Quaternary evolution of the northern North Sea margin through glacigenic debris-flow and contourite deposition

Christine L. Batchelor[1*], Dag Ottesen[2], Julian A. Dowdeswell[1]

[1]Scott Polar Research Institute, University of Cambridge, Cambridge CB2 1ER, UK.

[2]Geological Survey of Norway, Postboks 6315 Sluppen, N-7491 Trondheim, Norway.

*Corresponding author. Email: clb70@cam.ac.uk/

Abstract

The Norwegian Channel Ice Stream of the Scandinavian Ice Sheet extended across the northern North Sea margin during the mid to late Quaternary, eroding older sediment from the continental shelf. Consequently, little is known about early Quaternary sedimentation on this margin. We use 2D and 3D seismic-reflection data to investigate changing sediment volumes and sources in the northern North Sea through the Quaternary. The northern North Sea Basin was infilled during the early Quaternary by intercalated glacigenic debris-flows and contourites, which provide a record of the delivery of glacigenic sediment to the slope and the intensity of North Atlantic thermohaline circulation during early Quaternary glacial-interglacial cycles. The infilling of the basin reduced accommodation and led to the deflection of mid to late Quaternary sediments into the Norwegian Sea, forming the North Sea Fan. Close to the onset of the mid Quaternary, the south-western Scandinavian Ice Sheet margin was drained by an ice stream located beneath Måløy Plateau, 60 km east of the Last Glacial Maximum Norwegian Channel Ice Stream. The southward-flowing Norwegian Sea Bottom Water current was directed into the partially-filled northern North Sea Basin during the early Quaternary, and deflected progressively northwards as the basin became infilled.

Keywords: northern North Sea; Quaternary; palaeo-ice stream; glacigenic debris-flows; contourites

1. Introduction

The northern North Sea is presently an epicontinental sea bordered by Norway to the east and the Shetland Islands to the west (Fig. 1). To the north, the low-gradient (*c.* 0.5°) continental slope extends down to a depth of more than 3000 m in the Norwegian Sea. At the start of the Quaternary, around 2.7 Ma, the bathymetry of the northern North Sea was dominated by the N-S orientated North Sea Basin (Ottesen *et al*., 2014), which has been infilled subsequently by acoustically semi-transparent prograding wedges of clinoform geometry (Fig. 2). The source of these sediments has been shown to have shifted from the Norwegian mainland in the east, to the Norwegian Channel in the south sometime during the early Quaternary (*c.* 2.6 to 0.8 Ma). The south-western margin of the Scandinavian Ice Sheet (SIS) has been suggested to have advanced to the palaeo-shelf break during the early Quaternary (Ottesen *et al*., 2014). However, little is known about the detailed patterns and processes of early Quaternary sedimentation.

In this study, we use 2D and 3D seismic-reflection data to describe and interpret the Quaternary seismic stratigraphy of the northern North Sea margin including the North Sea trough-mouth fan (TMF). We show that the early Quaternary evolution of the margin involved the gradual infilling of the northern North Sea Basin by predominantly glacial and contour-current derived sediment, and that the architecture of the margin, in turn, exerted a significant influence on subsequent ice-sheet and ocean-current configuration.

2. Background: glacial history and oceanographic conditions

The northern North Sea is a key site for reconstructing the extent and dynamics of the SIS through the Quaternary, which is necessary for constraining ice-sheet models (e.g. Hughes *et al*., 2016). The Norwegian Channel Ice Stream (NCIS) of the SIS, which occupied and eroded the deep (up to 700 m) Norwegian Channel (Fig. 1), extended to the shelf break during several mid and late Quaternary full-glacial periods (Sejrup *et al*., 1995, 2000; Nygård *et al*., 2005). The NCIS eroded a significant proportion of early Quaternary sediment from the continental shelf and led to the construction of the North Sea Fan on the adjacent slope (Fig. 1) (King *et al*., 1996; Taylor *et al*., 2002; Nygård *et al*., 2005).

A prominent Upper Regional Unconformity (URU), which becomes younger towards the present-day shelf break, (Fig. 2) was produced by the oldest or most erosive advance of the NCIS (Sejrup *et al*., 1995). The NCIS has been suggested to have initiated around 1.1 Ma, based on amino-acid, micropalaeontological and palaeomagnetic analysis of glacial and related sediments in the Troll borehole (Sejrup *et al*., 1995). There is also a suggestion, based on the position of the Bruhnes-Matuyama magnetic boundary, that the initiation of the NCIS is somewhat younger, around 0.8 Ma (Stoker *et al*., 1983; Ottesen *et al*., 2014).

As a consequence of mid and late Quaternary ice-stream erosion, comparatively little is known about early Quaternary sedimentation on the northern North Sea margin (Lee *et al*., 2010; Ottesen *et al*., 2014). The configuration of the south-western margin of the SIS during the early Quaternary, before the initiation of the NCIS, is uncertain. Some authors have advocated a relatively restricted ice sheet over Norway (Sejrup *et al*., 1995; Mangerud *et al*., 1996), whereas others have proposed an extensive SIS extending intermittently into the northern North Sea (Dowdeswell and Ottesen, 2013; Ottesen *et al*., 2014).

The geological record from the northern North Sea also contains valuable information about palaeo-oceanographic conditions through the Quaternary. At present, the warm, northeast-flowing Norwegian Current occupies the upper 200 to 500 m of the water column, whist a layer of colder Norwegian Sea Bottom Water (NSBW) flows south-westwards below around 600 m (Turrell *et al*., 1999; Masson, 2001) (Fig. 1). These currents drive water-mass exchange between the North Atlantic and the Norwegian-Greenland Sea via the Faeroe-Shetland Channel (Fig. 1), representing a vital component of the global thermohaline circulation. The location and intensity of along-slope currents and the development of contour-current derived depocentres are influenced strongly by seafloor geometry and global climatic changes such as glacial-interglacial cycles (Bryn *et al*., 2005). However, the impact of Quaternary glaciations and filling of the northern North Sea Basin on contourite development this region has not been examined previously.

3. Methods

We use a *c.* 80,000 km² grid of 2D seismic-reflection profiles, supplemented by a cube of 3D seismic data (Fig. 1), to investigate the evolution of the northern North Sea margin (Figs. 3 and 4). The 2D seismic-reflection data were acquired by the hydrocarbons industry over the past three decades. A velocity of 1700 m/s was used for depth conversion of the seismic data, based on velocity measurements in exploration wells in the northern North Sea (Ottesen *et al*., 2014). We acknowledge that the use of a consistent velocity for all depth conversions results in some uncertainty in horizon depth and unit thickness.

The 3D seismic cube was collected in 2007 by Petroleum Geo-Services (PGS) and covers 1540 km². The horizontal and vertical resolution of the cube, which is 25 m and around 10 m respectively, enables visualisation of relatively subdued glacial features on horizontal time slices and amplitude maps generated from interpreted horizons (e.g. Dowdeswell *et al*., 2007) (Fig. 5). Whereas a significant proportion of early Quaternary sediments was eroded and removed from the landward region of the shelf, a thick (> 600 m) sequence of these sediments is preserved close to the present-day shelf break (Fig. 2). These sediments, which include several preserved palaeo-shelves, are interpreted using the 3D cube of seismic-reflection data. Seismic horizons were picked using Petrel software, and visualised, mapped and interpreted using ArcGIS and Fledermaus.

4. Results

The base-Quaternary in the northern North Sea (Figs. 2, 3a) is defined by correlation with the base of the predominately glacially-influenced NAUST formation on the mid-Norwegian margin, which was deposited from around 2.75 Ma (Eidvin *et al*., 1999; Dahlgren *et al*., 2002; Rise *et al*., 2005; Ottesen *et al*., 2009). We divide the 1600 m-thick Quaternary infill of the basin (Fig. 4a) into four major units, A to D, following the seismo-stratigraphic framework of Ottesen *et al*. (2014). We deviate from this framework by placing the base of Unit D at a higher level in the stratigraphy, which corresponds with a change in the acoustic character of the sediments (Fig. 2). Unit C is divided into two sub-units of similar architecture, Ci and Cii.

4.1 Units A and B

Units A and B reach a combined thickness of greater than 400 m (Figs. 2 and 4b). They are characterised by a series of westerly-prograding clinoform packages (Fig. 2). The clinoform packages are composed of acoustically semi-transparent sediment and are bounded by continuous, high-amplitude reflections that downlap onto the Base NAUST horizon (Fig. 2c). A number of lobate features, with widths of around 2 km and thicknesses of 10 to 50 m, have been observed previously in 3D seismic data within Units A and B (Ottesen *et al*., 2014).

The clinoforms within Units A and B are interpreted to be palaeo-slope surfaces that record the westerly progradation of sediment into the northern North Sea Basin from a source on the

Norwegian mainland. Accommodation was provided by early Quaternary subsidence of the northern North Sea (Riis, 1996). The lobate features have been interpreted to be glacigenic debris-flow deposits (GDFs) produced by the remobilisation of subglacially-derived sediment on the upper-continental slope (Ottesen *et al*., 2014). The distribution of Units A and B suggests that Sognefjorden (Fig. 4b), which is presently the longest and deepest fjord in Norway, may have been a significant drainage pathway of the early Quaternary SIS.

4.2 Basin-fill unit

The northern North Sea Basin floor is blanketed by a unit of acoustically semi-transparent sediment that is up to 50 m thick (Fig. 2c and d). The clinoform wedges of Unit Ci downlap onto the upper reflection of this unit, indicating that it was deposited prior to Unit Ci. The semi-transparent unit can be traced onto the continental slope northeast of the Shetland Islands, where it follows the slope contours at a present-day water depth of 1000 to 1800 m and increases in thickness to greater than 150 m (Figs. 2c, d and 4c). It is thickest along a central axis that is parallel to the slope contours. On the continental slope, the unit consists of aggrading, acoustically transparent lenses separated by continuous, low-amplitude reflections (Fig. 2c). It is underlain and overlain by sediments of similar acoustic character and geometry.

The basin-fill unit (Figs. 2c, d and 4c) is interpreted as the eastern extension of the Western Shetland Drift (here, termed the Shetland Drift (SD)). The SD is a plastered contourite drift that was formed from the Late Neogene by the southwest-flowing NSBW current impinging on the continental slope beyond the Shetland Islands (Turrell *et al*., 1999; Knutz and Cartwright, 2002; Hohbein and Cartwright, 2006). The lower section of the Quaternary contourite unit, which drapes the northern North Sea Basin floor (Fig. 2 c and d), is not intercalated with prograding clinoform units, suggesting that it may have been deposited during a period of restricted glaciation.

4.3 Units Ci and Cii

Units Ci and Cii, which reach thicknesses of more than 600 and 450 m, respectively (Fig. 4d and e), are composed predominantly of northwesterly to north-northwesterly prograding clinoform packages (Fig. 2). The approximate shelf break migrated seaward and clockwise through these units, in response to the gradual infilling of the northern North Sea Basin (Figs. 3f, 4d and e). Amplitude maps generated from interpreted horizons on 3D data reveal that the upper slopes of the clinoform packages contain overlapping, elongate lobes up to 2 km wide and 10 km long (Fig. 5d).

The geometry and dimensions of the elongate lobes (Fig. 5d) suggest that they are GDFs produced by remobilisation of subglacial sediment delivered to the shelf break. Similar lobate features, interpreted as GDFs, have been identified on the upper continental slope of many high-latitude margins (Laberg and Vorren, 1995; Dowdeswell *et al*., 1996), including the North Sea Fan (King *et al*., 1996, 1998; Nygård *et al*., 2002; Taylor *et al*., 2002).

To the north of the study area, the clinoform packages within Units Ci and Cii are separated on the lower slope by nine intercalated and on-lapping symmetrical lenses of acoustically transparent sediment (Figs. 2a, b and 5b). The upper-reflection of each lense is bounded by a continuous, high-amplitude reflection of negative polarity. The negative acoustic impedance contrast indicates that the sediment in each lense is of lower acoustic impedance (lower density) compared with the overlying material. The lenses occur in present-day water depths of 1000 to 1400 m (Fig. 4g-i). They have maximum thicknesses of 25 to 80 m and possess an elongate geometry in plan-view, with the thickest sediment occurring along a central axis (Figs. 4g-I, 5c). Lense orientation shifts from north/south to northeast/southwest through Units Ci and Cii, maintaining parallel conformity with the palaeo-shelf break.

The mounded geometry of the lenses, together with their high-amplitude upper and lower reflections and position at the foot of the palaeo-slope (Figs. 4g to i, 5b and c), suggests that they are contourites (e.g. Laberg *et al*., 1999). The present-day water depth of the contourites, which is between 1000 and 1400 m, indicates that they were formed by the southwest-flowing NSBW current. The modern NSBW current operates below a water depth of around 600 m (Turrell *et al*., 1999; Masson, 2001). In contrast to GDFs, which are formed during ice-sheet advances to the shelf break (Laberg and Vorren, 1995; King *et al*., 1996), the contourites were probably produced during interglacial periods of reduced ice cover and active thermohaline circulation in the North Atlantic (Raymo *et al*., 1990; Rahmstorf, 2002).

4.4 Unit D

Unit D encompasses the North Sea Fan, which has been interpreted to have developed from around 1 Ma ago (Sejrup *et al*., 1995; Nygård *et al*., 2005). The base of Unit D therefore represents an approximate boundary between early and mid Quaternary sediments.

Unit D reaches a thickness of greater than 1400 m, with the thickest sediments close to the present-day shelf break (Fig. 4f). The Unit D TMF is characterised by northerly-prograding clinoform packages and acoustically chaotic units up to 200 m thick (Fig. 2a). Elongate lobes of similar dimensions and geometry to those within Units Ci and Cii (Fig. 5d) are identified in several clinoform packages (Fig. 5e). The chaotic units have irregular upper surfaces displaying a distinctive pattern of curvilinear ridges and depressions on amplitude maps of 3D seismic-reflection data (Fig. 5f).

The clinoform packages are interpreted as ice-sheet derived GDFs (Fig. 2). However, it is possible that the lower parts of these packages also contain turbidites. The acoustically chaotic units within Unit D are interpreted as mass-transport deposits (MTDs) resulting from the Stad, Møre and Tampen submarine sediment slides, which occurred on the TMF around 0.5 Ma, 0.4 Ma and 0.15 Ma ago (Evans *et al*., 1996; King *et al*., 1996; Nygård *et al*., 2005; Hjelstuen and Grinde, 2015). The curvilinear ridges and depressions on the upper surfaces of the MTDs (Fig. 5f) are interpreted as rafted sediment blocks (e.g. Hampton *et al*., 1996). Although it is possible that evidence of contourite deposition has been obscured by high rates of sediment delivery to the TMF, the absence of acoustically transparent sediment lenses at the base of Unit D clinoforms (Fig. 2) suggests that contourite deposition was not significant on the TMF during mid to late Quaternary interglacial periods.

At the base of Unit D, a 130 km-wide, relatively flat-floored depression of around 400 m below present-day sea level extends north-westwards from close to the mouth of Sognefjorden to the palaeo-shelf break (Fig. 3d). A number of northwest/southeast-orientated ridges up to a few hundred metres wide and 5 km long are identified from 3D seismic-reflection data of a preserved palaeo-shelf at the base of Unit D (Fig. 5g). Elongate ridges of similar dimensions are observed on several other palaeo-shelves within Unit D (red triangles in Fig. 2b). Beneath the URU, the elongate ridges display a northwest/southeast orientation (Fig. 5g), whereas the ridges on and above the URU have a north-northwest/south-southeast orientation (Fig. 5h).

The elongate ridges (Figs. 2b, 5g and h) are interpreted as mega-scale glacial lineations (MSGLs) (Clark, 1993). MSGLs have been observed on many formerly glaciated seafloor and palaeo-shelf surfaces, and have been interpreted as direct evidence of grounded, fast-flowing ice (Elverhøi *et al*., 1995; Andreassen *et al*., 2004; Ottesen *et al*., 2005; Dowdeswell *et al*., 2007).

The 130 km-wide depression at the base of Unit D (Fig. 3d) is interpreted as a cross-shelf trough that was eroded and occupied by an ice stream (Batchelor and Dowdeswell, 2014).

The trough location suggests that an ice stream flowed from the southwest to the palaeo-shelf break over what is presently the shallow inter-trough bank of Måløy Plateau (Fig. 3e). This is supported by the northwest/southeast-orientated MSGLs on the palaeo-shelf at the base of Unit D (Fig. 5g) and by north/south-orientated elongate ridges, which have been interpreted as MSGLs, around 100-200 m below the present-day seafloor of Måløy Plateau (Nygård *et al.*, 2004; Rise *et al.*, 2004, 2016). The ice stream is shown to have occupied an outer-shelf position approximately 60 km east of the flow path of the NCIS during the Last Glacial Maximum (LGM) (Fig. 3e). The changing orientation of the MSGLs within Unit D (Fig. 5g and h) probably reflects westerly migration of this ice stream through the mid to late Quaternary.

Irregular, linear to curvilinear depressions, with widths of a few hundred metres and lengths of up to 10 km, are identified on many of the preserved palaeo-shelves within Unit D (Fig. 5i). They are interpreted as iceberg ploughmarks produced by iceberg keels grounding in seafloor sediments (Dowdeswell *et al.*, 1993; Dowdeswell and Ottesen, 2013; Newton *et al.*, 2016).

5. Discussion: ice-sheet and ocean-current configuration through the Quaternary

We use seismic data to infer changes in ice-sheet and ocean-current configuration through the Quaternary (Fig. 6). Evidence for the expansion of the south-western margin of the SIS during the earliest Quaternary includes elongate lobes interpreted as GDF deposits (debrites) on palaeo-slope horizons in the northern North Sea (Ottesen *et al.*, 2014) and iceberg ploughmarks on palaeo-shelf surfaces of at least 2 Ma in the central and southern North Sea (Kuhlmann and Wong, 2008; Stewart and Huuse, 2012; Dowdeswell and Ottesen, 2013).

This interpretation of an expanded SIS during the earliest Quaternary is supported by an increase in IRD on the Vøring Plateau of the mid-Norwegian margin from around 2.7 Ma

(Mangerud *et al.*, 1996; Jansen *et al.*, 2000). Initial ice-sheet expansion was followed by a period of reduced glaciation between around 2 and 1.6 Ma (Jansen *et al.*, 2000), which may correspond with contourite deposition on the floor of the partially filled northern North Sea Basin (Fig. 6b).

The filling of the northern North Sea Basin occurred gradually during the early Quaternary and is recorded by the shifting position of the palaeo-shelf break (Figs. 3f, 6c and d). The basin infill is inferred to consist predominantly of debrites derived from an ice sheet flowing perpendicular to the palaeo-shelf break during full-glacial periods of reduced thermohaline circulation (Fig. 5d), and contourites that were deposited by along-slope currents during periods of reduced glaciation and active thermohaline circulation (Figs. 5c, 6c and d) (Raymo *et al.*, 1990; Rahmstorf, 2002).

The south-western margin of the SIS is assumed to have expanded significantly later in the Quaternary compared with the onset of large-scale glaciation further north in Norway and the Barents Sea, which occurred from around 1.5 Ma (Solheim *et al.*, 1998; Andreassen *et al.*, 2004; Knies *et al.*, 2009; Ottesen *et al.*, 2009; Rydningen *et al.*, 2016). However, our results suggest that the south-western SIS margin advanced repeatedly to the palaeo-shelf break in the northern North Sea during the early Quaternary (Fig. 6).

Sedimentation rates of 1-2 m/ka have been recorded for Holocene contourites in the Norwegian Sea (Bryn *et al.*, 2005), suggesting that each contourite within Units Ci and Cii may represent a period estimated as at least 20,000 years. In contrast, GDF packages within Units Ci and Cii (Fig. 2) were probably associated with higher rates of sedimentation during intervals of shelf-break glaciation. The sequence of intercalated GDFs and contourites within Units Ci and Cii (Fig. 2a and b) is interpreted to record fluctuations in regional climate that are linked to the Milankovitch-driven *c.* 41 k glacial-interglacial cycles of the early Quaternary; the identification of nine contourite and GDF packages suggests, therefore, that these units span at least 0.4 Ma. This implies that the base of Unit Ci is older than around 1.2 or 1.5 Ma, depending on whether an age of 0.8 or 1.1 Ma is assigned to the base of Unit D (Sejrup *et al*., 1995; Ottesen *et al*., 2014).

Although the base of Unit D is interpreted as the base of the North Sea TMF (Ottesen *et al*., 2014), substantial seaward progradation of sediment occurred during the early Quaternary, within Units Ci and Cii (Figs. 2, 4d and e). The sediment within Units Ci and Cii could therefore be considered as a proto-fan of the North Sea TMF.

The early Quaternary infilling of the northern North Sea Basin reduced accommodation on the margin and led to the deflection of mid to late Quaternary sediments into the deep Norwegian Sea (Ottesen *et al*., 2014) (Figs. 4f and 6e). Although ice-sheet expansion was probably driven by the intensification of Northern Hemisphere glaciation at around 1 Ma (Raymo *et al*., 1997), the changing architecture of the margin may have encouraged initiation of a major ice stream by increasing the palaeo-shelf width, and, consequently the ice-stream catchment area, and reducing water depth and, by implication, the rate of mass loss by iceberg production during full-glacials (Fig. 3a to d). A similar pattern of early Quaternary ice-sheet expansion and shelf progradation, followed by the initiation of efficient mid to late Quaternary ice streams within deep cross-shelf troughs, has been recognised on the mid- and north-Norwegian margins (Ottesen *et al*., 2009; Rydningen *et al*., 2016).

The mid to late Quaternary SIS exhibited significant spatial and temporal variations in ice flow (Dowdeswell *et al*., 2006). Close to the onset of the mid Quaternary, the south-western SIS margin was drained by an ice stream that flowed about 60 km east of the present-day Norwegian Channel (Figs. 3e and 6e). At that time, the shallow Måløy Plateau, which was covered by slow-flowing ice during the LGM (Ottesen *et al*., 2005), was occupied by a fast-flowing ice stream (Fig. 3e) (Nygård *et al*., 2004; Rise *et al*., 2004, 2016). The westerly migration of this ice stream through the mid to late Quaternary may have occurred in response to filling of accommodation by continuing glacier-derived sedimentation and/or glaciological changes in the dimensions or thermal structure of the SIS.

The onset of major sediment sliding on the North Sea Fan at around 0.5 Ma coincides with ice-sheet expansion into the central North Sea and across the continental shelf north of the Shetland Islands (Stoker, 1995; Sejrup *et al*., 2000; Stewart and Lonergan, 2011). This suggests that sediment failure on the TMF may have been encouraged by increased rates of glacigenic-sediment delivery to the shelf break (King *et al*., 1996, 1998).

The changing architecture of the northern North Sea margin through the Quaternary influenced the palaeo-oceanography of this region. The southwest-flowing NSBW current was directed into the partially filled northern North Sea Basin during the early Quaternary (Fig. 6b), depositing a contourite unit of 50 m or more in thickness on the western basin floor (Figs. 2c, d and 4c) and a series of intercalated contourite lenses at the foot of the glacially-influenced slope to the northeast (Figs. 2a, b and 5b). Contourite deposition may have been encouraged by the concave geometry of the partially filled basin, acting as a sediment trap. The NSBW current was deflected progressively northwards through the early Quaternary as the basin became gradually infilled (Figs. 4g to i and 6). The absence of extensive contourites from the mid to late Quaternary TMF may be a consequence of intensification of thermohaline circulation and/or the convex slope geometry produced by rapid delivery of ice-stream derived sediments to the margin. The North Sea Fan is presently characterised by net contour-current erosion, with some isolated contourite accumulation taking place to the northeast within the concave slide scar of the Holocene Storegga Slide (Bryn *et al*., 2005).

Contourites represent a significant component of the early Quaternary infill of the northern North Sea Basin (Figs. 2a, b and 5b). In addition to their potential as a palaeo-climatic archive, contourites may have important seal-potential for trapping hydrocarbons and can also provide reservoir rocks; they are therefore significant for petroleum exploration.

6. Conclusions

2D and 3D seismic-reflection data reveal the shelf and slope architecture and the changing volumes and sources of sediment in the northern North Sea through the Quaternary (Figs. 3 and 4). The filling of the northern North Sea Basin occurred as a result of the progressive infilling of the basin during the early Quaternary. A gradual shift from a westerly to a northerly sediment-progradation direction is recorded within the early Quaternary sediments (Fig. 3f), probably occurring in response to filling of available accommodation.

The early Quaternary northern North Sea Basin infill contains glacial and contour-current derived sediments (Figs. 2 and 5b to e). At the edge of the northern North Sea Basin, bordering the Norwegian Sea, a sequence of intercalated GDFs and contourites (Figs. 2a, b and 5b) provides a record of glacigenic-sediment delivery to the continental slope and the changing intensity of thermohaline circulation in the North Atlantic during the glacial-interglacial cycles of the early Quaternary.

Early Quaternary sedimentation increased the width and reduced the water depth of the continental shelf (Fig. 3), facilitating the initiation of a major ice stream. The ice stream draining the south-western margin of the SIS close to the onset of the mid Quaternary was located around 60 km east of the position of the NCIS during the LGM (Figs. 3d, e, 6e and f), indicating that ice-stream migration occurred during the mid to late Quaternary (Nygård *et al*., 2004; Rise *et al*., 2004, 2016). The intensification of glacierization from around 0.5 Ma (Stoker, 1995; Sejrup *et al*., 2000) may have triggered major sediments sliding on the North Sea Fan by increasing the rate of sediment delivery to the continental slope (King *et al*., 1996, 1998).

The southwest-flowing NSBW current was directed into the concave, partially filled northern North Sea Basin during the early Quaternary, and was deflected progressively northwards as the basin became infilled (Figs. 4g, i and 6). The absence of significant contourites from the mid to late Quaternary North Sea Fan may be a result of intensification of thermohaline circulation and/or the convex geometry of the continental slope.

7. Acknowledgements

We thank Petroleum Geo-Services (PGS) for access to the 3D cube and for permission to reproduce 2D and 3D seismic-reflection data from the northern North Sea margin. We thank M. Stewart and M. Huuse for their helpful reviews of this paper. During this work, C.L. Batchelor was in receipt of a Junior Research Fellowship at Newnham College, Cambridge.

8. References

Andreassen K, Nilssen LC, Rafaelsen B, Kuilman L. 2004. Three-dimensional seismic data from the Barents Sea margin reveal evidence of past ice streams and their dynamics. *Geology* **32** : 729-732.

Batchelor CL, Dowdeswell JA. 2014. The physiography of High Arctic cross-shelf troughs. *Quaternary Science Reviews* **92** : 68-96.

Bryn P, Berg K, Stoker MS, Haflidason H, Solheim A. 2005. Contourites and their relevance for mass wasting along the Mid-Norwegian Margin. *Marine and Petroleum Geology* **22** : 85-96.

Clark CD. 1993. Mega-scale glacial lineations and cross-cutting ice-flow landforms. *Earth Surface Processes and Landforms* **18** : 1-29.

Dahlgren KIT, Vorren TO, Laberg JS. 2002. Late Quaternary glacial development of the mid-Norwegian margin – 65-68ºN. *Marine and Petroleum Geology* **19** : 1089-1113.

Dowdeswell J.A *et al*. 1996. Large-scale sedimentation on the glacier-influenced Polar North Atlantic margins: long-range side-scan sonar evidence. *Geophysical Research Letters* **23** : 3535-3538.

Dowdeswell JA, Ottesen D. 2013. Buried iceberg ploughmarks in the early Quaternary sediments of the central North Sea: a two-million year record of glacial influence from 3D seismic data. *Marine Geology* **344** : 1-9.

Dowdeswell JA, Ottesen D, Rise L. 2006. Flow-switching and large-scale deposition by ice streams draining former ice sheets. *Geology* **34** : 313-316.

Dowdeswell JA, Ottesen D, Rise L, Craig J. 2007. Identification and preservation of landforms diagnostic of past ice-sheet activity on continental shelves from three-dimensional seismic evidence. *Geology* **35** : 359-362.

Dowdeswell JA, Villinger H, Whittington RJ, Marienfeld P. 1993. Iceberg scouring in Scoresby Sund and on the East Greenland continental shelf. *Marine Geology* **111** : 37-53.

Eidvin T, Riis F, Rundberg Y. 1999. Upper Cainozoic stratigraphy in the central North Sea (Ekofisk and Sleipner fields). *Norwegian Journal of Geology* **79** : 97-128.

Elverhøi A *et al,* 1995. The growth and decay of the Late Weichselian ice sheet in western Svalbard and adjacent areas based on provenance studies of marine sediments. *Quaternary Research* **44** : 303-316.

Evans D, King E.L, Kenyon NH, Brett C, Wallis D. 1996. Evidence for long-term instability in the Storegga Slide region off western Norway. *Marine Geology* **130** : 281-292.

Hampton MA, Lee HJ, Locat J. 1996. Submarine landslides. *Reviews of Geophysics* **34** : 33-59.

Hjelstuen BO, Grinde S. 2015. 3D seismic investigations of Pleistocene mass transport deposits and glacigenic debris flows on the North Sea Fan, NE Atlantic Margin. In: Lamarche E et al. (Eds.) *Submarine Mass Movements and their Consequences* : 265-272.

Hohbein M, Cartwright J. 2006. 3D seismic analysis of the West Shetland Drift system: Implications for Late Neogene palaeoceanography of the NE Atlantic. *Marine Geology* 230 : 1-20.

Hughes ALC, Gyllencreutz R, Lohne ØS, Mangerud J, Svendsen JI. 2016. The last Eurasian ice sheets – a chronological database and time-slice reconstruction, DATED-1. *Boreas* **45** : 1–45.

Jansen E, Fronval T, Rack F, Channel JET. 2000. Pliocene-Pleistocene ice rafting history and cyclicity in the Nordic Seas during the last 3.5 Myr. *Palaeoceanography* **15** : 709-721.

King EL, Haflidason H, Sejrup HP, Løvlie R. 1998. Glacigenic debris flows on the North Sea Trough Mouth Fan during ice stream maxima. *Marine Geology* **152** : 217-246.

King EL, Sejrup HP, Haflidason H, Elverhøi A, Aarseth I. 1996. Quaternary seismic stratigraphy of the North Sea Fan: glacially-fed gravity flow aprons, hemipelagic sediments, and large submarine slides. *Marine Geology* **130** : 293-315.

Knies J *et al*. 2009. The Plio-Pleistocene glaciation of the Barents Sea-Svalbard region: a new model based on revised chronostratigraphy. *Quaternary Science Reviews* **28** : 812-829.

Knutz PC, Cartwright JA. 2003. Seismic stratigraphy of the West Shetland Drift: implications for Late Neogene paleocirculation in the Faeroe-Shetland gateway. *Paleoceanography* **18** : 1093.

Kuhlmann G, Wong TE. 2008. Pliocene paleoenvironment evolution as interpreted from 3D-seismic data in the southern North Sea, Dutch offshore sector. *Marine and Petroleum Geology* **25** : 173-189.

Laberg JS, Vorren TO. 1995. Late Weichselian submarine debris flow deposits on the Bear Island trough mouth fan. *Marine Geology* **127** : 45-72.

Laberg JS, Vorren TO, Knutsen SM. 1999. The Lofoton contourite drift off Norway. *Marine Geology* **159** : 1-6.

Lee JR, Busschers FS, Sejrup HP. 2010. Pre-Weichselian Quaternary glaciations of the British Isles, The Netherlands, Norway and adjacent marine areas south of 68ºN: implications for long-term ice sheet development in northern Europe. *Quaternary Science Reviews* **44** : 213-228.

Mangerud J, Jansen E, Landvik J.Y. 1996. Late Cenozoic history of the Scandinavian and Barents Sea ice sheets. *Global and Planetary Change* **12** : 11-26.

Masson DG. 2001. Sedimentary processes shaping the eastern slope of the Faeroe-Shetland Channel. *Continental Shelf Research* **21** : 825-857.

Newton AMW, Huuse M, Brocklehurst SH. 2016. Buried iceberg scours reveal reduced North Atlantic Current during the stage 12 deglacial. *Nature Communications* **7** : 10927.

Nygård A, Sejrup HP, Haflidason H, Bryn P. 2005. The glacial North Sea Fan, southern Norwegian margin: architecture and evolution from the upper continental slope to the deep-sea basin. *Marine and Petroleum Geology* **22** : 71-84.

Nygård A, Sejrup HP, Haflidason H, Cecci M, Ottesen D. 2004. The deglaciation history of the southwestern Fennoscandian Ice Sheet between 15 and 13 ^{14}C ka. *Boreas* **33** : 1-17.

Nygård A, Sejrup HP, Haflidason H. King EL. 2002. Geometry and genesis of glacigenic debris flows on the North Sea Fan: TOBI imagery and deep-tow boomer evidence. *Marine Geology* **188** : 15-33.

Ottesen D, Dowdeswell JA, Bugge T. 2014. Morphology, sedimentary infill and depositional environments of the Early Quaternary North Sea Basin (56º - 62ºN). *Marine and Petroleum Geology* **56** : 123-146.

Ottesen D, Dowdeswell JA, Rise L. 2005. Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: the 2,500 km-long Norwegian Svalbard margin (57º to 80ºN). *Geological Society of America Bulletin* **117** : 1033-1050.

Ottesen D, Rise L, Andersen ES, Bugge T, Eidvin T. 2009. Geological evolution of the Norwegian continental shelf between 61ºN and 68ºN during the last 3 million years. *Norwegian Journal of Geology* **89** : 251-265.

Rahmstorf S. 2002. Ocean circulation and climate during the last 120,000 years. *Nature* **419** : 207-214.

Raymo ME, Oppo DW, Curry W. 1997. The Mid-Pleistocene climate transition: a deep sea carbon isotopic perspective. *Paleoceanography* **12** : 546-559.

Raymo ME, Ruddiman WF, Shackleton NJ, Oppo DW. 1990. Evolution of Atlantic-Pacific d13C gradients over the last 2.5 m.y. *Earth and Planetary Science Letters* **97** : 353-368.

Riis F. 1996. Quantification of Cenozoic vertical movements of Scandinavia by correlation of morphological surfaces with offshore data. *Global and Planetary Change* **12** : 331-357.

Rise L, Olesen O, Rokoengen K, Ottesen D, Riis F. 2004. Mid-Pleistocene ice drainage pattern in the Norwegian Channel imaged by 3D seismics. *Quaternary Science Reviews* **23** : 2323-2335.

Rise L, Ottesen D, Berg K, Lundin E. 2005. Large-scale development of the mid-Norwegian margin during the last 3 million years. *Marine and Petroleum Geology* **22** : 33-44.

Rise L, Ottesen D, Olesen O, Dowdeswell JA. 2016. Buried mid-Quaternary mega-scale glacial lineations in the Norwegian Channel from 3D seismic imagery. *In*: Dowdeswell JA, et al. (Eds.) *Atlas of Submarine Glacial landforms: Modern, Quaternary and Ancient.* Geological Society, London, Memoirs, 46.

Rydningen TA, Laberg JS, Kolstad V. 2016. Late Cenozoic evolution of high-gradient trough mouth fans and canyons on the glaciated continental margin offshore Troms, northern Norway – Paleoclimatic implications and sediment yield. *Geological Society of London, Bulletin* **128** : 576-596.

Sejrup HP *et al*. 1995. Quaternary of the Norwegian Channel: glaciation history and palaeoceanography. *Norwegian Journal of Geology* **75** : 65-87.

Sejrup HP *et al,* 2000. Quaternary glaciations in southern Fennoscandia: evidence from southwestern Norway and the northern North Sea region. *Quaternary Science Reviews* **19** : 667-685.

Solheim A *et al*. 1998. Late Cenozoic seismic stratigraphy and glacial geological development of the East Greenland and Svalbard-Barents Sea continental margins. *Quaternary Science Reviews* **17** : 155-184.

Stewart MA, Lonergan L. 2011. Seven glacial cycles in the middle-late Pleistocene of northwest Europe; geomorphic evidence from buried tunnel valleys. *Geology* **39** : 283-286.

Stuart JY, Huuse M. 2012. 3D seismic geomorphology of a large Plio-Pleistocene delta – 'Bright spots' and contourites in the Southern North Sea. *Marine and Petroleum Geology* **38** : 143-157.

Stoker MS. 1995. The influence of glacigenic sedimentation on slope-apron development on the continental margin off Northwest Britain. In: Scrutton RA, Stoker MS, Shimmield GB, Tudhope AW (Eds.) The Tectonics, Sedimentation and Paleoceanography of the North Atlantic Region. *Geological Society of London, Special Publication* **90** : 159-177.

Stoker MS, Skinner AC, Fyfe JA, Long D. 1983. Palaeomagnetic evidence for early Pleistocene in the central and northern North Sea. *Nature* **304** : 332-334.

Taylor J, Dowdeswell JA, Siegert MJ. 2002. Depositional processes, fluxes, and sediment volumes on the margins of the Norwegian Sea (62-75ºN). *Marine Geology* **188** : 61-77.

Turrell WR, Slesser G, Adams RD, Payne R, Gillibrand PA. 1999. Decadal variability in the composition of Faroe Shetland Channel bottom water. *Deep Sea Research* **46** : 1-25.

9. Figure Legends

Fig. 1. Location map of the northern North Sea margin, showing the extent of the 2D (black outline) and 3D seismic-reflection data (red outline). Dashed orange line is the main depocentre of the North Sea trough-mouth fan (TMF) from Nygård *et al*., 2005. Blue arrow is deep Norwegian Sea Bottom Water (NSBW) current and red arrow is shallow Norwegian Current.

Fig. 2. (a) Seismic profile of the northern North Sea margin. Yellow lines show the approximate location of the features in Fig. 5. VE = 18. (b) Interpretation of the profile shown in (a). URU = Upper Regional Unconformity. Red triangles are palaeo-shelf surfaces on which elongate lineations (e.g. Fig. 5g and h) are identified. Dark green line is the top of Unit C. (c) Composite seismic profile of the northern North Sea margin. VE = 21. (d) Interpretation of the seismic profile in (c). Key is the same as in (b). White line is the top of the basin-fill unit.

Fig. 3. Structure maps showing the shelf and slope architecture of the northern North Sea margin, as interpreted from regional 2D seismic-reflection data, at (a) the base NAUST horizon, (b) the base of Unit Ci, (c) the base of Unit Cii, (d) the base of Unit D, and (e) the present-day seafloor. NSB = northern North Sea Basin; MP = Måløy Plateau. Blue circle is Ålesund, Norway. Contours are 200 m. Dashed white line in (d) and (e) shows the location of the palaeo-trough at the base of Unit D. (f) The changing approximate position of the palaeo-shelf break through Units A to D, superimposed on greyscale bathymetry of the present-day seafloor (GEBCO). The red, orange, yellow, green and blue lines are palaeo-shelf breaks at

the base of the NAUST horizon, Unit Ci, Unit Cii, Unit D and the present-day seafloor, respectively. Dark grey lines are palaeo-shelf breaks within Units Ci and Cii.

Fig. 4. Isopach maps of the distribution and thickness of the units identified from the northern North Sea margin, superimposed upon the palaeo-shelf and slope depth as shown in Fig. 2. Approximate volumes are given. The isopach maps are of (a) base NAUST to the present-day seafloor, i.e. the Quaternary infill of the northern North Sea Basin, (b) Units A and B, (c) the basin-fill unit (blue shading is Shetland Drift as mapped by Hohbein and Cartwright, 2006), (d) Unit Ci, (e) Unit Cii, (f) Unit D. Contours are 200 m in (a) and (f) and 100 m in (b) to (e). (g) to (i) Isopach maps of the nine contourite lenses within Units Ci and Cii. The isopach maps show (g) Contourites 1 to 3 within Unit Ci, (h) Contourites 4 to 6 within Unit Ci, and (i) Contourites 7 to 9 within Unit Cii. Contours are 10 m.

Fig. 5. Examples of features identified using the cube of 3D seismic-reflection data. See Fig. 2 for locations of (d) to (i). (a) Location map of (b) to (i) within the 3D cube, superimposed on present-day seafloor bathymetry. Coloured lines show palaeo-shelf breaks from Fig. 3f. (b) Seismic profile showing the intercalated lenses (contourites) and clinoform packages (GDFs) on the lower slope of Units Ci and Cii. VE = 12. (c) Isopach map of Contourite 7 within the 3D cube. (d) Greyscale amplitude map generated from an interpreted slope horizon within Unit Ci, showing a network of elongate lobes, which are interpreted as GDFs. (e) Time slice of elongate lobes on a palaeo-slope unit within Unit D, which are interpreted as GDFs. (f) Time slice showing a MTD surface within Unit D, showing curvilinear ridges and depressions, which are interpreted as detached slide blocks. (g) Horizon showing northwest/southeast-orientated elongate ridges on the palaeo-shelf at the base of Unit D, which are interpreted as MSGLs. (h) Interpreted palaeo-shelf horizon within Unit D, showing

north-northwest/ south-southeast-orientated elongate ridges, which are interpreted as MSGLs. (i) Time slice of linear to curvilinear depressions on a palaeo-shelf within Unit D, which are interpreted as iceberg ploughmarks.

Fig. 6. (a) to (f) Schematic models of the evolution of the northern North Sea margin through the Quaternary and the corresponding ice-sheet and ocean-current configuration. A = Ålesund; B = Bergen; SD = Shetland Drift; SI = Shetland Islands. Blue shading is the Scandinavian Ice Sheet (SIS) and darker blue shading shows the locations of palaeo-ice streams. Green shading shows contourites and the blue arrow is the NCBW current. Brown to yellow shading shows the distribution of the predominantly glacier-derived sediments of Units A to D. Red lines show the orientation of elongate ridges that have been interpreted as MSGLs. Dark red lines show location of palaeo-shelf break.

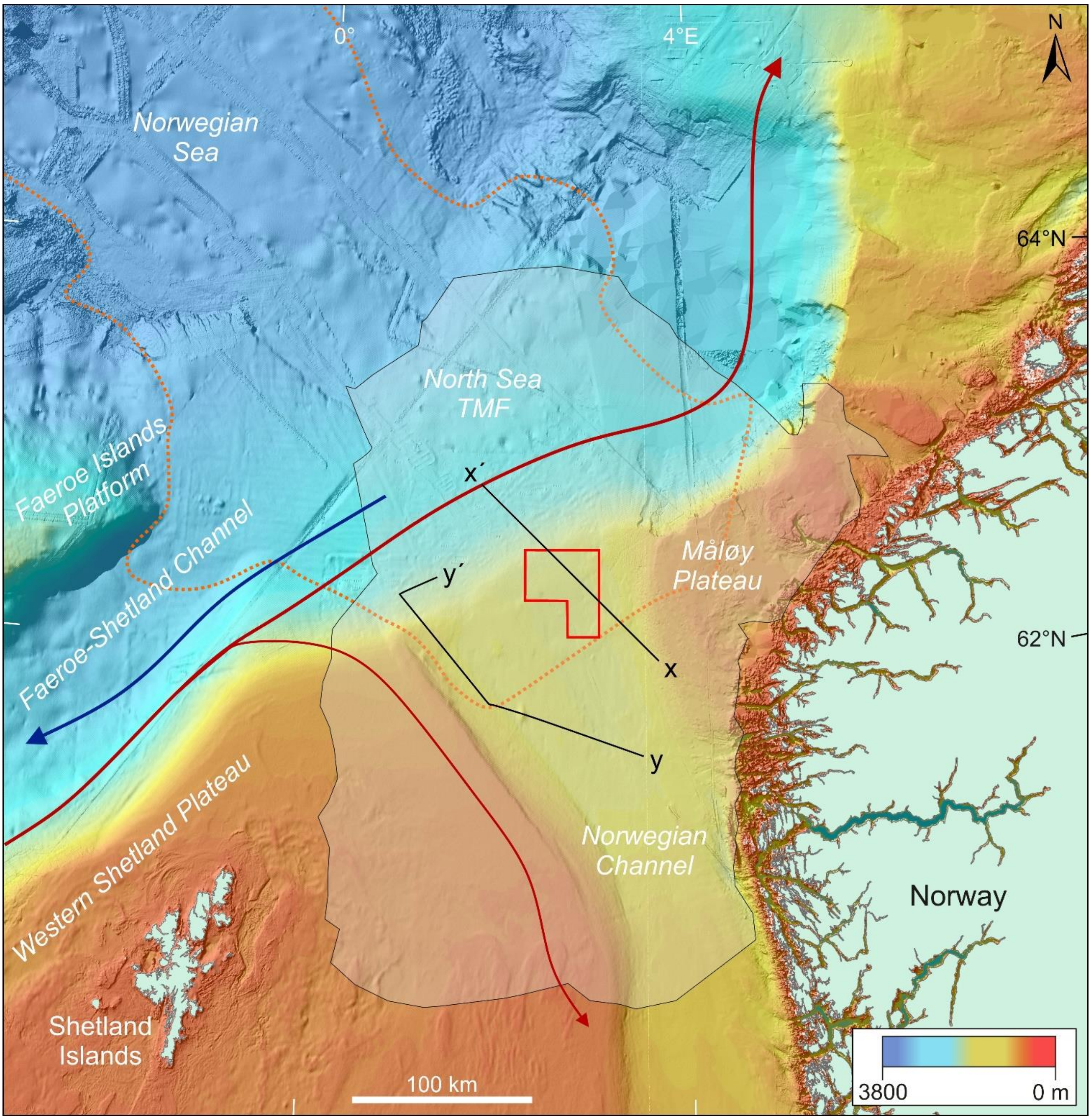

0°
4°E
N
Norwegian Sea
64°N
North Sea TMF
Faeroe Islands Platform
Faeroe-Shetland Channel
x´
Måløy Plateau
y´
62°N
x
y
Western Shetland Plateau
Norwegian Channel
Norway
Shetland Islands
100 km
3800
0 m

Figure 1

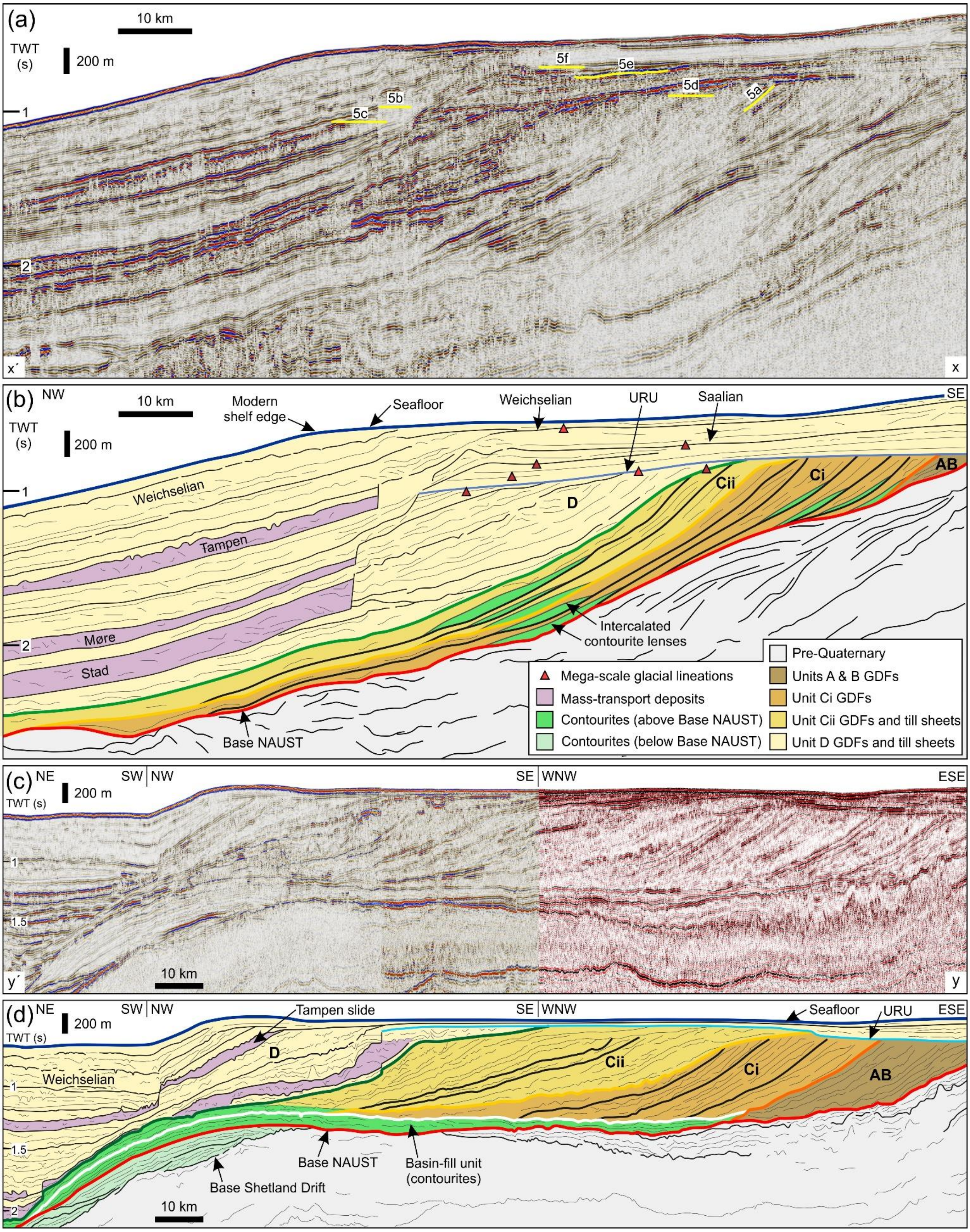

(a)
10 km
TWT (s)
200 m
5f
5e
5d
5a
5b
5c
1
2
x´
x
(b)
NW
SE
10 km
Modern shelf edge
Seafloor
Weichselian
URU
Saalian
TWT (s)
200 m
Weichselian
Tampen
Møre
Stad
D
Cii
Ci
AB
Intercalated contourite lenses
Base NAUST
Mega-scale glacial lineations
Mass-transport deposits
Contourites (above Base NAUST)
Contourites (below Base NAUST)
Pre-Quaternary
Units A & B GDFs
Unit Ci GDFs
Unit Cii GDFs and till sheets
Unit D GDFs and till sheets
(c)
NE
SW
NW
SE
WNW
ESE
200 m
TWT (s)
1
1.5
10 km
y´
y
(d)
NE
SW
NW
SE
WNW
ESE
200 m
TWT (s)
Tampen slide
Seafloor
URU
D
Weichselian
Cii
Ci
AB
1
1.5
2
Base NAUST
Basin-fill unit (contourites)
Base Shetland Drift
10 km

Figure 2

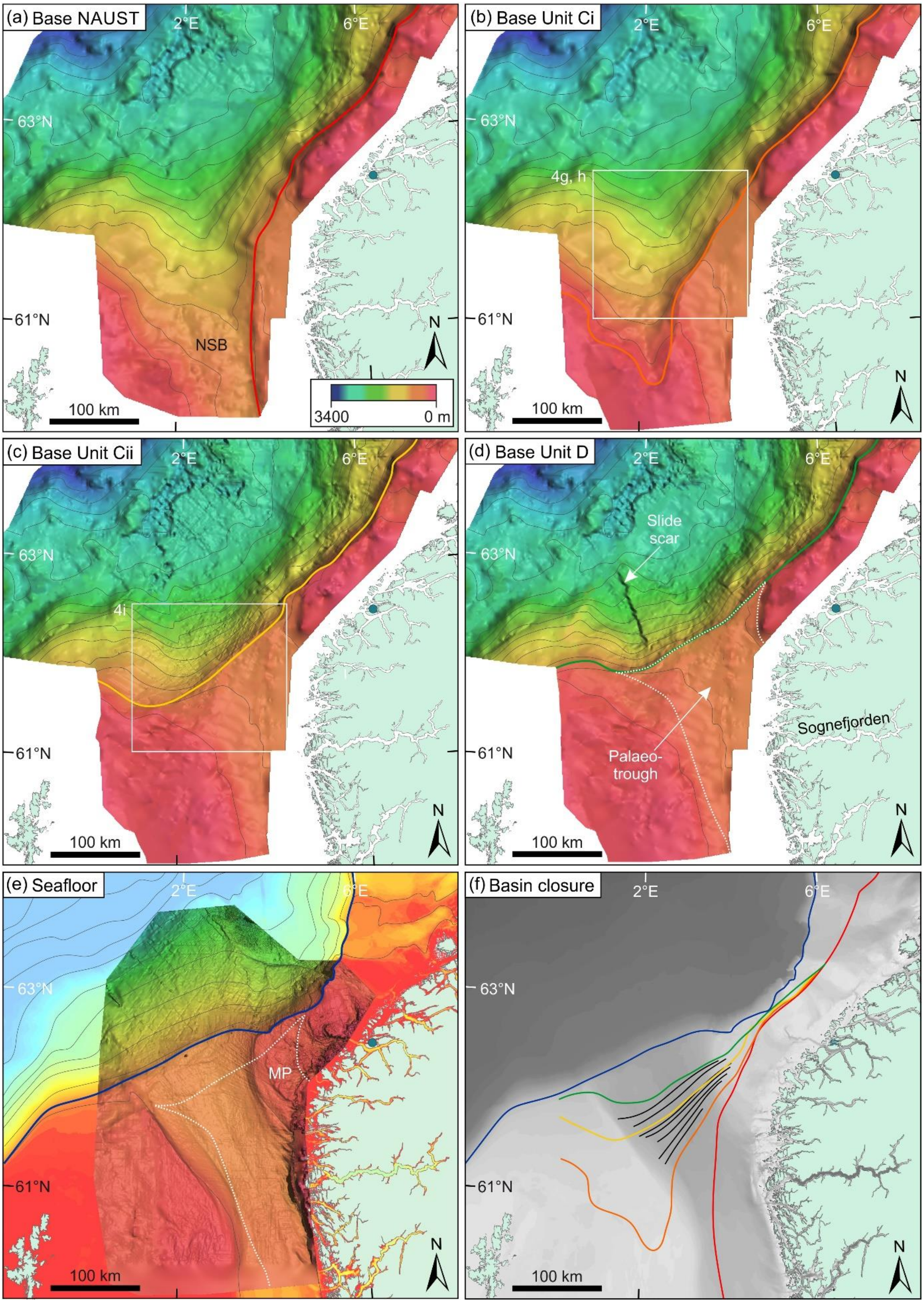

(a) Base NAUST
2°E
6°E
63°N
61°N
NSB
N
3400
0 m
100 km
(b) Base Unit Ci
4g, h
(c) Base Unit Cii
4i
(d) Base Unit D
Slide scar
Sognefjorden
Palaeo-trough
(e) Seafloor
MP
(f) Basin closure

Figure 3

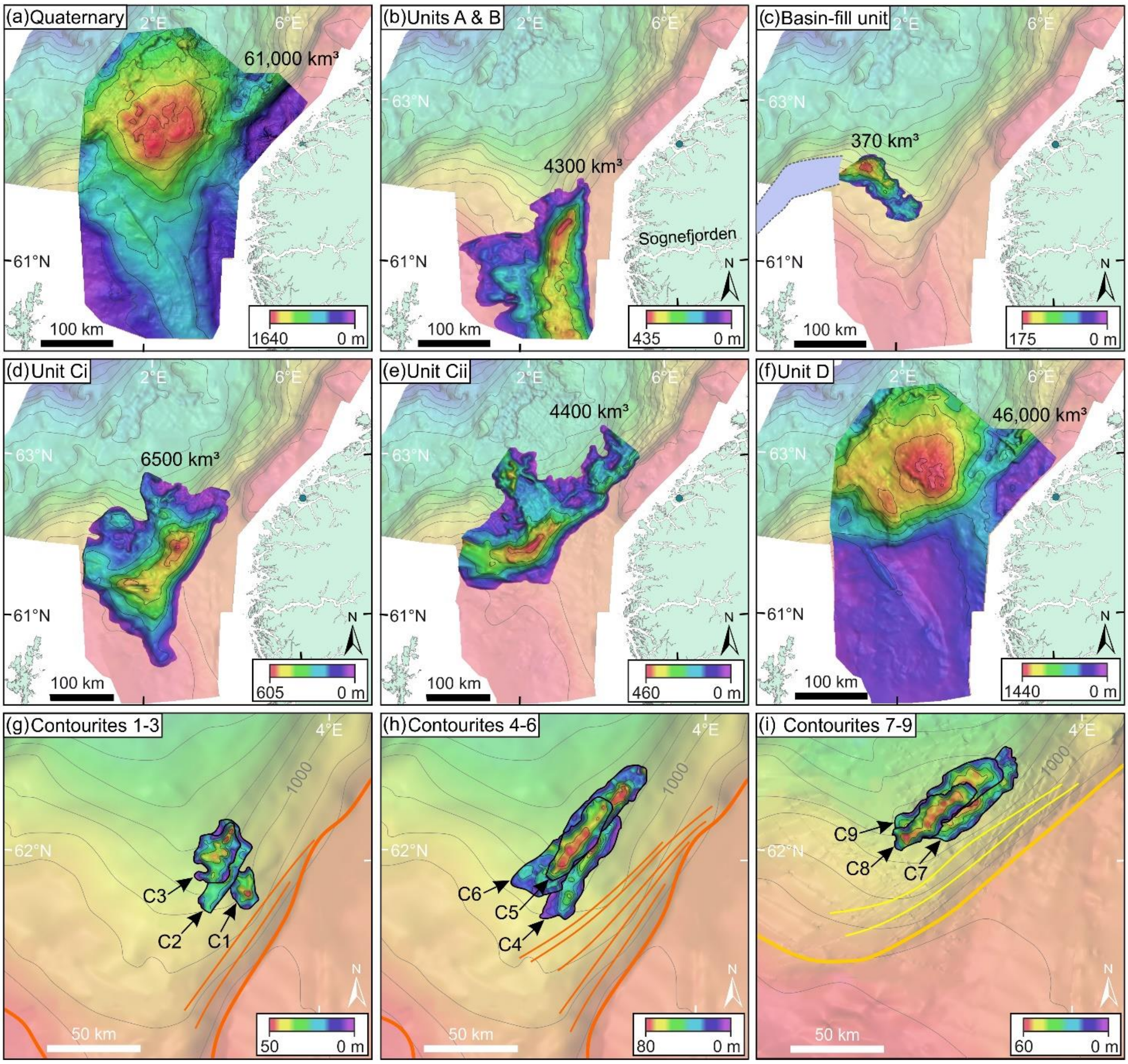
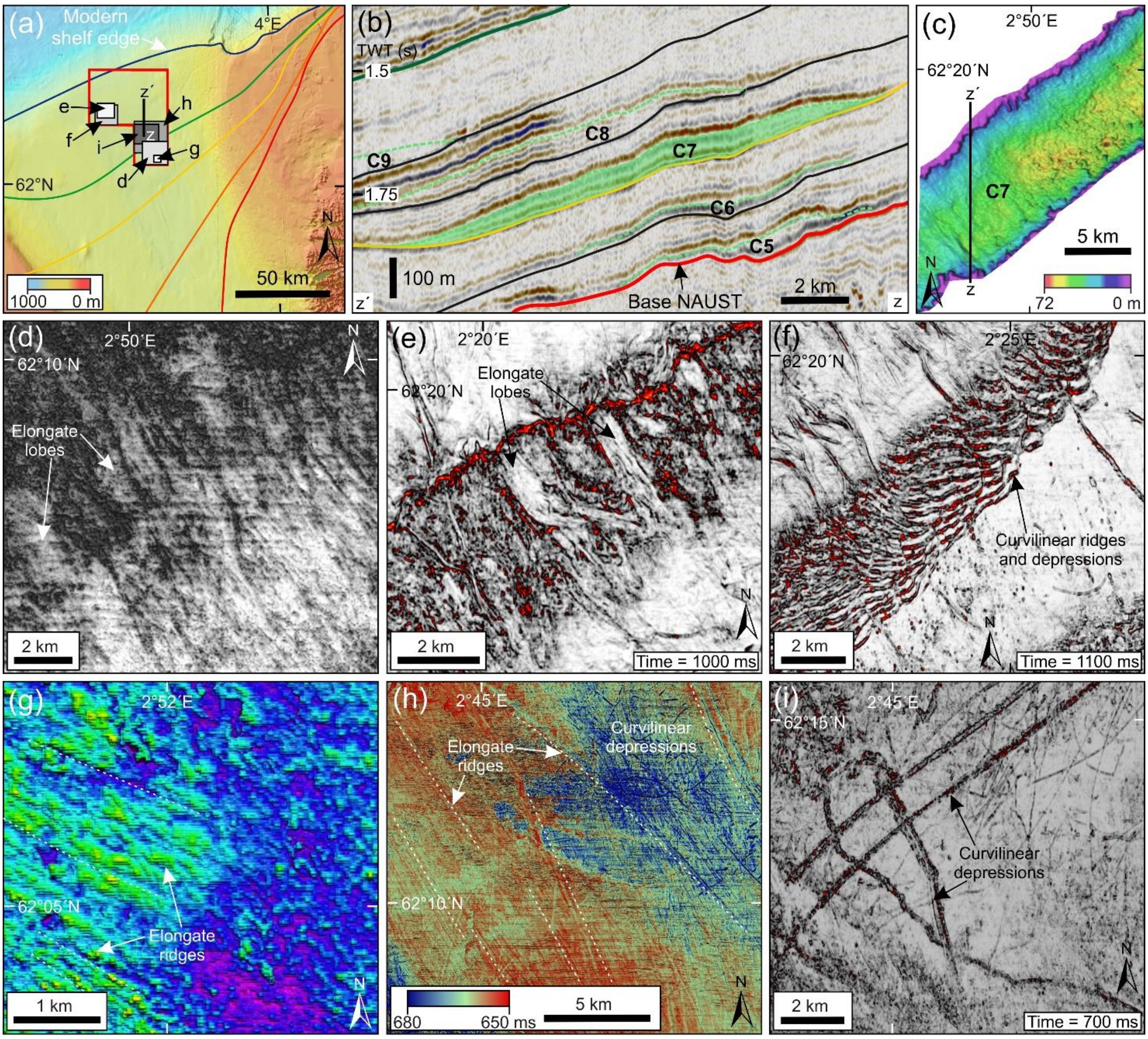

(a)Quaternary
61,000 km³
61°N
100 km
1640
0 m
(b)Units A & B
63°N
4300 km³
Sognefjorden
61°N
100 km
435
0 m
(c)Basin-fill unit
63°N
370 km³
61°N
100 km
175
0 m
(d)Unit Ci
63°N
6500 km³
61°N
100 km
605
0 m
(e)Unit Cii
63°N
4400 km³
61°N
100 km
460
0 m
(f)Unit D
63°N
46,000 km³
61°N
100 km
1440
0 m
(g)Contourites 1-3
4°E
1000
62°N
C3
C2
C1
50 km
50
0 m
(h)Contourites 4-6
4°E
1000
62°N
C6
C5
C4
50 km
80
0 m
(i) Contourites 7-9
4°E
1000
62°N
C9
C8
C7
50 km
60
0 m
2°E
6°E
N

Figure 4



(a)
Modern shelf edge
4°E
62°N
e
f
i
z´
z
h
g
d
N
50 km
1000
0 m
(b)
TWT (s)
1.5
1.75
C9
C8
C7
C6
C5
100 m
Base NAUST
2 km
z´
z
(c)
2°50´E
62°20´N
z´
z
C7
5 km
72
0 m
N
(d)
2°50´E
62°10´N
Elongate lobes
2 km
N
(e)
2°20´E
62°20´N
Elongate lobes
2 km
Time = 1000 ms
N
(f)
2°25´E
62°20´N
Curvilinear ridges and depressions
2 km
Time = 1100 ms
N
(g)
2°52´E
62°05´N
Elongate ridges
1 km
N
(h)
2°45´E
62°10´N
Elongate ridges
Curvilinear depressions
680
650 ms
5 km
N
(i)
2°45´E
62°15´N
Curvilinear depressions
2 km
Time = 700 ms
N

Figure 5

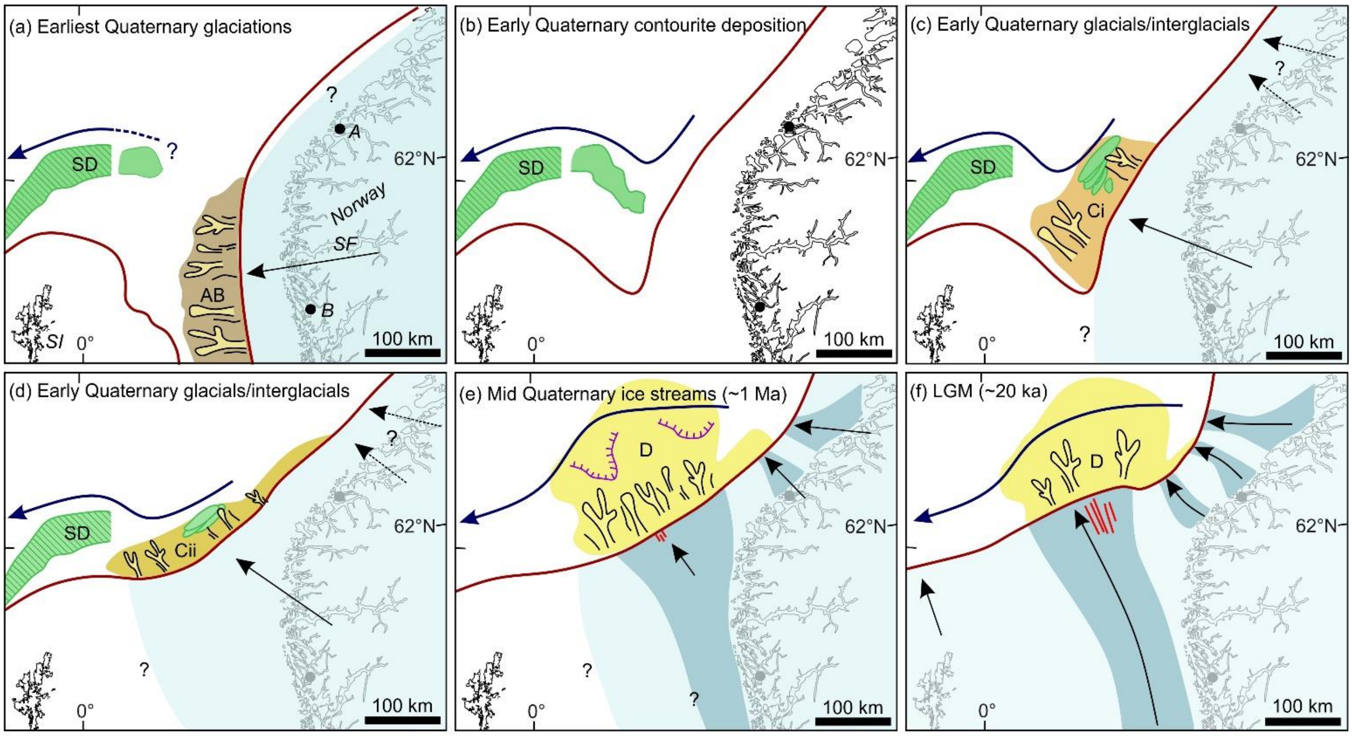

(a) Earliest Quaternary glaciations
SD
?
AB
A
B
Norway
SF
62°N
SI
0°
100 km
(b) Early Quaternary contourite deposition
SD
62°N
0°
100 km
(c) Early Quaternary glacials/interglacials
SD
Ci
?
62°N
0°
100 km
(d) Early Quaternary glacials/interglacials
SD
Cii
?
62°N
0°
100 km
(e) Mid Quaternary ice streams (~1 Ma)
D
?
62°N
0°
100 km
(f) LGM (~20 ka)
D
62°N
0°
100 km

Figure 6