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Research paper

Morphology, sedimentary infill and depositional environments of the Early Quaternary North Sea Basin (56°–62°N)

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A B S T R A C T

The North Sea Basin has been subsiding during the Quaternary and contains hundreds of metres of fill. Seismic surveys (170 000 km^2) provide new evidence on Early Quaternary sedimentation, from about 2.75 Ma to around the Brunhes-Matuyama boundary (0.78 Ma). We present an informal seismic stratigraphy for the Early Quaternary of the North Sea, and calculate sediment volumes for major units. Early Quaternary sediment thickness is > 1000 m in the northern basin and >700 m in the central basin (total about 40 000 km^3). Northern North Sea basin-fill comprises several clinoform units, prograding westward over 60 000 km^2. Architecture of the central basin also comprises clinoforms, building from the southeast. To the west, an acoustically layered and mounded unit (Unit Z) was deposited. Remaining accommodation space was filled with fine-grained sediments of two Central Basin units. Above these units, an Upper Regional Unconformity-equivalent (URU) records a conformable surface with flat-lying units that indicate stronger direct glacial influence than on the sediments below. On the North Sea Plateau north of 59°N, the Upper Regional Unconformity (URU) is defined by a shift from westward to eastward dipping seismic reflectors, recording a major change in sedimentation, with the Shetland Platform becoming a significant source. A model of Early Quaternary sediment delivery to the North Sea shows sources from the Scandinavian ice sheet and major European rivers. Clinoforms prograding west in the northern North Sea Basin, representing glacigenic debris flows, indicate an ice sheet on the western Scandinavian margin. In the central basin, sediments are generally fine-grained, suggesting a distal fluvial or glacifluvial origin from European rivers. Ploughmarks also demonstrate that icebergs, derived from an ice sheet to the north, drifted into the central North Sea Basin. By contrast, sediments and glacial landforms above the URU provide evidence for the later presence of a grounded ice sheet.

1. Introduction

The sediments of the North Sea contain evidence that is crucial to understanding the growth and decay of the Scandinavian and British ice sheets throughout the Quaternary (e.g. Ehlers, 1990). The location of the North Sea between Norway, the UK and mainland Europe means that its depositional history records the changing pattern of sediment delivery from the surrounding land masses and ice sheets (e.g. Sejrup et al., 1987; Bradwell et al., 2008; Graham et al., 2011). The Late Quaternary sediments and landforms of the North Sea, especially those produced during the last or Weichselian glacial cycle, have been investigated by many previous workers (e.g. Cameron et al., 1987; Bradwell et al., 2008; Graham et al., 2011). The presence of major infilled subglacial channel systems, known as tunnel valleys (Ó Cofaigh, 1996), is also a particular characteristic of the upper part of the Quaternary record in the North Sea (e.g. Wingfield, 1990; Huuse et al., 2001; Praeg, 2003; Lonergan et al., 2006; Kristensen et al., 2007; Stewart and Lonergan, 2011), and indeed of the southern margins of the ice sheets that have covered much of Europe intermittently over the past three million years or so (e.g. Piotrowski, 1997; Huuse and Lykke-Andersen, 2000; Passchier et al., 2010). However, the morphology of the North Sea and the nature of the sediments that infilled it earlier in the Quaternary, particularly those found below a major upper regional unconformity (URU), remain less comprehensively described and interpreted (Rise et al., 1984; Johnson et al., 1993; Gatliff et al., 1994; Rasmussen et al., 2005; Lee et al., 2010).

This study presents new evidence on the pattern and history of sediment delivery to the North Sea during the Early Quaternary, an

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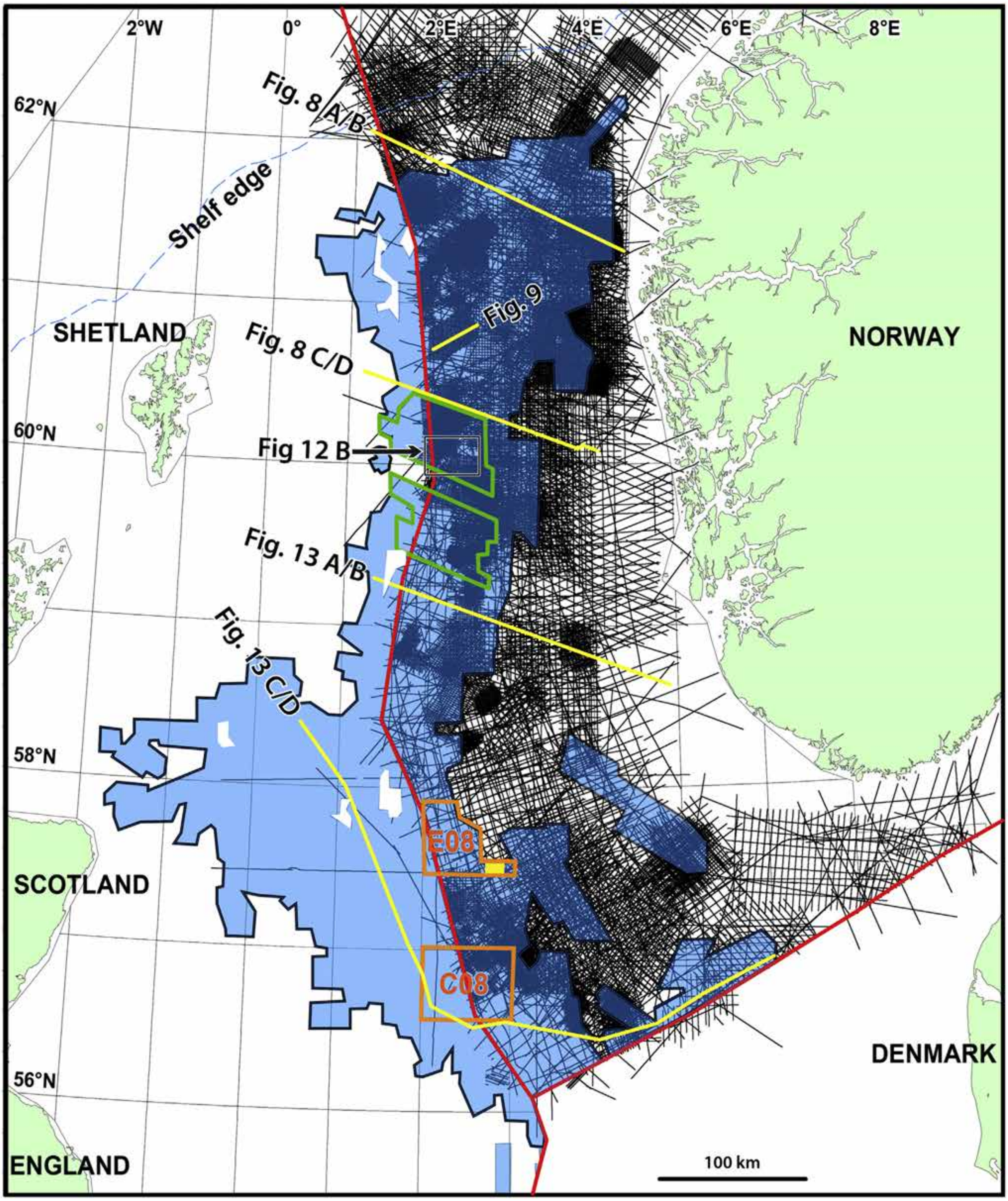


Figure 1. Map of the North Sea showing the coverage of 3D (blue shading) and 2D (black lines) seismic data used in this study. Red lines are dividing lines between national sectors of the North Sea. Seismic lines in Figures 8, 9 and 13 are located. 3D seismic cubes C08 and E08, used in Figure 17, are marked in orange. Yellow rectangle locates Figure 17. Green polygons show 3D-cubes used for mapping the Pleistocene delta. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

interval of about two million years beginning about 2.75 Ma and ending at the Brunhes-Matuyama magnetic boundary at 0.78 Ma. It utilises a large database of 3D-seismic surveys of the Norwegian and UK sectors of the central and northern North Sea basins between 56° and 62°N, together with a dense grid of 2D-seismic lines where 3D surveys are absent (Fig. 1). These data, which together cover an area of about 170 000 km^2, provide insights into basin morphology, sedimentary architecture and ice-sheet configuration in the North Sea during the early part of the Quaternary between about 2.75 Ma and the formation of an Upper Regional Unconformity (URU) whose age and formation we discuss in the text (Stoker et al., 1983; Eidvin et al., 2000). We have compiled an informal seismic stratigraphy for the Quaternary of the northern and central parts of the North Sea (Fig. 2) and calculated the volumes for the different units deposited inside the study area.

2. Study area and background

Post-Eocene uplift of the East Shetland Platform produced four sandy systems in the northern North Sea Basin (Rundberg and Eidvin, 2005): an Early-Late Oligocene set of mainly gravity-flow sands; Early Miocene mainly turbidite sands (Skade Formation); Middle Miocene shelf sands and Late Miocene-Early Pliocene shallower shelf sands (Utsira Formation). The latter were formed between approximately 12 and 4.0 million years ago, probably by high-energy marine currents in a relatively shallow and elongate seaway between the deeper Møre Basin to the north and the central and southern North Sea to the south (e.g. Galloway, 2002; Rundberg and Eidvin, 2005; Gregersen and Johannessen, 2007). The palaeogeography of the Late Miocene was, therefore, of a semi-enclosed North Sea (Rundberg and Eidvin, 2005). Except for a

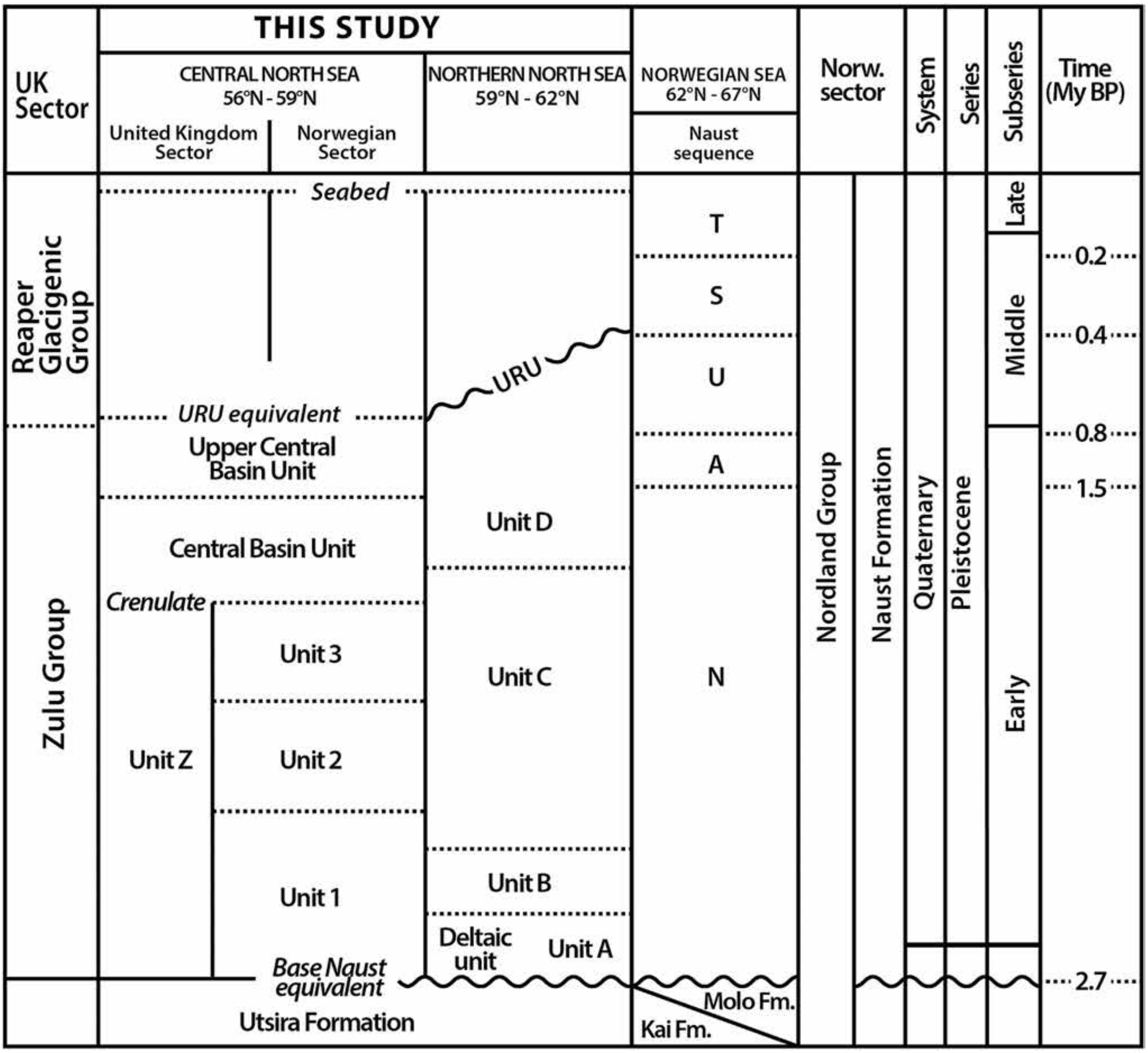


Figure 2. Stratigraphic column for the Quaternary of the central and northern North Sea basins and the adjacent Norwegian Sea. Suggested ages for the Naust N, A, U, S and T sequences are from Rise et al. (2006, 2010).

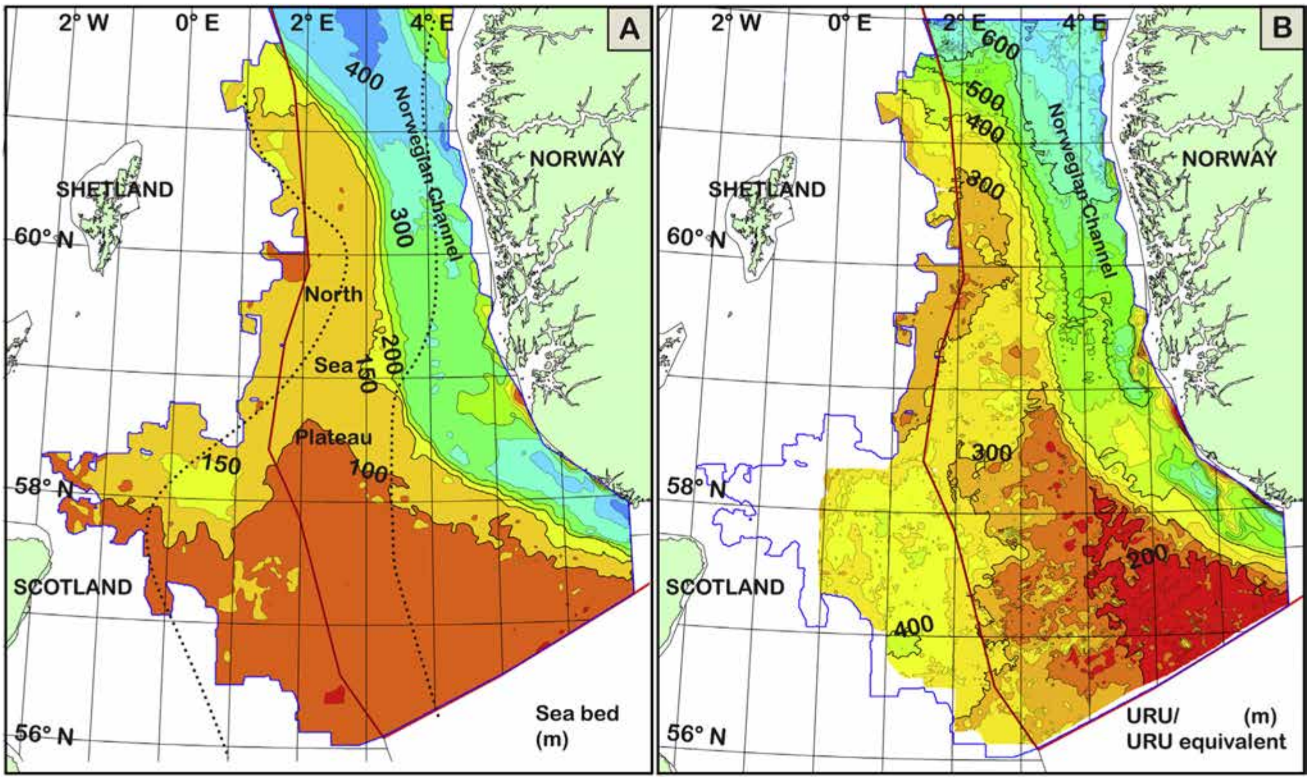


Figure 3. (A) Modern regional bathymetry of the study area based on 2D and 3D seismic data. Black stippled lines mark the outline of the central and northern North Sea basins (500 m depth contour of the Base Naust-equivalent surface shown in Fig. 4A). 50 m depth contours. (B) The URU (Upper Regional Unconformity) and URU-equivalent surface (50 m depth contours). The URU is an erosional surface in the Norwegian Channel (NC) produced by the first or most extensive ice forming the channel. The URU west of the NC in the northern North Sea is represented by a shift from sediments deposited from the east to those delivered from west. For the areas west and southwest of the NC south of c. 59°N, the URU is represented by a conformable surface separating the deeper units with a general eastwards infill pattern from overlying generally flat-lying layers with a more glacial character. Blue line marks the outline of the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

condensed Upper Pliocene unit in the southern Viking Graben (Head et al., 2004; Eidvin et al., 2013), the Utsira Formation immediately underlies the Quaternary sediments of the North Sea, which are the topic of this paper.

The North Sea has been subsiding slowly throughout the Quaternary and contains hundreds of metres of sedimentary fill along its main N–S axis (Gatliff et al., 1994; Riis, 1996). An early published thickness map of Quaternary sediments in the UK sector of the North Sea was produced by Cameron et al. (1987) and further maps for the whole of the North Sea through the Cenozoic were presented in Anell et al. (2011). Ice appears to have built up to reach the western coast of Scandinavia from about 2.75 million years ago (Jansen and Sjøholm, 1991; Eidvin et al., 2000; Ottesen et al., 2009). Indeed, irregular features on the former sea-floor of the central and southern North Sea, imaged from 3D seismic data, have been interpreted to indicate the presence of icebergs about 2 million years ago (Kuhlmann and Wong, 2008; Dowdeswell and Ottesen, 2013). The Naust Formation on the mid-Norwegian margin is of mainly glacial origin (Rise et al., 2005; Ottesen et al., 2009) (Fig. 2), and glacial inputs to the North Sea from both the Scandinavian and British ice sheets characterize Middle to Late Quaternary sediment sources (Stoker et al., 2005). According to Cameron et al. (1987) and Long et al. (1988), the Early Quaternary sediments are mainly fluvio-deltaic to marine. These sediments are overlain by interbedded glacigenic and fine-grained tidal marine deposits, related to the onset of strong glacial–interglacial cycles from the mid-Quaternary (Jansen and Sjøholm, 1991).

The North Sea was inundated by ice sheets on several occasions in the last 0.5 million years, with the earliest glaciation suggested by some workers to have occurred at 1.1 My ago forming the Norwegian Channel (Sejrup et al., 1995) (Fig. 3). This date is derived from amino acids, micropalaeontological and palaeomagnetic analyses. Diamict interpreted as subglacial till (known as the Fedje Till) lies unconformably on Oligocene rock at the base of the channel (Sejrup et al., 1995, 2000). There is also a suggestion, based on diamictic sediments identified in a 200 m long core from the Fladen area of the central North Sea, that grounded ice may have been present prior to the Bruhnes-Matuyama magnetic boundary at 0.78 Ma (Sejrup et al., 1987).

Beyond the Norwegian Channel (Fig. 3A), the sediments above an Upper Regional Unconformity (URU) (Fig. 3B) are cut by up to seven generations of tunnel valleys which are produced by subglacial channel erosion and subsequent fill (e.g. Huuse and Lykke-Andersen, 2000; Praeg, 2003; Lonergan et al., 2006; Stewart and Lonergan, 2011; Stewart et al., 2013). This, in turn, suggests that the earlier interpretation of three major Middle to Late Quaternary glacial episodes of North Sea glaciation (Elsterian, Saalian and Weichselian) may be too simple (e.g. Stewart and Lonergan, 2011; Graham et al., 2011; Stewart et al., 2013). It has been shown, nonetheless, that these three periods are linked to the maximum fluvial discharge through the English Channel, which suggests that they may also have been the periods of maximum ice extent (Toucanne et al., 2009).

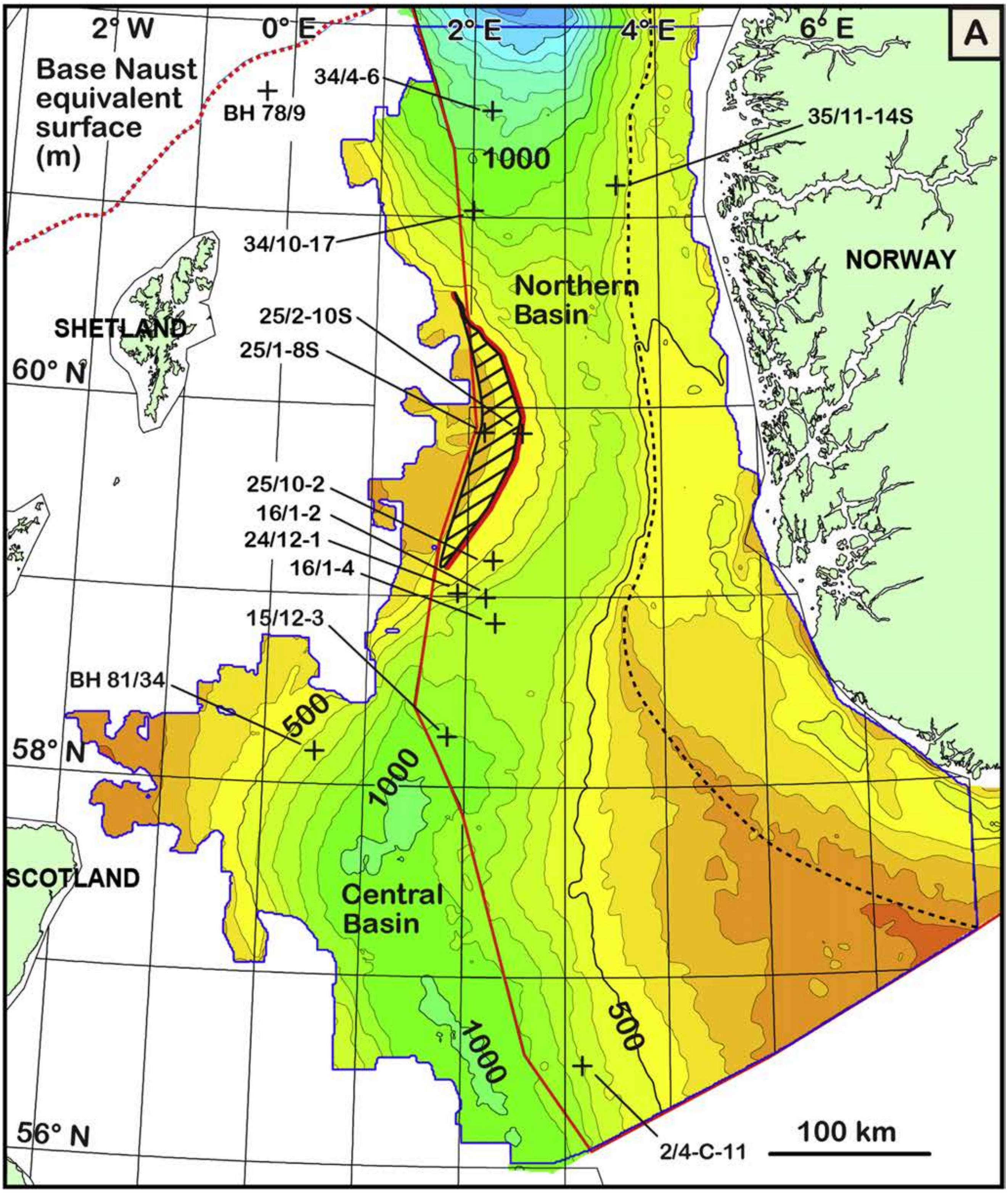


Figure 4. (A) Morphology of Base Naust-equivalent surface (m) combined with the URU/URU equivalent surface in the east (east of thin black stippled line) representing mainly the base of the Norwegian Channel. Wells used for deciding the depth to the Base Naust-equivalent surface and discussed in the text are shown. The positions of BGS boreholes BH 81/34 and BH 78/9 are indicated. A Pleistocene delta mapped along the western side of the basin is marked by black hachuring. Delta front is marked by thick red line. (B) Thickness map of the Quaternary sediments in the North Sea Basin (above the Base Naust-equivalent surface). Contours at 100 m intervals in each panel. A Pleistocene delta mapped along the western side of the basin is marked by black hachuring. Delta front is marked by thick red line. The boundary line between Norway and UK is shown in red. Red stippled line marks the present shelf edge. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

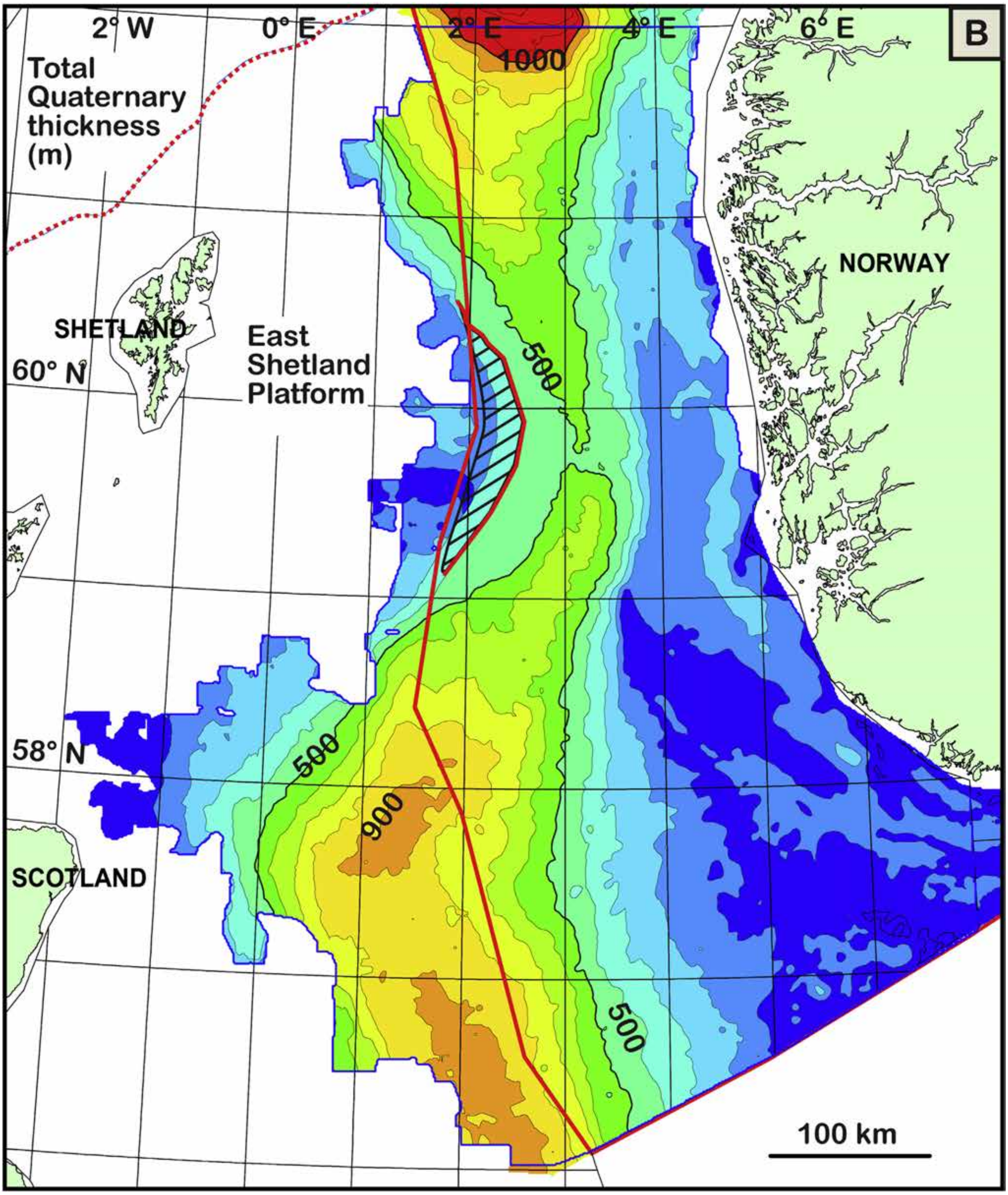


Figure 4. (*continued*).

Many studies of the glacial geology of the North Sea area have been carried out (e.g. Stoker et al., 1985a, 1985b; Cameron et al., 1987; Sejrup et al., 1987; Lee et al., 2010; Graham et al., 2011; Hjelstuen et al., 2012). For the Late Weichselian Last Glacial Maximum (LGM) in particular, Laban (1995) summarized as many as fifteen proposed ice-sheet reconstructions. Clark et al. (2010) reconstructed several LGM scenarios and the following deglaciation pattern outlining the large uncertainty of the ice sheet

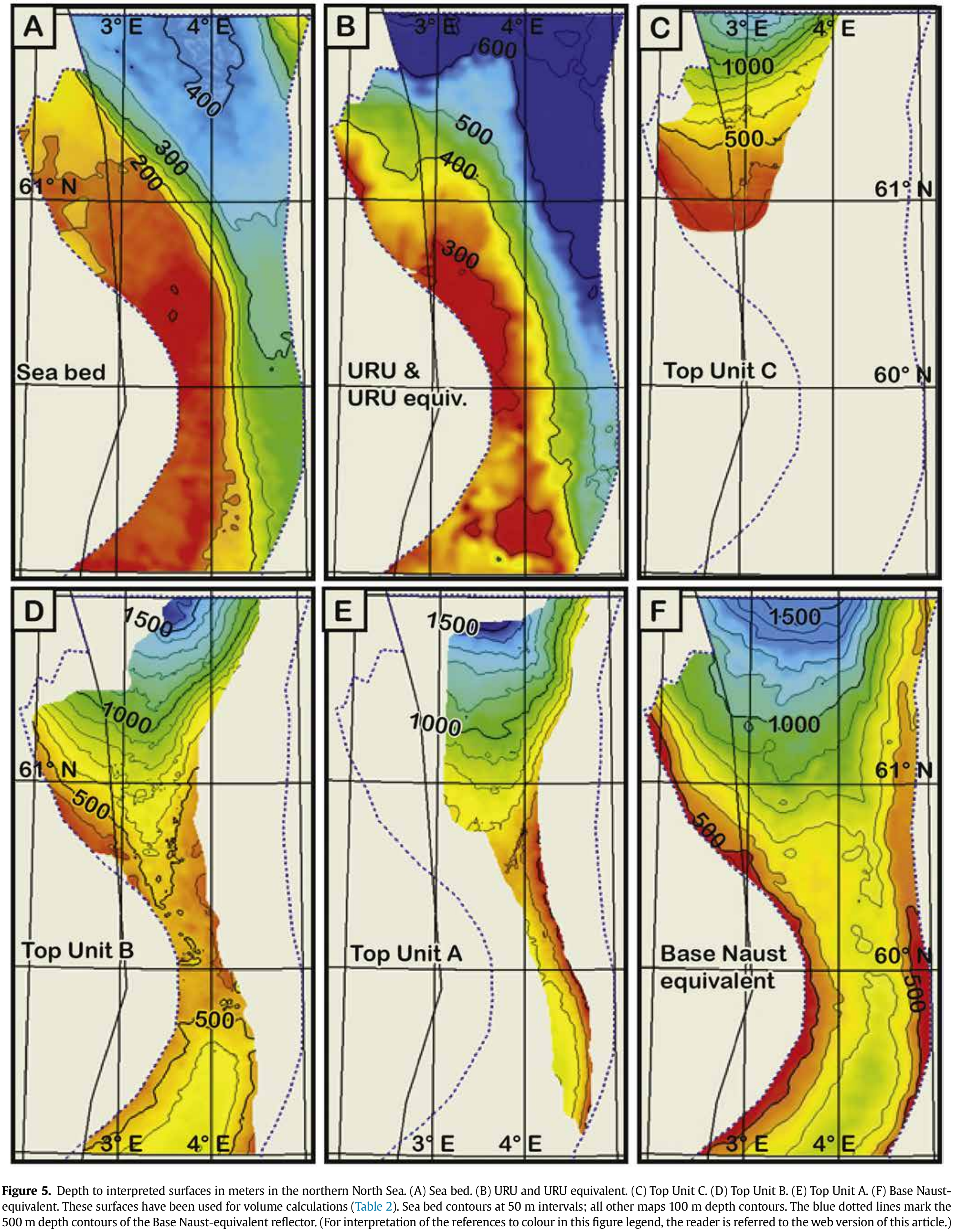


Figure 5. Depth to interpreted surfaces in meters in the northern North Sea. (A) Sea bed. (B) URU and URU equivalent. (C) Top Unit C. (D) Top Unit B. (E) Top Unit A. (F) Base Naust-equivalent. These surfaces have been used for volume calculations (Table 2). Sea bed contours at 50 m intervals; all other maps 100 m depth contours. The blue dotted lines mark the 500 m depth contours of the Base Naust-equivalent reflector. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

configurations over the North Sea Plateau. The presence of a Late Weichselian fast-flowing ice stream in the Norwegian Channel is now generally accepted (Longva and Thorsnes, 1997; Sejrup et al., 2003; Ottesen et al., 2005; Stalsberg et al., 2003; Houmark-Nielsen and Kjær, 2003; Nygård et al., 2005, 2007), but until recently less has been published about older glaciations in the North Sea. The acquisition of 3D seismic data and comprehensive sea-floor morphological observations have provided new data from this area, showing ice flow in several directions during the Late Weichselian and older glaciations (Rise et al., 2004; Graham et al., 2007, 2011; Bradwell et al., 2008).

The Quaternary basin of the North Sea is largely sediment-filled and is elongate in an approximately N–S direction (Fig. 4A). The basin is narrowest at about 60°N where the East Shetland Platform extends for 100–150 km east of the Shetland Islands. From this narrowing, the basin widens towards the north into the deep Norwegian Sea. The northern North Sea Basin is filled by more than 1000 m of sediments at the present shelf edge at 62°N (Fig. 4B). The eastern flank of the basin is cut by the glacially eroded Norwegian Channel (Sejrup et al., 2003). The central North Sea Basin is much wider than the northern; about 200 km at 57°N. The basin floor is relatively flat between 56° and 58°N, with a fill of about 900 m of Quaternary sediments (Fig. 4B).

Using the regional 3D and 2D seismic database described below, covering both the British and Norwegian sectors of the North Sea (Fig. 1), it is now possible to investigate the development of the North Sea Basin during the last 3 million years or so; here we focus on the less well-known early part of the Quaternary below a major regional unconformity in the North Sea record.

3. Methods

3.1. Seismic data

Petroleum Geo-Services (PGS) have compiled a mega-survey of a large number of individual 3D seismic surveys covering about 40 000 km^2 of the Norwegian North Sea and 50 000 km^2 of the British North Sea (Fig. 1). In addition, some individual 3D cubes from the Norwegian North Sea were utilised in this study, giving a total 3D data coverage of about 110 000 km^2. These cubes have a vertical sampling interval of 4 ms, giving a vertical resolution of 10–20 m. The seismic bin size of the cubes in the PGS MegaSurvey is 25 by 25 m. The data quality can vary between the individual cubes within the MegaSurvey dependent on acquisition parameters and the subsequent processing.

We also use a reflection-seismic database consisting of conventional 2D seismic records in the Norwegian North Sea (Fig. 1). The exploration 2D seismic lines have a relatively low vertical resolution, but are well suited for studying the regional development of the upper part of the North Sea stratigraphic record. We have selected some of the strongest reflectors, often clinoform in shape, mapped their distribution across the North Sea, and given each an identification number or letter. Due to the large area, it has not been possible to map all the units across the whole study area.

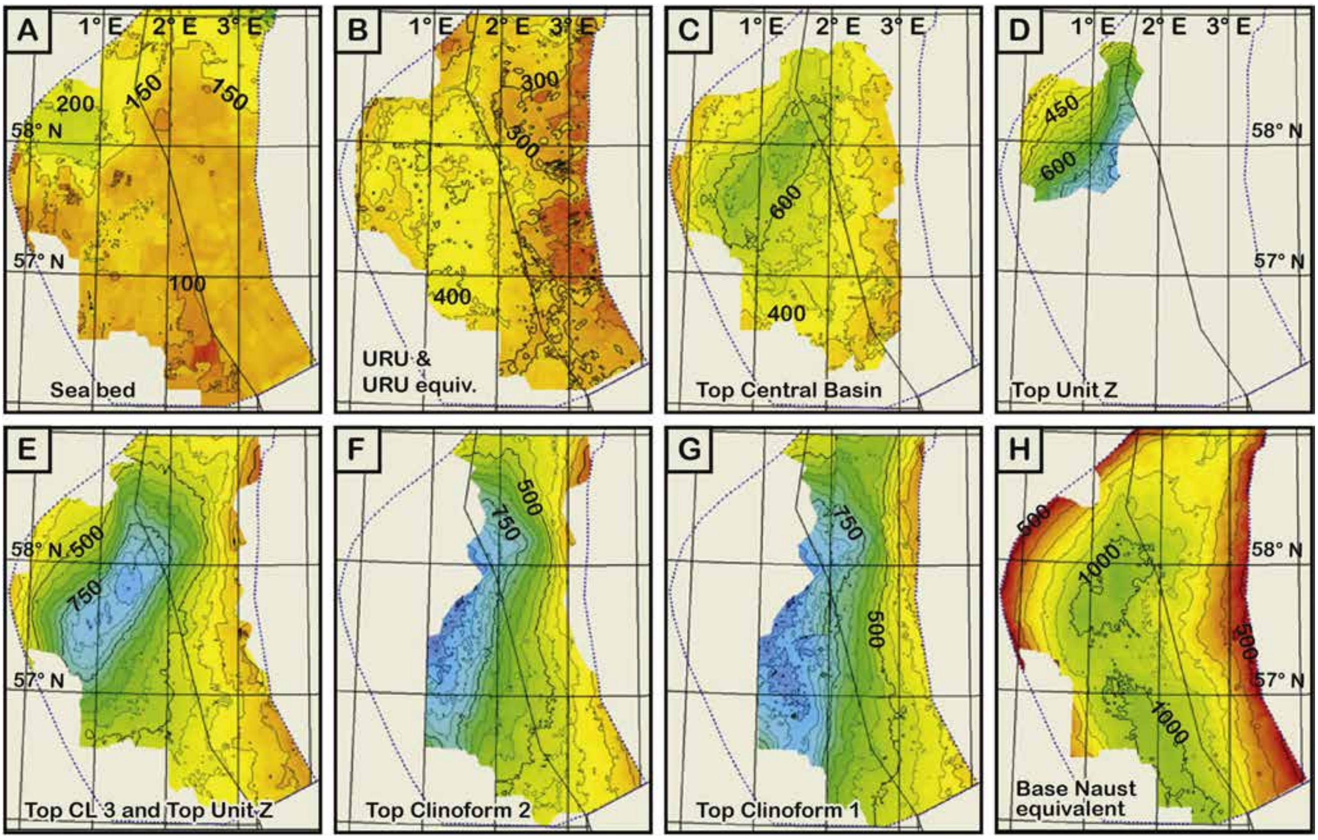


Figure 6. Depth to interpreted surfaces (m) in the central North Sea. (A) Sea bed. (B) URU and URU-equivalent. (C) Top Central Basin. (D) Top Unit Z. (E) Top Clinoform 3 combined with Top Unit Z. (F) Top Clinoform 2. (G) Top Clinoform 1. (H) Base-Naust equivalent. These surfaces have been used for generating the thickness maps and the volume calculations (Figs. 11B, 14 and Table 3). The blue dotted lines mark the 500 m contours of the Base Naust-equivalent reflector. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

We have therefore separated the North Sea into northern and central parts (Fig. 4A). The interpreted depth surfaces for the two areas are shown in Figures 5 and 6 and these surfaces form the basis for our volume calculations. For depth conversion of the time surfaces, a simple velocity model has been used based on gridded data from velocity measurements in exploration wells in the North Sea (Fig. 7). Most of the velocities are in the range of 1700–1900 m/s.

For the identification of buried glacial landforms, we have used horizontal time slices or seismic amplitude maps. Seismic amplitude maps show the variation in amplitudes along a seismic horizon or in a specific 3D seismic volume. Interpreted seismic horizons in a 3D cube can be used as a basis for the generation of attribute maps along the horizon or from a volume above, below or around the surface. We have used amplitude maps to reveal the depositional environment of the well-developed debris-flow deposits in the northern North Sea, and also to investigate some glacial erosional surfaces. The use of horizontal time slices is a fast technique that allows us to scan through large data volumes, involving stepping downwards in a 3D cube every 2 or 4 ms, depending on the processing of individual data cubes (Dowdeswell and Ottesen, 2013). The visualisation of glacial features is often excellent in the time slices and assists in interpreting the depositional environments.

3.2. Biostratigraphy and dating of the Base Naust-equivalent surface

Eidvin et al. (1999, 2013) and Eidvin and Rundberg (2007) have carried out extensive studies on the Late Cenozoic litho-, bio- and seismostratigraphy of the North Sea Basin generating an improved chronology of the post-Eocene sediment package of the North Sea. They investigated a series of exploration wells with emphasis on the Upper part of the Hordaland Group (Oligocene and Early Miocene sediments) and the Lower part of the Nordland Group (Middle and Late Miocene and Early Pliocene sediments) including the Utsira Formation. The lower part of the Pleistocene was also studied in most wells (Fig. 4A). The results of these investigations have formed the basis for our seismic interpretation of the Base Naust-equivalent surface in the North Sea. Generally, our seismic interpretation of the Base Naust-equivalent surface is in agreement with the wells analysed by Eidvin and co-workers. Eidvin and Rundberg (2001, 2007) and Eidvin et al. (2013) have placed the Base Naust-equivalent surface at the following depths in the wells shown in Figure 4A: 1210 m (34/4-6), 740 m (35/11-14S), 890 m (34/10-17), 475 m (25/2-10S), 370 m (25/1-8S), 510 m (25/10-2), 495 m (24/12-1), 740 m (16/1-2), 770 m (16/1-4), 900 m (15/12-3) and 980 m (2/4-C-11).

The Utsira Formation covers large areas of the northern North Sea Basin and parts of the central North Sea Basin down to 58°N and is a well-developed sand sheet unit up to 300 m thick (Rundberg and Eidvin, 2005; Eidvin et al., 2013). It is composed mainly of well-sorted sands and is easily identified on geophysical logs. The Naust Formation equivalent is located above the Utsira Formation (Fig. 2). Eidvin and co-workers have reported a regional hiatus above the Utsira Formation in the northern North Sea Basin. This hiatus spans a large part of the Pliocene period (c. 4.5 Ma–c. 2.7 Ma). At c. 2.7 Ma, infill by the thick lower Naust-equivalent sequence started in the northern North Sea Basin (Eidvin et al., 2013). Infilling probably began at the same time as a pronounced increase in supply of ice-rafted debris (IRD) to the Norwegian Sea (Jansen and Sjøholm, 1991; Fronval and Jansen, 1996). The infill appears to represent a new sedimentation regime, with glaciers from the east entering the edge of the basin and providing a sediment source. Eidvin and Rundberg (2001) and Ottesen et al. (2009) have documented IRD in the lowermost part of the Naust Formation equivalent, which supports this interpretation. According to Eidvin et al. (2013), the hiatus might have been caused by erosive debris flows, which probably eroded the Pliocene and in some areas also some of the Miocene sediments.

Eidvin et al. (2013) suggested that there was more or less continuous sedimentation through the Pliocene and the early part of the Pleistocene in the central North Sea Basin, south of 59°N. In this area, the Lower part of the Pleistocene is fine-grained and contains little IRD. This implies a different depositional environment compared to the northern North Sea Basin. In the transition zone between the northern and southern basins, at around 59°N, Head et al. (2004) have documented that the Late Pliocene succession is very condensed.

Dalland et al. (1988) introduced the term 'Naust Formation' for the Upper Pliocene and Pleistocene in the Norwegian Sea. Eidvin et al. (2013) suggested that the use of the term should be extended into the North Sea and that well 15/12-3 from 900 m to 200 m depth should be used as a new well-reference section. In well 2/4-C-11, in the southern part of the central North Sea basin (Fig. 4A), there is an apparent discrepancy between our present work and that by Eidvin and co-workers. Eidvin et al. (1999, 2013) have interpreted the Base Naust-equivalent at the same level as the base Upper Pliocene (c. 980 m depth). According to Eidvin et al. (2013), it is only in the southern part of the Norwegian sector of the central North Sea that the Upper Pliocene is not eroded. Consequently, the Base Naust-equivalent is older in this area than north of c. 59°N. Our investigations have recorded a seismic reflection at about 700 m in well 2/4-C-11; that is about 280 m above base Upper Pliocene. We suggest that the sedimentological change which produced this reflection probably took place when the hiatus was formed north of 59°N. As result of our investigations, Eidvin and co-workers (T. Eidvin, personal communication) will

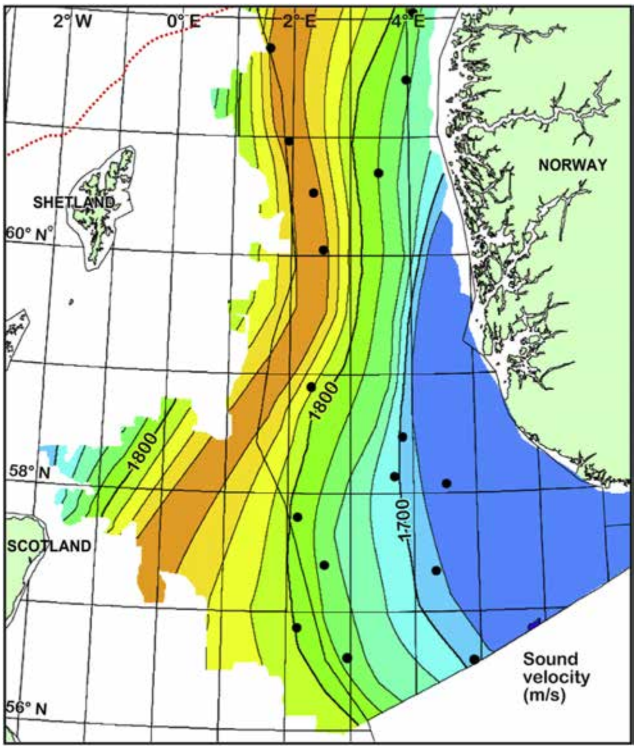


Figure 7. Map of average sound velocities (m/s) in Naust-equivalent sediments used for depth conversion, based on measurements in exploration wells (wells used shown as black dots).

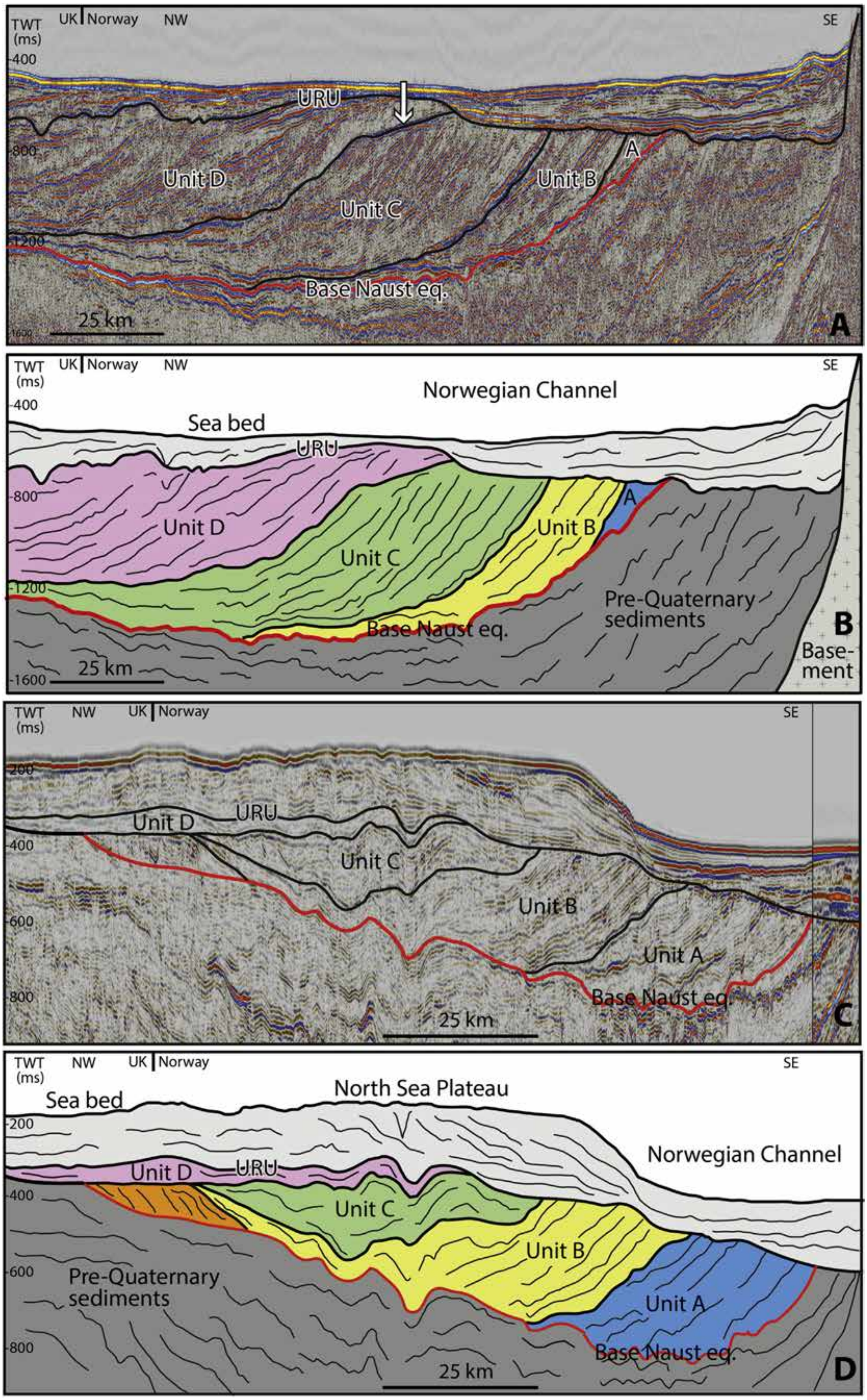


Figure 8. Seismic profiles of the northern North Sea Basin (located in Fig. 1). (A) Seismic profile NVGTI-92-108. The position of a palaeo-shelf is indicated by the white arrow. (B) Geoprofile of line shown in A. (C) Seismic profile NSR06-11168. (D) Geoprofile of line shown in C. Deltaic unit shown in orange colour. V-shaped feature marks tunnel valley. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

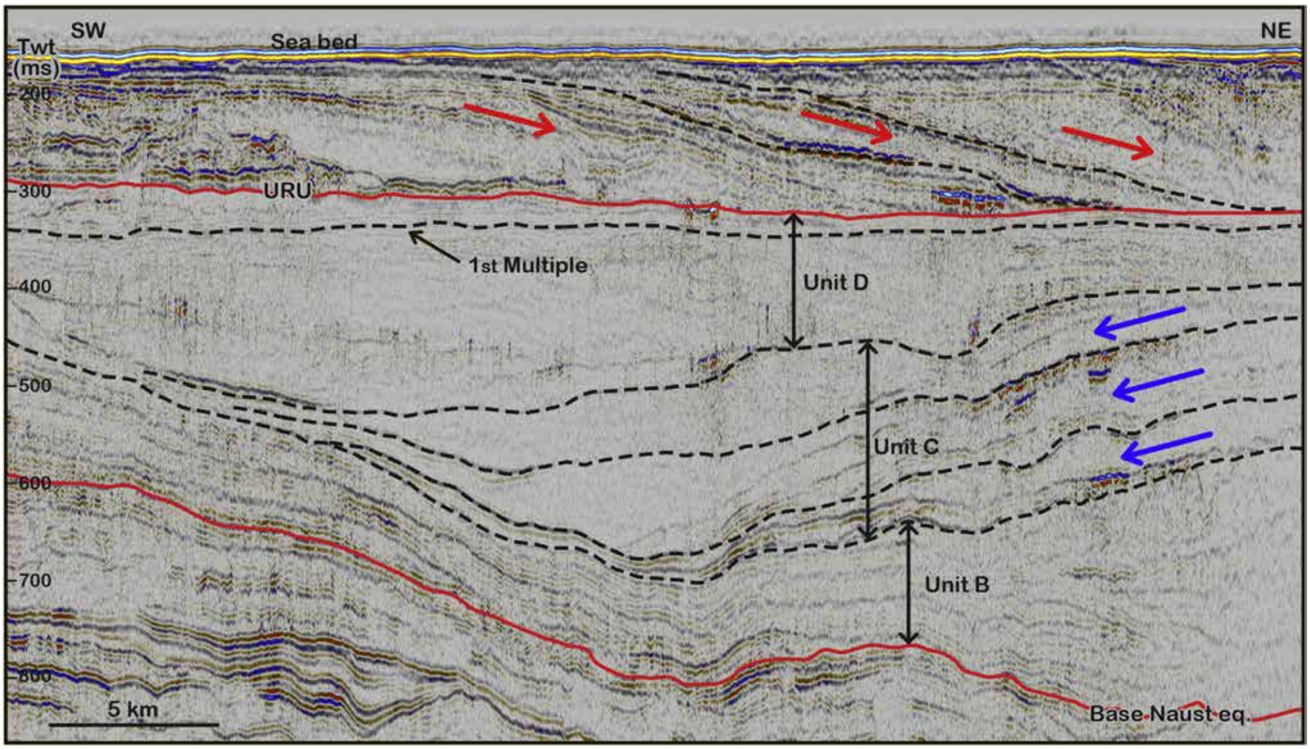


Figure 9. Seismic profile DN0904-0209 displaying the Quaternary seismic stratigraphy including the Upper Regional Unconformity (URU). Note the sea-bed multiple close to the URU. The URU marks the transition from a general depositional pattern with clinoforms deposited from the east (blue arrows) to clinoforms deposited from west (red arrows). Seismic profile is located in Figure 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

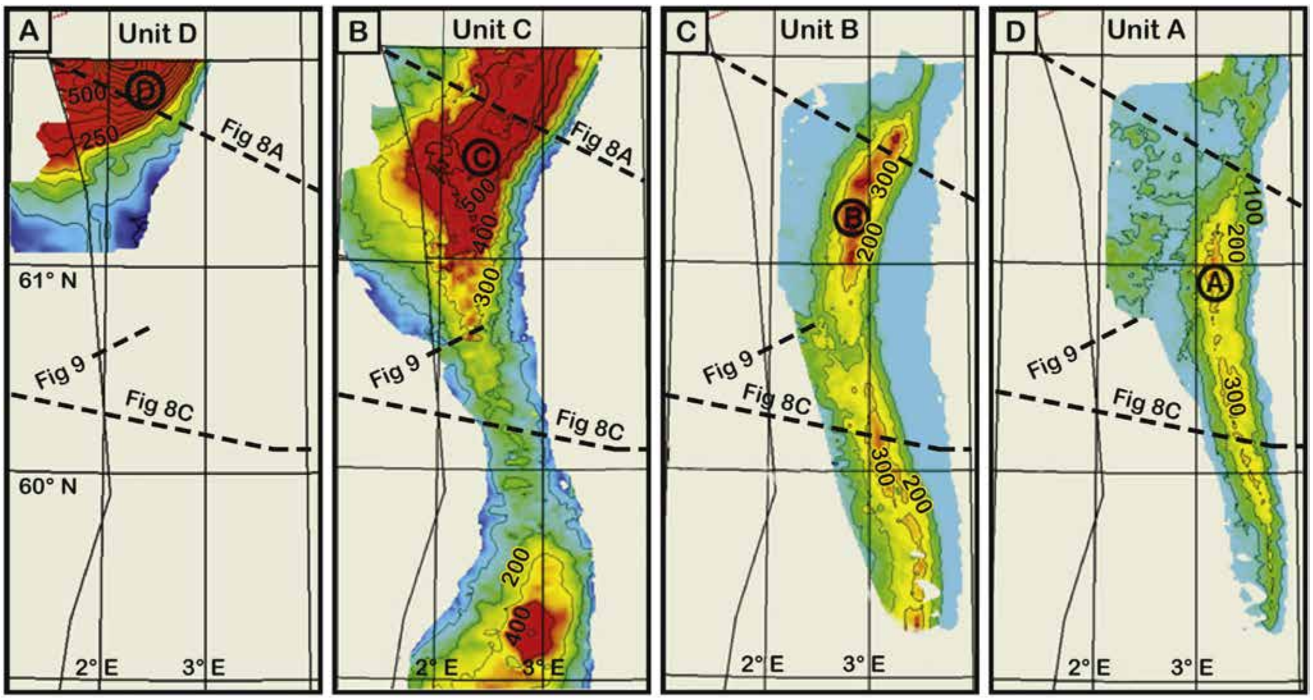


Figure 10. Thickness maps of units A, B, C and D in the northern North Sea. 50 m depth contours in A, elsewhere 100 m depth contours.

suggest moving the interpretation of the Base Naust-equivalent in well 2/4-C-11 up to the level of the reflector at c. 700 m and to name the section between 980 m and 700 m as part of the Nordland Group.

4. Morphology and sediment fill of the North Sea Basin

4.1. Basin morphology at approximately 2.75 Ma

The lowermost sediments of the Nordland Group in the North Sea comprise sands of the Utsira Formation (north of about 58°N) and clays of the Nordland Group further south (Dalland et al., 1988; Eidvin et al., 1999; Eidvin and Rundberg, 2001, 2007). The equivalents offshore of mid-Norway, north of the North Sea, are the youngest, southwestern part of the sandy Molo and the fine-grained Kai formations (Eidvin et al., 2013) (Fig. 2). The unconformity present at the top of the Utsira sands can be correlated into the clays of the Nordland Group in the central North Sea. In the southern Viking Graben and in the central North Sea Basin (Fig. 4A) there is most probably not a clear break between Quaternary and Upper Pliocene sediments (Eidvin et al., 2000; Head et al., 2004). This horizon therefore defines the base of the overlying glacially influenced sediments in the northern and central North Sea and is the equivalent of the base of the Naust Formation off mid-Norway north of 62°N. We use the term 'Base Naust-equivalent' to describe this horizon, which we have identified throughout our study area in the North Sea stratigraphy. The base-Naust on the mid-Norwegain shelf has been given the same age as that of the onset of the delivery of ice-rafted debris into Ocean Drilling Program cores on the Vøring Plateau (2.75 Ma: Jansen and Sjøholm, 1991; Eidvin and Rundberg, 2001). Our Base Naust-equivalent horizon allows the approximate shape of the North Sea Basin at the beginning of the Quaternary to be defined.

The present-day morphology of the base Quaternary surface of the central and northern North Sea basins is shown in Figure 4A. This encompasses an area of about 110 000 km^2 between 56° and 62°N (below the 500 m contour of the Base Naust-equivalent surface), a distance of approximately 700 km. Although we have mapped the morphology of the North Sea Basin using the Base Naust-equivalent horizon (Fig. 4A), which marks the start of the Quaternary in the North Sea and mid-Norwegian margin, it should be noted that the shape of the Base Naust-equivalent surface has been altered due to sediment loading and tectonic influence during the last 2.75 million years or so. Sediment infill from extensive erosion of surrounding land areas has caused both subsidence of the basin and also uplift of the land areas in Norway and the UK to either side (Riis, 1996; Stuevold and Eldholm, 1996).

The North Sea Basin provided accommodation space at the beginning of the Quaternary (Cameron et al., 1987; Eidvin et al., 1999, 2000) into which sediments were delivered from the great European rivers to the south (e.g. Gibbard, 1988; Toucanne et al., 2009), and from the intermittently glaciated Norwegian and UK landmasses to the east and west, during the Quaternary. The central and northern North Sea Basin is elongate from south to north (Fig. 4A). In the central North Sea at 58°N the basin is at its widest at approximately 210 km in width and a maximum of about 1000 m

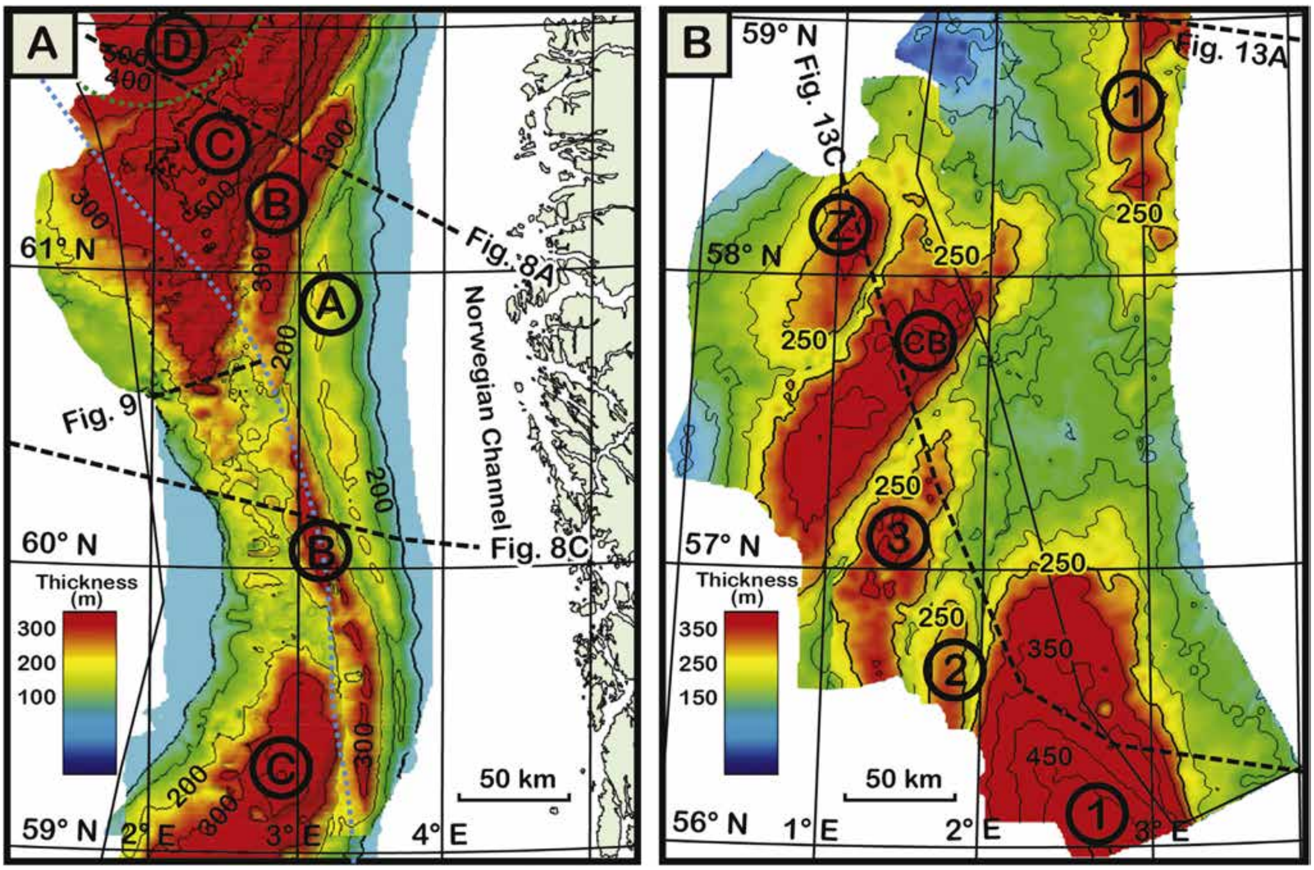


Figure 11. Thickness of mapped Quaternary units in the North Sea. (A) Thickness maps of units A, B, C and D within the northern North Sea. Blue stippled line marks the western edge of the modern Norwegian Channel and green stippled line marks the southern limit of the North Sea Fan. (B) Thickness maps of units 1, 2, 3, Central Basin and Z within the central North Sea Basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

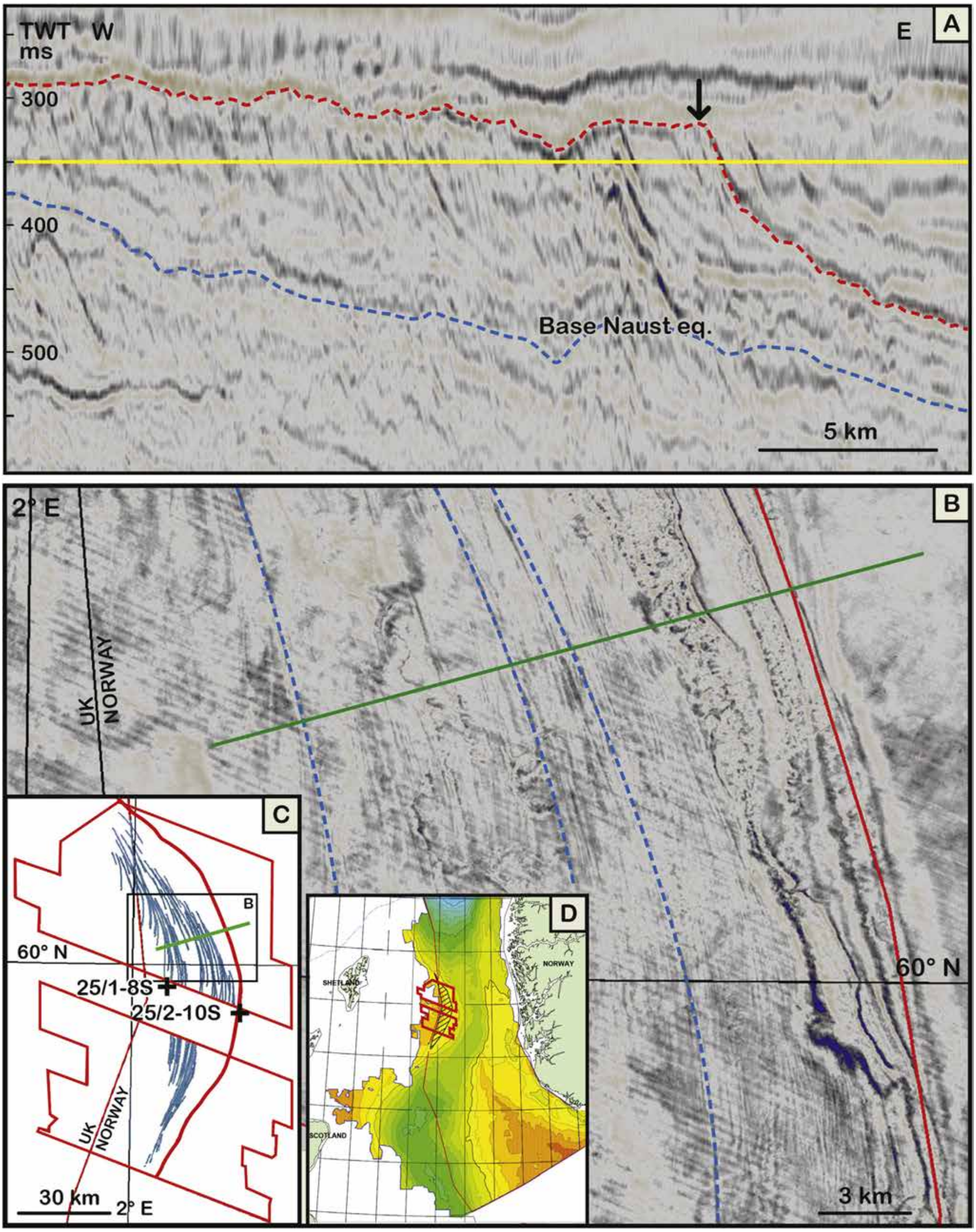
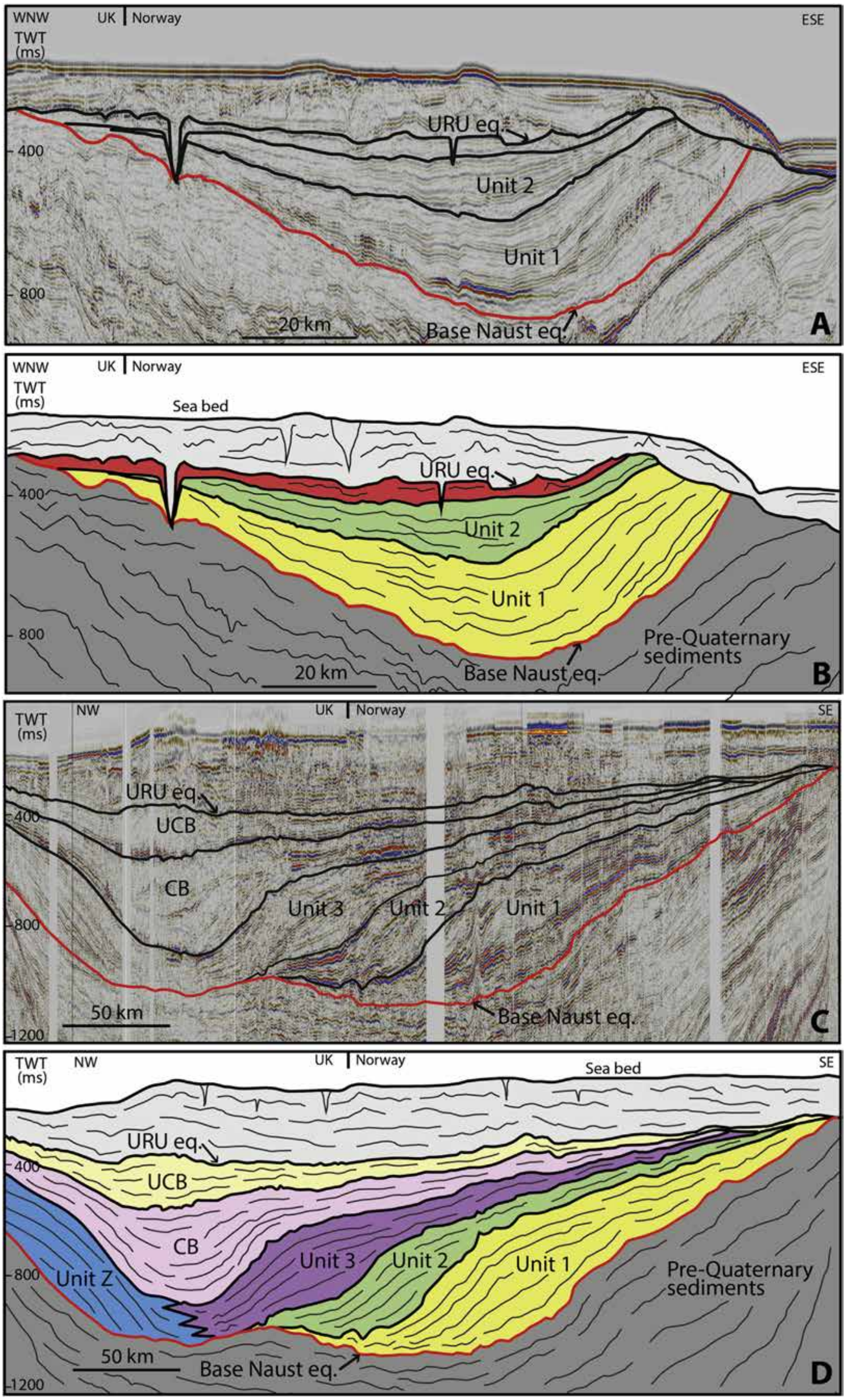


Figure 12. (A) Random seismic line from the 3D seismic cube NVG10M-N across a Pleistocene delta mapped along the western side of the northern North Sea Basin at c. 60° N (outline of delta shown in Fig. 4). Yellow line locates the depth of the time slice shown in B. Red stippled line marks the top of the delta and slope of the delta front. Blue stippled line is the Base Naust-equivalent surface. Black arrow marks delta front. (B) Time slice (350 ms time depth) displaying cut clinoforms of the delta as slightly curved lines (a few are marked as blue stippled lines). Red line marks the delta front. Green line locates seismic line shown in A. (C) Map showing the two seismic cubes (red polygons) with cut clinoforms of the delta mapped in time slices between 320 and 370 ms (blue lines). Thick curved red line marks the front of the Pleistocene delta. Black rectangle locates part B. (D) Map of Base Naust-equivalent surface (Fig. 4A) with location of the 3D cubes shown in C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)


WNW
UK
Norway
ESE
TWT (ms)
400
800
URU eq.
Unit 2
Unit 1
20 km
Base Naust eq.
A
WNW
UK
Norway
ESE
TWT (ms)
Sea bed
400
800
URU eq.
Unit 2
Unit 1
Pre-Quaternary sediments
20 km
Base Naust eq.
B
TWT (ms)
NW
UK
Norway
SE
400
800
1200
URU eq.
UCB
CB
Unit 3
Unit 2
Unit 1
50 km
Base Naust eq.
C
TWT (ms)
NW
UK
Norway
Sea bed
SE
URU eq.
400
UCB
CB
800
Unit Z
Unit 3
Unit 2
Unit 1
Pre-Quaternary sediments
50 km
Base Naust eq.
1200
D

deep, remembering that later sediment infill has caused subsidence. The basin then narrows and shallows northwards offshore of western Norway at about 60°N, reaching a minimum width and depth of about 80 km and 700 m, respectively (Fig. 4A). It then widens and deepens again into the northern North Sea and then into the deep Møre Basin of the Norwegian Sea beyond 62°N; at this latitude the basin is about 160 km wide and approximately 1500 m deep (Fig. 4A). We define the central and northern North Sea areas as those south and north of 59°N, respectively, because this is where the central basin starts to narrow and also where, as we will see later, sedimentation begins to be dominated by that from Norway rather than from the south.

4.2. Basin fill

The shape of the North Sea Basin defined by the Base Naust-equivalent surface allows us to calculate the total sediment fill of the basin. The calculation takes no account of material that has been eroded between ~2.75 Ma and today, especially from the deep erosion by the Norwegian Channel Ice Stream during the Middle to Late Quaternary. The thickness of the fill is shown in Figure 4B. The maximum Quaternary sediment thickness in the central North Sea is more than 900 m, thinning to about 500 m at about 60°N, and thickening once more in the northern North Sea Basin before the North Sea Fan is approached close to the limit of our study area at 62°N (Fig. 4B) (King et al., 1996; Nygård et al., 2005). The total volume of Quaternary sediments in the study area (172 000 km^2, blue outline in Fig. 4A), comprising the areas between about 1°W and 7°E and 56°N and 62°N, is 71 000 km^3; of this, 57 000 km^3 is in the central and northern North Sea basins.

We also map the thickness of Early Quaternary sediments and find a total volume of 40 000 km^3. The maximum sediment thickness for the Early Quaternary in the central basin is more than 700 m, and in the northern basin in excess of 1000 m.

5. Northern North Sea Basin (59°–62°N)

5.1. Seismic stratigraphy

The boundary between the Early and Middle Quaternary sediments in the North Sea is defined by the Bruhnes-Matuyama reversal (Stoker et al., 1983) and the URU or URU- equivalent that we identify at around this time interval. In the eastern part of the North Sea, the URU is an erosion surface produced by the first, or the most extensive, ice forming the Norwegian Channel west of Norway. This event has been previously dated to 1.1 Ma by Sejrup et al. (1995, 2000). On the North Sea Plateau, west of the Norwegian Channel (Fig. 3A), the URU reflector is indicated by a shift in the direction of sediment delivery from a predominantly eastern source to one from the west (Figs. 8C, D, 9). The URU may be time transgressive and is not well dated, as discussed in more detail below.

The seismic stratigraphy of the northern North Sea is illustrated by the sections in Figure 8. The Early Quaternary basin infill comprises a series of clinoforms which prograde predominantly from east to west. In the northern part of the area, however, the clinoforms have a more northwesterly infill pattern. The clinoforms are thickest at the palaeo-shelf edges and tend to thin towards the palaeo-basin floor (Fig. 8). We have mapped four units within the clinoforms; A, B, C and D (Figs. 2 and 8). Unit D appears in the northwestern part of the basin and might also be present in some other areas as a thin unit. Palaeo-shelves and shelf edges can sometimes be identified in seismic profiles (Fig. 8A), providing observational evidence of some aggradation as well as progradation into the basin. In the eastern part of the northern North Sea Basin, in many seismic sections, the clinoforms have been cut by later ice flowing through the Norwegian Channel and the palaeo-shelf has been removed (e.g. Dowdeswell et al., 2007). Therefore, while we can observe that progradation has taken place into the basin west of Norway, we are often left to infer that aggradation has also occurred due to the absence of the shelf and shelf-edge in the area of the modern Norwegian Channel (Fig. 8).

Unit D represents, in the north, the southern part of the North Sea Fan, whereas further south it appears to be a transitional unit. This unit is up to 800 m thick in the northwesterly part of the study area (Fig. 8A), and thins rapidly towards the south to become a relatively thin layer (<50 m) at 60°N (Fig. 8C). Due to poor seismic coverage, we have not been able to map Unit D completely. The precise position of the URU is often obscured by the first sea-floor multiple (Fig. 9). Above the sea-floor multiple, however, there is a clear shift to clinoforms indicating sediment delivery from the Shetland Plateau to the west (Fig. 9). The top of Unit D therefore marks the URU, which we define as the upper limit of our study. Stoker et al. (1983) located the Brunhes/Matuyama (B/M) boundary in many shallow boreholes, but always at the western flank of the basin in the UK sector. The B/M boundary (0.78 Ma) seems to be located close to the URU-equivalent, and we therefore suggest an age of 0.8 Ma or somewhat younger for the URU-equivalent surface on the North Sea Plateau.

5.2. Basin infill

The infill of the northern North Sea Basin in the Early Quaternary is illustrated in Figures 8, 10 and 11A. The pattern of infill for units A, B, C and D is shown (Figs. 10 and 11A). It can be seen that the basin was filled predominantly from the east, and progradation of more than 100 km was mainly westward. There is a north-westerly component to progradation in the northernmost part of the basin (Figs. 10 and 11A). It is here that Unit D reaches about 800 m in thickness. It can also be seen in Figures 10A and 11A that an important part of Unit D represents the southernmost part of the North Sea Fan. Maximum sediment infill thicknesses are 300 m, 450 m and 700 m for units A, B and C, respectively. It should be remembered, however, that the original maximum thickness of each unit has been reduced through subsequent erosion by the Norwegian Channel Ice Stream during the later part of the Quaternary. The position of the palaeo-ice stream is shown in Figures 8 and 11A, and only to the west of its western margin is the original thickness of the Early Quaternary depocentre likely to be preserved.

5.3. Deltaic unit along the western margin of the northern basin

A Pleistocene deltaic unit has been mapped along a 150 km long stretch of the western flank of the northern North Sea Basin (Fig. 4A). The unit is located on the outermost part of the East Shetland Platform and curves along the narrowest part of the basin from 59°N in the south to about 60°30′N in the north. A seismic line shows the steeply dipping clinoforms of the delta (Fig. 12A). The top of the delta is rather flat at around 250 m depth, and the clinoforms are more than 150 m high (Fig. 12A). The unit is more than 20 km wide, and the clinoforms are well imaged in the two 3D cubes

Figure 13. Seismic profiles of the central North Sea Basin (located in Fig. 1). (A) Seismic profile NSR06-31142 (c. 59°N). (B) Geoprofile of the line shown in A. Unnamed red unit above Unit 2 comprises an amalgation of Unit 3, Central and Upper Central Basin units. V-shaped features mark tunnel valleys. (C) Seismic composite profile across the central North Sea Basin. (D) Geoprofile of the line shown in C. V-shaped features mark tunnel valleys. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

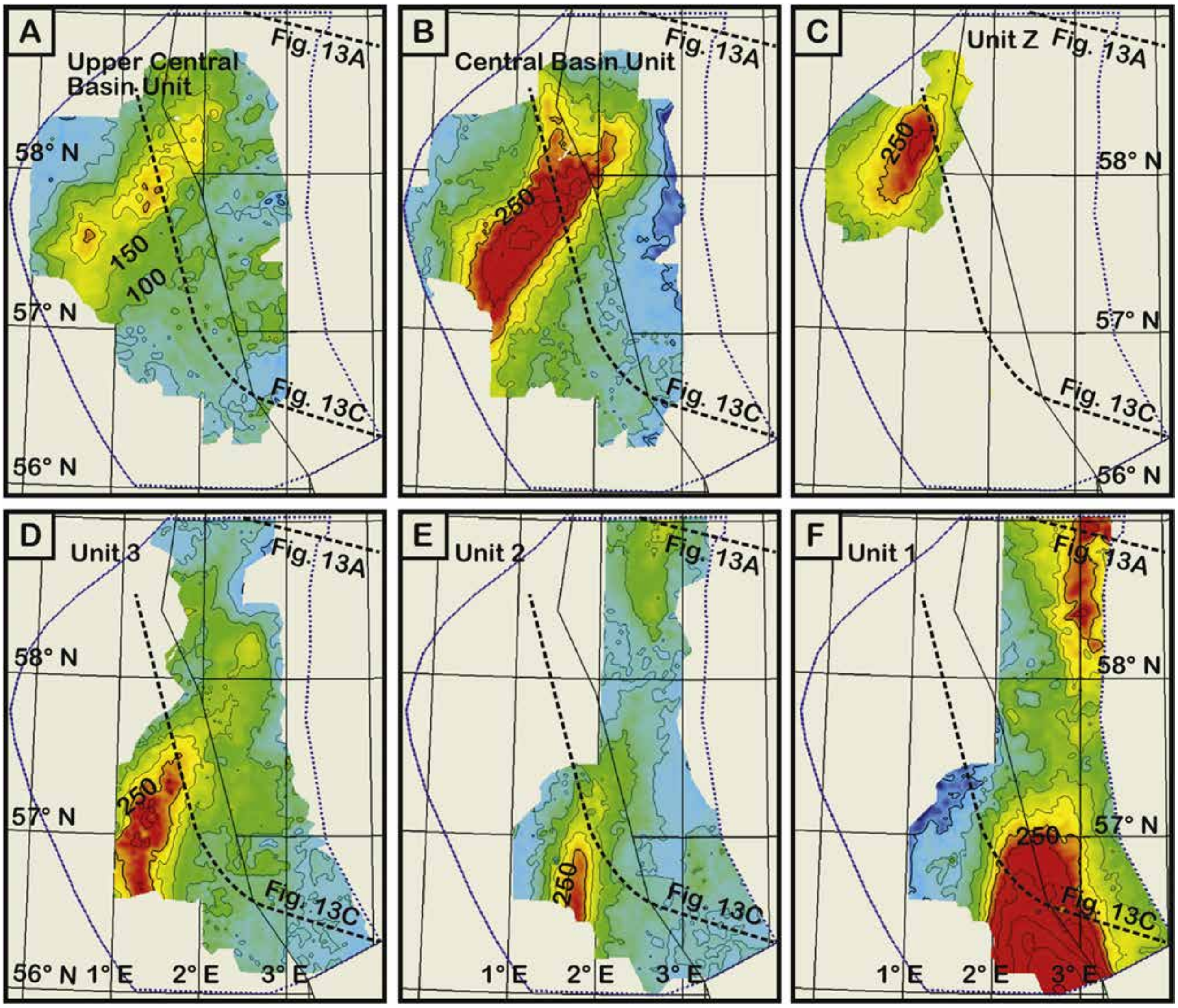


Figure 14. Thickness maps of the different units within the central North Sea Basin (Fig. 2). 50 m depth contours. The blue stippled lines mark the 500 m contours of the Base-Naust-equivalent reflector. (A) Upper Central Basin Unit. (B) Central Basin Unit. (C) Unit Z. (D) Unit 3. (E) Unit 2. (F) Unit 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

NVG10M South and North which cover most of the deltaic unit (Figs. 1 and 12C). The clinoforms have a regular form, and appear as slightly curved, parallel lines in the time slices from cube NVG10M North (Fig. 12B and C).

Table 1
Volume of major Quaternary sequences in the North Sea (56°N – 62°N), including both the Norwegian and UK sectors within the 500 m contour of the Base Naust-equivalent surface (Fig. 4).

Area	Unit (see Fig. 2)	Area (km^2)	Volume (km^3)
North Sea 56°N – 62°N	Seabed – Base-Naust eq.	100 000	57 000
	Seabed – URU/URU eq.	100 000	15 000
	URU/URU eq. – Base-Naust eq.	100 000	40 000
Northern North Sea 59°N – 62°N	Seabed – Base-Naust eq.	38 000	20 000
	Seabed – URU/URU eq.	38 000	5300
	URU/URU eq. – Base-Naust eq.	37 000	14 600
Central North Sea 56°N – 59°N	Seabed – Base-Naust eq.	55 000	37 000
	Seabed – URU/URU eq.	50 500	9600
	URU/URU eq. – Base-Naust eq.	50 000	25 000

Eidvin et al. (2013) have dated the deltaic unit, from samples in wells 25/2-10S and 25/1-8S (Fig. 12C), to belong to the Early Quaternary. Well 25/2-10S shows more than 200 m of deltaic sands on top of the Utsira Formation, whereas the deltaic sands have thinned to slightly more than 100 m in well 25/1-8S, which is 22 km farther west.

Table 2
Volumes of Quaternary units in the northern North Sea Basin within the 500 m contour of the Base-Naust equivalent surface (59°N–62°N) (Fig. 4A).

Unit (see Fig. 2)	Area (km^2)	Volume (km^3)
Seabed – Base-Naust eq.	38 000	20 000
Seabed – URU/URU eq.	38 000	5300
URU/URU eq. – Base-Naust eq.	37 000	14 600
Unit A	19 300	2140
Unit B	16 000	1990
Unit C	28 000	6000
Unit D	23 000	1800

Table 3
Volumes of Quaternary units in the central North Sea Basin within the 500 m contour of the Base-Naust equivalent surface (56°N – 59°N) (Fig. 4A).

Unit (see Fig. 2)	Area (km^2)	Volume (km^3)
Seabed – Base-Naust eq.	55 000	37 000
Seabed – URU/URU eq.	50 500	9600
URU/URU eq. – Base-Naust eq.	50 000	25 000
Unit 1	39 000	7600
Unit 2	33 000	2500
Unit 3	33 500	3700
Unit Z	9400	2200
Central Basin Unit	38 000	5500
Upper Central Basin Unit	36 000	3100

6. Central North Sea Basin (56°–59°N)

6.1. Seismic stratigraphy

Two representative seismic sections across the central North Sea Basin are shown in Figure 13. The northernmost line crosses the North Sea in the transition zone between the northern and central basins at 59°N (Fig. 13A). The more southerly seismic line crosses the eastern part of the central basin and then follows the axis of the basin towards the northwest (Fig. 13C). The morphology of the base Naust-equivalent surface suggests a basin of a few hundred metres in depth at the time when Early Quaternary infill began, bearing in mind possible subsidence from later infill (Fig. 4). The seismic architecture of the central basin comprises a series of prograding wedges with a characteristic clinoform shape, building out from the southeast towards the northwest (Fig. 13C and D). The clinoforms have surfaces dipping towards the northwest and, in the western part of our study area, they become steeper (Fig. 13C and D). The clinoforms thin towards the basin floor. Three clinoform sequences have been mapped in the central North Sea (units 1, 2 and 3; Fig. 2), over an area of about 60 000 km^2 (Fig. 6E–G).

At the same time that the clinoform units were deposited in the eastern part of the central basin, an acoustically layered and mounded unit, known as Unit Z (Fig. 2), was deposited along the western slope of the basin (Fig. 13C and D). Unit Z has been interpreted by some as a contourite deposit on the basis of its acoustic character (Faugères et al., 1999). The upper surface of Unit Z is irregular, and is known as the Crenulate Surface (Fyfe et al., 2003) (Fig. 13C). The crenulate reflector has often been taken to mark the onset of Quaternary glacial deposition. We have located the base-Naust-equivalent reflector at the base of this slightly mounded unit. This interpretation is based on Rundberg and Eidvin's (2005) work on well logs and seismic correlation.

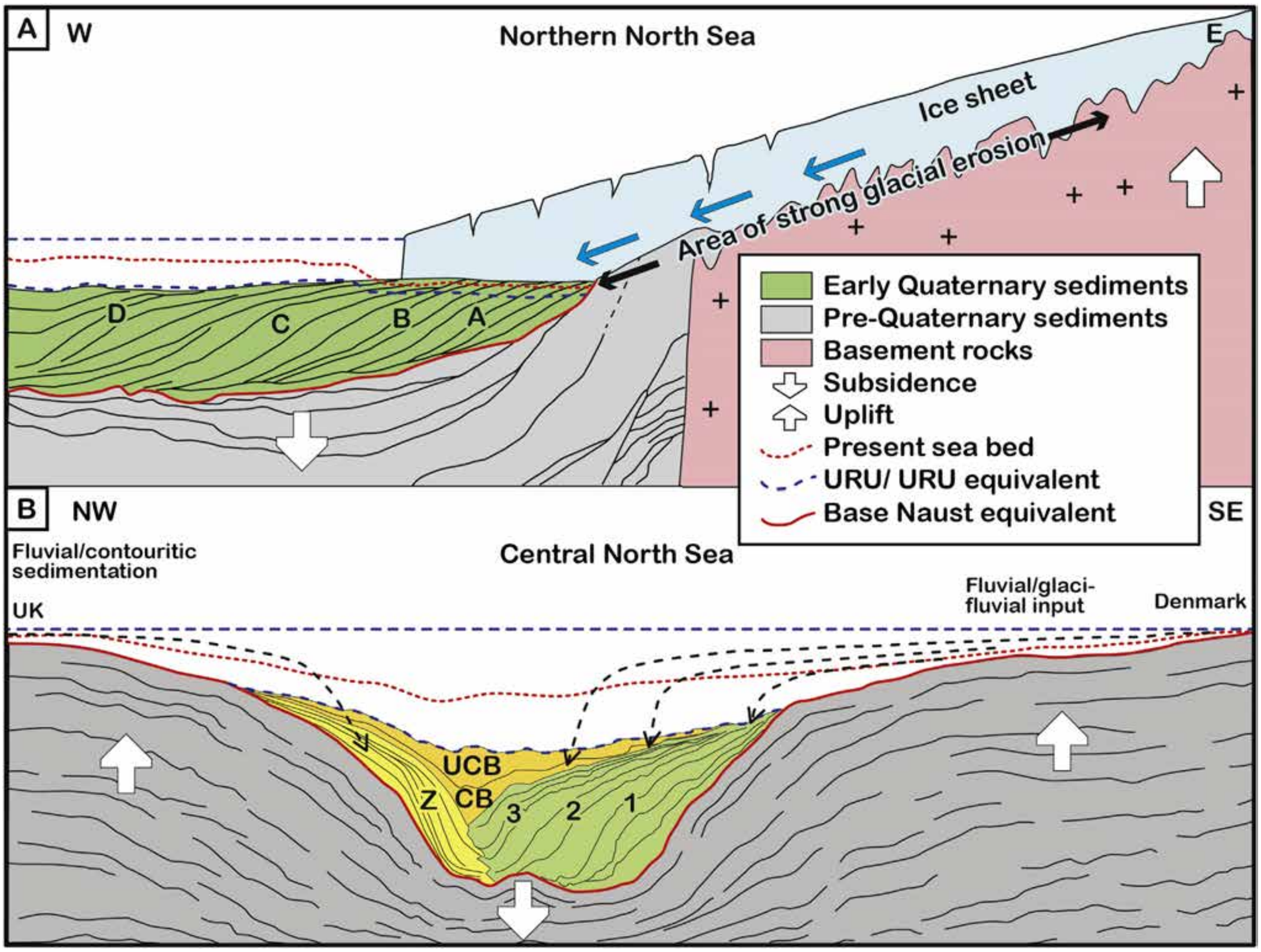


Figure 15. Schematic summary sections of the seismic stratigraphy of the North Sea Basin in the Early Quaternary, before the cutting of the Norwegian Channel by ice–stream activity. (A) Northern North Sea Basin (also showing continuation of clinoforms across Norwegian Channel). (B) Central North Sea Basin.

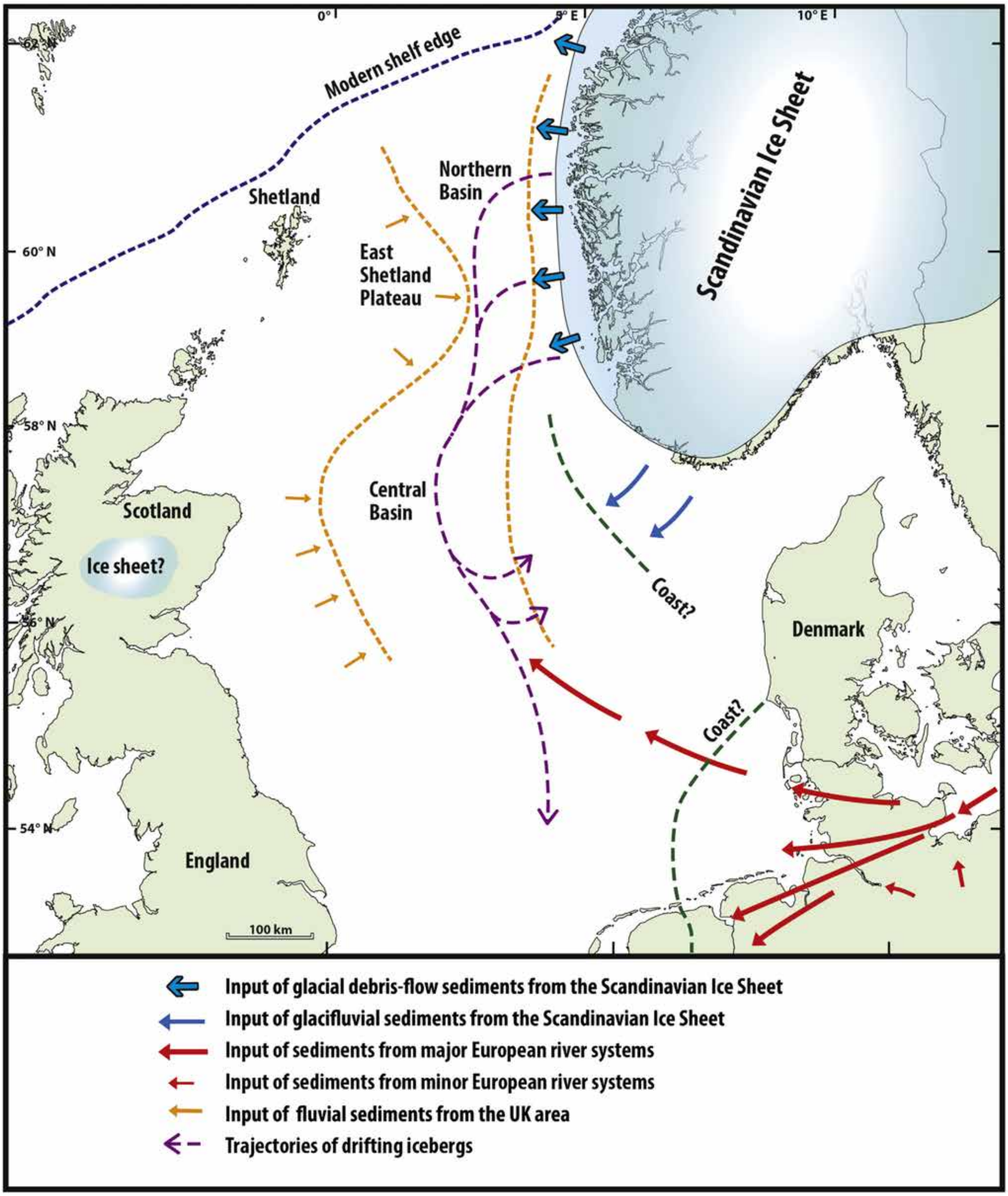


Figure 16. Schematic model of landscape, ice-sheet configuration and delivery of sediments in the Early Quaternary of the North Sea. Large and small red arrows show input of water and sediment from major and minor European river systems during the Early Pleistocene partly derived from Gibbard (1988). Orange stippled lines show the general form of the North Sea Basin (500 m contour of the Base Naust-equivalent reflector). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

After the three clinoform units and Unit Z were deposited, a central basin with a maximum depth of 900 m was left open (Fig. 13C and D). The basin axis trended SW–NE and was 200 km long and 120 km wide (Fig. 6E). This was then filled with fine-grained sediments making up the Central Basin Unit (Figs. 2, 13C, D). The Central Basin Unit is, in turn, subdivided into upper and lower parts. The top of the Upper Central Basin Unit is mapped at the onset of flat-lying reflectors with a conformable appearance (Fig. 13). This change to a sub-horizontal seismic character, above what are interpreted to be the basin-infill sediments of the Central Basin units, is proposed to represent an URU-equivalent in much of the central North Sea (Fig. 13). The URU-equivalent surface dips slightly towards the west, where it reaches up to 400 m depth in the British sector (Fig. 6B). Generally, the units filling in the central basin thin towards the north (Fig. 13A). Here, Unit 1 is still more than 300 m thick, Unit 2 has thinned to about 170 m, whereas the other units below the URU are not mappable. The package of sedimentary units that includes both our Unit Z and Central Basin units is referred to as the Zulu Group in the UK sector (Fig. 2) (Stoker et al., 2011).

6.2. Basin infill

Unit 1 in the central North Sea Basin has a maximum thickness of 500 m (Figs. 14F and 11B). The maximum thickness of units 2 and 3 is 290 m and 320 m, respectively (Figs. 14D and E and 11B). Unit Z, to the west (Fig. 14C), has a maximum thickness of 310 m and thins rapidly towards the south and north. The central basin is filled with layered sediments up to 370 m thick, forming the Central Basin Unit (Figs. 2, 11B and 14B). The basin has an elongate appearance with a NE–SW trend (Fig. 6E). The Upper Central Basin Unit has rather flat reflectors with a maximum sediment thickness of c. 270 m (Fig. 14A). This depocentre is located on top of the Central Basin Unit and has a similar appearance with an elongate basin axis trending NE–SW (Figs. 6C and 14A).

7. Sediment volume calculations for the North Sea Basin

The depth-converted surfaces form the basis for the volume calculations in the study area (Figs. 5 and 6). First, we have calculated volumes for the whole area. The 500 m contour of the base Naust-equivalent surface has been used as an outer limit for our volume calculations (Fig. 4). The outermost parts of the basin are therefore excluded, but only where minor volumes of sediment occur and the interpreted surfaces are not easily mapped. The volumes for the whole Naust Formation have been calculated, covering an area of about 100 000 km^2 (Table 1). In total, 57 000 km^3 of sediment has been deposited. The volumes above and below the URU or URU-equivalent surface have also been calculated, showing that about 70% of the total sediment volume is below the URU (40 000 km^3).

Similar calculations have taken place for the northern and central North Sea basins. In the northern North Sea, four units have been mapped below the URU-surface (Figs. 2, 10 and 11A, Table 2). All four units show a prograding pattern from east to west/north-west, with volumes of 1800 km^3, 6000 km^3, 1990 km^3 and 2140 km^3 from the youngest to the oldest, respectively (Table 2). The largest unit is Unit C, which comprises a series of prograding wedges (Fig. 8).

In the Central North Sea, six units have been mapped (Figs. 2, 11B and 14; Table 3). Unit Z was deposited along the western flank of the basin and is assumed to have been laid down during the same period as clinoform units 1, 2 and 3 (Fig. 2). Unit Z contains 2200 km^3 of sediment, whereas clinoform units 1, 2 and 3 contain 13 800 km^3. This implies that most of the sediment has been sourced from the southeast during this period. The Central Basin Unit contains 5500 km^3 of material which represents the infill of the remaining area of the central basin. The Upper Central Basin Unit covers a large area and contains 3100 km^3 of debris (Table 3).

8. Stratigraphic relationships in the Early Quaternary of the North Sea

Based on the identification and correlation of reflectors in the northern and central basins of the North Sea (Figs. 8 and 13), the Early Quaternary seismic stratigraphy of the two basins is summarized in the schematic diagrams in Figure 15. The interpretation of the base of the Naust Formation on the mid-Norwegian shelf has been extended southward into the North Sea based on 2D and 3D seismic data. Eidvin and Rundberg (2001) presented a detailed study of the stratigraphy along seismic line NVGTI-92-105 in the northern North Sea, where they identified a flat-lying basinal unit above the Utsira Formation but below a series of prograding wedges. This flat-lying unit is rich in ice-rafted debris observed both in side-wall cores and several conventional cores. It has a likely maximum age of about 2.75 Myr. Our Base Naust-equivalent reflector in the North Sea is at the base of this unit (Fig. 15).

For the northern North Sea Basin, the schematic diagram in Figure 15A shows the infilling of the basin during the Early Quaternary by a series of prograding clinoform units (Units A–C), followed by Unit D, which is thickest in the northwest. During this period, the northern North Sea was subsiding and the Norwegian landmass was rising (Riis, 1996), providing accommodation space in the basin (Fig. 15A). The diagram also shows the modern sea floor and the presence of the Scandinavian Ice Sheet that provided sediment to the basin.

For the central North Sea Basin (Fig. 15B), subsidence of the basin and uplift along its UK and continental European flanks again took place in the Early Quaternary. Clinoform units 1 to 3 developed from a source to the southeast from predominantly fluvial and fluvioglacial sources during the Early Quaternary, while Unit Z was deposited by fluvial and contouritic sedimentation from the west (Fig. 15B). In the later part of the Early Quaternary, basin filling continued with the deposition of the Central Basin and Upper Central Basin units. Above are the URU-equivalent and the predominantly flat-lying sediments of the Middle and Late Quaternary.

The relationship between the Naust Formation of the mid-Norwegian shelf and its equivalent in the northern and central basins of the North Sea is also shown in the stratigraphic column (Fig. 2). In this paper we have described in some detail the seismic stratigraphy of the Early Quaternary of the North Sea, below the URU or URU-euivalent (Figs. 8, 9 and 13). We provide no detail on the stratigraphic units of the Middle and Late Quaternary here,

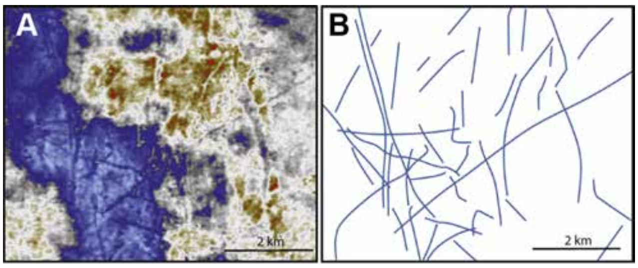
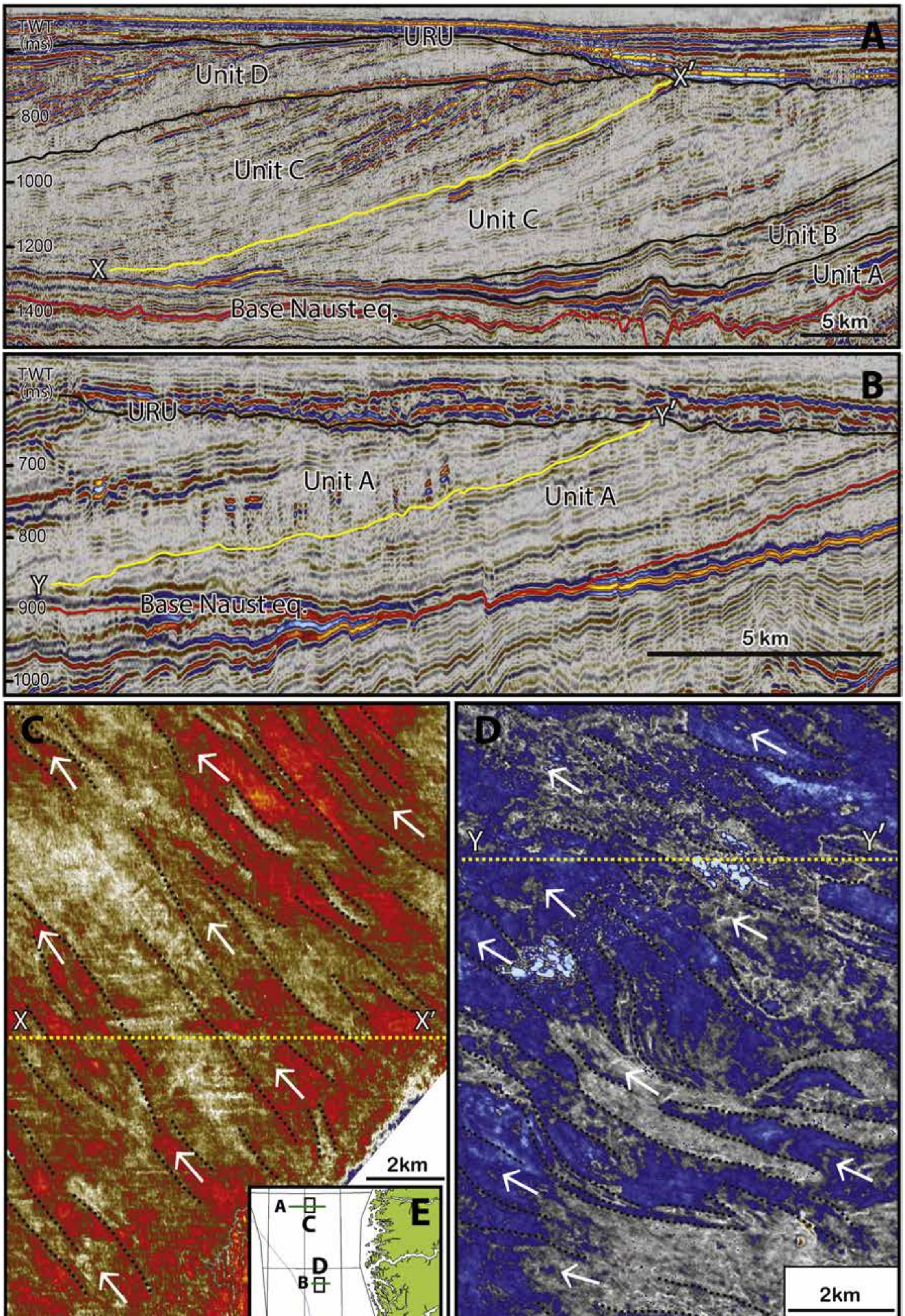


Figure 17. (A) Time slice (720 ms time depth) showing buried Early Quaternary iceberg ploughmarks in 3D seismic cube E08 (located in Fig. 1). The time slice is located in the lower part of seismic Unit 1, close to the Base Naust-equivalent surface (Figs. 2, 13C and 13D) and the ploughmarks are more than 2 million years old. (B) Interpreted characteristic chaotic pattern of iceberg ploughmarks.


A
TWT (ms)
URU
Unit D
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Unit C
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Unit C
1200
Unit B
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Unit A
1400
Base Naust eq.
5 km
B
TWT (ms)
URU
Y′
700
Unit A
Unit A
800
Y
900
Base Naust eq.
5 km
1000
C
X
X′
2km
A
C
E
D
B
D
Y
Y′
2km

except to suggest that they encompass at least the Elsterian, Saalian and Weichselian periods (Naust units S and T on the mid-Norwegian shelf), and the Reaper Glacigenic Group in the British Sector of the North Sea, and the glacial advance and retreat cycles associated with them over the past 0.5 My or so.

The chronology for the Early Quaternary is tentative, with the base of the Naust Formation given a maximum age of 2.75 Ma and the upper surface of the Naust N unit at 1.5 Ma (Rise et al., 2006). The Brunhes-Matuyama magnetic reversal at 0.78 Ma has been located in several geotechnical boreholes, but always at the western flank of the basin in the UK sector (Stoker et al., 1983). We have not managed to correlate this marker horizon into the central parts of the basin with confidence, but it appears to be located somewhere close to the URU or URU-equivalent horizon.

Identification of the URU in the North Sea sediments is relatively straightforward on the eastern side of the basin. This is because there is a well-developed erosional unconformity here (Figs. 8, 13A, 13B), linked to the cutting of the Norwegian Channel by an ice stream. In the west of the northern basin and in the central basin the URU is more difficult to identify because the sediments, in this part of the record, are conformable with the URU (Figs. 8 and 13). The URU in the southern North Sea is similarly difficult to identify (Moreau et al., 2012). A seismic line at 61°N illustrates this problem clearly, with the critical part of the seismic stratigraphy often masked by the first seabed multiple (Fig. 9). We use a shift from seismic reflectors that dip westward to those dipping east to define the URU (used here as a horizon name without the implication that the sediments are unconformable west of the Norwegian Channel). This change is interpreted to result from a shift in the pattern of sediment delivery from the surrounding landmasses. Scotland, and in particular the Shetland Islands and adjacent platform, appear to become a significant source area of sediment from the west (Fig. 9). This change is assumed to have taken place at about the same time as the expansion of ice from Scandinavia which generated the Norwegian Channel Ice Stream.

Within the Early Quaternary sediments of the North Sea, which are part of the Nordland Group (Dalland et al., 1988), a number of major reflectors and seismic units are defined, several of which are correlated between the central and northern North Sea basins (Fig. 13). Generally, the sediments in the central North Sea Basin (Fig. 14) thin towards the north into the northern North Sea (Fig. 13). In the central North Sea Basin five units have been mapped. At about 59°N, in the transition zone to the northern basin, only the two lowermost units (Units 1 and 2) can be mapped and the three uppermost units merge into a single unit. As shown in Figure 2, Unit 1 in the central North Sea is equivalent to both units A and B and the lower part of Unit C in the northern basin. Because Units 2 and 3 thin into the northern basin, we have not been able to trace these units into the northern basin. Nonetheless, Units 2 and 3 represent parts of the relatively thick Unit C in the northern North Sea Basin (Fig. 2).

9. Discussion: Early Quaternary sedimentary environments

The sediments of the Middle and Late Quaternary in the North Sea, above the URU or URU-equivalent, are widely regarded as predominantly of glacial origin (e.g. Cameron et al., 1987; Sejrup et al., 2000; Bradwell et al., 2008; Graham et al., 2010, 2011). Prograding clinoforms from the west above the URU suggest the growing importance of the British Ice Sheet as a sediment source (Fig. 9), as well as a large ice sheet over Scandinavia. Several sets of mega-scale glacial lineations, reflecting subglacial streamlining of glacial till (e.g. Clark, 1993; Dowdeswell et al., 2004; Rise et al., 2004; Ó Cofaigh et al., 2005), have been reported from the Middle to Late Quaternary sediments of, for example, the Witch Ground Basin between 58° and 59°N (Graham et al., 2007, 2010). In addition, a number of sets of tunnel valleys, usually thought to have been formed by subglacial meltwater flow, have also been observed in Middle and Late Quaternary sediments (above the URU) from many areas within the North Sea (e.g. Huuse et al., 2001; Praeg, 2003; Fichler et al., 2005; Lonergan et al., 2006; Stewart and Lonergan, 2011). The presence of these glacial landforms is strong evidence for the inundation of the North Sea by a grounded ice sheet on several occasions over the past few hundred thousand years. The origins of debris forming the Early Quaternary of the North Sea, however, have been more equivocal; almost no streamlined glacial lineations or tunnel valleys, indicative of a grounded ice sheet, have yet been reported from Early Quaternary palaeo-surfaces in the North Sea.

We present a schematic model of Early Quaternary sediment delivery to the North Sea Basin that relates to sources from both the major European river systems to the south and from an ice sheet over Scandinavia to the east of the basin (Fig. 16). The principal evidence for a major contribution from the great European rivers, including the palaeo-Rhine and the Baltic River system, is the fact that the clinoforms are built out towards the northwest and sediment fill in the central basin clearly suggests northwestern progradation through the Early Quaternary from a source to the south and south-east of our study area (Figs. 11B, 13C, 13D, and 14). The sediments making up the fill of the Early Quaternary of the central North Sea Basin are fine-grained, suggesting a distal fluvial or glacifluvial origin with an additional hemipelagic component. Gibbard (1988), for example, has mapped the major northwest European river systems for the Early Quaternary period, and we show these locations in Figure 16.

In addition, it is important to note that irregular furrows, shown in Figure 17, have also been observed on palaeo-surfaces buried between 300 and 900 m deep within two 3D cubes (C08 and E08, shown in Fig. 1) covering an area of about 5000 km^2 at 57°N in the central North Sea Basin (Dowdeswell and Ottesen, 2013). These features are interpreted to have been produced by the ploughing action of iceberg keels as the icebergs drifted in the central basin. This interpretation is based on close morphological similarity with modern and Late Quaternary iceberg ploughmarks observed on high-latitude continental shelves (e.g. Woodworth-Lynas et al., 1985; Dowdeswell et al., 1993, 2010). This evidence demonstrates that icebergs, probably derived from calving marine ice-sheet termini to the north outside the coast of western Norway (Fig. 16), drifted into the central North Sea as far back in time as at least 2 Ma (Dowdeswell and Ottesen, 2013). In fact, buried iceberg ploughmarks in the Early Quaternary sediments of the North Sea have also been reported from the central basin (Graham, 2007; Knutz, 2010; Buckley, 2012) and as far south as the Dutch sector (Kuhlmann and Wong, 2008).

The presence of mega-scale glacial lineations (MSGL), indicative of fast-flowing ice streams (e.g. Clark, 1993; Dowdeswell et al.,

Figure 18. (A) Seismic profile with a series of debris flows in the northern North Sea (located in E). X–X′ mark the interpreted horizon (yellow). Parts of the surface are shown in C. (B) Seismic profile showing a series of debris flows in the northern North Sea (located in E). Y–Y′ mark the interpreted horizon (yellow). Parts of the surface are shown in figure D. (C) Amplitude map illustrating the pattern of glacigenic debris flows, generally towards the northwest. (D) Amplitude map illustrating the pattern of glacigenic debris flows, generally towards the northwest. (E) Location map with seismic profiles (green lines) and amplitude maps shown in C- D. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2004), in Early Quaternary sediments from the central North Sea has also been proposed by Buckley (2012). The amplitude of these linear features, identified from palaeo-surfaces in 3D seismic cubes, is apparently up to 50 m. These North Sea features are much larger, often by an order of magnitude, than the vast bulk of MSGL reported by many workers from Late Quaternary glaciated shelves in the Arctic and Antarctic (e.g. Ó Cofaigh et al., 2002; Ottesen et al., 2005; Graham et al., 2009; Jakobsson et al., 2012), and from beneath the modern Rutford Ice Stream in West Antarctica (King et al., 2009). It is unlikely, therefore, that the deeply buried landforms described by Buckley (2012) were formed as MSGL at the base of an Early Quaternary ice stream in the central North Sea. In addition, although Buckley (2012) has also proposed that incised channels in the same area may present Early Quaternary subglacial or proglacial tunnel valleys, other workers have interpreted them as formed in association with contour currents (Knutz, 2010).

Clinoforms prograding west and then northwest in the northern North Sea Basin also indicate a predominant sediment source from Norway during the Early Quaternary (Figs. 8, 10 and 11A). In addition, the clinoforms have an internal architecture that suggests the presence of glacigenic debris flows (Fig. 18), similar to those reported from Late Weichselian trough-mouth fans on Arctic and Antarctic margins (e.g. Laberg and Vorren, 1995; Dowdeswell et al., 1996; Vorren et al., 1998; Nygård et al., 2007; Dowdeswell et al., 2008) and the North Sea Fan immediately north of our study area (King et al., 1996; Taylor et al., 2002a, b). In plan-form, the lobe-like features we have observed in 3D seismic cubes (Fig. 18C, D) clearly resemble the dimensions of Late Weichselian glacigenic debris flows. Glacigenic debris flows close to the surface of the North Sea and Bear Island fans have typical widths of about 2–10 km, thicknesses of 10–50 m, and lengths of 30 to about 200 km down the faces of these large Late Weichselian trough-mouth fans (e.g. Taylor et al., 2002a, b). The mid-Norwegian shelf has also been built out up to 150 km towards the west and northwest by similar processes (Rokoengen et al., 1995; Dahlgren et al., 2002; Rise et al., 2005; Ottesen et al., 2009). The implication is that, in the Early Quaternary, an ice sheet was present on the western Scandinavian margin and delivered debris into the adjacent Early Quaternary basin to the west (Figs. 8 and 15A).

Quaternary sediments in the northern North Sea and on the mid-Norwegian shelf also include clay-rich diamicts with ice-rafted pebbles of sedimentary and crystalline origin (Eidvin et al., 2000; Ottesen et al., 2009). Some intervals of sandy diamict deposition in the North Sea also have lithologies similar to those of glacimarine sediments in the Norwegian Sea (Jansen and Sjøholm, 1991; Fronval and Jansen, 1996). In the Norwegian Sea, the frequency of ice-rafted debris shows a large increase from 2.75 Ma that reflects marked expansion of the ice cover of northern Europe. It is unlikely that the icebergs were derived from the Greenland Ice Sheet; this would require a major reorganisation of the present ocean-circulation system in the Norwegian-Greenland Sea.

These indicators imply that an ice sheet was present, at least intermittently, over the Scandinavian mainland during the Early Quaternary (Fig. 16). In addition, this ice sheet reached the sea in waters sufficiently deep to calve icebergs whose keels then ploughed the former sea floor as they drifted away from their source on the Scandinavian margin (Dowdeswell and Ottesen, 2013). Ploughmarks in the northern North Sea Basin are usually orientated north–south, suggesting that drift was parallel to the shelf, providing a source of icebergs to the central North Sea Basin. Further, because ploughmarks are present continuously from 300 to 900 m depth in the stratigraphy of the central North Sea Basin (Dowdeswell and Ottesen, 2013), icebergs must have been produced over a number of intervals during the Early Quaternary.

More generally, the basins present in the northern and central North Sea at close to 2.75 Ma were filled with sediments during the Early Quaternary (Fig. 4). Debris was derived both from the European rivers to the south and south-east, to a minor extent from Britain, and from the Scandinavian Ice Sheet to the east (Fig. 16). Both enhanced glacifluvial and glacial activity appear to have begun in northwest Europe after 2.75 Ma (Jansen and Sjøholm, 1991; Eidvin et al., 2000). The filling of the accommodation space in the North Sea Basin during the Early Quaternary may have led to the inception of the Norwegian Channel Ice Stream, advancing into shallower water in the Middle to Late Quaternary with extensive erosion on the eastern side of the North Sea. This cutting produced an unconformable URU in the eastern part of the northern and central North Sea. Sejrup et al. (1995) proposed that the start of formation of the URU, linked to the initial development of the Norwegian Channel Ice Stream, was at 1.1 Ma. We suggest that it is likely that the initiation of the ice stream is somewhat younger, within the Brunhes magnetic period (Fig. 2). Early Quaternary sedimentation within the North Sea Basin, which has a minimum total volume of 40 000 km^3 within our study area (Fig. 1), may therefore extend over a period of about 2 million years (Fig. 2).

10. Conclusions

- A very large collection of 2D and 3D seismic datasets (Fig. 1) has made it possible to elaborate the large-scale geological evolution of the central and northern North Sea basins during the Early Quaternary, prior to the formation of the Norwegian Channel. Both the Norwegian and the UK sectors of the North Sea have been investigated, allowing the reconstruction of the infill history of the northern and central North Sea (c. 170 000 km^2) during the Early Quaternary.
- The infilling pattern for the northern and central North Sea basins has been different (Fig. 15). The northern North Sea has been filled largely by prograding sediments, interpreted as glacigenic debris flows (Fig. 18), from the east. These sediments were deposited along the western margin of the advancing Scandinavian Ice Sheet outside western Norway. This documents a long glacial history in the northern North Sea before the Norwegian Channel existed, with recurrent ice sheets covering large parts of southern Norway and expanding across the palaeo-shelf to the former shelf-edge west of Norway. The central North Sea was filled by distal fluvial/glacifluvial and hemipelagic sediments deposited from the southeast, south and east.
- A regional unconformity (URU) has been mapped on the North Sea Plateau west of the Norwegian Channel (north of 59°N). This unconformity represents the transition between sediments deposited mainly from the east (below the URU) and sediments deposited predominantly from the west (above). The age of the URU is uncertain, but based on the location of the Brunhes/Matuyama (B/M) boundary in several shallow boreholes (Stoker et al., 1983) and seismic correlation, we suggest an age of 0.8 Ma or somewhat younger for the URU-surface on the North Sea Plateau. This transition also marks the start of the formation of the Norwegian Channel and the deposition of the North Sea Fan by the recurrent Norwegian Channel Ice Stream.
- The interpretation of URU in the northern North Sea has been extended southwards, where it represents a conformable surface called the URU-equivalent. The surface represents mainly the top of the sedimentary sequence that filled in the central North Sea from the east, southeast and south. The flat-lying units above this surface show indications of a stronger direct glacial influence, including tunnel valleys and glacial lineations.

- The findings of this study also document a strong although indirect glacial influence on the North Sea during the Early Quaternary through the presence of both prograding glacigenic debris flows (Fig. 18) and a long record of iceberg-keel ploughing. The whole lower package of Early Quaternary sediments in the central North Sea exhibits iceberg ploughmarks (Fig. 17; Dowdeswell and Ottesen, 2013), linked to the large increase in iceberg-rafted debris in the deep-sea sediments of the Norwegian Sea from about 2.8 Myr ago.
- About 70 000 km^3 of Quaternary sediments have been mapped in the study area (170 000 km^2) (1°W–7°E, 56°N–62°N). Inside the central parts of the North Sea Basin (Fig. 4), delimited by the 500 m contour of the base Naust-equivalent surface, 57 000 km^3 have been deposited. Of these, 40 000 km^3 (70%) are found below the URU or URU-equivalent surface, representing the period between 2.75 Ma and 0.8 Ma (Early Quaternary).

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