sedimentary response to variable basin physiography and tectonic setting. In: Fleet, A.J., Boldy, S.A.R. (Eds.), *Petroleum Geology of Northwest Europe: Proceedings of the Fifth Conference*, pp. 293–304.
- Miller, K.G., Fairbanks, R.G., Mountain, G.S., 1987. Tertiary oxygen isotope synthesis, sea level history, and continental margin erosion. *Paleoceanography* 1, 1–19.
- NPD-papers. Reports with well data, the Norwegian Petroleum Directorate, Stavanger.
- Pearce, J.M., Czernichowski-Lauriol, I., Rochelle, C.A., Springer, N., Brosse, E., Sanjuan, B., Bateman, K., Lanini, S., 2000. How will reservoir and caprock react with injected CO₂ at Sleipner? Preliminary evidence from experimental investigations. In: Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies (GHGT-5). CSIRO Publishing, Cairns, Australia.
- Piasecki, S., Gregersen, U., Johannessen, P.N., 2002. Lower Pliocene dinoflagellate cysts from cored Utsira formation in the Viking Graben, northern North Sea. *Marine and Petroleum Geology* 19, 55–67.
- Riis, F., Fjeldskaar, W., 1992. On the magnitude of the late Tertiary and Quaternary erosion and its significance for the uplift of Scandinavia and Barents Sea. In: Larsen, R.M., Brekke, H., Larsen, B.T., Talleraas, E. (Eds.), *Structural and Tectonic Modelling and its Application to Petroleum Geology*. Norwegian Petroleum Society, Special Publication, vol. 1, pp. 163–185.
- Rohrman, M., Van der Beek, P., Andriessen, P., Cloetingh, S., 1995. Meso-Cenozoic morphotectonic evolution of southern Norway: Neogene domal uplift inferred from apatite fission track thermochronology. *Tectonics* 14, 704–718.
- Rokoengen, K., Rise, L., Bryn, P., Frengstad, B., Gustavsen, B., Nygaard, E., Sættem, J., 1995. Upper Cenozoic stratigraphy on the Mid-Norwegian continental shelf. *Norsk Geologisk Tidsskrift* 75, 88–104.
- Rundberg, Y., 1989. Tertiary sedimentary history and basin evolution of the Norwegian North Sea between 60N and 62N—an integrated approach, Dr. Ing. Thesis, University of Trondheim, Norway, 308pp.
- Rundberg, Y., Eidvin, T., 2005. Controls on depositional history and architecture of the Oligocene–Miocene succession, northern North Sea Basin. In: Wandas, B., et al. (Eds.), *Norwegian Petroleum Society, NPF Special Publication*, vol. 12, pp. 207–239.
- Rundberg, Y., Olausen, S., Gradstein, F., 1995. Incision of oligocene strata; evidence for northern north sea Miocene uplift and key to the formation of the Utsira Sand. *GeoNytt* I-95, 62 Abstract.
- Sejrup, H.P., Aarseth, I., Hafidason, H., 1991. The quaternary succession in the northern North Sea. *Marine Geology* 101, 103–111.
- Sejrup, H.P., Aarseth, I., Hafidason, H., Løvlie, R., Bratten, Å., Tjøstheim, G., Forsberg, C.F., Ellingsen, K.L., 1995. Quaternary of the Norwegian Channel, glaciation history and palaeoceanography. *Norsk Geologisk Tidsskrift* 75, 65–87.
- Sørensen, J.C., Gregersen, U., Breiner, M., Michelsen, O., 1997. High-frequency sequences of Upper Cenozoic deposits in the central and southeastern North Sea areas. *Marine Petroleum Geology* 14 (2), 99–123.
- Tongban, H., Courme, B., Jacquin, T., Dunay, R., 1999. Biostratigraphic calibration of Neogene depositional sequences of the North Viking Graben. In: Martinsen, I.J., Dreyer, T. (Eds.), *Sedimentary Environments Offshore Norway; Palaeozoic to Recent*. Norwegian Petroleum Society/NPF, pp. 45–48 (Extended abstracts).
- Wilkinson, I.P., 1999. Biostratigraphical and palaeo-ecological application of calcareous microfaunas from the Utsira Formation in Norwegian Well 15/9A-23. *British Geological Survey Technical Report, Stratigraphic Series No. WH99/124R*, BGS, Keyworth, UK.

- Zweigel, P., Hamborg, M., Arts, R., Lothe, A.E., Tommeras, A., 2000. Prediction of migration of CO₂ injected into an underground depository: reservoir geology and migration modelling in the Sleipner case (North Sea). In: Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies (GHGT-5). CSIRO Publishing, Cairns, Australia.
- Zweigel, P., Arts, R., Bidstrup, T., Chadwick, A., Eiken, O., Gregersen, U., Hamborg, M., Johannessen, P., Kirby, G., Kristensen, L., Lindeberg, E., 2001. Results and experiences from the first industrial-scale underground CO₂ sequestration case (Sleipner Field, North Sea). American Association of Petroleum Geologists, Annual Meeting, June 2001, Denver, Paper No. ID7204 in Abstract Volume (CD), 6pp.