Large-scale glacitectonic deformation in response to active ice sheet retreat across Dogger Bank (southern central North Sea) during the Last Glacial Maximum

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Abstract

High resolution seismic data from the Dogger Bank in the central southern North Sea has revealed that the Dogger Bank Formation records a complex history of sedimentation and penecontemporaneous, large-scale, ice-marginal to proglacial glacitectonic deformation. These processes led to the development of a large thrust-block moraine complex which is buried beneath a thin sequence of Holocene sediments. This buried glacitectonic landsystem comprises a series of elongate, arcuate moraine ridges (200 m up to > 15 km across; over 40-50 km long) separated by low-lying ice marginal to proglacial sedimentary basins and/or meltwater channels, preserving the shape of the margin of this former ice sheet. The moraines are composed of highly deformed (folded and thrust) Dogger Bank Formation with the lower boundary of the deformed sequence (up to 40-50 m thick) being marked by a laterally extensive décollement. The ice-distal parts of the thrust moraine complex are interpreted as a "forward" propagating imbricate thrust stack developed in response to S/SE-directed ice-push. The more complex folding and thrusting within the more ice-proximal parts of the thrust-block moraines record the accretion of thrust slices of highly deformed sediment as the ice repeatedly reoccupied this ice marginal position. Consequently, the internal structure of the Dogger Bank thrust-moraine complexes can be directly related to ice sheet dynamics, recording the former positions of a highly dynamic, oscillating Weichselian ice sheet margin as it retreated northwards at the end of the Last Glacial Maximum.

Keywords

Large-scale glacitectonics; Dogger Bank; North Sea; Weichselian glaciation

Highlights

- Structural architecture of a glacitectonic landsystem, Dogger Bank, North Sea
- Detailed study using high-resolution 2D seismic data
- Large-scale glacitectonics at an oscillating margin during surge-related readvance
- Deformation during Weichselian ice sheet retreat in the southern central North Sea

1. Introduction

The North Sea (c. 500 km wide, 50 to 400 m deep) separating the UK from Scandinavia and northern mainland Europe (Figure 1a) has had a long and complex geological history, commencing with rifting during the Jurassic–Early Cretaceous and followed by subsequent thermal cooling and subsidence (Glennie and Underhill, 1998; Zanella and Coward, 2003). Its more recent history has been dominated by the deposition of a locally thick sequence (over 800 m) of Quaternary sediments (Caston, 1977, 1979; Gatliff *et al*., 1994). This sedimentary record preserves evidence for the advance of several major ice sheets from the surrounding land masses into the North Sea at different stages during the Quaternary. This glacial history has previously been described in terms of three major glacial episodes, the Elsterian (oldest, Marine Isotope Stage [MIS] 12), Saalian (MIS 10–6), and Weichselian (youngest, MIS 5d–2) stage glaciations, separated by warmer interglacial periods (Eisma *et al*., 1979; Jansen *et al*., 1979; Caston 1979; Balson and Cameron, 1985; Sejrup *et al*., 1987, 1995, 2000, 2003; Cameron *et al*., 1987, 1992; Ehlers, 1990; Graham *et al*., 2007, 2011; Kristensen *et al*., 2007; Bradwell *et al*., 2008; Stoker *et al*., 2011; Stewart *et al*., 2013; Ottesen *et al*., 2014; Phillips *et al*., 2017). However, several recent studies (e.g. Beets *et al*., 2005; Lonergan *et al*., 2006; Stewart and Lonergan, 2011) have suggested that there may have been many more glacial episodes. An increasing body of geomorphological and sedimentological data is not only providing the key evidence for the existence of these former Pleistocene ice sheets, but is also being used to demonstrate that they extended across the NW European continental shelves (Graham *et al*., 2007, 2010, 2011; Bradwell *et al*., 2008; Dunlop *et al*., 2010; Howe *et al*., 2012). Consequently, the Quaternary of the North Sea is critical to our understanding the evolution of the major northern European palaeo-ice masses, such as the British and Irish (BIIS) and Fennoscandian (FIS) ice sheets.

Several models proposed for the Weichselian glaciation within the North Sea (e.g. Boulton and Hagdorn, 2006; Carr *et al*., 2006; Graham *et al*., 2007, 2011; Bradwell *et al*., 2008; Sejrup *et al*., 2009, 2016; Hughes *et al*., 2016) require the BIIS and FIS to have converged forming a "confluence zone" within the central part of the basin located to the north of, and between Dogger Bank and Denmark. However, the maximum extents of these major ice masses are poorly constrained resulting in a complex, often conflicting pattern of postulated ice limits within the southern North Sea (see Figure 1a) (e.g. Jansen *et al*., 1979; Catt, 1991; Clark *et al*., 2004; Carr *et al*., 2006; Hubbard *et al*., 2009; Brooks et al., 2009; Sejrup *et al*., 1987, 2000, 2009, 2016). Importantly, until recently this lack of understanding was further compounded by the fact that very little was known about the Quaternary sediments underlying the Dogger Bank. Consequently, establishing a robust model for the evolution of Dogger Bank is critical to our understanding Weichselian ice sheet dynamics within this part of the North Sea basin.

The Dogger Bank is an isolated, approximately NE-SW-trending topographic high (100 km wide, 250 km long) which is mainly located within the UK sector of the North Sea (Figure 1a), but also extends into Dutch and German territorial waters. The earliest reference to the Dogger Bank being glacial in origin was made by Thomas Belt (1874) who stated that "*The ice north was now gradually receding, and leaving great banks of moraine rubbish in the old ocean bed, to be ultimately levelled by the sea when it long afterwards returned, and which now form the Dogger and other great submarine banks*". Stride (1959) and Veenstra (1965) also argued for Dogger Bank being a moraine suggesting that this shallow area of the North Sea comprised a *"frame work of moraines covered by younger Pleistocene sediments"*. Veenstra (1965) went on to suggest that this "*former glaciated landscape covered with soft sediments*" *"consists of moraine ridges belonging presumably to the Weichsel glaciation, the last Pleistocene glaciation"*. Subsequent work (Balson and Cameron 1985; Cameron *et al*., 1992) suggested that the stratigraphy and structure of the Dogger Bank was a relatively simple "layer-cake" with the upper 60 m of the Quaternary sedimentary sequence being assigned to the Dogger Bank Formation. However, Wingfield (unpublished) suggested in the late 1980s to early 1990s that the Dogger Bank had been pushed from the N (see Carr *et al*., 2006). Laban (1995) suggested that the wavy nature of the reflectors on the seismic data obtained from the Dogger Bank Formation from several locations within the Dutch and British sectors of the Dogger Bank was consistent with deformation resulting from "*ice-pushing from the north-west*". Furthermore, van der Meer and Laban (1990) presented micromorphological evidence from the Dogger Bank Formation in the Dutch sector of the Dogger Bank had locally been subjected to glacial shear. However, the extent and complexity of the deformation recorded by the Dogger Bank Formation was still essentially unknown.

Recently acquired high-resolution geophysical and ground truthing datasets acquired by the Forewind Consortium (Statoil, Statkraft, RWE and SSE) between 2010 and 2014 (see Figure 1b) as part of the site investigation for a major offshore windfarm development revealed that the Quaternary stratigraphy on the Dogger Bank is far from being a simple "layer cake". Using these high-resolution datasets Cotterill *et al*. (2017a, b) have been able to demonstrate that the evolution of the Dogger Bank during the Quaternary is far more complex than previously thought and can be directly linked to the interplay between climatic variation, sea level changes (both rise and fall) and ice sheet movement. Importantly these data suggest that during the Weichselian glaciation the Dogger Bank was inundated by ice on more than one occasion.

This paper uses high-resolution seismic data from the Dogger Bank to reveal a complex history of sedimentation and penecontemporaneous large-scale, ice-marginal to proglacial glacitectonic deformation recorded by the sediments of the Dogger Bank Formation during the Weichselian stage glaciation. A buried glacial landsystem comprising a series of elongate, arcuate ridges (up to 15-20 km across, over 50 km long) separated by low-lying linear basins and/or meltwater channels has been identified, and interpreted as preserving the changing shape of the former Weichselian ice sheet margin as it retreated northward from Dogger Bank. The moraines within this landsystem are composed of highly deformed Dogger Bank Formation sediments with the geometry of the folds and thrusts being consistent with their formation in response to S/SE-directed ice-push. Consequently, the internal structural architecture of the Dogger Bank glaciotectonic complexes can be directly related to ice sheet dynamics, recording the former positions of an oscillating ice sheet margin as it retreated northwards at the end of the Last Glacial Maximum.

2. Methods

In 2008 the Forewind consortium (then RWE Npower Renewables, SSE, Statoil and Statkraft) undertook a detailed site investigation of the Dogger Bank Zone (DBZ) as part of the Round 3 windfarm development within the North Sea instigated by The Crown Estate. The DBZ is located 125 to 290 km to the NE of the Yorkshire coast and occurs entirely within the UK sector of the Dogger Bank (Figure 1). It is the largest of the Round 3 zones and covers an area of 8660 km^2, with water depths ranging from 18 to 63 m Lowest Astronomical Tide (LAT). An initial regional geophysical survey (conducted in 2010) across the entire DBZ (Figure 1b) involved the acquisition of sub-bottom profiles (Sparker and Pinger), magnetometer, sidescan sonar and multibeam datasets with a grid spacing of 2.5 km. In addition, boreholes and Cone Penetration Tests (CPT's) were also acquired. The same methods were then used to obtain high-resolution datasets over three smaller subareas

(Tranches A (2010), B (2011/2012) and C (2013); see Figure 1b), with sub-bottom profiles run at 100 m inline and 500 to 1000 m crossline spacing, and 100% coverage of multibeam bathymetry and sidescan sonar.

Analysis of the sub-bottom seismic profiles has led to the identification of several laterally extensive reflections which could be traced across the DBZ, and a number of laterally discontinuous ones that although not present everywhere, proved important in understanding the evolution of the Dogger Bank (Cotterill *et al*., 2017b). These key reflections were then gridded, and the resultant "horizon maps" interpreted in terms of sedimentary landsystems (Figure 2; see section 4). In addition, detailed work was undertaken in Tranche A (see Figure 1b) to gain a greater understanding of glacitectonic deformation, formation of desiccation surfaces, and the lateral variability in sedimentary depositional style. A total of 15 seismic profiles (line spacing 300 m to 1500 m apart) from four key areas within Tranche A (Areas A to D on Figure 2) were selected for analysis in order to gain an understanding of the nature and lateral variation in the relative intensity of glacitectonism, and its spatial and temporal relationship(s) to the formation of the buried ice-marginal landsystem and deposition of the Dogger Bank Formation sequence. The profiles all occur approximately orthogonal to the trend of the glacial landforms (see Figure 2) and are therefore aligned parallel to the proposed direction of ice-push responsible for glacitectonic deformation. Consequently the seismic profiles provide a series of structural cross-sections (e.g. Figures 3, 4, 5 and 6) through the landforms providing a complete record of deformation. Large format, high-resolution digital (jpeg) versions of these structural cross-sections are available on request from the authors and are also provided as supplementary publications.

Each seismic profile was exported from IHS Kingdom® as high-resolution digital image files (jpegs) and imported into a commercial computer graphics package (CorelDraw version X6/X7 (64 bit)). A graphics package was used for the detailed structural analysis as it not only allows individual reflectors in the seismic profiles to be digitised, but also enables the attribution of different line styles to particular geological structures (e.g. bedding, fold axes, thrusts, faults), and colour coding of polygons representing individual seismo/tectonostratigraphical units, and, where applicable, their constituent sedimentary subunits (Figures 3 to 11). These stratigraphical and sedimentary elements were identified on the basis of differences in their acoustic properties on the seismic profiles (Figures 7 to 11; also see Table 1). It must be stressed that the colours used to distinguish between the sedimentary subunits (packages) present within the relatively undeformed part of the Dogger Bank Formation are not intended to infer any direct correlation of these subunits as seismostratigraphic units, but rather used to highlight the geometry of these individual sediment packages. An approximate depth conversion was calculated to aid correlation of the identified structural/sedimentological features and thicknesses of the sedimentary units were obtained using the following velocities: Water Column - 1550 m/s; Holocene sediments - 1600 m/s; Upper Dogger Bank Formation - 1680 m/s; and Lower Dogger Bank Formation - 1750m/s, based on previous velocities gained from glacial sediments in the North Sea by RPS Energy.

3. Regional setting and stratigraphy of the Dogger Bank

Regional mapping of the North Sea basin, completed by the late 1980's and early 1990's (BGS 1989, 1991; Cameron *et al*., 1992) demonstrated that the Quaternary sedimentary sequence in the Dogger Bank area can be up to 800 m thick (one of the thickest occurrences in the North Sea) and comprises a mix of glacial, deltaic and shallow marine deposits (Balson and Cameron, 1985; Cameron *et al*., 1992; Gatliff *et al*., 1994; Cotterill *et al*., 2017b). Stoker *et al*. (2011) divided the Quaternary succession in the southern North Sea into three major groups: *(i)* Southern North Sea Deltaic Group (oldest) ranging in age from Lower Pleistocene to Lower Middle Pleistocene; *(ii)* Dunwich Group comprising a deltaic sequence of Lower Middle Pleistocene age; and *(iii)* Californian Glacigenic Group (youngest) ranging from Middle Pleistocene to Holocene in age. The Dogger Bank Formation which dominates the upper 60 m of the Quaternary sequence on the Dogger Bank forms an integral part of the Californian Glacigenic Group (table 7 of Stoker *et al*., 2011) and was, until recently, described as a tabular unit (up to 45 m thick) composed of stratified to well-bedded sediments deposited in proglacial or glaciolacustrine setting (Cameron *et al*., 1992). Cameron *et al*. (1992) suggested that these sediments formed in an ice-dammed lake environment, or standing body of water trapped along the confluence between the BIIS and FIS (also see Valentin, 1955; Veenstra, 1965). However this interpretation relied heavily on the extrapolation of seismic stratigraphies from adjacent areas. Consequently, until recently, very little was known about the exact nature of the sedimentary sequence beneath the Dogger Bank.

Cotterill *et al*. (2017b) have begun to address this lack of understanding by utilising high-resolution seismic and borehole data recently acquired during the DBZ windfarm site survey. These authors provided a revised stratigraphic framework for the Dogger Bank, concluding that the upper part of this sequence (the focus of the present study) can be divided into three main units, namely; *(i)* the Eem Formation and earlier sediments (oldest) (here referred to as the pre-Dogger Bank Formation deposits), *(ii)* Dogger Bank Formation (c. 40-50 m thick) and *(iii)* an overlying thin (< 1 m thick) sequence of fine- to medium-grained Holocene sands (youngest) which are locally being reworked by contemporary marine processes. The pre-Dogger Bank Formation deposits comprises a sequence of dense to very dense poorly sorted, silty to fine-grained sands containing interbeds of hard clay and silty fine sand. The presence of shell fragments and organic matter within the sands has been used to suggest that they were deposited in a marine (?nearshore) environment, consistent with their belonging to either the Eem and/or Egmond Ground formations (Cameron *et al*., 1992; Cotterill *et al*., 2017b).

The overlying Dogger Bank Formation is composed of generally stiff to very stiff clays containing multiple sand-rich layers. Based on the geotechnical responses, combined with lateral extent of significant seismic reflections (Table 1), Cotterill *et al*. (2017b) subdivided the formation into three informal tectonostratigraphy subunits (c.f. Cotterill *et al*., 2017a) here referred to as the "Basal", "Lower" and "Upper" Dogger Bank (see Figures 3 to 11). The structurally lowest unit, Basal Dogger Bank (BDB; Table 1), forms a series of discrete, laterally discontinuous ridges which occur immediately above the marine sands of the underlying Eem/Egmond Ground formations (see Figures 3 to 6). The top of the Basal Dogger Bank is marked by a strong top reflection (see Figures 7 and 11) with available borehole and engineering data (cone penetration tests) indicating that the sediments (sands, silts and clays) within this zone possess a high degree of over-consolidation (Norwegian Geotechnical Institute, unpublished data). The over-consolidated nature of the sediments at the top of the BDB surface has led to this surface being is interpreted as a desiccation surface. Furthermore the degree of over-consolidation requires that the surface to be exposed for a prolonged time period. Consequently, this laterally extensive desiccation surface is thought to have formed as a result of its exposure (terrestrial) to prolonged periglacial weathering and alteration (Norwegian Geotechnical Institute, unpublished data). The lower part of the Dogger Bank Formation is dominated by the Lower Dogger Bank (LDB; Table 1) which ranges from < 5 m up to 40 m thick and forms a series of complex "ridge-like" features (Figures 3 to 6). A strong reflection is locally observed marking the top of the Lower Dogger Bank (see Figures 9 and 10) and is once again interpreted as a subaerial exposure surface. The overlying Upper Dogger Bank (UDB; Table 1) is the structurally highest unit within the Dogger Bank Formation and ranges from ≤ 5 m to c. 40 m thick (Figures 3 to 6). The UDB is often acoustically well-layered (see Figure 7), with the thicker parts of the sequence apparently draping and infilling topographic lows, forming basin-like features located between the "ridges" of LDB sediments (Figures 3 to 6). In Tranche A the LDB and UDB are locally separated by a thin, laterally discontinuous layer of sand and gravel. Although the Dogger Bank Formation is mainly composed of stiff to very stiff clay and silt, the UDB is distinguished from the underlying units by the increased occurrence of sand containing some organics and detrital micas. The LDB and, to a lesser extent, UDB both show evidence of locally intense glacitectonic deformation.

4. Buried thrust-moraine complex within the Dogger Bank Formation

The strong reflections marking the desiccation surfaces at the top of the LDB (Cotterill *et al*., 2017a, b) define a laterally extensive horizon which has been mapped across the DBZ (Figure 2a). This horizon has been gridded to produce a "map" of the top surface of the deformed lower part of the Dogger Bank Formation. The resultant sub-bottom "horizon map" is shown in Figure 2a. The red and yellow colours represent areas where the upper surface of the deformed sequence is located close to sea bed (minimum depth c. 2.5 m). In contrast, the green and blue colours indicate areas where this surface occurs at a much deeper level (maximum depth c. 66 m below sea bed). The resultant pattern of relatively "topographically higher" (i.e. closer to sea bed) areas defines a number of elongate, arcuate features (Figure 2a) which are interpreted as a series of moraines (purple colours on Figure 2b).

The horizon map reveals the presence of a buried glacial landscape (Figure 2b) comprising a number of large, roughly E-W-trending moraines (up to 20 km wide, 90-100 km long, 40-50 m high; labelled MC1 to MC4 on Figure 2) buried beneath the UDB and Holocene sedimentary successions (c.f. Cotterill *et al*., 2017a, b). These moraines are complex and composed of a number of locally intersecting to cross-cutting, arcuate, approximately E-W-trending ridge-like features (individual ridges ≤ 3 km wide) consistent with an overall ice movement direction from the N/NW. These moraines are separated by a series of topographically lower areas interpreted as ice-marginal to proglacial sedimentary basins (up to c. 30 km across) and/or meltwater channels (1-5 km wide) (Figure 2b). Analysis of the subsurface seismic profiles show that the moraine ridges are composed of highly deformed BDB and LDB (up to 40-50 m thick), with the intervening basins being occupied by a sequence of relatively undeformed UDB sediments (Figures 3 to 6) (c.f. Cotterill *et al*., 2017a). The complex nature of the moraines (Figure 2b) is thought to indicate that they represent periods of stillstand and preserve the changing shape of the ice margin.

The remainder of this paper describes the internal structure of the moraine complexes as well as the sedimentary architecture of the intervening basins. This detailed analysis is used to construct a model for the structural evolution of the moraine complexes relating their construction to former ice sheet dynamics.

5. Structural and sedimentary architecture of the Dogger Bank Formation

The glacial landform map constructed for the top surface of the deformed lower part of the Dogger Bank Formation was used to identify four key areas for further detailed study (Figure 2) in order to gain an understanding of the nature and lateral variation in the relative intensity of glacitectonism:

- **Area A** (lines 1 to 4; Figures 2 and 3) – a trending NE-SW and located within the central part of the largest and most complex moraine system (MC1 on Figure 2);
- **Area B** (lines 5 to 8; Figures 2 and 4) – trending NE-SW and located in the northwestern part the same large moraine complex (MC1 on Figure 2a) where the individual moraine-ridges are less apparent and appear to be cut by a system of meltwater channels (Figure 2b);
- **Area C** (lines 9 to 11; Figures 2 and 5) – trending NW-SE and located at the southeastern end of the moraine complex (MC1 on Figure 2); and
- **Area D** (lines 12 to 15; Figures 2 and 6) – trending NW-SE and providing a sub-bottom profile through the entire buried glacial landsystem enabling the relationships between the glacitectonic deformation and deposition of the UDB sediments within the intervening sedimentary basins to be established.

The seismic profiles all occur approximately orthogonal to the trend of the axes of the moraine ridges (see Figure 2) and provide a series of structural cross-sections (Figures 3 to 6) orientated parallel to the proposed direction of ice-push responsible for glacitectonism. For ease of description the deformed parts of the Dogger Bank Formation sequence have been divided into 8 structural domains (see Figures 3 to 6) which exhibit a similar style and relative intensity of deformation. The characteristics of each of these domains is summarised in Table 2 (after Cotterill *et al*., 2017a). A detailed description of the structure and sedimentary architecture of the Dogger Bank Formation in the four key areas is provided below.

5.1. Area A

5.1.1. Structural geology

The deformed lower part of the Dogger Bank Formation (purple colours on Figure 3) within Area A thickens rapidly towards the NE forming a distinct wedge-shaped unit on all the cross-sections (Figure 3). The relative intensity and complexity of deformation increases northwards, consistent with the cross-sections providing a series of transects from the southern margin (Domains 1 and 2; Table 1, Figure 3) into the core (Domains 3, 4 and 5; Table 2, Figures 3, 7, 8 and 9) of this glacitectonic landform (MC1 on Figure 2). Deformation is dominated by a series of locally well-developed, NE-dipping thrusts and associated SW-verging asymmetrical folds (Figures 7, 8 and 9). The sense of offset of the reflectors across the thrusts records a consistent SW-directed sense of displacement. This, coupled with the geometry of the folds within their hanging-walls, supports the conclusion that ice-push responsible for glacitectonism was primarily directed towards the S/SW.

Observed changes in the style and relative intensity of glacitectonism from SW to NE across Area A can be illustrated using line 3 (Figures 7, 8 and 9). At the southern end of this seismic profile (Domains 1 and 2) the deformed part of the Dogger Bank Formation is solely represented by the BDB (Figure 7). This unit thickens northwards where it is increasingly deformed by a series of NE-dipping thrusts which clearly offset a band of bright reflectors equated with a prominent desiccation surface at the top of the BDB (Figure 7). This relationship indicates that the periglacial weathering/alteration responsible for the formation of this desiccation surface proposed by Cotterill *et al*. (2017b) pre-dated thrusting and that there was potentially a significant time gap separating the deposition of the basal part of the Dogger Bank Formation and its subsequent glacitectonism. The thrusts become progressively steeper towards the NE where the larger structures have accommodated up to several hundred metres (c. 100-200m) of displacement (Figures 3 and 7). This increased shortening within the BDB led to folding within the hanging-walls of the thrusts. These thrusts also deform the lower part of the structurally overlying UDB indicating that thrusting locally post-dated the deposition of at least the lower parts of this unit. The thickening of the deformed sequence Domain 1 into Domain 2 coupled with progressive increase in the relative intensity of deformation towards the NW is consistent with this part of Area A representing the distal parts of a S/SW-propagating thrust-block moraine.

The thrusts affecting the BDB and LDB propagate upwards from a major décollement surface located at the base of the Dogger Bank Formation (Figure 3). This subhorizontal to gently N-dipping basal detachment occurs at a deeper structural level within the northern part of Area A. It climbs upwards (c. 10-15 m vertical climb over a horizontal distance of approximately 2 to 3 km) towards the SW via a number of step-like ramps located beneath the central part (Domains 3 and 4) of the moraine (MC1) complex (Figure 3). Immediately above these ramps, the sequence is repeated by a number of stacked elongate (1-2 km long) thrust-bound slices of LDB sediments (Figures 3 and 8). However, the presence of the ramps within this décollement suggests that thrusting also affected at least the upper part of the underlying pre-Dogger Bank succession. This would have resulted in the detachment and incorporation of thrust-bound blocks or glacitectonic rafts of Eem and/or Egmond Ground formation sediments into the developing thrust (MC1) moraine complex. However, no obvious glacitectonic rafts have been recognised due to the similar nature of the acoustic properties displayed by the LDB and structurally underlying pre-Dogger Bank succession (see Figures 7 to 11).

In the central and northern parts of line 3 the deformed LDB is between 40 to 50 m thick (Domains 3, 4 and 5; Figure 3) and contains moderately to steeply inclined reflectors which are variably folded and disrupted by a series of NE-dipping, SE-directed thrusts (Figures 8 and 9). Changes in fold vergence within Domain 3 (Table 2) has led to the identification of a large-scale (c. 2-3 km across), upright to steeply inclined anticline. On the southern-limb of this anticline, weakly to moderately developed reflectors within the LDB are deformed by NE-verging mesoscale parasitic folds (see Figures 3 and 8). In contrast, on its northern-limb, the mesoscale folds once again verge towards the SW, consistent with the main S/SW-direction of glacitectonic deformation. This major anticline can be traced laterally across Area A where it occurs immediately to the S of the prominent ramp(s) within the basal décollement surface (Figure 3) and forms a relatively flat-topped hanging-wall anticline due to deformation occurring above this ramp. Domains 3, 4 and 5 record a progressive increase in the relative intensity of folding and thrusting within the LDB (Figures 3, 8, and 9). Earlier formed thrusts within this part of the thrust-block (MC1) moraine are themselves folded, indicative of a polyphase deformation history. Immediately to the N within Domain 6, the LDF is acoustically "blank" with very few, if any, recognisable reflectors (see Figures 8 and 9). The "massive"/"structureless" appearance may reflect the highly deformed and disrupted nature of the UDB within this part of the thrust (MC1) moraine. This same progressive increase in the relative intensity of deformation from Domain 3, through Domains 4 and 5, and into Domain 6 can be recognised on all the seismic profiles from Area A. Importantly the blanked area occurs immediately S of a prominent, arcuate basin/channel (labelled AB on Figure 2b); the latter separates the main thrust complex (MC1) from a narrow ridge-like moraine (MC2) located immediately to the N (see Figures 2 and 3). As a result the blanked area may represent a highly deformed zone developed immediately adjacent to a former ice-contact slope with the intense disruption of the LDB possibly recording a prolonged period of stillstand.

5.1.2. Sedimentary architecture

The locally thick UDB sequence in the southern and northern parts of Area A is typically undeformed (Figure 3) with variably developed subhorizontal to inclined reflectors preserving the well-bedded nature of these sediments (Figures 7 and 9). Changes in the acoustic properties of the sediments, coupled with changes in dip of the reflectors has enabled the UDB to be divided into a number of tabular to lenticular sedimentary "packages". Cross-cutting relationships between these packages have revealed the presence of several major erosion surfaces as well as a number of channels (e.g. Figures 3a and c). Bands of bright reflectors within the UDB may represent desiccation/weathering surfaces within this sequence, potentially recording significant breaks in sedimentation. The sedimentary packages locally possess inclined, SW-dipping bedding surfaces (foresets) (Figures 3 and 7). The presence of inclined foresets, the lenticular geometry and cross-cutting relationships between these sediment packages suggests that they record the southward progradation of a series of outwash fans or aprons. These fans/aprons would have prograded into a low-lying, proglacial basin located to the S of the thrust-moraine (MC1) complex fed by meltwater channels cut into their upper surfaces (see Figures 2b and 3). As noted above the lower part of the UDB sequence within these aprons/fans is locally folded and thrust (Figures 3 and 7), indicating that deposition of at least the early part of the UDB sequence probably accompanied glacitectonism (syntectonic sedimentation). However, the well-bedded upper part of the UDB clearly overlies the highly deformed sediments of the LDB (Figures 3 and 8) with the boundary between the two units being interpreted as a prominent erosion surface; a conclusion supported by the presence of a thin, laterally discontinuous layer of sand and gravel along the boundary between the LDB and UDB in Tranche A (Cotterill *et al.*, 2017b).

In the northern part of the Area A, the UDB infills a 2 to 3 km wide, arcuate channel-like feature (AB on Figure 2) and is variably deformed by a series of SW-verging folds and associated thrusts which propagate upwards from the structurally underlying LDB (Figure 3). On Figure 9d a band of bright reflectors within the UDB sequence infilling this channel is dissected by a number of steeply inclined, NE-dipping faults (displacements of a few metres). However, along the northern margin of Area A, the UDB sequence thickens northwards and lacks any evidence of deformation; further indicating that deposition of the UDB has a complex relationship with glacitectonic deformation (see Section 5).

5.2. Area B

5.2.1. Structural geology

The deformed Dogger Bank Formation sequence (up to c. 40 m thick) in Area B records a similar style of SW-directed folding and thrusting (Domains 2, 3 and 6; Table 2) to that observed in Area A (compare Figures 3 and 4). The base of the Dogger Bank sequence is once again marked by a prominent subhorizontal to very gently dipping décollement surface (Figure 4). Deformation accompanied the formation of a series of symmetrical to asymmetrical, thrust moraine ridges (≤ 40 m high) which locally possess a core of BDB enclosed within a thick carapace of LDB (Figures 4 and 10). The asymmetrical moraines locally possess a distinctive morphology characterised by a shorter, more steeply dipping slope on their NE-side and a much longer, more gently dipping surface to the SW. The shape of the buried moraines is thought to preserve the original morphology of these glacitectonic landforms with their steeper NE-side potentially representing an ice-contact slope. Elsewhere within Area B, however, the shape of the moraines has been strongly modified due to erosion associated with the incision of a series of small (200-400 m wide) to large-scale (0.5-1 km wide) channels (see Figure 2b) filled by undeformed UDB sediments (Figures 4 and 10). The top of the deformed sequence is marked by a band of bright reflectors (Figure 10) consistent with this former glacial land surface having undergone a period of desiccation/weathering prior to, or during the early stages of the deposition of the overlying UDB. This boundary is locally offset by a series of NE-dipping, SW-directed thrusts (Figure 4) indicating that periglacial weathering may have coincided with at least the later stages of glacitectonic deformation.

5.2.2. Sedimentary architecture

The relatively thick, well-bedded UDB sequence which covers much of Area B is essentially undeformed (Figure 4). Changes in the acoustic properties of the sediments, coupled with changes in dip of the reflectors, have revealed the presence of a number of tabular to lenticular sedimentary packages separated by prominent erosion surfaces (Figures 4 and 10). The geometry and cross-cutting relationships between these sediment packages are consistent with southward progradation of a series of outwash fans or aprons (see Figures 4a and b). Bands of bright reflectors within the UDB (Figure 10), denoting desiccation/weathering surfaces, can be interpreted as recording significant breaks in sedimentation. In contrast to Area A, the moraine (MC1) complex in Area B is locally dissected by a number of large (0.5-1 km wide, 40-60 m deep), deeply incised channels which have locally cut through the deformed part of the Dogger Bank Formation and into the underlying pre-Dogger Bank Formation sequence (Figures 4c, 4d and 10). Marked changes in the dip of the reflectors (bedding) and acoustic character of the UDB indicates that the sedimentary sequence filling the channels is complex (Figure 10) and that they were probably active over a prolonged period.

5.3. Area C

5.3.1. Structural geology

Deformation of the BDB and LDB in Area C is comparable to that recognised in the other areas (compare Figures 3, 4 and 5) in that it is dominated by southerly directed folding and thrusting (Domains 3 and 6; Table 2) with the base of the deformed sequence being marked by a prominent subhorizontal to gently undulating décollement surface (Figure 5). However, the geometry of the folds and sense of offset on the thrusts indicate that deformation in this area was directed towards the SE, rather than SW as in Areas A and B. This variation in sense of shear is consistent with the three study areas being located at different points around an arcuate (see Figure 2) glacitectonic landform consistent with a radial pattern of ice-push resulting from an advancing, lobate ice sheet margin. Local changes in the geometry (S, M and Z-shaped) meso-to small-scale (amplitudes 10 to 20 m) folds indicates that the LDB within the core of the moraine complex in Area C is deformed by a number of large, kilometre-scale anticlines (Domain 3; Figure 5b).

5.3.2. Sedimentary architecture

In the northern part of Area C the deformed LDB is overlain by an undeformed sequence of UDB sediments which comprise several laterally extensive tabular subunits which thicken towards the NW (Figures 5a and b). A laterally extensive desiccation surface present at the top of the LDB (dark purple layer on Figure 5) indicates that the surface of the moraine was exposed to periglacial alteration prior to deposition of the UDB sequence. Although a clear distinction can be made between the moraine complexes MC1 and MC2 on the horizon map (Figure 2) and seismic profiles from Area A (Figure 3), this distinction is less apparent on the cross-sections from Area C (Figure 5). The irregular upper surface of the deformed LDB forms a series of symmetrical to asymmetrical ridges with the intervening small basins and/or channels (400-600 m wide) filled by essentially undeformed UDB sediments (Figure 5). The lower part of this sequence, however, locally appears folded or distorted as these well-bedded sediments drape the undulating, structurally controlled topographic surface marking the top of the underlying deformed LDB (Figure 5c).

5.4. Area D

5.4.1. Structural geology

The NW-SE-trending seismic profiles (lines 12 to 15; Figure 6) from Area D provide cross-sections through several of the glacitectonic moraine complexes identified within Tranche A (MC1/2, MC3 and MC4; Figure 2) as well as the larger sedimentary basins (Domain 8; Table 2) separating these landforms. They reveal that the moraines are all composed of folded and thrust BDB and LDB, up to at least 50 m thick (Figures 6 and 11). The tops of the larger moraine ridges are truncated at the seabed or at the base of a thin Holocene sequence. Elsewhere the top of the LDB is marked by a band of bright reflectors (e.g. Figures 11d and e); interpreted as a periglacially weathered/desiccated surface (dark purple colour on Figures 6 and 11). The overall style and relative intensity of deformation locally observed within the thrust-block moraines in Area D is comparable to that in the other areas (compare Figures 3, 4, 5 and 6) and is once again dominated by southerly directed folding and thrusting which is most apparent towards the northern-end of the cross-sections (Figures 6 and 11). The S/SE-directed thrusts once again propagate upwards from a subhorizontal to gently undulating décollement surface forming the base of the Dogger Bank Formation (Figure 6). Although much thinner (≤ 5-10 m thick) this deformed sequence extends beneath the sedimentary basins separating the larger thrust-block moraine complexes (Figures 6 and 11). This relatively thin deformed sequence locally thickens to form a number of small (10-15 m high) symmetrical to asymmetrical moraine ridges composed of apparently massive/structureless (acoustically blank) UDB (Domain 6; Table 2), with or without a core of BDB sediments. These smaller moraines (2-4 km wide) are completely buried beneath a cover sequence of undeformed UDB (Figures 6 and 11).

5.4.2. Sedimentary architecture

The sedimentary basins separating the moraine complexes (MC1/2, MC3 and MC4; Figure 2) contain a locally thick (up to 30-40 m) sequence of UDB well-bedded sediments (Figure 6) indicated by variably developed subhorizontal to inclined reflectors (Figure 11). Changes in the acoustic properties of these sediments, coupled with changes in the dip of the reflectors has enabled the sequence to be once again divided into a number of tabular to lenticular sedimentary packages. On Figures 6 and 11 it can be seen that the lenticular sediment packages are typically developed on the SE-side (down-ice) of the moraine ridges where they form the lowest part of the UDB sequence. They range in size from relatively small-scale deposits (c. 10-15 m thick, 1-2 km across; Figures 11c and g) to much larger (5-10 km across; Figure 12e), internally complex sequences comprising several lenticular subunits (Figures 6a and d). Inclined bedding surfaces (reflectors) within these sediment packages are interpreted as foresets formed in response to the southerly progradation of these deposits. These relationships support the conclusion that the lenticular sediment packages represent ice-marginal fans/aprons and were formed when the ice occupied the moraine ridge. If correct it would suggest that ice occupied this position for some time; once again indicating that the moraines record the position of the ice margin as it retreated northwards across Dogger Bank.

Elsewhere within Area D the UDB basin-fill is dominated by sub-horizontally bedded, laterally extensive, tabular packages of sediments (Figures 6 and 11). Cross-cutting relationships between these packages record the presence of several major erosion surfaces (e.g. Figures 6a and c). These surfaces are locally marked by bands of bright reflectors (e.g. Figure 11f) which represent significant breaks in sedimentation enabling periglacial desiccation/weathering. In the southernmost and largest basin (LB on Figures 2 and 6) a prominent, laterally extensive desiccation surface divides the UDB basin-fill into two: (i) a lower, more complex sequence of lenticular to tabular sediment packages which drapes the underlying glacial land surface and infills the low-lying areas between the moraine ridges; (ii) overlain by an upper sequence of laterally more extensive, sheet-like sediments (Figures 6 and 11). It is possible that these sheet-like sediment packages record the development of a laterally more extensive outwash deposits. Cotterill *et al*. (2017b) describe the presence of loess deposits and desiccation surfaces within the upper part of the Dogger Bank Formation consistent with its deposition on an exposed terrestrial land surface. To the NE on line 12 the upper sequence thins rapidly and locally appears to onlap onto a thick, lenticular to wedge-shaped subunit of UDB sediments (Figures 6a and 11e). This subunit is interpreted as representing a 2 to 3 km wide apron/fan mantling the southern side of the MC4 moraine (Figures 2 and 11) complex. The lower part of this apron/fan sequence is deformed by a series of open, upright folds and faults which propagate upwards from the underlying deformed LDB (Figures 6 and 11e), suggesting that glacitectonic deformation may have accompanied the deposition of the lower part of the UDB.

6. Model of active ice retreat resulting in large-scale glacitectonic deformation

Although in detail the style and relative intensity of deformation recorded by the BDB, LDB and, to a lesser extent, UDB varies across the Tranche A (Figure 3 to 6) a number of general observations can be made regarding the glacitectonic deformation of the Dogger Bank Formation:

- The deformed sediments dominating the lower part of the Dogger Bank Formation form a series of ridge-like landforms (individual ridges 0.5-3 km wide, up to 40 m high) composed of folded and thrust BDB and LDB. These glacitectonic landforms can be traced laterally for several hundred metres to kilometres forming arcuate, linear bodies within the larger thrust-block moraine complexes or composite ridges (MC1 to MC4; Figure 2) (as defined by Benn and Evans, 2010), the largest of which (MC1) is up to 15-20 km across;

- Glacitectonic deformation is dominated by southerly-directed folding and thrusting (Figures 3 to 11) consistent with it having been driven by ice advancing from the N/NW. The variation in the direction of shear from towards the SW in Area A, through to SE in Area D is consistent with a radial pattern of ice-push resulting in ice-marginal to proglacial deformation in front of the advancing, lobate ice sheet margin;

- The base of the deformed sequence is marked by a prominent, laterally extensive décollement surface (Figures 3 to 6) which modified/overprinted the original stratigraphical relationship(s) between the Dogger Bank Formation and the underlying pre-Dogger Bank Formation sequence. Locally developed ramps indicate that thrusting may have affected the upper part of the underlying pre-Dogger Bank succession;

- The thickness of the BDB is highly variable with this structurally lowest unit within the Dogger Bank Formation locally forming the cores to the larger thrust-block moraines (Figures 3 to 6). A prominent periglacial desiccation/weathering surface at the top of the unit is deformed indicating that deposition of the BDB and its subsequent glacitectonism were separated by a potentially significant time gap;

- The tops of the larger thrust-block moraine complexes (Benn and Evans, 2010) are locally truncated (eroded) at the sea bed or at the base of a thin sequence of undeformed UDB and/or Holocene sediments. Elsewhere the top of the deformed LDB sequence is marked by a desiccation surface indicating that the moraines underwent a period of periglacial weathering/alteration and/or erosion prior to the deposition of the UDB;

- The UDB is in general undeformed suggesting that deposition of these sediments largely post-dated glacitectonism. Locally, however, folding and thrusting can be seen to propagate upwards from the underlying LDB to affect the overlying UDB, indicating that deposition of at least the lower part of the UDB accompanied deformation. Elsewhere (e.g. Area B) the moraines are deeply incised by a series of meltwater channels filled by undeformed UDB sediments; and

- The UDB can be divided into two main subunits: (i) a lower, more complex succession of lenticular to tabular sediment packages which drape the underlying land surface and infill the low-lying areas between the moraine ridges; and (ii) an overlying succession composed of laterally extensive, sheet-like sediment packages (Figures 3 to 6). Lenticular to wedge-shaped sediment packages within the UDB are interpreted as southerly prograding fans or aprons mantling the distal (down-ice) side of the moraines. Whereas the sheet-like sediment packages record the subsequent development of a more laterally extensive outwash deposits.

Consequently the simplest model for the construction of the thrust-block moraines (MC1 to MC4; Figure 2) identified on the Dogger Bank is one of ice-marginal to proglacial deformation resulting from ice-push associated with the repeated advance of a lobate ice-margin from the N/NW. Although the shape of these glacitectonic landforms has locally been modified as a result of erosion accompanying the deposition of the overlying UDB sequence, there is no evidence to suggest that the thrust-block moraines have been overridden. Consequently the phases of ice sheet advance responsible for the large-scale glacitectonic deformation are thought to have occurred during an overall pattern of ice sheet retreat (deglaciation) from the Dogger Bank (see Section 6.2). Deposition of the deformed lower part of the UDB occurred whilst the ice sheet occupied the individual ice limits represented by the thrust-block moraines, forming a series of lenticular aprons/fans which prograded southward into the adjacent ice-marginal to proglacial sedimentary basins. The undeformed, tabular to sheet-like deposits which characterise the upper part of the UDB are considered to represent laterally more extensive outwash deposits laid down as the ice sheet retreated northward.

6.1. Construction of large, thrust moraine complexes as a result of glacitectonic deformation at an oscillating ice sheet margin

The largest of the thrust-block moraine complexes (MC1; Figure 2) identified within Tranche A (Areas A to D) is in the order of 15-20 km across and can be traced laterally for over 40 to 50 km. Cross-sections through this thrust-block moraine system (lines 1 to 4; Figure 3) reveal that it is internally structurally complex (see Section 5.1) and composed of a large volume of highly deformed sediments (Figures 3, 7, 8 and 9). The large scale of this thrust-block moraine, coupled with the observed marked changes in structural style and relative intensity of deformation of the deformed sequence enabling it to be divided into a series of structural domains (c.f. Cotterill et al., 2017a), as well as evidence for the polyphase deformation (e.g. folding of earlier developed thrusts in response to later deformation) and the presence of a deformed channel-fill sequence included within the landsystem (Figure 3) indicate that this complex glacitectonic landform did not form as a result of a single phase of ice-push. Furthermore, cross-cutting relationships between the individual ridge-like features identified within this thrust-block moraine (Figure 2b) are also consistent with this complex landforms having been constructed in response to several phases of ice advance (Stages 1 to 9; Figure 12). Consequently, the individual thrust-block moraine complexes (MC1 to MC4; Figure 2) are not the product of a single phase of ice sheet advance, but evolved over a prolonged period and resulted several phases of readvance during which the ice sheet repeatedly reoccupied essentially the same ice limit. Each readvance would have been followed by a phase of retreat, accompanied by the deposition of an outwash sequence laid down within an ice-marginal to proglacial sedimentary basin which opened between the rear of the evolving moraine complex and the retreating ice margin (Stages 3, 5 and 7; Figure 12). During the following readvance these outwash sediments would have been deformed (folded and thrust) and accreted onto the up-ice side of the evolving moraine complex (Figure 12). This interpretation is supported by the similar acoustic properties displayed by the deformed LDB and undeformed UDB sequences (see Figures 7 to 11). Furthermore, boreholes through the Dogger Bank Formation reveal that both units are composed of lithologically similar sequences of stiff to very stiff clays containing multiple sand interbeds (Cotterill *et al*., 2017b). Consequently, these large-scale thrust moraine complexes owe their origins to the complex interplay between glacitectonism and penecontemporaneous sedimentation at a highly dynamic, oscillating ice sheet margin.

The model proposed for the evolution of the largest of the internally complex glacitectonic landforms on Dogger Bank is shown in Figure 12. During the initial phase of ice sheet advance the ice is thought to have overridden the BDB sequence (Stage 1; Figure 12). This basal unit was deposited prior to the development of the glacitectonic landsystem which characterises the Dogger Bank Formation within Tranche A. The presence of a well-developed desiccation surface at the top of the

BDB indicates that Dogger Bank was subaerially exposed (c.f. Cotterill *et al*., 2017b) and this terrestrial land surface was subjected to a period of periglacial weathering and alteration prior to its inundation by ice. The presence of BDB sediments across Tranche A can be used to suggest that the advancing ice sheet may have been decoupled from its bed facilitating the preservation of these mud-rich sediments beneath the overriding ice mass (Stage 1; Figure 12). However at some point during this advance the ice began to couple with its bed, possibly due to the dewatering of the ice-bed interface leading to a reduction in basal sliding and transmission of increasing amounts of shear into the underlying BDB. Coupling of the ice to its bed initially led to the development of a forward propagating imbricate thrust stack (Stage 2; Figure 12). This southerly propagating thrust system is preserved along the southern margin of the MC1 moraine complex in Area A (Domain 1; Figure 3). The propagation of the basal décollement into the forefield in advance of ice sheet would lead to the sequential detachment of progressively "younger" (structurally) thrust-bound slices of BDB sediments. These detached slabs were accreted to the base of the evolving imbricate stack leading to the "back-rotation" (i.e. northward sense of rotation of the detached thrust-bound slab is towards the advancing ice sheet) of structurally higher and older thrust-slices; the latter becoming increasingly steeper in attitude towards the ice margin (Figures 3 and Stage 2 on 12). As the ice sheet continued to advance the deforming BDB would have accommodated a greater degree of shortening, reflected in the increasing complexity and relative intensity of deformation northwards towards the ice margin (Figures 3 and Stage 2 on 12). Furthermore the progressive accretion, back-rotation and up-thrusting of successively younger thrust-bound slabs of BDB may have resulted in an increase in the surface topography (height) of the evolving thrust-block moraine. At some point forward motion of the ice mass is thought to have ceased due to either: the "locking up" of the imbricate thrust stack; the size of this evolving landform reaching a "critical mass" so that it acted as a "buffer" preventing further ice sheet advance; and/or a change in ice sheet dynamics.

The ice sheet appears to have remained at this maximum position for some time allowing the deposition of a sequence of UDB outwash sediments mantling the upper surface of the moraine (Stage 2; Figure 12). Minor oscillations in the position of the ice margin whilst it was at this stillstand position may have resulted in the penecontemporaneous deformation of the recently deposited outwash. The ice mass subsequently underwent a phase of retreat laying down sediments in a temporary sedimentary basin which opened between the moraine and the retreating ice margin (Stage 3; Figure 12). A subsequent readvance led to the deformation of these recently deposited sediments and their accretion onto the up-ice side of the moraine complex (Stage 4; Figure 12). This cycle of sedimentation during ice sheet retreat followed by glacitectonic deformation in response to a readvance is thought to have occurred a number of times (Stages 5 to 9; Figure 12) resulting in the observed structurally complexity within the thrust moraine system. This model can be applied to all of the moraine complexes within Tranche A (MC1 to MC4) with the individual ridges identified on the horizon and landform maps (Figure 2) marking the readvance positions of the ice sheet margin during their construction. The accretion of progressively younger thrust-sheets onto the up-ice side of the evolving moraine complex may have led to the localised reactivation and/or folding of earlier developed structures (e.g. thrusts; see Figure 3) resulting in the locally observed polyphase deformation history recorded by the LDB and large-scale folding within the cores of the moraine complexes. Apparently structureless (acoustically blank) sections within the moraine complex (Figures 7 to 9) are considered to represent highly disrupted parts of the LDB sequence resulting from locally intense deformation adjacent to former ice-contact slopes.

6.2. Factors controlling the location and development of the décollement surface at the base of the Dogger Bank Formation

The laterally extensive subhorizontal to very gently dipping décollement surface marking the base of the Dogger Bank Formation is apparently developed at essentially the same stratigraphic/structural level across Tranche A (Areas A to D; Figures 3 to 6). A number of previous studies have argued that proglacial to ice marginal thrusting can be facilitated by the introduction of pressurised meltwater along evolving thrust planes (Bluemle and Clayton, 1983; Ruszczynska-Szenajch, 1987, 1988; Phillips *et al*., 2008; Phillips and Merritt, 2008; Burke *et al*., 2009). For example Vaughan-Hirsch and Phillips (2016) and Phillips *et al*. (2017) have suggested that the décollement surface at the base of large-scale imbricate thrust stacks which deform the Aberdeen Ground Formation of the central North Sea and Cretaceous bedrock at the Mud Buttes, southern Alberta (Canada), respectively, formed in response to the over-pressurisation of the groundwater system during rapid ice sheet advance (surge-type behaviour). These authors argue that the resulting increase in the hydrostatic gradient would force groundwater from beneath the ice sheet (higher overburden pressure) into its forefield (lower pressure) (Boulton and Caban, 1995), facilitating the propagation of this detachment in front of the advancing ice mass.

A similar model could be applied to the Dogger Bank thrust moraines where surge-type behaviour could lead to a rapid advance of the ice sheet lobe and pressurisation of groundwater within the underlying Quaternary sediments. The lithological contrast between the sands of the Eem/Egmond Ground formation(s) at the top of the underlying sequence and the Dogger Bank Formation may have resulted in the focusing of this pressurised groundwater along this major lithostratigraphic boundary. The mud-rich BDB sediments would have acted as an aquitard trapping water beneath the ground surface and within the upper part of the Eem/Egmond Ground formation. The trapping and localisation of pressurised groundwater at this boundary may have been further aided by the presence of a well-established permafrost layer at the top of the BDB; evidence for this layer being provided by the laterally extensive desiccation surface developed at the top of this unit (see Figures 3 to 11). The resultant increase in pore water pressure within the unconsolidated Eem/Egmond Ground formation sands could have led to a lowering of their cohesive strength, leading to failure and propagation of a water-lubricated décollement out into the forefield. Once formed, this essentially bedding-parallel detachment would have represented an ideal fluid pathway, helping to transmit pressurised water further into the forefield, leading to "thrust gliding" (Nieuwland *et al*., 2000; Mourgues *et al*., 2006) and facilitating transmission of shear in front of the advancing ice sheet.

7. Active retreat of a Weichselian ice sheet from Dogger Bank

It is clear from the above that rather than being a stratigraphically simple "layer-cake" composed of stratified to well-bedded sediments deposited in proglacial or glaciolacustrine setting (Cameron *et al*., 1992) the Dogger Bank Formation is far more complex. Concealed beneath an undeformed sequence of outwash sediments (UDB) and Holocene to recent deposits is evidence of a buried glacitectonic landsystem (cf. Cotterill *et al*., 2017a, b), comprising large (up to 40-50 m high, 15-20 km across, over 40-50 km in length) arcuate thrust-block moraine complexes separated by low-lying sedimentary basins (Figure 2). Comparable large-scale glaciotectonic complexes comprising folded and thrusted glacigenic sediments have been described elsewhere within the North Sea Basin and adjacent areas where they are associated with glaciations of different ages (e.g. Huuse *et al*., 2001; Andersen *et al*., 2005; Phillips *et al*., 2008; Burke *et al*., 2009; Bakker and van der Meer, 2015; Vaughan-Hirsch and Phillips, 2017; Lee *et al*., 2013, 2017; Pedersen and Boldreel 2017). Prominent desiccation surfaces developed at the tops of the BDB and LDB, and within the UDB which are interpreted as having formed in response to intense periglacial weathering/alteration clearly indicate that this was a subaerially exposed, terrestrial landscape (cf. Cotterill *et al*., 2017b). The internal structural complexity of the glacitectonic landforms has led to the conclusion that their construction occurred at a highly dynamic, oscillating ice sheet margin which repeatedly readvanced and reoccupied a series of recessional ice limits (Figure 12). The result of this model is that the relative age of the deformation recorded by the BDB/LDB sequences and depositional age of the overlying UDB outwash sediments is diachronous; both become progressively younger towards the N/NW across Tranche A. The construction of comparable regionally extensive glacitectonic landsystems (Neutral Hills, Sharp Hills, Misty Hills, Mud Buttes) have been associated with the surge-like activity within the Prospect Valley lobe of the Central Alberta Ice Stream (Canada). This phase of highly dynamic activity within the Prospect Valley lobe occurred during the overall northward retreat of the Laurentide Ice Sheet across Alberta (Evans *et al*., 2008, 2014; O'Cofaigh *et al*., 2010; Atkinson *et al*., 2014; Phillips *et al*., 2017) and links large-scale glacitectonism to fast ice flow. A similar model of surge-related large-scale glacitectonism during the retreat of an oscillating ice sheet margin can be applied to the Dogger Bank area of the North Sea (Figure 13).

The glacitectonic landsystem (MC1 to MC4, Figure 2) preserved within the Dogger Bank Formation comprises a network of anastomosing, arcuate to locally cross-cutting moraine-ridges separated by large ice-marginal to proglacial sedimentary basins (e.g. LB on Figure 2). The presence of this landsystem provides unequivocal evidence that, at its maximum extent, the Weichselian ice sheet not only inundated the Dogger Bank, but probably extended further south into the North Sea basin; supporting the postulated ice limits within the southern North Sea proposed by Jansen *et al*. (1979), Carr *et al*. (2006), Boulton and Hagdorn (2006), Hubbard *et al*. (2009), Graham *et al*. (2011) and Sejrup *et al*. (2016) amongst others (see Figure 1a). Furthermore, no evidence has been found to suggest that the moraine ridges have been overridden during a later glaciation suggesting that this complex landsystem was formed during the Last Glacial Maximum (LGM). The large thrust moraine complexes within Tranche A (M1 to M4; Figure 2) are interpreted as delineating recessional ice limits formed in response to the repeated readvance of a highly dynamic, lobate ice margin, occurring during the overall northward (N/NW) retreat of the Weichselian ice sheet from this part of the North Sea. This retreat history is illustrated on Figure 13 where the progressive changes in the shape and positions of the ice sheet margin have been established using the morphology of the moraine-ridges (Figure 2b). Due to the lack of published seismic data, no attempt has currently been made to project the ice margin to the south and east of Tranche A. However, based on the evidence from this data set the ice margin is thought to have extend further to the south of the DBZ.

The largest moraine complex (MC1; Figures 2 and 13) marks the most southerly position of the Weichselian ice sheet within Tranche A; although, at its maximum extent, the ice is likely to have extended further to the S (see Figure 2a). The ice sheet clearly repeatedly reoccupied this position over a prolonged period (Figures 13a to f) resulting in the construction of this internally complex, 15-20 km wide glacitectonic landform. Its construction was accompanied by the deposition of an UDB outwash sequence which formed a series of southerly prograding aprons or fans mantling the down-ice side of the moraine complex (Figure 12). Meltwater expelled from the retreating ice incised a network of small to locally large-scale drainage channels (see Figure 2b) which locally modified the shape of the evolving moraine complex (Area B; Figure 4). Although there is likely to have been localised ponding of meltwater between the evolving moraine ridges and at the ice margin, the incision of deep (up to 40 to 60 m; see Figures 4 and 10) drainage channels which cut through the MC1 moraine will have drained the area adjacent to the ice sheet margin (Figure 13), effectively preventing the establishment of the large proglacial lake (at least in this part of the Dogger Bank) proposed by Cameron *et al*. (1992) (also see Valentin 1955; Veenstra 1965; Cohen *et al*., 2014; Hijma *et al*., 2012; Murton and Murton, 2012; Sejrup *et al*., 2016). This conclusion is supported by the occurrence of several well-developed, regionally extensive desiccation surfaces within the Dogger Bank Formation of Tranche A providing unequivocal evidence that this part of Dogger Bank was a subaerially exposed terrestrial land surface and subject to repeated phases of periglacial weathering and alteration (Cotterill *et al*., 2017b). Eventually the ice sheet retreated northward leaving the MC1 and MC2 moraine complexes separated by an arcuate, elongate basin or channel (Figures 2 and 13) filled by variably deformed UDB outwash (Figure 3). The shape of the arcuate moraine ridges within both of these complexes, coupled with the kinematics obtained from the glacitectonic structures indicates that ice sheet movement at this stage of the retreat history was predominantly N/NNW-S/SSE (Figure 13a to e).

Following the accretion of MC2 moraine complex onto the up-ice side of the much larger MC1 system (Figure 13e) the Weichselian ice sheet is thought to have retreated further N (Figure 13f). Its subsequent readvance into Tranche A was less extensive and led to the construction of the outer, southernmost moraine-ridges of the MC3 complex (Figure 13i). The large, low-lying basin formed between the MC1/2 and MC3 moraines (LB on Figure 2) was progressively filled by a sequence of UDB outwash sediments (Figure 6). This sequence includes a series of fans/aprons developed on the down-ice side of the MC3 moraine complex which prograded southwards into the basin. These sediments were locally deformed as the ice repeatedly reoccupied the MC3-limit building up a series of arcuate moraine ridges separated by small ice-marginal/proglacial basins (Figures 2 and 13h to i) filled by penecontemporaneous outwash (Figure 6). At its southwestern-end the MC3 moraine clearly crosscuts and truncates the earlier formed MC1 and MC2 systems (Figures 2 and 13g). Furthermore, the shape of the MC3 moraine is more consistent with it having been constructed by ice advancing from the NW (Figure 3i) rather than the predominantly N-S sense of movement established for the earlier part of the retreat history (Figure 13). A prominent desiccation/weathering surface within the UDB sequence (see Figure 6) filling the proglacial basin (LB on Figure 3) represents a break in sedimentation; possibly coinciding with one of the readvances/oscillations responsible for the construction of the MC3 moraine. Meltwater production and associated sedimentation within the proglacial area is likely to be lower during ice sheet advance enabling the development of permafrost within the forefield.

The final phase of readvance of the Weichselian ice sheet into Tranche A was apparently more localised in extent and led to the construction of the MC4 moraine (Figure 13j). The shape of the moraine-ridges within this complex once again suggests that the main ice-movement direction was from the NW. This change from a N-S (MC1 and MC2 moraines) to more NW-SE (MC3 and MC4 moraines) direction of ice-movement (see Figure 13) during the northwards retreat of the Weichselian ice sheet suggests that there was a significant change in the structural configuration of this ice mass during deglaciation. Furthermore the size and spacing between the individual moraine-ridges within these larger glacitectonic moraine complexes varies from S to N across Tranche A. The ridges within the MC3 and MC4 moraines are relatively smaller and more widely spaced than the tightly packed landforms present within the structurally more complex MC1 moraine (Figure 2). This decrease in size and increase the spacing of the glacitectonic landforms northward across Tranche A is thought to record an overall decrease in the magnitude of the readvances/oscillations responsible for the construction of these glacitectonic landforms. Comparable relationships between the size and spacing of annual recessional moraines formed during the recent retreat histories of contemporary Icelandic glaciers, reflecting changes in the magnitude of the winter/spring readvance, have been described by several authors (e.g. Evans and Twigg, 2002; Bradwell *et al*., 2013; Phillips *et al*., 2014). The geomorphological record preserved within the Dogger Bank Formation is therefore thought to not only record a significant change in the structural configuration of Weichselian ice sheet, but also the progressive weakening of this ice mass as it retreated northwards.

The N-S to NW-SE direction of ice movement derived from the landforms and glacitectonic deformation structures preserved within the Dogger Bank Formation is consistent with the regional-scale pattern ice flow derived from the ice sheet modelling of Boulton and Hagdorn (2006) and the reconstruction for Weichselian ice sheet within the North Sea basin of Sejrup *et al*. (2016). Both of these approaches suggest that at its maximum (i.e. when the BIIS and FIS were confluent forming a single ice mass) and during the initial stages of collapse, the Weichselian ice inundating Dogger Bank would have been flowing S/SSE from an approximately E-W-trending ice divide linking NE Scotland and southern Norway (see fig. 10 of Boulton and Hagdorn, 2006 and fig. 3 of Sejrup *et al*., 2016). Furthermore the model simulations of Boulton and Hagdorn (2006) also predict relatively fast ice flow across the Dogger Bank region, supporting the proposed model for the construction of the Dogger Bank moraine complex as having occurred in response to large-scale glacitectonics during surge-related marginal readvance as the Weichselian ice sheet retreated northwards from the southern central North Sea.

8. Conclusions

The detailed analysis of high-resolution seismic data from the Dogger Bank in the southern central North Sea has revealed that the Dogger Bank Formation records a complex history of sedimentation and penecontemporaneous, large-scale, ice-marginal to proglacial glacitectonism associated with the active retreat of the Weichselian ice sheet. The 2D seismic profiles provide a series of cross-sections through a large thrust moraine complex which is buried beneath a thin sequence of Holocene sediments. This glacitectonic landsystem comprises a series of elongate, arcuate moraine-ridges separated by low-lying ice marginal to proglacial sedimentary basins and/or meltwater channels, preserving the shape of the former ice sheet margin. The individual moraines, the largest of which is up to 15-20 km across, are composed of folded and thrust sediments belonging to the basal and lower units of the Dogger Bank Formation. Deformation was dominated by southerly-directed folding and thrusting, with glacitectonism having been driven by ice advancing from the N/NW. The base of the deformed sequence is marked by a prominent, laterally extensive décollement surface which modified the original stratigraphical relationship(s) between the Dogger Bank Formation and the underlying sequence. The upper part of the Dogger Bank Formation is in general undeformed; suggesting that deposition of these sediments largely post-dated glacitectonism and that they were laid down as a series of ice-marginal fans/aprons and sheet-like sandur deposits which prograded southwards into the adjacent proglacial sedimentary basins located between the moraines. The internal structural architecture of the Dogger Bank thrust moraine complexes can be directly related to ice sheet dynamics, recording the former positions of an highly dynamic, oscillating Weichselian ice sheet margin as it retreated northwards at the end of the Last Glacial Maximum.

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11. Figures

Figure 1. (a) Map showing the location of the Dogger Bank in the southern North Sea Basin, and the Round 3 windfarm zone indicated by the red polygon. The limit of the UK territorial waters is also marked in red. EMODNET DigBath bathymetry (UK waters) and GEBCO bathymetry (Non UK waters); and **(b)** Map showing the location of the Dogger Bank windfarm zone (DBZ) and Tranches A, B and C, as well as the extent of the regional and high-resolution seismic surveys acquired during the site survey.

Figure 2. (a) Horizon map constructed for the top of the Older Dogger Bank within Tranche A; and **(b)** Landform map of the buried glacial landscape concealed within the Dogger Bank Formation comprising a suite of topographically higher arcuate moraine ridges separated by lower lying basinal areas and meltwater channels (after Cotterill *et al*., 2017b).

Figure 3. Structural interpretation of lines 1 to 4 from Area A located within the central part of the thrust-moraine complex (see Figure 2): **(a)** line 1; **(b)** line 2; **(c)** line 3; and **(d)** line 4. A high-resolution, large format version of this figure is provided as a supplementary publication.

Figure 4. Structural interpretation of lines 5 to 8 from Area B located towards the north-western end of the thrust-moraine complex (see Figure 2): **(a)** line 5; **(b)** line 6; **(c)** line 7; and **(d)** line 8. A high-resolution, large format version of this figure is provided as a supplementary publication.

Figure 5. Structural interpretation of lines 9 to 11 from Area C located towards the south-eastern end of the thrust-moraine complex (see Figure 2): **(a)** line 9; **(b)** line 10; and **(c)** line 11. A high-resolution, large format version of this figure is provided as a supplementary publication.

Figure 6. Structural interpretation of lines 12 to 15 from Area D (see Figure 2): **(a)** line 12; **(b)** line 13; **(c)** line 14; and **(d)** line 15. A high-resolution, large format version of this figure is provided as a supplementary publication.

Figure 7. Diagram showing the seismic data (b and d) and detailed structural interpretation (c and e) of the south-western end of line 3. Line 3 is representative of the glacitectonic deformation observed within Area A (see Figure 2). The intensity of glacitectonic deformation (folding and thrusting) increases towards the NE and is largely confined to the seismically brighter Basal Dogger Bank with the overlying bedded sediments of the Upper Dogger Bank being relatively undeformed (see text for details).

Figure 8. Diagram showing the seismic data (b and d) and detailed structural interpretation (c and e) of the central part of line 3. Line 3 is representative of the glacitectonic deformation observed within Area A (see Figure 2). Glacitectonic deformation within this part of the thrust-moraine is dominated by locally intense SE-directed folding and thrusting of the Basal and Lower Dogger Bank units (see text for details). The base of the deformed Dogger Bank Formation sequence is marked by a laterally extensive décollement surface.

Figure 9. Diagram showing the seismic data (b, d and f) and detailed structural interpretation (c, e and g) of the north-eastern of line 3. Line 3 is representative of the glacitectonic deformation observed within Area A (see Figure 2). Glacitectonic deformation within this part of the thrust-moraine is dominated by locally intense SE-directed folding and thrusting of the Basal and Lower Dogger Bank units (see text for details). A prominent ridge marking the northern limit of the main part of thrust-moraine is separated from the remainder of the complex by a c. 1.5 km wide linear trough or channel filled with variably deformed Upper Dogger Bank sediments.

Figure 10. Diagram showing the seismic data (b, d and f) and detailed structural interpretation (c, e and g) for key parts of line 7. Line 7 is representative of the glacitectonic deformation observed within Area B (see Figure 2). Glacitectonic deformation within this part of the thrust-moraine is dominated by locally intense SE-directed folding and thrusting of the Basal and Lower Dogger Bank units. This deformed sequence is overlain by a locally thick sequence of undeformed Upper Dogger Bank sediments which also infill deeply incised channels which locally cut through the entire

thickness of the deformed Lower and Basal Dogger Bank units and into the underlying Pre-Dogger Bank sequence (see text for details).

Figure 11. Diagram showing the seismic data (b, d and f) and detailed structural interpretation (c, e and g) for key parts of line 12. Line 12 is representative of the glacitectonic deformation observed within Area D (see Figure 2). The moraine ridges are composed of highly deformed (SE-directed folding and thrusting) Basal and Lower Dogger Bank sediments. The topographic highs formed by the main moraine complexes identified in the southern and northern parts of the study area are separated by a low-lying basin filled by typically undeformed Upper Dogger Bank sediments. However SE-directed deformation associated with the development of the northern moraines can be seen to propagate upwards from the Basal and Lower Dogger Bank units to affect the overlying Upper Dogger Bank sediments (see text for details).

Figure 12. Diagram showing the proposed conceptual model for the evolution of the main thrust-moraine complex identified within the southern part of Tranche A in response to the active retreat of an oscillating ice margin. This model can be divided into a number of stages: ***Stage 1*** – initial ice advance across the Basal Dogger Bank unit; ***Stage 2*** – ice-marginal to proglacial deformation of the Basal Dogger Bank and the formation of a forward propagating thrust stack; ***Stage 3*** – retreat of the ice margin from its advance limit and contemporaneous deposition of a sequence of outwash sediments; ***Stage 4*** – readvance of the glacier resulting in ice-marginal to proglacial thrusting of the outwash sequence deposited in stage 3 and accretion of these deformed sediments (Lower Dogger Bank) onto the up-ice side of the evolving thrust moraine complex; ***Stage 5*** – retreat of the ice margin from the stage 4 advance limit and contemporaneous deposition of a sequence of outwash sediments; ***Stage 6*** – further readvance of the glacier resulting in ice-marginal to proglacial thrusting of the outwash sequence deposited in stage 5 and accretion of the thrusted and folded blocks (Lower Dogger Bank) onto the up-ice side of the thrust moraine complex; ***Stage 7*** – retreat of the ice margin from the stage 6 advance limit and contemporaneous deposition of a sequence of outwash sediments; ***Stage 8*** – a further readvance of the glacier leading to further SE-directed folding and thrusting during the accretion of the outwash sediments deposited during stage 7 onto the up-ice margin of the increasing structurally complex thrust-moraine. Accretion of these relatively younger thrusted and folded sediments may have accompanied the folding of earlier developed thrusts within the main part of the thrust-moraine to the south; and ***Stage 9*** onwards – further phases of ice margin retreat and advance (see text for details).

Figure 13. Cartoon showing the active retreat of an ice sheet northwards across Tranche A of the Dogger Bank (see text for details).

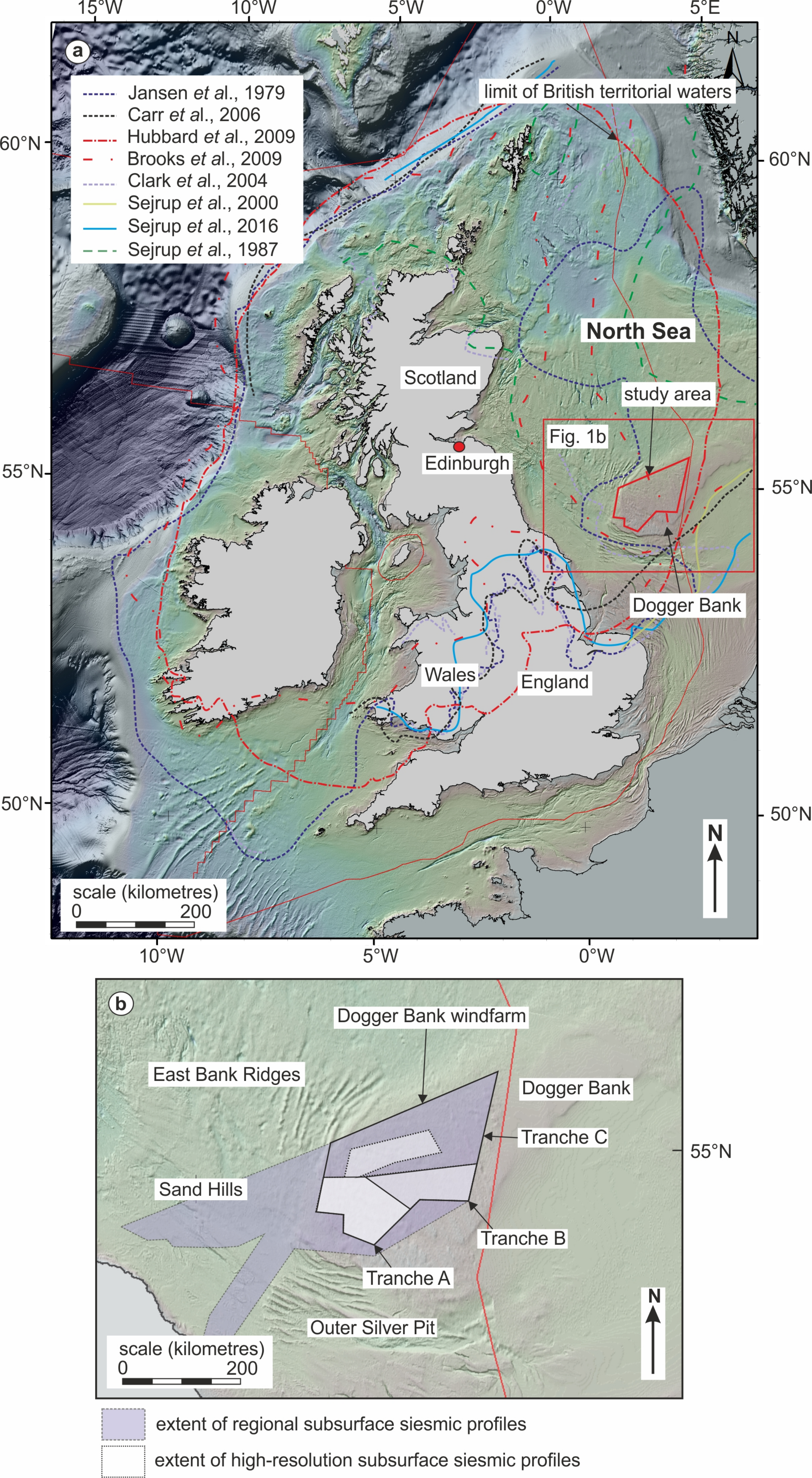
12. Tables

Table 1. Summary of the characteristics of the Basal, Lower and Upper Dogger Bank subunits identified on the seismic profiles examined from Tranche A.

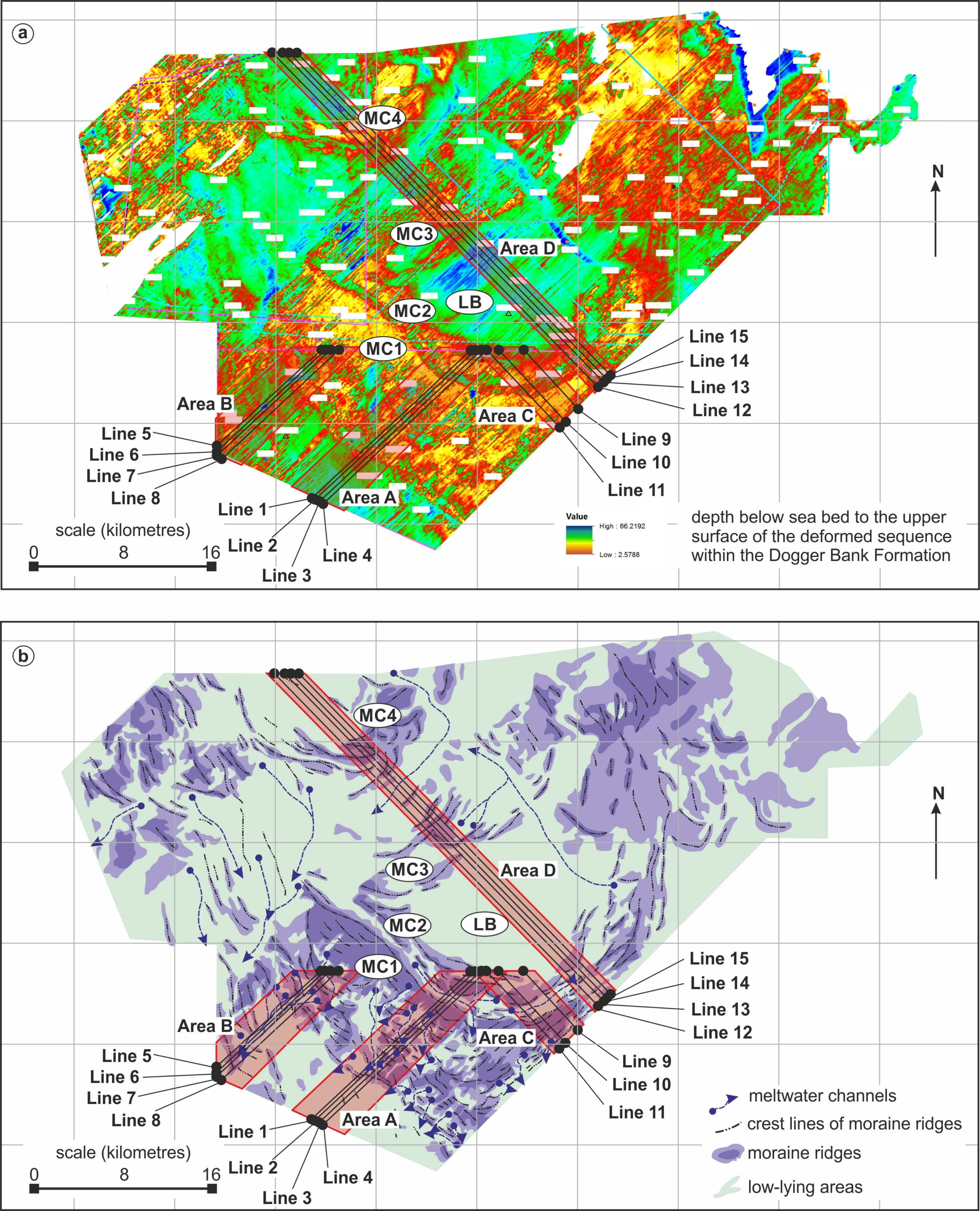
Seismic subunit	Description
Basal Dogger Bank (BDB)	Structurally lowest unit within the Dogger Bank Formation (0-30 m thick); distinguished by its overall brighter appearance on the seismic profiles; upper surface marked by a band of bright reflectors interpreted as a prominent desiccation/weathering surface; varies from acoustically "massive"/"structureless" to containing laterally variably dipping reflectors; reflectors locally appear crenulated/folded and/or disrupted due to glacitectonic deformation; base interpreted as a laterally extensive décollement surface
Lower Dogger Bank (LDB)	Represents main deformed part of Dogger Bank Formation (up to 40-50 m thick); acoustic appearance highly variable ranging from acoustically "blank", lacking internal reflectors and apparently internally "massive"/"structureless", through to stratified, containing weakly to strongly developed reflectors; laterally variably dipping reflectors; reflectors locally appear folded and/or disrupted due to glacitectonic deformation; upper surface locally marked by a band of bright reflectors interpreted as a desiccation/weathering surface
Upper Dogger Bank (UDB)	Structurally highest unit within the Dogger Bank Formation (0-50 m thick); acoustic character is laterally variable ranging from areas with no ("blank") or very weakly developed reflectors through to sections with moderately to strongly developed subhorizontal (bedding) to inclined (foresets) reflectors; base of unit irregular (erosive) and clearly truncates structures identified within the underlying subunits

Table 2. Summary of the characteristic features of the eight structural domains identified within the Dogger Bank Formation of Tranche A (after Cotterill *et al*., 2017a).

Domain	Description	Comments
1	Dominated by southerly directed thrusting and folding of both Basal and Upper Dogger Bank sediments, and characterised by the progressive increase in the relative intensity of deformation northwards towards the southern margin of the moraine complex	Interpreted as a forward propagating thrust stack denoting the leading edge of the thrust-moraine complex
2	Zones of well-developed, S/SE-directed thrusting and folding affecting the Basal and Lower Dogger Bank sediments	
3	Zones of large-scale (≥ 1 km wavelength), upright folding deforming the Lower Dogger Bank. The presence of these large-scale, warp-like folds is recognised by the change in vergence of parasitic (S, M and Z-shaped), mesoscale folds (50-200 m wavelength) developed on their limbs	Domain 3 is typically developed within the cores of the larger thrust moraine
4	Dominated by stacked, elongate thrust-bound slices (1-2 km long) of Lower Dogger Bank sediments	
5	Highly deformed parts of the sequence characterised by steeply inclined reflectors (bedding) and interpreted as denoting zones of relatively intense folding and thrusting	
6	Most widely developed of the structural domains corresponding to parts of the Lower Dogger Bank where reflectors are either very poorly developed or absent (blanked areas) on the seismic lines	Interpreted as indicating parts of the sequences which are either massive and/or highly disrupted due to deformation
7	Currently only identified in Area B and corresponds to large (0.5-1 km wide), deeply incised channels filled by a thick sequence of Upper Dogger Bank sediments.	Interpreted as ice-marginal to proglacial meltwater channels cut through the deformed Basal and Lower Dogger Bank units and into the underlying pre-Dogger Bank sequence
8	Characterised by a thick sequence of typically undeformed Upper Dogger Bank sediments. Horizontal to gently inclined reflections are interpreted as representing primary bedding and large-scale foresets preserved within this sedimentary sequence	Interpreted as a complex sequence of Upper Dogger Bank outwash sediments which infill the larger sedimentary basins formed between the topographic highs formed by the thrust moraines



a
Jansen et al., 1979
Carr et al., 2006
Hubbard et al., 2009
Brooks et al., 2009
Clark et al., 2004
Sejrup et al., 2000
Sejrup et al., 2016
Sejrup et al., 1987
limit of British territorial waters
North Sea
study area
Fig. 1b
Scotland
Edinburgh
Dogger Bank
Wales
England
scale (kilometres)
0
200
N
15°W
10°W
5°W
0°W
5°E
60°N
55°N
50°N
b
Dogger Bank windfarm
East Bank Ridges
Dogger Bank
Tranche C
55°N
Sand Hills
Tranche B
Tranche A
Outer Silver Pit
scale (kilometres)
0
200
N
extent of regional subsurface siesmic profiles
extent of high-resolution subsurface siesmic profiles

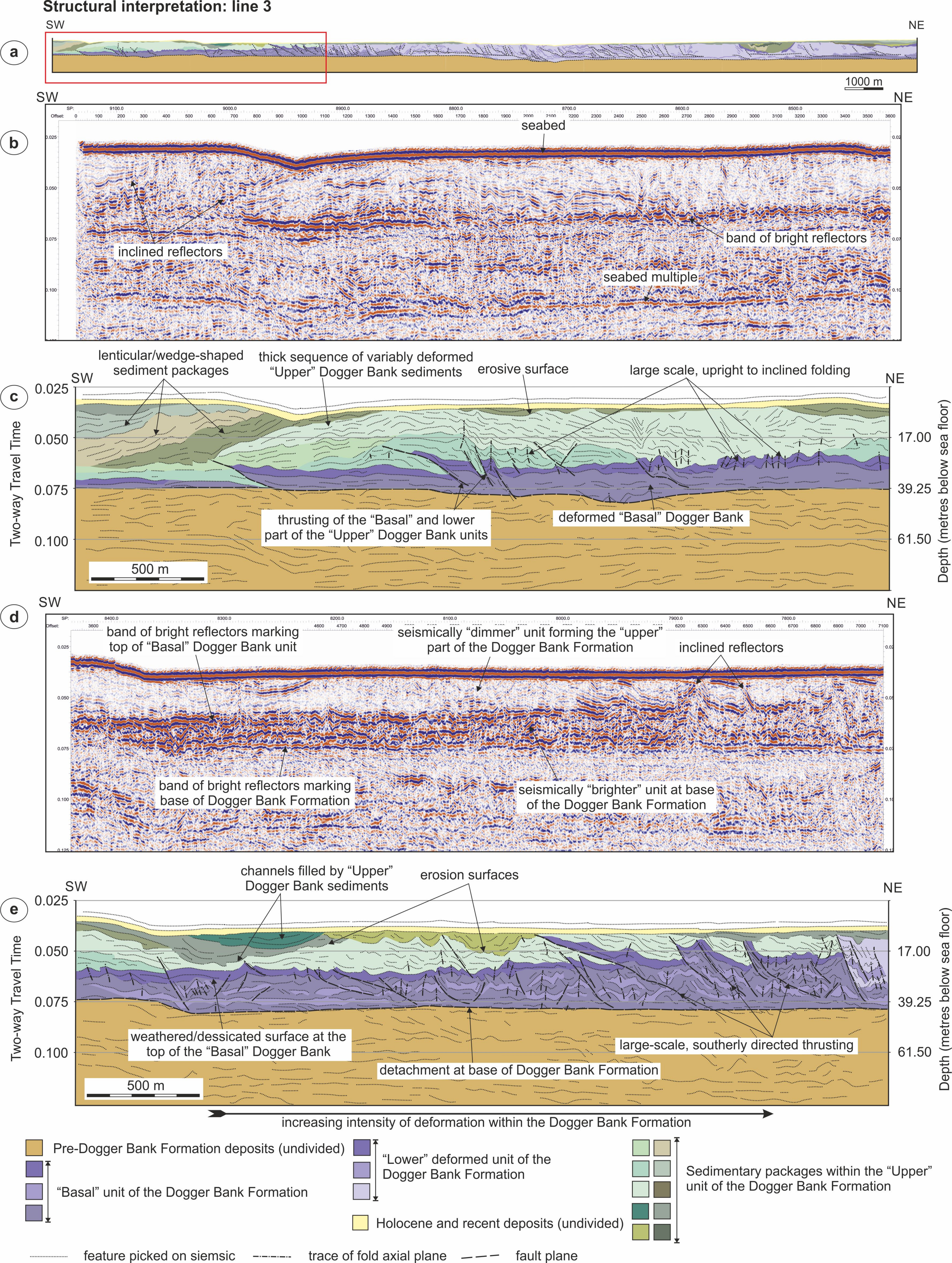

a
MC4
MC3
Area D
MC2
LB
MC1
Area B
Area C
Area A
Line 1
Line 2
Line 3
Line 4
Line 5
Line 6
Line 7
Line 8
Line 9
Line 10
Line 11
Line 12
Line 13
Line 14
Line 15
N
scale (kilometres)
0 8 16
Value
High : 66.2192
Low : 2.5788
depth below sea bed to the upper surface of the deformed sequence within the Dogger Bank Formation
b
MC4
MC3
Area D
MC2
LB
MC1
Area B
Area C
Area A
Line 1
Line 2
Line 3
Line 4
Line 5
Line 6
Line 7
Line 8
Line 9
Line 10
Line 11
Line 12
Line 13
Line 14
Line 15
N
scale (kilometres)
0 8 16
meltwater channels
crest lines of moraine ridges
moraine ridges
low-lying areas

Dogger Bank structural interpretation: Area A
Structural interpretation: line 1
a
SW
NE
erosion surfaces
thick sequence of variably deformed lower part of "Upper" Dogger Bank
channels filled by "Upper" Dogger Bank sediments
erosion surfaces
erosion surface truncating the top of the moraine complex
SW limit of main thrust-moraine complex
deformed "Lower" Dogger Bank
core of major anticline
structurally massive ("blanked") area
moraine ridge composed of highly deformed "Lower" Dogger Bank
possible weathered/dessicated surface marking the top of "Lower" Dogger Bank
large scale, upright to inclined folding
structurally massive ("blanked") area
"Upper" Dogger Bank sediments infilling a channel/basin located between topographic highs formed by the moraine ridges
possible weathered/dessicated surface at the top of the "Lower" Dogger Bank
Two-way Travel Time
0.025
0.050
0.075
0.100
Depth (metres below sea floor)
17.00
39.25
61.50
500 m
large scale, upright to inclined folding within the lower part of "Upper" Dogger Bank
weathered/dessicated surface at the top of "Basal" Dogger Bank
detachment at base of Dogger Bank Formation
stacking of thrust slices of "Basal" Dogger Bank
large scale, upright to inclined folding
ramp
stacking of thrust slices of "Lower" Dogger Bank
large scale, upright to inclined folding
folding of earlier formed imbricate thrust stack
detachment at base of the Dogger Bank Formation
increasing intensity of deformation
SW-directed thrusting and stacking of "Basal" and "Lower" Dogger Bank
zone of NE-verging, Z-shaped asymmetrical folds
zone of large scale thrusting and folding within the "Older" Dogger Bank
large channel/basin filled by variably deformed "Upper" Dogger Bank
Domain 1 - ice-distal, SW-directed thrusting and folding
Domain 2 - marginal zone of main thrust-moraine complex
Domain 3 - large-scale anticline in core of thrust-moraine complex
Domain 4 - large-scale thrust stacking and imbrication
Domain 5 - steeply inclined zone and large-scale folding
Domain 6 - thrusting and folding variably developed
Structural interpretation: line 2
b
SW
NE
thick sequence of variably deformed "Upper" Dogger Bank sediments
channels filled by "Upper" Dogger Bank sediments
SW-limit of main thrust-moraine complex
moraine ridge composed of deformed "Lower" Dogger Bank
erosive surface
core of major anticline
large scale, upright to inclined folding
erosion surface
structurally massive ("blanked") area
variable deformation of "Upper" Dogger Bank sediments infilling a large channel
moraine ridge composed of highly deformed "Lower" Dogger Bank
thrusting effecting both "Basal" and "Upper" Dogger Bank
weathered/dessicated surface marking the top of "Basal" Dogger Bank
large scale, upright to inclined folding
detachment at base of Dogger Bank Formation
stacking of thrust slices of Dogger Bank Formation Unit 1
ramp
large scale thrust ramp and stacking of "Lower" Dogger Bank
ramp
stacking of thrust slices of "Lower" Dogger Bank
weathered/dessicated surface at the top of the "Lower" Dogger Bank
increasing intensity of deformation within the "Lower" Dogger Bank
zone of SW-directed thrusting and stacking of "Basal" and "Lower" Dogger Bank
zone of NE-verging, Z-shaped asymmetrical folds
zone of large scale thrusting and folding
large channel/basin filled by variably deformed "Upper" Dogger Bank
Domain 1 - ice-distal, SW-directed thrusting and folding
Domain 2 - marginal zone of main thrust-moraine complex
Domain 3 - large-scale anticline in core of thrust-moraine complex
Domain 4 - large-scale thrust stacking and imbrication
Domain 5 - steeply inclined zone and large-scale folding
Domain 6 - thrusting and folding variably developed
Structural interpretation: line 3
c
SW
NE
thick sequence of variably deformed "Upper" Dogger Bank sediments
thick sequence of "Upper" Dogger Bank sediments filling channels
SW limit of main thrust-moraine complex
moraine ridge composed of deformed "Lower" and "Basal" Dogger Bank
core of major anticline
large scale, upright to inclined folding
stacking of thrust slices of "Lower" Dogger Bank sediments
erosion surface
structurally massive ("blanked") area
variably deformed "Upper" Dogger Bank sediments infilling a large channel
weathered/dessicated surface at the top of the "Lower" Dogger Bank
thrusting effecting both "Upper" and "Basal" Dogger Bank sediments
weathered/dessicated surface at the top of the "Basal" Dogger Bank
large scale, upright to inclined folding
detachment at base of the Dogger Bank Formation
ramp
large scale thrust ramp and stacking of the "Lower" Dogger Bank
ramp
stacking of thrust slices of "Lower" Dogger Bank sediments
weathered/dessicated surface at the top of the "Lower" Dogger Bank
increasing intensity of deformation within Dogger Bank Formation
zone of SW-directed thrusting and stacking of "Lower" and "Basal" Dogger Bank sediments
zone of NE-verging, Z-shaped asymmetrical folds
zone of intense deformation and disruption
zone of large scale thrusting and folding
zone of folding of earlier formed imbricate thrust stack
large channel/linear basin separating moraine ridges
Domain 1 - ice-distal, SW-directed thrusting and folding
Domain 2 - marginal zone of main thrust-moraine complex
Domain 3 - large-scale anticline in core of thrust-moraine complex
Domain 4 - large-scale thrust stacking and imbrication
Domain 5 - steeply inclined zone and large-scale folding
Domain 6 - thrusting and folding variably developed
Structural interpretation: line 4
d
SW
NE
thick sequence of variably deformed "Upper" Dogger Bank sediments
thick sequence of "Upper" Dogger Bank sediments
SW-limit of main thrust-moraine complex
erosion surface
core of major anticline
moraine ridge composed of deformed "Lower" and "Basal" Dogger Bank sediments
small sediment-filled channels incised into the top of the "Lower" Dogger Bank Formation Unit 3
structurally massive ("blanked") area
variably deformed "Upper" Dogger Bank sediments infilling a large channel
weathered/dessicated surface at the top the "Lower" Dogger Bank
weathered/dessicated surface at the top of the "Basal" Dogger Bank
detachment at base of Dogger Bank Formation
large scale, upright to inclined folding
large scale, upright to inclined folding
ramp
stacking of thrust slices of "Lower" Dogger Bank sediments
stacking of thrust slices of "Lower" Dogger Bank sediments
large scale, upright to inclined folding
increasing intensity of deformation within Dogger Bank Formation
zone of intense deformation within the "Basal" and "Lower Dogger Bank
zone of NE-verging, Z-shaped asymmetrical folds
zone of intense deformation and disruption
zone of large scale thrusting and folding
zone of folding of earlier formed imbricate thrust stack
large channel/basin filled by variably deformed "Upper" Dogger Bank sediments
Domain 1 - ice-distal, SW-directed thrusting and folding
Domain 2 - marginal zone of main thrust-moraine complex
Domain 3 - large-scale anticline in core of thrust-moraine complex
Domain 4 - large-scale thrust stacking and imbrication
Domain 5 - steeply inclined zone and large-scale folding
Domain 6 - thrusting and folding variably developed
structural domains
Domain 1
Domain 2
Domain 3
Domain 4
Domain 5
Domain 6
feature picked on siesmic
trace of fold axial plane
fault plane
Pre-Dogger Bank Formation deposits (undivided)
"Basal" unit of the Dogger Bank Formation
"Lower" deformed unit of the Dogger Bank Formation
Holocene and recent deposits (undivided)
Sedimentary packages within the "Upper" unit of the Dogger Bank Formation

Dogger Bank structural interpretation: Area B
a
Structural interpretation: line 5
NE
SW
small-scale channels incised into the upper surface of the "Lower" Dogger Bank
lenticular/wedge-shaped sediment packages defining fan/apron
inclined bedding (foresets)
"Upper" Dogger Bank sediments infilling a basin located between the moraine ridges
moraine ridge composed of deformed "Lower" and "Basal" Dogger Bank sediments
erosion surfaces
weathered/dessicated surface at the top of "Lower" Dogger Bank
core of major anticline
moriane ridge composed of deformed "Lower" Dogger Bank sediments
small channels incised into the upper surface of the "Lower" Dogger Bank
detachment at base of the Dogger Bank Formation
large scale, upright to inclined folding
weathered/dessicated surface at the top of "Lower" Dogger Bank
ramp
lenticular/wedge-shaped sediment packages defining fan/apron
large scale, upright to inclined folding
large scale, upright to inclined folding
500 m
zone of thrusting and folding within Dogger Bank Formation units 1 and 3 forming a well-developed moraine ridge
zone of thrusting and folding within Dogger Bank Formation forming a well-developed moraine ridge
zone of M-shaped folds in core of anticline
zone of S-shaped, NE-verging asymmatrical folds
Domain 2 - well-developed SE-directed thrusting and folding
Domain 6 - thrusting and folding variably developed
Domain 2 - well-developed SE-directed thrusting and folding
Domain 6 - thrusting and folding variably developed
Domain 3 - large-scale anticline in core of thrust-moraine complex
Domain 6
b
Structural interpretation: line 6
NE
SW
moraine ridge composed of deformed "Lower" and "Basal" Dogger Bank sediments
small channels incised into the upper surface of the Lower Dogger Bank
lenticular/wedge-shaped sediment packages defining fan/apron
inclined bedding (foresets)
incised channel within the "Upper" Dogger Bank
thick sequence of "Upper" Dogger Bank Formation sediments
complex sequence "Upper" Dogger Bank sediments infilling a basin located between topographic highs formed by the moraine ridges
channel within the "Upper" Dogger Bank
"Upper" Dogger Bank sediments infilling a channel incised into the underlying "Lower" Dogger Bank
core of major anticline
detachment at base of the Dogger Bank Formation
large scale, upright to inclined folding
weathered/dessicated surface at the top of the "Lower" Dogger Bank
large scale, upright to inclined folding
lenticular/wedge-shaped sediment packages defining fan/apron
large scale, upright to inclined folding
weathered/dessicated surface at the top of the "Lower" Dogger Bank
500 m
zone of thrusting and folding within the "Lower" and Basal" Dogger Bank forming a well-developed moraine ridge
thick sequence of "Upper" Dogger Bank sediments overlying a prominent erosion surface
thick sequence of "Upper" Dogger Bank sediments overlying a prominent erosion surface
zone of S-shaped, NE-verging asymmatrical folds
Domain 2 - SE-directed thrusting and folding
Domain 6 - thrusting and folding variably developed
Domain 3 - large-scale folding in core of thrust-moraine complex
Domain 6 - thrusting and folding variably developed
c
Structural interpretation: line 7
NE
SW
moraine ridge composed of deformed "Lower" and "Basal" Dogger Bank sediments
weathered/dessicated surface at the top of the "Lower" Dogger Bank
erosion surfaces
large channel filled by "Upper" Dogger Bank sediments
erosion surface
"Upper" Dogger Bank sediments infilling a basin located between the topographic highs formed by the moraine ridges
large channel filled by "Upper" Dogger Bank sediments
erosion surfaces
"Upper" Dogger Bank sediments infilling a basin located between topographic highs formed by the moraine ridges
detachment at base of the Dogger Bank Formation
large scale, upright to inclined folding
Domain 7
weathered/dessicated surface at the top of the "Lower" Dogger Bank
large scale, upright to inclined folding
inclined bedding (foresets)
weathered/dessicated surface at the top of the "Lower" Dogger Bank
500 m
zone of thrusting and folding within "Lower" and "Basal" Dogger Bank units forming a well-developed moraine ridge
thick sequence of "Upper" Dogger Bank sediments overlying a prominent erosion surface resulting in local removal of underlying "Lower" and "Basal" Dogger Bank
thick sequence of "Upper" Dogger Bank sediments overlying a prominent erosion surface resulting in local removal of underlying "Lower" and "Basal" Dogger Bank
thick sequence of "Upper" Dogger Bank sediments
Domain 2 - SE-directed thrusting and folding
Domain 6 - thrusting and folding variably developed
Domain 7
Domain 6 - thrusting and folding variably developed
d
Structural interpretation: line 8
NE
SW
moraine ridge composed of "Lower" Dogger Bank sediments
weathered/dessicated surface at the top of the "Lower" Dogger Bank
thick sequence of "Upper" Dogger Bank sediments infilling a large, deeply incised channel
lenticular/wedge-shaped sediment packages defining fan/apron
erosion surfaces
"Upper" Dogger Bank sediments infilling a basin located between topographic highs formed by the moraine ridges
small channels incised into the top of the "Lower" Dogger Bank
moraine ridge composed of deformed "Lower" Dogger Bank sediments
large scale, upright to inclined folding
detachment at base of the Dogger Bank Formation
weathered/dessicated surface at the top of the "Lower" Dogger Bank
large scale, upright to inclined folding
weathered/dessicated surface at the top of the "Lower" Dogger Bank
500 m
zone of SE-directed thrusting and folding
thick sequence of "Upper" Dogger Bank sediments, base marked by prominent erosion surface
Domain 2 - SE-directed thrusting and folding
Domain 6 - variably developed thrusting and folding
Domain 2 - SE-directed thrusting and folding
Domain 6 - thrusting and folding variably developed
Domain 2 - SE-directed thrusting and folding
Domain 6 - thrusting and folding variably developed
Two-way Travel Time
0.025
0.050
0.075
0.100
0.125
Depth (metres below sea floor)
17.00
39.25
61.50
structural domains
Domain 1
Domain 2
Domain 3
Domain 4
Domain 5
Domain 6
feature picked on siesmic
trace of fold axial plane
fault plane
Pre-Dogger Bank Formation deposits (undivided)
"Basal" unit of the Dogger Bank Formation
"Lower" deformed unit of the Dogger Bank Formation
Holocene and recent deposits (undivided)
Sedimentary packages within the "Upper" unit of the Dogger Bank Formation

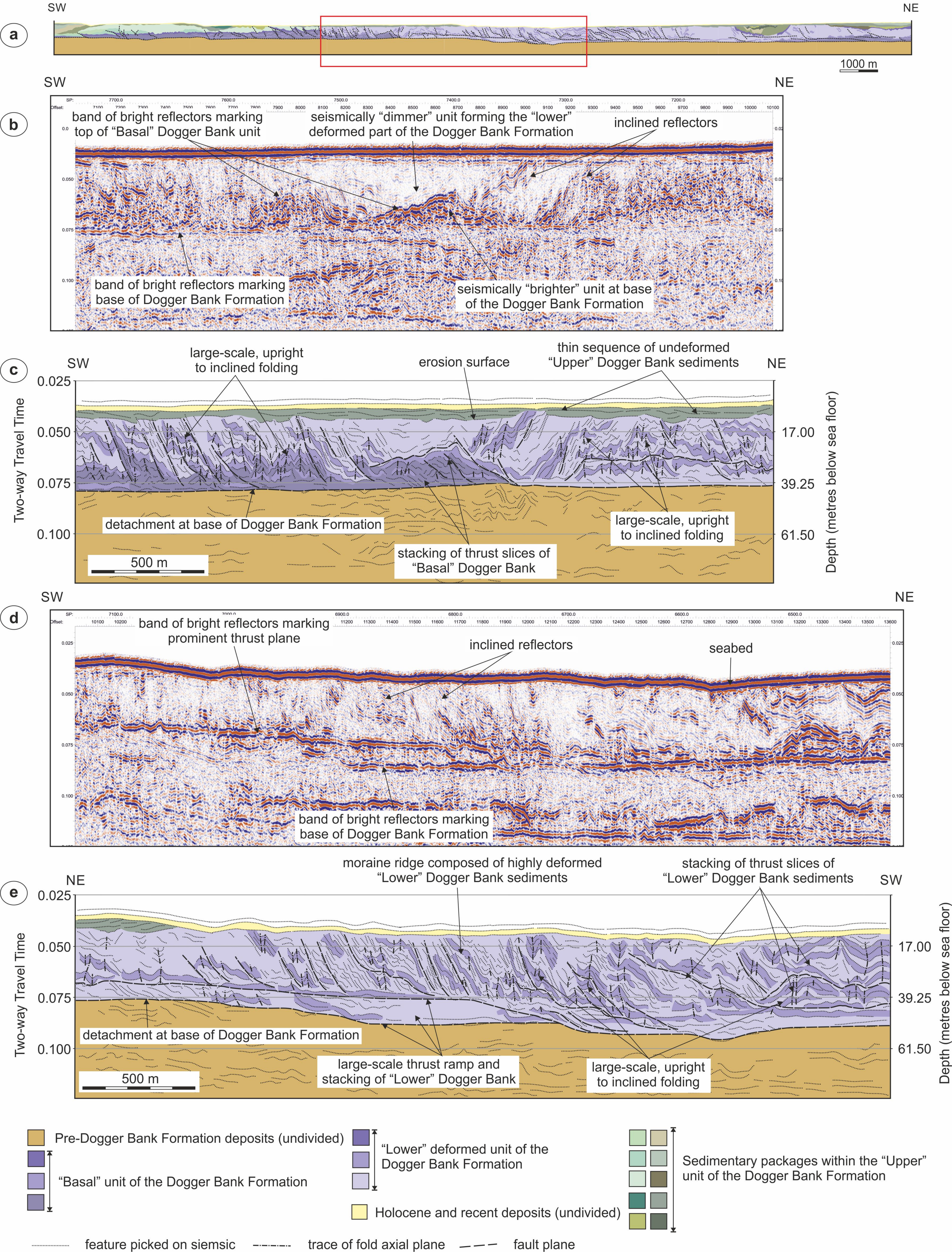
Dogger Bank structural interpretation: Area C

Dogger Bank structural interpretation: Area D

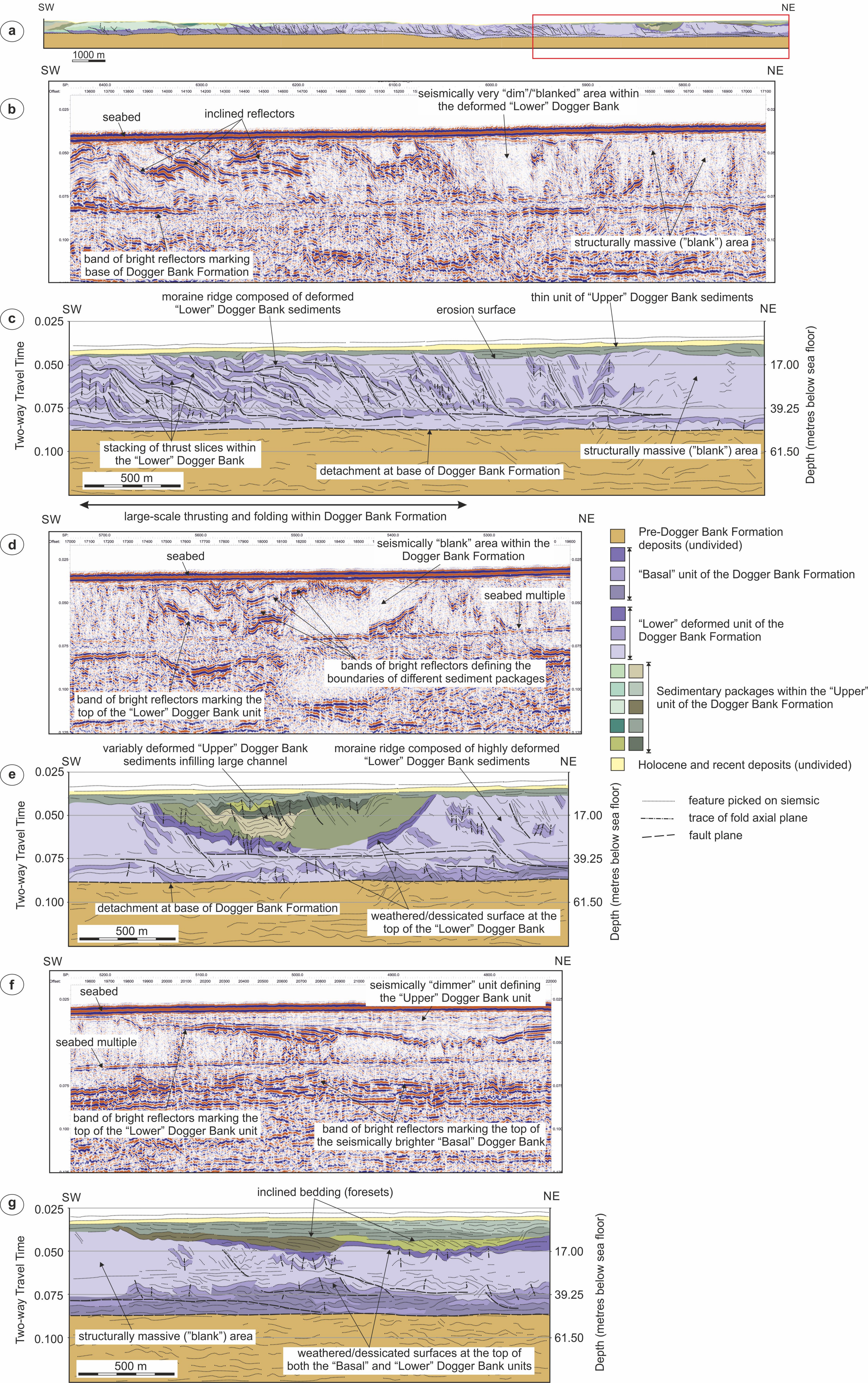


Structural interpretation: line 3
SW
NE
a
1000 m
b
seabed
inclined reflectors
band of bright reflectors
seabed multiple
c
lenticular/wedge-shaped sediment packages
thick sequence of variably deformed "Upper" Dogger Bank sediments
erosive surface
large scale, upright to inclined folding
thrusting of the "Basal" and lower part of the "Upper" Dogger Bank units
deformed "Basal" Dogger Bank
500 m
Two-way Travel Time
Depth (metres below sea floor)
0.025
0.050
0.075
0.100
17.00
39.25
61.50
d
band of bright reflectors marking top of "Basal" Dogger Bank unit
seismically "dimmer" unit forming the "upper" part of the Dogger Bank Formation
inclined reflectors
band of bright reflectors marking base of Dogger Bank Formation
seismically "brighter" unit at base of the Dogger Bank Formation
e
channels filled by "Upper" Dogger Bank sediments
erosion surfaces
weathered/dessicated surface at the top of the "Basal" Dogger Bank
detachment at base of Dogger Bank Formation
large-scale, southerly directed thrusting
increasing intensity of deformation within the Dogger Bank Formation
Pre-Dogger Bank Formation deposits (undivided)
"Basal" unit of the Dogger Bank Formation
"Lower" deformed unit of the Dogger Bank Formation
Holocene and recent deposits (undivided)
Sedimentary packages within the "Upper" unit of the Dogger Bank Formation
feature picked on siemsic
trace of fold axial plane
fault plane

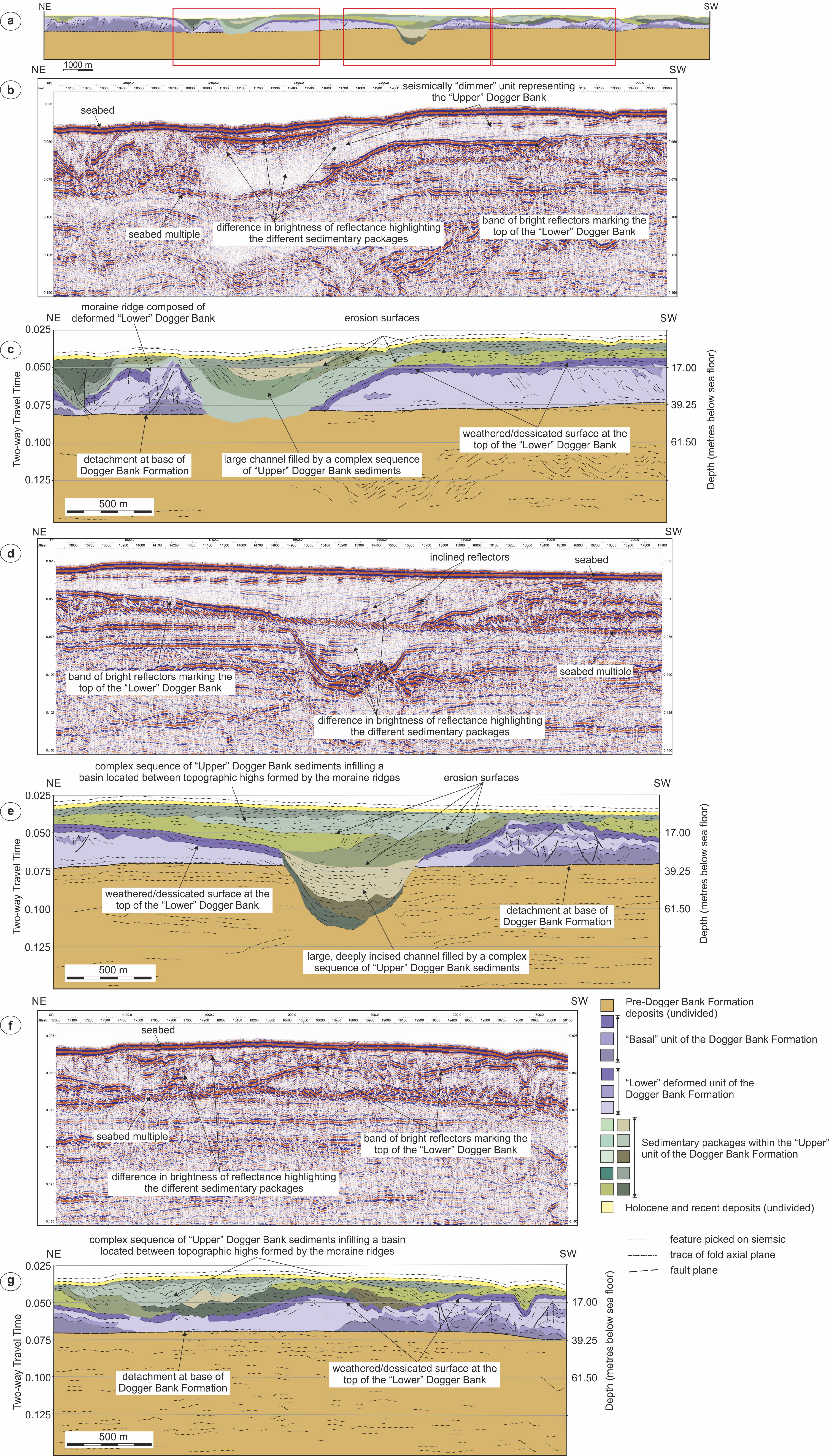
Structural interpretation: line 3



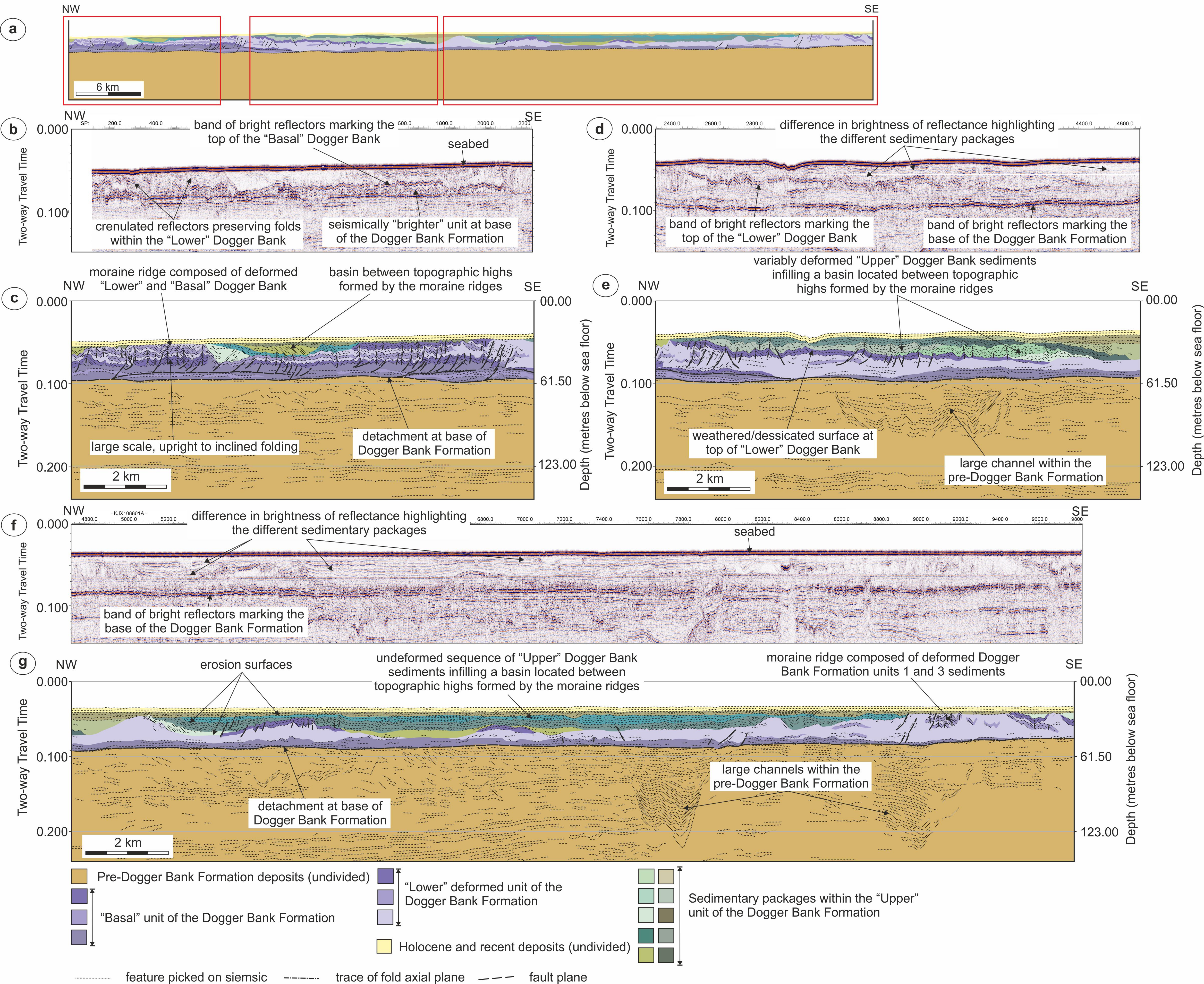
Structural interpretation: line 3

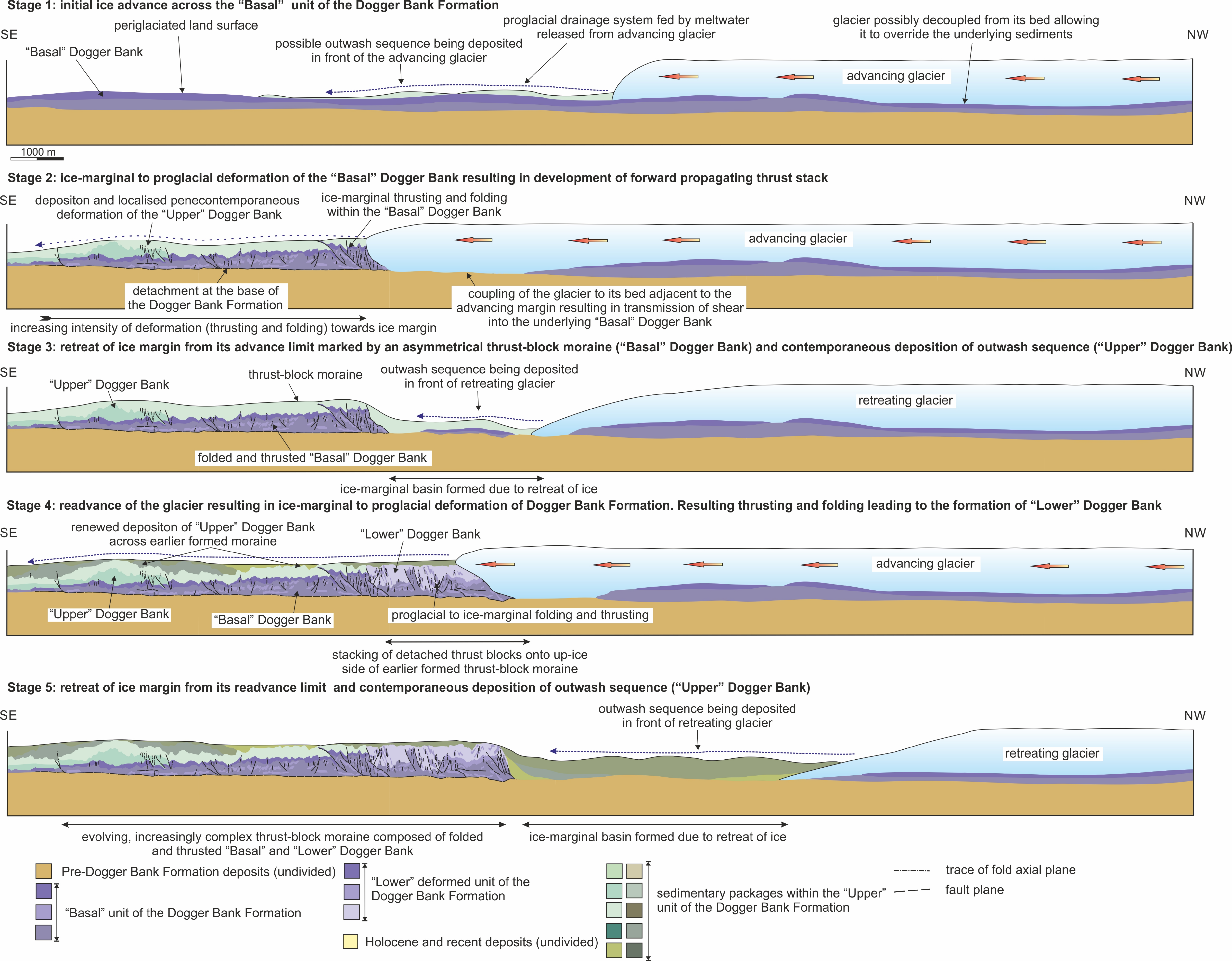


Structural interpretation: line 7

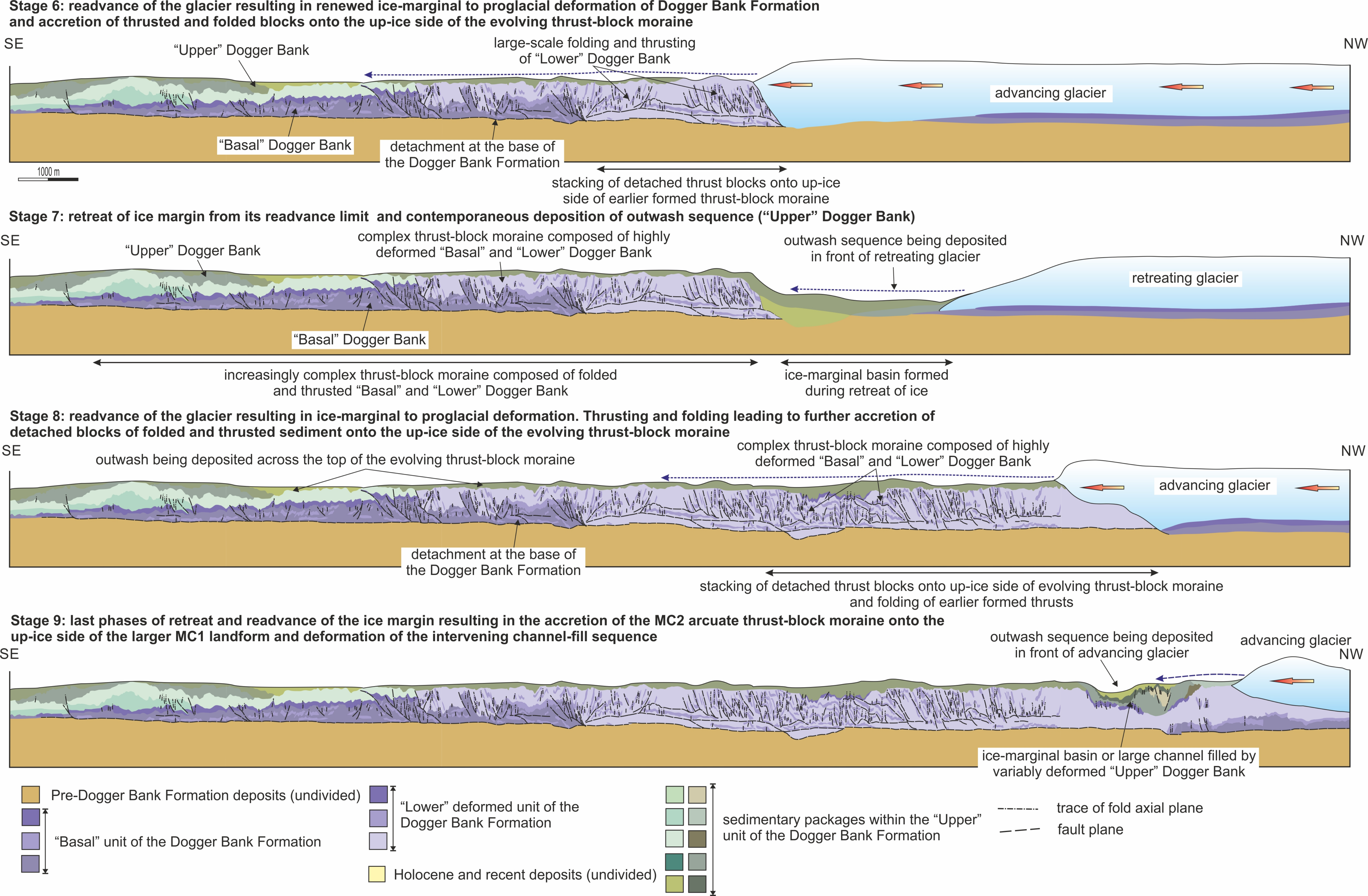


Structural interpretation: line 12

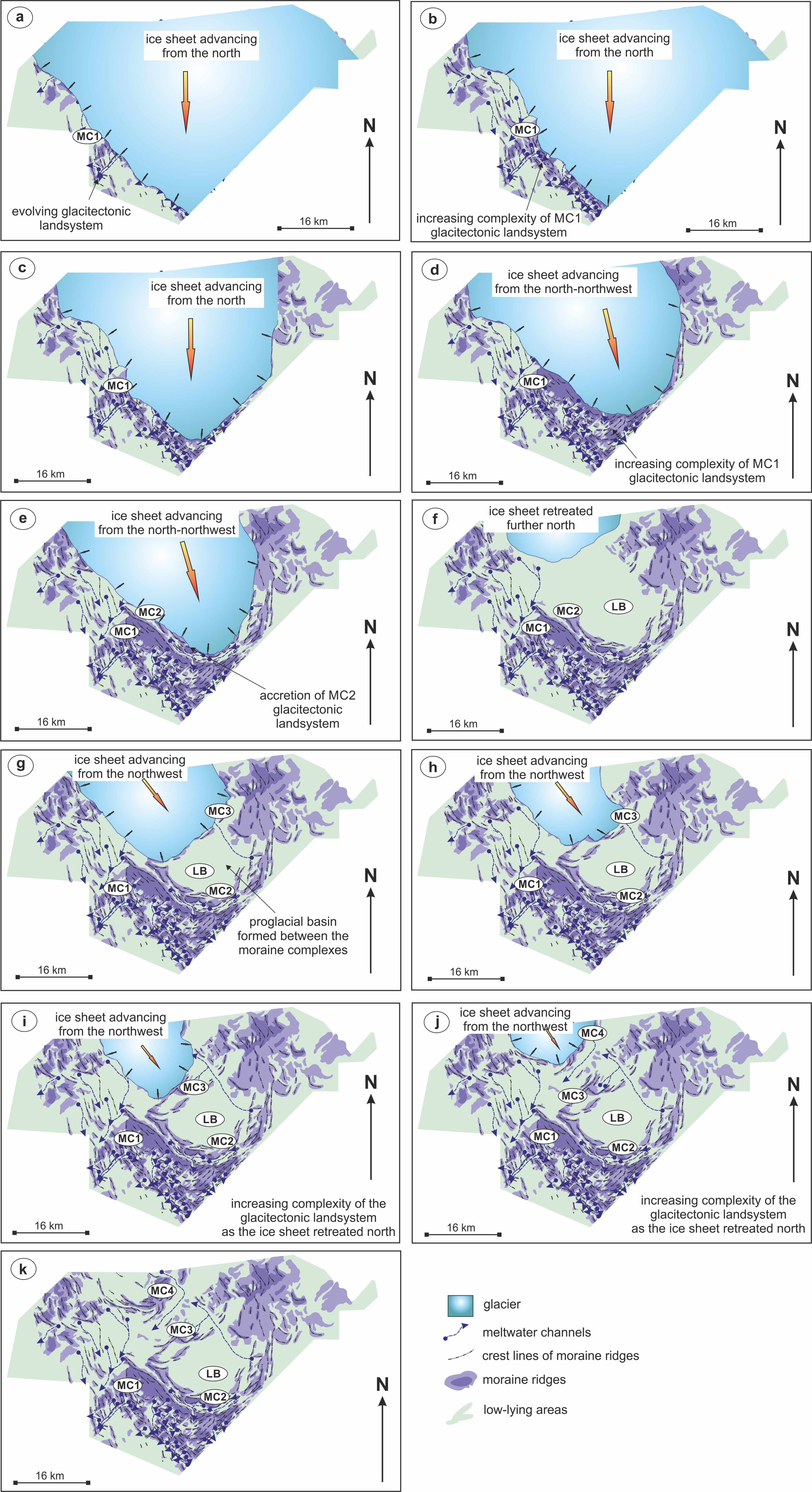




Stage 1: initial ice advance across the "Basal" unit of the Dogger Bank Formation
SE
NW
periglaciated land surface
"Basal" Dogger Bank
possible outwash sequence being deposited in front of the advancing glacier
proglacial drainage system fed by meltwater released from advancing glacier
glacier possibly decoupled from its bed allowing it to override the underlying sediments
advancing glacier
1000 m
Stage 2: ice-marginal to proglacial deformation of the "Basal" Dogger Bank resulting in development of forward propagating thrust stack
SE
NW
depositon and localised penecontemporaneous deformation of the "Upper" Dogger Bank
ice-marginal thrusting and folding within the "Basal" Dogger Bank
advancing glacier
detachment at the base of the Dogger Bank Formation
coupling of the glacier to its bed adjacent to the advancing margin resulting in transmission of shear into the underlying "Basal" Dogger Bank
increasing intensity of deformation (thrusting and folding) towards ice margin
Stage 3: retreat of ice margin from its advance limit marked by an asymmetrical thrust-block moraine ("Basal" Dogger Bank) and contemporaneous deposition of outwash sequence ("Upper" Dogger Bank)
SE
NW
"Upper" Dogger Bank
thrust-block moraine
outwash sequence being deposited in front of retreating glacier
retreating glacier
folded and thrusted "Basal" Dogger Bank
ice-marginal basin formed due to retreat of ice
Stage 4: readvance of the glacier resulting in ice-marginal to proglacial deformation of Dogger Bank Formation. Resulting thrusting and folding leading to the formation of "Lower" Dogger Bank
SE
NW
renewed depositon of "Upper" Dogger Bank across earlier formed moraine
"Lower" Dogger Bank
advancing glacier
"Upper" Dogger Bank
"Basal" Dogger Bank
proglacial to ice-marginal folding and thrusting
stacking of detached thrust blocks onto up-ice side of earlier formed thrust-block moraine
Stage 5: retreat of ice margin from its readvance limit and contemporaneous deposition of outwash sequence ("Upper" Dogger Bank)
SE
NW
outwash sequence being deposited in front of retreating glacier
retreating glacier
evolving, increasingly complex thrust-block moraine composed of folded and thrusted "Basal" and "Lower" Dogger Bank
ice-marginal basin formed due to retreat of ice
Pre-Dogger Bank Formation deposits (undivided)
"Basal" unit of the Dogger Bank Formation
"Lower" deformed unit of the Dogger Bank Formation
Holocene and recent deposits (undivided)
sedimentary packages within the "Upper" unit of the Dogger Bank Formation
trace of fold axial plane
fault plane



Stage 6: readvance of the glacier resulting in renewed ice-marginal to proglacial deformation of Dogger Bank Formation and accretion of thrusted and folded blocks onto the up-ice side of the evolving thrust-block moraine
SE
NW
"Upper" Dogger Bank
large-scale folding and thrusting of "Lower" Dogger Bank
advancing glacier
"Basal" Dogger Bank
detachment at the base of the Dogger Bank Formation
1000 m
stacking of detached thrust blocks onto up-ice side of earlier formed thrust-block moraine
Stage 7: retreat of ice margin from its readvance limit and contemporaneous deposition of outwash sequence ("Upper" Dogger Bank)
SE
NW
"Upper" Dogger Bank
complex thrust-block moraine composed of highly deformed "Basal" and "Lower" Dogger Bank
outwash sequence being deposited in front of retreating glacier
retreating glacier
"Basal" Dogger Bank
increasingly complex thrust-block moraine composed of folded and thrusted "Basal" and "Lower" Dogger Bank
ice-marginal basin formed during retreat of ice
Stage 8: readvance of the glacier resulting in ice-marginal to proglacial deformation. Thrusting and folding leading to further accretion of detached blocks of folded and thrusted sediment onto the up-ice side of the evolving thrust-block moraine
SE
NW
outwash being deposited across the top of the evolving thrust-block moraine
complex thrust-block moraine composed of highly deformed "Basal" and "Lower" Dogger Bank
advancing glacier
detachment at the base of the Dogger Bank Formation
stacking of detached thrust blocks onto up-ice side of evolving thrust-block moraine and folding of earlier formed thrusts
Stage 9: last phases of retreat and readvance of the ice margin resulting in the accretion of the MC2 arcuate thrust-block moraine onto the up-ice side of the larger MC1 landform and deformation of the intervening channel-fill sequence
SE
NW
outwash sequence being deposited in front of advancing glacier
advancing glacier
ice-marginal basin or large channel filled by variably deformed "Upper" Dogger Bank
Pre-Dogger Bank Formation deposits (undivided)
"Basal" unit of the Dogger Bank Formation
"Lower" deformed unit of the Dogger Bank Formation
Holocene and recent deposits (undivided)
sedimentary packages within the "Upper" unit of the Dogger Bank Formation
trace of fold axial plane
fault plane



a
ice sheet advancing from the north
MC1
evolving glacitectonic landsystem
16 km
N
b
ice sheet advancing from the north
MC1
increasing complexity of MC1 glacitectonic landsystem
16 km
N
c
ice sheet advancing from the north
MC1
16 km
N
d
ice sheet advancing from the north-northwest
MC1
increasing complexity of MC1 glacitectonic landsystem
16 km
N
e
ice sheet advancing from the north-northwest
MC2
MC1
accretion of MC2 glacitectonic landsystem
16 km
N
f
ice sheet retreated further north
MC2
LB
MC1
16 km
N
g
ice sheet advancing from the northwest
MC3
LB
MC1
MC2
proglacial basin formed between the moraine complexes
16 km
N
h
ice sheet advancing from the northwest
MC3
LB
MC1
MC2
16 km
N
i
ice sheet advancing from the northwest
MC3
LB
MC1
MC2
increasing complexity of the glacitectonic landsystem as the ice sheet retreated north
16 km
N
j
ice sheet advancing from the northwest
MC4
MC3
LB
MC1
MC2
increasing complexity of the glacitectonic landsystem as the ice sheet retreated north
16 km
N
k
MC4
MC3
LB
MC1
MC2
16 km
N
glacier
meltwater channels
crest lines of moraine ridges
moraine ridges
low-lying areas