The northern sector of the Last British Ice Sheet: maximum extent and demise

Tom Bradwell[1], Martyn Stoker[1], Nick Golledge[1], Christian Wilson[1], Jon Merritt[1], Dave Long[1], Jez Everest[1], Ole B. Hestvik[2], Alan Stevenson[1], Alun Hubbard[3], Andrew Finlayson[1], Hannah Mathers[1,4]

[1] British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA, UK
[2] Olex AS, Pirsenteret, N-7462 Trondheim, Norway
[3] Institute of Geography and Earth Sciences, University of Wales, Aberystwyth, Ceredigion, SY23 3DB, UK
[4] Department of Geographical and Earth Sciences, East Quadrangle, University Avenue, University of Glasgow, Glasgow, G12 8QQ, UK

Abstract

Strongly divided opinion has led to competing, apparently contradictory, views on the timing, extent, flow configuration and decay mechanism of the last British Ice Sheet. We review the existing literature and reconcile some of these differences using remarkable new seabed imagery. This bathymetric data provides unprecedented empirical evidence of confluence and subsequent separation of the last British and Fennoscandian Ice Sheets. Critically, it also allows a viable pattern of ice-sheet disintegration to be proposed for the first time. Covering the continental shelf around the northern United Kingdom, extensive echosounder data reveals striking geomorphic evidence – in the form of tunnel valleys and moraines – relating to the former British and Fennoscandian Ice Sheets. The pattern of tunnel valleys in the northern North Sea Basin and the presence of large moraines on the West Shetland Shelf, coupled with stratigraphic evidence from the Witch Ground Basin, all suggest that at its maximum extent a grounded ice sheet flowed from SE to NW across the northern North Sea Basin, terminating at the continental shelf edge. The zone of confluence between the British and much larger Fennoscandian Ice Sheets was probably across the northern Orkney Islands, with fast-flowing ice in the Fair Isle Channel focusing sediment delivery to the Rona and Foula Wedges. This period of maximum confluent glaciation (c. 30-25 ka BP) was followed by a remarkable period of large-scale ice-sheet re-organisation. We present evidence suggesting that as sea-level rose, a large marine embayment opened in the northern North Sea Basin, as far south as the Witch Ground Basin, forcing the two ice sheets to decouple rapidly along a north-south axis east of Shetland. As a result, both ice-sheets rapidly adjusted to new quasi-stable margin positions forming a second distinct set of moraines (c. 24-18 ka BP). The lobate overprinted morphology of these moraines on the mid-shelf west of Orkney and Shetland indicates that the re-organisation of the British Ice Sheet was extremely dynamic – probably dominated by a series of internally forced readvances. Critically, much of the ice in the low-lying North Sea Basin may have disintegrated catastrophically as decoupling progressed in response to rising sea levels. Final-stage deglaciation was marked by near-shore ice streaming and increasing topographic control on ice-flow direction. Punctuated retreat of the British Ice Sheet continued until c. 16 ka BP when, following the North Atlantic iceberg-discharge event (Heinrich-1), ice was situated at the present-day coastline in NW Scotland.

Key words: UK continental shelf, North Sea, ice stream, sea-level rise, deglaciation

Introduction

At present, views vary widely regarding the extent, thickness and geometry of the last British Ice Sheet (BIS), and its interaction with the neighbouring Fennoscandian Ice Sheet (FIS). Nowhere is this problem better highlighted than in the North Sea Basin. Whilst some authors have claimed that, at its maximum, the last BIS coalesced with the Fennoscandian Ice Sheet (FIS) in the North Sea Basin (e.g. Sejrup et al., 1994; 2005; Carr et al., 2006); others have contended that it terminated only a short distance offshore (e.g. Sutherland, 1984; Bowen et al., 2002). These differences in ice-sheet extent are contradictory and appear impossible to reconcile (cf. Bowen et al., 2002; Hall et al., 2003). Resolving this impasse has important implications, not only for underpinning past changes in the geometry and dynamics of the last BIS, but also for environmental change on a global scale. Questions regarding Northern Hemisphere ice-sheet volume, concomitant sea-level changes and the potential impact of meltwater and calving flux on the North Atlantic thermohaline circulation are central to our understanding of the coupled ocean-atmosphere system.

The glacial history of the continental shelf east of the UK, predominantly comprising the North Sea Basin, remains relatively poorly understood (Figure 1). Previous reconstructions for the northern North Sea area (north of 57ºN) depict both ice-free (e.g. Sutherland, 1984; Boulton et al., 1985; Bowen et al., 2002) and ice-covered scenarios (e.g. Sissons, 1967; Boulton et al., 1977; Sejrup et al., 1994). Only recently has opinion begun to converge on the idea of a glaciated North Sea Basin in Late Weichselian times (Marine Isotope Stage 2) (Sejrup et al., 2005; Carr et al., 2006). This view has been strongly reinforced by the recent identification of mega-scale glacial lineations (MSGLs) in the central part of the northern North Sea (Graham et al., 2007). These sub-surface lineations, imaged on 3D seismic profiles in the Witch Ground Basin, represent the signature of fast-flow within a grounded ice sheet. Their presence and orientation are compatible with a major ice stream draining the northern North Sea fed by the coalescent British and Fennoscandian ice sheets. Stratigraphic evidence from British Geological Survey (BGS) boreholes in the Witch Ground Basin supports the interpretation of a palaeo-ice stream flowing over deformable sediment, and crucially constrains the timing of ice flow to between <42 ka ^{14}C BP and ~22 ka ^{14}C BP (i.e. <47-26 cal ka BP). On this basis, Graham et al. (2007) place the most likely period of ice streaming in the Late Weichselian (MIS 2). These recent important findings, and those of Carr et al. (2006), echo the views first proposed by Sejrup et al. (1994) and developed in subsequent papers (Sejrup et al., 2003; Sejrup et al., 2005). Although the exact timing of the glaciation needs refining, unequivocal evidence that a grounded Weichselian ice sheet occupied the North Sea Basin, to at least 58.5ºN, has now been demonstrated (Graham, 2007; Graham et al., 2007).

Previous work on the palaeoglaciology of the western margins of the FIS has highlighted the role of the Norwegian Channel in concentrating flow along the west coast of Norway. The Norwegian Channel palaeo-ice stream, first identified in the 1990s, drained much of the western sector of the FIS and operated during the last glacial cycle (MIS 2) (Sejrup et al., 1994, 1998; Rise et al., 2004; Ottesen et al., 2005). However, geophysical data from the seafloor ~50 km west of the Norwegian Channel has also revealed the signature of streaming grounded ice flowing NW on the Egersundbanken (Stalsberg et al., 2003). These glacial lineations indicate that at some periods during the Late Weichselian the FIS was not confined by the Norwegian Channel and may have flowed into the North Sea Basin. Graham et al. (2007) inferred ice flow from the SW sector of the FIS across the North Sea Basin to explain the presence of MSGLs in the northern North Sea. This evidence is supported by sensitive computer modelling experiments of the last FIS which simulate the ice sheet periodically overspilling the Norwegian Channel during periods of maximum glaciation (Boulton and Hagdorn, 2006).

In this paper we present a new model for the deglaciation of the continental shelf around the northern United Kingdom based on a synthesis of new offshore imagery. This model allows us to explain and subsequently reconcile much of the previously published evidence relating to the former extent of the last BIS and FIS. We first review the existing literature pertaining to the extent and demise of the northern sector of the last BIS. We then present virtually complete coverage of echosounder data from the continental shelf around the northern United Kingdom, held within the Olex database (www.olex.no). This phenomenal dataset allows an unprecedented view of the seafloor geomorphology, enabling some of the controversies outlined in our review to be resolved. Focusing principally on geomorphic evidence from the Hebrides Shelf, West Shetland Shelf and the North Sea Basin, we describe and interpret the morphology and distribution of many previously unreported glacial features. Based on these findings we propose a new, glaciologically plausible, reconstruction for the northern half of the last BIS, showing the extent and flow configuration of the ice sheet at Last Glacial Maximum and at two prominent stages during deglaciation. Finally, we discuss the causes of ice-sheet break up; the likely feedbacks within the ocean-cryosphere system; and the wider implications of our findings.

[FIGURE 1 HERE]

Terminology

This paper refers to the last ice-sheet glaciation to have affected the British Isles. Many onshore workers refer to this as the Late Devensian glaciation (UK) (e.g. Shotton, 1977; Sissons, 1980; Merritt et al., 1995; Ballantyne et al., 1998; Carr et al., 2006) or Late Weichselian glaciation (Norway) (e.g. Sejrup et al., 1994, 2003; 2005; Stalsberg et al., 2003; Ottesen et al., 2005); whilst most marine geologists use Marine Isotopic Stages to classify glacial events (i.e. MIS 2) (e.g. Stoker et al., 1993; Gatliff et al., 1994). Unfortunately, confusion still surrounds the use of the term 'Last Glacial Maximum (LGM)' when referring to the British Ice Sheet. The term LGM has been used by various workers to refer to two temporally distinct periods: 18-24 ka BP[1] (Boulton et al., 1991; Mix et al., 2001; Bowen et al., 2002) and 25-35 ka BP (Sejrup et al., 2005; Carr et al., 2006). This has led to debate over the exact timing of the Last Glacial Maximum in Britain, Ireland and western Scandinavia.

In this paper, to avoid confusion, we define the term 'LGM' with reference to the last global ice-sheet maximum, determined from sea-level records to have been between 30-22 ka BP – culminating c. 26 ka BP (Peltier and Fairbanks, 2006). With reference to the British Ice Sheet, the LGM encompasses the period of extensive shelf-wide glaciation identified by previous workers (e.g. Stoker et al., 1993; Sejrup et al., 1994, 2000, 2005; Knutz et al., 2001; Kroon et al., 2002; Peck et al., 2007). Although loosely defined chronologically, this period of maximum glaciation probably occurred between ~30-25 ka BP (i.e. during the earliest part of the Late Devensian (MIS 2) (Figure 2).

[FIGURE 2 HERE]

Footnote 1: unless otherwise stated, dates are expressed in calendar (sidereal) years (i.e. 18 ka BP = 18,000 years before present).

Record of glaciation

In this section we review the key morphological and chronological evidence for ice-sheet glaciation, both onshore and offshore northern Britain – providing a context in which to place our new observations. Dates are quoted in both radiocarbon years (^{14}C BP) and calibrated to calendar years before present (cal BP) where appropriate. Calibrations were performed using CALIB 5.0 (Stuiver et al., 2005) and Fairbanks et al. (2005).

Onset of glaciation

The record of ice rafting offshore northern Britain dates from the Late Pliocene (~2.5 Ma), although expansive glaciation of the continental shelf probably did not occur until the early Mid-Pleistocene, about 0.44 Ma (MIS 12) (Shackleton et al., 1984; Cameron et al., 1987; Stoker et al., 1994). In the central and northern North Sea Basin, and on the Hebrides and West Shetland shelves, seismic reflection profiles reveal stacked glacigenic sequences that imply recurrent glaciation of the continental shelf between MIS 12 and MIS 2 (Skinner and Gregory, 1983; Stoker et al., 1985, 1993, 1994; Cameron et al., 1987; Sejrup et al., 1987, 1991, 1994, 2000, 2005; Johnson et al., 1993; Gatliff et al., 1994; Holmes, 1997). This has resulted in a glacial succession that is locally several hundreds of metres thick.

Controversy surrounds the timing of onset of the 'Late Devensian glaciation' (MIS 2) in Britain. Traditionally the presence of ice-free conditions in Scotland during the Middle Devensian has been based on a handful of key sites. Organic lake sediments beneath a till at Tolsta Head in northern Lewis yielded a radiocarbon date of 27,333± 240 ^{14}C BP (Von Weymarn and Edwards, 1973); whilst organic deposits beneath till at Sourlie, near Glasgow, suggest that an ice-free, periglacial environment prevailed here at around the same time (29-33 ka ^{14}C BP = 34-38 ka cal BP) (Jardine et al., 1988). These two sites are often used to indicate that much of Scotland was ice free in MIS 3 (e.g. Gordon and Sutherland, 1993).

Based on numerous cosmogenic dates from Ireland, Bowen et al. (2002) speculate that the BIS had reached its maximum size by 37 ka BP, and in doing so challenged the validity of the radiocarbon dates from Sourlie and elsewhere. However, six AMS dates of between 34,480 and 28,050 ^{14}C BP on Carex fruit and Coleopteran fragments have been recently reported from Balglass, close to the southern end of the Loch Lomond basin (Brown et al., 2007). The presence of these glacitectonised organic deposits constrain the onset of the last regional glaciation in Scotland to c. 31.5 ka ^{14}C BP (36.5 ka cal BP), because they are located close to an important conduit of the last ice sheet and they occur between two distinct tills, the lower one being weathered. A detailed re-investigation of the fossil flora and fauna at Sourlie by Bos et al. (2004) produced four new conventional radiocarbon dates of between 33.3 and 29.3 ka ^{14}C BP, reinforcing the original findings of Jardine et al. (1988). Furthermore, a re-investigation of the organic horizon within the Tolsta Head deposits (Whittington and Hall, 2002) has yielded seven AMS dates spanning the period 31,700 ka to 26,150 ^{14}C BP (31-37 ka cal BP), similar in age to those from Balglass and Sourlie. On the basis of these results it is evident that much of Scotland was ice free towards the end of MIS 3, with build up of the last BIS occurring from 35-32 ka cal BP onwards.

It is worth noting that the presence of reindeer bones found in limestone caves near Inchnadamph and radiocarbon dated to between ~22-32 ka ^{14}C BP (c. 25-37 ka cal BP) suggest that the NW Highlands were substantially ice-free at this time (Lawson, 1984; Murray et al., 1993). However, these dates are likely to be anomalously young, as demonstrated by bone remains on carbonate geology elsewhere (Jacobi et al., 1998; Hedges and Millard, 1995). Furthermore, improved analytical techniques (ultrafiltration) have recently resulted in revised ^{14}C ages for Pleistocene faunal remains from the UK (Higham et al., 2006), casting further doubt on the radiocarbon ages of the Inchnadamph bones.

Offshore evidence

Key indicators of glacial activity on the UK continental shelf include several generations of tunnel valleys in the North Sea (Cameron et al., 1987; Wingfield, 1989, 1990; Ehlers and Wingfield, 1991; Huuse and Lykke-Andersen, 2000; Praeg, 2003; Lonergan et al., 2006), and moraines preserved to the NE and NW of Britain (e.g. Rokoengen et al., 1982; Stoker et al., 1985, 1993; Selby, 1989; Hall and Bent, 1990; Stoker and Holmes, 1991; Austin and Kroon, 1996). The continuation of these glacial sequences across the shelf edge to the north and west of Britain indicates that ice-marginal and proglacial processes have contributed to the growth of the slope aprons bordering the Hebrides and West Shetland shelves. This is expressed by the development of large trough-mouth fans, including the Barra-Donegal and Sula Sgeir Fans and the Rona and Foula Wedges (Stoker, 1995, 2002; Bulat and Long, 2001; Davison and Stoker, 2002; Holmes et al., 2003; Long et al., 2004) (Figures 1, 3).

[FIGURE 3 HERE]

The recognition of subglacial till in BGS borehole 77/2 in the Witch Ground Basin (Figure 1), dated at between 43 and 22 ka ^{14}C BP led Sejrup et al. (1994) to propose coalescence of the BIS and FIS during the interval 35-26 cal ka BP. A confluent BIS-FIS is also consistent with micromorphological studies that have recognised a much more extensive cover of subglacial till within the central and northern North Sea glacial succession (Carr et al., 2006). Graham et al. (2007) have recently reported unambiguous evidence for grounded ice crossing the northern North Sea Basin. From 3D seismic data, they identify highly elongate (up to 150:1) MSGLs – formed on top of the subglacial till unit described by Sejrup et al. (1994) in BGS borehole 77/2. The MSGLs are orientated NW–SE, and help define a palaeo-ice stream, at least 30 to 50 km wide and >90 km in length (the extent of the 3D image). Graham et al. (2007) refer to this as the Witch Ground palaeo-ice stream, and infer that it was sourced from the FIS overspilling the Norwegian Channel during the LGM (MIS 2).

A number of discrete overdeepened troughs have been identified crossing the Hebrides and West Shetland shelves, linking the Scottish hinterland to the adjacent continental slope (Stoker, 1990, 1995; Stoker et al., 1993). The location of these major cross-shelf troughs is marked by the landward indentation of the 100 m bathymetric contour. Significantly, each of these pathways links the Scottish hinterland to a specific trough-mouth fan on the adjacent continental slope (Figure 1). The best studied of these pathways links The Minch to the Sula Sgeir Fan. In total, this trough is about 200 km long, up to 50 km wide, and contains locally thick accumulations (50–150 m) of subglacial and proglacial sediments, including basal till, multiple ice-contact sequences, stratified proglacial outwash and glacimarine sediments (Stoker et al., 1994; Stoker and Bradwell, 2005). The occurrence of highly elongate (up to 70:1) MSGL, identified at several stratigraphic levels within the trough infill, has been cited as evidence of a palaeo-ice stream. This fast-flow corridor – The Minch palaeo-ice stream – was responsible for draining about 15 000 km^2 of the NW sector of the BIS and probably operated during several Mid- to Late Pleistocene glaciations, including the LGM (Stoker and Bradwell, 2005; Bradwell et al., 2007).

The Barra–Donegal Fan represents a major focus of glacial sediment (Knutz et al., 2001; Wilson et al., 2002), most probably fed by ice streams that periodically crossed the continental shelf, draining much of western Scotland and northwest Ireland. Ice-rafted debris recovered from the Barra Fan, sourced from British volcanic rocks, suggest extensive glaciation c. 45 ka BP prior to full glaciation c. 27 ka BP (Knutz et al., 2001; Peck et al., 2007). Further north, the Rona and Foula Wedges also represent trough-mouth fans probably fed by focused flow zones acting between northern mainland Scotland and Shetland during the LGM (Stoker et al., 1993; Davison, 2005).

Onshore evidence

Onshore landform evidence confirms that during the last ice-sheet glaciation several large fast-flow zones dominated the northern sector of the BIS. An ice stream sourced in the western Scottish Highlands stretched to the Moray Firth, invading the coastal lowlands of Moray, Banffshire and Buchan (Merritt et al., 2003). This same ice stream also flowed north-westwards across Caithness and Orkney (Hall and Bent, 1990), laying down shelly tills, and rafts of Mesozoic strata and Pleistocene marine sediment dredged up from the seafloor (Sutherland, 1984; Gordon and Sutherland, 1993). Shells, dated by AMS, from within the ice-stream till in northern Caithness indicate that it was laid down after 46 ka ^{14}C BP (Auton, 2003). The pronounced deflection of ice flow in the Moray Firth NW across Caithness was most likely caused by the presence of Scandinavian ice in the central North Sea (Peach and Horne, 1879; Sissons, 1967; Hall and Whittington, 1989; Sutherland, 1984). In NW Scotland a powerful ice stream sourced in the NW Highlands, Skye and Lewis flowed north along The Minch and then northwest onto the continental shelf (Stoker and Bradwell, 2005; Bradwell et al., 2007). An ice stream probably also occupied the Vale of Strathmore, Firth of Forth and adjoining lowlands, flowing broadly northeast towards the North Sea Basin (Golledge and Stoker, 2006). Other ice streams have been identified within the northern sector of the last British Ice Sheet: flowing northeast from the Cairngorms (Hall and Glasser, 2003) and along the Tweed Valley towards the North Sea (Clapperton, 1970; Everest et al., 2005).

Glacial evidence on Orkney and Shetland indicates that an ice sheet sourced in Scandinavia occupied the northern North Sea Basin. The presence of rare Norwegian erratics on Sanday (Orkney), Fair Isle and on southernmost Shetland has long been taken as evidence that a far-travelled ice sheet crossed these islands (Peach and Horne, 1879, 1880; Finlay, 1926; Birnie et al., 1993). Ice-flow indicators on Orkney, most notably striae and ice-directional bedforms, clearly suggest the passage of a powerful ice sheet in a west-northwesterly direction, even on the northernmost islands (Peach and Horne, 1880, 1983; Wilson et al., 1935; Rae, 1976). The presence, on Fair Isle, of large-scale bedrock grooves and streamlined forms trending in the same orientation (WNW) is key, as this island has not been affected by glaciers since the LGM (Mykura, 1976). This evidence is incompatible with the deflection of British ice from the Moray Firth on glaciological grounds, but is entirely consistent with glacial overriding from the southeast by a coalescent BIS-FIS. Although most workers have accepted that this ice-sheet configuration existed (e.g. Wilson et al., 1935; Boulton et al., 1977, 2002; Flinn, 1978; Sutherland, 1984; Sejrup et al., 1994; Carr et al., 2006), some have argued that it predated the LGM (Sutherland, 1984; Bowen, 1989; Bowen et al., 2002; Hall et al., 2003). Much of this debate rests on the evidence for a local Shetland ice cap, thought by many to equate to the LGM. However, there is no reason why the presence of a locally nourished ice cap on Shetland is incompatible with the islands being overwhelmed by an ice sheet during the early part of the same glaciation, as has previously been suggested (e.g. Flinn, 1978; Stoker et al., 1993; Ross, 1996; Carr et al., 2006; Golledge et al., 2008).

Extent of glaciation

The maximum extent of the last ice sheet to cover northern Britain is currently poorly defined (Clark et al., 2004; Evans et al., 2005). The most comprehensive attempts at ice-sheet reconstruction on the continental shelf, based on offshore stratigraphy and geomorphology, are those of Stoker et al. (1993, 1994) and Hall et al. (2003). These reconstructions incorporate geomorphological indicators – end moraines – preserved on the Hebrides and West Shetland shelves (Figure 1) (Selby, 1989; Stoker and Holmes, 1991), and suggest an expansive LGM, reaching the continental-shelf edge in most places except, perhaps, on the northern Hebrides Shelf. Here the presence of undisturbed glacimarine deposits on the outer shelf, with Amino-acid ratios typical of MIS 4 (Stoker et al., 1993), suggests that the grounded ice-sheet limit was on the mid-shelf during LGM (Stoker and Bradwell, 2005). However, the reliability and precision of this dating technique has been seriously questioned (McCarroll, 2002). Expansive glaciation across the southern Hebrides Shelf is supported by increased sedimentation on the Barra Fan in MIS3 (Kroon et al., 2000; Knutz et al., 2001, 2002; Wilson et al., 2002), followed by a major increase c. 26 ka BP (Peck et al., 2007) associated with widespread shelf-edge glaciation at LGM. Other published reconstructions and models, which propose that the last ice sheet terminated only a short distance offshore at its maximum, are therefore probably too conservative (e.g. Sutherland, 1984; Bowen et al., 1986, 2002; Lambeck, 1993, 1995; Ballantyne et al., 1998; Stone et al., 1998).

Prior to 1980, textbook reconstructions showed the FIS crossing Shetland during the last glaciation and deflecting the BIS northwest across Orkney (e.g. Sissons, 1976; Boulton et al., 1977). However, oil-related exploration of the central North Sea Basin in the 1970s and 1980s revealed an apparent absence of Late Devensian/Late Weichselian tills (e.g. Cameron et al., 1987). This led to Sutherland's (1984) reconstruction of an independent BIS of restricted size terminating at the Wee Bankie and Bosies Bank moraines off eastern Scotland and on Lewis, NW of the Scottish mainland (Figure 1). Radiocarbon dates between 21.7 ka and 17.7 ka ^{14}C BP, obtained from lignitised wood sampled from glacimarine deposits adjacent to the eastern margin of the Wee Bankie moraine (Holmes, 1977), have traditionally formed the basis for interpreting these moraines as the maximum eastern limit of the last BIS, at around 18-22 ka BP (Sutherland, 1984; Boulton et al., 1985, 1991, 2002; Cameron et al., 1987; Hall and Bent, 1990; Lambeck, 1991; Bowen et al., 2002; Clark et al., 2004). However, such a limit fails to reconcile the occurrence of subglacial tunnel valleys largely formed during the Late Devensian (MIS 2), located east of these moraines (Wingfield, 1989; Ehlers and Wingfield, 1991; Lonergan et al., 2006). Many of the tunnel valleys remain exposed at the present-day sea bed (e.g. Devil's Hole Deeps and Fladen Deeps (Figure 1) and, hence, must have formed before ice retreated to the Wee Bankie and Bosies Bank moraines.

Unglaciated enclaves such as those proposed by Sutherland (1984) in Caithness and Buchan have subsequently appeared on many published reconstructions of the northern sector of the last BIS (e.g. Bowen et al., 1986; Nesje and Sejrup, 1988; Lambeck, 1993, 1995; Bowen et al., 2002), some long after Sutherland's evidence had been seriously questioned by Peacock (1985), and then refuted by Stoker et al. (1993), Merritt et al. (2003) and Hall et al. (2003).

Controversy also surrounds the vertical extent and thickness of the last BIS. Although high-level trimline evidence from mountains has been used to reconstruct the ice-sheet surface in NW Scotland (Ballantyne et al., 1998), the validity of trimlines as ice-sheet surface indicators has been seriously questioned (Fabel et al., 2002; Boulton and Hagdorn, 2006; Shennan et al., 2006; Kleman and Glasser, 2007). Cosmogenic-isotope analyses by Stone et al. (1998) were unable to determine whether mountain summits in NW Scotland were buried beneath non-erosive cold-based ice or if they had experienced long subaerial exposure histories. It is therefore uncertain whether ice-free areas existed in Scotland during the LGM, when the ice sheet terminated on the continental shelf.

Evidence of glacial activity directly attributed to the FIS is preserved in the northeastern part of the North Sea, where the Tampen Ridge (Figure 1) is interpreted as a lateral moraine associated with the western flank of the Norwegian Channel palaeo-ice stream. This moraine has been attributed to a minor readvance of the ice margin on the flank of the Norwegian Channel (Sejrup et al., 1994, 2000). Radiocarbon dates from shells indicate a maximum age of 18.86 ±2.6 ka ^{14}C BP for the moraine (Rokoengen et al., 1982).

Palaeo-ice streams that link the source regions of the BIS to the continental shelf and slope are recognised both east and west of Scotland (Clapperton, 1970; Everest et al., 2005; Stoker and Bradwell, 2005; Golledge and Stoker, 2006). Palaeo-ice stream bedforms have strong morphological expression on the extant landsurface and sea bed, suggesting that these ice streams probably operated during deglaciation of the last BIS. Significant dates and other key elements relating to deglaciation of the northern sector of the last BIS are summarised below.

A sequence of glacimarine sediments overlies the MSGL surface in the Witch Ground Basin, dated at between ~22 and 13 ka ^{14}C BP (Sejrup et al., 1994; Graham et al., 2007). These sediments record repeated iceberg scouring, which has been taken to indicate the presence of a marine embayment – an ice-free enclave – within the central and northern North Sea from about 22 ka ^{14}C BP (~26 ka cal BP) onwards. It has been suggested that the Wee Bankie and Bosies Bank moraines were formed in this deglacial phase (Carr et al., 2006). Sporadic readjustments of the receding ice margin offshore NE Scotland may have resulted in readvances, between about 18 and 16 ka ^{14}C BP (Merritt et al., 2003), correlated with the Tampen Readvance in the NE North Sea (~20 ka cal BP; Sejrup et al., 1994, 2000) and possibly the Dimlington Stadial advance in eastern England (Rose, 1985; Wintle and Catt, 1985). However, the preservation of shoreline fragments, such as the Main Perth Shoreline, and the occurrence of shelly glacimarine sediment overlying till in NE Scotland indicate that the adjacent coastal area may have been largely ice free by 15–16 ka ^{14}C BP (Cullingford and Smith, 1980; Armstrong et al., 1985; Hall and Jarvis, 1989), although this is still debated (cf. McCabe et al. 2007; Peacock et al., 2007). Offshore SW Norway, the Norwegian Channel was deglaciated by about 15.1 ka ^{14}C BP (~18 ka cal BP)(Lehmann et al., 1991).

North of Shetland, shell fragments from a diamicton (probably till), equivalent in stratigraphic status to the large sea-floor moraines west of Shetland (Figure 1), date from 17.8 ka ^{14}C BP (~21 ka cal BP)(Ross, 1996); whereas the earliest organic deposits (overlying till) on Shetland date from 13 ka ^{14}C BP or a little earlier (Hoppe, 1974; Birnie et al., 1993). On the southern Hebrides Shelf, the formation of the St Kilda moraine banks is dated to between 22.48 and 15.65 ka ^{14}C BP (Selby, 1989; Austin and Kroon, 1996). In The Minch region, recently performed cosmogenic ^{10}Be analyses of glacially deposited boulders on the east coast of Harris yield exposure ages of 15.4 to 17.6 ka cal BP (Stone and Ballantyne, 2006). Cosmogenic ^{10}Be analyses of boulders on an ice-sheet moraine in Gairloch, Wester Ross (Figure 1), yield a comparable age (15-17 ka cal BP: Everest et al., 2006). These data, combined with environmental information from marine fauna in borehole 78/4 east of Lewis (Graham et al., 1990) (Figure 2) and from several short cores south and west of St Kilda (Austin and Kroon, 1996) indicate open marine conditions from >12,785 ka ^{14}C BP (c.15 ka cal BP) in The Minch and from >13.5 ka ^{14}C BP around St Kilda. These dates provide minimum ages for deglaciation of the continental shelf off northern Britain. By 15 ka cal BP arctic open-water conditions existed on the continental shelf when the ice-sheet margin was situated at, or close to, the present-day coastline of NW Scotland (Everest et al., 2006; Stoker et al., 2006; Stone and Ballantyne, 2006).

Following LGM it is thought that the eastern margin of the last ice sheet retreated slowly in a cold climate, owing to precipitation starvation (Sutherland, 1984). Dates from eastern Scotland suggest that the ice-sheet margin had retreated to the present-day coastline in Buchan by about 18 ka cal BP (Peacock and Merritt, 2000; Merritt et al., 2003). During deglaciation a number of prominent push moraines were formed including one at Ardersier, near Inverness, probably dating from c. 15 ka cal BP (Merritt et al., 1995). This event has been tentatively correlated with the Killard Point Readvance in Ireland, which in turn has been linked with the North Atlantic iceberg-discharge event Heinrich-1 (McCabe et al., 1998, 2005). Deglaciation of the west coast of Scotland was also punctuated by a series of ice-marginal stillstands or oscillations. The Wester Ross Readvance, dated to c.15-17 ka cal BP, may have also been in response to wider events in the North Atlantic (i.e. Heinrich-1) (Everest et al., 2006).

Data Compilation and Methods

This section outlines the datasets and techniques used to elucidate the geomorphology of the UK continental shelf (Figures 4, 5).

[FIGURE 4 HERE]

Offshore data

The marine dataset (Figure 4) is part of the Olex bathymetric database compiled, processed and managed by the Norwegian company Olex AS (www.olex.no). The sea-bed image is based upon echosounder data acquired mainly by commercial fishing vessels, but also including data from research vessels. The datasets are contributed voluntarily, the data is then individually merged with the central dataset, after which the contributor has access to all of the shared bathymetry. The data are located by global positioning systems (GPS) and the positional error is generally less than 10 m. The database represents the earth's surface as a series of 5 x 5 m cells. Vertical resolution is 1 m in water depths >100 m and 0.1 m at depths <100 m. Horizontal datum is WGS84; vertical reference is equinoctial spring low water from predicted tides. The speed of sound in water is harmonised to 1500 ms^{-1}. This means that relative depths are highly accurate with an error range of only 1-2%. The density of soundings depends on instrumental output rates; ideally systems record one sounding for every echosounder value. Depth position is adjusted for installation offsets and timing between the echosounder and the GPS. The strength of the Olex system lies in the integration of data contributed by a number of users over several years. Any depth errors are minimised during database compilation and processing by comparing an individual contributor with the large number of other soundings covering the same area. The resultant bathymetric surface can be viewed as 2D contours, 2D shaded relief, 3D views or as 2D profiles. A 2D shaded relief map, with illumination from the north, is shown in Figure 4.

Onshore data

The onshore topography (Figure 4) is from NEXTMap Britain (Intermap Technologies, 2003). Heights are acquired from an aircraft using interferometric synthetic aperture radar (IFSAR) with a vertical resolution of +/- 1 m (95%) and a grid cell size of 5 m. Artefacts in areas of steep slopes are possible where the data are degraded either by the rate of change in elevation or by 'shadows' on the far side of a positive object or on the nearside of a steep depression. The dataset is provided in UK Ordnance Survey GB36 projection (as derived from OSTN97) and referenced to Ordnance Datum. The surface model is not vertically exaggerated but is illuminated from the NW at an angle of 45^o to highlight the relief.

Methods

The processed echosounder data were georectified and merged in a geospatial database, from which a sea-bed surface model was generated (Figure 4). The use of three-dimensional vector data allowed surface models to be illuminated and viewed from any angle (using Olex or ESRI software) thus enabling clear, accurate identification of sea-bed morphology. All positive and negative, linear, bathymetric features within the offshore area (Figure 1) were digitized on screen in ArcGIS 9.0

(ESRI). Onshore landforms were not digitized. The data capture method used is similar to that outlined by Stokes and Clark (2003) and Golledge and Stoker (2006). To overcome problems of azimuth bias, identified by Smith and Clark (2005), digital surface models were illuminated first from the northeast and then from the northwest. Digitizing scales varied between 1:50,000 and 1:200,000. Landform dimensions, such as length, height and width were measured digitally within the GIS. The final dataset was output in map format at A0 size, whereby some generalization was made for cartographic clarity (Figure 5).

[FIGURE 5 HERE]

Results

Here we describe the morphology and spatial distribution of sea-bed landforms imaged in the bathymetric Olex dataset (Figure 4). Relevant geographical information is shown in Figure 1.

The continental shelf around the UK is presently less than 160 m below sea level, with the exception of isolated deeps that incise to depths locally in excess of 200 m (Figure 1). The Witch Ground Basin and the Norwegian Channel are the most notable large bathymetric depressions on the continental shelf between Britain and Norway reaching depths of 155 and 415 m respectively. The shelf break to the north and west of Britain generally occurs around 200 m below present-day sea level and slopes at between 1 and 6 degrees (Figure 1).

The Olex data reveal channels and ridges across the majority of the sea bed around northern Britain, in particular: around St Kilda; west of Orkney and Shetland; in the Moray Firth; offshore Strathmore; and flanking the western margin of the Norwegian Channel. By contrast, the Witch Ground Basin in the northern North Sea is largely devoid of landforms. Systematic analysis of the Olex dataset has resulted in over 700 individual landform elements being digitised in a GIS:– 174 negative linear topographic features (channels) and 537 positive linear topographic features (ridges) (Figure 5).

Channels

The digitised negative features fall broadly into two groups: A) a north to northwest-trending population widely distributed across the northern North Sea Basin; B) and a second set that lie close to the present coastline of eastern Scotland (Figure 5).

Group A comprises 67 channels ranging from 3 to 50 km in length. The channels have a strongly consistent orientation, trending north to northwest, and are relatively evenly spaced across a zone about 300 km west to east and 450 km from north to south. The majority of the channels occur around the northern margin of the Witch Ground Basin; whilst others are located on the southern edge of the basin; and west of the Norwegian Channel (Figure 3). This group of major channels includes the Fladen Deeps (Figure 1) which are cut up to 280 m below sea level, with individual channels up to 4.5 km in width (Andrews et al., 1990; Johnson et al., 1993) (Figure 6).

[FIGURE 6 HERE]

Group B consists of two main sets of channels in geographically separate areas. The first set of 26 channels flanking the east coast of mainland Scotland, trend NNE roughly parallel to the present coastline. These features range in length from 2 to 30 km, are relatively evenly spaced, and incise an area 40 x 65 km. The channels are cut up to 120 m below sea level and range from 1.5 to 3 km wide (Thomson and Eden, 1977; Golledge and Stoker, 2006). Many have branching, sinuous courses. The second set of 60 channels, occur in the outer Moray Firth and are tightly grouped in an area covering 60 x 65 km. They trend broadly west to east and range in length from 1.5 to 58 km. Many have branching, sinuous courses. Approximately three quarters of the channels are greater than 10 km in length. The longest of these, the Southern Trench (Figure 1), is 40 km long has a maximum width of 9 km and is locally up to 200 m deep (Andrews et al., 1990). Numerous other isolated channels, with similar dimensions to those above, occur on the mid-shelf west of Shetland and in the Fair Isle Channel.

In both of these groups, thalwegs do not exhibit consistent downstream deepening but undulate along the length of the channel (Figure 6). Most channels in the northern North Sea Basin begin or terminate abruptly; many possess branching tributaries. It should also be noted that whereas these channels retain bathymetric expression, due to only partial sediment infill, they form part of a more extensive system of north to northwest-trending channels in the central and northern North Sea Basin that have been subsequently buried by sediment (Stoker et al., 1985; Gatliff et al., 1994; Praeg, 2003; Fitch et al., 2005; Lonergan et al., 2006). Whether open or infilled, the bases of all these channels generally lie between 50 and 100 m below the surrounding sea bed. Consequently, the area of the North Sea Basin dissected by large-scale channels is much greater than shown by the Olex data alone.

Ridges

Over 500 crestlines were digitised from the Olex dataset. These are broadly divided into three groups based on geographical setting (Figure 5).

Group 1: This group comprises the westernmost landforms, occurring on the outermost shelf. They are large, curvilinear, gently arcuate ridges, concave to the east, trending approximately northeast-southwest. Most are broad features, 2 to 10 km wide, with moderately well-defined seabed expression. The two longest of these ridges run unbroken for over 60 km; between St Kilda and the Flannan Isles, and close to the shelf break west of Shetland (Figure 5). Previously, some of these broad ridges have been mapped from seismic profiles as shelf-edge ice-sheet moraines (Stoker et al., 1993; Stoker and Holmes, 1991) (Figures 1, 3).

Group 2: This group comprises the mid-shelf ridges to the north and west of Scotland. Most of these are large, strongly arcuate ridges, with well-defined expression. These ridges can be further subdivided based on location: (a) those west of Orkney and Shetland; (b) those north and east of Shetland; (c) those around St Kilda. A further subset of more-linear Group 2 ridges occurs adjacent to the eastern margin of the Norwegian Channel.

[FIGURE 7 HERE]

Those ridges on the mid-shelf, west of Orkney and Shetland are typically 10 to 100 km in length, and often occur as nested, lobate forms. The striking pattern of ridges, NW of Orkney is strongly concentric from west to east (Figure 7). Here, up to 10 large nested ridges occur within a horizontal distance of 60 km. The outer ridges are broad features, up to 6 km wide and 50 m high, some display pronounced crenulate or zig-zag morphologies. Many of the ridges show overprinting patterns. The innermost ridge is a delicate sharply defined feature, <1 km wide, with simple arcuate plan form. This innermost ridge forms a remarkable unbroken loop ~70 km in length. Further south, due west of Orkney, numerous large curvilinear ridges trend perpendicular to the coastline of mainland Scotland. Here too, overprinting can be seen between these ridges and those to the north. Further north, due west of Shetland (Figure 8), numerous ridges form a separate set of sub-concentric nested arcs and loops. Overprinting of one ridge on another can be clearly seen in places, particularly on the sea bed NW of Foula. The innermost mid-shelf ridges west of Shetland are approximately parallel to the present-day coastline.

The greatest concentration of large ridges on the UK continental shelf occurs north and east of Shetland (Figures 4, 5, 8). The northernmost ridges have irregular outlines with highly crenulated, distinctly lobate form. The largest of these extends for 30 km, is between 1 and 3 km wide, and locally exceeds 30 m in height. The nested pattern of these lobate ridges follows a broadly north-south axis. Overprinting of ridges on one another can be clearly seen.

Two morphologically similar mid-shelf ridges occur on the seabed southwest of St Kilda on the Hebrides Shelf (Figure 5). These large features are 30 to 40 km in length and 2 to 5 km wide. Like those west of Orkney and Shetland they have pronounced lobate and crenulated plan form, and are concave towards the east.

A further set of curvilinear, subparallel Group 2 ridges flank the western margin of the Norwegian Channel trending approximately southeast-northwest. This high-density cluster of ridges lies on the relatively flat sea-bed high west of the Norwegian Channel and east of Shetland (Figure 5). The ridges range in length from 2 to 55 km, and occur within a broad zone c. 600 km long and c. 100 km wide. The majority have subtle sea-bed expression; many are less than 10 m high. Individual ridges are linear or curvilinear in plan. To the north, a well-defined and distinct linear ridge occurs along the Norwegian Channel margin – it has been mapped previously as the Tampen Ridge (Figure 1) (Sejrup et al., 1994) and is formed of a stratigraphic unit 50 m thick and up to 7 km wide. This ridge can be traced for ~200 km along the western edge of the Norwegian Channel (Figure 5).

Group 3: The final group of ridges are those on the inner shelf, closer to the present day coastline of Scotland, generally east of Groups 1 and 2. These smaller-scale features range in length from 500 m to 25 km and are typically <500 m wide and <20 m high. They are widely geographically distributed and many occur as concentrations of closely spaced ridges (Figure 5).

Immediately east of Shetland, numerous closely spaced linear and curvilinear ridges occur, trending NW-SE. These features are generally concave towards the south, and are best preserved within a topographic sea-bed trough, although many extend beyond its lateral margins (Figure 8). Some of the landforms within the trough have clearly visible zigzag morphologies whilst others are more linear. Crestline orientations are strongly oblique to the trough margins and cut across topographic undulations. The ridges range in length from 1 to 20 km, and exhibit intra-ridge spacings of 700 to 2000 m. Most ridges are well-defined features with vertical sea bed expression of between 10 and 20 m.

[FIGURE 8 HERE]

Southeast of Shetland few clear landforms are resolved on the Olex sea-bed image. However, a cluster of subparallel linear ridges occur around 1°E, 59°N. These features range from 1.5 to 20 km in length, have heights generally <10 m, widths <100 m, and exhibit consistent spacing distances of 2.5 to 3 km. Within this population there are also shorter, WNW-ESE-trending linear ridges 1.5 to 6 km in length (Figure 3).

Northeast of Orkney is a cluster of short ridges, 800 m to 6 km in length, aligned WSW-ENE. As with those east of Shetland, these 1 to 2 km-spaced ridges occur within a topographic trough, but are aligned oblique to its margins (Figure 3).

In the generally flat ground northeast of the Moray Firth and northwest of the Witch Ground Basin, a spatially distributed population of nearly 100 ridges is mapped. Most are aligned generally northwest-southeast, are curvilinear in plan and less than 10 m in height. These ridges range in length from 1 to 35 km (Figure 5), with the exception of the large, arcuate, outermost ridge in this group which can be traced for 65 km.

Other well-defined small-scale Group 3 ridges occur in coastal parts of The Minch, off NW Scotland; adjacent to western Orkney; and in the Fair Isle Channel (Figure 3). These features are considerably smaller than the ridges seen on the mid- and outer shelf, being less than 10 m high and <1000 m wide. They typically range from 5 to 20 km in length and generally occur within ~50 km of the present-day coastline. The features in The Minch and adjacent to Orkney are broadly parallel to the coastline, whereas some of the ridges off the east coast of Shetland are perpendicular to the coast. An assemblage of small, sharply defined, subparallel ridges occur in the Fair Isle Channel. They are distinctive linear features, less than 10 m high, extending over 30-40 km and trending NNE-SSW (Figure 8).

Finally it should be noted that large parts of the seabed with good echosounder coverage have a poor landform record. Most notably, parts of the shelf north of Orkney and southwest of Shetland; the inner shelf immediately west of Lewis; the shelf to the southwest of Barra; and the central core of the Witch Ground Basin. With the exception of the Witch Ground Basin, which is underlain by thick Quaternary sediment (Long et al., 1986), the absence of landforms is probably related to the presence of crystalline bedrock at seabed in these areas (Johnson et al., 1993; Stoker et al., 1993).

Landform interpretation

Sea-bed mapping based on the Olex dataset reveals over 700 geomorphological features relating to glaciation of the continental shelf around the northern UK (Figures 4, 5). We interpret these features by comparison with glacial landsystems described elsewhere (e.g. Evans, 2003), coupled with inferences from existing seismostratigraphic data within the study area (e.g. Stoker and Holmes, 1991; Davison, 2005; Sejrup et al., 2005). On the basis of their morphology, distribution and setting we interpret the vast majority of positive linear features as end moraines marking the margins of former ice masses. Whilst some of the smaller near-shore features (Group 3) are distinctly straight, the majority of mapped moraines are arcuate, lobate or curvilinear in form (Groups 1 and 2) – typical of features formed at grounded terrestrial ice margins (e.g. Benn and Evans, 1998; Colgan et al., 2003). Most studies agree that end moraine morphology closely reflects the geometry and position of former ice margins. Consequently, their distribution, orientation and size are commonly used in glaciological inversion models to reconstruct the decay dynamics of former ice sheets and glaciers (e.g. Kleman et al., 1997; Clark et al., 2004).

The population of straight, sub-parallel, sharp-crested ridges identified in the vicinity of Orkney and Shetland, by contrast, more closely resemble moraines formed at the subaqueous grounding line of a marine-terminating ice-sheet margin, and consequently are interpreted as De Geer-type moraines (e.g. Sollid, 1989; Larsen et al., 1991; Blake, 2000; Linden and Moller, 2005).

We interpret the negative linear features on the sea-bed as glacial meltwater channels, largely on the basis of their morphology (Figure 3). Many of these landforms have been previously described as tunnel valleys by numerous authors (e.g. Wingfield, 1990; Praeg, 2003; Lonergan et al., 2006). Although the exact mechanism of tunnel valley formation is still debated, there is general agreement that these major erosional features are formed by subglacial meltwater flowing more-or-less parallel to former ice flow (Ó Cofaigh, 1996). There is also evidence to suggest that the features in the central North Sea Basin were repeatedly occupied (Lonergan et al., 2006).

On the basis of the geomorphology and distribution of the features, described above, we have grouped the mapped features into three main assemblages. Assemblage 1 includes the large, broadly curvilinear moraines on the shelf edge (Group 1), and the tunnel valleys (Group A) in the northern North Sea Basin that trend broadly perpendicular to these moraines. Assemblage 2 comprises the strongly arcuate, lobate, and often convolute, Group 2 moraines found on the mid-shelf. Assemblage 3 includes the Group 3 moraines and Group B channels on the inner shelf, principally east and north of the Scotland. We now interpret each of these 3 assemblages in turn, with reference to the last British and Fennoscandian ice sheets.

Assemblage 1: The major moraines on the northwestern UK continental shelf margin represent substantial volumes of Pleistocene sediment relating to former, coherent, shelf-wide ice-sheet glaciation. These moraines occur in direct association with major shelf-edge fans such as the Sula Sgeir Fan, the Rona and Foula Wedges and the Barra-Donegal Fan – themselves representing large volumes of sediment deposited over a prolonged period (Stoker et al., 1993) (Figures 1, 3). We believe that this coupling of shelf-edge moraines and trough-mouth fans is best interpreted as reflecting the position of a formerly extensive continental ice sheet with overall flow towards the Atlantic Ocean in the west and northwest of the study area. This geometry is consistent with orientations of tunnel valleys and buried mega-scale glacial lineations (MSGLs), identified in the North Sea Basin by Graham et al. (2007). When used as the basis for a glaciological inversion model, these three components – moraines, tunnel valleys, and MSGLs – strongly suggest, at maximum stage, an ice-sheet surface across the northern North Sea Basin declining in altitude from southeast to northwest. By implication, the former BIS and FIS must have been confluent at this time.

Assemblage 2: The mid-shelf moraines on the West Shetland Shelf and those NE of Shetland must have formed after the extensive shelf-edge glaciation described above, most probably during a significant retreat stage. By this time the ice sheet had receded and thinned sufficiently to allow topography to influence ice-flow somewhat. It is notable that there are very few moraines of this stage on the low-lying shelf northwest of the Witch Ground Basin. The mid-shelf moraines to the west of Orkney and Shetland are lobate and highly convolute in morphology; many are strongly reminiscent of push moraines and thrust-block complexes formed at the margins of modern surging glaciers (Figure 7) (e.g. Clayton et al., 1985; Evans et al., 1999; Evans and Rea, 2003). Although their exact genesis cannot be determined at this point in time, the large number and density of these features shows that dynamically oscillating lobes were common within the last BIS. Importantly, the lobate margins defined by these moraines show that the ice-sheet terminus was grounded, highly irregular and quite different to the form of the terminus represented by the older, curvilinear, shelf-edge moraines (Figures 2 & 6). The lobate, bifurcating, overprinting nature of these younger moraines indicates that ice-marginal oscillations were a feature of mid-shelf deglaciation. This assertion is confirmed by seismic profiles showing considerable readvances during overall recession within the moraine sequence NW of Orkney (Figure 6) (Stoker and Holmes, 1991). The convolute, often zigzag, form of these moraines is intriguing and may reflect marginal flow variations or the outline of highly crevassed palaeo-ice margins. Significantly, the vast majority of the moraines in Assemblage 2 are concave towards the UK landmass, even east of Shetland, suggesting that, by this stage, the influence of Scandinavian ice on the overall geometry of the BIS was considerably diminished. At this time an ice sheet appears to have occupied the ground north and west of the Witch Ground Basin and a separate ice sheet still occupied the Norwegian Channel and its western margin. However, the lowest part of the northern North Sea Basin, between the retreating BIS and FIS, was probably an ice-free marine embayment.

Assemblage 3: The third assemblage of landforms include generally smaller-scale near-shore moraines and meltwater channels that vary in alignment in different areas – compare the moraines and channels adjacent to the Moray Firth and Strathmore coasts, for example (Figures 1 & 3). The largest features – the Bosies Bank and Wee Bankie moraine complexes – are perhaps the earliest moraines of this stage, marking the transition into a more stable phase of deglaciation from the dynamically oscillating behaviour immediately preceding it. During this period the Witch Ground Basin was ice free and is known to have begun accumulating glaciomarine muds (c. 22-19 ka ^{14}C BP) (Gatliff et al., 1994; Sejrup et al., 1994; 2004; Graham et al., 2007). On the basis of highly elongate landforms in NW Scotland and Strathmore, on land and on the seabed, and the deep channels at the mouth of the Moray Firth, it is likely that ice streams were still active within the BIS at this time (Merritt et al., 1995; Stoker and Bradwell, 2005; Golledge and Stoker, 2006). These fast-flowing outlets may have been prone to periods of flow instability – as highlighted by Merritt et al. (1995) in the Moray Firth region. Ice streaming was probably highly effective at discharging mass from the centres of ice sheet accumulation and therefore strongly conditioned recession of the BIS during this time.

To summarise, we interpret the sea-bed landforms on the UK continental shelf to show a complex pattern of ice-sheet deglaciation. Extensive shelf-edge glaciation occurred first, at LGM, characterised by confluence of the British and Fennoscandian Ice Sheets. This coalescent ice sheet flowed broadly northwestwards across the northern North Sea transporting vast volumes of sediment to the continental slope, forming prominent moraines and shelf-edge fans. Subsequent oscillatory retreat of both ice sheets led to separation and the re-establishment of ice-free marine conditions in the North Sea Basin. At this time, the BIS margin was probably highly irregular – dominated by numerous, large, dynamic lobes. Final-stage deglaciation of the independent BIS was marked by near-shore ice streaming and increasing topographic control on ice-flow directions.

Discussion

Our results show that the glacial geomorphology on the sea bed around the northern United Kingdom preserves the footprint of a retreating ice sheet that significantly re-organised during its decay. Whilst each of the three stages identified in this study have been broadly suggested by previous workers (e.g. Boulton et al., 1977; Sejrup et al., 1994, 2005, Carr et al., 2006; Graham, 2007), no investigations to date have explicitly attempted to unravel the complexities inherent in such an ice-sheet retreat pattern. Specifically, no-one has yet identified the zone of confluence at ice-sheet maximum, or the zone of pull-apart where the British and Fennoscandian ice sheets separated, or the mechanism by which this happened. We believe that the Olex dataset provides the best empirical evidence for ice-sheet confluence and subsequent separation and, critically, enables a viable hypothesis of British Ice Sheet disintegration to be proposed for the first time.

The bathymetric data show a broad, weakly sinuous depression extending north from the Witch Ground Basin to the continental shelf margin east of Shetland (Figure 6). The relative absence of moraines in this area, together with the bifurcating pattern of retreat inferred from moraines to the east and west of this broad depression, suggest that this zone may have been the focus for ice-sheet separation. The present bathymetry indicates that the seafloor in this area would have been only 10-30 m below sea level during the last global sea-level minimum (at LGM). The conjoined BIS-FIS was probably sufficiently thick during early deglaciation to have been grounded in this area, despite some possible tidewater calving. However, as deglaciation proceeded, we propose that the interplay between sea-level and the ice-sheet margin along this corridor would have been crucial.

[FIGURE 9 HERE]

Calving is known to be responsible for the majority of mass loss in contemporary ice sheets (Reeh, 1968; Paterson, 1994), and so was probably equally important in palaeo-ice sheets such as the BIS-FIS. Floating ice is considerably more vulnerable to rapid collapse than grounded ice, since the highly viscous nature of ice means that stresses are transmitted throughout an ice shelf almost instantly. 'Debuttressing' occurs when ice shelves calve resulting in an acceleration of grounded ice flow and an increase in ice supply to the calving front, consequently leading to further mass loss (e.g. Mercer, 1978; Paterson, 1994; Alley et al., 2005).

In light of the above, it is evident that if calving were to initiate along a sector of the margin of the former BIS-FIS, significant mass might be drawn-down from the interior of the ice sheet in the North Sea Basin. Overall surface lowering would be greatest nearer to the calving front, with lesser effects in grounded ice away from the margins. Initial calving may have been triggered by glacio-isostatic depression that produced rising relative sea levels in the period after the maximal ice volume occurred (cf. P.U. Clark et al., 2004). We suggest that, an initially small calving sector of the confluent BIS-FIS margin propagated southward, governed by the greater water depths east of Shetland and in the Witch Ground Basin, leading to the development of a large calving bay in the northern North Sea Basin (Figure 9). Rapid recession forced both grounded ice masses to re-organise, as surface lowering close to the calving bay led to a change in overall surface slope of the BIS. Changing flow directions as a result of this ice sheet re-organisation probably led to the formation of well-developed moraines north and east of Shetland. That this period of re-organisation is preserved in the geomorphic record as large, lobate, readvance moraines may suggest that the readjusting ice sheet was in a state of considerable disequilibrium. It was also during this episode that the De Geer moraines around Orkney and Shetland were formed – indicative of a tidewater margin. Final separation of the ice sheets occurred when sea levels had risen sufficiently to inundate the Witch Ground Basin, causing glaciomarine deposition. The subsequent marginal retreat of the British Ice Sheet may have been relatively rapid – dominated in eastern Scotland by ice stream activity in the Moray Firth, the Firth of Forth and Strathmore.

We have proposed a new model for the geometry of the confluent BIS-FIS at its maximum. We have also described the subsequent ice-sheet separation, reconfiguration and demise based on entirely new empirical evidence (Figures 4, 5). The validity of this hypothesis can be evaluated by comparison with other global accounts of ice sheet demise. The Laurentide Ice Sheet has been investigated extensively, and the repeated delivery of ice from its interior to its calving bays – via 'Binge-Purge' cycles – is now widely accepted (Heinrich, 1988; MacAyeal, 1993; Andrews and Maclean, 2003). Indeed, calving bays along the eastern Laurentide Ice Sheet margin are thought to have been instrumental in its eventual disintegration (Hughes et al., 1977; Thomas, 1977; Hughes, 2002; Shaw et al., 2006). Similar mechanisms have been proposed for the Fennoscandian Ice Sheet (Hoppe, 1948) and for the Barents Sea Ice Sheet (Siegert et al., 2002). Modern analogues also exist: the Larsen B Ice Shelf in West Antarctica collapsed rapidly in 2002 leading to the development of a large calving bay and changing the flow dynamics of the surrounding glaciers (Rack and Rott, 2004; Scambos et al., 2004). The fast-flowing Pine Island and Thwaites Glaciers on the Amundsen Coast of West Antarctica are currently undergoing rapid thinning and increased draw-down as a result of recent sea-level rise (Payne et al., 2004; Thomas et al., 2004). It remains uncertain how the flow dynamics of the West Antarctic Ice Sheet will be affected by these rapid changes. Modern glaciers in Greenland are experiencing accelerated calving rates associated with enhanced melting, rapid flow and thinning (Zwally et al., 2002). In Alaska, the Columbia Glacier is also known to have experienced a recent abrupt increase in calving rate as a result of surface lowering (van der Veen, 1996). Hence, we suggest, it would be unusual if disintegration of the marine-terminating sectors of the BIS had **not** involved substantial calving and subsequent draw-down. Studies in Ireland lend further plausibility to this suggestion. McCabe and co-workers postulate that Irish Sea deglaciation was triggered by an isostatically induced rise in relative sea level, perhaps occurring in as little as 500 years (McCabe and Clark, 1998; P.U. Clark et al., 2004; McCabe et al., 2005); whilst in the Irish Midlands, Delaney (2002) describes scenarios in which flooding of a central area of low ground was instrumental in the re-organisation of the Irish Ice Sheet. We propose that the calving-bay mechanism provides a plausible explanation for the geomorphic evidence present in the study area described here. Furthermore, that calving and unzipping was principally focused along a north-south axis east of Shetland extending as far south as the Witch Ground Basin (Figure 9). This new insight provides a radically revised framework for BIS research, and a testable hypothesis for future modelling experiments.

Synthesis : combining the evidence

Seismostratigraphic evidence from the North Sea shows that a grounded ice sheet flowed approximately northwest across the Witch Ground Basin (Graham et al., 2007). During this extensive period of ice-sheet glaciation, ice from Scandinavia coalesced with the BIS in the North Sea Basin (Sejrup et al., 2005). The presence of buried MSGLs in the Witch Ground Basin, dated stratigraphically to 22-28 ka ^{14}C BP, have been used to infer the presence of fast ice-sheet flow in this area. However, no surface expression of fast flow exists in this area today (Figure 4).

We present a reconstruction of the conjoined BIS-FIS during the LGM, around 25-30 ka BP (Figure 10). During periods of maximum glaciation, when the FIS overspilled the Norwegian Channel, we suggest that Fennoscandian ice flowed west into the North Sea Basin and coalesced with ice from the eastern margins of the BIS. This coalescent, convergent flow resulted in a fast-flow corridor across deformable sediment in the lowest part of the basin (CZ, Figure 10). The presence of NW-orientated convergent MSGLs in the Witch Ground Basin (Graham et al., 2007); a widespread deformable bed; and the presence of large shelf-edge fans (Rona and Foula Wedges); are all consistent with a palaeo-ice stream flowing NW across the northern North Sea Basin. The reconstructed coalescent FIS-BIS is reinforced by its glaciological plausibility (Figure 8); with convergent flow focused in the low-lying corridor between Orkney and Shetland. The presence of strongly streamlined bedrock forms on Orkney, Shetland and Fair Isle indicate the former passage of a powerful ice sheet in a northwesterly direction (Peach and Horne, 1879, 1880; Hoppe, 1974; Mykura, 1976; Golledge et al., 2008). The presence of rare Norwegian erratics is also consistent with a far-travelled ice stream crossing these islands during the last glaciation (Finlay, 1926; Mykura, 1976; Birnie et al., 1993).

[FIGURE 10 HERE]

Although this scenario has been previously challenged by numerous authors, we think opposing views can be reconciled when new geomorphological dataset from the whole continental shelf is considered. Examination of the wider picture during this glacial maximum event shows a concordant ice-flow pattern across much of northern and eastern Scotland. Glacial bedforms and striae in Strathmore and the inner Moray Firth suggest ice streams flowing in a northeasterly direction before being deflected northwest (Figure 10). The deflection of the Moray Firth ice stream northwest across Caithness has often been cited as evidence that the FIS occupied the northern North Sea Basin at this time (Peach and Horne, 1879; Hall and Bent, 1990; Carr et al., 2006). Far-travelled erratics, glacial striae and elongate bedforms in Orkney indicating WNW flow are all best explained by our revised BIS reconstruction – with ice flowing NE from the northeast Scottish mainland, before converging and being deflected to the NW by the more powerful FIS. At this time the zone of confluence between the BIS and the much larger FIS probably lay across the northern Orkney Islands (Figure 10).

The timing of confluent shelf-edge BIS-FIS glaciation is not well constrained. However, it is likely to have occurred after Heinrich Event 3 and before Heinrich Event 2 (i.e. between 32-24 ka BP). Seismostratigraphic evidence from the West Shetland Shelf shows that the moraines within the Otter Bank Formation formed during the Late Weichselian (Stoker et al., 1993). Sediment sequences on the Rona and Foula Wedges also demonstrate ice-proximal deposition at the shelf edge during the Late Weichselian (MIS 2) (Stoker et al., 1993, 1994). This evidence, combined with other moraines mapped in this study, indicate that the last BIS-FIS reached the continental-shelf edge west of Orkney and Shetland at LGM. Previously published radiocarbon dates from marine fauna place the moraines south of St Kilda, associated with the Barra-Donegal Fan, within the same period (i.e. MIS 2) (Selby, 1989; Peacock et al., 1992). The Barra Fan largely comprises sediment sourced in SW Scotland and NW Ireland and shows a major increase in ice-rafted debris c. 27 ka BP (Kroon et al., 2000; Knutz et al., 2001; Peck et al., 2007). NW of Lewis, however, moraines at the shelf edge adjacent to the Sula Sgeir Fan, are overlain by deposits of probable MIS 4 age (Stoker, 1995). However, given the wider evidence for shelf-edge MIS 2 glaciation to the north and south, it is likely that this Amino-acid age-assessment is in need of revision. Other ice-sheet flow lines relating to the BIS at maximum stage are inferred based on bathymetry, seafloor geomorphology and unpublished BGS mapping. Some of those relating to the FIS have been taken from previously published work (Sejrup et al., 1994; Ottesen et al., 2005). Crucially, we suggest that our new ice-sheet reconstruction is the most likely scenario for the BIS at LGM (Figure 10), and that this scenario is entirely consistent with most of the previously published evidence.

Following extensive shelf-edge glaciation, at LGM, the BIS underwent a period of large-scale re-organization (Figure 11). We propose that this ice-mass re-organization was largely the result of rapidly rising sea levels (Figure 9), probably owing to glacio-isostatic loading, causing major changes in ice-sheet configuration and flow dynamics. It is possible that this re-organisation was closely associated with the North Atlantic iceberg-discharge event – Heinrich Event 2 (c. 24 ka BP; cf. Bond et al., 1993; Peck et al., 2007). However, current dating constraints do not permit more certainty on this linkage. During this stage, both ice sheets underwent rapid recession, we suggest largely as a result of calving into a marine embayment. As this embayment opened, along a north-south axis east of Shetland, both ice-sheet margins receded c. 100 km back towards higher ground, probably over a relatively short period of time (Figure 11). Sea water had inundated the Witch Ground Basin by ~20 ka ^{14}C BP (~24 ka cal BP) (Sejrup et al., 1994; Graham et al., 2007). As the BIS re-organized, ice divides migrated rapidly. Large ice-sheet-lobe moraines on the mid-shelf west of Orkney suggest that this northwestern margin was dynamically unstable during overall ice-sheet re-organization. The innermost moraine loop off Orkney has sharp fresh-looking morphology and is clearly the youngest ice-sheet moraine in this suite. However, the absence of similar lobate moraines on the seafloor east of Orkney suggest that these islands did not host an independent active ice cap during this time, and that the dynamic behaviour was probably a short-lived consequence of ice-sheet readjustment. By contrast, large lobate moraines north, east and west of Shetland suggest that these islands maintained an independent, dynamic ice cap during this deglacial stage (Figure 11) – a model in line with many previous findings (e.g. Hoppe, 1974; Mykura, 1976; Long et al., 2004; Carr et al., 2006; Golledge et al., 2008). The large size and linear morphology of the Bosies Bank and Wee Bankie moraine complexes suggest a considerable period of ice-sheet stability. We suggest that these moraines, previously attributed to the 'Last Glacial Maximum' (e.g. Sutherland, 1984;

Bowen et al., 2002), represent a readvance of the BIS in the aftermath of major ice-sheet re-organization (Figure 11). This latter episode probably occurred after Heinrich Event 2 and before Heinrich Event 1, between c.18-24 ka BP.

[FIGURE 11 HERE]

In summary, we have reconstructed a new model for the glaciation and subsequent deglaciation of the northern UK and the surrounding continental shelf (Figures 10, 11). At LGM the reconstructed BIS was coalescent with the FIS in the northern North Sea and was drained by several ice streams – the most dominant of these, fed from western Norway and eastern Scotland, flowed NW across the Witch Ground Basin to the continental-shelf edge west of Shetland. We propose that following relative sea-level rise, the BIS-FIS broke apart and re-organized into two independent ice sheets which may have remained unstable for some time as they adjusted to new boundary conditions (Figure 11). Widespread, dynamic, ice-margin oscillations probably occurred in response to this re-organisation. Final-stage deglaciation was marked by ice-sheet thinning and increasing topographic control on ice-flow dynamics in the BIS. This stage was also typified by near-shore ice streaming and numerous ice-marginal oscillations in east and west Scotland.

We believe that this 3-stage model explains the long-standing apparent contradiction between those who have argued for ice-free conditions in the North Sea Basin at LGM and those who have argued against. Crucially, our new interpretation, based on shelf-wide sea-bed imagery (Olex), suggests that the period of ice-sheet separation was one of dynamic instability – ultimately leading to large-scale ice-sheet collapse in the North Sea Basin.

Conclusions

Access to the entire Olex echosounder dataset has revealed the geomorphology of the sea floor around the northern UK in unprecedented detail. From this, and the wider evidence, we have drawn the following conclusions regarding the British Ice Sheet at Last Glacial Maximum:

1. A large number of previously unidentified geomorphic features relating to the last ice sheet occur on the continental shelf around the northern UK.
2. The BIS was coalescent with the FIS during a relatively recent phase of extensive ice-sheet glaciation. NW-oriented MSGLs of Late Devensian/Late Weichselian age and NW-oriented tunnel valleys in the northern North Sea, coupled with large shelf-edge moraines west of Shetland, north and west of Lewis and south of St Kilda, dated to MIS 2, all indicate an extensive glaciation between c. 30-25 ka BP. This was also a time when large shelf-edge fans received a major increase in glacially derived sedimentation. This interpretation is consistent with previously published geological evidence from the western sector of the FIS. We propose that at LGM the zone of ice-sheet confluence probably stretched from 1°deg E longitude, NW across the northern Orkney Islands, to the shelf edge west of Shetland. Fast-flowing confluent ice in the Fair Isle Channel during this time would have focused sediment delivery to the Rona and Foula Wedges.
3. Ice-sheet retreat occurred primarily by calving as a result of rising sea levels. We suggest that, during abrupt relative sea-level rise around the time of Heinrich-2 (c. 24 ka BP), a large marine embayment opened in the northern North Sea, as far south as the Witch Ground Basin. This marine embayment changed the entire configuration of the two ice sheets forcing them to decouple rapidly along a north-south axis east of Shetland. Similarities are striking between this scenario and the ongoing, rapid, break-up of marine-terminating parts of the West Antarctic Ice Sheet.
4. The northern sector of the last BIS underwent a remarkable period of ice-sheet re-organisation in response to the opening of a large marine embayment centred on the Witch Ground Basin. Dynamic ice-front oscillations – deduced from overprinted lobate moraine patterns and seismic stratigraphy – occurred during this period as the BIS rapidly adjusted to new quasi-stable margin positions.
5. A period of relative stability followed, when the BIS margin was situated in the vicinity of the Bosies Bank–Wee Bankie moraine complex off eastern Scotland. This ice-sheet configuration probably equates to the traditional

'LGM' c. 18-24 ka BP – with an ice-free North Sea Basin and a substantial ice cap on Shetland.

6. Ice-sheet thinning and punctuated retreat continued, increasing topographic control and invigorating several near-shore ice streams. Around 16 ka BP, following Heinrich Event 1, the BIS margin was stably situated at the present-day coastline in NW Scotland. Subsequent ice-sheet retreat was probably slower and took place primarily by melting, rather than calving.
7. We suggest that this new 3-stage reconstruction of the northern half of the last BIS offers a glaciologically plausible model which reconciles much of the previously published, apparently contradictory, evidence from the wider area.

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Figure captions

Figure 1. Map showing the general bathymetry and main glacio-geological sea-bed landforms around the northern UK. Data sources are given in the legend. Extent of the study area (Figure 4) and key placenames are also shown.

Figure 2. Summary of Late Quaternary chronostratigraphic stages (UK) and their correlation with Marine Isotope Stages (modified from Bowen, 1999 and Walker et al., 1999). Dates are in calendar years BP. The timing of the Last Glacial Maximum (LGM) in NW Europe is also shown. Note: diagram is not to scale and correlations are not fully resolved.

Figure 3. BGS airgun profile and interpreted line drawing across the West Shetland margin showing the geometry and stratigraphic architecture of the Rona Wedge (see Figure 1 for location). Inset image shows the sea bed morphology of the West Shetland slope (A-A' on the profile) derived from first returns from 3D exploration surveys (cf. Long et al., 2004). The Glacial Unconformity (GU) is interpreted to represent the instigation of shelf-wide glaciation during the early Mid-Pleistocene (Stoker, 1995, 2002). Prominent ridges preserved on the outer shelf represent submarine moraine banks, up to 50 m high and 6 km wide. The West Shetland Slope surface morphology displays abundant glacigenic debris flows sourced from an ice-sheet margin at the continental shelf edge (Davison and Stoker, 2002). Abbreviations: SBM, sea bed multiple; WD, water depth.

Figure 4. Merged onshore-offshore (topographic-bathymetric) surface model for the northern UK and surrounding continental shelf. Offshore data – Olex AS; Onshore data – derived from NEXTMap Britain digital surface model (Intermap Technologies, 2003). See text for details of data collection and image production.

Figure 5. Sea-bed landforms on the northern UK continental shelf mapped from the Olex dataset (Figure 4). Solid lines – positive linear features (ridges, primarily moraines); dashed lines – negative linear features (channels, primarily tunnel valleys). There is some generalisation, in places, for the sake of cartographic clarity. Colours denote feature groups outlined in Key (1, 2, 3, A, B).

Figure 6. (A) Olex bathymetry of the northern North Sea showing the morphology and distribution of large tunnel valleys (Fladen Deeps). For location see Figure 5. Most authors relate these features to subglacial hydrological phenomena (e.g. Ó Cofaigh, 1996; Lonergan et al., 2006). (B) Rose diagram showing the preferred orientation of the tunnel valleys in the northern North Sea. (C) Oblique view, looking SE from point X, along a well-developed sea-floor tunnel valley. The feature is >100 m deep, 1 km wide and over 30 km long. Note the undulating long profile and abrupt initiation/termination. 5x vertical exaggeration. Faint orthogonal linear features are data artefacts.

Figure 7. (A) Olex bathymetry and (B) geomorphological map of the sea bed NW of Orkney. For location see Figure 5. Black polygons – large ridges; black lines – narrow ridges. The large concentric ridges with irregular, in places overprinted, morphology are interpreted as recessional moraines relating to a grounded, highly dynamic, oscillatory lobe of the last BIS. Note the sharp-crested coherent morphology of the innermost arcuate loop – strongly reminiscent of a terrestrial thrust-block or push moraine. (C) BGS seismic profile and interpreted line drawing of submarine moraine banks along line X-X' (modified after Stoker and Holmes, 1991). The moraine banks are up to 50 m high and 6 km wide; the crests of the banks are currently at water depths of 100-150 m. The moraines are largely acoustically structureless. The observation that the most landward moraine imaged in the seismic profile overlies layered strata which post-date the middle moraine reflects a considerable readvance of the BIS during the general phase of overall recession.

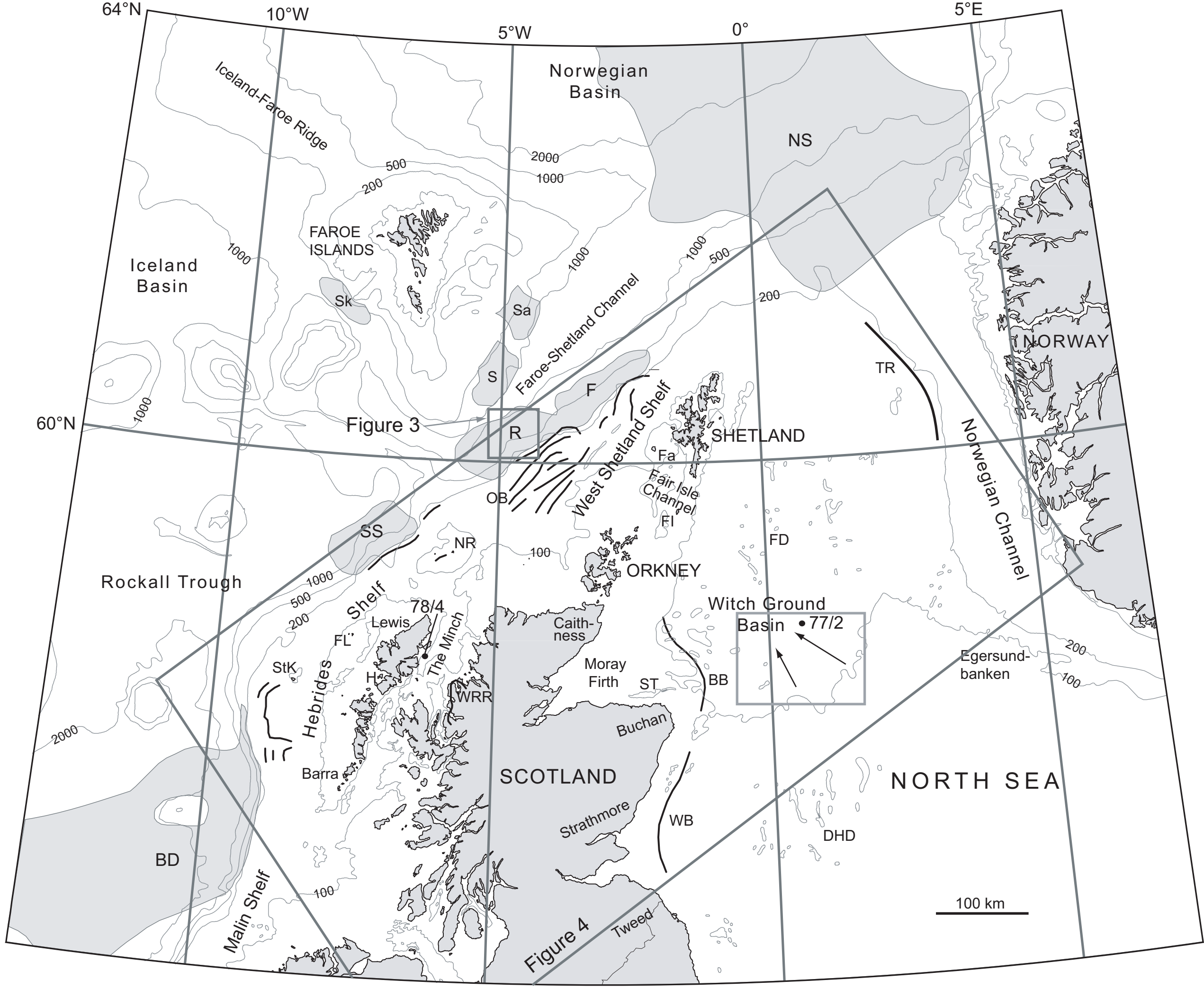
Figure 8. (A) Olex bathymetry and (B) geomorphological map of the sea bed NE of Shetland. For location see Figure 5. Black polygons – large ridges; black lines – narrow ridges; trough margin shown as triangle-ornamented line. The high density of arcuate, convoluted, occasionally overprinting ridges NE of Unst are interpreted as recessional moraines of a grounded, highly dynamic, oscillatory lobe of the last BIS. The broadly concentric configuration of moraines around Shetland supports the notion of an independent ice cap on the islands during the latter stages of the last glaciation. (C) Close-up image of subparallel more-linear ridges within the trough east of Shetland. Based on their geomorphological expression, these are interpreted as De Geer moraines – strongly suggestive of a tidewater glacier margin. (D) Olex bathymetry and geomorphological map of closely spaced low-elevation ridges in the Fair Isle channel, also interpreted as De Geer moraines.

Figure 9. Olex bathymetry of the northern North Sea showing coloured bathymetric slices at various elevations: (i) 160-190 m below present day; (ii) 120-150 m below present day; and (iii) 90-120 m below present day sea level. Darker tones are deeper water. The pattern of sea-level rise associated with ice-sheet deglaciation would have followed this sequence, resulting in a large north-south marine embayment in the northern North Sea Basin. Note: No corrections for glacio-isostatic loading or forebulge development have been incorporated into these sea-level scenarios.

Figure 10. Reconstruction of the confluent British (BIS) and Fennoscandian ice sheets (FIS) at LGM (30-25 ka BP), with hypothesised flow lines. Solid lines inferred from this study; dashed flow lines (FIS) taken from Sejrup et al. (1994) and Ottesen et al. (2005). Dark shading shows approximate zone of confluence (CZ); small arrows show MSGL orientations recorded (from west to east) by Bradwell et al. (2007), Stalsberg et al. (2003) and Graham et al. (2007). Hatching denotes trough-mouth fans. FB denotes possible ice sheet frozen-bed patches in Buchan and on Lewis. Sea-bed contours refer to present-day bathymetry (see Figure 1). Faeroe Ice cap not shown, extent uncertain (see Nielsen et al., 2007).

Figure 11. Reconstruction of British and Fennoscandian ice sheets during LGM deglaciation. Three sequential stages are shown: 1 (black line) – calving bay initiation; lobes dominate western margin. 2 (grey line) – calving bay well developed; dynamic ice-sheet separation and re-organisation ongoing. 3 (shaded fill) – separate

BIS and FIS; ice free central North Sea Basin; independent Shetland ice cap. Hypothesised flow lines shown for final stage only; those for FIS taken from Sejrup et al. (1994) and Ottesen et al. (2005). Sea-bed contours refer to present-day bathymetry (see Figure 1).



Key to abbreviations:

Trough Mouth Fans

BD Barra-Donegal Fan
SS Sula Sgeir Fan
R Rona Wedge
F Foula Wedge
S Suduroy Fan
Sa Sandoy Fan
Sk Skeivi Fan
NS North Sea Fan

Moraines

BB Bosies Bank
WB Wee Bankie
OB Otter Bank
TR Tampen Ridge
WRR Wester Ross Moraine

Bathymetric Deeps

FD Fladen Deeps
DHD Devil's Hole Deeps
ST Southern Trench

Islands

StK St Kilda
FL Flannan Islands
H Harris
NR North Rona
FI Fair Isle
Fa Foula

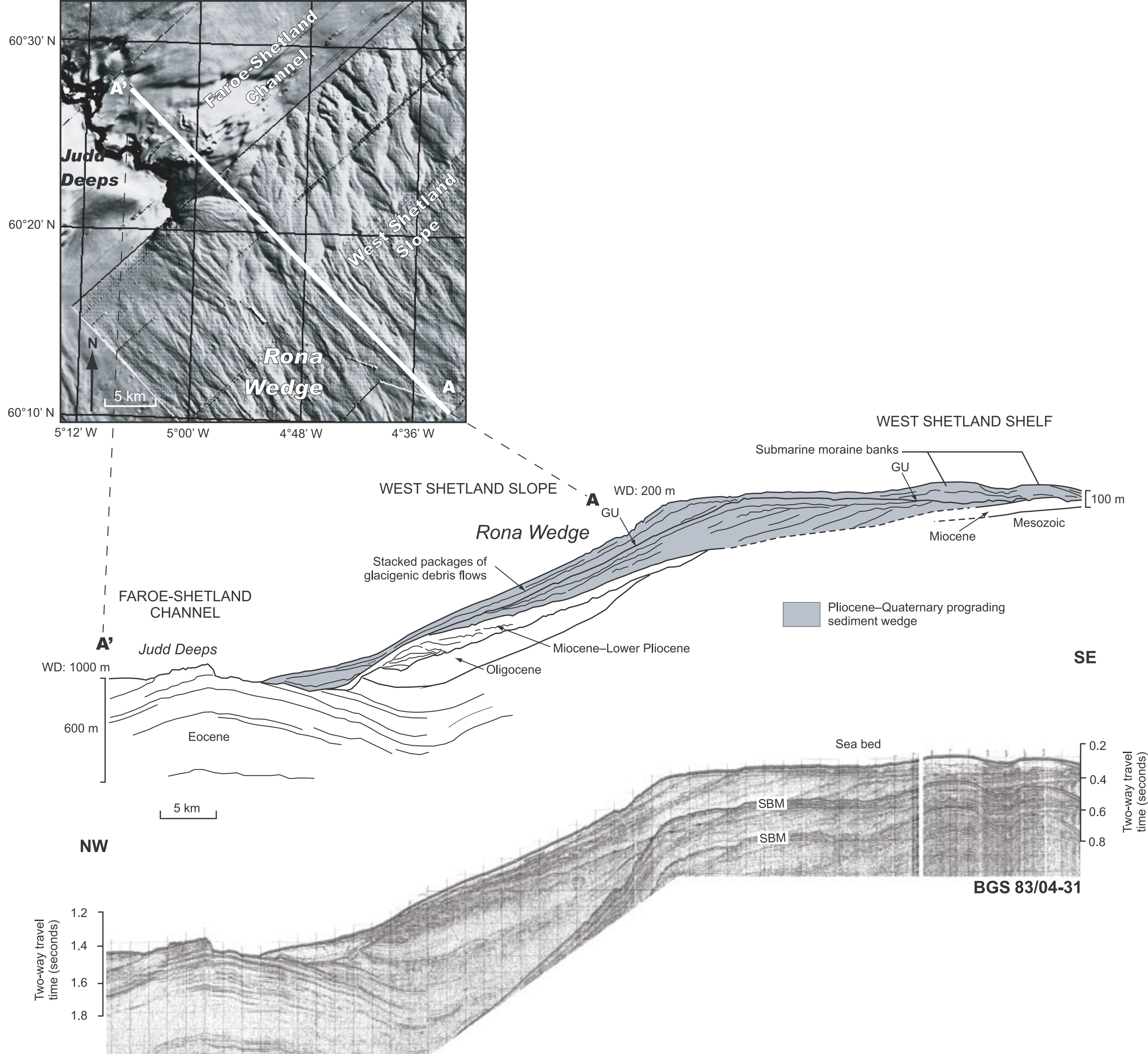
Box showing extent and orientation of mega-scale glacial lineations, mapped by Graham et al. (2007)

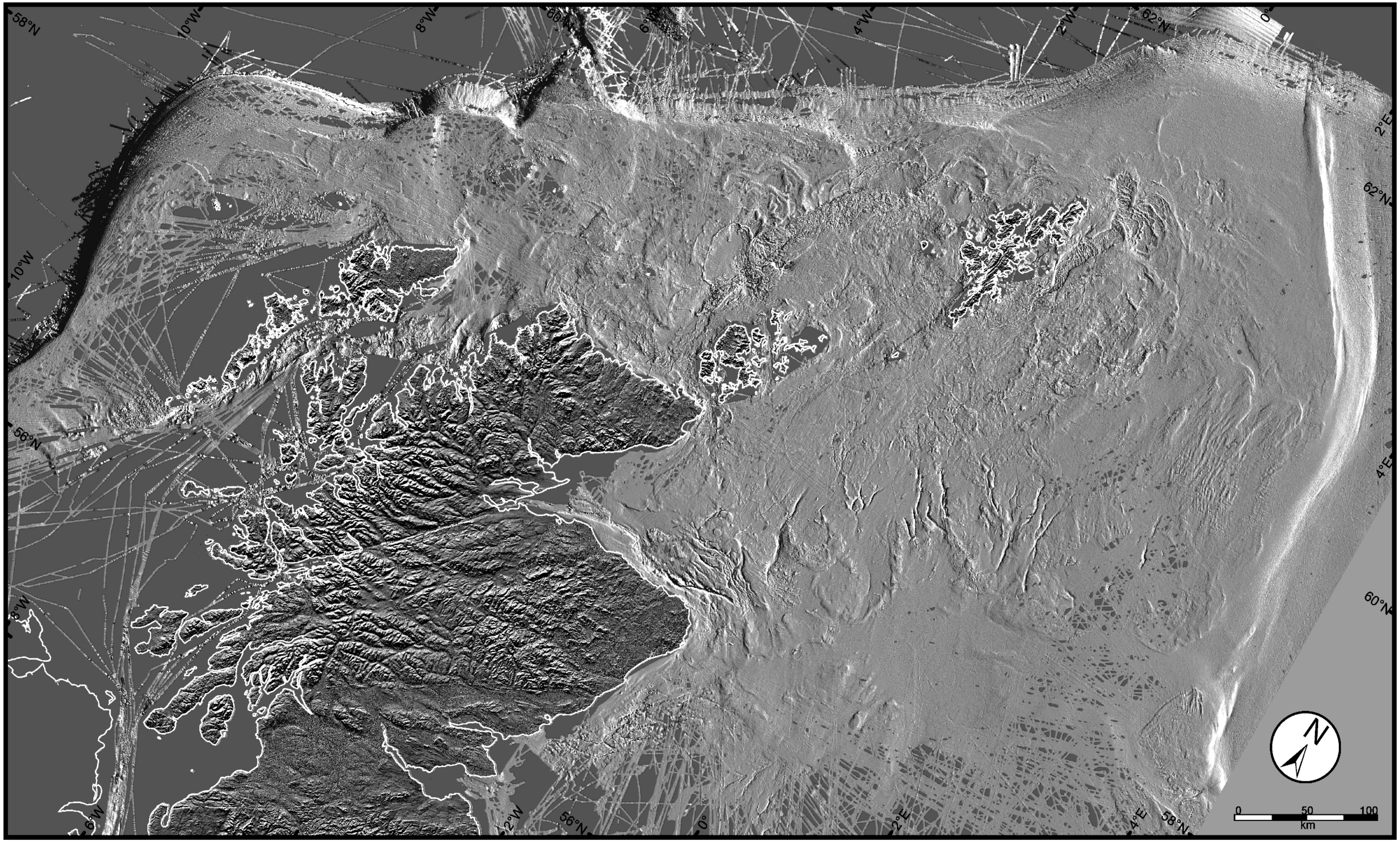
Data sources

Moraines
Robinson and Ballantyne (1979)
Cameron et al. (1987)
Hall and Bent (1990)
Selby (1989)
Stoker (1990)
Stoker and Holmes (1991)
Davison (2005)

Trough-Mouth Fans
Sejrup et al. (2005)
Nygard et al. (2005)
Stoker and Varming (in press)
Stoker (in press)

Period	Marine Isotope Stage	Stage		Age (ka)
QUATERNARY	1	HOLOCENE		
				11.5
	2	DEVENSIAN = Weichselian	LATE	
		LGM		
				31
	3		MID	
				58
	4		EARLY	
				116
	5	IPSWICHIAN = Eemian		


60°30' N
60°20' N
60°10' N
5°12' W
5°00' W
4°48' W
4°36' W
Faroe-Shetland Channel
Judd Deeps
West Shetland Slope
Rona Wedge
A'
A
N
5 km
WEST SHETLAND SHELF
Submarine moraine banks
GU
WEST SHETLAND SLOPE
WD: 200 m
100 m
Mesozoic
Miocene
Rona Wedge
Stacked packages of glacigenic debris flows
FAROE-SHETLAND CHANNEL
Judd Deeps
WD: 1000 m
600 m
Eocene
Pliocene–Quaternary prograding sediment wedge
Miocene–Lower Pliocene
Oligocene
SE
NW
Sea bed
SBM
SBM
Two-way travel time (seconds)
0.2
0.4
0.6
0.8
1.2
1.4
1.6
1.8
BGS 83/04-31



58°N
10°W
8°W
6°W
4°W
2°W
62°N
0°
2°E
62°N
10°W
56°N
4°E
60°N
8°W
6°W
2°W
56°N
0°
2°E
4°E
58°N
N
0
50
100
km

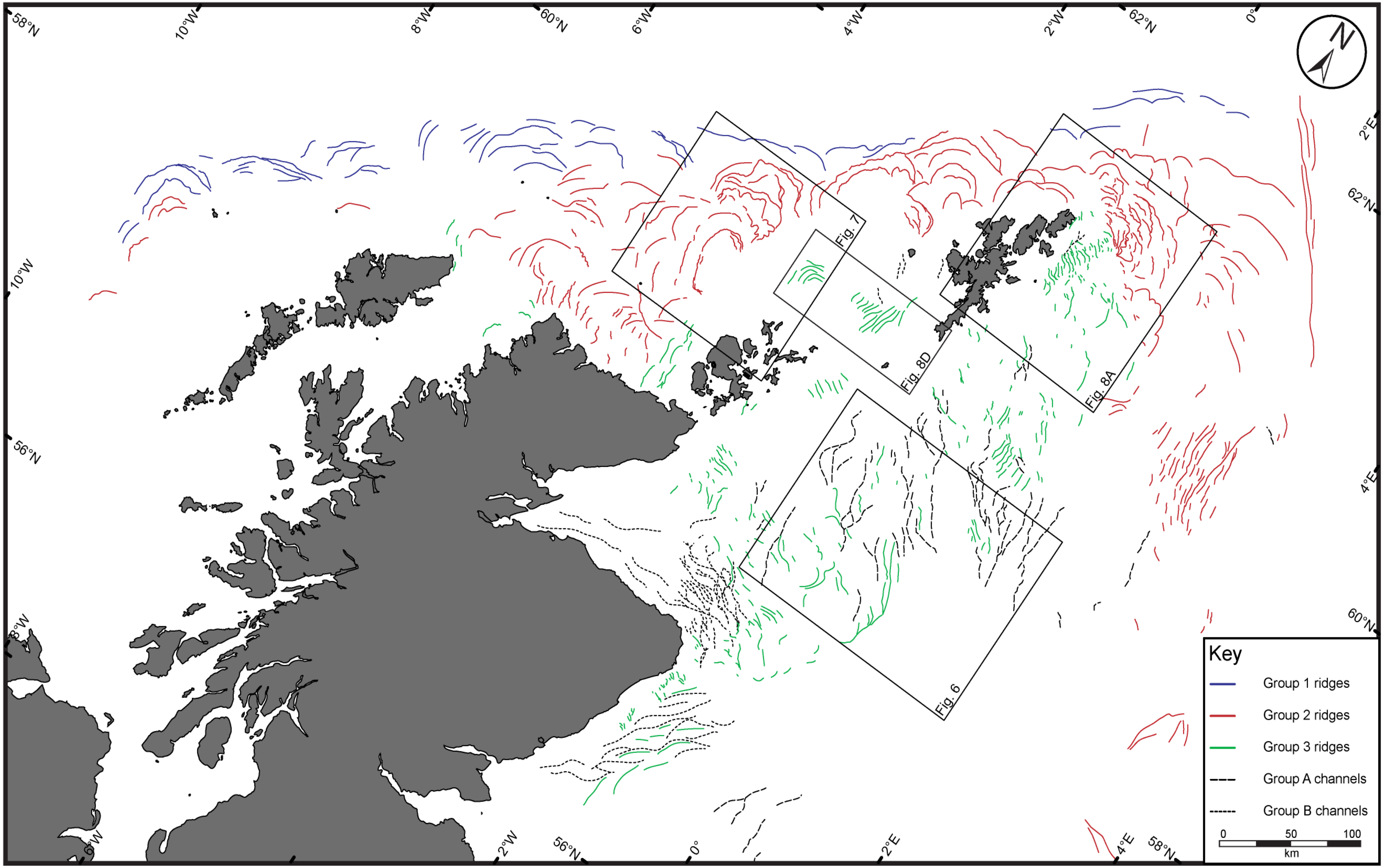
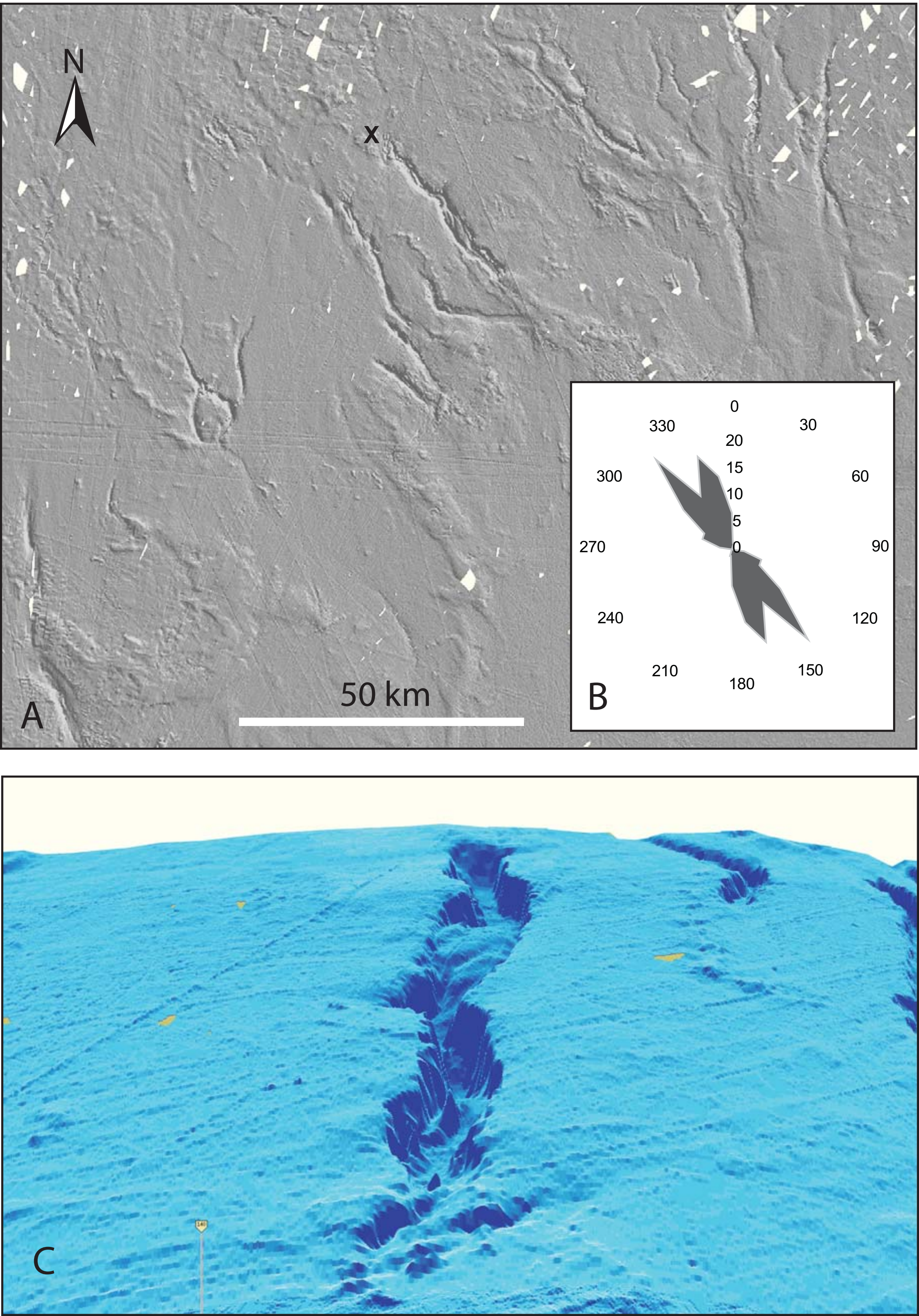
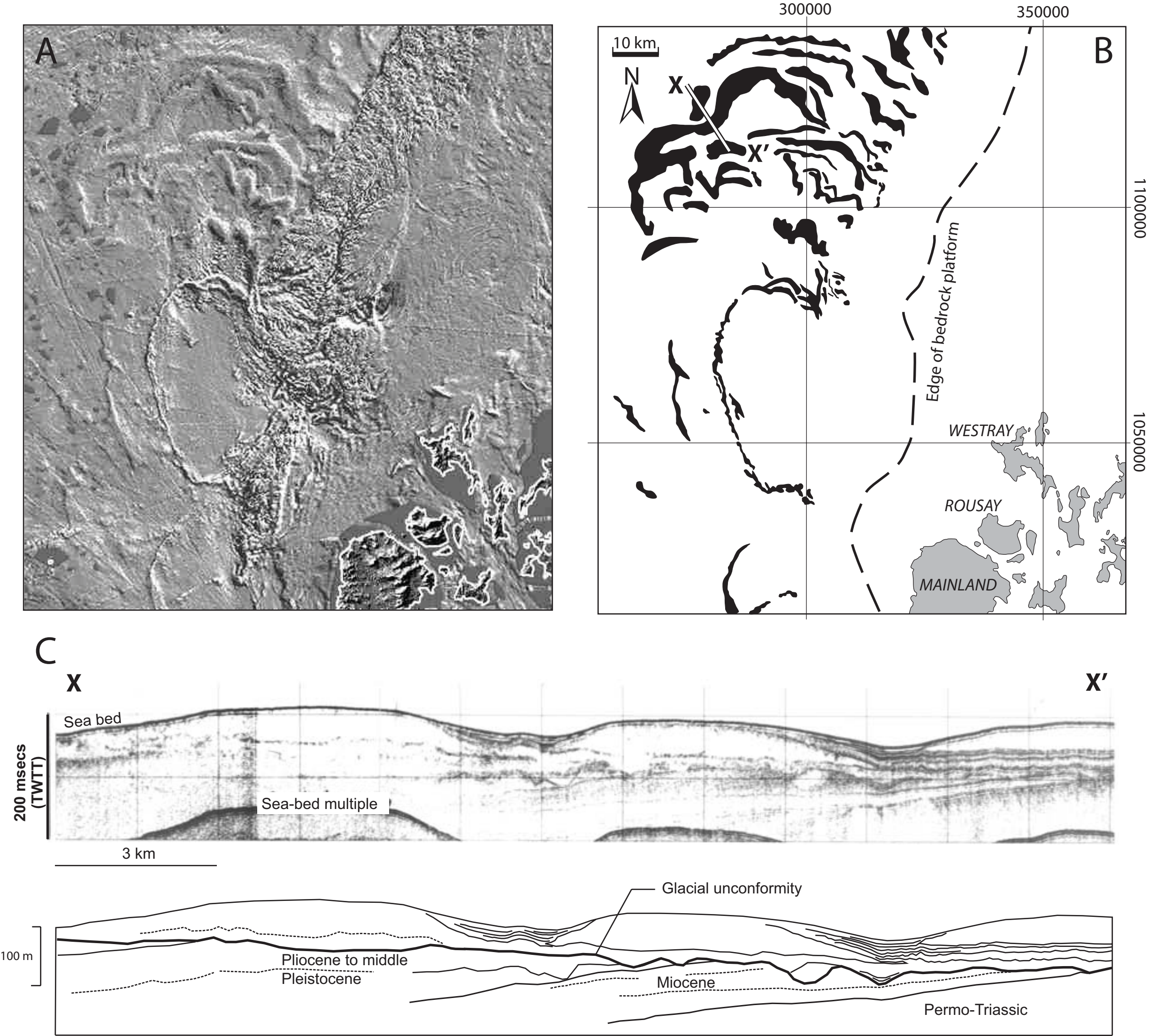


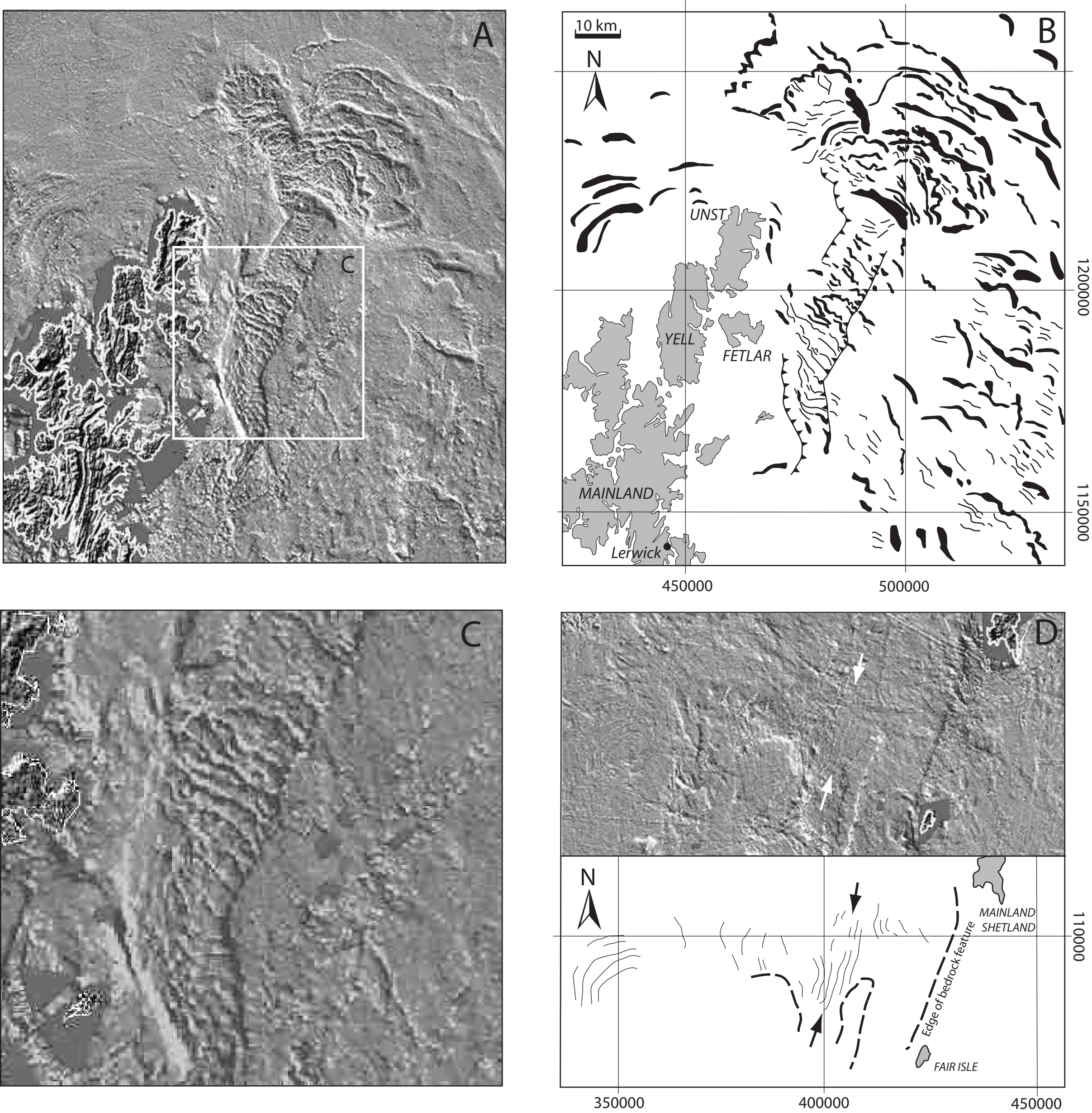
Fig. 7
Fig. 8D
Fig. 8A
Fig. 6
Key
Group 1 ridges
Group 2 ridges
Group 3 ridges
Group A channels
Group B channels
0 50 100
km
N

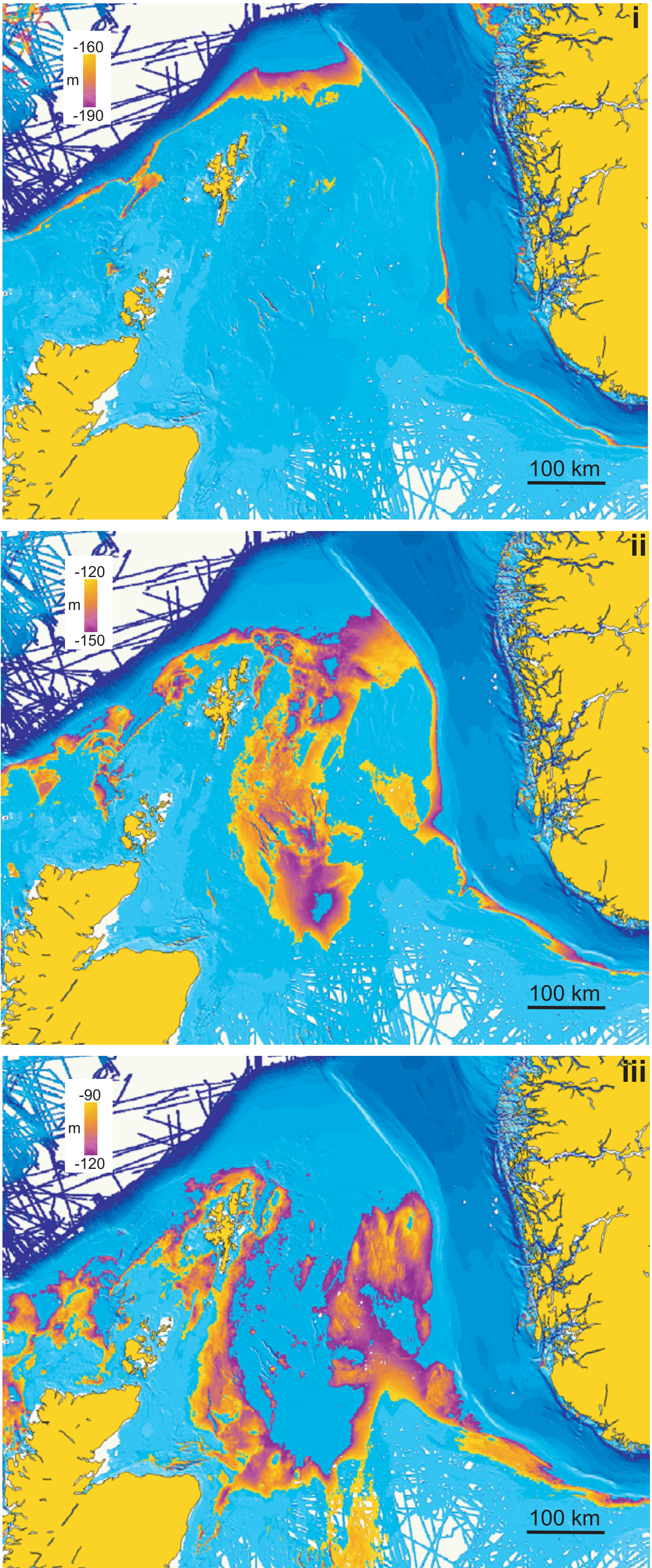


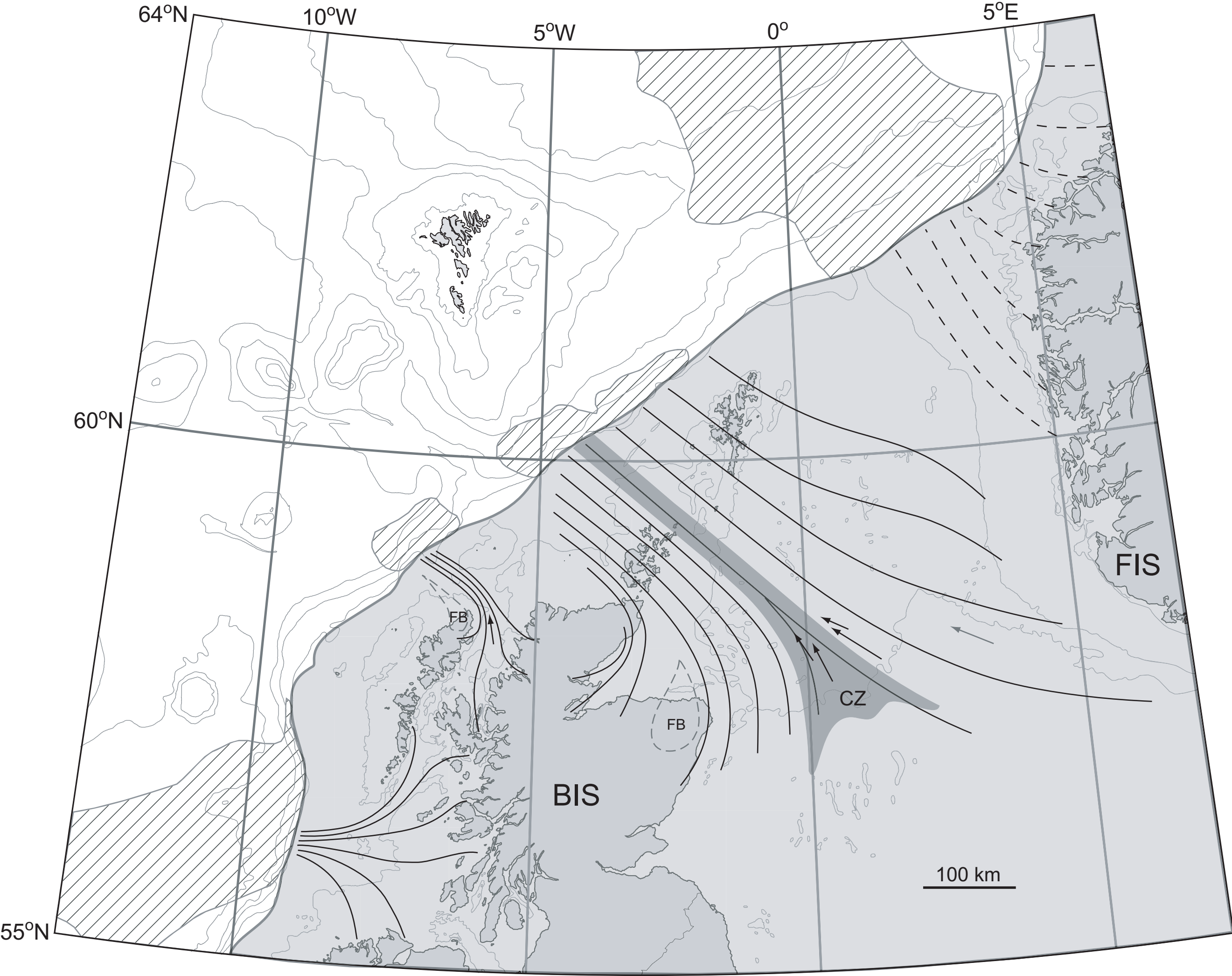
N
x
50 km
A
0
330
30
20
15
300
60
10
5
270
0
90
240
120
210
180
150
B
C



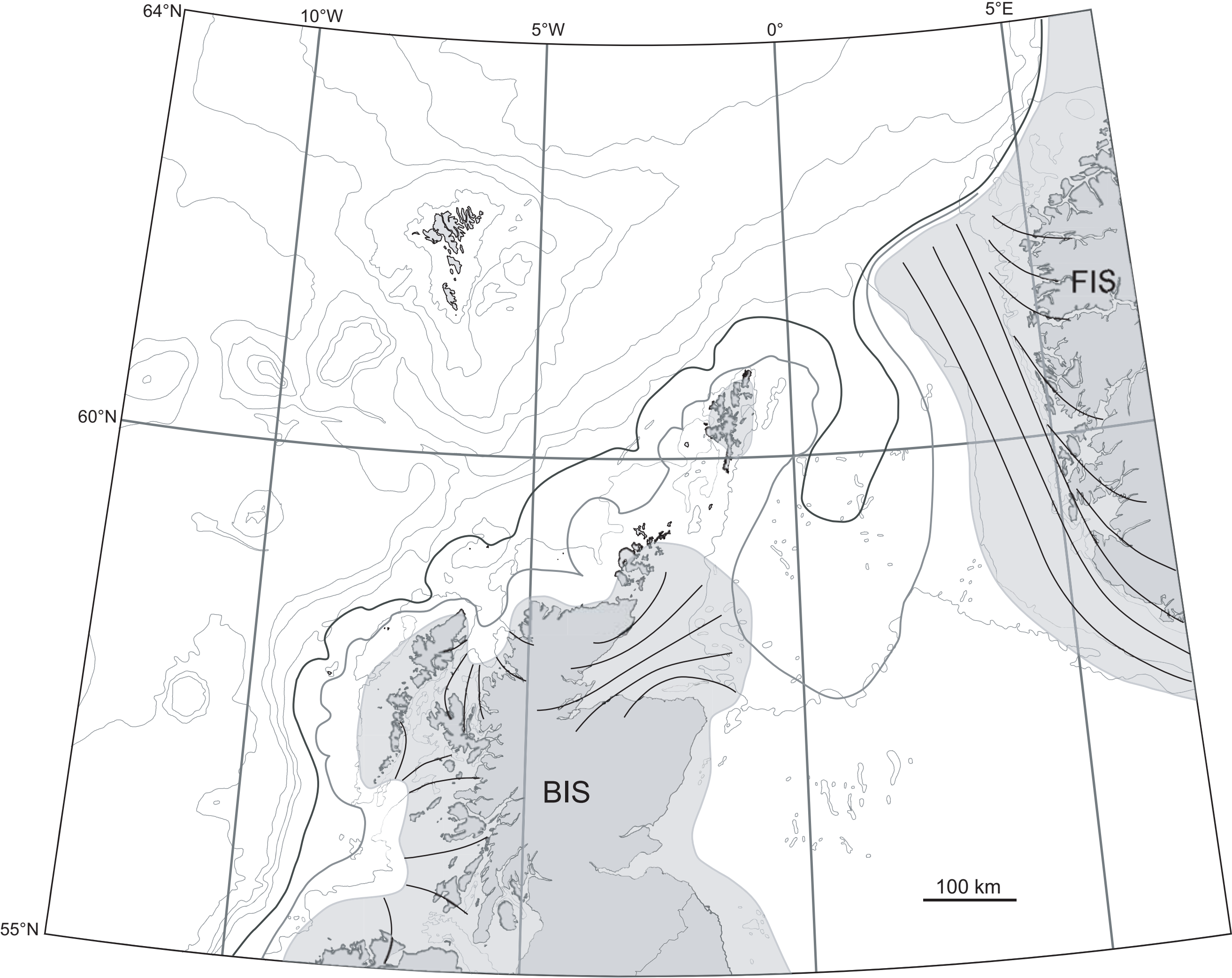
A
B
300000
350000
10 km
N
X
X′
1100000
1050000
Edge of bedrock platform
WESTRAY
ROUSAY
MAINLAND
C
X
X′
Sea bed
200 msecs (TWTT)
Sea-bed multiple
3 km
Glacial unconformity
100 m
Pliocene to middle Pleistocene
Miocene
Permo-Triassic


A
C
B
10 km
N
UNST
YELL
FETLAR
MAINLAND
Lerwick
1200000
1150000
450000
500000
C
D
N
MAINLAND
SHETLAND
Edge of bedrock feature
FAIR ISLE
110000
350000
400000
450000


i
-160
m
-190
100 km
ii
-120
m
-150
100 km
iii
-90
m
-120
100 km



64°N
10°W
5°W
0°
5°E
60°N
55°N
FB
FB
CZ
BIS
FIS
100 km



64°N
10°W
5°W
0°
5°E
60°N
55°N
FIS
BIS
100 km