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The Pleistocene Glaciations of the North Sea basin

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Abstract

It has long been recognised that Quaternary glaciations had a major influence upon the geological history of the North Sea basin, with at least three main phases of ice-sheet growth and decay over the last 0.5 Ma. However recent investigations, often based on novel methods including the analysis of commercial 3-D seismic datasets, have begun to add further detail to knowledge of the North Sea Pleistocene succession. Here, we review the Quaternary geology of the North Sea area, summarising the evidence for extents, configurations, and timing of former glacial activity, focusing attention on key sites across the basin, and for the first time, integrating the stratigraphy with up-to-date information on the geomorphic (morphological) framework of the Pleistocene sequence. Our review demonstrates that, although prominent in the Pleistocene record, the conventional threefold model of glaciation is oversimplified. Basin-wide, ice sheets have been a key depositional and erosional influence since at least 1.1 Ma, and dominantly so since ~0.5 Ma. Multiple glacial events probably characterised each of the Mid-to-Late Pleistocene glacial stages, through Marine Isotope Stages 12, 10, 8, 6, 4 and 2, consistent with the accepted global model for Late Cenozoic glaciation. Thus, we conclude that the North Sea's glaciated history has a much greater complexity than previous workers have argued.

Introduction

The North Sea has had a long and complex geological history, with its present-day structural configuration largely the result of Late Jurassic–Early Cretaceous rifting, followed by thermal cooling and subsidence (Glennie and Underhill, 1999; Zanella and Coward, 2003). During the Cenozoic, the basin was gently deformed by tectonic inversion and basin-margin uplift driven by intraplate compression, resulting from the interplay between the opening of the NE Atlantic Ocean and Alpine orogeny. Since the Mid-Cenozoic, up to 3000 m of Oligocene to Holocene sediment has accumulated in the central graben region, including, locally, in excess of 800 m of Quaternary sediment (Caston, 1977; Gatliff et al., 1994) (Figure 1A). At the present-day, the North Sea forms a shallow, epicontinental shelf that is mostly <100 m deep, but increases to 200 m water depth towards the shelf edge, along its northern margin and in the Norwegian Channel (Figure 1B).

Ice sheets are known to have transgressed into the North Sea at several key stages of the Quaternary, contributing to the episodic erosion and infill of the basin. Traditional models of North Sea Pleistocene glaciations suggest three major glacial episodes during the last 500 kyrs: known locally, and recorded sequentially, as the Elsterian (Marine Isotope Stage [MIS] 12), Saalian (MIS 10-6), and Weichselian (MIS 4-2) glaciations. Discrete sets of tunnel valleys have been used as the main criterion for this threefold subdivision, delimiting the broad (sub-marginal) extents of ice sheets during each of the dominant glaciations in the North Sea (Cameron et al., 1987; Wingfield, 1989, 1990; Ehlers and Wingfield, 1991; Praeg, 2003) (Figure 1B). However, this simple three-stage model has come under considerable scrutiny in recent years and there is now growing evidence, which we will review in this chapter, that many more glacial episodes are preserved in the North Sea sedimentary sequence (Lonergan et al., 2006; Graham, 2007; Stewart, 2009). Nevertheless, in a recent study of the link between glaciation and fluvial discharge from the West European Atlantic margin, Toucanne et al. (2009) have demonstrated that maximum fluvial discharge rates of the Fleuve Manche palaeo-river (through the English Channel) are associated with the Elsterian, Saalian and Weichselian glaciations. This implies that North Sea ice sheets were indeed at their maximum extent during these stages.

The recognition of the North Sea as a key ‘archive’ of information on Quaternary glacial activity has become increasingly apparent in recent times, in conjunction with a mounting interest in the role of ice sheets on the northwest European continental shelves. In particular, a number of the Mid-to-Late Pleistocene ice sheets are now known to have had terminal extents on or at the margins of these shelf regions (Stoker et al., 1993; Sejrup et al., 2005), and were commonly marine-based.

Thus, the North Sea is likely to preserve significant evidence for former continental glaciation in the bordering regions.

In addition, the basin was an important pathway for large-scale glacial transport to the deeper ocean, as shown by the presence of large glacigenic accumulations (glacial debris fans) on the northwest European continental margin (Stoker et al., 1993, 1994; Stoker 1995; Sejrup et al., 2005; Bradwell et al 2008). Ice streams, comparable with those that drain the majority of ice from modern-day Greenland and Antarctica, are known to have fed these fans and were probably a key feature of the North Sea ice sheets (Stoker et al., 1993; Graham, 2007). As a result, the North Sea basin is also likely to be an important site for understanding the discharge and stability of the major northern European palaeo-ice masses, including the British and Fennoscandian Ice Sheets (BIS; FIS).

This paper reviews the evidence for extents and timings of glaciations in the North Sea basin through the Pleistocene, from ~2.58 Ma to the present. We draw upon an extensive body of existing literature, from the work of Valentin (1957), through to state-of-the-art marine geological survey and analytical techniques. The main objectives of this paper are: 1) to review information related to North Sea Quaternary glaciations, in terms of ice-sheet limits, configuration, and chronology; and, 2) to link this information to a geomorphic framework. For the latter, new observations of glacial landforms on commercial 3D seismic reflection data and single-beam sea-floor mapping comprise some of the most novel lines of evidence. Our review highlights that the North Sea has a complex glaciated history, which is likely to have been affected by a range of glacial environments throughout the Pleistocene. As this is a regional review of the North Sea basin, the existing BGS lithostratigraphic nomenclature for the Quaternary units is utilised (cf. Stoker et al., 2010). As direct correlation between the Quaternary continental sedimentary record and the deep-ocean oxygen isotope sequence (Marine Isotope Stages: MIS) remains to be fully substantiated, we primarily correlate our glacial events to the NW European stage nomenclature (Figure 2). It should be noted, however, that the last 2.6 Ma of the continental Quaternary record has recently been correlated to the marine isotope stratigraphy (Gibbard and Cohen, 2008; Toucanne et al., 2009), and we note such correlations where appropriate.

Evidence for glaciation: techniques and methods

Evidence for glaciations in the North Sea basin, including their extents and timings, were inferred in the past from two main data sources: (1) rotary-drilled sedimentary boreholes; and, (2) comprehensive networks of 2D marine reflection seismic surveys. For the most part, these datasets were largely acquired by the British Geological Survey [BGS], by the Dutch Geological Survey, and by the University of Bergen, Norway, during the 1970s and 1980s (e.g. Sejrup et al., 1987). Traditionally two types of information were used for interpreting glacial depositional environments from these sources: 1) sedimentary data, including the identification and characterisation of glacigenic sediments (e.g., tills) in association with seismostratigraphic analysis; and 2) landform data, specifically the mapping of glacial bedforms (e.g., meltwater valleys and ice-keel ploughmarks).

Many early studies focused primarily on the sedimentary and seismic-stratigraphic information. Palaeoenvironmental interpretations were constrained using conventional biostratigraphic, chronostratigraphic, and lithostratigraphic tools (Stoker et al., 1985; Long et al., 1986; Sejrup et al., 1987), and seismic datasets were interpreted in terms of their broad acoustic facies and inter-relationships. Together with the core data, these interpretations led to the establishment of a formal seismic stratigraphic nomenclature for the UK continental shelf, which remains a key foundation for studies of Quaternary depositional history today (e.g. Stoker et al., 1985).

However, there were several problems with these early investigations: (1) in many cases, sediment sequences were often poorly recovered, giving fragmentary geological insights; (2) the genesis of the sediments was not always clear from the cores alone, and detailed sedimentology was sometimes lacking (e.g. provenance analyses); (3) dating was not well constrained for much of the sequence; (4) interpretation of the high frequency Boomer and Sparker seismic data was limited by its shallow depth penetration and its two-dimensional nature; and 5) the geomorphic context for the features observed (e.g. landforms) was not easily identifiable except where side-scan data were also available, as in Stoker and Long (1984)

3-D seismic reflection data have been acquired for North Sea hydrocarbon exploration for over 30 years and the application of these types of dataset to understanding former glacial activity from shallow Pleistocene successions has developed significantly over the past decade (e.g. Praeg, 2003; Rise et al., 2004; Andreassen et al., 2004; Lonergan et al., 2006; Kristensen et al., 2007; Lutz et al., 2009). Several recent, in-depth 3-D seismic studies have been used to revise understanding of parts of the Quaternary framework of the North Sea basin (Graham, 2007; Stewart, 2009), and to address some of the problems outlined above. Merged commercial datasets (e.g., PGS mega-survey) supplemented by higher-resolution commercial 3-D seismic volumes provide a basis for updating some of the information reviewed herein. High-resolution 2D seismic datasets and single-beam (fisheries-sourced) sea-floor bathymetric compilations have also been utilised to improve understanding of more recent glacial activity (e.g. Bradwell et al., 2008; Sejrup et al., 2009), and to capture geological features beneath the resolution of 3-D datasets.

Recent sedimentological studies have also begun to take advantage of higher-precision AMS radiocarbon dating of carbonate material, leading to improved chronological control over the Late Quaternary sequence (Sejrup et al., 2009; Graham et al., 2010). Where problems with the genetic interpretation of sediments once stood, the use of micromorphological techniques to complement macro-scale studies of cores has become an important tool (Carr, 2004; Carr et al., 2006). In addition, new core material has been collected from the basin in recent years (Sejrup et al., 2009; Graham et al., 2010), and 3-D seismic data have afforded consideration of these deposits in a glacial geomorphic context. In view of these recent methodological developments a review of the Quaternary history of the North Sea basin is timely.

Early Pleistocene glaciation(s)

Lower to Middle Pleistocene sediments comprise a large proportion of the Quaternary succession in the North Sea region (Figure 2). Existing studies of this succession are generally limited to discrete evidence for interglacials (e.g. Gibbard, 1991; Zagwijn 1992; Ekman and Scourse, 1993; Sejrup and Knudsen, 1993), or have targeted the non-glacial sequence of Lower to lower Middle Pleistocene sediments, consisting of deltaic sediments and pro-deltaic bottomsets deposited by rivers emanating from continental Europe (Zagwijn, 1974; Cameron et al., 1987; Stoker and Bent, 1987). The latter was associated with the development of the southern North Sea delta, which has been compared in size to the largest modern delta complexes in the world (Ekman and Scourse, 1993), and was accountable for the majority of non-glacial deposition during the Early to Mid-Pleistocene in the southern and central North Sea (Cameron et al., 1992). This delta was probably instigated in the Latest Pliocene–early Pleistocene, and comprises a number of well-defined formations that record its progradation northwards towards the central North Sea where it passes into the pro-deltaic–marine Aberdeen Ground Formation, (Gatliff et al., 1994) (Figure 2).

To date, the earliest known glaciation of the North Sea basin, based on sedimentary records, is found within the Norwegian Channel (Figure 1B). Here, subglacial diamict lies unconformably upon Oligocene rocks at the base of the channel which has been tentatively assigned a 1.1 Ma age based on Sr-isotope, palaeomagnetic, and micropalaeontological data (Sejrup et al., 1995; 2000). Deposition of this till (the ‘Fedje’ till; Figure 2) was followed by a period of extensive marine deposition, interbedded with glacimarine sediments. A thin interglacial layer found within this sequence, and below the 0.78 Ma Bruhnes-Matuyama palaeomagnetic reversal, provides further evidence to justify the till’s c. 1 million year age (related to the Radøy interglacial in corresponding literature; Sejrup et al., 1995; see chapter ‘Pleistocene Glaciations in Norway’ in this volume). North of the Norwegian Channel (Lomre shelf; Figure 1B) time-structure maps of the base-Pleistocene unconformity, mapped from 3-D seismic data, also imaged localized buried iceberg scours, with a possible age of 1.7-2.6 Ma (Jackson, 2007). If correct, these features indicate relatively proximal marine ice-sheet margins during a period of glaciation pre-dating the ‘Fedje’ glaciation, although the sources of the icebergs could be distal to the North Sea itself (e.g. northern Norwegian margin).

Similar coeval records are scarce outside of the Norwegian Channel. However, in BGS borehole 81/27 on the western margin of the central North Sea (Marr Bank; Figure 1), Graham (2007) noted glacigenic sediments consisting of dropstone-rich muddy glacimarine sands overlying the Tertiary rockhead. These muddy sands may give fragmentary evidence for Early Pleistocene glacial activity in the North Sea basin because the deposits occur well below the Bruhnes-Matuyama reversal in the core (BGS unpub. data).

All other lines of evidence indicate significantly younger Pleistocene glacial activity in the North Sea region. For example, indirect evidence for glaciation of the basin during the Menapian stage of the Early Pleistocene, has been described by Bijlsma (1981) and Gibbard (1988). The former suggested that a proto-Baltic basin was scoured by regional glaciation, which resulted in a paucity of pre-Menapian deposits in the North Sea that bear an eastern European provenance (Carr, 2004).

Sejrup et al. (1987) presented the earliest known sedimentary records of glaciation in the central North Sea itself with evidence for Early Pleistocene subglacial tills in borehole records from the Witch Ground area (Figure 1B, 2). In BGS 81/26, a Menapian age, of between 800-900 ka was suggested for a buried subglacial till (‘diamicton F’) using palaeomagnetic, biostratigraphic and amino acid stratigraphic evidence (Figure 2) (Sejrup et al., 1987; Sejrup et al., 2000). Sejrup et al. (1987) originally used these findings to suggest that British-Fennoscandian ice sheets were extensive in the North Sea during this time. Later investigation of the borehole by Ekman and Scourse (1993) identified a cold-stage pollen assemblage for the sediments that correlate with the Menapian till, and they identified extinct pollen taxa (species of *Carya* and *Ostrya*) along with abundant reworked Neogene taxa which prove a pre-Cromerian age.

Mid- Pleistocene/Pre- Elsterian glaciations

Evidence for Mid-Pleistocene, pre-Elsterian glaciation was suggested by Stoker and Bent (1985) by the presence of subglacial and glacimarine sediments in cores recovered from Firth of Forth (Figure 1, 2). These deposits were assigned a tentative early Cromerian age based on their stratigraphic position and palaeomagnetic evidence (Figure 2). Terrestrial studies of the neighbouring glacial stratigraphy in Norfolk have argued, more recently, for a probable Cromerian (MIS 16) glaciation (the ‘Happisburgh’ glaciation), on the basis of subglacial diamictons correlated against well-dated fluvial terrace sequences (Lee et al., 2004). However recent work in the area, including optically stimulated luminescence dating, and detailed biostratigraphic and aminostratigraphic analyses, suggests that these deposits may be younger than first thought, and most likely relate to the later Elsterian glaciation (of MIS 12, or ‘Anglian’ in the UK) (Preece et al., 2009).

Nevertheless, supporting evidence for Cromerian glaciation comes from the equivalent central European Donian glaciations (Figure 2). A subglacial diamicton termed the Don till is constrained to a probable MIS 16 age by the presence of Pleistocene mammalian faunal remains and by pollen stratigraphy in discrete beds surrounding the deposit (Velichko et al., 2004). Ice sheets are interpreted to have been extensive across mainland Europe during the Donian, and to have reached coastal positions in western Norway (Gibbard, 1988). However, no record of tills are present in the Norwegian Channel during equivalent times (between ~1.1 Ma and 500 ka) suggesting that, if present, the Don glaciation was of relatively limited extent (Sejrup et al., 1995, 2000) and ice did not enter the central North Sea during this period.

Graham (2007) suggested evidence for pre-Elsterian glacial influence on the North Sea succession, based on the study of 3-D seismic datasets from the Witch Ground basin, central North Sea. Geomorphic evidence for a proximal ice-sheet limit is present in the form of iceberg ploughmarks which are mapped at 130-170 metres depth, within layers of pre-glacial strata corresponding to the Aberdeen Ground Formation (Figure 2). Age constraints on the iceberg scours in this locality, as constrained from palaeomagnetic data from BGS borehole 77/02, indicate that the scours probably formed during the Cromerian. The fact that the scours have also been cross-cut by tunnel valleys of a minimum Elsterian age and younger provides a strong support to their pre-Elsterian age (Graham, 2007).

The Elsterian glaciation

Glacial limits

The Elsterian glaciation – unequivocally correlated to MIS 12 by Gibbard and Cohen (2008) and Toucanne et al. (2009) – was probably the most extensive in the North Sea Pleistocene glacial history (Figure 1B), marking the onset of repeated shelf-edge glaciations on the NW European margin (Stoker et al., 1993, 1994, 2010; Sejrup et al., 2005), and also a major switch in North Sea sedimentation from non-glacial, to predominantly glacial deposition (Cameron et al., 1987) (Figure 2). Southern ice limits for the Elsterian glaciation have been mapped onshore based on the presence of extant end moraines and incised tunnel valleys (Anglian ‘rinnen’; Figure 3A) which are observed throughout continental Europe and into the United Kingdom. Offshore, the southerly Elsterian limit is associated with morphologically-similar buried, subglacial tunnel valleys, glaciotectonic deformation structures and subglacial 'till tongues' (Figure 3A and 3B; Laban, 1995; Praeg, 2003). For example, Praeg (1996) showed unequivocal evidence that south-north oriented tunnel valleys are associated with an Elsterian margin in the southwestern North Sea, at approximately 53° N (Figure 3B). Taken together, the various geomorphic elements serve as good indicators for large, coalescent ice sheets in the North Sea basin at this time (Figure 3). A major consequence of this was the southerly redirection of the European drainage network south of the ice margin, with the Fleuve Manche palaeo-river draining into the Bay of Biscay (Toucanne et al., 2009). For the northern ice sheet margin, sedimentary fans on the Atlantic continental margin record elevated rates of glacial sedimentation during the Elsterian (Stoker et al., 1994; Sejrup et al., 2005), consistent with an ice sheet which reached the shelf break during this stage. Ice in the northeastern North Sea (Norwegian Channel), and further northeast along the Norwegian margin, also reached the shelf break at least once during the Elsterian glaciation (Rise et al., 2004).

Morphological features

The main morphological evidence for Elsterian glaciation in the North Sea is restricted to subglacial tunnel valleys (Figure 3). In the central and southern North Sea, south of c. 58˚ N, separate generations of tunnel valleys are relatively easy to distinguish from each other (see Ehlers and Wingfield, 1991); the oldest generation of valleys having often been related to a southern margin of the Elsterian ice sheet in the North Sea (Huuse and Lykke-Anderson, 2000). The timing of incision of this valley network has been inferred from cross-correlation to onshore stratigraphy and features, in the UK, the Netherlands and Germany (e.g. Kluving et al., 2003; Lutz et al. 2009), although from a careful review of the literature it appears that no valleys of presumed-Elsterian age have been directly dated. On seismic records these older valleys are associated with a strong glacial unconformity, which can be traced throughout the North Sea basin (Cameron et al., 1987; Huuse and Lykke-Anderson, 2000; Stoker et al., 2010). This unconformity surface is incised into the underlying southern North Sea deltaic units, as well as into the laterally equivalent Aberdeen Ground and Shackleton formations in the central and northern North Seas, respectively (Figure 2). The unconformity overlying each formation is believed to correlate approximately with the Elsterian glacial stage.

From 3-D seismic datasets, Lonergan et al. (2006) have mapped, in detail, the geometry of tunnel valleys in the Witch Ground area of the central North Sea, and have proposed a complex polygenetic origin for the larger Elsterian valleys, which they attribute to the action of episodic meltwater erosion. The number and complexity of cross-cutting patterns probably suggest that the ice sheet was actively eroding and re-eroding its bed throughout this stage. Stewart (2009) has mapped over 180 tunnel valleys in the central North Sea from 3-D seismic data, identifying seven separate phase of valley incision (Figure 3B). The author related several generations of deeply-buried cross-cutting valleys to the Elsterian (at least three phases between MIS 12 and 10), and proposed that it is unlikely that the complex valley sequences observed formed during just two glacial stages (Elsterian and Saalian). Lutz et al. (2009) report at least three generations of cross-cutting tunnel valleys mapped on 3D seismic data from the German North Sea, which they too infer are of Elsterian age, supporting greater complexity to the Elsterian stage than previously thought. Lonergan et al. (2006) and Stewart (2009) also suggest that, based on the orientation and fill of valleys, it is unlikely that all of the valleys are ice-marginal. However, the overall distribution of valleys (Fig. 3) implies that the ice sheet, at its maximum extent, covered the North Sea basin. This is consistent with the southerly deflection of the North Sea fluvial system at this time due to the expansive ice sheet (Toucanne et al., 2009).

Key sites

Little sedimentary evidence for Elsterian glaciation is forthcoming from the central North Sea (Long et al., 1988; Carr, 2004), although some upper units of the Aberdeen Ground Formation have been interpreted as an Elsterian till (Figure 2) (Sejrup et al., 1987; 1991). Given the apparent size of the ice sheet(s), and the pervasive presence of subglacial meltwater features (which implies a significant bedload) it is likely that the absence of tills in cores relates to either a lack of penetration by existing boreholes, or reflects their reworking by ice rather than non-deposition (e.g., Carr, 2004).

In the southern North Sea, south of the Dogger Bank, some authors have suggested that buried channels contain tills and sediments derived from subglacial meltwater that can be assigned to the Swarte Bank Formation of probable-Elsterian age (Balson and Cameron, 1995). In the Inner Silver Pit area of the southwestern North Sea, temperate marine sediments belonging to the locally restricted Sand Hole Formation are sandwiched between the Egmond Ground and Swarte Bank Formations (Figure 2). In BGS borehole 81/52a, and from neighbouring vibrocores, Scourse et al. (1998, 1999) reliably correlated the Sand Hole Formation to the Holsteinian interglacial, of MIS 9 (Figure 2), thus proving an Elsterian age for the underlying Swarte Bank diamictons. Corroborrating this evidence, recent detailed micromorphological, provenance and sedimentary analyses have interpreted the Swarte Bank Formation as a subglacial till, and provide additional sedimentary data in support of the landform record for subglacial environments and extensive Elsterian glaciation (Davies, 2009).

The Saalian glaciation

Glacial limits

According to Gibbard and Cohen (2008) and Toucanne et al. (2009), the Saalian glacial stage spans MIS 6–10 (Figure 2). Onshore (e.g. in Denmark, Poland and the Netherlands) evidence for Saalian glacial activity is widespread, and we refer the reader to respective chapters in this volume for further details.

In the central North Sea region, Ehlers (1990) has suggested that it is possible to reconstruct two phases of Saalian glaciation. For the earliest phase, till of early Saalian age (MIS 8), found offshore of the Netherlands, requires British ice-sheet occupation of the North Sea, in order to explain a south-easterly ice-sheet flow onshore (Rappol et al., 1989). In support, Beets et al. (2005) presented convincing evidence from Dutch Survey borehole 89/2 in the southern North Sea for an extensive ice-sheet advance during MIS 8, which deposited a till that was subsequently overlain by shallow marine sands, correlated with MIS 7.

For the later Saalian (MIS 6), evidence for glaciation comprises a single glacial erosion surface that can be traced through large parts of the North Sea (Figure 2) (Cameron et al., 1987; Ehlers, 1990; Laban, 1995; Holmes, 1997). Glacial incisions which correspond to this surface suggest a minimum southern ice sheet terminus at ~56° N, and extending to the shelf-edge in the northern North Sea (Holmes, 1997; Carr, 2004). This erosion surface is overlain by glacigenic sediments, including till and glacimarine deposits within the Fisher, Coal Pit and Ferder formations in the central and northern North Sea (Figure 2) (Stoker et al., 1985; Cameron et al., 1987; Sejrup et al., 1987; Holmes, 1997). The presence of tills in the Southern North Sea, offshore of the Netherlands and offshore of Denmark has been used in the past to infer more extensive glacial occupation of the North Sea basin during the later Saalian (Carr, 2004). This has been further implied by more recent studies of tunnel valleys and sediments in coastal areas of the southern North Sea (e.g. Kluiving et al., 2003; Kristensen et al., 2004) (Figure 3B), which provide minimum constraints on southerly Saalian ice-sheet extents at ~54° N (Figure 1B and 3B).

Morphological features

Tunnel valleys of supposed Saalian age are relatively common across the North Sea (Cameron et al., 1997; Wingfield, 1989; Huuse and Lykke-Andersen, 2000); although none of these have been directly dated (Figure 3A). Whereas the central North Sea valleys are deeply buried, some Saalian tunnel valleys lie as relict, filled features at the sea floor, in the southern North Sea (Figure 3A). In the central North Sea, Stewart (2009) recently mapped up to seven regionally correlatable tunnel valley generations, incising into the Aberdeen Ground Formation (Fig 3B). Some of these are most likely Elsterian as previously discussed but the authors' correlation of tunnel valley generations to the marine isotope record is consistent with phases of repeated valley incision during each glacial stage of the Saalian, during MIS 10, 8 and 6. The cross-cutting tunnel valleys document a complicated pattern of reoccupation and overprinting during extensive glaciations of the Mid-to-Late Pleistocene.

Graham et al. (2007) also described localised patches of sub-ice-stream bedforms (mega-scale glacial lineations; MSGLs), which they mapped on 3-D seismic datasets in the Witch Ground basin. A small suite of MSGLs occurs on an erosion surface at the base of the Coal Pit Formation in this area (Figure 2), which is thought to range from late Saalian to Weichselian in age (Graham et al., 2007). These lineations, termed the 'lower surface' by Graham et al. (2007) and shown as flowset 1 in Figure 4, have been interpreted as the buried signature of a palaeo-ice-stream, with fast-flow sourced from west, within the BIS. The authors tentatively relate the bedforms to a late Saalian (or possibly early Weichselian) expansion of ice into the Witch Ground basin.

Key sites

To-date, the only record of a central North Sea Saalian-aged till comes from BGS borehole 81/26 where a diamict is found in the Fisher Formation, containing clasts of a probable Scottish source and interpreted as subglacial in origin (Figure 2) (Sejrup et al., 1987; Carr, 2004; Davies, 2009). However, recent re-assessment of the borehole site based on 3-D seismic observations has indicated that this deposit is probably found only locally, infilling one of the many buried tunnel valleys that characterise the subsurface (Graham, 2007). No other known or published reports of Saalian till have been found from the central and northern North Sea regions (Johnson et al., 1993; Carr, 2004), though tills of both MIS 8 and 6 age appear to be relatively common farther south, recovered in a number of boreholes from several sites in the southern North Sea and northern European coastal regions (e.g., Laban and van der Meer, 2004; Beets et al., 2005).

The Weichselian: MIS 4-2 glaciation

In the North Sea, there is good evidence for at least two phases of extensive Weichselian ice-sheet growth; in the early Weichselian (MIS4) and during the Late Weichselian (MIS 3/2; Figure 2) (Carr et al., 2006; Graham, 2007). This is consistent with evidence for a two-stage Weichselian ice sheet on the Atlantic margins of NW Scotland (Stoker and Holmes, 1991; Stoker et al., 1993) and northern Norway (Mangerud, 2004).

Early Weichselian Glaciation: Glacial limits, morphological features, and key sites

In the northern North Sea, a till forming the upper part of the Ferder Formation overlies Eemian interglacial deposits and glacimarine sediments, in which the Blake magnetic event has been proven (Figure 2) (Stoker et al., 1985; Johnson et al., 1993; Carr, 2004; Carr et al., 2006). Infilled tunnel valleys provide primary evidence for glaciation, which correlate with this early stage (Figure 3A). Evidence for the offshore limits of this stage remain unclear, although it is thought that the northern ice edge reached the shelf break, based on sedimentary evidence from the Norwegian Channel and Atlantic margin (Sejrup et al., 2003; Mangerud, 2004), and from the analysis of microstructures in sediments from the northern North Sea area (Carr et al., 2006). All three sites indicate extensive grounded MIS 4 ice sheets. Southerly ice extents are uncertain, but onshore, Scandinavian and Baltic ice sheets reached at least as far central Denmark, implying significant ice cover in the North Sea also (see relevant chapters in this volume)

In 3-D seismic datasets from the central North Sea, Graham (2007) described well-preserved morphological evidence for palaeo-ice stream activity, and inferred extensive glaciation, which may correspond to the Early Weichselian. Graham (2007) mapped at least four separate suites of MSGLs which correspond to palaeo-ice stream bed signatures (flowsets) within the Coal Pit Formation (Figure 2), infilling the Witch Ground basin (Figure 4). Existing chronostratigraphic constraints on this part of the sequence are poor, but suggest at least two of these flowsets correspond to pre-MIS 2 shelf glaciations, between MIS 10-6 and 2. On this basis, at least one of the palaeo-ice streams is thought to have operated during MIS 4 (flowset 2); the other was assigned a tentative late Saalian MIS 6 age (flowset 1). The acoustic stratigraphy and bedform record also indicate that ice streams are associated with discrete till horizons in a stacked sedimentary sequence, and may be interlayered with glacimarine or proglacial deposits (Graham, 2007). Notably these sediments had previously been ascribed a simple glacimarine-marine genesis, comprising a single formation (Figure 2) (the Coal Pit Formation; Stoker et al., 1985; Cameron et al., 1987).

Recent syntheses of marine and terrestrial geological evidence by Svendsen et al. (1999) and Sejrup et al. (2005) as well as offshore evidence of Carr et al. (2006) provide good support to ice sheet occupation of the North Sea basin during MIS 4. Depositional fans located variously along the North Atlantic continental margin provide additional independent evidence for shelf edge glacial limits revealing dramatic increases in sediment flux to the margin during the MIS 4 glacial period (Elverhøi et al., 1998; Sejrup et al., 2003, 2005; Mangerud, 2004). Diamictons interpreted as subglacial till are also recorded in the neighbouring Norwegian Channel, and are assigned an MIS 4 age (Sejrup et al., 1995), while onshore to the west, there is general agreement for two extensive mid-to-late Weichselian glaciations corresponding to MIS 4 and 3-2, shown by a two-tiered till stratigraphy separated by organic horizons at Balglass Burn in central Scotland (Brown et al., 2006).

Late Weichselian Maximum Glaciation: limits

The limits of Late Weichselian glaciation in the North Sea basin (MIS 3-2) have been heavily debated over the last two decades due to a lack of information regarding palaeo-ice flow extents and palaeo-ice sheet configuration. Numerous ice-sheet reconstructions have been proposed, often based on relatively select pieces of data (e.g. single cores), and, for the purposes of this review a range of these are shown (Figure 1B). In some areas, there was a general agreement between ice-sheet limits; however, poor agreement surrounded others, in particular in the central North Sea where various forms of ice-free, proximal glacial, and subglacial environments were interpreted and where ice-sheet reconstructions were clearly at odds (Figure 1B).

Superseding the borehole studies of Sejrup et al. (1987, 1991), which reconstructed an ice-free North Sea at the Late Weichselian maximum, seismic-based studies by Graham et al. (2007) documented that an ice stream occupied the central North Sea at the last maximum ice extent. The main phase of ice cover is associated with subglacial tills recovered in two marine cores that have been related to a period of extensive North Sea glaciation, dated to between 29-22 ^{14}C ka B.P. when ice is thought to have covered the entire North Sea shelf, and reached the shelf break (Figure 5 and 6) (Rise and Rokoengen, 1984; Sejrup et al., 1994, 2000, 2005, 2009; Carr et al., 2006; Bradwell et al., 2008). In this model, the period of maximum areal extent was followed by widespread retreat and a series of subsequent stillstands and possible readvances to inner-shelf limits, which we will discuss below.

Extensive glacial cover followed by at least one localised glacial stillstand or readvance is supported by geomorphic and chronostratigraphic evidence from the onshore record, (Merritt et al., 2003; Mangerud, 2004), and the Barents Sea, Norwegian and Atlantic margins (Davison, 2004; Sejrup et al., 2005) as well as recent micromorphological studies on the North Sea deposits themselves (Carr et al., 2006). Based on all these data, the northern extent of the extensive ice sheet is now accepted to have reached the shelf break. Moraines and tills recovered on the shelf to the northwest of Shetland (Stoker and Holmes, 1991; Davison, 2004, Bradwell et al. 2008), and ice-flow patterns mapped across the Shetland Isles themselves, both support this interpretation (Golledge et al., 2008) (Figure 7).

In contrast to the northwestern margin, the southern extent of the Late Weichselian maximum ice sheet is less well defined. In the eastern North Sea, ice is known to have filled the Skagerrak and the Norwegian Channel at the last glacial maximum (LGM), based on information from cores and landform data (Sejrup et al., 2003). Farther south Baltic ice extended onshore into Denmark, while to the west, the Dogger Bank remains a likely southernmost limit of the 'North Sea' lobe part of the last BIS (Figure 1B and 5). Evidence for deformation structures on seismic reflection data in this area indicate ice movement from the north, and geomorphological mapping as well as sediment provenance analyses from cores recovered from the Bolders Bank Formation (Figure 2) show that ice-streams emanating from the east of Scotland and northern England were clearly deflected south along the coast by Scandinavian ice occupying the central North Sea basin (Everest et al., 2005; Davies, 2009).

Between the Dogger Bank and western Denmark, it is now widely accepted that British and Fennoscandian ice probably coalesced (Sejrup et al., 1994, 2000, 2009; Graham et al., 2007; Bradwell et al., 2008), and an arbitrary southern ice boundary is mapped, broadly coincident with the limit of exposed sea-floor tunnel valleys at ~56° N (Figure 1B and 5). In terms of timing, the period of maximum ice extent appears to have been attained earlier (at ~25 cal. ka B.P.) than the global LGM as conventionally defined by sea-level records (Mix et al., 2001), based on evidence from the Barra–Donegal Fan, as well as the North Sea basin itself (Figure 5 and 6) (Peck et al., 2006; Sejrup et al., 2009; Scourse et al., 2009). A corollary is that the prominent Wee Bankie and Bosies Bank moraines, which were used in the past to demarcate the limits of the LGM east of Britain, (Figure 6 and 7) (Hall and Bent, 1990; Stewart, 1991) probably correlate with the 'Dimlington Stadial' (c. 21 cal. ka B.P.) or younger deglacial events, but were almost certainly preceded by more extensive North Sea glacial cover, and thus, do not represent Late Weichselian maxima (Sejrup et al., 2000, 2009; Carr et al., 2000, 2006; Bradwell et al., 2008; Graham et al., 2009, 2010).

Late Weichselian Maximum Glaciation: morphological features

Morphological features relating to the last main phase of ice-sheet activity are well preserved in the North Sea geological record. Geomorphological evidence for ice flow during the extensive Late Weichselian maximum comes primarily from the central Witch Ground basin. Buried submarine landforms mapped on 3-D reflection seismic datasets provided the first glacial geomorphic evidence for glacial occupation of the central North Sea by at least one late Quaternary palaeo-ice stream (Figure 4) (Graham et al., 2007). Streamlined subglacial bedforms (MSGLs) and iceberg ploughmarks, mapped from 40 m below sea bed to near sea-floor, record the presence and subsequent break-up of grounded ice in the region. The most extensive and best-preserved lineation flowset is attributed to the action of the Witch Ground Ice Stream, which was probably sourced from the southeast within the FIS (Figure 4, flowset 3; and Figure 5) (Graham et al., 2007, 2010). The palaeo-ice stream is imaged over an area at least 30–50 kilometres wide and along-flow for a minimum of 100 km, trending NW–SE. Cored sedimentary records tied to the 3D seismic observations support the age, and subglacial interpretation, of the bedforms. Importantly, the lineations provide independent geomorphic evidence in support of previous ice-sheet reconstructions that favoured complete ice coverage of the North Sea between Scotland and Norway during the Late Weichselian (e.g. Figure 5 and 6; Sejrup et al., 1994, 2000; Carr et al., 2000).

Shelf-edge moraines probably mark the limit of this extensive ice sheet, which concentrated the delivery of sediment through ice streams (the Witch Ground Ice Stream included) to glacial debris fans on the continental margin (Figure 5) (Stoker, 1990; Stoker and Holmes, 1991; Sejrup et al., 2005; Stoker and Bradwell, 2005; Graham et al., 2007). Ice-flow trajectories on Shetland and in northern Scotland support the offshore morphological observations of a dominant northwesterly ice-drainage (Bradwell et al., 2008; Golledge et al., 2008), although there remains some contention over the extent to which Scandinavian ice overran these fringing islands (Flinn, 2009).

Late Weichselian Maximum Glaciation: key sites

The shallow Quaternary successions in the central and northern North Seas preserve good evidence for extensive glaciation and palaeo-ice-stream activity, and include sediments that relate to the Coal Pit and Cape Shore Formations (Figure 2) (Carr et al., 2006). These sequences have been cored, and were analysed for their sedimentology and chronology. BGS boreholes 77/02 and 04/01 both show evidence for glacial overriding of the Coal Pit Formation and secondary deformation of pre-existing Late Weichselian sediments by the Witch Ground Ice Stream (Sejrup et al., 1994; Graham et al., 2010). Thin section analysis of the broadly correlative Cape Shore Formation in other BGS boreholes confirms glacial overriding and deformation by grounded ice in the northern North Sea (Figure 2) (Carr et al., 2000, 2006). The glacimarine sediments that were deformed by the passage of ice were previously emplaced during the Alesund/Tolsta interstadial, when the North Sea was believed to be largely ice-free (Figure 2 and 6) (Mangerud, 2004) The corresponding sequence of sediments relating to ice-sheet extents along the southern margin of the North Sea ice sheet are also heavily deformed but have not been examined in detail. Limited existing micromorphological analyses from this region including samples from the Dogger Bank, suggest that the feature may be a terminal moraine formed during the Late Weichselian maximum, corresponding to the Bolders Bank Formation (Figure 2) (Carr, 2004). The Dogger Bank was likely shaped further by a more localised, and predominantly land-based lobe of the BIS during the later ‘Dimlington Stadial’, when North Sea ice sheets had receded to coastal fringes (Figure 5; e.g. Davies, 2009; Sejrup et al., 2009).

Last deglaciation: limits, morphological features, and key sites

While the maximum extent of Late Weichselian ice seems clear to the Northwest and largely inferred to the South, simple ‘two-stage’ models for the deglaciation of the North Sea basin (e.g. Sejrup et al., 1994) have now given way to a model of more complex dynamic and oscillatory ice-margin retreat (Boulton & Hagdorn, 2006; Bradwell et al., 2008; Graham et al., 2009; Hubbard et al., 2009; Sejrup et al., 2009). Details on ice-sheet limits during the last deglaciation have been described by Bradwell et al. (2008), based on mapping from a new fisheries-sourced bathymetric compilation derived from single-beam echo-sounder data (Olex data) (Figure 7). The authors showed convincing evidence for coalescent British and Fennoscandian ice sheets in the central and northern North Sea, and a subsequent pull-apart or ‘unzipping’ of the ice sheet, followed by a stepped, landward retreat to coastal positions. The retreat formed abundant hummocky topography, meltwater channels, and terminal moraines that are traceable on the sea bed today (Figure 7). In many cases, the morainic features appear to comprise the sediments that correlate with the Sperus Formation in the northern North Sea (Johnson et al., 1994), and Swatchway Formation in the central North Sea (Stoker et al., 1985); both formations record subglacial-to-glacimarine conditions, from ~14 ^{14}C ka onwards (Figure 2) (Sejrup et al., 1994, 2000; Carr et al., 2006; Graham et al., 2007). The arrangement, and existing age constraints on the sequence led Bradwell et al. (2008) to suggest that initial deglaciation in the northern North Sea may have been forced, at least in part, by rising sea-level, and was focused in the Witch Ground region at the confluence between British and Scandinavian ice (Figure 5 and 6). This forcing appears to mirror the pattern of retreat in other major marine ice-sheet systems in northern Europe (e.g. the Barents Sea; Winsborrow et al., 2009), and has been supported by modelling studies (Hubbard et al., 2009).

Several of the Late Weichselian stillstands or readvances have been studied discretely, including the Tampen (Sejrup et al., 2000), Fladen (Sejrup et al., 2009), and Bosies Bank episodes (Figure 6 and 7) (Hall and Bent, 1990; Graham et al., 2009). Moraine units relating to these events, including the Tampen Till (northeastern North Sea), as well as tills of the Norwegian Trench Formation (eastern North Sea), are correlated with the Swatchway and Sperus Formations farther seaward (Carr et al., 2006), which indicate ice-free conditions in large parts of the North Sea during their deposition (Figure 2).

The Tampen episode probably marks one of the earliest North Sea deglacial events, and is recorded by the presence of a sandy, shelly subglacial diamicton (interpreted as till) in cores from the eastern Witch Ground area (Figure 1B, 6). Dates from shell fragments within the till were used to date a major pause or incursion of the FIS on the North Sea plateau, at about 18.6-15 ^{14}C ka BP (Rise and Rokoengen, 1984; Sejrup et al., 1994). The ice-margin terminus is believed to lie east of BGS borehole 77/02, which records marine deposition continuously during the equivalent time-period in the Swatchway and Witch Ground Formations (Figure 2, 6).

Until recently, the Bosies Bank readvance (correlated with the Bolders Bank readvance by Carr et al., 2006) of the BIS was believed to correlate broadly with the Tampen readvance, in the east (Sejrup et al., 1994, 2000). Graham et al. (2009) originally supported this argument, showing that the Bosies Bank formed as a redvance or stillstand subsequent to a more extensive phase of ice-streaming (Figure 7). At the mouth of the Moray Firth, a morainal suite, consisting of a large terminal bank and superimposed by smaller crescentic ridges formed by ice-push, clearly overrides an older bedform signature of a palaeo-ice-stream (Graham et al., 2009; see also Hall and Bent, 1990). Although no chronological data were presented, the authors assigned the main phase of ice-streaming to the North Sea Late Weichselian maximum, because the bedforms and moraine unit appeared to override sediments belonging to the Coal Pit Formation (Figure 2), and suggested that the younger moraine-forming event may have been correlative with the Tampen/Dimlington readvance, as described above.

Since then, the work of Bradwell et al. (2008), Sejrup et al. (2009) and Graham et al. (2010) have confirmed that the Bosies Bank is actually significantly younger, and was likely formed as part of a relatively late-stage stillstand of the BIS (Figure 6). Graham et al. (2010) suggested that its age may be younger than ~14-13.5 ^{14}C ka BP, based on dates on the Fladen readvances – the evidence for which lies seaward of the Bosies Bank moraine (Figure 7) (Sejrup et al., 2009) – and on ^{14}C ages from bivalves (Graham et al., 2010) from an ice-proximal deposit recovered in BGS 04/01, which indicates extensive British ice in the Witch Ground region prior to ~13.9 ^{14}C ka BP. These results would also imply that ice-streaming in the Moray Firth, as recorded in the bedform patterns (Graham et al., 2009), relates to a phase of deglacial activity, rather than to the Late Weichselian maximum as originally proposed. The precise stratigraphic context of the Moray Firth ice stream, however, is unclear at present.

To the south of the Bosies Bank, the Wee Bankie moraine may form a lateral equivalent to the Bosies Bank feature, and presumably marks an ice-recessional morphological feature too (Figure 7). South of the Wee Bankie, the history of ice recession is poorly understood, but the broadly corresponding sediments, including those of the Botney Cut Formation, record the gradual, ice-recessional infill of subglacial channels cut by the LGM ice sheet in the southern North Sea (Figure 2).

Most recently, cores from the western Witch Ground basin have been studied which support evidence for further oscillations of the BIS during its late-stage retreat. Buried grounding zone wedges (or 'till tongues') have been mapped from subsurface acoustic profiles to the west of BGS borehole 77/02 (Sejrup et al., 2009). The moraines correlate to glacigenic diamictons recovered in cores, which were deposited during at least two supposed ice-sheet readvances dated to between 17.5-15.5 cal. ka BP. These readvances have been termed the Fladen readvances, and suggest rapid localised ice advances akin to those modelled by Boulton and Hagdorn, (2006) and Hubbard et al., (2009) late on in the deglaciation (Figure 6, 7). They may correspond, chronologically, to a similar advance of Norwegian ice onto the Maløy plateau, west of Norway, which formed streamlined bedforms and large arcuate moraines at the sea bed (Nygard et al., 2004). Stratigraphically, the Fladen moraines form part of the polygenetic Swatchway Formation, which encompasses many of the features formed during the last deglaciation of the central North Sea area (Figure 2).

A compilation of all published offshore chronological data, together with inferred ice-sheet extents for the North Sea, portrays multiple ice-margin oscillations and a stepped pattern of retreat during Late Weichselian deglaciation (Figure 6) (Sejrup et al., 2009). The glaciation curve (Figure 6) still lacks ties to many of the features mapped by Bradwell et al. (2008) in Figure 7, and therefore we predict even more complexity to the ice-margin retreat pattern than shown here. One possible clue to the dynamic retreat, however, lies in numerous discrete ice-stream systems that drained into the basin during the last deglaciation (Figure 5) (e.g. Moray Firth, Tweed, Strathmore, Witch Ground, North Sea Lobe, and Norwegian Channel ice streams). Indeed recent modelling experiments by Hubbard et al. (2009) seem to confirm that these arteries of flow were influential in controlling the overall dynamics of the decaying BIS.

During the latter stages of deglaciation, ice sheets remained in contact with the open-marine North Sea basin as late on as ~12 ^{14}C ka BP (Graham et al., 2010). Purges of icebergs discharged from the fronts of landward-retreating tidewater glaciers or ice streams, depositing the most distal part of the Swatchway Formation, and the lower parts of the Witch Ground Formation in the central North Sea (Figure 2). Icebergs scoured the sea floor, and keel-marks are now found as the buried and exposed signatures of deglaciation, between these two formations in the stratigraphy (Stoker and Long, 1984; Graham et al., 2010). Age measurements on the most pervasive and prominent scoured horizon constrain iceberg activity to ~13.9-12 ^{14}C ka BP (Stoker and Long, 1984; Graham et al., 2010). The overlying sediments show that distal-glacimarine conditions persisted in the central North

Sea until, and for some time after 12 ^{14}C ka BP, as ice sheets shrank to smaller ice-caps and became restricted to the adjacent land-masses.

In the northern and central North Sea sediments relating to the Witch Ground, Forth, upper parts of the Botney Cut, and the Kleppe Senior Formations record the transition from glacimarine to temperate (shallow) marine conditions through the Lateglacial and early Holocene (Figure 2). The connection between the North Sea and the English Channel was only established between 9 and 7 ka BP, and the North Sea only existed as a full marine basin as recently as ~6 ka BP. The southern North Sea was, therefore, likely exposed as a periglacial plain until the Early Holocene.

Summary

We have presented an up-dated review of the Quaternary stratigraphy of the North Sea basin, which demonstrates a complicated history influenced by glacial environments throughout the last 2.6 Ma.

The North Sea may have had glacimarine influences from fringing marine ice sheets during times of traditionally non-glacial activity: in the Early Pleistocene, during the Menapian (MIS 36; ~1.1-1 Ma BP), and in the Mid-Pleistocene, during the Cromerian between MIS 19-12 (900-450 ka BP). A switch from a deltaic–marine setting to a glacial setting during the Mid-Pleistocene saw the first major expansions of continental ice sheets into the North Sea.

Complete ice cover of much of the North Sea basin occurred during the Elsterian (MIS 12) glaciation, and significant phases of glacial activity are inferred during each stage of the Saalian (MIS 10, 8, and 6) as well as early Weichselian glaciations, based on information from bedform geomorphology and sediments. Combined 2-D and 3-D seismic observations, and associated geomorphological and sediment core studies suggest that meltwater drainage systems dominated the subglacial environment during the period MIS 12-6. The MIS 12 and MIS 10-6 ice sheets appear to have been particularly erosive, and ice-sheet extents have been determined by tunnel valley networks mapped across the basin, although these do not always demonstrate an ice-marginal association and are more complex than previously indicated. Indeed, based on the generations of buried tunnel valleys mapped in the central North Sea, it is clear that the bedforms record a much more complex glacial history for the North Sea than the conventional three-stage model first proposed (Stewart 2009). Stewart's (2009) recent correlation of North Sea stratigraphy and the marine isotope record is consistent with the seven generations of tunnel valleys so-far observed which provide direct geomorphic evidence for frequent, extensive glaciation of the central North Sea during glacial stages of the Pleistocene.

Ice sheets from Norway, Denmark and Scotland coalesced in the North Sea at least once during the Elsterian and Saalian glaciations, and during the Weichselian, possibly during MIS 4 and certainly during MIS 2. Palaeo-ice streams drained into, and crossed, the central North Sea, leaving footprints of their flow at least three times, correlated to MIS 10-6, 4 and 2. The best-preserved palaeo-ice-stream bed relates to the Late Weichselian-aged Witch Ground Ice Stream, which was sourced from the southeast Fennoscandian ice sheet, and probably drained to the shelf edge near Shetland.

The breakup of the last ice sheets was probably initiated in the northern North Sea and Witch Ground areas, and the ensuing deglaciation of the North Sea basin was characterised by a dynamic ice-sheet system; the retreat was punctuated by regular re-advances and stillstands, which formed buried and sea-floor moraines that document final ice-marginal recession onto land.

Note on the maps

Although we have provided ‘a closer look’ at Quaternary glaciations of the North Sea basin in this chapter, the regional picture concerning extents of the main Pleistocene glacial stages has not changed since the first edition of ‘Quaternary Glaciations – Extent and Chronology’. While new work has focused on the buried geomorphology, such studies show local detail beyond the remit of this project. Also, where the glacial features have been mapped regionally, chronological constraints are often poor, and the features do little to change the broad ice-marginal extents. Hence, for this review, we make no update to the digital maps of ice extents in the North Sea, presented in the first volume.

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Figures

Figure 1. (A) Isopach (thickness) map of Quaternary sediments in the North Sea basin, derived from interpreted 2D seismic datasets (after Caston, 1977); (B) Bathymetry of the North Sea basin, and Quaternary ice-sheet extents for each of the three major Mid-to-Late Pleistocene northwest European glaciations. Key sites are also shown. FF – Firth of Forth, MF – Moray Firth, ISP – Inner Silver Pit.

Figure 2. Summary panel outlining the Quaternary framework for the North Sea basin (after Stoker et al., 1985; Cameron et al., 1987; 1992; Johnson et al., 1993; Gatliff et al., 1994; Scourse et al., 1998;; Stoker, 2010), showing geomorphic observations, key glacial event stratigraphy, inferred ages, and correlation to the regional stratigraphic nomenclature. Palaeomagnetic events (Ma): 0.047 = Laschamp; 0.120 = Blake; 0.465 = Emperor; 0.990 = Jaramillo; 1.77 = Olduvai.

Figure 3. (A) Compilation map of previously published tunnel valleys in the North Sea basin, and their assignment to the major Pleistocene glaciations in the region based on 2D seismic reflection data (modified from Huuse and Lykke-Anderson, 2000) (B) Recently reported distribution of buried tunnel valleys mapped from 3-D seismic datasets in the North Sea region (from Stewart, 2009), which updates signifcantly the older compilation in Figure 3A. The new mapping of tunnel valleys in central North Sea (top inset map) illustrates seven generations of tunnel valleys formed from Elsterian to MIS 5e. The most recent tunnel valleys formed during the Weichselian glaciation are not shown on this map.

Figure 4. Map of flowsets that record the flow pathways of Pleistocene palaeo-ice streams in the Witch Ground basin. Flowsets were interpreted from suites of buried, mega-scale glacial lineations corresponding to relict palaeo-ice stream beds in 3-D seismic datasets (Graham et al., 2007, 2010). 3-D datasets are shown as grey boxes. A lower-resolution, regional 3-D seismic mega-survey, also used for lineation mapping, covers the majority of the area shown in the figure. The underlying basemap shows the thickness of the glacial package in which bedforms are observed, correlative with the Coal Pit and Swatchway Formations in the central North Sea.

Figure 5. Reconstruction of ice-sheet extent and configuration for the Late Weichselian glacial maximum (MIS 3-2), in the North Sea Basin. The reconstruction is based on existing literature, and is intended to highlight the broad flow patterns recorded within the northwest European ice sheets. It cannot replicate the full dynamics and various advance/retreat configurations that this ice mass

certainly possessed. Arrowed flow lines represent fast-flow elements of the ice sheet (N.B. not necessarily ice streams), at certain times during its lifespan, whilst headless black lines show generalised ice flow characteristics. Ice streams were likely active at different times (see text for details). Confluence is inferred for the British and Scandinavian ice sheets as shown by the grey stipled area. In this configuration, the majority of ice-flow drainage is directed towards the North Atlantic shelf edge, feeding sedimentary fans at the continental margin. Sizes and locations of glacigenic fans from Stoker et al. (1993), Stoker (1995), Davison (2004), and Sejrup et al. (2005).

Figure 6. Simplified glaciation curve for the Late Weichselian in the North Sea basin, showing changing ice-sheet extents through time, constrained by a published radiocarbon chronology. Modified from Sejrup et al. (2009).

Figure 7. Map of sea-floor moraine ridges and meltwater channels in the northern North Sea and north of Scotland. The features were mapped from high-resolution sea-floor bathymetry, and record the dynamics and decay of British ice during the last deglaciation (Bradwell et al., 2008). Thick grey and stipled lines depict moraines formed during readvances or stillstands of the British Ice Sheet during the last deglaciation. Moraine positions drawn from Stewart (1991), Graham et al. (2009), and Sejrup et al. (2009).

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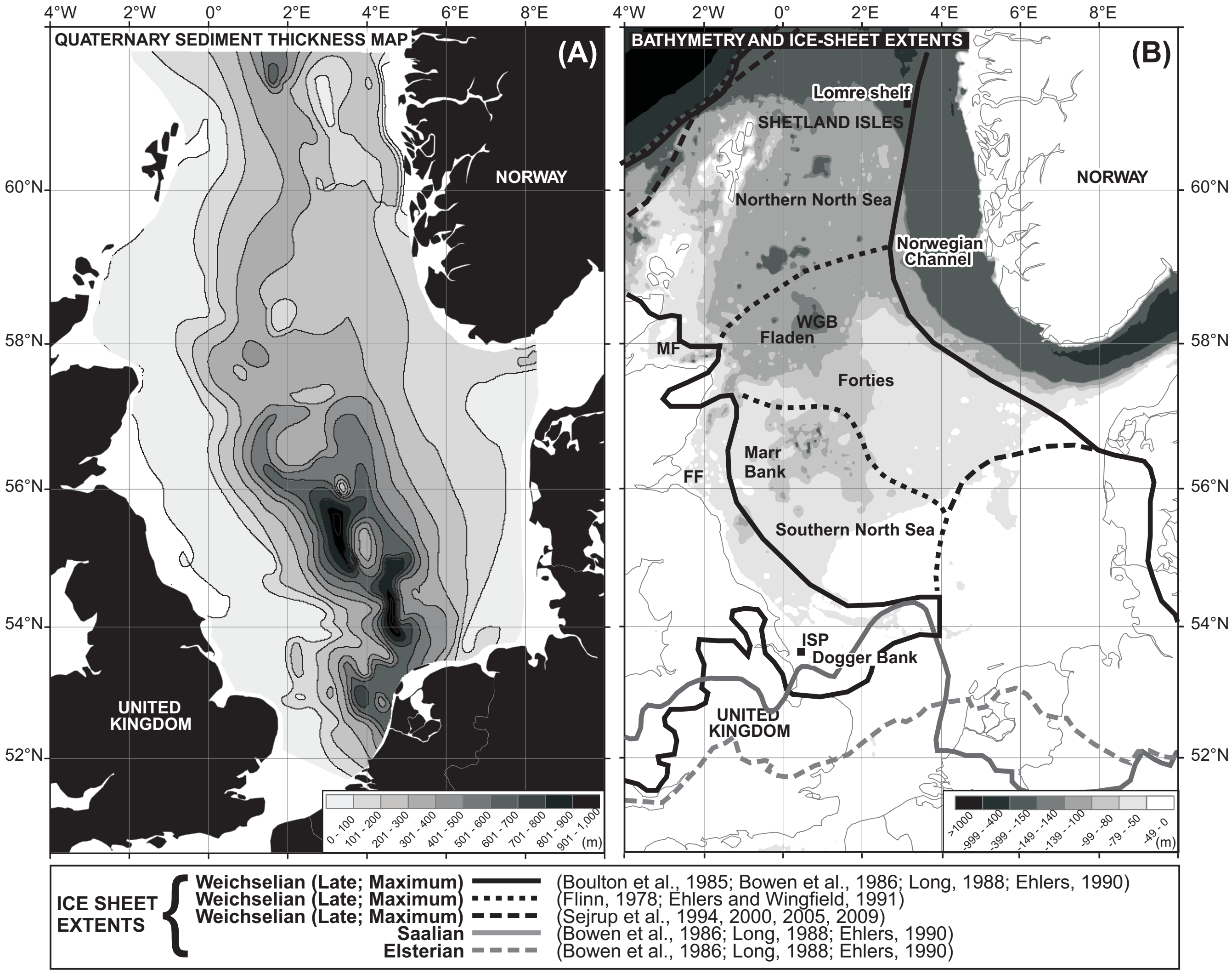
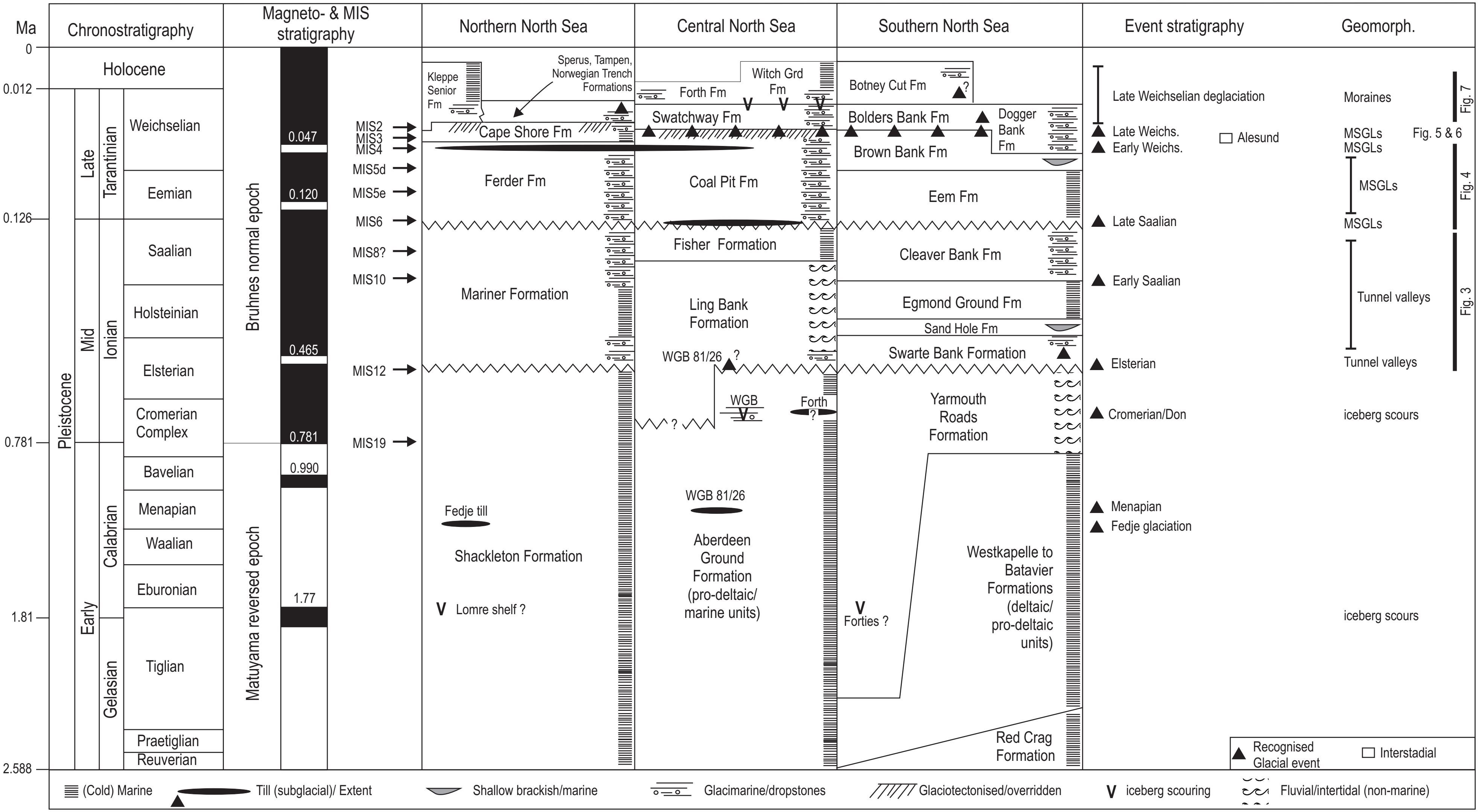


Figure 1, Graham et al.



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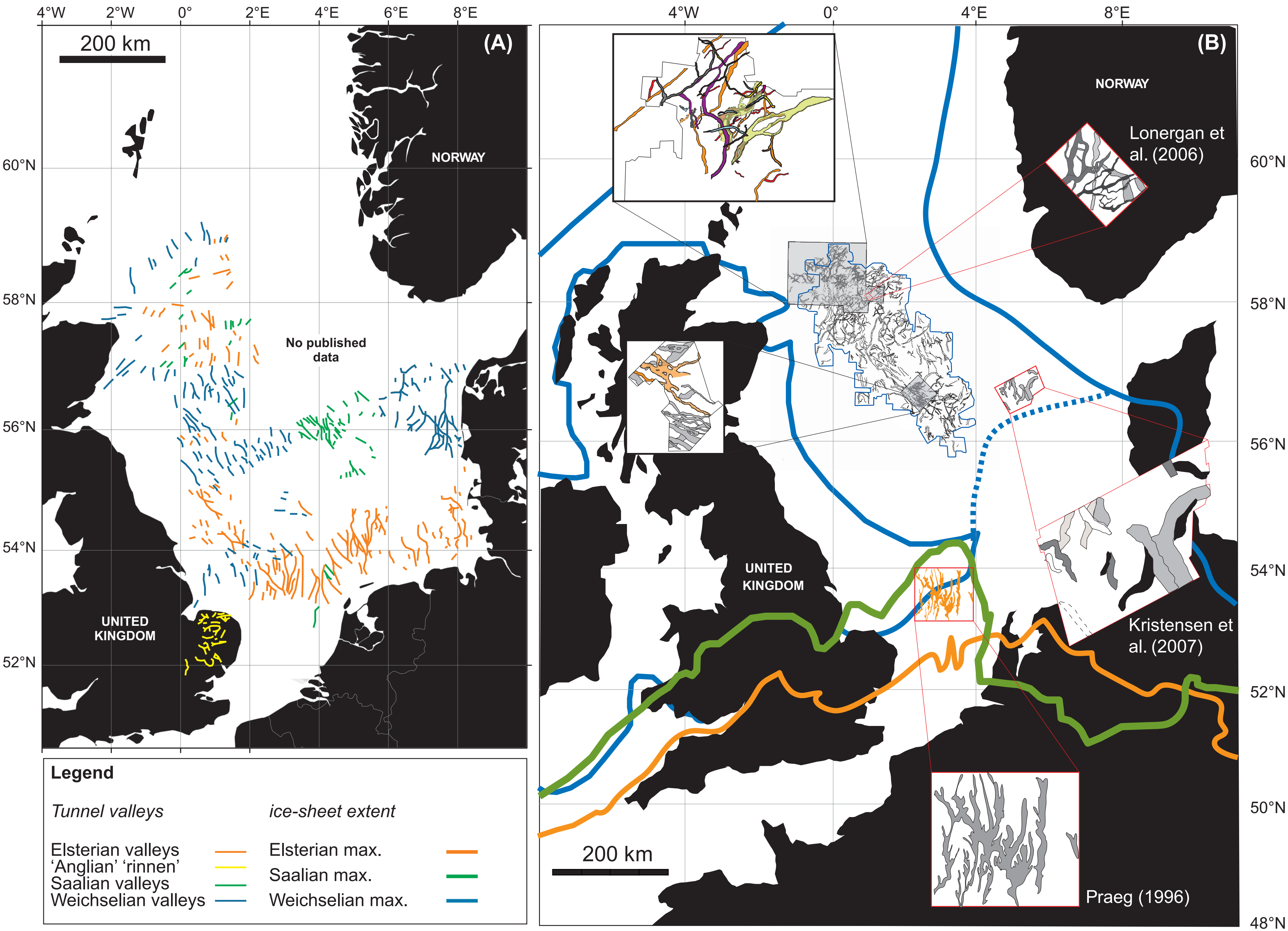

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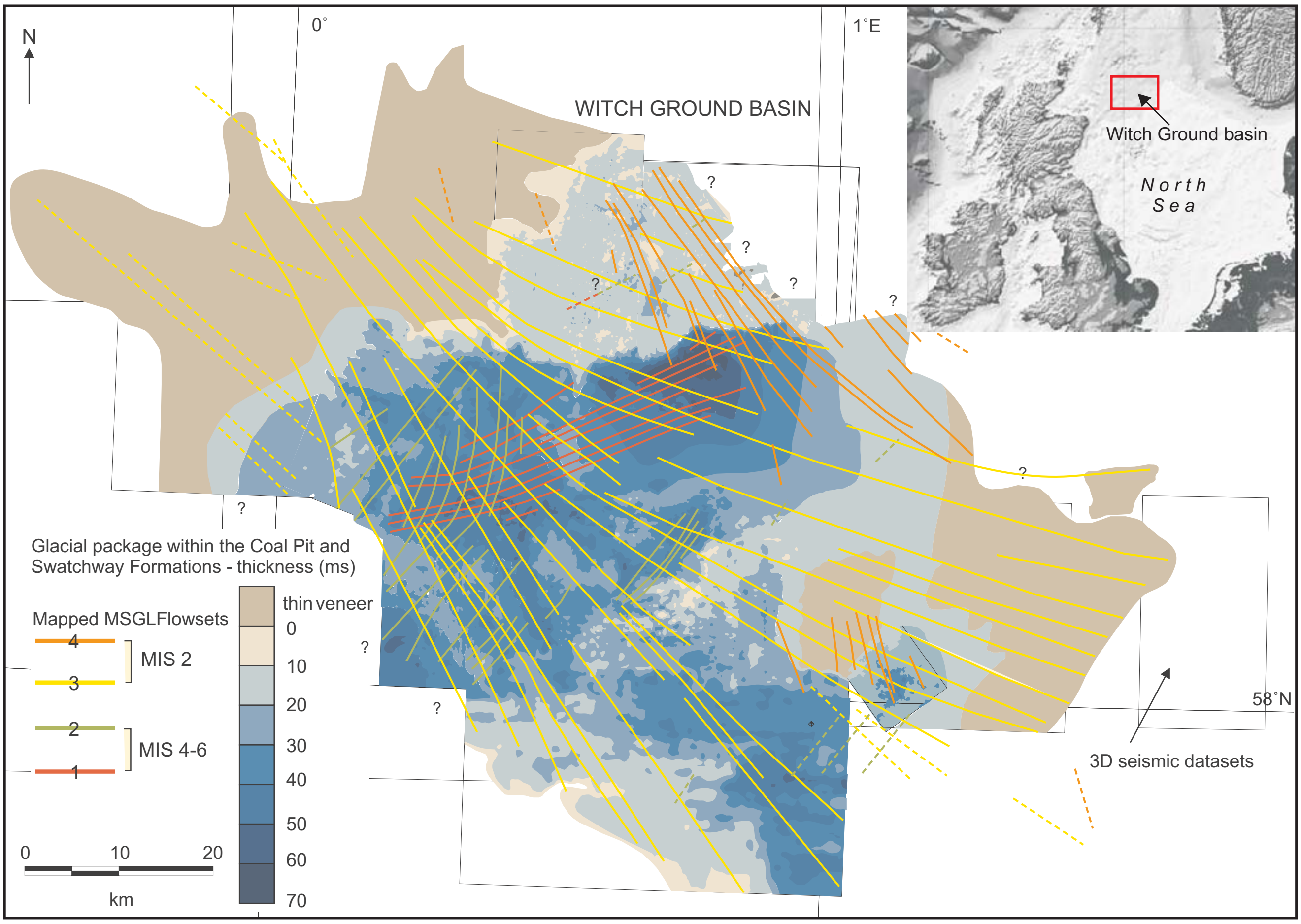

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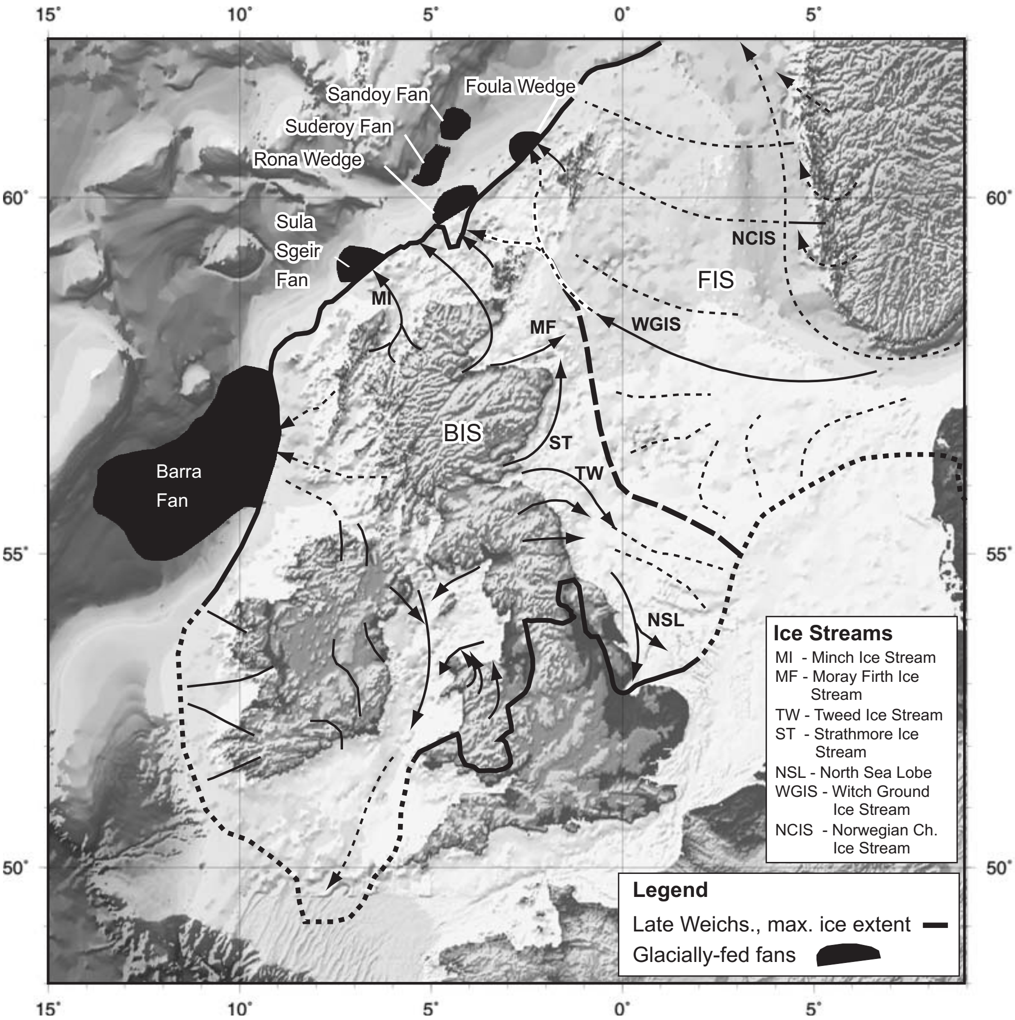

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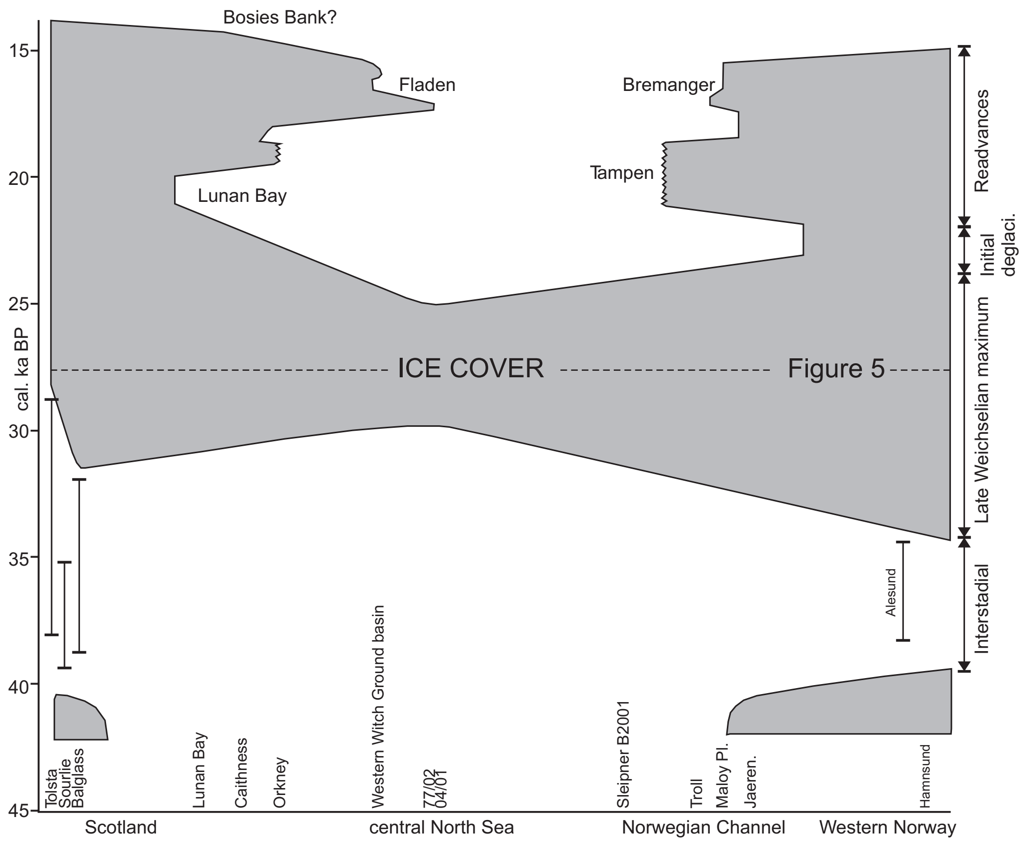

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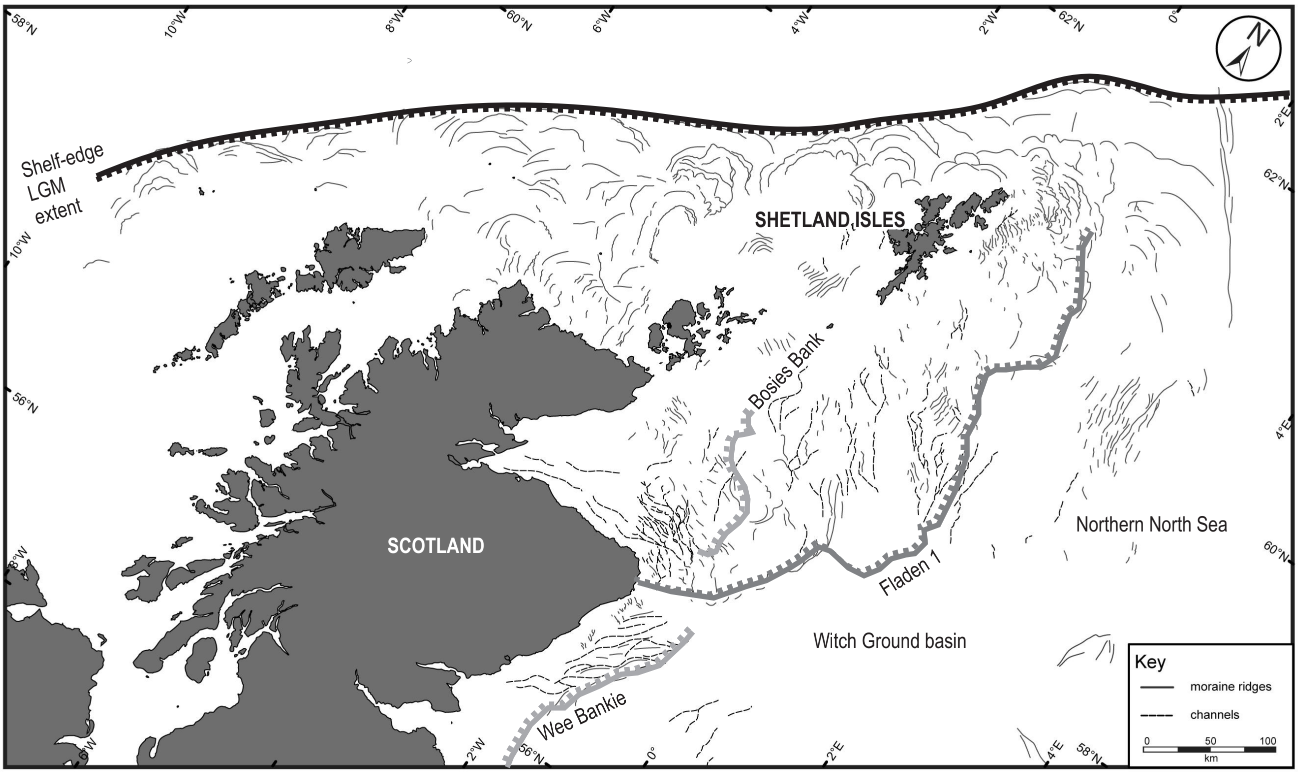

Figure 7, Graham et al.