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Glacial, fluvial and contour-current-derived sedimentation along the northern North Sea margin through the Quaternary

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ABSTRACT

The thick sequence of Quaternary sediments preserved within the northern North Sea contains important information about the glacial history, palaeo-oceanographic conditions and slope stability of this region during the last 2.6 million years. The interplay between glacial, fluvial and contouritic processes can be determined from seismic stratigraphic studies. Here, seismic horizon, attribute and geomorphological interpretations of an extensive 2D seismic dataset (~100,000 km^2) and two 3D seismic cubes (~18,400 km^2) are integrated with lithological data from eight exploration wells to map sandy sedimentary units. Mapping of seismic horizons and facies reveals that, in addition to prograding glacial sediments derived from the Norwegian mainland, the Quaternary succession includes wedge-shaped units with prograding internal clinoforms building out from the East Shetland Platform, relatively flat-lying units of acoustically stratified sediments within the central northern North Sea, and aggrading to prograding units with low-amplitude internal reflections on the continental slope. The lowermost unit of Quaternary sediment is interpreted as an ~800 km^3 earliest Pleistocene (~2.6 Ma) turbidite-contourite deposit, in which turbidites derived from a fluvial delta building out from the East Shetland Platform transition seaward into aggrading to prograding sediments of the Shetland Drift. The wedge-shaped units are intercalated with glacigenic sediments in the central northern North Sea, showing that the East Shetland Platform was a major source area for the delivery of coarse-grained sediments during the Early Pleistocene (~2.6–0.8 Ma). The distribution of units of aggrading to prograding geometries suggests that contourites continued to develop on the continental slope, including on the North Sea trough-mouth fan, throughout the Quaternary. These interpretations constrain a new model for the Quaternary evolution of the northern North Sea that reconciles the development of the eastern and western sides of this margin, and shows the importance of fluvial-deltaic and contouritic sedimentation during periods of reduced glacigenic sediment input. Our model also provides a high-resolution analogue for the sedimentary architectures and seismic facies that can be produced by the interplay of down-slope and along-slope processes on other continental margins.

1. Introduction

At the onset of the Quaternary, the northern North Sea was dominated by a north-south-orientated sub-basin of the North Sea Basin (Fig. 1) (Ottesen et al., 2014, 2018). The evolution of the eastern side of the northern North Sea is relatively well-documented; a series of west- to northwest-prograding clinoforms (Fig. 2) record the infilling of the sub-basin during the Early Pleistocene (*c.* 2.6–0.8 Ma) by predominantly glacigenic sediments, prior to the excavation of the Norwegian Channel by the Norwegian Channel Ice Stream (Eidvin and Rundberg, 2001; Ottesen et al., 2014, 2018; Batchelor et al., 2017; Reinardy et al., 2017; Løseth et al., 2020).

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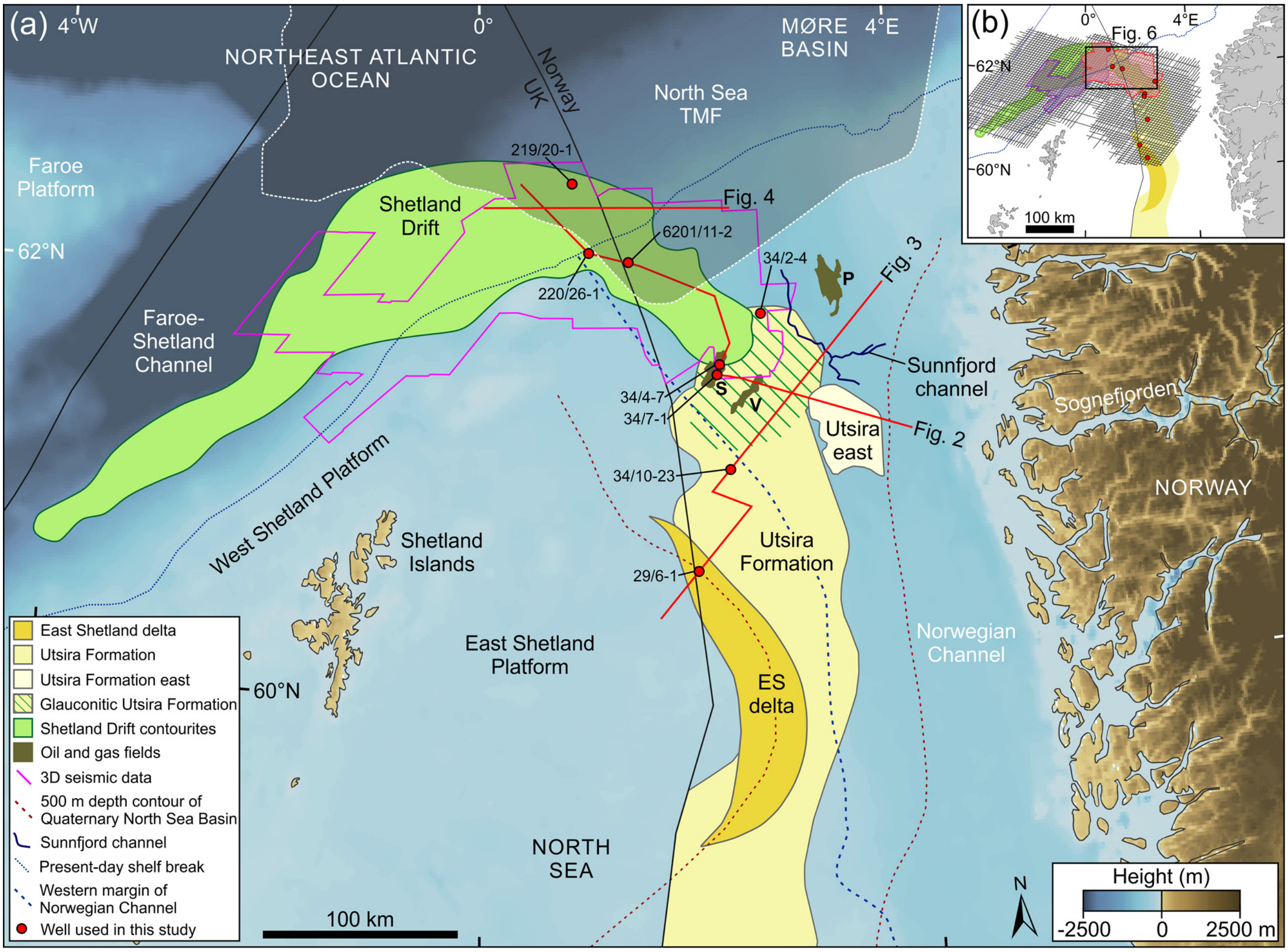


Fig. 1. **(a)** Location map, showing the distribution of Late Cenozoic sediment units in the northern North Sea. The extent of the Utsira Formation is adapted from Eidvin et al. (2014); the Utsira east and Sunnfjord channel are from Løseth et al. (2020); the Early Pleistocene East Shetland (ES) delta and the 500 m depth contour of the Quaternary North Sea Basin are from Ottesen et al. (2018); the Shetland Drift is from Knutz and Cartwright (2003) in the British sector and Batchelor et al. (2017) in the Norwegian sector. Grey shading is the main depocentre of the North Sea trough-mouth fan (TMF) from Nygård et al. (2005). P = Peon gas field; S = Snorre hydrocarbon field; V = Visund hydrocarbon field. Background bathymetry is ETOPO1 1 arc-minute global relief model of the Earth's surface (Amante and Eakins, 2009). **(b)** Map showing the distribution of the 2D seismic data (dark grey lines), and the End Of The World (EOTW; pink) and Northern Lights (NL; purple) 3D seismic cubes that are used in this study. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

Non-glacial sediments are also preserved within the complex Quaternary stratigraphy, particularly along the western side of the margin. A fluvial delta has been identified beyond the East Shetland Platform (Ottesen et al., 2014), and part of the Shetland Drift contourite system is suggested to have extended into the northern part of the sub-basin (Fig. 1a) (Batchelor et al., 2017). In addition, a distinctive flat-lying unit of uncertain extent and origin, termed the Basal Pleistocene Unit, has been identified underlying prograding glacigenic sediments on the basin floor (Eidvin and Rundberg, 2001; Eidvin et al., 2019). Together, these sediments contain information about past environmental and climatic conditions in the northern North Sea, and provide insights into the configuration of past river drainage networks and the changing location and intensity of ocean currents. The Early Pleistocene age of the sediments also makes them important to our understanding of the onset of Quaternary 'icehouse' conditions along the Northeast Atlantic margin. However, investigations into how these sediments relate to the broader stratigraphy and evolution of the margin have hitherto been hindered by gaps in high-resolution geophysical data coverage and a general lack of data spanning both the British and Norwegian sectors.

Here, we use two-dimensional (2D) and three-dimensional (3D) seismic data, supplemented by information from wells (Fig. 1), to investigate the Quaternary sediments of the northern North Sea. The aims of this work are to: 1) map the distribution and thickness of the Basal Pleistocene Unit and interpret its composition and origin; 2) interpret several other, potentially sandy, units of sediment that are preserved within the Quaternary succession; 3) produce new reconstructions of the evolution of the entire northern North Sea margin that show the changing relative importance of glacial, fluvial and contour-current-derived sedimentation through the Quaternary.

2. Background

2.1. Geological setting

Norway and the British Isles were uplifted during the Mid- and Late Miocene by compressive stresses, resulting in the subaerial exposure of parts of their continental shelves and the formation of a subsiding basin in the North Sea (Riis, 1992; Løseth et al., 2017). The East Shetland Platform (Fig. 1a) was a major source area for the delivery of clastic sediments to the North Sea throughout the Cenozoic, leading to the formation of several laterally extensive sand accumulations. The sand-rich Utsira Formation of Mid-Late Miocene to Pliocene age (Fig. 1a) (Eidvin et al., 1999; De Schepper and Mangerud, 2017), which directly underlies the predominantly

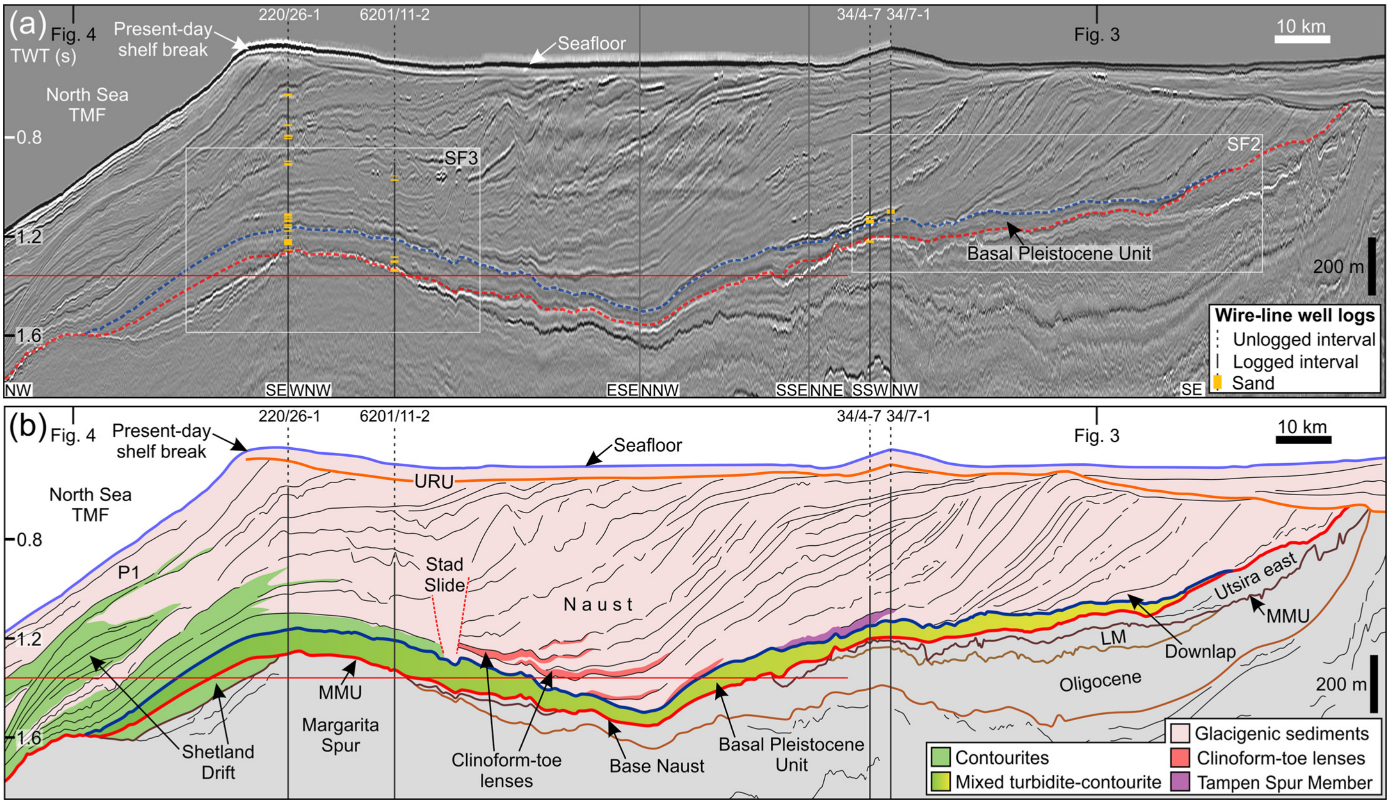


Fig. 2. **(a)** Composite seismic profile extending from the upper slope of the North Sea trough-mouth fan (TMF) in the northwest, to close to Sognefjorden, Norway in the southeast. Location is shown in Fig. 1a. The profile is from 3D seismic data to the northwest of well 34/7-1, and from 2D seismic data to the southeast of this well. Red and blue dashed lines are the basal and upper reflections, respectively, of the Basal Pleistocene Unit, as interpreted in this study. SF = Supplementary Figure; TWT = two-way travel time. Vertical exaggeration = ~50. **(b)** Interpretation of the seismic profile in (a). LM = Late Miocene; MMU = Mid-Miocene Unconformity; P1 = package 1 of Nygård et al. (2005), which is interpreted as glacigenic channel-levee sediments (Bellwald et al., 2020a) deposited during MIS 2 (Nygård et al., 2007; Lekens et al., 2009); URU = Upper Regional Unconformity. Horizontal red line in (a) and (b) shows depth of time-slice displayed in Fig. 6. Seismic data provided by TGS.

glacially influenced sediments of the Quaternary Naust Formation across most of the northern North Sea (Fig. 2), is interpreted to have been formed by high-energy currents in a shallow-marine setting (Rundberg, 1989; Eidvin and Rundberg, 2001; De Schepper and Mangerud, 2017). The Utsira Formation comprises a thick (up to 200 m), westward-thinning unit of mainly quartzose sand that is overlain by a thin glauconitic sand (Eidvin and Rundberg, 2001; De Schepper and Mangerud, 2017). Only the glauconite-rich sand is present in the wells of the Visund and Snorre fields in the northernmost North Sea (Fig. 1a) (Eidvin and Rundberg, 2001). An easterly component of the Utsira Formation is present west of Sognefjorden, Norway (Fig. 1a). 3D seismic data have revealed that the Utsira Formation east is a fluvial delta that contains numerous anastomosing and bifurcating channels (Løseth et al., 2020).

At the onset of the Quaternary, the northern North Sea was defined by a north-south-orientated sub-basin where the shelf break was located parallel and relatively close to the western Norwegian coastline (Fig. 1a) (Ottesen et al., 2014, 2018). A prominent unconformity, suggested to have been produced by erosive submarine debris flows, marks the Base Naust (Base Quaternary) in the northern North Sea and represents a hiatus spanning ~4.5–2.7 Ma (King, 1989; Eidvin et al., 2013). New age assignments indicate a younger, Pliocene age for the Utsira Formation, implying that this hiatus may be shorter than suggested previously (De Schepper and Mangerud, 2017).

The northern North Sea sub-basin was infilled in a clockwise direction during the Early Pleistocene by predominantly glacigenic sediments derived from the Norwegian mainland (Ottesen et al., 2014, 2018; Batchelor et al., 2017; Løseth et al., 2020). The Norwegian Channel Ice Stream, which initiated after about 1 Ma (Sejrup et al., 1995; Ottesen et al., 2014), eroded a significant proportion of these Early Pleistocene sediments, together with older strata, from the northern North Sea, forming an Upper Regional Unconformity (URU) across much of the continental shelf (Figs. 2 and 3). The Norwegian Channel Ice Stream delivered a large amount of sediment to the North Sea trough-mouth fan (Fig. 1a). This depocentre comprises numerous stacked glacigenic debris-flow lobes (King et al., 1996; Taylor et al., 2002; Nygård et al., 2005; Hjelstuen and Grinde, 2016)) and/or glacially sourced turbidite channel-levee systems (Bellwald et al., 2020a), together with mass-transport deposits from three major sediment slides (Figs. 2 and 4) (King et al., 1996; Nygård et al., 2005; Bellwald et al., 2019; Barrett et al., 2021).

2.2. *Oceanographic setting*

The Faroe-Shetland Channel (Fig. 1a) is a key site of water-mass exchange between the Northeast Atlantic and the Norwegian-Greenland Sea, representing a vital component of the global thermohaline circulation. At present, warm, northeast-flowing North Atlantic intermediate waters (temperature >5 °C; salinity >35 psu) occupy the upper 400 m of the water column, whilst colder Norwegian Sea Deep Water (temperature <3 °C; salinity <35 psu) flows towards the southwest below approximately 600 m (Masson, 2001; Furevik et al., 2002). A mounded contourite body, termed the Shetland Drift (Figs. 1a and 2), built up on the continental slope beyond the Shetland Islands during the Pliocene to Mid-Pleistocene (Knutz and Cartwright, 2003; Hohbein and Cartwright, 2006). The present-day water depth of the slope por-

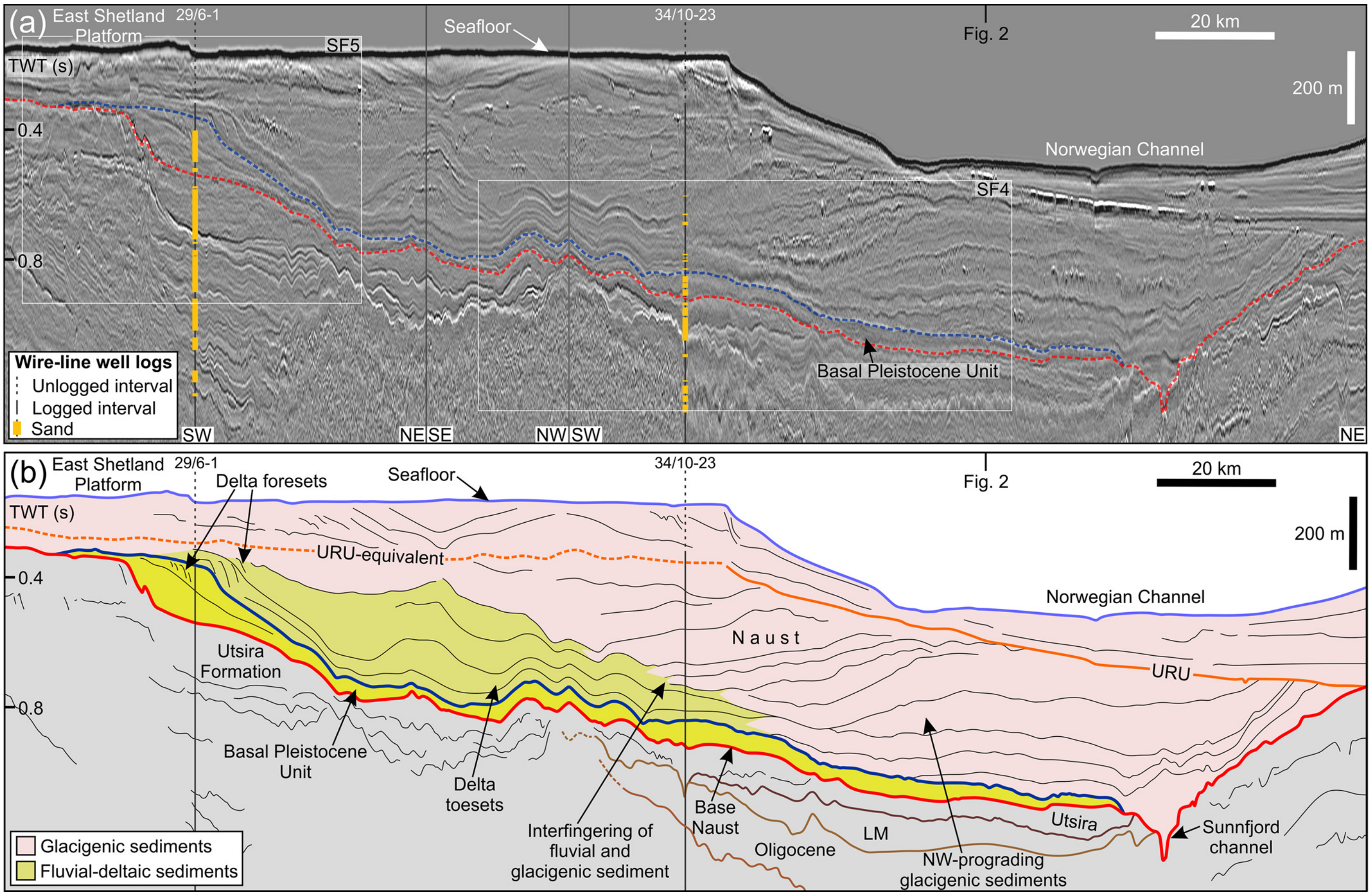


Fig. 3. **(a)** 2D seismic profile extending from the East Shetland Platform in the southwest to the eastern flank of the Norwegian Channel in the northeast. Location is shown in Fig. 1a. Red and blue dashed lines are the basal and upper reflections, respectively, of the Basal Pleistocene Unit, as interpreted in this study. SF = Supplementary Figure; TWT = two-way travel time. Vertical exaggeration = ~60. **(b)** Interpretation of the seismic profile in (a). LM = Late Miocene; URU = Upper Regional Unconformity. Seismic data provided by TGS.

tion of the Shetland Drift is between around 500 and 1000 m, which, accounting for a few hundred metres of subsidence during the Pliocene and Pleistocene, suggests that these contourites were formed by the southwest-flowing Norwegian Sea Deep Water current (Hohbein and Cartwright, 2006). The crest orientations and cross-sectional geometries of sediment waves within the contourite stratigraphy also indicate a south-westerly flow direction for this current (Hohbein and Cartwright, 2006).

3. Data and methods

3.1. Two-dimensional (2D) seismic data

Our seismic database includes a ~100,000 km^2 grid of 2D seismic-reflection profiles that spans the British and Norwegian sectors of the northern North Sea in water depths of approximately 100–1600 m (Fig. 1). This extensive dataset of new and reprocessed regional long-offset 2D seismic-reflection lines was acquired by TGS with a line spacing of 0.5–5 km (Fig. 1b). The vertical resolution of the 2D seismic data varies between surveys, but is generally around 5–8 m.

The Kingdom Suite seismic interpretation software was used to pick two horizons across the 2D seismic dataset: (i) the Base Naust reflection, and (ii) the upper reflection of the lowermost unit of the Naust Formation (Figs. 2–4 and S1–S5). Gridded surfaces, with cell sizes of 1 km, were generated from these picked horizons, and an isopach map of the intervening sediment thickness was produced (Fig. 5). A constant velocity of 1700 ms^{-1} was used for depth conversion of the isopach map, based on velocity measurements in exploration wells in the northern North Sea (Ottesen et al., 2014). The seismic profiles are shown in European normal standard wavelet polarity, whereby a positive-amplitude (black) peak reflection represents an increase in acoustic impedance, and a negative-amplitude (white) trough represents a reduction in acoustic impedance.

3.2. Three-dimensional (3D) seismic data

Two, slightly overlapping, 3D seismic cubes that together cover ~18,400 km^2 of the outer shelf and upper slope are also used (Fig. 1b). The End Of The World (EOTW) dataset comprises several surveys collected by TGS (2011–2013) and covers ~12,000 km^2. These data were acquired using two sources, a record length from 7,000 to 10,000 ms, and a shooting rate of 2 ms. The typical acquisition bin size was 6.25 by 25 m. These modern surveys have been merged with several older 3D surveys to fill gaps and generate a uniform dataset over a large area. The Northern Lights (NL) cube covers ~10,000 km^2 and consists of TGS surveys (2012–2014) also merged with vintage data. The modern surveys were acquired using similar acquisition parameters, using two sources, a record length of 8,000 ms, and 2 ms sampling. The processed grids for both 3D cubes were resampled to 4 ms, and the output grids are 12.5 by 12.5 m. The vertical resolution of the 3D seismic cubes is 3–4 m and the horizontal resolution (based on the output grid) is 12.5 by 12.5 m.

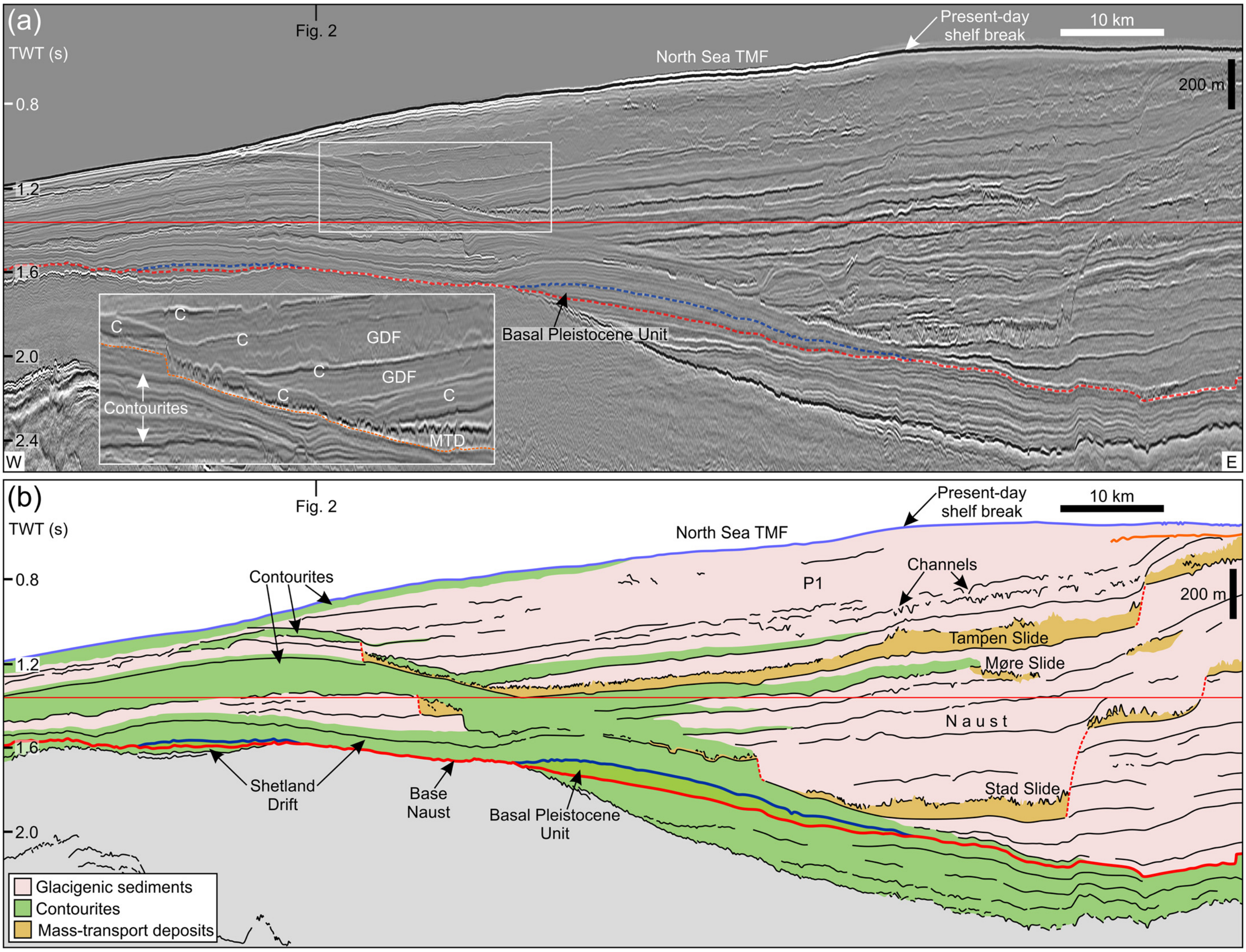


Fig. 4. (a) Profile within a 3D seismic cube that extends across the western lateral margin of the North Sea trough-mouth fan (TMF). Location is shown in Fig. 1a. Red and blue dashed lines are the basal and upper reflections, respectively, of the Basal Pleistocene Unit, as interpreted in this study. Inset shows detail of intercalated contouritic (C) and glacigenic debris-flow (GDF) units at the western margin of the TMF. Orange dashed line is the base of the Tampen Slide in inset. MTD = mass-transport deposit; TWT = two-way travel time. Vertical exaggeration = ∼25. **(b)** Interpretation of the seismic profile in (a). P1 = package 1 of Nygård et al. (2005), which is interpreted as glacigenic channel-levee sediments (Bellwald et al., 2020a) deposited during MIS 2 (Nygård et al., 2007; Lekens et al., 2009). Horizontal red line in (a) and (b) shows depth of time-slice displayed in Fig. 6. Seismic data provided by TGS.

The 3D seismic data were used to assist horizon picking and enable correlation between wells. In addition to their higher vertical resolution compared to the 2D data, use of the 3D seismic cubes enabled 'arbitrary' seismic profiles to be constructed at orientations other than those permitted by the (SW-NE, SE-NW-orientated) 2D grid (Figs. 1b, 2 and 4). Time-slice images through the 3D seismic cubes were also used to visualise the broad-scale evolution of the margin (e.g. Fig. 6).

3.3. Well logs

Our seismic interpretations are integrated with data derived from wire-line well logs that were accessed using TGS's Facies Map Browser. The well logs were analysed by the drilling companies and compiled subsequently by the Norwegian Petroleum Directorate.

Lithological interpretations and gamma-ray values are displayed for eight wells in the northern North Sea (Figs. 1 and 7). These data were used to support geological interpretations and to aid seismic-reflection correlation with previous research (Eidvin and Rundberg, 2001; Ottesen et al., 2009, 2014; Eidvin et al., 2019). The eight wells were chosen because they include information about Pleistocene sediments and form a roughly north-south transect across the study area (Fig. 1).

4. Results: seismic stratigraphy

4.1. Lowermost Naust Formation

Two reflections are mapped across the northern North Sea: (i) the Base Naust, and (ii) the top of the lowermost unit of the Naust Formation (Figs. 2–4 and S1–S5).

4.1.1. Base Naust

The Base Naust (Base Quaternary) reflection (red in Figs. 2–4 and S1–S5) is a well-defined erosional unconformity of negative polarity along much of the eastern basin margin (Jordt et al., 1995; Eidvin and Rundberg, 2001; Goledowski et al., 2012; Ottesen et al., 2014). Here, the Base Naust reflection truncates older sediments, including the eastern part of the Utsira Formation, and, in some areas, merges with the high-amplitude Mid-Miocene Unconformity (Figs. 2, S2). The Base Naust reflection incorporates the base of

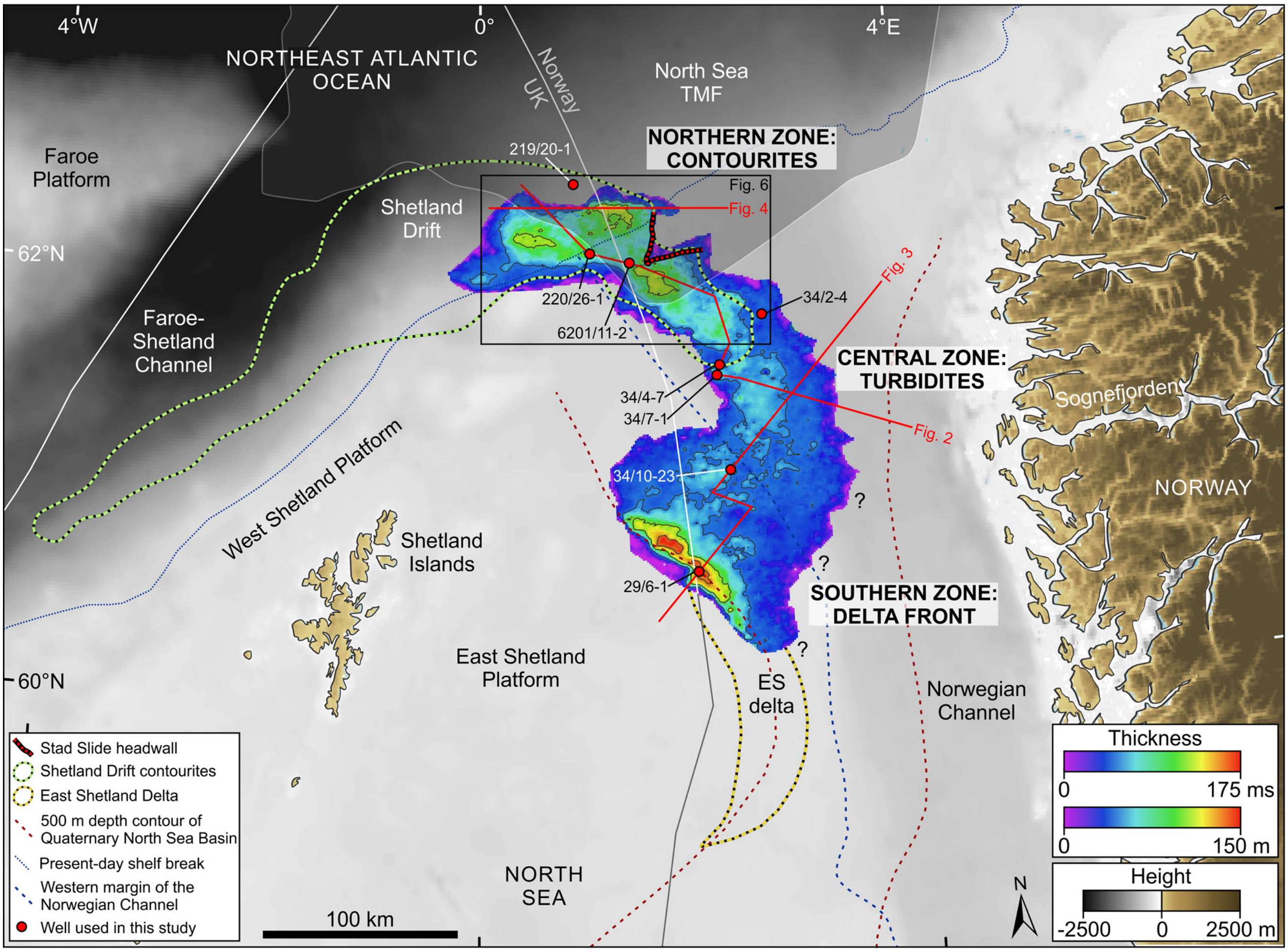


Fig. 5. Isopach map of the ~19,000 km^2 (~800 km^3) Basal Pleistocene Unit, as mapped from 2D and 3D seismic data in this study. Grid-cell size is 1 km. Contours are every 50 ms (~45 m). The Shetland Drift, East Shetland (ES) delta, and 500 m depth contour of the Quaternary North Sea Basin are as in Fig. 1a. Grey shading is the main depocentre of the North Sea trough-mouth fan (TMF) from Nygård et al. (2005). Background bathymetry is ETOPO1 1 arc-minute global relief model of the Earth's surface (Amante and Eakins, 2009).

the late Pliocene to Early Pleistocene Sunnfjord channel (Figs. 1a and 3) (Gregersen, 1998; Eidvin and Rundberg, 2001; Løseth et al., 2020). Correlation of the seismic data with published seismic profiles shows that our Base Naust reflection along the eastern basin margin is the same as in several previous investigations (Eidvin and Rundberg, 2001; Ottesen et al., 2009, 2014, 2018; Batchelor et al., 2017; Eidvin et al., 2019; Løseth et al., 2020).

Towards the western basin margin, the Base Naust reflection is conformable with underlying strata and can be traced as a clinoform within a prograding wedge extending from the East Shetland Platform (Figs. 3, S4 and S5). Towards the north of the margin, the Base Naust reflection is interpreted to be close to the base of the Stad Slide, which occurred about 0.5 Ma ago (Fig. 2) (Nygård et al., 2005). The relatively condensed section between the base of this slide and the Base Naust reflects a time, during the Early Pleistocene, when the focus of sedimentation in the northern North Sea was several tens of kilometres closer to the Norwegian coastline relative to the Mid- to Late Pleistocene component of the trough-mouth fan (Fig. 2). The Base Naust reflection merges with the high-amplitude Mid-Miocene Unconformity over some parts of the outer shelf to upper slope (Figs. 2 and S3). On the continental slope beyond the Shetland Islands, the Base Naust is traced as a low-amplitude reflection within the aggrading to prograding Shetland Drift contourite body (Figs. 2, 4 and S3).

4.1.2. *Top of the Basal Pleistocene Unit*

The top of the lowermost unit of the Naust Formation (blue in Figs. 2–4 and S1–S5) is a prominent downlap surface in the eastern and central parts of the northern North Sea. Although this reflection is of variable (negative) amplitude, it represents a distinctive facies boundary between the overlying west- to northwest-prograding clinoforms and underlying relatively flat-lying reflections (Figs. 2 and S2). Towards the western side of the basin, the top of the lowermost Naust Formation unit can be traced as a conformable reflection within a prograding wedge (Figs. 3, S4 and S5). This reflection is also conformable with overlying strata to the north of the margin, where it can be mapped as a low-amplitude reflection within the aggrading to prograding Shetland Drift before downlapping onto the Base Naust reflection (Figs. 2 and S3).

4.1.3. *Basal Pleistocene Unit*

The two reflections that were mapped across the northern North Sea bound the lowermost unit of the Naust Formation (Figs. 2–4 and S1–S5). This unit has been identified in parts of the basin in previous studies, including Eidvin and Rundberg (2001; 'basal Upper Pliocene'), Batchelor et al. (2017; 'basin-fill unit'), and Løseth et al. (2020; 'condensed basal unit with dropstones'). We refer to this unit as the Basal Pleistocene Unit following the nomenclature of Eidvin et al. (2019).

The Basal Pleistocene Unit reaches a maximum thickness of 175 ms (~150 m) beyond the East Shetland Platform (Figs. 3 and 5). It

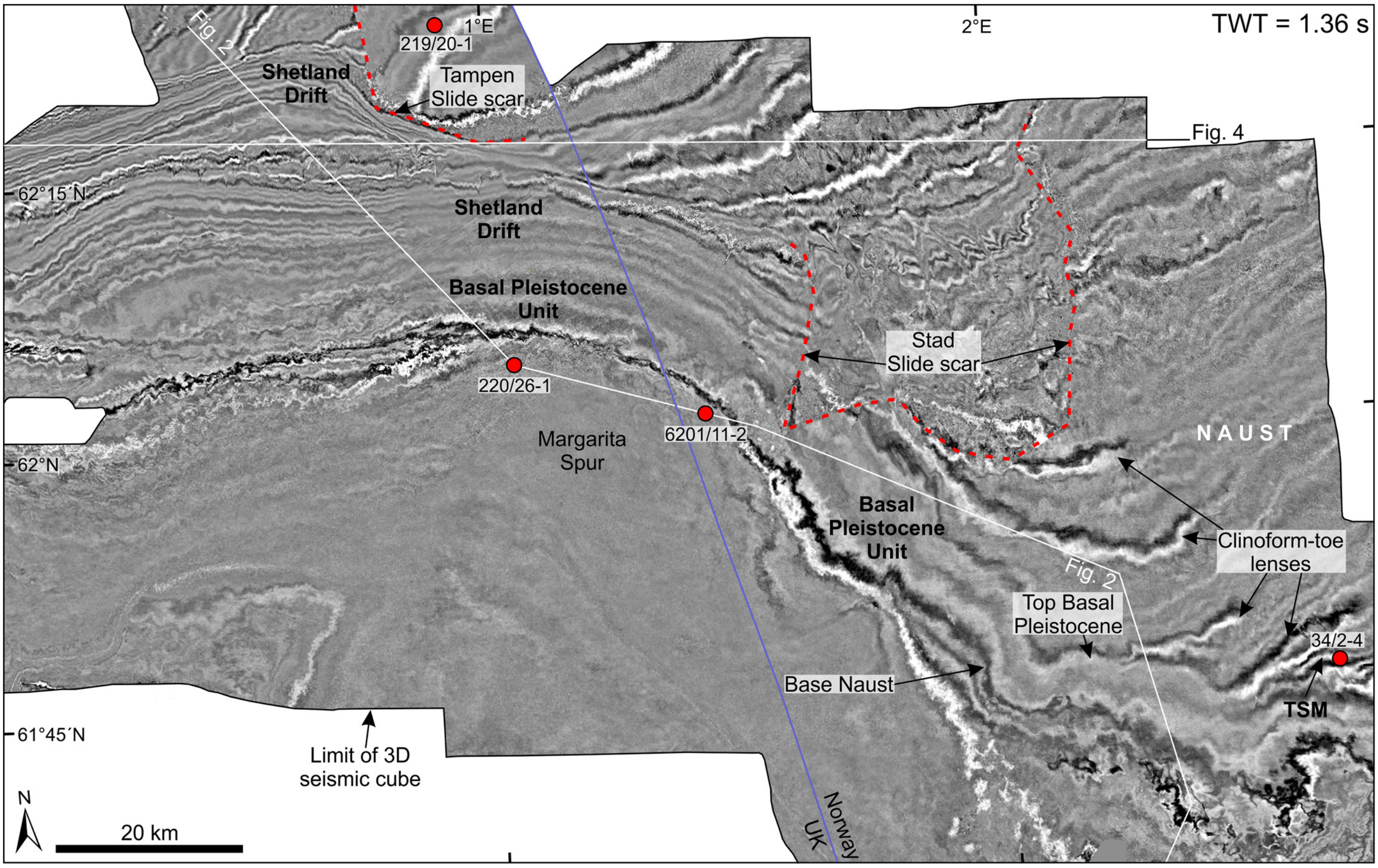


Fig. 6. Time-slice through a 3D seismic cube at 1.36 seconds two-way travel time (TWT), showing the northwest progradation of slope clinoforms within the Naust Formation, and the northward progradation of the Shetland Drift. Location is in Figs. 1b and 5. White lines are locations of seismic profiles shown in Figs. 2 and 4. TSM = Tampen Spur Member. Seismic data provided by TGS.

is ~50 ms (~45 m) thick over most of the central northern North Sea, thickening to ~100 ms (~85 m) on the upper slope beneath the North Sea trough-mouth fan (Figs. 2 and 5). The unit thins to the northwest on the upper slope (Figs. 2 and 4) and cannot be mapped west of ~0° longitude. A significant proportion of the Basal Pleistocene Unit appears to have been removed by the Stad Slide (Figs. 5 and 6).

The Basal Pleistocene Unit has variable geometry and internal seismic character along the margin. To the south, it forms part of a prograding wedge that contains northeast-prograding clinoforms of up to 3° inclination (Figs. 3 and S5; Table S1). It is relatively flat-lying in the central basin, where it displays low-amplitude stratified internal reflections (Figs. 2, 3 and S4; Table S1). To the north of the margin, the Basal Pleistocene Unit is acoustically stratified with low-amplitude parallel to sub-parallel internal reflections (Figs. 2 and S3; Table S1). The progradational to aggradational geometry of this part of the Basal Pleistocene Unit is demonstrated in time-slice in Fig. 6, which shows how this unit and overlying sediments have built out in a northward direction into the Northeast Atlantic.

4.2. Naust Formation overlying the Basal Pleistocene Unit

The seismic stratigraphy of the Naust Formation above the Basal Pleistocene Unit has been well-documented, particularly along the eastern basin margin. The west- to northwest-prograding clinoforms building out from the eastern basin flank (Fig. 2) have been shown to comprise glacigenic debris-flows produced during successive full-glacial periods (Ottesen et al., 2014; Batchelor et al., 2017; Løseth et al., 2020). Towards the north of the margin, the North Sea trough-mouth fan is composed mainly of acoustically transparent to chaotic glacigenic debris-flow and/or glacial turbidite channel-levee systems, and mass-transport deposits (Table S1) (King et al., 1996; Taylor et al., 2002; Nygård et al., 2005; Hjelstuen and Grinde, 2016; Bellwald et al., 2020a; Barrett et al., 2021).

Three additional architectural elements are identified within the Naust Formation. First, towards the western basin flank, some of the sediments overlying the Basal Pleistocene Unit have wedge-shaped geometry and contain northeast-prograding clinoforms (Figs. 3 and S5; Table S1). In the central sub-basin, these sediments intercalate with the west- to northwest-prograding clinoforms of the glacial depocentre building out from the eastern basin flank (Figs. 3 and S4).

Secondly, along the eastern basin margin, some of the glacially influenced northwest-prograding clinoform packages are separated on the lower slope by intercalated and onlapping acoustically transparent lenses up to 50 ms (~45 m) thick (Figs. 2, S1b and c) (Eidvin and Rundberg, 2001; Batchelor et al., 2017; Bellwald et al., 2020b). Nine lenses are identified towards the northern part of the margin (Fig. S1b and c), together with a tenth lens in the vicinity of the Snorre field about 20 km farther south (Figs. 2 and S1b). The upper reflection of each lens is high-amplitude and of negative polarity (Figs. 2, 6 and S1c; Table S1). Some of the clinoform-toe lenses appear to transition seaward into the sediments of the Shetland Drift, although correlation is made difficult by the headwall of the Stad Slide (Figs. 2 and 6).

Finally, on the outer shelf and upper slope, some of the Naust Formation sediments above the Basal Pleistocene Unit have aggrading to prograding geometry and contain low-amplitude parallel to sub-parallel reflections (Figs. 2, 4, 6 and S3; Table S1). These acoustically stratified sediments are intercalated with the acoustically

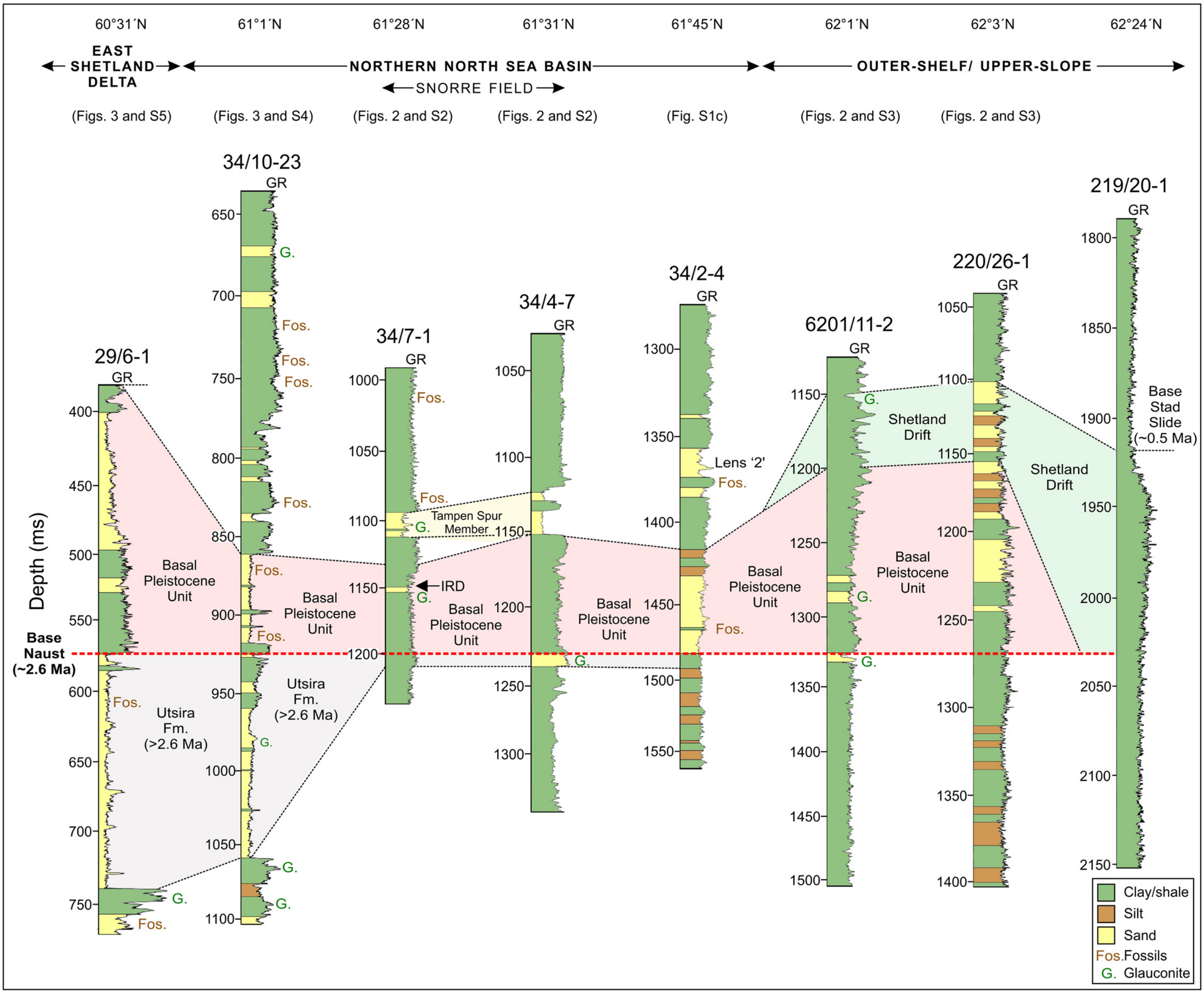


Fig. 7. Well log correlation diagram of selected wells from the northern North Sea margin, showing the thickness and distribution of the Basal Pleistocene Unit (of probable earliest Pleistocene age). Well locations are shown in Figs. 1a and 5. Correlation of wells with seismic data is shown in Figs. 2 and 3 and Supplementary Figs. 1–5. Black arrow shows where ice-rafted debris (IRD) was identified in a dissolved and sieved side-wall core from well 34/7-1 (Ottesen et al., 2009). Our placement of the Basal Pleistocene Unit in wells 34/7-1, 34/4-7 and 34/2-4 is consistent with the interpretations of Eidvin and Rundberg (2001) and Eidvin et al., 2019. GR = gamma-ray log.

transparent to chaotic sediments of the North Sea trough-mouth fan (Figs. 2 and 4). The acoustically stratified sediments are thickest towards the western, British, side of the trough-mouth fan and thin to the east (Fig. 4).

5. Geological interpretations

5.1. *Basal Pleistocene Unit*

The Basal Pleistocene Unit is categorised into three zones (southern, central, and northern; Fig. 5) defined by its geometry and internal seismic character. The wedge-shaped geometry and prograding internal reflections of the southern Basal Pleistocene Unit (Figs. 3 and S5; Table S1) suggest that these sediments are part of a delta (henceforth the East Shetland delta). The clinoforms record the north-eastward progradation of the delta front from the East Shetland Platform into the northern North Sea. This interpretation is consistent with information from wells 29/6-1 and 34/10-23 (Figs. 1a and 5), which show that this interval is relatively sand-rich, with shallow-marine fossils (Figs. 7, S4 and S5). The Base Naust horizon does not correspond with a change in lithology in this region because it is underlain by the similarly sand-rich Utsira Formation (Figs. 3, 7, S4 and S5).

In the central zone, the geometry of the Basal Pleistocene Unit, which thickens to the southwest (Fig. 5), together with its acoustically stratified character (Figs. 3, S2 and S4; Table S1), suggests that these sediments are turbidites deposited on the mid- to lower slope of the delta building out from the East Shetland Platform. The presence of freshwater algae and terrestrial palynomorphs in the sediments of this interval (De Schepper and Mangerud, 2017) also indicates a strong riverine influence. Lithological information derived from well logs suggests that the Basal Pleistocene Unit is composed variably of clay to sand in the central northern North Sea (Figs. 7, S2 and S4). A thin (~5 m), glauconite-rich layer of sand is identified close to the Base Naust boundary in wells 34/4-7 and 6201/11-2 (Figs. 2, 7, S2 and S3), which may represent the underlying glauconitic part of the Utsira Formation (Fig. 1a) (Eidvin and Rundberg, 2001). Previous investigations have revealed that there is a significant increase in ice-rafted debris (IRD) at the

Base Naust reflection in this region compared to the underlying units (Eidvin and Rundberg, 2001; Ottesen et al., 2009).

In the northern zone, the aggrading to prograding geometry and low-amplitude stratified reflections of the Basal Pleistocene Unit (Figs. 2, 4, 6 and S3; Table S1) suggest that it is part of the Shetland Drift contourite system that developed on the continental slope since the Pliocene (Knutz and Cartwright, 2003; Hohbein and Cartwright, 2006). Here, the Base Naust reflection, which merges with the Mid-Miocene Unconformity across some parts of the outermost shelf, corresponds with a change from clays to overlying sand layers (Figs. 2, 7 and S3).

Collectively, these interpretations suggest that the Basal Pleistocene Unit is a turbidite-contourite deposit that records a lateral transition from fluvial-deltaic turbidites derived from the East Shetland delta to the contourites of the Shetland Drift (Figs. 2–5).

5.2. Naust Formation overlying the Basal Pleistocene Unit

Most of the Naust Formation sediments that overlie the Basal Pleistocene Unit are recorded in the well logs as clay (Figs. 2, 7, S1 and S2), and have been interpreted previously as fine-grained diamicton with abundant IRD (Eidvin and Rundberg, 2001; Ottesen et al., 2009). Here, we provide interpretations of three additional architectural elements within the Naust Formation, based on their geometry and internal character on seismic profiles and supported by geological information derived from wells.

5.2.1. East Shetland delta

The wedge-shaped geometry and prograding internal reflections of some of the sediments overlying the Basal Pleistocene Unit at the western basin flank (Figs. 3 and S5; Table S1) suggest that the East Shetland delta continued to supply fluvial-deltaic sediments to the northern North Sea during the Early Pleistocene (Ottesen et al., 2014). Some of these northeast-prograding sediments are intercalated in the central northern North Sea with northwest-prograding sediments building out from the eastern basin flank (Figs. 3 and S4) (Løseth et al., 2020). Although they are not as sand-rich as the sediments of the underlying Basal Pleistocene Unit and Utsira Formation, the fluvio-deltaic sediments sourced from the west contain more sand layers than the glacigenic sediments sourced from the east (Figs. 3 and S4).

5.2.2. Clinoform-toe lenses

Along the eastern basin margin, the strong negative polarity of the upper reflection of each of the nine clinoform-toe lenses within the Naust Formation (Figs. 2, 6 and S1; Table S1) suggests that these lenses are coarser grained than overlying sediments. One of these lenses (lens ‘2’) is penetrated by well 34/2-4, where it corresponds to a ~15 m-thick layer of sand (Figs. 2, 7 and S1) (Eidvin and Rundberg, 2001). The clinoform-toe lenses are interpreted as fan deposits produced when glacigenic debris-flows diminished in velocity on the basin floor (Eidvin and Rundberg, 2001; Eidvin et al., 2013). The elongate plan-view geometry of these lenses, which are orientated parallel to the palaeo-shelf break (Fig. S1), implies that down-slope sediment transport took place mainly through unchannelised turbidites rather than within channels on the continental slope (e.g. Patruno and Helland-Hansen, 2018). The elongate and mounded geometry and sand-rich lithology of the clinoform-toe lenses (Figs. 2 and S1) suggest that these features may be mixed turbidite-contourite deposits, formed when along-slope currents stripped the finer-grained particles from turbidity flows (e.g. Shanmugam et al., 1993; Mulder et al., 2008; de Castro et al., 2020; Fonnesu et al., 2020).

The tenth clinoform-toe lens that is identified, in the vicinity of the Snorre field, corresponds with a sandy interval in wells 34/4-7 and 34/7-1 (Figs. 2, 7, S1 and S2). This sand, which is informally termed the Tampen Spur Member (Eidvin et al., 2013, 2019), has been interpreted to have been extruded to the palaeo-seafloor sometime during the Early Pleistocene (Løseth et al., 2012). However, we note that the Tampen Spur Member sand has similar dimensions and geometry to the other clinoform-toe lenses that are mapped to the north of the margin (Figs. 2, S1 and S2).

5.2.3. Shetland Drift contourites

Within the North Sea trough-mouth fan, several units with aggrading to prograding geometry and low-amplitude stratified internal reflections are interpreted as contourites (Figs. 2, 4, 6 and S3; Table S1). These contouritic sediments are separated within the trough-mouth fan stratigraphy by acoustically transparent to chaotic sediments interpreted as glacigenic debris-flows/turbidites, and mass-transport deposits (Figs. 2 and 4) (Nygård et al., 2005; Lekens et al., 2009; Hjelstuen and Grinde, 2016; Bellwald et al., 2020a). The identification of aggrading to prograding sediment layers within the upper part of the trough-mouth fan stratigraphy (Fig. 4) suggests that contourites, which have accumulated in this location since at least the Pliocene, continued to build up through the Mid- to Late Pleistocene and may still be accumulating on the seafloor today. The contouritic sediments that immediately overlie the Basal Pleistocene Unit on the outermost shelf (well 220/26-1) are relatively sand-rich (Figs. 2, 7 and S3). However, younger contouritic sediments ~30 km farther to the north (well 219/20-1) are composed of fine-grained material (clay/shale) (Figs. 1a and 7). The intercalation of contourites and glacigenic debris-flows/turbidites within the slope stratigraphy (Fig. 4) implies that this is a mixed turbidite-contourite system, in which the relative importance of along-slope and down-slope processes of sedimentation varied through time (e.g. Mulder et al., 2008; Fonnesu et al., 2020; Rodrigues et al., 2021).

6. Discussion

6.1. Age of the Basal Pleistocene Unit

Three lines of evidence suggest that the Basal Pleistocene Unit is earliest Pleistocene in age. First, this unit directly overlies the Base Naust reflection of ~2.6 Ma, and immediately underlies most of the west- to northwest-prograding clinoforms of the glacial depocentre building out from the eastern basin flank (Fig. 2) (Ottesen et al., 2014; Løseth et al., 2020). Secondly, although the Basal Pleistocene Unit was previously assigned a Miocene age and included as part of the Utsira Formation (Gradstein et al., 1992), more recent microfossil and Strontium isotope analyses suggest that it was formed during the Gelasian Stage of the Early Pleistocene, sometime between *c.* 2.6 and 1.8 Ma (Eidvin and Rundberg, 2001; De Schepper and Mangerud, 2017; Eidvin et al., 2019, 2020). It should, however, be noted that Strontium isotope analyses of Pleistocene sections along this margin do not generally yield reliable ages because of the reworking of calcareous fossils, in addition to the uncertainty in calculating ages from a relatively flat Strontium isotope curve (Eidvin et al., 2020). Finally, as grounded ice is suggested to have first reached the western Norwegian coastline during the latest Pliocene to earliest Pleistocene, the presence of IRD in side-wall cores from this interval suggests that the Basal Pleistocene Unit is younger than ~2.75 Ma (Eidvin and Rundberg, 2001; Ottesen et al., 2009).

6.2. Origin of the Basal Pleistocene Unit

The Basal Pleistocene Unit is interpreted as a turbidite-contourite deposit that records the source to sink transfer of sediment from the East Shetland Platform to the Northeast Atlantic Ocean

(Figs. 5 and 8e). The southern zone of the Basal Pleistocene Unit forms a ~20 km-wide wedge-shaped depocentre along the East Shetland Platform that shows the basinward progradation of the East Shetland delta front (Figs. 3 and 5). The East Shetland delta likely also extends beyond our data coverage into the central North Sea (Fig. 1a and 5) (Ottesen et al., 2014). The central zone of the Basal Pleistocene Unit is interpreted to be composed of prodeltaic turbidites deposited on the gently sloping mid- to lower delta (Fig. 5). These sediments transition into a thicker, aggrading to prograding sediment body on the outer shelf to upper slope, suggesting that at least some of the turbiditic sediments nourished the Early Pleistocene part of the Shetland Drift (Fig. 2). The implied south-westerly transfer of sediments by along-slope ocean currents (Fig. 8) is consistent with the interpretation that the Shetland Drift was formed by the southwest-flowing Norwegian Sea Deep Water current (Hohbein and Cartwright, 2006).

The mapped Basal Pleistocene turbidite-contourite system (Fig. 5) covers ~19,000 km^2 and has a volume of ~800 km^3. To the south of the study area, the prograding delta front is relatively sand-rich and has similar lithology and gamma-ray values in well logs to the underlying Utsira Formation (Figs. 3, 7, S4 and S5). The central and northern parts of the system are mainly clay with sand beds (Figs. 2, 7 and S1–S3). This is broadly consistent with models that show how the transition from a turbidite to a contourite involves a continuous transition from a sandy deposit to alternating layers of mud and sand (Stanley, 1993; de Castro et al., 2020; Fonnesu et al., 2020).

6.3. *Evolutionary model for the northern North Sea*

Our extensive seismic dataset (Fig. 1b) enables the, largely nonglacial, Quaternary evolution of the western side of the northern North Sea sub-basin to be reconciled with the mainly glacially influenced development of its eastern flank (Fig. 8). These data inform a new evolutionary model, presented in Fig. 8, that shows the changing relative importance of glacial, fluvial and contour-current-derived sedimentation through the Quaternary.

Fluvial-deltaic and contouritic sedimentation dominated during the earliest Pleistocene (~2.6 Ma), as demonstrated by the formation of the turbidite-contourite Basal Pleistocene Unit (Figs. 5 and 8e). A grounded ice mass extended to the palaeo-shelf break west of Sognefjorden during this time, but it delivered glacial sediment to only a limited area of the eastern basin margin (Løseth et al., 2020). The northernmost part of the margin, including the Møre Basin (Fig. 1a), was distal to the main fluvial and glacial sediment sources during the earliest Pleistocene; sediment delivery to this area probably took place mainly by along-slope currents (Fig. 8e).

The intercalated sediments that are preserved in the central northern North Sea (Figs. 3 and S4) show that the proportion of sediment derived from the eastern and western basin flanks varied through the Early Pleistocene. This pattern may reflect glacial-interglacial cycles. Given that high rates of glacial sediment delivery from the east would have dominated sedimentation during relatively short (up to a few thousand years; Nygård et al., 2007) periods of shelf-break glaciation (Fig. 8d), fluvial sediments derived from the non-glaciated western basin flank are likely to have accumulated and/or been preserved mainly during longer non-glacial intervals (Fig. 8c). The continued development of the East Shetland delta and the Shetland Drift (Figs. 2 and 3) suggests that contour currents may have continued to redistribute fluvial-deltaic sediments derived from the western side of the basin during the Early Pleistocene. The presence of sandy clinoform-toe lenses along the eastern basin margin (Figs. 2 and S1) indicates that along-slope currents may have also played a role in stripping fine-grained particles from glacially derived turbidity flows (Shanmugam et al., 1993; de Castro et al., 2020).

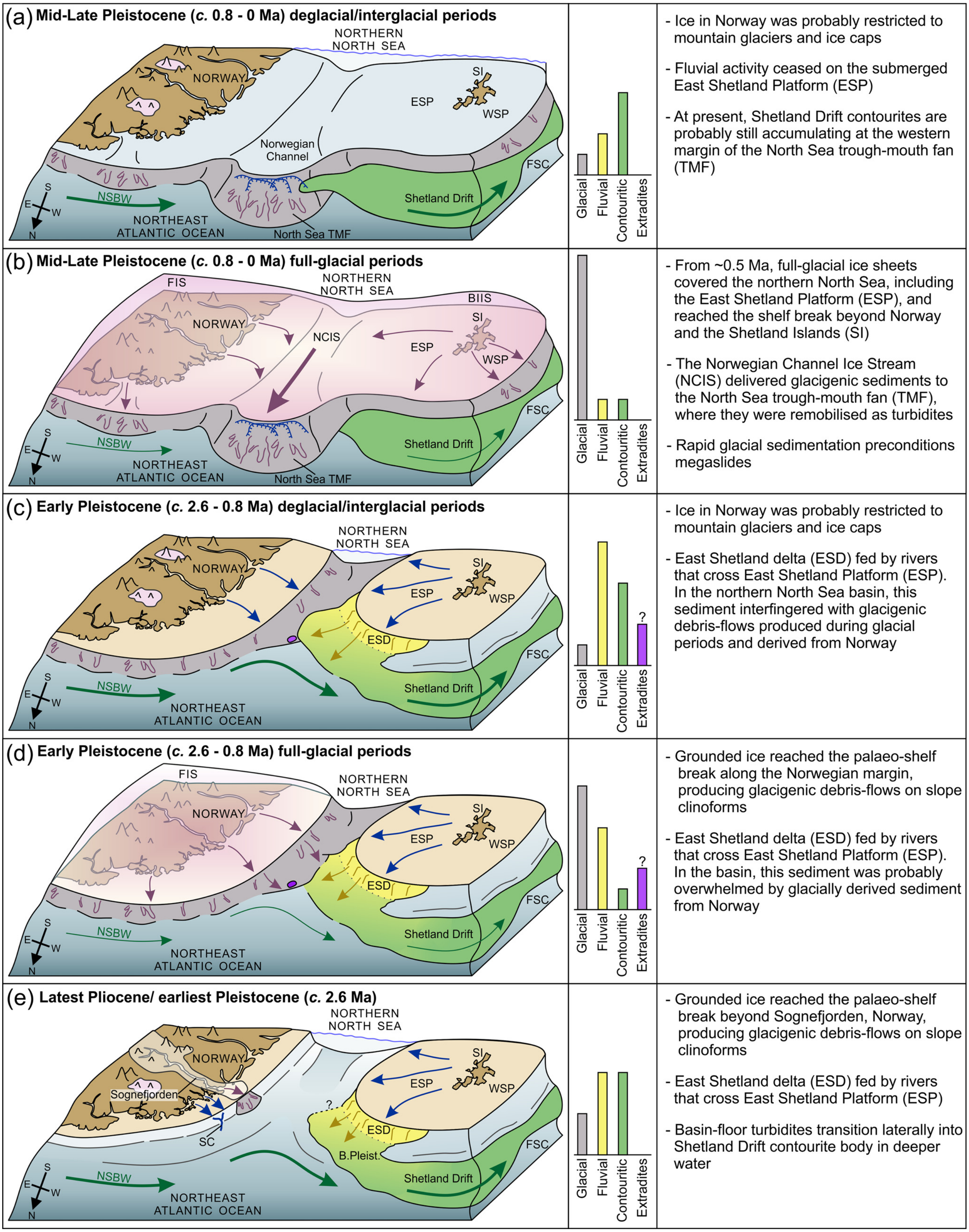
Development of the East Shetland delta ceased when the East Shetland Platform became submerged, which was probably sometime during the Early to Mid-Pleistocene (Fig. 8a and b). The infilling of most of the northern North Sea sub-basin by *c*. 1 Ma (Reinardy et al., 2017; Ottesen et al., 2018) enabled the confluence of the Fennoscandian and British-Irish ice sheets during several Mid- to Late Pleistocene glaciations (Ehlers et al., 2011; Stewart and Lonergan, 2011) and caused the focus of glacigenic sediment deposition to shift northward into the Northeast Atlantic (Fig. 8b) (Batchelor et al., 2017). The delivery of large quantities of glacigenic sediment to the palaeo-shelf break by the Norwegian Channel Ice Stream resulted in a significant increase in downslope sediment transport to the northernmost part of the margin during the Mid- to Late Pleistocene (Fig. 8b), with rates as high as 100 m/kyr on the North Sea Fan during shelf-edge glaciation in MIS 2 (Bellwald et al., 2020a). The rapid deposition of glacial sediments also resulted in overpressure build-up, which preconditioned megaslides and instigated overpressure-driven sediment remobilization (Bellwald et al., 2019, 2020b).

The intercalation of contouritic sediments with glacigenic debris-flows/turbidites on the western side of the North Sea trough-mouth fan (Fig. 4) shows that contourites continued to develop along this margin during the Mid- to Late Pleistocene. This intercalated pattern may record changes in the nature of sediment deposition and/or preservation during glacial-interglacial cycles. Reduced rates of glacigenic sediment input, combined with fewer/no erosive glacial debris-flows (Ottesen et al., 2014, 2018; Løseth et al., 2020), would have enabled non-glacial sediments including contourites to build up, albeit at a lower rate, on the seafloor during interglacial periods. In contrast, contour-current-derived sediments are more likely to have been eroded or masked by high rates of glacigenic sediment input during relatively short periods of shelf-break glaciation (Nygård et al., 2007). The identification of acoustically transparent lenses of sediment, which are interpreted as contourites, at or close to the present-day seafloor (Fig. 4) suggests that along-slope ocean currents may still be providing sediments to the western side of the North Sea trough-mouth fan today.

6.4. *Implications*

We recognise three different types of sedimentary deposits within the Quaternary stratigraphy that are interpreted to have been formed by the interaction of down-slope and along-slope processes (e.g. Mulder et al., 2008; Fonnesu et al., 2020; Rodrigues et al., 2021). First, the Basal Pleistocene Unit records a lateral transition from fluvial-deltaic turbidites derived from the East Shetland delta to the contourites of the Shetland Drift (Figs. 2–5). Secondly, sand-rich clinoform-toe lenses along the eastern basin flank (Figs. 2 and S1), which are Early Pleistocene in age, are interpreted to have been formed when along-slope currents stripped the finer-grained particles from glacigenic debris-flows/turbidites. Finally, at the western side of the North Sea trough-mouth fan, the intercalation of contourites with glacigenic debris-flow/turbidite packages (Fig. 4) records temporal variations in the dominance of along-slope (contourite) and down-slope (turbidite) processes during the Mid- to Late Pleistocene. The northern North Sea is one of the most data-rich and comprehensively investigated glaciated continental margins on Earth. The turbidite-contourite deposits that we have investigated here therefore provide a high-resolution analogue for the sedimentary architectures and seismic facies that can be produced by the interplay of down-slope and along-slope processes on other continental margins (e.g. de Castro et al., 2020; Fonnesu et al., 2020; Rodrigues et al., 2021).

The identification of intercalated contourites and glacigenic debris-flow packages within the North Sea trough-mouth fan



(a) Mid-Late Pleistocene (*c.* 0.8 - 0 Ma) deglacial/interglacial periods

- Ice in Norway was probably restricted to mountain glaciers and ice caps
- Fluvial activity ceased on the submerged East Shetland Platform (ESP)
- At present, Shetland Drift contourites are probably still accumulating at the western margin of the North Sea trough-mouth fan (TMF)

(b) Mid-Late Pleistocene (*c.* 0.8 - 0 Ma) full-glacial periods

- From ~0.5 Ma, full-glacial ice sheets covered the northern North Sea, including the East Shetland Platform (ESP), and reached the shelf break beyond Norway and the Shetland Islands (SI)
- The Norwegian Channel Ice Stream (NCIS) delivered glacigenic sediments to the North Sea trough-mouth fan (TMF), where they were remobilised as turbidites
- Rapid glacial sedimentation preconditions megaslides

(c) Early Pleistocene (*c.* 2.6 - 0.8 Ma) deglacial/interglacial periods

- Ice in Norway was probably restricted to mountain glaciers and ice caps
- East Shetland delta (ESD) fed by rivers that cross East Shetland Platform (ESP). In the northern North Sea basin, this sediment interfingered with glacigenic debris-flows produced during glacial periods and derived from Norway

(d) Early Pleistocene (*c.* 2.6 - 0.8 Ma) full-glacial periods

- Grounded ice reached the palaeo-shelf break along the Norwegian margin, producing glacigenic debris-flows on slope clinoforms
- East Shetland delta (ESD) fed by rivers that cross East Shetland Platform (ESP). In the basin, this sediment was probably overwhelmed by glacially derived sediment from Norway

(e) Latest Pliocene/ earliest Pleistocene (*c.* 2.6 Ma)

- Grounded ice reached the palaeo-shelf break beyond Sognefjorden, Norway, producing glacigenic debris-flows on slope clinoforms
- East Shetland delta (ESD) fed by rivers that cross East Shetland Platform (ESP)
- Basin-floor turbidites transition laterally into Shetland Drift contourite body in deeper water

Fig. 8. **(a)** to **(e)** Schematic diagrams showing the evolution of the northern North Sea margin through the Quaternary. Coloured bars in the middle panel show the suggested relative importance of glacial, fluvial, contouritic and extruded sediments during each time period. Blue lines in (a) and (b) show the headwalls of three major slides (Stad, Møre and Tampen). BIIS = British-Irish Ice Sheet; ESD = East Shetland delta; ESP = East Shetland Platform; FSC = Faroe-Shetland Channel; FIS = Fennoscandian Ice Sheet; NCIS = Norwegian Channel Ice Stream; NSBW = Norwegian Sea Bottom Water; SC = Sunnfjord channel; SI = Shetland Islands; SO = Sognefjorden; TMF = trough-mouth fan; WSP = West Shetland Platform.

(Fig. 4) also has implications for understanding and modelling the pre-conditioning and triggering of submarine slides on glaciated continental margins, including the Stad, Møre and Tampen slides that occurred within this depocentre approximately 0.5, 0.4 and 0.15 Ma, respectively (Figs. 4 and 8) (King et al., 1996; Nygård et al., 2005; Bellwald et al., 2019; Barrett et al., 2021). Glide planes for slope failure can develop where contouritic sediments act as weak layers (Laberg et al., 2003; Bryn et al., 2005) or where a rapid change in sediment strength occurs at the interface between contourites and geotechnically stronger glacigenic sediments (Laberg et al., 2016). Numerical modelling of the Tampen Slide suggests that the presence of a glide plane, which is most likely a contourite bed, contributed significantly to the preconditioning of the slope to instability (Bellwald et al., 2019).

Although most of the Naust Formation sediments are fine-grained glacial clay, the East Shetland delta is sand-rich (Figs. 3, 7, S4 and S5) and sand beds are present in some of the landward parts of the Shetland Drift (Figs. 2, 7 and S3). The high-amplitude lenses at the toe of the prograding Naust clinoforms, including the Tampen Spur Member, are also sand-rich (Figs. 2, 7 and S1). Information about the distribution of potentially sandy sediments within the Naust Formation is needed to understand the role of Quaternary hydrocarbon reservoirs in the North Sea (Bellwald et al., 2020b; Kurjanski et al., 2020). Whereas the search for reservoir facies in the petroleum industry has traditionally focused on turbidite systems, mixed turbidite-contourite deposits can comprise well-sorted sands that have good potential reservoir properties on burial (Shanmugam et al., 1993; Viana et al., 2007; Mulder et al., 2008; de Castro et al., 2020; Fonnesu et al., 2020).

7. Conclusions

We use a grid of 2D seismic data and two large 3D seismic cubes, combined with lithological information from wells (Fig. 1b), to investigate the distribution, composition and origin of the Quaternary sediments of the northern North Sea. The lowermost unit of the Naust Formation, termed the Basal Pleistocene Unit, is mapped across the northern North Sea (Figs. 2–5) and is interpreted as a turbidite-contourite deposit of earliest Pleistocene age. In this system, turbidites derived from a fluvial delta building out from the East Shetland Platform transition laterally into part of the Shetland Drift. The broad coverage of the seismic data enables us to produce an evolutionary model that reconciles the, largely non-glacial, development of the western side of the northern North Sea sub-basin with the, mainly glacially influenced, evolution of its eastern flank (Fig. 8). The East Shetland Platform continued to be a significant source area for the delivery of sediments to the northern North Sea sub-basin, and possibly also to the Shetland Drift, during the Early Pleistocene. Turbiditic sediments derived from the East Shetland delta are interpreted to have accumulated and/or been preserved mainly during periods of reduced glacial sediment input from the east (Fig. 8c). The intercalation of contourites with glacigenic debris-flow/turbidite packages within the North Sea trough-mouth fan (Fig. 4) records temporal variations in the relative importance of down-slope and along-slope processes of sedimentation during the Mid- to Late Pleistocene. Contourites are probably preserved mainly within the non-glacial intervals of the slope stratigraphy and may still be accumulating on the seafloor today.

CRediT authorship contribution statement

Christine L. Batchelor: Conceptualization, Funding acquisition, Investigation, Visualization, Writing – original draft. **Benjamin Bellwald:** Conceptualization, Project administration, Resources, Supervision, Writing – review & editing. **Sverre Planke:** Conceptualization, Project administration, Resources, Supervision, Writing – review & editing. **Dag Ottesen:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Sverre Henriksen:** Funding acquisition, Project administration, Supervision, Writing – review & editing. **Reidun Myklebust:** Funding acquisition, Project administration, Resources, Writing – review & editing. **Ståle E. Johansen:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Julian A. Dowdeswell:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

High-quality, non-interpreted images of the seismic profiles shown in this study, together with information about their location and processing, are available on the Open Science Framework https://osf.io/vftq3/.

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Appendix A. Supplementary material

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