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Buried iceberg ploughmarks in the early Quaternary sediments of the central North Sea: A two-million year record of glacial influence from 3D seismic data ☆

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ABSTRACT

Buried linear to curvilinear depressions, interpreted as iceberg ploughmarks, were identified through most of the 2 Ma-long and about 700 m thick early Quaternary sedimentary record in two 3D seismic cubes from the central North Sea Basin (56–58°N, 2–3°E). The mean width of 402 features measured at 6 time slices in cube C08 was between 49 and 63 m and mean length was 2.5 to 3.7 km. Mapping the <2.75 Ma old base-Quaternary horizon enabled the approximate shape of the central North Sea Basin to be estimated. The basin provided accommodation space for sediments, delivered in part by glacial processes from Scandinavia and northern Britain and from European rivers during the Quaternary. Images of seismic time slices of the chaotic and irregular features found in these sediments are similar to multibeam swath-bathymetric images of iceberg ploughmarks from modern polar shelves. The buried features indicate drifting icebergs in the central North Sea Basin through most of the early Quaternary. Lack of iceberg ploughmarks in the last few hundred thousand years of the North Sea Basin record suggests that by the Middle/Late Quaternary the basin was largely sediment filled. The iceberg source was probably an early Quaternary Scandinavian ice sheet extending intermittently onto the westward prograding shelf of western Norway. N–S orientated ploughmarks indicate iceberg drift from the north and a W–E component suggests iceberg circulation within the basin. By analogy with maximum thickness of modern icebergs, water depths were <600 m at most when ploughing took place.

1. Introduction

The production of icebergs requires that ice-sheet margins reach the adjacent oceans in order to calve ice from their marine termini. Evidence for the presence of icebergs in the geological record takes several forms. Sedimentological indicators include the occurrence of outsized clasts, or dropstones, known as ice-rafted debris (IRD) within predominantly fine-grained marine sediments. Geomorphological evidence is provided through the identification of linear to curvilinear depressions, sometimes with associated marginal berms, in the sedimentary sea floor (Dowdeswell et al., 1993). These features, interpreted to have formed through the erosive action of drifting-iceberg keels, are known as iceberg ploughmarks (Woodworth-Lynas et al., 1991). They are observed on the modern or buried high-latitude sea floor using swath-bathymetric or 3-dimensional (3D) seismic methods (e.g. Andreassen et al., 2007; Dowdeswell et al., 2007; Hill et al., 2008; López-Martínez et al., 2011).

In this paper, we identify buried iceberg ploughmarks in 3D seismic records from the central North Sea Basin, located between Britain and Norway at about 56 to 58°N and 2 to 3°E (Fig. 1). The ploughmarks are found on seismic reflectors that represent the former sea floor of the basin, buried up to almost 1000 m within sediments that have infilled the basin over the past 2.75 Ma or so (Jansen and Sjøholm, 1991; Eidvin et al., 2000). Seismic reflectors in the basin dip roughly east to west towards the basin axis (Fig. 1B), suggesting loading of the former basin floor by subsequent sedimentation. Although ice sheets have flowed across much of the North Sea several times over the past 0.5 Ma or so (e.g. Long et al., 1988; Rise et al., 2004; Stewart and Lonergan, 2011), the earlier Quaternary infill appears not to have been eroded by glacier ice. Here we show that the central North Sea Basin was influenced by icebergs derived from adjacent marine ice-sheet margins, although not by overriding ice sheets, during much of the approximately 2 Ma-long early Quaternary beneath the Brunhes–Matuyama boundary at 0.78 Ma (Stoker et al., 1983).

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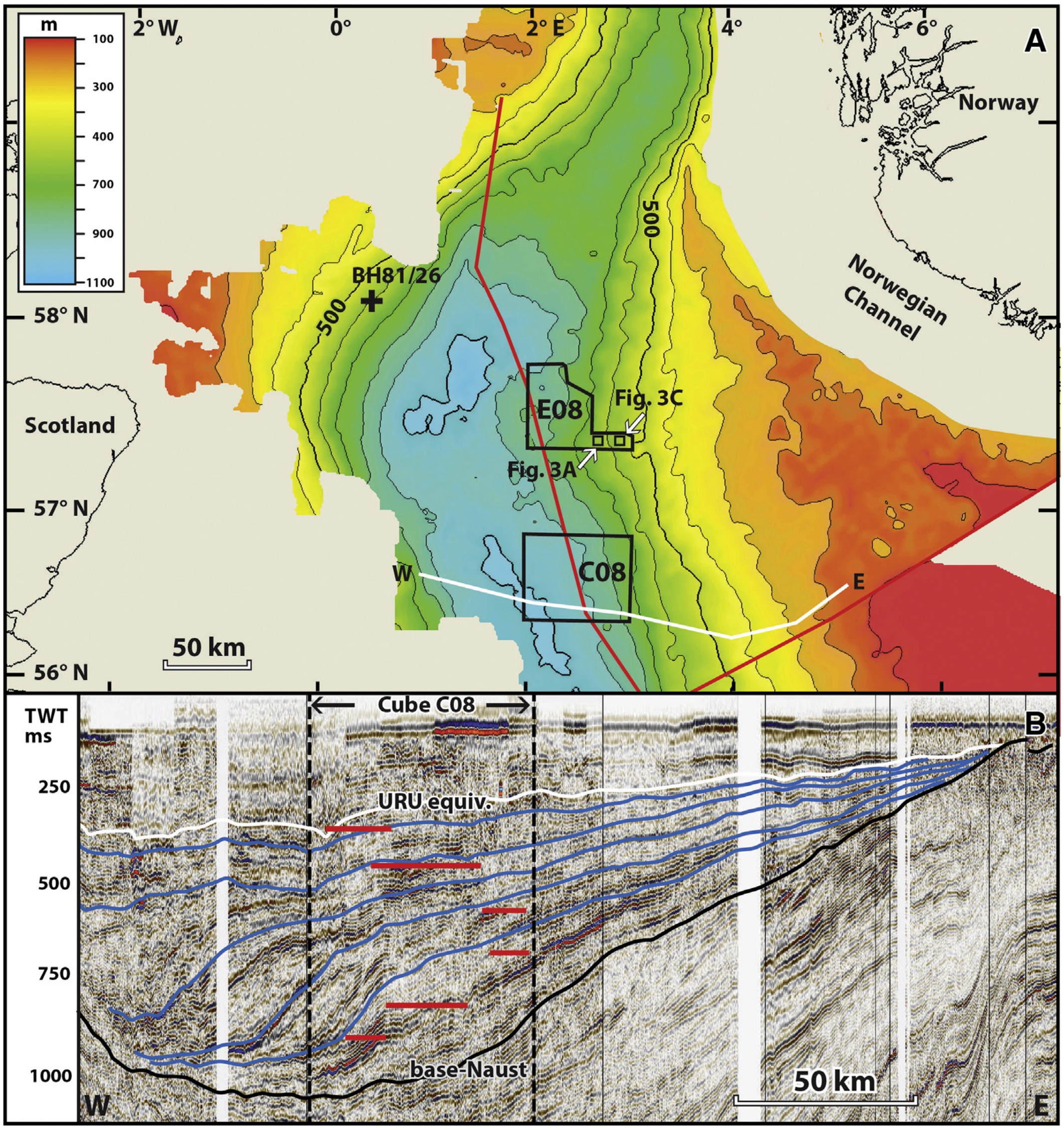

Fig. 1. (A) Map of the base-Naust surface (depth-converted using a simple sound-velocity model of 1750 to 1900 m s^{-1}) showing the morphology of the central North Sea basin at the beginning of the Quaternary based on analysis of 3D seismic cubes and conventional 2D seismic lines (100 m depth contours). The locations of 3D seismic cubes C08 and E08, the seismic profile in B, and borehole BH81/26 (58°08.4′N, 00°10.6′W) are shown. Red lines mark the boundaries between the UK, Norwegian and Danish sectors of the North Sea. (B) West (W) to east (E) composite seismic profile through 3D cube C08 (located as white line in A) showing the seismic stratigraphy and the locations of time slices from which iceberg ploughmarks are identified (thick red lines). The URU-equivalent (white) and base-Naust (black) horizons, marking the stratigraphic boundaries of the early Quaternary, are indicated, and other major reflectors are shown in blue. TWT is two-way travel time. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

2. Methods: iceberg ploughmark detection and measurement

Two 3D seismic cubes in the central North Sea Basin were inspected systematically for iceberg ploughmarks; C08 (62 km by 50 km; 3100 km^2) and E08 (of less regular shape and 1900 km^2) of the Petroleum Geo-Services (PGS) MegaSurvey dataset (Fig. 1A). The seismic bin size of the cubes in the PGS dataset is 25 by 25 m. The quality of individual cubes within the MegaSurvey varies, however, depending on the specific equipment used for data acquisition and subsequent processing. The vertical sampling interval is 4 ms, giving a vertical resolution of 10 to 20 m, again depending on specific data quality. Cubes C08 and E08 are of relatively high quality compared with many other cubes from the North Sea, and the values given above are therefore likely to represent a minimum resolution.

The cubes have a Quaternary sediment thickness of about 1000 m (Fig. 1B), calculated using a simple sound-velocity model that varied between 1850 and 1900 m s^{-1} across the cubes. Examination for the presence of ploughmarks on buried surfaces proceeded through analysis of horizontal time slices by stepping down from the sea floor every 10 ms through the cubes. We attempted several processing techniques to visualise these subtle linear features on specific reflector horizons, but the result was generally poorer than using time slices across the cubes.

Deciding if a linear structure can be classified as an iceberg ploughmark, a non-glacial feature or an artefact requires experience from the interpreter. This is especially important where ploughmarks are orientated close to the direction of the seismic lines themselves. Knowledge of the observed characteristics of iceberg ploughmarks on modern high-latitude shelves demonstrates that a curvilinear to irregular plan-form and quasi-parallel paired margins, with a v- or u-shaped depression below the ambient surface between, are typical characteristics (Woodworth-Lynas et al., 1985). Exemplars are widely available from high-latitude shelves affected by iceberg-keel ploughing during deglaciation from the Last Glacial Maximum (LGM) about 20,000 years ago (e.g. Dowdeswell et al., 2010). Indeed, ploughing of some polar-shelf sediments has persisted up to the present, for example offshore of fast-flowing ice streams which release large numbers of icebergs into Antarctic and Greenland waters today (e.g. Dowdeswell et al., 1992; Dowdeswell and Bamber, 2007).

Each individual ploughmark was digitised by tracing linear features with the cursor on-screen at each time slice using the *Petrel* 3D software package; the lines were then exported to perform statistical work. Ploughmark length, width and orientation data have been extracted routinely. Orientations were measured either for a single direction on relatively linear features, or as line segments if the features had a more complex form. In some cases, ploughmark depth could also be measured, although this was sometimes difficult because ploughmark depth may fall below the vertical resolution of the seismic data.

3. Basin morphological and stratigraphical context

The lowermost sediments of the Nordland Group in the central and northern North Sea Basin comprise clays and the Utsira sands, respectively (Dalland et al., 1988; Eidvin et al., 1999; Eidvin and Rundberg, 2001). The equivalents offshore of mid-Norway, to the north, are the fine-grained Kai and sandy Molo formations (Eidvin et al., 2007). We have correlated the unconformity at the top of the Utsira sands into the clays of the Nordland Group in the central North Sea. This horizon therefore defines the base of the Quaternary sediments in the North Sea and is the equivalent of the base of the Naust Formation off mid-Norway north of 62°N (Fig. 1B). We use the term 'base-Naust' equivalent to describe this horizon, which we have identified throughout our study area in the North Sea stratigraphy (Fig. 1B).

The mapping of the base-Naust equivalent reflector allows the approximate morphology of the central North Sea Basin at the beginning of the Quaternary to be estimated. The shape of the basin is shown in Fig. 1A. Note, however, that the absolute values shown for depth of burial do not represent former water depth in a simple way because it is difficult to apply a systematic correction for subsequent downwarping by Quaternary sediment loading. In the central North Sea at 58°N, immediately north of our study area, the basin was at its widest, at approximately 210 km in width (Fig. 1A), and has a modern sediment thickness of up to about 1000 m (Fig. 1). The basin provided accommodation space at the beginning of the Quaternary into which sediments were delivered during the Quaternary by glacial and related processes from Scandinavia and northern Britain (e.g. Cameron et al., 1987; Graham et al., 2011; Stoker et al., 2011) and from the major European rivers to the south and southeast (e.g. Gibbard, 1988).

Initial mapping of the shallow geology of the UK sector of the North Sea was undertaken by the British Geological Survey (e.g. Holmes, 1977; Stoker et al., 1983; Fyfe, 1986; Cameron et al., 1987; Long, 1987; Stoker et al., 2011). In the present study, based on more recent 2D and 3D seismic data, the early Quaternary sediments we examine are mainly equivalent to those of the Shackleton Formation of the northern North Sea (Johnson et al., 1993) and the Aberdeen Ground Formation in the central North Sea (Gatliff et al., 1994; Graham et al., 2011). A seismic record representative of the stratigraphy of the central North Sea Basin is shown in Fig. 1B. The seismic architecture shows a series of sedimentary units infilling the basin mainly from the east and southeast. These units are fine-grained and are interpreted as hemipelagic distal marine sediments deposited by the large rivers from northern Europe and the Baltic region (Gibbard, 1988). The chronology for these early Quaternary sediments is tentative, with the base of the Naust Formation equivalent dated to be younger than 2.75 Ma and older than 2.4 Ma (Jansen and Sjøholm, 1991; Eidvin et al., 2000). Palaeomagnetic studies of borehole sediments on the UK side of the central North Sea have identified the 0.78 Ma Brunhes–Matuyama magnetic boundary (Stoker et al., 1983). Preliminary correlation to our seismic stratigraphy, tied using borehole BH81/26 (Fig. 1A) where the Brunhes–Matuyama boundary is at 140 m depth, locates this reversal close to an Upper Regional Unconformity-equivalent (URU) surface, which is just above the youngest occurrence of ploughmarks (Fig. 1B). We have interpreted the URU based on correlation from the plateau areas west of the Norwegian Channel, north of our study area, where the URU surface separates progradational units from the east (below) and units deposited from the west (above). This surface is more conformable in the study area compared with the areas further north. We recognise, however, that age constraints on the early Quaternary sediments of the central North Sea have potentially large errors.

In our study area, the URU-equivalent and base-Naust surfaces therefore largely define the early Quaternary period, of about 2 Ma length (Fig. 1B). The URU surface separates the infilled sediments of the early Quaternary, lower part of the basin from more flat-lying units above (Fig. 1B). Cores show that the early Quaternary sediments of the central North Sea are mainly marine and prodeltaic muds with thin sand layers (Fyfe, 1986; Stoker and Bent, 1987). There appears to be little evidence of the diamictic sediments, sometimes know as ice-keel turbates (Vorren et al., 1983), in core material from the central North Sea. Such glacimarine diamicts are characteristic of depositional environments in which icebergs both deliver debris of heterogeneous grain size through melting and rain-out, and also mix any initially sorted sediments through the mechanical action of their keels (Vorren et al., 1983; Dowdeswell et al., 1994). The younger, flat-lying units above appear to have a more direct glacial influence through the presence of, for example, subglacially formed tunnel valleys and mega-scale glacial lineations, as well as ice-keel ploughmarks (e.g. Graham et al., 2007; Stewart and Lonergan, 2011).

4. Iceberg ploughmarks in the central North Sea Basin

4.1. Observations

Linear to curvilinear depressions have been identified at between about 330 ms and 1000 ms below the modern sea floor in 3D seismic cubes C08 and E08 from the central North Sea (Figs. 2, 3). In both seismic cubes, similar features appear to be absent at burial depths of less than about 300 ms. Individual features imaged in the panels of Fig. 2 are in some cases linear, in others curvilinear (Fig. 2B–C), and some exhibit abrupt changes in direction (Fig. 2D). Occasionally the features are seen to have berms on one or both sides of a flat-floored central depression (Fig. 2B, inset). Some linear features of up to several kilometres in length appear either to terminate in sub-rounded depressions or 'pits', or to change direction in association with such features (Fig. 2D, inset). When the pattern of features is considered in any one panel from Fig. 2, or in Fig. 3A and C, it is clear that the overall distribution is irregular and that individual depressions cross-cut one another.

We measured the dimensions of 402 such features at six horizontal slices (time-variable, since the slices cut obliquely across seismic reflectors in Fig. 1B) through 3D seismic cube C08 (370, 490, 600, 720, 860 and 940 ms; Fig. 4A). Statistics are given in Fig. 4B–G. Average width and length of features varied little between the different sample horizons. Mean width was between a minimum of 49 m at 860 ms and a maximum of 63 m at 600 ms. The widest feature was about 300 m across, with berms on either side of a central depression (Fig. 2B, inset). Average feature length was between 2.5 km and 2.9 km in five of the slices, and 3.7 km at 490 ms (Fig. 3). The longest single feature measured was in excess of 9 km. Where measurements of linear-feature depths could be made, values were usually between 5 and 10 m. 'Pits' were also typically a few metres in depth. These geometric measurements represent a conservative estimate of actual values. This is because features may diverge above or below a given time slice, particularly given that the palaeo-sea floor is a dipping surface (Fig. 1B). In addition, some longer features extended beyond the edges of the cubes.

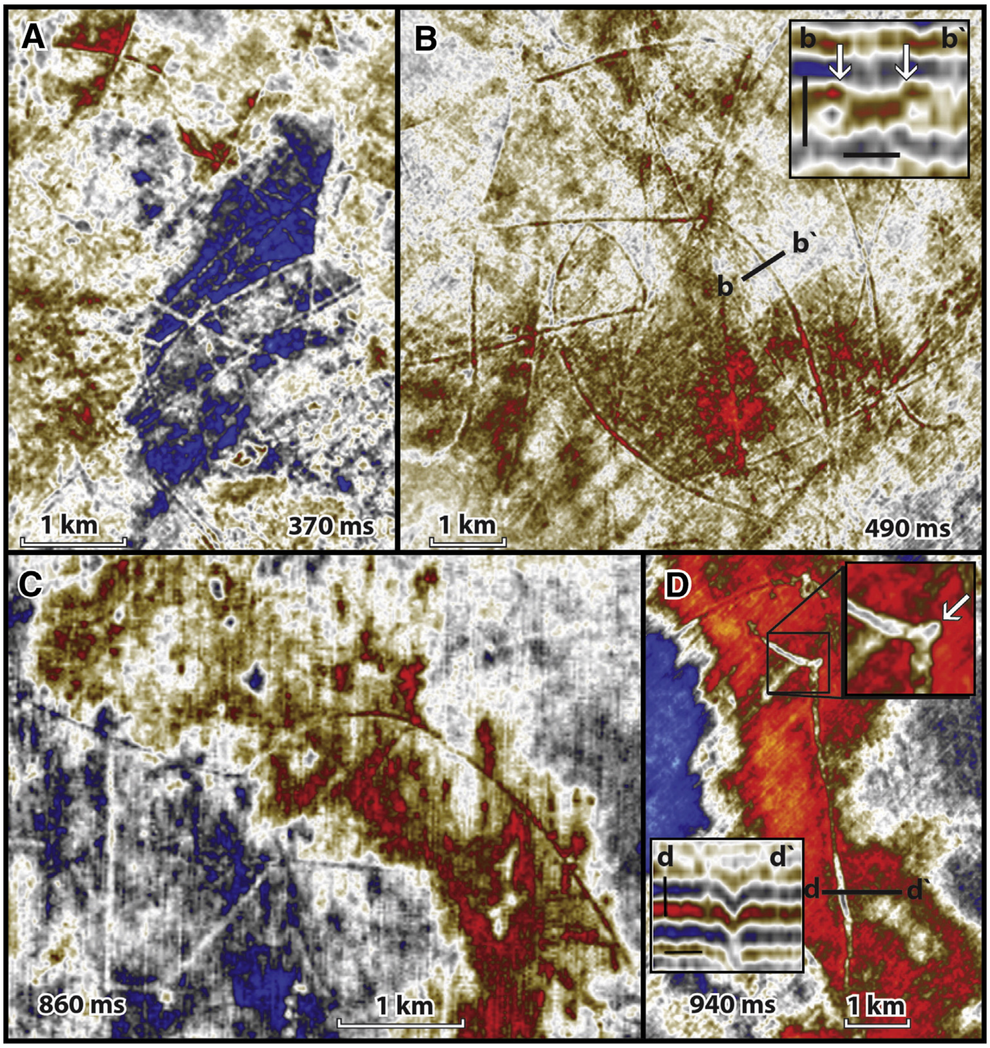

Fig. 2. Images showing iceberg ploughmarks in four time slices of the central North Sea basin from 3D seismic cube C08 (located in Fig. 1A). (A) 370 ms. (B) 490 ms, with inset showing a single wide ploughmark with berms arrowed (vertical scale 25 ms, horizontal scale 250 m). (C) 860 ms. (D) 940 ms, with insets showing a single ploughmark (vertical scale 25 ms, horizontal scale 250 m) and an enlargement of a grounding pit about 10 m deep (arrowed, top right). The four images are shown in Fig. 4A and the time-slice locations are indicated in Fig. 1B.

The distribution pattern of these linear and curvilinear depressions is shown for several time slices in Fig. 4. It is clear that there is a variety of orientations both for different features and, sometimes, for segments of the same feature (Fig. 2). Although the pattern initially appears chaotic, the orientations of features at each time slice have been measured and are plotted as rose diagrams in Fig. 4. The predominant directional component trends N–S for the upper four time slices, although three of them also have a W–E sub-trend (Fig. 4C–E). For the two lowest time slices, which are located at approximately the same position within the seismic stratigraphy (Fig. 1B), the dominant directional trend is W–E (Fig. 4F–G).

4.2. Interpretation

The 3D seismic images of sets of chaotic and irregular linear to curvilinear features from the former floor of the central North Sea (Figs. 2, 3), sometimes with pit-like depressions and abrupt changes of direction, are very similar in morphology to side-scan sonar and swath-bathymetric data from modern high-latitude continental shelves from which ice sheets have retreated since the LGM about 20,000 years ago (e.g. Woodworth-Lynas et al., 1985; Barnes and Lien, 1988; Dowdeswell et al., 1993; Syvitski et al., 2001; Dowdeswell et al., 2010). After ice retreat, the sea-floor sediments of these Arctic and Antarctic shelves were ploughed heavily by the keels of drifting icebergs, a process that continues today in the polar seas. Pits formed where semi-grounded icebergs rotated due to short-term tidal change or longer-term melting and fragmentation (Woodworth-Lynas et al., 1991; Syvitski et al., 2001). The features that we describe from the early Quaternary sediments of the central North Sea are, therefore, interpreted to be produced by the keels of icebergs that impinged on and ploughed the former sea floor as they drifted and grounded in the basin at that time; they are iceberg ploughmarks (sometimes also referred to as iceberg scours or furrows).

This interpretation is supported by a comparison of the dimensions of our early Quaternary features with the geometry of iceberg ploughmarks observed from modern polar continental shelves. Typical ploughmark widths of 40 to 70 m, depths of 5 to 10 m and lengths of a few kilometres were measured from our 3D seismic data (Fig. 4). From the modern East Greenland shelf (65° to 67.5°N), for example, observations of over 1000 ploughmarks record mean widths and depths of 44 m and 5 m, respectively, together with quasi-circular grounding pits of up to 50 m diameter and 10 m depth (Syvitski et al., 2001). Syvitski et al. (2001) concluded that most of the ploughmarks, which

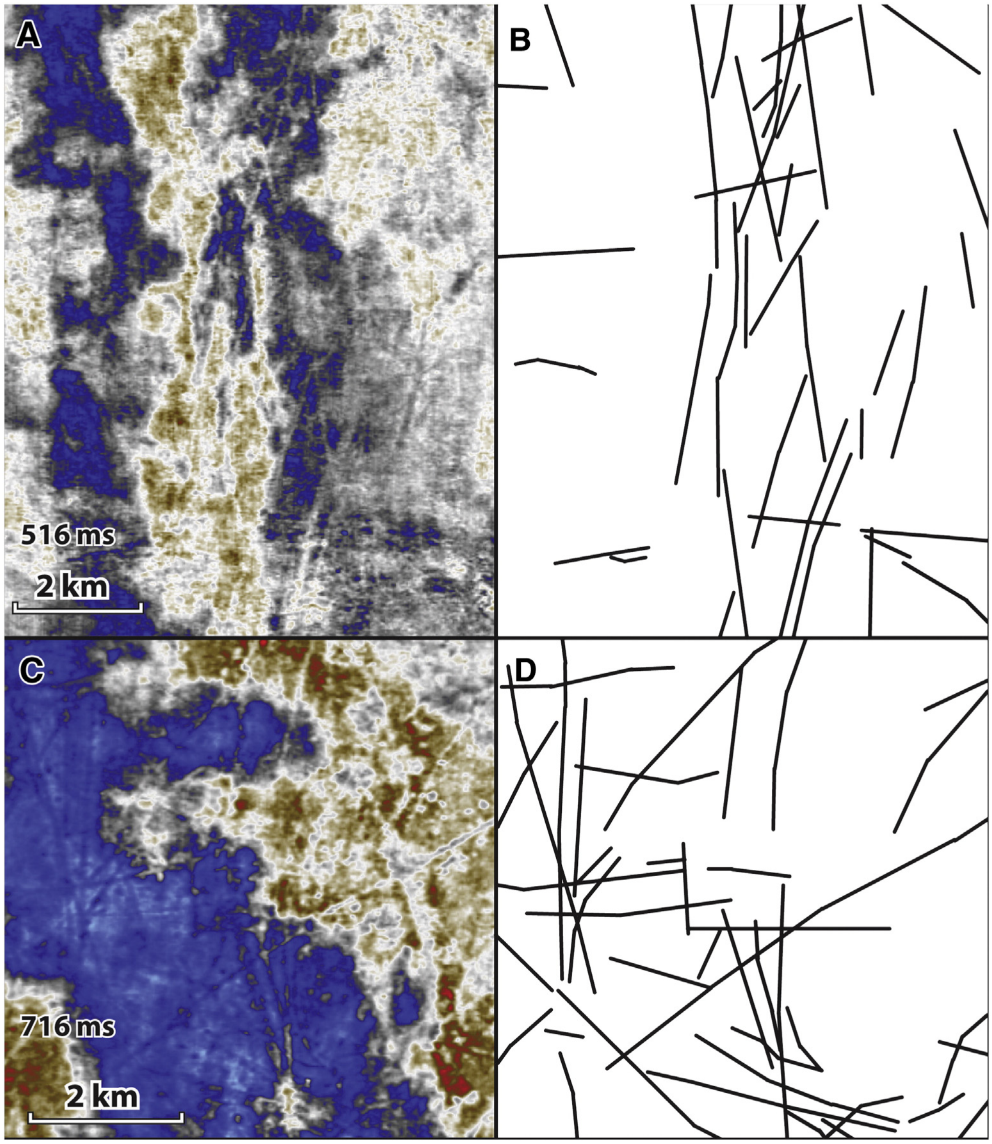

Fig. 3. Images showing iceberg ploughmarks and the mapping of their orientations for two time slices in the central North Sea Basin from 3D seismic cube E08 (located in Fig. 1A). (A) and (B) 516 ms. (C) and (D) 716 ms. The areas of cube E08 examined at each time slice are shown in Fig. 1A.

are at water depths of several hundred metres, were produced by large icebergs calved mainly during the most recent deglaciation of the East Greenland shelf. Similarly, on the modern shelf of northern Svalbard (81.2°N), a chaotic pattern of ploughmarks in water depths <400 m had widths typically of between about 50 m and <100 m and depths usually <10 m (Dowdeswell et al., 2010). On both the modern East Greenland and northern Svalbard shelves, ploughmark lengths were a few kilometres at most.

By contrast, observations of 2200 ploughmarks produced by sea-ice keels on the shallow Canadian Beaufort Shelf showed mean widths and depths of 11 m and 0.3 m, respectively (Héquette et al., 1995). The keels of sea-ice floes seldom reach deeper than 20 m even when pressuring ridging has occurred (Héquette et al., 1995); the maximum depth of modern sea ice pressure ridges in the Beaufort Sea is 55 m. This compares with iceberg keel depths of several hundred metres (Dowdeswell et al., 1992; Dowdeswell and Bamber, 2007). We conclude that the ploughmarks observed in the early Quaternary sediments of the central North Sea Basin (Figs. 2, 3), which are much larger than those reported from the shallow Beaufort Sea, were formed by the interaction of icebergs with the sea floor in relatively deep water and not by the keels of much thinner sea ice.

5. Discussion

5.1. Ice-sheet influence on the early Quaternary North Sea

The observation of iceberg ploughmarks on a number of palaeo-surfaces within the early Quaternary sediments of the central North Sea has several implications. The simplest, and most important, is that the occurrence of buried ploughmarks indicates the presence of drifting icebergs that grounded and ploughed the sediments of the basin through most of the early Quaternary. This, in turn, means that there must have been both open water in the North Sea (at least seasonally) and an ice mass that reached to the sea in relatively deep water in order to calve the icebergs found there. Given that the deep-sea marine-isotope record suggests glacial-interglacial cycles throughout the Quaternary (Huybers, 2007), it is likely that the ice mass grew and decayed a number of times during this period.

Iceberg ploughmarks are present between about 1000 ms, close to the base-Naust reflector, and about 300 ms in the central North Sea sedimentary record (Fig. 4). In more detail, in cube C08 iceberg ploughmarkers were detected in every 10 ms time slice between 340 ms and 1020 ms. In cube E08, ploughmarks were also observed

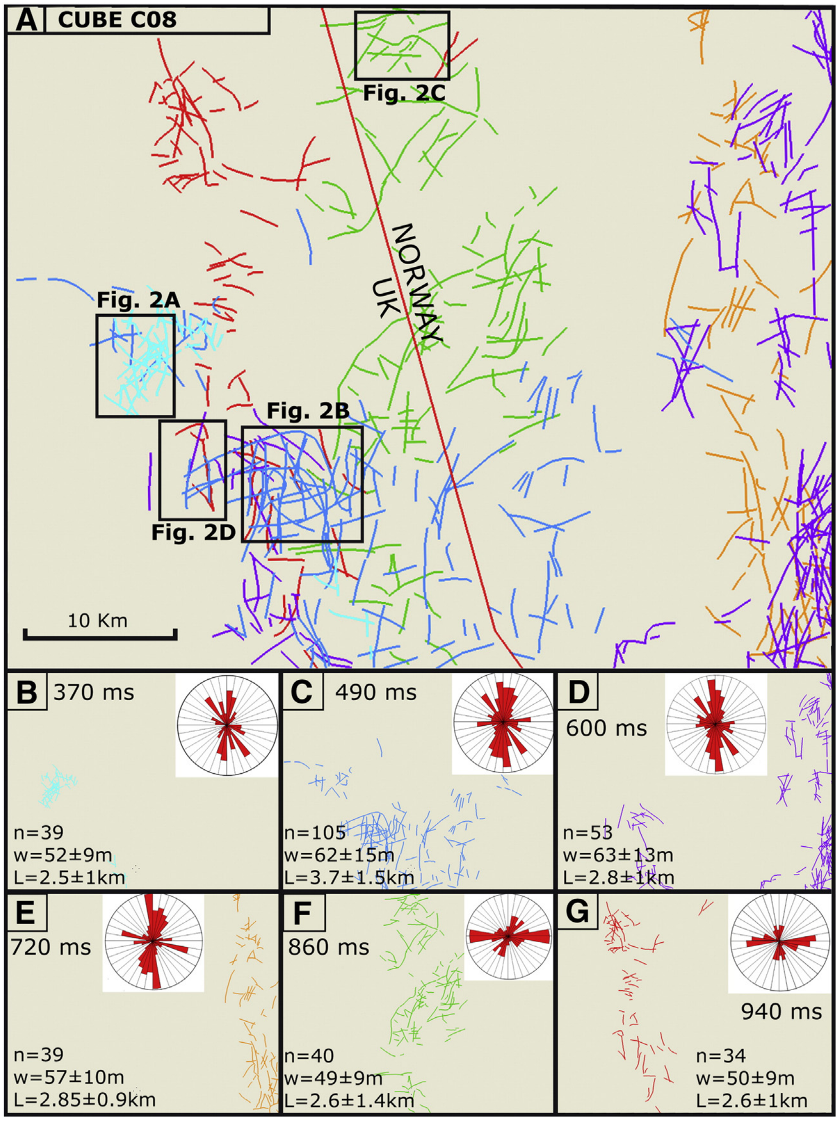

Fig. 4. (A) Composite map showing interpreted and digitised iceberg ploughmarks from six time slices through seismic cube C08 in the central North Sea Basin. Ploughmark colours represent the six time slices shown below. Parts B-G show mapped ploughmarks and their orientations (rose diagrams) for each individual time slice (located in Fig. 1B). Statistics for ploughmark dimensions are also given for each time slice (n is number of ploughmark-segment observations, w is width, L is length). Values are mean ± standard deviation).

in every time slice between 330 ms and 850 ms with the densest distribution between 660 and 720 ms. The occurrence of ploughmarks throughout this interval suggests that icebergs were drifting in the basin through most of the early Quaternary period from approximately 2.75 Ma to about 0.5 Ma ago. We cannot give a more accurate age for the deepest ploughed horizon that we examined, at 1020 ms, although this reflector appears to dip westward and to lap onto the base-Naust just outside cube C08 (Fig. 1B).

It should be noted that Graham (2007) has mapped pre-Elsterian features identified as iceberg ploughmarks in the Aberdeen Ground Formation in two areas of the central North Sea: first, in a single discrete package within the Brunhes-chron sediments of the Witch Ground Basin; and, secondly, at 250 to 430 m below the sea bed in pre-Brunhes sediments to the immediately east of cube C08, which he considers tentatively may be between 1.1 and 1.8 Ma old. In addition, similarly irregular linear features, also interpreted as iceberg ploughmarks, have been imaged from 3D seismic data in the Dutch sector of the southern North Sea at 660 ms depth; an age of about 2 Ma ago (Kuhlmann and Wong, 2008).

A wider point to develop from the occurrence of buried iceberg ploughmarks in the early Quaternary of the North Sea is that they demonstrate that the predominantly laminated fine-grained sediments filling the basin above the base-Naust reflector (marking the base of the Quaternary in Fig. 1B) were influenced by ice sheets. This glacial influence was indirect, through the drift of icebergs from an ice sheet on an adjacent landmass. Indeed, there have been no reports of subglacially produced landforms (e.g. streamlined features such as mega-scale glacial lineations or drumlins, or those linked to subglacial water flow such as tunnel valleys; Benn and Evans, 2010), which would provide strong evidence that an ice sheet extended across the central North Sea during the early Quaternary. Such buried subglacial landforms, however, have been reported widely from the overlying Middle/Late Quaternary sediments of the North Sea record, significantly above the Brunhes–Matuyama boundary (Stewart and Lonergan, 2011). These buried subglacial landforms indicate the presence of grounded ice sheets in the North Sea on several occasions during the last 0.5 Ma or so (e.g. Praeg, 2003; Lonergan et al., 2006; Graham et al., 2007, 2009, 2010, 2011; Stewart and Lonergan, 2011; Kristensen and Huuse, 2012; Stewart et al., 2012).

There is a further implication that can be drawn from the lack of iceberg ploughmarks above about 300 ms in the stratigraphy, in what is the most intensively studied upper part of the Quaternary record. This lack of iceberg ploughmarks in the upper part of the record indicates that the central North Sea Basin was, from this time, filled with sediments to the point that icebergs with deep draughts were no longer able to enter it from the north. Further, at some intervals during the Middle/Late Quaternary, ice sheets also advanced across the central North Sea (e.g. Graham et al., 2007, 2009). An alternative, that icebergs were not produced later in the Quaternary, is unlikely given the intensification of glaciation at this time (e.g. Svendsen et al., 2004). Our interpretation is also consistent with that of Stoker and Long (1984), who reported a buried ice-scoured surface of Late Weichselian age from the Witch Ground area (58.5°N). Given that the ploughmarks they observed were relatively small and formed in a basin with an estimated palaeo-water depth of no more than 80 m, it was initially inferred that sea-ice keels, rather than those of larger ice-sheet derived icebergs, were the instruments of ploughing (Stoker and Long, 1984). More recently, Graham et al. (2010) have reinterpreted these features as iceberg ploughmarks.

The ice mass producing icebergs during the early Quaternary was probably an ice sheet that developed intermittently over Scandinavia, and was present not only in the mountainous interior of the area, but also extended out beyond the coastline onto the prograding early Quaternary shelf beyond (Eidvin and Rundberg, 2001; Ottesen et al., 2009). Progradation along the western Norwegian margin and into the northern and central North Sea Basins took place from the early Quaternary, beginning about 2.75 Ma ago (Jansen and Sjøholm, 1991). This demonstrates a dominant sediment source from Scandinavia rather than from Shetland and Scotland to the west during the early Quaternary, although a switch to northern Britain as an important sediment source occurs later in the Quaternary above the URU, which lies just below the 0.78 Ma Brunhes–Matuyama magnetic boundary and above our sample horizons (Stoker et al., 1983).

A schematic diagram of possible iceberg drift tracks from an early Quaternary Scandinavian ice sheet into the North Sea is shown in Fig. 5; the outline of the North Sea Basin at that time, derived in part from Fig. 1A, is indicated. The predominant N–S trend of iceberg ploughmarks in the upper four time slices (Fig. 4B–E), and a secondary N–S trend in the lowermost two slices (Fig. 4F–G), supports iceberg drift through the North Sea basins from a source to the north (Fig. 5). Given that the basin is closed to the south, and no past ice sheets are known to have been present here, a N–S orientation is preferred to a S–N drift. We suggest that the main source area is likely to have been a marine-terminating ice-sheet margin off the coast of western Norway between about 59° and 62°N, noting that IRD has been reported from close to the base of the early Quaternary prograding sediments in this area west of Norway (Eidvin and Rundberg, 2001; Ottesen et al., 2009). The strong W–E trend to iceberg drift direction in the lowermost slices (Fig. 4), which forms a secondary component in the others, also suggests iceberg circulation within the central North Sea Basin, which has no deep-water exit to the south (Fig. 5). Given the shape of the former central North Sea Basin (Figs. 1A, 5), we again prefer a W–E direction of iceberg drift, as the deepest parts of the basin are likely to have been to the north and, importantly, west of the two cubes (Fig. 1A).

5.2. Iceberg dimensions and water depth

Modern observations of icebergs, and the margins of the parent ice sheets from which they calve, in East Greenland and Antarctica show that initial iceberg thickness is seldom greater than about 600 m (Dowdeswell et al., 1992; Dowdeswell and Bamber, 2007). Side-scan sonar and swath mapping of heavily ploughed polar continental shelves also indicates that iceberg keels seldom impinge on the sea floor below 500 to 650 m of water (e.g. Barnes and Lien, 1988; Dowdeswell et al., 1993; Metz et al., 2008), although occasional features have been observed at greater depths (e.g. Vogt et al., 1994; Kuijpers et al., 2008; Dowdeswell et al., 2010). Based on the grounding depths observed by these workers, it is likely that water depths in the early Quaternary central North Sea Basin where iceberg ploughing took place were no more than about 600 m at most. In addition, in order for large icebergs derived from the Scandinavian ice sheet to enter the area, a relatively deep-water passage must have been open between the central and northern North Sea basins (Fig. 5).

At a mean width of 50–60 m, the iceberg ploughmarks in the early Quaternary sediments of the central North Sea are an order of magnitude smaller than the very large post-LGM ploughmarks observed in, for example, Hudson Strait in the eastern Canadian Arctic (Metz et al., 2008), northwest and north of Svalbard (Vogt et al., 1994; Dowdeswell et al., 2010), and on parts of the Antarctic continental shelf (Barnes and Lien, 1988). In both Hudson Strait and north of Svalbard, there is a relatively sharp transition from very large ploughmarks of several hundred metres across and tens of metres deep, to those that have smaller and more irregular drift tracks, in water depths shallower than 560 m and 400 m, respectively (Metz et al., 2008; Dowdeswell et al., 2010). There is also little evidence of sets of ploughmarks that run parallel to one another over considerable distances in our North Sea data. These striking features, present for example on the northern Svalbard margin (Dowdeswell et al., 2010), have been interpreted to result from one of two processes: either very large icebergs with multiple deep keels (up to 7 km wide off northern Svalbard); or sets of smaller bergs trapped together within very large floes of multi-year sea ice (Vogt et al., 1995; Dowdeswell et al., 2010). The relatively restricted size of North Sea ploughmarks is therefore an indication that very large tabular icebergs, sometimes known as 'megabergs' (Vogt et al., 1994), and/or large coherent flows of multi-year sea ice with embedded icebergs were probably not present in the waters of the early Quaternary North Sea. This, in turn, could imply some combination of relatively mild water in which both icebergs and sea ice melted relatively rapidly, and/or that very large icebergs were either not produced from the Scandinavian ice sheet in the early Quaternary (unlikely) or could not enter the central North Sea Basin due to sea-floor bathymetric constraints.

6. Conclusions

Two 3D seismic cubes (area 5000 km^2) in the central North Sea Basin (56–58°N; Fig. 1A) were examined for buried iceberg ploughmarks. Within the early Quaternary sediments, linear to curvilinear depressions were identified between 330 ms and 1000 ms (Figs. 1B, 2, 3). The mean width of 402 features measured at 6 time slices was between 49 and 63 m and mean length was 2.5 to 3.7 km. The widest features are about 300 m across with berms on either side of a central depression (Fig. 2B, inset), with the longest single feature about 9 km (Fig. 3).

Mapping the horizon marking the beginning of the Quaternary at approximately 2.75 Ma ago in the North Sea enabled the approximate morphology of the central North Sea Basin at this time to be estimated (Fig. 1A). The basin provided accommodation space into which sediments were delivered by glacial and related processes from Scandinavia and northern Britain and from the huge European rivers during the Quaternary.

3D seismic images of chaotic and irregular linear to curvilinear features are very similar in size and pattern to swath and side-scan images of iceberg ploughmarks from modern high-latitude continental shelves (Syvitski et al., 2001; Dowdeswell et al., 2010). Here drifting-iceberg keels have impinged on the sea floor both during deglaciation from the last full-glacial period and, in some areas, continue to do so today (Dowdeswell et al., 1992; Dowdeswell and Bamber, 2007). The features we observe are therefore interpreted as buried iceberg ploughmarks. In addition, because they are much larger than those reported from the shallow Canadian Beaufort Sea where sea-ice processes dominate (Héquette et al., 1995), we infer that they were not produced by sea-ice keels of shallow draught.

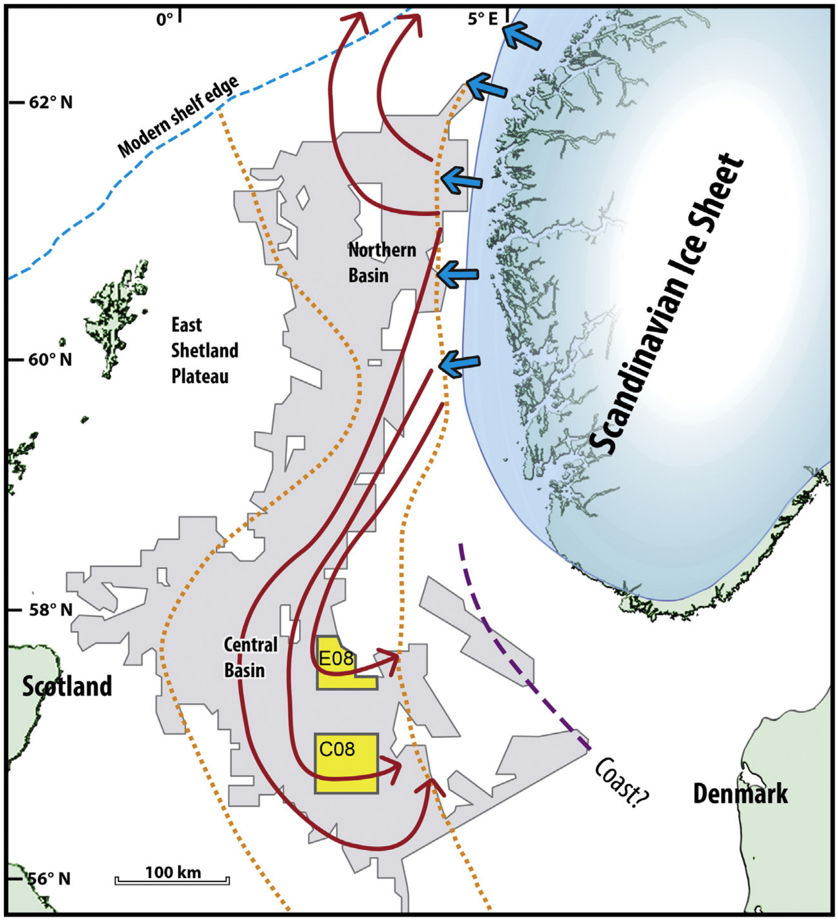

Fig. 5. Schematic map of the North Sea and surrounding land masses in the early Quaternary with the basins of the North Sea outlined (orange dashed line) and the likely drift tracks (long red lines) and sources of icebergs from the Scandinavian ice sheet (thick blue arrows) shown schematically. Grey lines and associated light grey shading show the extent of PGS MegaSurvey 3D seismic coverage. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

Buried iceberg ploughmarks indicate the presence of drifting icebergs in the central North Sea Basin through most of the early Quaternary (Figs. 2–4). At least seasonally open water and an adjacent ice sheet that calved icebergs into relatively deep water must have been present. The lack of iceberg ploughmarks in the last few hundred thousand years of the central North Sea basin record suggests that by the Middle/Late Quaternary the basin was largely filled with sediments.

The ice mass producing the icebergs was probably an early Quaternary Scandinavian ice sheet that extended onto the westward-prograding shelf outside western Norway (Fig. 5). The predominantly N–S trend of ploughmarks supports iceberg drift through the North Sea basins from a source to the north and a W–E component also suggests iceberg circulation within the central North Sea Basin (Fig. 5). By analogy with the maximum thickness of most modern icebergs, water depths were probably a maximum 600 m, and probably less than this, where ploughing took place. With a mean width of 50–60 m, the buried ploughmarks are an order of magnitude smaller than the very large post-LGM ploughmarks observed on parts of the Arctic and Antarctic continental shelf.

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