The Last Scottish Ice Sheet

Journal:	*Earth and Environmental Science Transactions of the Royal Society of Edinburgh*
Manuscript ID	TRE-2017-0022.R1
Manuscript Type:	The Quaternary of Scotland
Date Submitted by the Author:	n/a
Complete List of Authors:	Ballantyne, Colin; University of St Andrews, Geography and Sustainable Development Small, David; Durham University, Department of Geography
Keywords:	British-Irish Ice Sheet, Deglaciation, Dimlington Stade, Ice streams, Late Devensian, Radiocarbon dating, Readvances, Terrestrial cosmogenic nuclide dating

The Last Scottish Ice Sheet

Colin K. Ballantyne[1] and David Small[2]

[1] School of Geography and Sustainable Development, University of St Andrews, St Andrews KY16 9AL, UK. Corresponding Author (ckb@st-and.ac.uk)

[2] Department of Geography, Durham University, Lower Mountjoy, South Road, Durham DH1 3LE, UK.

Running head: The last Scottish Ice Sheet

ABSTRACT: The last Scottish Ice Sheet (SIS) expanded from a pre-existing ice cap after ~35 ka. Highland ice dominated, with subsequent build up of a Southern Uplands ice mass. The Outer Hebrides, Skye, Mull, the Cairngorms and Shetland supported persistent independent ice centres. Expansion was accompanied by ice-divide migration and switching flow directions. Ice nourished in Scotland reached the Atlantic Shelf break in some sectors but only mid-shelf in others, was confluent with the Fennoscandian Ice Sheet (FIS) in the North Sea Basin, extended into northern England, and fed the Irish Sea Ice Stream and a lobe that reached East Anglia. The timing of maximum extent was diachronous, from ~30–27 ka on the Atlantic Shelf to ~22–21 ka in Yorkshire. The SIS buried all mountains, but experienced periods of thickening alternating with drawdown driven by ice streams such as the Minch, Hebrides and Moray Firth Ice Streams. Submarine moraine banks indicate oscillating retreat and progressive decoupling of Highland ice from Orkney-Shetland ice. The pattern and timing of separation of the SIS and FIS in the North Sea Basin remain uncertain. Available evidence suggests that by ~17 ka, much of the Sea of the Hebrides, Outer Hebrides, Caithness and the coasts of E Scotland were deglaciated. By ~16 ka the Solway lowlands, Orkney and Shetland were deglaciated, the SIS and Irish Ice Sheet had separated, the ice margin lay along the western seaboard, nunataks had emerged in Wester Ross, the ice margin lay N of the Cairngorms and the sea had invaded the Tay and Forth estuaries. By ~15 ka most of the Southern Uplands, Firth of Clyde, Midland Valley and upper Spey valley were deglaciated, and in NW Scotland ice was retreating from fjords and valleys. By the onset of rapid warming at ~14.7 ka, much of the remnant SIS was confined within the limits of Younger Dryas glaciation. The SIS therefore lost most of its mass during the Dimlington Stade. It is uncertain whether fragments of the SIS persisted on high ground throughout the Lateglacial Interstade.

KEY WORDS: British-Irish Ice Sheet; deglaciation; Dimlington Stade; flowsets; ice streams; Late Devensian; lithostratigraphy; radiocarbon dating; readvances; terrestrial cosmogenic nuclide dating.

The last Scottish Ice Sheet (SIS) was the dominant component of the last British-Irish Ice Sheet (BIIS), and for much of its existence extended far beyond the present land area of Scotland. Here we use 'SIS' to refer to glacier ice nourished in Scotland during the period ~35–14 ka, which incorporates the later part of Marine Isotope Stage (MIS) 3 and most of MIS 2. During much of this period the SIS was confluent with ice sourced in England, Wales, Ireland and Norway, but remained an independent, though complex, centre of ice dispersal; there is no convincing evidence that external ice encroached on the present land area of Scotland. We use the abbreviation LGM to denote the last global glacial maximum of ~26.5 ka to ~19 ka (P. U. Clark *et al.* 2009) and LLGM (local last glacial maximum) to refer to the maximum extent of different sectors of the last SIS, some of which reached their outermost limits millennia before others.

Over the past two decades, our understanding of the extent, dynamics and chronology of the SIS has undergone radical transformation. Not only is it now accepted that the ice sheet was much more extensive than previously believed, but it has also been shown that it was drained by fast-flowing ice streams, exhibited marked changes in configuration and flow patterns, and experienced numerous readvances as the ice margin retreated from its outermost reach. This transformation largely reflects the application of new approaches, notably: (1) increasing use of offshore bathymetric, seismostratigraphic and borehole evidence to reconstruct events relating to the extent and retreat of the ice sheet on the continental shelf; (2) the employment of satellite imagery and digital elevation models to establish sequential regional ice-flow directions and landsystems characteristic of former ice streams; (3) increasingly sophisticated analyses of regional lithostratigraphy; (4) the use of terrestrial cosmogenic nuclide (TCN) dating to establish the timing of deglaciation and readvances on land; and (5) numerical modelling of ice-sheet extent and behaviour. An important development has been the collation of all dating evidence relating to the last BIIS (Hughes *et al.* 2011) and the integration of this chronological database with terrestrial landform evidence (C. D. Clark *et al.* 2004; Evans *et al.* 2005; Hughes *et al.* 2010) and offshore moraine sequences to reconstruct the evolution of the entire BIIS (Clark *et al.* 2012; Hughes *et al.* 2014, 2016).

This review considers the impact of these new approaches on our understanding of the SIS, focusing on developments over the past 20 years, many of which nevertheless build on a vast body of earlier research (Sutherland 1984; Gordon & Sutherland 1993). Following sections considering chronological framework, terminology, dating calibration and the history of ideas concerning the SIS, we outline first current understanding of the pattern of ice-sheet expansion, then the nature of ice-sheet retreat and associated readvance episodes. Details of the stratigraphy associated with these events are given in the reviews by Merritt *et al.* (2018) and Stewart *et al.* (2018) in this issue, and are considered here only where essential. This review concludes with the demise or near-demise of the SIS during the Lateglacial Interstade (~14.7–12.9 ka); later glacial events, during the Younger Dryas Stade, are reviewed by Golledge (2010). Key locations mentioned in the text are identified in Figure 1.

1. Chronological framework, terminology and dating calibration

The last glacial stage in Great Britain is termed the Devensian, and is chronologically equivalent to the Weichselian in Europe. Chronostratigraphic subdivision of the Devensian on the basis of terrestrial evidence is poorly constrained, so here we follow the convention of equating subdivisions with marine oxygen isotope stages (MIS) using the temporal boundaries of Lisiecki & Raymo (2005): Early Devensian (= MIS 5d–4, ~109–57 ka; Middle Devensian (= MIS 3, ~57–29 ka) and Late Devensian (= MIS 2, ~29–11.7 ka), though some authors place the MIS3/2 boundary at 31 ka or 30 ka. The Late Devensian encompasses Greenland Stadials (GS) 5 to 1 as defined in the Greenland ice core isotope record (~32.0 ka to 11.7 ka; Rasmussen *et al.* 2014) and in Great Britain is subdivided into the Dimlington Stade (~31–14.7 ka), Lateglacial (or Windermere) Interstade (~14.7–12.9 ka) and Younger Dryas (or Loch Lomond) Stade (~12.9–11.7 ka). The last SIS began to expand near the end of the Middle Devensian, reached its maximum extent during the Dimlington Stade and had probably fragmented into remnants in the Highlands within a few centuries after the beginning of the Lateglacial Interstade at ~14.7 ka.

Ages cited below are expressed as ka (thousands of years before present), and mean ages derived from two or more individual ages are uncertainty-weighted means. Cited uncertainties are ± 1σ. Uncalibrated radiocarbon ages are cited as ^{14}C a BP or ^{14}C ka and calibrated radiocarbon ages as cal ^{14}C ka. We have recalibrated all radiocarbon ages with the CALIB 7.10 calibration software (Stuiver *et al.* 2016), using the IntCal 13 dataset for terrestrial samples and the Marine 13 dataset for marine samples (Reimer *et al.* 2013). We have applied a 400-year reservoir correction for marine shells and foraminifera whilst acknowledging that reservoir age is likely to have varied (Austin *et al.* 2011). Calibrated radiocarbon ages are expressed as the ± 1σ age range. All TCN exposure ages based on cosmogenic ^{10}Be have been recalibrated using the Lm scaling of the CRONUS-Earth online calculator (Balco *et al.* 2008) and the Loch Lomond production rate (LLPR; Fabel *et al.* 2012), which yields a reference production rate of 4.00 ± 0.18 atoms g^{-1} a^{-1}; other scaling schemes generally produce ages < 1.5% older or < 0.5% younger. Exposure ages based on cosmogenic ^{36}Cl have been calculated using the CRONUScalc online calculator (Marrerro *et al.* 2016a) and reference production rates of 56.0 ± 4.1, 155 ± 11, 13 ± 3 and 1.9 ± 0.2 atoms ^{36}Cl g^{-1} a^{-1}, for Ca, K, Ti and Fe, respectively (Schimmelpfennig *et al.* 2009; Marrero *et al.* 2016b) using the SA scaling of Lifton *et al.* (2014), as this yields ages similar to those produced by independent ^{10}Be exposure dating. For all TCN ages we cite full (external) uncertainties at ± 1σ and assume a sample erosion rate of 1 mm ka^{-1}; assumption of zero erosion for samples analysed using ^{10}Be produces ages ~1% younger and assumption of 2 mm ka^{-1} produces ages ~1% older.

All dating techniques used to constrain the timing of glaciation and deglaciation are associated with quantifiable (systematic and random) and unquantifiable (geological) uncertainties. The latter are not included in the cited uncertainty term for any date, but may result in the date being unrepresentative of the event being dated. The sources of geological uncertainty associated with the dating techniques referred to here are reviewed by Small *et al.* (2017b), who provide quality assurance protocols applicable to the use of published dates in ice-sheet reconstructions. In this account we discuss published dates in terms of their original interpretation and evaluate their significance and representativeness within the context of wider chronological considerations.

2. Evolving ideas concerning the extent of the last Scottish Ice Sheet

Early research based on erratic transport, till lithology and observations of striae demonstrated that all of Scotland had been glaciated during the Pleistocene. James Geikie (1876) concluded that 'one great sheet of ice enveloped the whole country' and Archibald Geikie (1901), Peach & Horne (1910) and Wright (1914) produced maps of ice-sheet extent showing directions of ice flow, with glacier ice terminating westwards at the Atlantic Shelf break and confluence of the SIS and Fennoscandian Ice Sheet (FIS) in the North Sea Basin (NSB) (Fig. 2). Their interpretations were broadly similar to present understanding of former ice extent, but in the absence of dating controls they were unable to demonstrate that the inferred extent of ice cover represented the *last* ice sheet, rather than an earlier glaciation. The earliest models of the dimensions of the last SIS (Boulton *et al.* 1977, 1985) adopted this interpretation, placing the western limit of Scottish ice near the Atlantic Shelf break and accepting confluence of the SIS and FIS in the NSB.

The final decades of the 20th century witnessed radical reassessment of the dimensions of the SIS. This revision was stimulated by interpretation of the stratigraphy and chronology of offshore sediments in the NSB as indicating that the ice sheet extended only 50–100 km E of the Scottish coast (Holmes 1977; Thomson & Eden 1977). This interpretation implied that the SIS and FIS were not confluent, and thus that Moray Firth ice could not have been diverted NW across Caithness and Orkney, implying that these areas remained outside the limit of the last ice sheet. Evidence for eastward ice movement across the Uists and Benbecula (Coward 1977; Peacock & Ross 1978) and radial ice movement on Harris, Lewis and Shetland (Flinn 1977, 1978a, 1978b; Von Weymarn 1979) also suggested that these areas were not over-run by the last mainland ice sheet, but nourished independent ice caps. Collectively, these findings prompted Sissons (1981) to argue that the SIS had been of limited extent, and that Orkney, Caithness and part of NE Scotland lay outside its limits. This 'restricted ice sheet' model was developed by Sutherland (1984) and adopted by Bowen *et al.* (1986) in an influential reconstruction that depicted ice-free enclaves in NW Lewis, Orkney, Caithness and NE Scotland (Fig. 3). Their proposed ice-sheet limits were employed to constrain a second generation of ice-sheet models (Boulton *et al.* 1991; Lambeck 1995) and were accepted by some researchers for two decades (Bowen *et al.* 2002; C. D. Clark *et al.* 2004; Fretwell *et al.* 2008).

The 'restricted ice sheet' model was soon contested. The evidence favouring an ice-free enclave in Lewis and termination of the last ice sheet across Caithness and NE Scotland was challenged (Hall & Whittington 1989; Hall & Bent 1990; Hall 1995, 1996), and seismostratigraphic, borehole and dating evidence from the Hebrides and Shetland shelves was interpreted as indicating much greater westward extension of the last ice sheet (Davies *et al.* 1984; Selby 1989; Peacock *et al.* 1992; Fyfe *et al.* 1993; Stoker *et al.* 1993). Sejrup *et al.* (1994) revived the argument for confluence of the SIS and FIS in the NSB, a hypothesis subsequently vindicated by evidence for grounded ice occupying this area during the LGM (Sejrup *et al.* 2005; Carr *et al.* 2006; Graham *et al.* 2007). The upper limits of erosion by the last ice sheet on mountains in NW Scotland were shown to indicate extension of ice cover far beyond the limits of the 'restricted ice sheet' model (Ballantyne *et al.* 1998a, 1998b). Finally, bedrock and boulder samples from Orkney, Caithness and NE Scotland yielded post–LGM TCN ages within the (recalibrated) age range ~21–16 ka, demonstrating that these areas were over-run by the SIS (Phillips *et al.* 2008; Ballantyne 2010). Such findings forced abandonment of the 'restricted ice sheet' model in favour of a much larger ice sheet that in many respects resembles that proposed a century earlier.

3. Ice-sheet expansion and maximum extent

Recent reconstructions of the maximum extent of the last BIIS (Bradwell *et al.* 2008b; Chiverrell & Thomas 2010; Gibbard & Clark 2011; Clark *et al.* 2012; Hughes *et al.* 2014, 2016) depict extension of Scottish ice to the Atlantic Shelf edge, and southward into the Irish Sea Basin (ISB) and across northern England. To the east, they show confluence with the FIS, flow of ice from the Moray Firth northwestward across Caithness and Orkney, and southeastward diversion of ice from eastern Scotland in the western NSB. The only outer terminus of glacier ice nourished solely in Scotland therefore lay along the Atlantic Shelf between ~56°N and ~61°N (Fig. 3), as in all other sectors it was confluent with ice nourished in Norway, northern England, Wales and Ireland, and such confluence zones migrated during ice-sheet expansion and retreat. The evidence favouring this interpretation is outlined below.

Reconstructed flowlines indicate that as the ice sheet expanded, ice from different centres of dispersal met and interacted, ice divides built up and migrated, and the directions of ice movement changed in response. As the ice sheet grew, ice streams (zones of fast flow) developed and assumed dominance in discharging ice towards the ice-sheet margins, probably triggering drawdown of the ice surface. Moreover, ice expansion was asynchronous: different sectors of the SIS reached their maximum extent at different times. Below we consider the evidence relating to timing of the initial growth of the SIS and a reconstruction of the overall pattern of ice-sheet expansion, before focusing on the detailed evidence in three sectors: (1) southern and SW Scotland; (2) eastern Scotland, Orkney, Shetland and the NSB; and (3) western Scotland, the Hebrides and the Atlantic Shelf.

3.1. Initial expansion of the last ice sheet

The extent of glacier ice in Scotland prior to expansion of the last ice sheet is unknown, but may be inferred from the flux of ice-rafted detritus (IRD) of British provenance in cores retrieved from the NE Atlantic. Investigation of the magnetic signature of IRD in core MD95-2006 from the distal northern part of the Barra-Donegal Fan (BDF) by Peters *et al.* (2008) indicates very limited contribution from Scotland prior to ~38.5 ka, but an increased contribution thereafter, suggesting expansion of marine-terminating glaciers nourished in the Highlands. Core MD04-2882 from the Rockall Trough contains evidence of IRD derived from a nascent BIIS after ~43 ka (Hibbert *et al*. 2010) and suggests the intermittent presence of marine-terminating glaciers in western Scotland until ~35 ka and the continuous presence of a tidewater ice margin thereafter. This evidence implies that an ice cap or icefield extended to sea level in the western Highlands several millennia before its expansion to cover low ground and the adjacent shelves.

Radiocarbon ages for organic material buried under till deposited by the SIS (Table 1) indicate that most low ground was ice free before ~35 cal ^{14}C ka and possibly as late as ~32 cal ^{14}C ka. Faunal and floral assemblages from the sites at Balglass Burn and Sourlie indicate cold tundra conditions and permafrost (Bos *et al.* 2004; Brown *et al.* 2007), consistent with the coeval presence of glaciers in the Highlands. The Balglass site lies only ~20 km from the Highland edge, yet the mean age of six samples from this site indicates that it was not over-run by Highland ice until after 36.0–34.9 cal ^{14}C ka, and the youngest age suggests that it may not have been over-run until after ~32 cal ^{14}C ka. Of the uppermost four radiocarbon ages obtained by Whittington & Hall (2002) for bulk samples from organic-rich sands and silts buried under till at Tolsta Head in eastern Lewis, the youngest (30.8–30.1 cal ^{14}C ka) probably reflects contamination, as the underlying three samples yielded consistent ages averaging 33.4–32.8 cal ^{14}C ka; there is also some uncertainty as to whether the overlying till was deposited by Outer Hebrides ice or mainland ice. Collectively, the limiting ages for ice expansion across low ground suggest that during the final millennia of MIS 3 glacier ice expanded from mountain source areas, over-running most low ground after ~35 ka and possibly two or three millennia later.

The timing of ice expansion across the NSB is broadly consistent with the ages obtained from terrestrial sites. Three radiocarbon ages for shells in marine sediments overlain by till within a core from the North Sea Plateau, ~330 km NE of Shetland, yielded (in stratigraphic order) ages of 34.6–34.0, 34.5–33.8 and 34.1–33.3 cal ^{14}C ka, implying that this area remained ice-free until at least ~34 ka (Rise & Rokoengen 1984; Sejrup *et al.* 1994). Similarly, samples of foraminifera and shell fragments in glacially deformed glacimarine sediments in core BGS BH 04/01, from the Witch Ground Basin, ~175 km NE of Rattray Head, produced ages of 35.0–33.9, 39.1–30.9, 35.0–29.1 and 35.8–31.3 cal ^{14}C ka (Graham *et al.* 2010). Although three of these ages have large uncertainties, the median ages associated with these samples (34.8–32.2 cal ^{14}C ka) suggest that the Witch Ground Basin remained largely ice-free until ~34–33 ka.

3.2. The overall pattern of ice-sheet expansion

Understanding of the evolution of the SIS has been transformed by remote mapping of landforms indicative of the direction of former ice movement (drumlins, streamlined drift ridges, mega-scale glacial lineations (MSGLs), ribbed moraine and meltwater channels) and the grouping of such landforms into discrete flowsets that represent different phases of ice movement. Overprinting of one flowset by another indicates the relative chronology of ice flow trajectories (Fig. 4), though it does not exclude the possibility that the oldest flowsets identified in this way represent pre-Late Devensian ice flow directions, and some supposed flowsets in areas of thin drift cover may be influenced by underlying rock structure (Hall & Riding 2016; Merritt *et al.* 2017). Using this approach, and incorporating data on erratic transport and offshore landforms, Hughes *et al.* (2014) developed a first-order reconstruction of the stages of ice sheet expansion (Fig. 5). Stage 1 of their reconstruction envisages congruent ice caps over the Highlands and Outer Hebrides, and approximates conditions around 35–32 ka when ice enveloped the Midland Valley. Stage 2 depicts initial build-up of an ice divide over SW Scotland and extension of Scottish ice deep into the Irish Midlands. By stages 3 and 4 thickening and expansion of the Irish

Ice Sheet and Southern Uplands ice dome has resulted in development of an ice divide between SW Scotland and Ireland; at this time the ice margin is inferred to have approached or reached the Atlantic Shelf edge. Stage 5 depicts the SIS terminating westward at the Atlantic Shelf edge and eastward confluence with the FIS, forcing ice flowing eastward from Scotland to divert northwestward across Caithness and Orkney and southeastward across NE England and into the southern NSB. This stage approximates the maximum extent of glacier ice sourced in Scotland, which Hughes *et al.* (2014) suggested occurred between 28 ka and 26 ka. Southward ice expansion, however, is depicted as continuing during stage 6, by which time they depict retreat of the northern ice margin, development of an ice cap over Shetland and partial decoupling of the SIS and FIS.

Notable features of the pattern of ice-sheet build up proposed by Hughes *et al.* (2014) include persistence of a migratory N–S ice divide extending southward from the NW Highlands, and development of an ice divide between SW Scotland and NE Ireland, which limited the flow of Scottish ice into the ISB. They acknowledged that the timing of ice-sheet build-up is poorly constrained, and that their reconstruction (Fig. 5) may conflict with more detailed evidence in particular sectors. It nevertheless shows reasonable congruence with numerical models of the pattern of ice-sheet build-up (Boulton & Hagdorn 2006; Hubbard *et al.* 2009; Patton *et al.* 2016) and represents a first approximation that forms a basis for future refinement.

3.3. The southern sector of the ice sheet

The evolution of the southern sector of the SIS has been reconstructed through identification of cross-cutting and overprinted flowsets that indicate migrating ice sheds and major changes in ice movement during ice-sheet expansion. This approach was pioneered in this sector by Salt & Evans (2004) and subsequently developed by Finlayson *et al.* (2010, 2014) for west-central Scotland, and Evans *et al.* (2009) and Livingstone *et al.* (2008, 2010b, 2012, 2015) for northern England and southern Scotland. Palaeoflow directions reconstructed from landforms are complemented by evidence provided by striae, erratic transport and lithostratigraphy. The methodology employed is essentially similar to that employed by Hughes *et al.* (2014; Fig. 4), and it is noteworthy that the flowsets derived independently by three groups of researchers are broadly similar.

Finlayson *et al.* (2010, 2014) showed that initial expansion (after ~35 ka) of ice nourished in the SW Highlands resulted in ice movement eastward across the Midland Valley and southward down the Firth of Clyde, eventually meeting the expanding Southern Uplands ice cap in south Ayrshire (Fig. 6a). Flowset evidence indicates that during this stage Scottish ice may have penetrated up to 200 km southwestward into the Irish Midlands (Greenwood & Clark 2009), and the presence of Ailsa Craig microgranite erratics along the coasts of Wales and eastern Ireland (Sissons 1967; McCabe & Ó Cofaigh 1995) suggests that ice from the SW Highlands reached the ISB. Subsequent expansion and thickening of Southern Uplands ice, however, led to its confluence with the Irish Ice Sheet and formation of a persistent but migratory ice divide across the North Channel between NE Ireland and SW Scotland, so that ice N of the divide was rerouted westward across the Malin Shelf (Finlayson *et al.* 2014) and only ice nourished in the Galloway Hills flowed south into the ISB. A N–S trending ice divide also developed across the

Firth of Clyde from the SW Highlands to the western Southern Uplands, feeding ice movement both westward across the Malin Shelf and eastward across the Midland Valley (Fig. 6b). The flowset evidence mapped by Finlayson *et al.* (2010) suggests that this divide subsequently migrated ~60 km eastward (Fig. 6c), possibly in response to drawdown of ice streaming westward across the Malin Shelf.

Using a similar approach, Livingstone *et al.* (2008, 2010b, 2012, 2015) and Evans *et al.* (2009) reconstructed the evolution of the last ice sheet in the Southern Uplands and northern England. Ice from the Galloway Hills and Southern Uplands initially predominated, carrying erratics into the Eden Valley and possibly crossing the Stainmore Gap through the Pennines. Subsequent development of a NW–SE ice divide across the Solway Firth from SW Scotland to the Lake District (Fig. 7) represents the continuation of that identified by Finlayson *et al.* (2010; Fig. 6b) farther north. This divide separated southward ice flow from Galloway into the ISB and eastward flow of ice from the Southern Uplands and Lake District into the Tyne valley. During the LLGM, high ground in the Southern Uplands and Cheviots appears to have been occupied by cold-based ice domes (Mitchell 2007, 2008) that fed ice flowing eastward across the Midland Valley and southwards into the Tweed valley (Everest *et al.* 2005). Ice flowing eastward through the Midland Valley to the Firth of Forth was diverted SE near the coast, joining that from the Tweed and Tyne and extending southwards to NE Yorkshire (Fig. 7). Livingstone *et al.* (2012) suggested that this general pattern of ice movement persisted for several millennia. Southward-flowing ice from Galloway continued to flow into the ISB, joining ice from the Lake District, Wales and Ireland to form the Irish Sea Ice Stream (ISIS). Scourse and Furze (2001) placed the southernmost extent of the ISIS at a transition from subglacial till to glacimarine facies at ~49.5°S, but Praeg *et al.* (2015) have presented lithostratigraphic and geophysical evidence suggesting that the ISIS extended > 150 km father south, potentially reaching the Celtic Sea shelf edge as a result of short-lived surging. Bayesian modelling based on published age data suggests that the ISIS achieved its maximum southern reach between ~24.3 and 23.0 ka (McCarroll *et al.* 2010; Chiverrell *et al.* 2013), but TCN and luminescence dating evidence implies that it impinged on the Scilly Isles at ~26–25 ka (Smedley *et al.* 2017a).

3.4. The northeastern and eastern sector of the ice sheet

Although it is generally accepted that the SIS was confluent with the FIS in the NSB, there remains uncertainty regarding the pattern and sequence of ice movement during both ice-sheet expansion and retreat. Here we consider first the terrestrial evidence for key areas (Shetland, Orkney, Caithness and NE Scotland) then changing interpretations of the pattern of ice movement in the NSB during the LLGM.

3.4.1. Shetland. Interpretation of the Late Devensian glacial history of Shetland has polarized around two viewpoints: (1) that the islands were over-ridden by ice moving westward towards the Atlantic shelf edge, but later developed an independent ice cap; and (2) that the archipelago nourished a persistent ice cap of sufficient size to repel invasion by ice advancing from the NSB. The first interpretation, promoted by Peach & Horne (1879), was accepted in recent syntheses based mainly on glacial bedforms on the adjacent shelf (Bradwell *et al.* 2008b;

Graham *et al.* 2011; Clark *et al.* 2012), and was supported by interpretation of onshore streamlined bedforms in parts of the archipelago (Golledge *et al.* 2008) and research on glacitectonic fabrics (Carr & Hiemstra 2013). These interpretations contrast with the work of Flinn (1977, 1978a, 2009) who demonstrated that striae, plucked bedrock and roches moutonnées exhibited a consistent radial pattern away from an ice divide aligned N–S along the spine of the Shetlands.

Review of the field evidence by Hall (2013) supports the independent ice cap hypothesis. He argued that the pattern of streamed bedforms is consistent with divergent ice flow beneath a Shetland ice cap, and that glacitectonic structures interpreted as indicating ice flow from the NSB (Carr & Hiemstra 2013) are unreliable. He noted also the absence of E–W streamlined bedforms or ice-moulded bedrock across central Shetland and, tellingly, the absence of erratics or marine shells derived from the NSB in the tills of eastern Shetland. Development of an independent Shetland ice cap that persisted during the LLGM is also evident in numerical simulations of the last BIIS (Hubbard *et al.* 2009) and supported by extension of till of Shetland provenance up to ~110 km E of the archipelago (Peacock 1995). It is also consistent with the pattern of retreat indicated by submarine moraine banks, which show that ice margins converged on Shetland after the LLGM (Bradwell *et al.* 2008b; Clark *et al.* 2012). The pattern of offshore moraine banks and data on offshore till lithology led Hall (2013) to conclude that during the LLGM the Shetland Ice Cap extended NW–SE over at least 160 km to the Atlantic shelf edge, diverting the FIS northwestward and ice from the Moray Firth and NSB across northern Orkney.

3.4.2. Caithness and Orkney. The last glaciation of Caithness has traditionally been interpreted as a two-stage event in which initial ice movement northeastward from Sutherland was succeeded by N to NW movement of Moray Firth ice, which deposited an extensive grey till containing marine shells (Peach & Horne 1881; Hall & Whittington 1989). Lithostratigraphic research by Hall *et al.* (2011) and Hall & Riding (2016) indicates a more complex event stratigraphy in which radial outflow of ice from ice centred over the hills of the Sutherland-Caithness border was succeeded in turn by (1) retreat of the ice margin from the north coast, (2) an initial advance of Moray Firth ice northwestward across the Caithness plain and (3) retreat of the ice margin, represented by deposition of fan gravels at the north coast. This was followed by the main northwestward advance of Moray Firth ice across Caithness, which deflected flow of Highland ice northwards and deposited the widespread shelly till (the Forse Till). Excluding outliers, six TCN ages obtained by Phillips *et al.* (2008) for deglaciation of sites in northern and SE Caithness range from 20.5 ± 3.2 ka to 16.0 ± 1.1 ka, indicating that the main advance of Moray Firth ice across Caithness occurred during the LLGM.

On Orkney the evidence provided by striae, glacial lineations, erratic transport and till containing marine shell fragments and palynomorphs demonstrates general ESE to WNW movement of glacier ice across the archipelago (Peach & Horne 1880; Sutherland 1984; Hall *et al.* 2016b). Eight TCN ages for low ground have produced post-LGM ^{10}Be exposure ages (Phillips *et al.* 2008), confirming that the last movement of glacier ice across the archipelago occurred during the Late Devensian; a single (recalibrated) TCN age of 20.6 ± 1.2 ka for a boulder at 467 m altitude on Ward Hill indicates complete over-running of all high ground.

Unlike Shetland, there appears to be no evidence for a former independent ice cap on Orkney (Hall *et al.* 2016b).

Hall *et al.* (2016b) identified three tills on Orkney, and related these to three phases of ice movement. The earliest till appears to record ice movement from a more southerly direction than the overlying widespread Scara Taing Till, the stratigraphic equivalent of the Forse Till of Caithness. This till was emplaced by ice moving SE–NW, and in northern Orkney contains rare far-travelled erratics that can be linked to sources in the Northern Highlands, Inner Moray Firth, Grampian Highlands, Fennoscandia and possibly eastern Scotland, implying a complex history of transport and reworking. The uppermost till was apparently deposited by a late readvance of ice across low ground. Noting that the palynomorph assemblages in the Orkney tills are dominated by material sourced from the inner Moray Firth and the shelf SE of Orkney, Hall *et al.* (2016b) argued that the rare Scandinavian erratics detected in Orkney till are reworked, and that the last FIS did not impinge on these islands.

Although Hall & Riding (2016) and Hall *et al.* (2016b) acknowledged that expansion of the FIS and Shetland Ice Cap could have been responsible for deflection of Moray Firth ice NW across Caithness and Orkney, they advocated other scenarios for such deflection, such as eastwards shift of the former ice shed or, somewhat confusingly, '…ice congestion in the northern North Sea'. An alternative solution is that a SW–NE aligned ice divide (Sejrup *et al.* 2016) or migrating ice divide (Merritt *et al.* 2017) developed between NE Scotland and SW Norway during the LLGM (Fig. 8) forcing ice from the Moray Firth to flow NW toward the Atlantic Shelf edge.

3.4.3. NE Scotland. The record of glaciation in NE Scotland (the Moray Firth lowlands and Buchan) has been reviewed by Merritt *et al.* (2017), who attempted to reconcile published data on erratic transport and striae with the detailed lithostratigraphy of Merritt *et al.* (2003), the pattern of subglacial bedforms mapped by Hughes *et al.* (2010) and the flowsets derived from these bedforms (Hughes *et al.* 2014) in an event stratigraphy. The earliest stage identified by Merritt *et al.* (2017) is represented by till deposited by ice flowing from the NW across the north coast of Buchan. Stage 2 in their scheme (Fig. 8a) involved southeasterly ice flow across the coastal lowlands of Moray and Buchan into central and eastern Buchan. They suggested confluence with southeasterly ice movement from the eastern Grampians across Angus at this time, and envisaged contemporaneity with ice movement NW across Caithness and Orkney. During stages 3 and 4, ice flow from the Moray Firth apparently swung to the ENE before curving northwestward across Orkney. To accommodate this switch, Merritt *et al.* (2017) suggested progressive eastwards migration of an ice divide (from position 1 in Fig. 8b to position 2) and establishment of a NW-flowing ice stream in the Orkney-Shetland Channel at this time, with the ice margin at the Atlantic Shelf edge. Their reconstruction of these stages depicts persistence of a Shetland Ice Cap as argued by Hall (2013), as well as ice from the Eastern Grampians flowing eastwards to southeastwards across eastern Buchan, Angus and Fife. Farther inland, the absence of schist erratics on the central Cairngorms (Sugden 1970) and radial dispersal of Cairngorm granite erratics (Sutherland 1984) suggests that this massif acted as a centre of ice dispersal and persisted as a local ice dome that diverted ice from the Grampians into Strathspey and the Dee valley.

3.4.4 The North Sea Basin (NSB). Confirmation that the central and northern NSB were completely covered by conjoined ice sheets during the LLGM comes from several sources. Radiocarbon ages of molluscs and foraminifera within undisturbed marine or glacimarine sediments overlying glacially-deformed marine sediments or till range from ~26.5 to ~17.2 cal ^{14}C ka (Sejrup *et al.* 1994, 2009, 2015; Graham *et al.* 2010). Though the oldest ages may be stratigraphically unrepresentative (Sejrup *et al.* 2016), these dates confirm that the underlying sediments were deformed or emplaced by Late Devensian (Late Weichselian) ice, and the younger ages indicate marine sedimentation following ice-sheet retreat prior to ~18–17 ka. Microfabric analyses of key formations in the NSB indicate complete ice cover during the LLGM (Carr *et al.* 2006) and mapping of moraines and subglacial tunnel valleys from bathymetric and seismostratigraphic data (Lonergan *et al.* 2006; Bradwell *et al.* 2008b; Clark *et al.* 2012) also indicates complete ice cover across the northern NSB during the LLGM. Finally, research by Graham *et al.* (2007, 2010) based on 3D reflection seismic data covering the Witch Ground Basin (Fig. 8) has revealed NW-trending buried mega-scale glacial lineations, 5–20 km long, interpreted as demonstrating confluence of the SIS and FIS, and development of a former ice stream that flowed NW towards the Orkney-Shetland channel or SE towards the central NSB. The timing of ice build-up in the NSB remains uncertain. Analysis of the available chronological data by Hughes *et al.* (2016) suggested that parts of the NSB may have been ice free as late as 29–28 ka, but that the central and northern NSB were completely ice-covered by 27 ka.

There are conflicting views regarding the pattern of ice movement in the NSB during the LLGM. The traditional view was that the expanding FIS acted as a barrier that forced eastward moving ice from NE Scotland to turn northwestward across Caithness and Orkney, and ice from SE Scotland to turn southeastward then southward toward the English coast. A refinement of this interpretation is that the NW-trending MSGLs in the Witch Ground Basin identified by Graham *et al.* (2007, 2010) represent a confluence zone between the FIS and SIS that extended NW across northern Orkney, implying that Shetland was over-run by ice from Norway (Bradwell *et al.* 2008b; Chiverrell & Thomas 2010; Hughes *et al.* 2014; Fig. 9). Clark *et al.* (2012), however, depicted a broad ice divide extending from NE Scotland to SW Norway, an interpretation consistent with modelling experiments (Boulton & Hagdorn 2006; Patton *et al.* 2016). This view was developed by Sejrup *et al.* (2016), who argued that the MSGLs in the Witch Ground Basin were produced by ice streaming to the SE rather than NW. The migratory ice shed proposed by Merritt *et al.* (2017, Fig. 8b) represents a variant of this model consistent with switching ice-flow directions on land. The concept of a SE-migrating divide spanning the northern NSB appears to accommodate the available terrestrial and offshore evidence better than the 'confluence' model (Fig. 9), but remains to be confirmed.

3.5. Western Scotland, the Hebrides and the Atlantic Shelf

The evidence provided by striae, erratic distribution and blockfields indicates that during ice-sheet build-up the islands of Skye, Mull and Arran developed cold-based mountain ice caps that diverted flow of mainland ice and probably remained centres of ice dispersal through the lifetime of the SIS, though all other islands in the Inner Hebrides were ultimately over-run by ice flowing westward from the Scottish Mainland (Bailey *et al.* 1924; Tyrrell, 1928; Gemmell 1973; Dahl *et al.* 1996; Ballantyne & McCarroll 1997; Ballantyne 1999; Finlayson *et al.* 2014; Ballantyne *et al.* 2016). A larger independent ice cap formed over the Outer Hebrides. Mapping of striae and ice-moulded bedrock by Flinn (1978b), Von Weymarn (1979) and Peacock (1984, 1991) demonstrated former radial ice movement on Lewis and Harris, though occurrences of shelly tills and mainland erratics indicate that mainland ice impinged on eastern Lewis at some stage, and probably crossed northernmost Lewis (Peacock 1984). Striae, ice moulding and erratic transport imply that a N–S aligned ice divide developed along the western margin of the Uists and Benbecula (Coward 1977; Flinn 1978b; Peacock & Ross 1978; Selby 1989). Preservation of blockfields and tors on mountain summits on Harris and South Uist suggests that these were occupied by cold-based ice throughout much or all of the Late Devensian (Ballantyne & McCarroll 1995; Ballantyne & Hallam 2001). The Outer Hebrides Ice Cap appears to have acted as a centre of ice dispersal throughout the evolution of the SIS, feeding ice W across the Hebrides Shelf (Selby 1989; Stoker *et al.* 1993; Ballantyne *et al.* 2017), NE into the Minch Ice Stream (Bradwell *et al.* 2007), and southward to feed the Hebrides Ice Stream (Howe *et al.* 2012; Dove *et al.* 2015; Fig. 9).

The evidence for extension of the SIS to the Atlantic Shelf edge has been inferred from the stratigraphy of large submarine shelf-edge fans (trough-mouth fans), and the distribution and alignment of moraine banks at or near the shelf edge. Four fans abut the shelf edge: the Barra-Donegal Fan (BDF; ~6300 km^2), the Sula Sgeir Fan (SSF; ~3750 km^2), and the smaller Rona and Foula Wedges (Fig. 9). Deposition of glacigenic sediment on the SSF has been linked to a former ice stream, the Minch Ice Stream (Stoker & Bradwell 2005; Bradwell *et al.* 2007; Bradwell & Stoker 2015b) and the BDF acted as depocentre for sediment deposited by converging ice from western Scotland (the Hebrides Ice Stream) and Ireland (Dunlop *et al.* 2010; Howe *et al.* 2012; Ó Cofaigh *et al.* 2012; Finlayson *et al.* 2014; Dove *et al.* 2015). The link between the Rona and Foula Wedges, submarine troughs and former ice streams is less clear, though the latter may have acted as a depocentre for ice flowing westward through the Orkney-Shetland channel (Fig. 9).

The advance of the ice margin toward the edge of the Malin Shelf is indicated by the lithostratigraphy and ice-rafted debris (IRD) flux recorded in core MD95–2006, a 30 m long sediment core recovered from the distal northern part of the BDF. At 21.5 m depth within this core there is an abrupt change from hemipelagite and muddy contourite to glacimarine mud with sandy turbidites, which has been interpreted as indicating proximity of the ice margin (Kroon *et al.* 2000; Knutz *et al.* 2001). This change is accompanied by a marked increase in basaltic IRD derived from the Cenozoic igneous provinces of western Scotland and NE Ireland. Radiocarbon dating of polar and subpolar foraminifera recovered from this core suggests that the onset of ice-proximal glacimarine conditions occurred shortly after ~30 cal ^{14}C ka, at the MIS 3/2 transition, though the precise timing of maximum ice extent is difficult to define (Wilson *et al.* 2002; Bradwell *et al.* 2008b). Based on this record, and associated geophysical data (Knutz *et al.* 2002), it has been inferred that ice feeding the BDF reached its maximum extent at ~27 ka, generating turbiditic flows on the fan (Wilson & Austin 2002; Scourse *et al.* 2009). This proposition may be supported by a marked increase in IRD flux in deep-ocean core MD04-2822, from a location distal to the BDF, at ~27.4 ka, though this could also represent partial ice-margin collapse or surging behaviour (Hibbert *et al.* 2010). The SSF also comprises marine or glacimarine muds alternating with packages of glacigenic mass-flow deposits and sandy turbidites, the latter indicating proximity of the former ice-sheet margin (Stoker & Holmes 1991; Stoker 1995; Baltzer *et al.* 1998), and sediment sequences on the Rona and Foula Wedges also demonstrate ice-proximal deposition, probably during MIS 2 (Stoker *et al.* 1993, 1994). Arrival of the ice margin at or near the West Shetland Shelf break may be indicated by increased IRD flux at ~29 ka in deep-ocean core MD04-2829 from the Rosemary Bank (58.95°N, 09.57°W; Scourse *et al.* 2009). Collectively, the available dating evidence appears to place the arrival of the Hebrides and Minch ice streams on the outer shelf within the period 30–27 ka. The latter date has been assumed by several authors, but it seems possible that these ice streams may have reached the outer shelf edge 2–3 ka earlier, depending on the interpretation of the lithostratigraphy and IRD flux in deep-ocean cores.

In this context, ^{10}Be exposure ages obtained for samples from eight glacially-transported boulders on the island of North Rona on the Shetland shelf (59.1°N, 05.8°W) are interesting. These indicate the timing of retreat of the ice margin from the outer shelf, and yielded a reported mean age of 24.8 ± 2.7 ka (Everest *et al.* 2013). Recalibration produces individual ages of 34.0 ± 2.0 ka to 23.4 ± 1.4 ka; excluding three outliers, the weighted mean age of the remaining five samples is 28.7 ± 1.4 ka. This appears to imply both extension of the ice margin in this sector *and its subsequent retreat* before ~29–28 ka. This conclusion should be treated with caution, however, because of the large dating uncertainty, and in the light of research suggesting that ^{10}Be exposure ages for sites at the periphery of former ice sheets may be compromised by subsurface production of ^{10}Be by deeply-penetrating muons, yielding exposure ages that may be 'too old', even when they exhibit good internal agreement (Briner *et al.* 2016; Smedley *et al.* 2017b).

Submarine moraine banks recording former ice margin positions on the Atlantic Shelf were first mapped by Selby (1989), Stoker & Holmes (1991) and Stoker *et al.* (1993). Identification of the pattern of moraine banks on the Hebrides and West Shetland Shelves and northern NSB has been transformed by mapping based on the Olex bathymetric database (www.olex.no), which has been used to generate images of seabed relief (Fig. 10). Ridges evident from Olex-based imagery have been mapped by Bradwell *et al.* (2008b) and Clark *et al.* (2012), both of whom interpreted these features as ice-marginal moraines (or moraine banks) deposited by grounded ice. These ridges often exceed 1 km in width, suggesting that they represent prolonged deposition and glacitectonic deformation of sediment at oscillating grounding-line margins. The maps produced by Bradwell *et al.* (2008b; Fig. 11) and Clark *et al.* (2012) differ only in detail.

The outermost ridges ('Group 1 ridges' in Fig. 11) are broadly arcuate features at or near the shelf edge. These are typically 2–10 km wide and up to 60 km long, and were interpreted by both Bradwell *et al.* (2008b) and Clark *et al.* (2012) as demonstrating extension of the SIS to the shelf break (Fig. 9). Farther south, the Olex database is incomplete, but using the multibeam swath bathymetric data of the Irish National Seabed Survey, Dunlop *et al.* (2010) mapped moraines deposited by westward-moving ice from Scotland on the Malin Shelf east of the BDF between 55.5°N and 56.3°N. Here the outermost ridge runs approximately parallel to the shelf edge, which exhibits furrows attributed to iceberg scour, suggesting that the grounded ice margin became marine-based as a result of advance into deep water or as a consequence of sea-level rise.

Although similar shelf-edge moraines W of Ireland have been shown to represent the limit of the last BIIS (Peters *et al.* 2015; Ballantyne & Ó Cofaigh 2017), there is persuasive evidence that those on the edge of the northern Hebrides Shelf were deposited by an earlier, pre-MIS3/2 ice sheet (Stoker *et al.* 1993, 1994; Stoker 1995, 2013). Seismostratigraphic research by Stoker & Holmes (1991) demonstrated that the shelf-edge moraines in this sector pre-date similar moraines on the West Shetland Shelf, being separated by an angular stratigraphic discordance. Though the time interval represented by this discordance is unknown, they postulated that that the two sets of moraines were deposited during two different glaciations. This conclusion was supported by amino-acid diagenesis, which indicated that the moraines on the outer Hebrides Shelf pre-date MIS 3 (Stoker & Holmes 1991; Stoker 2013; Stoker & Bradwell 2005). Recent reappraisal of the pattern of moraine systems on the northern and central Hebrides Shelf by Bradwell & Stoker (2015a) conforms to the stratigraphic evidence, and suggests that ice moving westward from the Outer Hebrides during the LLGM extended no farther than mid-shelf (Fig. 12). This interpretation is supported by research on the St Kilda archipelago, 65 km W of the Outer Hebrides and 40–60 km E of the shelf break, which has demonstrated that the last ice sheet failed to encroach on these islands (Sutherland *et al.* 1984; Hiemstra *et al.* 2015; Ballantyne *et al.* 2017). Collectively, the evidence outlined above conflicts with the simple 'shelf-edge' configuration of the last ice sheet promoted by Bradwell *et al.* (2008b) and Clark *et al.* (2012). The actual extent of the last ice sheet on the northern Hebrides shelf remains uncertain. It has been depicted as a broad arc extending west of the Outer Hebrides but terminating just east of St Kilda (Selby 1989; Stoker *et al.* 1993). Bradwell & Stoker (2015a, p. 317) suggested that the LLGM ice margin was '…situated close to the present-day coastline in NW Lewis…' though this interpretation is based solely on interpretation of submarine moraine configuration from bathymetric imagery. Conversely, the TCN ages obtained on North Rona (28.7 ± 1.4 ka; Everest *et al.* 2013) and a radiocarbon age of 22.5 ± 0.3 ^{14}C ka BP (27.2–25.9 cal ^{14}C ka) reported by Peacock *et al.* (1992) for a bivalve from glacimarine sediments west of moraine banks south of St Kilda suggest extension of Outer Hebrides ice to at least mid-shelf.

The evidence outlined above contravenes the widespread belief that there is '…unequivocal evidence for glaciation to the continental shelf edge all the way from SW Ireland to the Shetland Isles' (Clark *et al.* 2012, p. 141), a proposition widely accepted in most recent accounts (Hubbard *et al.* 2009; Chiverrell & Thomas 2010; Gibbard & Clark 2011; Hughes *et al.* 2014, 2016). It demonstrates that westward advance of the last ice sheet was not halted by increasing water depth in all sectors. On the West Shetland Shelf, however, the mapped shelf-edge moraines are associated with stratigraphic units of inferred Late Devensian age (Stoker & Holmes 1991; Bradwell & Stoker 2015a; Fig. 12), implying that ice moving NW across the shelf in this area terminated at the shelf break.

3.6. Ice sheet expansion: synthesis

The evidence summarised above indicates that marine-terminating ice existed in Scotland for several millennia prior to growth of the last SIS, and that ice expansion across low ground and the adjacent shelf commenced within the period 35–32 ka. To the south the expanding ice sheet initially invaded Ireland, the ISB and northern England before establishment of an ice divide across the North Channel limited southward ice flow. A N–S ice divide developed between the SW Highlands and N England producing dominantly westerly ice flow toward the Malin Shelf and easterly flow towards the NSB. Ice from eastern Scotland was confluent with the FIS in the NSB, but there is debate as to whether this ultimately resulted in confluent flow of ice towards the NW or establishment of a (migratory) ice shed between NE Scotland and Norway that resulted in northwesterly flow of ice from the Moray Firth and the NSB across Caithness and Orkney. Both Shetland and the Outer Hebrides probably developed independent ice caps that persisted as centres of ice dispersal throughout the expansion of the SIS. Glacigenic sedimentation on shelf-edge fans, the seismostratigraphy of the outer shelf, and the alignment of submarine moraine banks collectively suggest that the last SIS probably extended to the Atlantic shelf edge in most sectors, but no farther than mid-shelf on the Hebrides Shelf.

Assumption of ice-sheet expansion from the Scottish mainland after ~34 ka, as suggested by the terrestrial dating evidence, implies that growth of the SIS to its maximum extent on the Atlantic shelf occurred over 4000–7000 years. Irrespective of the exact timing of the LLGM in this sector, the northern parts of the SIS appear to have reached their maximum extent prior to the global LGM of ~26.5–19 ka (P.U. Clark *et al.* 2009), probably reflecting the relatively small size of the SIS and position adjacent to the Atlantic Ocean, which was a source of moisture-bearing airmasses that fed rapid ice-sheet growth so that ice centres responded rapidly to climate deterioration (Hughes *et al.* 2016; Patton *et al.* 2016).

4. Trimlines, blockfields and the vertical dimension of the last ice sheet

Two conflicting forms of evidence have informed interpretation of the vertical extent of the last ice sheet. Ice-moulded bedrock, striae, erratics and perched boulders occur on some mountain summits, implying over-running by wet-based glacier ice (Figs. 13a and 13b). Conversely, others are mantled by periglacial blockfields, sometimes interrupted by tors and outcrops of shattered rock (Figs. 13c and 13d). The contrast between blockfields on summits and ice-scoured bedrock on lower slopes in NW Scotland was initially interpreted as representing the upper limit of the SIS, implying that some summits remained above the ice sheet as nunataks (J. Geikie 1878, 1894; Godard 1965). The restricted ice sheet model proposed by Bowen *et al.* (1986) favoured this view, and stimulated mapping across NW Scotland of trimlines marking the altitudinal boundary between ice-scoured terrain and blockfields. In Sutherland, for example, mapped trimlines descend northwestward from ~850 m to ~600 m near the coast (McCarroll *et al.* 1995) and across Wester Ross they descend northwestward from > 900 m near the watershed to ~700 m near the coast (Ballantyne *et al.* 1997).

Ballantyne *et al.* (1998a, 1998b) noted that the trimlines in NW Scotland could represent either an englacial thermal boundary within the SIS, with cold-based ice on high ground remaining frozen to the underlying substrate, or the upper limit of the SIS, and they favoured the latter interpretation. TCN ages for bedrock samples from mountains in Wester Ross, Skye, Harris and Caithness confirmed that whereas below-trimline samples returned ages consistent with the timing of deglaciation, above-trimline samples yielded pre-LLGM ages (Fig. 14). Samples from two erratic boulders resting on a blockfield in Wester Ross gave TCN ages > 55 ka (Stone *et al.* 1998), suggesting that the erratics were deposited by an earlier, thicker ice sheet.

Mapping of trimline altitudes in Caithness, however, showed that that these were inconsistent with TCN ages indicating that Orkney was completely overrun by the last ice sheet (Ballantyne & Hall 2008), causing reinterpretation of Scottish trimlines as thermal boundaries marking the upper limit of erosion by wet-based ice within a much thicker SIS (Kleman & Glasser 2007; Ballantyne 2010; Kuchar *et al.* 2012). This reinterpretation is supported by numerical models of the BIIS, which indicate persistent cold-based ice over mountain summits (Boulton & Hagdorn 2006; Hubbard *et al.* 2009) and evidence of glacial modification of tors on the Cairngorm Mountains (Hall & Phillips 2006). Over-riding of blockfield-mantled summits in NW Scotland by the SIS was tested by Fabel *et al.* (2012), who obtained TCN ages for 14 erratic boulders resting on summit blockfields. Nine of these yielded post-LLGM (recalibrated) ages of 17.5 ± 1.0 ka to 14.9 ± 0.1.5 ka (Fig. 14), demonstrating that the last ice sheet must have overtopped all summits in this area. TCN dating of glacially-deposited boulders on a summit blockfield in southern Ireland confirmed this interpretation (Ballantyne & Stone 2015), suggesting that all summit blockfields in the British Isles represent periglacial regolith that was preserved under cold-based ice during the LGM (Hopkinson & Ballantyne 2014).

Over-running of all mountain summits by the SIS means that the maximum altitude of the ice sheet cannot be deduced directly from field evidence. An early model of the BIIS based on assumption of a uniform basal shear stress of 100 kPa suggested that the SIS had a maximum altitude (relative to present sea level) of 1800–1900 m across much of the Highlands and Southern Uplands (Boulton *et al.* 1977). Later models based on inferred glacio-isostatic depression have indicated maximum ice-surface altitudes of 1000–2500 m, with more recent models favouring thicker ice cover (Lambeck 1995; Shennan *et al.* 2002; Kuchar *et al.* 2012), and Hughes *et al.* (2014) calculated that the altitude of the ice divide over northern Scotland must have exceeded ~1400 m. The climate-proxy-driven, thermomechanically-coupled models of Boulton & Hagdorn (2006) indicate maximum ice altitudes of ~1500 m to ~2250 m across the Central Grampians. Subsequent numerical modelling, however, suggests that the SIS experienced 'binge-and-purge' behaviour, whereby the cold-based upland core was periodically drawn down by fast-flowing ice streams (Hubbard *et al.* 2009; see below). Such behaviour implies that rather than building to a maximum altitude then declining, the thickness of the SIS fluctuated, and that the maximum altitude of the ice sheet varied both spatially and temporally.

5. Ice streams and ice-sheet models

5.1. Palaeo-ice streams of the last Scottish Ice Sheet

Ice streams are corridors of fast-flowing ice within ice sheets (Bentley 1987; Truffer & Echelmeyer 2003; Bennett 2003; Benn & Evans 2010; Rignot *et al.* 2011). Velocities reach several hundreds of metres per year, often over deforming sediments, and their margins are defined by shear zones. Palaeo-ice streams that developed within former ice sheets can be identified by a range of criteria, notably a convergent flow pattern, a distinct flow track with sharply defined lateral margins, markedly elongate bedforms and lineations, and terminal sediment accumulations, often in the form of trough-mouth fans (Stokes & Clark 1999, 2001).

On the basis of such evidence, four eastward-flowing ice streams that drained the SIS have been identified. All exhibit topographic control and extended into the NSB. The Tyne Ice Stream drained ice from the Southern Uplands, Cheviots, Lake District and northern Pennines (Fig. 7). During the LLGM, flow was W–E, but a subsequent shift to southeasterly flow reflects increased dominance of Scottish ice (Livingstone *et al.* 2008, 2010b, 2012, 2015). The ~20 km wide Tweed Ice Stream, reconstructed by Everest *et al.* (2005) from the distribution and orientation of drumlins, megadrumlins and megaflutes, flowed NE to E between the Lammermuir and Cheviot Hills, draining an area of ~3500 km^2 and extending ~65 km to the present coastline. The Strathmore Ice Stream flowed eastward in a ~45 km wide corridor between the Highland edge and NE Fife, is defined by streamlined bedrock and bedforms, and exhibits evidence of a post-LLGM northeastward shift in flow (Golledge & Stoker 2006). Farther north, there is evidence of eastward streaming of ice in the Moray Firth, though changes in the offshore configuration of the Moray Firth Ice Stream remain to be worked out in detail (Merritt *et al.* 1995, 2003, 2017; Graham *et al.* 2009). In the NSB, the NW–SE trending MSGLs identified by Graham *et al.* (2007, 2010, 2011) crossing the Witch Ground Basin (section 3.4.4) have been interpreted as representing development of a former ice stream, though there is debate as to whether this represents former ice streaming NW towards the Orkney-Shetland channel (Fig. 9) or SE away from an ice divide over the northern NSB (Sejrup *et al.* 2016). Hall & Glasser (2003) used the term 'ice stream' to describe the effects of wet-based sliding ice in Glen Avon (Cairngorms), but whether true ice streams developed in the Cairngorm troughs is questionable.

In the western NSB, the coalescence of ice emanating from the Forth, Tweed and probably eastern Grampians (Davies *et al.* 2011) fed the North Sea Lobe (NSL), a major ice stream that moved southwards along eastern England, reaching the Norfolk coast. Livingstone *et al.* (2012) suggested that the NSL was initially constrained by the FIS to the east, but persisted after decoupling of the FIS and BIIS. Moss samples from beneath the lower of two tills (the Skipsea Till) at Dimlington on the Holderness coast of east Yorkshire produced radiocarbon ages of 22.9–21.9 cal ^{14}C ka and 22.4–21.9 cal ^{14}C ka (Penny *et al.* 1969), and OSL dating indicates deposition of the Skipsea Till at ~21.6 ka (Bateman *et al.* 2017), implying that the NSL reached its maximum extent several millennia after the LLGM on the Atlantic shelf. At Dimlington, laminated silts and cross-bedded sands separate the Skipsea Till from an upper till, the Withernsea Till. OSL and radiocarbon ages suggest that the latter was deposited by a readvance that culminated at ~16.8 ka, though as Bateman *et al.* (2011, 2017) acknowledged, this timing appears contrary to wider evidence for advanced deglaciation by this time.

To the south, ice from Galloway joined that from England, Wales and Ireland to feed the Irish Sea Ice Stream (ISIS), which drained >17% of the BIIS. The southern limit of this ice stream has been placed near the edge of the Celtic Sea Shelf (Praeg *et al.* 2015), implying a maximum travel distance exceeding 800 km. To the west, several authors have depicted a Hebrides Ice Stream that was confluent with a North Channel-Malin Shelf Ice Stream fed by ice from northern Ireland (Dunlop *et al.* 2010) and SW Scotland (Finlayson *et al.* 2014), and probably terminated at the shelf break, feeding sediment to the BDF (Fig. 9). Bedform evidence from the main flow track of this postulated ice stream is lacking, but Howe *et al.* (2012) and Dove *et al.* (2015) have shown that elongate streamlined bedforms cut southwestward across structural trends on the seafloor of the Sea of the Hebrides. They interpreted these as representing the onset zone of the Hebrides Ice Stream, where ice accelerated from an area dominated by bedrock obstacles onto the sediment-dominated shelf. Streamlined bedforms in western Kintyre probably represent associated westward ice streaming from the Firth of Clyde, and Finlayson *et al.* (2014) have suggested that the resulting drawdown of ice resulted in a ~60 km westward shift of the N–S ice divide across central Scotland. Whether the landform evidence in the Sea of the Hebrides relates to an ice stream at the LLGM or during overall retreat (as suggested by cross-cutting flow indicators) is uncertain (Dove *et al.* 2015).

The most intensively-researched Scottish palaeo-ice stream is the Minch Ice Stream, first identified by Stoker and Bradwell (2005). During the LLGM it drained an area of 10,000–15,000 km^2 and was fed by ice from the NW Highlands, Skye and eastern Lewis, which converged in the North Minch and followed a ~200 km long, 40–50 km wide trough that terminates at the SSF (Fig. 15). Bradwell *et al.* (2007) identified at least nine land-based onset zones characterised by streamlined landforms. Spectacular bedrock megagrooves formed by subglacial abrasion and meltwater erosion occur in a 20 km wide corridor north of Loch Broom (Bradwell *et al.* 2008c), but probably reflect erosion over several glacial cycles. In the onset zone around Loch Laxford, Bradwell (2013) showed that the zone of accelerated ice flow can be identified from the distribution of bedrock landforms such as roches moutonnées, whalebacks and plucked rock faces. Within the North Minch, the signature of former ice streaming includes an assemblage of 'hard bed' subglacial forms, including large submarine crag-and-tail features, bedrock megaflutes and megagrooves, as well as drumlinoid bedforms in areas of sediment cover (Bradwell & Stoker 2015b). Farther N, the ice stream followed the trough that terminates at the SSF, though it is uncertain whether grounded ice reached the shelf edge or terminated on mid-shelf (Bradwell & Stoker 2015a), possibly with a floating ice shelf extending to the shelf break. Fluctuations in the size and velocity of the ice stream may have resulted in periodic drawdown of ice in source areas, causing shifts in the location of the main N–S ice divide across the NW Highlands (Bradwell *et al.* 2007). Eastward migration of this divide probably explains the eastwards and westwards transport of erratics across the Moine Thrust Zone (Lawson 1990) and from an augen-gneiss outcrop ~15 km E of the present watershed (Sutherland 1984). This interpretation is also consistent with the easterly migration of the ice-divide inferred by Hughes *et al*. (2014; Fig. 5).

5.2. Ice-sheet models

Although the evidence for major ice streams draining the SIS is compelling, the history of most ice streams is poorly constrained. In their reconstruction of ice-sheet evolution, Hughes *et al.* (2014) envisaged initial development of a thick integrated ice sheet, with ice-stream development contributing to subsequent thinning and ice-divide migration during and after the ice sheet achieved its maximum extent, but did not preclude ice-stream formation during ice-sheet expansion. The first numerical simulation experiments driven by proxy climate functions (Boulton & Hagdorn 2006) indicated early development of ice streams draining the predominantly cold-based upland core of the SIS, with resultant drawdown of the ice-sheet surface. Their models also identified major ice discharge arteries at the locations of the Minch, Hebrides, Irish Sea and Moray Firth Ice Streams.

Later thermomechanically-coupled models of the BIIS driven by a scaled NGRIP oxygen isotope curve for the period 38–10 ka (Hubbard *et al.* 2009) have indicated a more detailed scenario. A key finding of the optimal (most geologically-consistent) model is that it retrodicts major 'binge and purge' cycles during the lifetime of the ice sheet, identifying prolonged phases of build-up of cold-based, high-viscosity ice succeeded by 'purge' phases triggered by abrupt warming. Such 'purge' phases are characterised by widespread development of ice streams around the cold-based core of the modelled ice sheet. At such times the ice sheet surface is drawn down but the ice margins advance. The optimal model generates transient but recurrent ice streaming at all the Scottish ice-stream locations described above, and also intervening areas of fast-flowing ice that may have captured ice flow from the known ice-stream locations. It retrodicts limited ice cover (mainly over the Highlands, with tidewater-terminating margins) prior to ~33 ka, followed by extension of the ice margin to (or near to) the Atlantic Shelf edge at ~29 ka during the first major 'purge' event, immediately followed by development of all the Scottish ice streams identified from the geomorphological evidence. It also suggests, however, that small ice streams may have developed during ice-sheet build-up. More generally, this model suggests that though the largest ice streams (the Hebrides and Irish Sea Ice Streams) were active throughout much of the last glacial cycle, smaller ice streams were only intermittently active over centennial timescales.

A notable feature of the optimum model of Hubbard *et al.* (2009) is that it suggests that the initial advance of the SIS to the Atlantic Shelf edge, deep into England and Ireland and far out into the NSB at ~29 ka was followed first by shrinkage to a much smaller ice mass centred on the Scottish Highlands by ~27 ka, then by climate-driven re-expansion to form an even more extensive ice sheet by ~23.7 ka. There appears to be no evidence to support drastic shrinkage of the SIS between 29 ka and 27 ka (many authors have inferred that ~27 ka approximates the timing of the SIS maximum) but this may be because of 'erosion censoring': later, more extensive ice advances obscure or obliterate the geomorphological evidence produced by earlier less extensive events (Kirkbride & Winkler 2012). The same caveat applies to moraine sequences on offshore shelves: nested ice-marginal moraines represent ice extent at particular times, but intervening events involving less extensive ice cover are likely to be absent from the landform record. There may therefore be a prolonged temporal hiatus between one set of moraines and the next, during which the ice margin may have retreated and readvanced on several occasions. Thus although 'outer' moraines are older than 'inner' moraines, the intervening time period may have involved complex changes in ice extent or flow direction.

Below we outline the results of attempts to reconstruct the deglaciation history of the SIS at ice-sheet scale before considering the detailed evidence for particular sectors. Apart from the numerical modelling by Hubbard *et al.* (2009), the former are based on the pattern of offshore landforms, terrestrial flowsets and a patchy distribution of radiocarbon and TCN ages, some of questionable validity. Not all reconstructions are adequately integrated with the stratigraphic record. At the time of writing, a major initiative (the BRITICE-CHRONO project) designed to refine the chronology of BIIS retreat is nearing completion, and promises to yield new insights into the retreat behaviour of the SIS (www.britice-chrono.group.shef.ac.uk).

6. Deglaciation at ice-sheet scale

The earliest reconstruction of the pattern of SIS retreat (Bradwell *et al.* 2008b) was largely based on mapping of moraine banks, moraines and tunnel valleys (excavated by subglacial meltwater) from Olex bathymetric data (Fig. 10). From the location of the outermost moraines ('Group 1' in Fig. 11) they placed the ice margin at the shelf edge at 30–25 ka (Fig. 9). The large lobate, bifurcating and overprinting moraines of their 'Group 2' set they attributed to oscillation of grounded but calving margins and changes in flow direction, possibly related to rising sea level, with localised De Geer moraines indicating grounded tidewater margins. The smaller moraines of Group 3 (Fig. 11) and associated meltwater channels are interpreted as marking a more stable phase of deglaciation (~24–18 ka) following decoupling of the SIS from the FIS. From these patterns and bathymetric data they argued that initial decoupling took the form of development of a elongate marine embayment that extended southward from the shelf edge E of Shetland to the Witch Ground Basin by ~24 ka as sea level rose.

The numerical model of Hubbard *et al.* (2009) differs in suggesting that widespread retreat then readvance of the ice margin occurred between ~29 ka and ~24 ka, with subsequent extensive ice cover until ~19.4 ka, after which it suggests thinning and retreat of all sectors in response to sustained warmer conditions. During the period ~19.4–17.4 ka it indicates dynamic ice-stream activity with switching and competition across core areas, numerous localised, short-lived readvances of the ice margin but persistence of ice cover across the present land area of Scotland. It suggests that after ~17.2 ka, ice was largely confined to Scotland but with substantial advances reaching northern Ireland, renewed ice-stream activity and possible surging into the NSB. By ~15.7–15.6 ka, it suggests break-up of the residual SIS into a substantial ice cap over the Highlands and small ice caps over the Southern Uplands, Outer Hebrides, Orkney and Shetland.

The empirical reconstruction of Clark *et al.* (2012) was based on the terrestrial landform record of the BRITICE database (C.D. Clark *et al.* 2004; Evans *et al.* 2005; subsequently updated by Clark *et al.* 2017), the subglacial bedform record of Hughes *et al.* (2010), independent interpretation of offshore bathymetric data, and compilation of all published ages constraining the timing of ice-margin retreat (Hughes *et al.* 2011). This information was interpreted as a retreat pattern for the entire BIIS (Fig. 16), though Clark *et al.* (2012) acknowledged the uncertainties associated with matching up fragmentary landform evidence. Like Bradwell *et al.* (2008b) the starting point for their reconstruction was an ice sheet terminating at the Atlantic shelf edge at ~27 ka, although as noted in section 3.5 it now seems unlikely that the SIS reached the shelf edge in all sectors. Clark *et al.* (2012) and updated reconstructions based on similar data (Hughes *et al.* 2014, 2016) have outlined subsequent changes to ice-sheet configuration as a series of time slices. Their interpretations of the sequence of events affecting the Scottish Ice Sheet are summarised in Table 2.

The reconstructions outlined above differ in detail and timing of events, but agree on the general sequence, with the exception of the retreat phase at ~27 ka modelled by Hubbard *et al.* (2009) and interpretation of events in the NSB. There is agreement that retreat of ice on the Atlantic shelf was probably driven by sea-level rise, development of calving margins and a prolonged period of dynamic reorganization of the northern SIS, represented by the multiple, sometimes overlapping moraines W of Orkney and N and E of Shetland. The reconstructions also suggest that substantial thinning and retreat of the SIS occurred mainly after ~22 ka, and particularly after ~19 ka, but was a complex affair involving transient ice streaming, divide migration and development of a polycentric ice sheet that was largely confined to the Scottish mainland and adjacent inner shelves by 17–16 ka, with some residual satellite ice caps or icefields.

7. Regional deglaciation 1: the offshore shelves, Northern Isles and Outer Hebrides

7.1. The northern sector of the last Scottish Ice Sheet

Deglaciation of the northern Hebrides Shelf and West Shetland Shelf has been reconstructed by Bradwell & Stoker (2015a), who employed the pattern of ice-marginal landforms mapped from high-resolution echo-sounder data and stratigraphic and sedimentological data (Stoker *et al.* 1993; Stoker & Varming 2011; Stoker 2013) to identify stages in ice-margin retreat (Fig. 12). Intervening and nearshore sequences of small, sharp-crested ridges in various locations are interpreted as De Geer moraines, implying that the larger moraine banks represent grounded ice margins terminating in shallow water.

On stratigraphic grounds (section 3.5 above) Bradwell & Stoker (2015a) assigned the outermost moraines of their stages 1 and 2 (Fig. 12) to deposition by a pre-Late Devensian ice sheet, implying that the oldest moraines of Late Devensian age are represented by their stage 3 ice limit, depicted at the edge of the West Shetland Shelf but on mid-shelf farther SW. As North Rona, where ice retreat was originally dated to ~25 ka (Everest *et al.* 2013; recalibrated as ~29 ka; section 3.5) lies outside this limit, this interpretation appears to imply that the last ice sheet locally extended beyond the mapped stage 3 limit but left no footprint, unless the stage 2 ice limit has been misattributed. Stage 4 implies subsequent recession of the ice margin along the entire sector and suggests early deglaciation of northernmost Lewis. If the suggested configuration of subsequent stages is correct, it implies: (1) very early deglaciation of Cape Wrath, possibly the first part of mainland Scotland to emerge from the ice sheet; (2) early deglaciation of the North Minch and probably parts of eastern Lewis; and (3) progressive decoupling of ice nourished in NW Scotland from an ice mass that covered NE Caithness, Orkney and Shetland. The configuration of this ice mass is less certain. Bradwell & Stoker (2015a) suggested correlation of their stage 9 limit W of Orkney with moraine banks SE of Orkney (Fig. 12), but this solution appears to imply southwards ice movement across the northern coast of Caithness and shrinkage of the ice margin towards a residual ice cap on Orkney. The terrestrial field evidence, however, suggests that the final ice movement across both Caithness and Orkney was SE–NW, with no reported evidence for a late-stage Orkney ice cap (Hall *et al.* 2011, 2016b; Hall & Riding 2016).

The published dating evidence for these events is slender. The inferred stage 3 ice limit must post-date the retreat of the ice margin from North Rona at 28.7 ± 1.4 ka, and TCN dating of the Wester Ross Readvance (section 8.1) places the ice margin across the fjords and peninsulas in the south of the area depicted in Figure 12 at 15.3 ± 0.7 ka (section 8.1 below). Samples from bedrock surfaces and boulders on low ground at sites on Orkney have, excluding outliers, produced five recalibrated ^{10}Be exposure ages of 17.2 ± 2.4 ka to 16.0 ± 2.0 ka (Phillips *et al.* 2008), with a weighted mean age of 16.5 ± 1.2 ka (Fig. 19), indicating that Orkney was largely ice-free by that time. Two samples from Dunnet Head on the N coast of Caithness have a mean age of 17.5 ± 1.1 ka, suggesting deglaciation of the Pentland Firth prior to the final deglaciation of Orkney.

7.2. Shetland

As outlined earlier, there is persuasive (though contested) evidence that an independent ice cap persisted over Shetland throughout the last glacial cycle (Hall 2013). The pattern of offshore moraines is consistent with this interpretation (Figs. 11 and 16), indicating oscillatory retreat of an independent Shetland Ice Cap from the shelf edge and from near the edge of the Norwegian Channel. Bradwell *et al.* (2008b), Clark *et al.* (2012) and Hughes *et al.* (2014, 2016) all depict the ice margin progressively retreating towards Shetland and eventual isolation of an ice cap over the archipelago. The TMC model of Hubbard *et al.* (2009) suggests separation of the Shetland Ice Cap before 17 ka. Radiocarbon dates from marine shells recovered from vibrocores indicate that Shetland ice retreated from the Viking Bank, ~155 ENE of Shetland, before 18.3–17.3 cal ^{14}C ka (Peacock 1995) and from a site ~70 km E of Shetland before ~15.1–14.1 cal ^{14}C ka (Peacock & Long 1994). Basal radiocarbon ages obtained from organic material at sites in southern Shetland indicate deglaciation prior to 15.4–15.2 cal ^{14}C ka (Whittington *et al.* 2003), 16.2–14.8 cal ^{14}C ka (Birnie 2000) and 16.1–15.8 cal ^{14}C ka (Hulme & Shirrifs 1994), though the last-mentioned inferred the onset of postglacial sedimentation as early as 16.9–16.6 ka. Collectively the available dating evidence suggests that isolation of the Shetland Ice Cap occurred before 17 ka, and that much of Shetland was deglaciated between 17 ka and 16 ka.

7.3. The North Sea Basin (NSB)

Interpretation of the timing and nature of the decoupling of the SIS and FIS in the NSB has proved controversial. Forminifera and molluscs within stratified glacimarine or marine sediments overlying till (deformed marine sediments) in a core from the Witch Ground Basin (~162 km NE of Rattray Head) have produced radiocarbon ages of 27.0–26.3, 25.3–24.2 to 23.8–23.0 cal ^{14}C ka (Sejrup *et al.* 1994). The oldest date suggests that the central NSB may have become deglaciated as early as ~27 ka (Sejrup *et al.* 1994, 2009, 2015; Graham *et al.* 2010). Other samples in contexts indicating deglaciation of this area are, however, much younger (< 22 cal ^{14}C ka), suggesting a hiatus in the stratigraphic record (Sejrup *et al.* 2016).

Bradwell *et al.* (2008b) suggested that initial decoupling of the SIS and FIS followed a bathymetric depression that extends from the shelf edge N of Shetland southwards to the Witch Ground Basin. They argued that a calving margin propagated rapidly southward from the shelf edge, creating a marine embayment between the two ice sheets, an interpretation accepted by several authors (Graham *et al.* 2010; Sejrup *et al.* 2015; Merritt *et al.* 2017). The reconstruction by Clark *et al.* (2012) offered two possible scenarios: (1) early (~25 ka) and complete separation of the BIIS and FIS; and (2) partial decoupling of the SIS from the FIS by ~23 ka along a marine embayment similar to that proposed by Bradwell *et al.* (2008b). They noted, however, that the latter scenario requires persistence of a residual ice dome south of the proposed embayment, for which there is no evidence.

An alternative interpretation, proposed by Sejrup *et al.* (2016), is based on bathymetric landform evidence indicating that initial westward extension of ice flowing NW along the Norwegian Channel (a broad bathymetric trough parallel to the coast of SW Norway) is overprinted by moraines indicating ice advance from a Shetland-Orkney ice centre. This evidence suggests that acceleration, thinning and retreat of the Norwegian Channel Ice Stream (NCIS) debuttressed the ice flowing from Shetland and Orkney, causing it to expand eastward (Fig. 17). Radiocarbon-dated records of glacigenic debris flows at the NCIS terminus demonstrate extremely high sediment flux at ~20–19 ka (Nygård *et al.* 2007), which Sejrup *et al.* (2016) attributed to the onset of NCIS acceleration and thinning, and radiocarbon ages relating to its subsequent retreat suggest decoupling of the ice sheets in the eastern NSB at ~18.5 ka, accompanied by drainage of a former ice-dammed lake in the southern NSB (Fig. 17). This interpretation places the line of disengagement of the BIIS and FIS farther east than previously depicted, suggesting that much of the ice occupying the NSB at the time of separation was of Scottish rather than Fennoscandian provenance. Sejrup *et al.* (2016) envisaged that decoupling of the two ice sheets led to reorganization of flow in the BIIS, accompanied by readvances, ice thinning and rapid retreat of its eastern margins (Fig. 17). This interpretation is consistent with persistence of a residual ice mass over Orkney and Shetland (Bradwell & Stoker 2015a) and does not require the existence of a remnant ice dome in the southern NSB, but conflicts with radiocarbon ages from the Witch Ground Basin and eastern Scotland that appear to imply much earlier deglaciation of these areas (McCabe *et al.* 2007; Sejrup *et al.* 1994, 2009, 2015).

Evidence for readvances of Scottish ice into the Witch Ground Basin has been identified by Sejrup *et al.* (2015), who presented bathymetric, stratigraphic and chronological evidence for two such events, the Fladen 1 and Fladen 2 readvances. The location and alignment of the associated ice margins suggests that although they may have been fed by ice from the Moray Firth, they could reflect advance of ice from an Orkney-Shetland centre to the NW. The associated radiocarbon ages are not all in sequence, but Sejrup *et al.* (2015) argued that the Fladen 1 readvance probably occurred at ~17.5 ka and the Fladen 2 event at ~16.2 ka. For the outer Moray Firth, west of the Witch Ground Basin, Graham *et al.* (2009) described evidence suggesting that formation of W–E aligned streamlined bedforms indicative of fast eastward flow of grounded ice was succeeded by westward retreat of the ice margin, then formation of broad N–S aligned morainic banks (the Little Halibut Bank and Bosies Bank) and multiple composite ice-marginal ridges. Farther W a series of transverse ridges indicate marine grounding-line positions or ice-push moraines that are succeeded westward by a zone of hummocky moraine. They interpreted this evidence as demonstrating that initial retreat of the ice margin in the outer Moray Firth was characterised by readvances, stillstands and possible 'surge-like' activity; the hummocky moraine farther west they interpreted as stagnant ice topography, indicating rapid retreat.

7.4. The Irish Sea Basin (ISB)

As outlined in section 3.3, the development of an ice divide between Scotland and NE Ireland during the LLGM appears to have limited the Scottish contribution to the Irish Sea Ice Stream (ISIS) to ice nourished in SW Scotland (Livingstone *et al.* 2012; Hughes *et al.* 2014; Figs. 5 and 7). Initial retreat of the ISIS from the Celtic Sea Shelf appears to have been rapid, with complete deglaciation of the southern ISB by 21.9–20.7 ka (Chiverrell *et al.* 2013; Patton *et al.* 2013; Smedley *et al.* 2017a). Foraminifera in raised marine muds in NE Ireland have yielded ages of 20.4–19.9 cal ^{14}C ka, implying ice-free conditions in the eastern sector of the northern ISB before ~20 ka (McCabe & Clark 1998; P. U. Clark *et al.* 2004).

Interpretation of terrestrial lithostratigraphy and flowsets suggests that the subsequent deglaciation of the northern ISB was complex. Livingstone *et al.* (2012) identified evidence for a readvance of the ice margin, the Blackhall Wood Readvance, fed in part by ice from the Solway region and Galloway. This event they tentatively correlated with the Gosport Oscillation of Merritt & Auton (2000), and they suggested that it may reflect widespread cooling of the NE Atlantic region due to decrease in Atlantic meridional overturning circulation at ~19 ka (P. U. Clark *et al.* 2004; Hall *et al.* 2006). Onshore stratigraphic evidence suggests subsequent deglaciation of the Solway lowlands and almost all of the ISB, followed by a second readvance, the 'Scottish Readvance'. During this event, ice from southern Scotland reoccupied the Solway region and extended as far south as the Isle of Man (Livingstone *et al.* 2010a, 2012, 2015; Fig. 18). Various authors (McCabe *et al.* 1998; McCabe & Clark 1998; Roberts *et al.* 2007; Merritt & Auton 2000) have suggested that the Scottish Readvance correlates with the Killard Point Readvance in NE Ireland, dated to 17.3–16.6 cal ^{14}C ka (Ballantyne & Ó Cofaigh 2017), but Livingstone *et al.* (2010a, 2012) noted that it may have been a short-lived event that could reflect local reorganization of ice flow rather than a regionally significant advance of the ice margin.

Decoupling of the Scottish and Irish Ice Sheets over the North Channel probably occurred between ~16.5 and ~16.0 ka (Clark *et al.* 2012; Finlayson *et al.* 2014), marking the end of ice occupance in the ISB. Retreat of Irish ice from the North Channel was succeeded by a readvance of ice from west-central Scotland across NE Ireland, the East Antrim Coastal Readvance. McCabe & Williams (2012) reconstructed the limits of this readvance across 1800 km^2 of NE Antrim, and argued that it occurred at ~15.6–15.0 ka. This timing was challenged by Finlayson *et al.* (2014), who argued that it conflicts *inter alia* with older TCN exposure ages from the Isle of Arran. They envisaged that invasion of SW-flowing Scottish ice across NE Antrim represented 'debuttressing' of the SW margin of the SIS following collapse of the Irish Ice Sheet around 16.5 ka, but both the timing and cause of this event remain uncertain.

7.5. The western sector of the last Scottish Ice Sheet

The western sector of the SIS comprised a northern zone, where ice from the Outer Hebrides Ice Cap (extended an unknown distance westward across the northern Hebrides Shelf, and a southern zone, dominated by SW flow of the Hebrides Ice Stream towards the shelf edge.

7.5.1. The Outer Hebrides and adjacent Hebrides Shelf. The timing and pattern of retreat of the Outer Hebrides Ice Cap on the Hebrides Shelf is poorly constrained. Peacock *et al.* (1992) reported radiocarbon ages of 22.5 ± 0.3 ^{14}C ka (26.7–26.0 cal ^{14}C ka) for a shell from glacimarine deposits distal to moraine banks in the St Kilda basin ~60 km W of North Uist, and 15.3 ± 0.2 ^{14}C ka (18.3–17.9 cal ^{14}C ka) for another from proximal glacimarine deposits on the same moraine banks. These dates indicate that the moraine banks were deposited by the last ice sheet, and that the ice margin retreated from this location before ~18 ka. For the southern part of the Outer Hebrides Ice Cap, Small *et al.* (2017a) reported mean TCN ages of 18.9 ± 1.1 ka for the deglaciation of Mingulay (but acknowledged that a single age of 17.3 ± 0.9 ka may indicate later deglaciation) and 17.1 ± 1.0 ka for deglaciation of Barra, 27 km farther N. A single (recalibrated) TCN age of 16.3 ± 0.9 ka obtained for a bedrock sample from a col in South Uist (Stone & Ballantyne 2006) suggests prior deglaciation of much of the southern Outer Hebrides (Fig. 19).

Three consistent TCN ages suggest that low ground in southern Harris was deglaciated by ~17.9 ka (unpublished data), implying that by that time the retreating ice cap had split into a southern component occupying the Uists and a northern component centred on the mountains of N Harris. Stone & Ballantyne (2006) obtained TCN ages for bedrock samples on low ground and cols in N Harris, but disparities amongst these suggest that most are compromised by nuclide inheritance. The two youngest (recalibrated) exposure ages indicate deglaciation by 17.3 ± 0.9 ka on low ground and by 16.6 ± 0.8 ka on a col at 425 m OD, and a single age of 15.6 ± 0.8 ka for a sample from the summit of Oreval (662 m OD) suggests that ice may have persisted over high ground as late as 16–15 ka (Fig. 19). No data have been published for the timing of ice retreat on Lewis, but as noted in section 6.2.1, early retreat of the Minch Ice stream and limited extension of the Outer Hebrides Ice Cap west of Lewis (Bradwell & Stoker 2015a) suggest early deglaciation of the coastal fringes of Lewis, followed by gradual ice retreat to the mountains of Harris.

7.5.2. The southern Hebrides Shelf, Malin Shelf and Sea of the Hebrides. The current interpretation of maximum ice extent in this sector is that the Hebrides Ice Stream was confluent with a westward-flowing Malin Shelf Ice Stream (or 'North Channel Ice Stream') that was fed by ice from the Firth of Clyde area, the North Channel ice divide and Ireland. During the LLGM, the confluent ice streams are thought to have terminated at the BDF (Greenwood & Clark 2009; Dunlop *et al*. 2010; Howe *et al*. 2012; Ó Cofaigh *et al*., 2012; Finlayson *et al*. 2014; Dove *et al*. 2015). Evidence for the early deglacial history of the Hebrides Ice Stream is scant. NW–SE aligned moraine banks on the outer Malin Shelf, deposited by ice flowing from the NE (Dunlop *et al*. 2010) suggest that the ice stream dominated the mid- and outer shelf during the early stages of retreat. TCN ages obtained for Bloody Foreland (the NW extremity of Ireland; Ballantyne *et al.* 2007; J. Clark *et al.* 2009) and from Tiree (Small *et al.* 2017a; Fig. 19) indicate deglaciation at ~21 ka, suggesting that at this time the Hebrides Ice Stream had retreated to a line between these two points. The early deglaciation of Tiree (20.6 ± 1.1 ka) and much later deglaciation of the southernmost islands of the Outer Hebrides (18.9 ± 1.1 ka or later; Small *et al.* 2017a) supports the view of Dove *et al.* (2015) that retreat of the ice stream occurred along calving margins above submarine troughs N and S of the Tiree-Coll platform. This interpretation implies that after ~21 ka a marine embayment extended northward, progressively severing the Outer Hebrides Ice Cap from mainland ice, much as a similar embayment developed in the North Minch during retreat of the Minch Ice Stream.

The timing of deglaciation of the Sea of the Hebrides is better established. TCN ages indicate deglaciation of southern Skye by 17.4 ± 1.2 ka, the Ross of Mull by 17.5 ± 0.9 ka and western Jura by 16.5 ± 0.8 ka (Small *et al*. 2016, 2017a; Fig 19), indicating that by ~17.5–16.5 ka the ice margin was restricted to the fjords, islands and peninsulas of the western seaboard. A remarkable implication is that during the ~3 ka separating deglaciation of Tiree from that of southern Skye, southern Mull and Jura, the ice margin underwent *net* retreat of only 50–70 km in this sector. Cross-cutting bedforms and recessional moraines on the sea floor indicate flow reorganization, increasing topographic control and readvances of the ice margin as it thinned and withdrew slowly to the E and NE (Howe *et al*. 2012, Dove *et al*. 2015, 2016). Prolonged persistence of the ice margin within a narrow corridor amongst the Inner Hebrides was anticipated by Sissons (1983), based on the distribution of high isostatically-uplifted coastal rock platforms that he attributed to post-deglaciation periglacial shore erosion. The implied slow net retreat of the ice margin across the onset zones of the Hebrides Ice Stream is consistent with the view of Small *et al.* (2017a) that it ceased to operate on a regional scale by the time of deglaciation of Tiree (21–20 ka).

8. Regional deglaciation 2: the Scottish mainland and Inner Hebrides

8.1. The NW Highlands and western seaboard

As noted in section 7.1, the configuration of ice-marginal moraines mapped by Bradwell & Stoker (2015a) suggests very early deglaciation of Cape Wrath and early development of a marine embayment in the North Minch, with the ice margin subsequently retreating eastward into the fjords of the NW mainland (Fig. 12). The nature of retreat in the Loch Ewe to Summer Isles area has been beautifully captured in bathymetric surveys (Stoker *et al.* 2006, 2009), which reveal numerous large crescentic or crenulate cross-fjord moraines 10–20 m high and up to 3 km long

(Fig. 20) and smaller ridges interpreted as De Geer moraines, a submarine landsystem indicative of pulsed retreat of a grounded ice margin. Shells in cores recovered between the Summer Isles and the mouth of Loch Broom provide minimum deglaciation ages of 14.0–13.6 cal ^{14}C ka and 13.8–13.6 cal ^{14}C ka. From this and other evidence, Stoker *et al.* (2009) inferred deglaciation of this area at ~14.5–13.0 ka. Recalibrated TCN ages for the Wester Ross Readvance, however, imply much earlier deglaciation, as outlined below.

The oldest TCN exposure ages in Wester Ross relate to erratic boulders deposited on the summit blockfields of Maol Chean-dearg, Beinn Liath Mhór and Slioch at altitudes of 916–967 m OD (Fabel *et al.* 2012; Figs. 14, 19 and 22). Excluding outliers, these yielded (recalibrated) uncertainty-weighted mean ages of 16.0 ± 0.8 k, 16.1 ± 0.8 ka and 16.1 ± 0.8 ka respectively, suggesting that mountain summits emerged from the thinning ice sheet as nunataks at ~16 ka.

Most dating evidence for retreat of the ice margin in NW Scotland relates to the moraines that mark the limit of the Wester Ross Readvance (WRR), which is intermittently defined by terrestrial moraines between the Applecross Peninsula and Achiltibuie (Robinson & Ballantyne 1979; Sissons & Dawson 1981; Sutherland 1984; Figs. 21 and 22), and designated individually as the Applecross, Redpoint, Gairloch, Aultbea and Achiltibuie moraines. Everest *et al.* (2006) obtained six TCN ages for erratics on the Gairloch moraine, but even after rejection of two dates as outliers, these yielded (recalibrated) ages of 20.4 ± 3.6 ka to 14.1 ± 2.1 ka, which permit no valid conclusions. Conversely, eight consistent TCN ages with an apparent average age of ~13.5 ka were reported by Bradwell *et al.* (2008a) for samples from boulders on the Achiltibuie moraine, a lateral moraine above Little Loch Broom and another in the Loanan Valley in Assynt. They concluded from these results and the record of submarine moraines between Loch Ewe and Loch Broom that 'substantial dynamic ice caps existed in NW Scotland between 13 and 14 ka' (Bradwell *et al.* 2008a, p. 401), a conclusion further developed by Stoker *et al.* (2009).

This proposition was initially supported by 14 ^{10}Be exposure ages obtained by Ballantyne *et al.* (2009a) for boulders on the Applecross, Gairloch, Redpoint and Achiltibuie moraines. These yielded apparent mean ages of 14.0–13.5 ka, almost identical to the eight TCN ages reported by Bradwell *et al.* (2008a), and indicate that all the dated moraines represent an isochronous or nearly isochronous readvance of the ice margin. Subsequent recalibration of all 22 TCN ages using a locally-derived ^{10}Be production rate, however, showed that the initially reported ages are too young (Ballantyne & Stone 2012). Recalibration of these ages using the protocol adopted here yields an uncertainty-weighted mean age of 15.3 ± 0.7 ka for the WRR (Fig. 23). This revised age implies much earlier retreat of the ice margin across low ground in Wester Ross, consistent with Lateglacial pollen-stratigraphic evidence from Loch Droma on the watershed inland from Wester Ross. Though the radiocarbon age of 15.6–15.1 cal ^{14}C ka obtained by Kirk & Godwin (1963) for this site (Fig. 24) may be compromised by 'old' carbon residues, the associated pollen assemblages appear to span the entire Lateglacial Interstade (Pennington *et al.* 1972). If so, most or all low ground in Wester Ross must have been deglaciated between the WRR at 15.3 ± 0.7 ka and the onset of the Lateglacial Interstade at ~14.7 ka. Deglaciation of low ground farther N was probably earlier. An age of 15.9–15.2 cal ^{14}C ka for organic material near the base of a core from Cam Loch in Assynt is minimal for deglaciation (Pennington 1975). Similarly, Boomer *et al.* (2012) obtained an age of 14.4–14.1 cal ^{14}C ka from near the base of a core from Loch Assynt, and inferred from their age-depth model that deglaciation occurred before ~17 ka.

Retreat of the ice margin along the NE coast of Skye, first southwards along the Sound of Raasay and then eastwards towards the mainland, is constrained by TCN ages. Two consistent TCN ages for ice-abraded bedrock at 450 m OD in southern Trotternish (Stone *et al.* 1998; Fig. 19) give a recalibrated mean age of 16.6 ± 1.2 ka, and five samples from boulders on a medial moraine near Broadford yield a recalibrated mean age of 16.0 ± 0.8 ka (Small *et al.* 2012). The latter age implies that the ice margin backstepped on to the adjacent mainland after ~16 ka, consistent with the timing of the WRR (15.3 ± 0.7 ka) on the adjacent Applecross peninsula.

Elsewhere on Skye, there is stratigraphic and geomorphological evidence that retreat of the mainland ice sheet was succeeded by expansion of a residual ice cap centred over high ground in the south-central part of the island (Benn 1997). In lower Glen Brittle, up-valley termination of a high Lateglacial shoreline coincides with end moraines marking the limit of ice advance down the glen (Walker *et al.* 1988). Four cosmogenic ^{36}Cl exposure ages obtained from boulders on these moraines give a weighted mean age of 17.4 ± 1.2 ka (Small *et al.* 2016), implying prior disengagement of mainland ice from the Skye ice cap, but the range of individual ages is wide (19.4 ± 1.7 to 15.5 ± 1.7 ka). In southern Skye, bathymetric mapping of Loch Scavaig has revealed a pronounced arcuate submarine end moraine that impinges on the adjacent island of Soay, and samples from erratic basalt boulders on the Soay moraine have produced four ^{36}Cl ages of 16.4 ± 1.5 to 14.6 ± 1.5 ka, with a weighted mean age of 15.1 ± 1.0 ka. The closeness of this age to that of the WRR moraines (15.3 ± 0.7 ka) suggests contemporaneity, though Small *et al.* (2016) cautioned against definitive correlation of the two because of uncertainties in the derivation of the mean exposure age for the Soay moraine.

Farther south, the TCN age of 17.5 ± 0.9 ka obtained for the Ross of Mull (Small *et al.* 2017a; Fig. 19) is consistent with a basal age of 16.0–15.7 cal ^{14}C ka for the onset of organic sedimentation in nearby Loch an t-Suidhe (Walker & Lowe 1982), the latter being minimal for deglaciation. North of Mull, a radiocarbon age of 16.8–16.2 cal ^{14}C ka for a shell in a core recovered from outer Loch Sunart (Baltzer *et al.* 2010) indicates prior deglaciation of the Ardnamurchan Peninsula and western Moidart (Fig. 24). On Jura, a medial moraine formed by a landslide onto the thinning ice sheet yielded a TCN age of 16.5 ± 0.8 ka (Small *et al.* 2017a), consistent with TCN ages obtained for nearby postglacial rockslide deposits (~15.4–13.7 ka), which are minimal for deglaciation (Ballantyne *et al.* 2014). Numerous recessional moraines recorded on the seafloor of the Firth of Lorne and Sound of Jura indicate subsequent oscillatory retreat of a grounded ice margin (Howe *et al.* 2012; Dove *et al.* 2015, 2016).

The available geochronological evidence for the western seaboard therefore indicates deglaciation of the extreme NW, and of parts of Skye and Mull, before ~17 ka. By ~16 ka the margin of mainland ice had backstepped from most of the Inner Hebrides and the westernmost mainland peninsulas, and mountain summits were emerging from the ice sheet. By 15 ka, following the WRR, the mainland ice margin had probably retreated east of the coastline, though residual ice masses may have occupied the mountains of Skye and possibly Mull. The subsequent deglacial history of this sector is difficult to assess, as many of the fjords and valleys of western Scotland were reoccupied by glaciers during the Younger Dryas Stade.

8.2. Caithness, NE Scotland and eastern Scotland

8.2.1. Caithness. Hall & Riding (2016) inferred from stratigraphic, geomorphological and flowline evidence that eastward retreat of the ice margin in the Pentland Firth was succeeded by a restricted readvance of Moray Firth ice northwestward into the firth, accompanied and succeeded by northeastward flow of ice from the Northern Highlands. The latter may have occupied central Caithness as Moray Firth ice retreated, first southeastwards then southwestwards along to the east coast. Till sheets and moraine systems record late readvances of ice moving NE and E from the Caithness-Sutherland border.

Recalibration of TCN ages reported by Phillips *et al.* (2008) suggests two interpretations for the timing of deglaciation in Caithness. Two TCN ages for bedrock samples from a col at 445 m OD on Morven in central Caithness gave a mean age of 19.3 ± 1.6 ka, and a bedrock-boulder pair from Hill of Yarrows (10 km S of Wick) produced a mean age of 19.9 ± 1.3 ka (Fig. 19). Both results suggest deglaciation of much of eastern Caithness before ~19 ka. Conversely, two samples from Dunnet Head in northernmost Caithness yielded a weighted mean age of 17.5 ± 1.1 ka, and two from Clyth (5 km SW of Hill of Yarrows) gave a weighted mean age of 16.9 ± 1.1 ka. These younger ages appear more realistic for the timing of deglaciation, given (1) the deglaciation age of 16.5 ± 1.2 ka inferred for deglaciation of low ground in Orkney, (2) a radiocarbon age of 15.9–14.7 cal ^{14}C ka obtained for the oldest organic sediments in Loch of Winless near Wick (Peglar 1979); and (3) the timing of retreat of ice in the Moray Firth (see below). They suggest that retreat of Moray Firth ice across Caithness mainly occurred within the period 17.5–17.0 ka, with later expansion of ice from high ground to the west (Hall & Riding 2016).

8.2.2. The Moray Firth and NE Scotland. Lithostratigraphic and flowset evidence (Merritt *et al.* 2003; Hughes *et al.* 2014) indicates that following the LLGM there was major reorganization of ice flow in NE Scotland. Merritt *et al.* (2017) envisaged that within the period ~22–19 ka, predominantly cold-based ice flowing E from the eastern Grampians and Cairngorms was surrounded along coastal areas by a pincer movement of ice flowing E then SE from the Moray Firth and NE-flowing ice from Strathmore (Fig. 25a). They concluded that initial deglaciation on land occurred near the confluence of these three ice masses, inland from Peterhead, but was succeeded by a localized readvance, the Logie-Buchan Readvance. They also suggested that subsequent disengagement of Grampian and Strathmore ice led to deglaciation of the east coast from Peterhead to the Tay estuary by ~20.9–20.1 ka (Fig. 25b), as indicated by radiocarbon ages obtained from foraminifera in raised marine muds at Lunan Bay (McCabe *et al.* 2007; see below).

The extent of Moray Firth ice during the period 22–19 ka is uncertain. At St Fergus, on the Buchan coast near Peterhead, a moraine formed by a localized readvance of Moray Firth ice from the E or NE contains glacitectonised marine sediments, and a radiocarbon age of 15,320 ± 200 ^{14}C a BP (18.0–17.5 cal ^{14}C ka) obtained for a shell in raised marine silts indicates prior ice-free conditions (Hall & Jarvis 1989) and provides a minimum age for the readvance. Organic material within a core recovered from marine silts in the Moray Firth itself, ~17 km NE of Banff, yielded radiocarbon ages ranging from 20.9–19.3 cal ^{14}C ka to 17.7–16.4 cal ^{14}C ka (Harkness & Wilson 1979), the youngest age suggesting that the ice margin had retreated to this position by ~17 ka. Subsequent ponding of lakes along the N coast of Buchan implies that the margin of the Moray Firth lobe lay along this coast after deglaciation of inland areas, and there is evidence for a readvance near Elgin, which Merritt *et al.* (2017) assigned to ~15 ka, though earlier deglaciation seems likely. A further oscillation of the retreating ice margin occurred at Ardesier near Inverness, where a moraine containing glacitectonised glacimarine silts indicates that retreat of a calving tidewater margin in response to rising sea level was interrupted by a readvance, tentatively assigned to ~13 ^{14}C ka (~15.6 cal ^{14}C ka) by Merritt *et al.* (1995). The ice margin then retreated into Loch Ness, at that time a fjord open to the sea. Recessional moraines in the north of the loch indicate punctuated retreat of a grounded ice margin, followed by deposition of a large moraine (the Foyers rise) midway down the loch, then rapid retreat towards Fort Augustus, where evidence of subsequent events is lost under Younger Dryas deposits (Turner *et al.* 2012).

8.2.3. Eastern Scotland. Present understanding of the timing of SIS retreat in E Scotland is based largely on radiocarbon dating of marine shells or foraminifera within raised glacimarine or marine muds deposited after deglaciation. Radiocarbon ages of 17,720 ± 50 and 17,050 ± 50 ^{14}C a BP (21.0–20.8 and 20.2–20.0 cal ^{14}C ka) for samples of *Elphidium clavatum* in raised marine muds at Lunan Bay near Montrose provide the earliest evidence of retreat of the ice margin to the east coast of Scotland (McCabe *et al.* 2007). The most widely-distributed raised muds are those of the Errol Clay Formation, which occurs along the Tay and Forth estuaries and valleys. These contain a sparse high-arctic marine fauna and are thought to have been deposited rapidly as the ice margin retreated (Peacock 1999). Radiocarbon dating of marine shells within the Errol Clay Formation in the Tay estuary area has yielded a wide range of ages (16.5–16.2 ^{14}C ka at Barry, near the mouth of the Tay estuary, to 14.6–14.1 cal ^{14}C ka farther inland); the oldest ages for Gallowflat 14 km E of Perth (16.3–16.1 cal ^{14}C ka), imply deglaciation of the Firth of Tay prior to ~16.3 ka (Peacock 2003; McCabe *et al.* 2007; Fig. 24).

Although the deglaciation ages (21.0–20.8 and 20.2–20.0 cal ^{14}C ka) obtained by McCabe *et al.* (2007) for raised marine muds at Lunan Bay are consistent with two (recalibrated) TCN ages averaging 20.6 ± 1.8 ka for an inland site at Pitfichie, 50 km farther N (Phillips *et al.* 2008; Fig. 19), these dates pose a conundrum. They appear incompatible with the inferred timing (~18.5 ka) of decoupling of the SIS and FIS in the NSB as proposed by Sejrup *et al*. (2016), and with the reconstructions of BIIS retreat stages based on flowsets (Hughes *et al.* 2014) or other geomorphological evidence (Clark *et al.* 2012, Fig. 16). Conversely, they are consistent with the southward extension of a marine embayment separating the SIS and FIS envisaged by Bradwell *et al.* (2008b), Merritt *et al.* (2017) and others (Fig. 25). These dates imply that a deglaciated enclave existed in eastern Scotland three to four millennia before the proposed timing of the Fladen 1 and Fladen 2 Readvances into the Witch Ground Basin (Sejrup *et al.* 2015), and possible extension of ice to east Yorkshire (Bateman *et al.* 2017). They also suggest that *net* retreat of the ice margin from Lunan Bay to Barry, a distance of ~23 km, took ~3–4000 years.

There are two solutions to the apparent paradoxes raised by the Lunan Bay dates. One is that the dates are too old. The alternative is that deglaciation of the E coast occurred prior to 21–20 ka and that there were subsequent readvances and surges of the ice margin both north and south of the deglaciated enclave, as illustrated by Clark *et al.* (2012). McCabe *et al.* (2007) inferred from the presence of kettled outwash gravels overlying the raised marine muds at Lunan Bay that ice had subsequently readvanced across this site. This evidence is compelling, though there is no evidence of intervening till or of glacitectonic deformation of the marine muds (Peacock *et al.* 2007). They also revived the concept of a later readvance of ice in eastern Scotland, the Perth Readvance, based on similar stratigraphic evidence (laminated muds and silty-sands overlain by kettled outwash gravels) at Bertha Park, 3 km NW of Perth. The concept of a widespread Perth Readvance of ice flowing out of the glens of the southern and SE Grampians and eastward into the Tay and Forth Valleys has a long and contested history (Simpson 1933; Sissons 1963, 1964, 1967, 1974; Paterson 1974), and though the limits and extent of this event remain uncertain, it is possibly consistent with the areal extent of a prominent raised shoreline (the main Perth raised shoreline) in the Forth and Tay valleys (Sissons & Smith 1965; Sissons *et al.* 1966; Cullingford 1977). If the laminated muds at Bertha Park are stratigraphically equivalent to the Errol Clay Formation at Gallowflat, then the readvance must have occurred after ~16.3 ka. McCabe *et al.* (2007) suggested that the Perth Readvance may be correlated with the Killard Point Readvance in NE Ireland (McCabe *et al.* 2005), though reassessment of the timing of the latter suggests that it occurred earlier, within the interval ~17.3–16.6 ka (Ballantyne & Ó Cofaigh 2017).

8.2.4. Strathspey, the Cairngorms and eastern Grampians. The distribution of schist erratics indicates that the Cairngorms acted as an independent centre of ice dispersal throughout the last glacial cycle (Sugden 1970), diverting ice from the Grampians into Strathspey and the Dee valley, where overall retreat was interrupted by readvances or stillstands (Brown 1993). There is abundant dating evidence for deglaciation of the Cairngorms and surrounding areas. Postglacial rockslide debris (possibly onto decaying ice) in Strath Nethy and the Lairig Ghru has produced recalibrated mean ^{10}Be ages of 18.2 ± 1.1 ka and 17.1 ± 1.0 ka respectively (Ballantyne *et al.* 2009b), tentatively suggesting early deglaciation of some valleys within the massif, and a single TCN age of 16.9 ± 1.1 ka for an erratic at 1156 m OD on Cnap à Chléirich may indicate the approximate timing of deglaciation of high ground (Phillips *et al.* 2006).

The retreat of ice in Strathspey is marked by lateral moraines and meltwater channels along the northern flanks of the Cairngorms, and decoupling of Strathspey ice from the Cairngorm ice cap resulted in formation of ice-dammed lakes in some valleys (Brazier *et al.* 1998; Golledge 2002). Samples from boulders on moraines associated with a former ice-dammed lake in the NW Cairngorms have yielded a mean recalibrated age of 16.2 ± 0.8 ka for the margin of the Strathspey ice that dammed one lake, and of 16.4 ± 0.8 ka for the margin of local ice entering the lake (Everest & Kubik 2006; Fig. 19). Boulder samples from high level (540–750 m OD) lateral moraines marking the S margin of Strathspey ice in the NE Cairngorms gave a recalibrated mean age (excluding outliers) of 15.8 ± 0.8 ka, interpreted by Hall *et al.* (2016a) as the timing of a readvance of Strathspey ice to near Grantown. The location of the moraines dated by Hall *et al.* (2016a) implies that these must have been deposited earlier than the more westerly moraines dated by Everest & Kubik (2006), but the two sets of ^{10}Be ages are statistically indistinguishable, and together indicate that retreat of Strathspey ice along the northern flank of the Cairngorms occurred at ~16.5–15.5 ka. This timing is consistent with radiocarbon ages obtained for basal organic sediments from Loch Etteridge in the upper Spey Valley: 13,150 ± 390 ^{14}C a BP (Sissons & Walker 1974) and 12,930 ± 40 ^{14}C a BP (Everest & Golledge 2004), equivalent to 16.4–15.2 and 15.6–15.4 cal ^{14}C ka, respectively.

Three TCN ages for boulders on till ridges at ~640 m OD in the Monadhliath Mountains, ~10 km NNW of Loch Etteridge were originally interpreted by Gheorghiu *et al.* (2012) as representing the timing of ice-sheet deglaciation. Recalibration of their data produced a range of ages (18.7 ± 1.0, 16.4 ± 0.9 and 13.4 ± 0.7 ka) that is too wide to permit meaningful inference. However, two boulder samples they obtained from a drift ridge in nearby Glen Banchor produced (recalibrated) ^{10}Be ages of 15.8 ± 1.3 and 15.4 ± 0.9 ka (Fig. 19). These ages are consistent with the Loch Etteridge radiocarbon dates and imply retreat of the ice margin to the upper Spey valley by 15.5 ± 0.9 ka. Six ^{10}Be ages obtained by Everest & Kubik (2006) for boulders on drift ridges near the mouth of Glen Geusachan (southern Cairngorms) are problematic. The recalibrated ages range from 18.6 ± 1.6 ka to 13.6 ± 1.4 ka with a mean age of 15.2 ± 0.7 ka. Given the range of ages, acceptance of the mean age as representative of the timing of deposition is not statistically justifiable, and the significance of these dates is unclear.

In summary, (1) some valleys within the Cairngorms may have been deglaciated when ice from the SW still encircled most of the massif; (2) there is reasonable evidence to suggest that the Strathspey ice lobe withdrew from the northern Cairngorms within the period ~16.5–15.5 ka; and (3) there is convincing evidence to indicate deglaciation of the upper Spey Valley by ~15.5 ka, long before the beginning of the Lateglacial Interstade at ~14.7 ka.

8.3. Deglaciation of southern and central Scotland

8.3.1 Southern Scotland. Using a combination of radiocarbon dating and TCN exposure dating, Livingstone *et al.* (2015) showed that the ice margin had retreated into the Solway Lowlands before 16.4–15.7 ka, and this is supported by a basal age of 15.9–15.2 cal ^{14}C ka for a site in Annandale near Lockerbie (Bishop & Coope 1977; Fig. 24). The high-arctic fauna in raised marine muds in SW Galloway suggests contemporaneity with the Errol Clay Formation in eastern Scotland (Peacock 1975), suggesting deglaciation before ~16.5–15.5 ka. TCN ages for two sites in the heart of the Galloway Hills (Fig. 19) have produced identical recalibrated mean ages of 15.0 ± 0.7 ka (Ballantyne *et al.* 2013), implying that ice had almost disappeared from SW Scotland by ~15 ka. It seems likely that the rest of the Southern Uplands was also extensively deglaciated by that time, though there is no geochronological evidence to confirm this.

8.3.2 East and central Midland Valley. Early deglaciation of E Fife is indicated by six raised shorelines that exhibit marked eastward tilt due to subsequent differential glacio-isostatic uplift (Cullingford & Smith 1966). Five of these shorelines have been identified at sites as far north as Stonehaven (Cullingford & Smith 1980), suggesting that eastern Fife may have been deglaciated as early as ~21–20 ka, based on the radiocarbon ages obtained by McCabe *et al.* (2007) at Lunan Bay (section 8.2.3 above). It is difficult, however, to reconcile this inference with the proposal that ice from the Grampians and Midland Valley participated in readvance of the North Sea Lobe to the Yorkshire coast at ~16.8 ka to deposit the Withernsea Till at Dimlington (Roberts *et al.* 2013; Livingstone *et al.* 2015; Bateman *et al.* 2017). Moreover, organic debris from silts overlying marine clays in the Howe of Fife has yielded a radiocarbon age of 16.7–16.3 cal ^{14}C ka (Harkness & Wilson 1979), and basal organic deposits in Black Loch, in northern Fife, have been dated to 15.4–14.8 cal ^{14}C ka (Whittington *et al.* 1991). Both ages are minimal for deglaciation, but imply that most of Fife was probably ice free before ~16.5 ka.

The timing of deglaciation across the southern Midland Valley has not been established, but Sutherland (1984) noted that meltwater channels from Ayrshire to the Forth are aligned ENE, implying that deglaciation of a broad swath of lowland terrain occurred when the ice divide was located over the Firth of Clyde, and hence that these areas and the Forth Valley were deglaciated before the retreat of ice from west-central Scotland. The final retreat of ice from the central Midland Valley is constrained by radiocarbon ages from sites near Callander on the Highland boundary (Fig. 24). Lowe (1978) obtained an age of 12,750 ± 120 ^{14}C a BP (15.5–15.0 cal ^{14}C) from basal organic deposits in a kettle hole, and Merritt *et al.* (1990) obtained an age of 12,750 ± 70 ^{14}C a BP (15.3–15.1 cal ^{14}C ka) for lacustrine deposits underlying Younger Dryas till. These ages suggest that the entire eastern and central Midland Valley was ice free before ~15.2 ka.

8.3.3. West Central Scotland and the Clyde Estuary. The pattern of deglaciation in this area has been reconstructed by Finlayson *et al.* (2010, 2014) from geomorphological and stratigraphic evidence. They inferred that at ~16.5 ka all of west-central Scotland was still covered by ice, with ice from the SW Highlands flowing E into the upper Forth valley, SE up the Clyde Valley and down the Firth of Clyde to impinge on NE Ireland. Subsequent northwards and northwestwards retreat resulted in decoupling from Southern Uplands ice and deglaciation of much of Ayrshire, with ice-dammed lakes forming in the Clyde and Irvine valleys whilst a substantial glacier continued to occupy the Firth of Clyde. The final stage of deglaciation involved retreat of the ice margin to the mouths of the fjords (such Loch Fyne and Loch Long) that formed the arteries of ice movement from the SW Highlands. Deposition of moraine belts at Kilmarnock, Blantyreferm in the Clyde Valley and Eaglesham imply that overall retreat was interrupted by localised readvances or stillstands, suggesting that the retreating ice margin remained climatically active.

Retreat of the ice from the Firth of Clyde resulted in marine transgression across low-lying coasts and deposition of the glacimarine or marine Clyde Clay Formation at altitudes of up to 40 m OD. These deposits incorporate molluscan assemblages of typically high boreal to low arctic provenance (Peacock & Harkness 1990) in contrast to the high-arctic affiliation of the Errol Clay Formation fauna of eastern Scotland, implying that the final stages of glacier retreat in the Clyde basin occurred later, under milder conditions.

The timing of initial ice retreat from the outer Firth of Clyde is difficult to establish. The lowest molluscan assemblages in cores from boreholes south of Arran (Fig. 24) were interpreted by Peacock *et al.* (2012) as being of Lateglacial Interstadial (~14.7–12.9) age, and the oldest radiocarbon ages from these cores (14.9–14.3 cal ^{14}C ka) are consistent with this interpretation. However, Peacock *et al.* (2012) also detected reworked high-arctic fauna at the base of these cores, indicating that the area was deglaciated sometime before ~14.7 ka. Finlayson *et al.* (2014) placed deglaciation of the Firth of Clyde south of Arran much earlier, on the basis two TCN ages with a mean recalibrated age of 16.5 ± 1.0 ka for boulders from moraines at Glen Dougarie on Arran. If valid, this date implies rapid advance (the East Antrim Coastal Readvance) then retreat of Clyde ice following the Killard Point Readvance (~17.3–16.6 cal ^{14}C ka) in NE Ireland (Ballantyne and Ó Cofaigh 2017). On present evidence, it appears that much of the Firth of Clyde was deglaciated sometime between ~16.5 ka and ~14.7 ka, but taking into account the wider evidence from Ireland, retreat after ~16 ka seems likely.

A large number of radiocarbon ages, mostly within the range 13.0–11.5 ^{14}C ka, have been obtained for marine shells in the Clyde Clay Formation, but few are sufficiently consistent to constrain the timing of deglaciation (Sutherland 1986). A clutch of ages obtained for *Arctica islandica* shells from near the head of the Clyde estuary around Paisley, however, indicate deglaciation prior to 14.8–13.9 cal ^{14}C ka, with one older sample yielding an age of 15.5–14.5 cal ^{14}C ka (Sutherland 1986; Peacock & Harkness 1990). The molluscan fauna of these deposits is consistent with a Lateglacial Interstadial age, and it seems reasonable to accept the view of Peacock *et al.* (2012) that the inner Clyde estuary and Glasgow area were deglaciated by 14.7 ka, at the beginning of the Lateglacial Interstade.

9. Ice-sheet demise

The Greenland ice-core record provides a regional stratotype sequence for climatic fluctuations in the North Atlantic and evidence of rapid warming at ~14.7 ka (Rasmussen *et al.* 2014). This warming is captured by subfossil chironomid assemblages at sites in Scotland, northern Ireland and NW England that indicate a rapid rise of 5–6°C in mean July temperatures to 11–13°C early in the Lateglacial Interstade (Brooks & Birks 2000; Lang *et al.* 2010; Watson *et al.* 2010; Brooks *et al.* 2012, 2016; Fig. 26). This warming is generally attributed to northward migration of the north Atlantic oceanic polar front and resumption of thermohaline circulation, which brought warmer waters to the seas surrounding the British Isles.

The evidence outlined above relating to retreat of the SIS suggests that by 15.0–14.7 ka the remaining ice mass was largely confined to the Western Grampians and NW Highlands, and thus lay mainly within the limits of the Loch Lomond Readvance (LLR), which reached its maximum extent during the Younger Dryas Stade of ~12.9–11.7 ka (Golledge 2010; Fig. 26). This implies that the SIS lost most of its mass under the cold (but varying) conditions of the Dimlington Stade. It also means that evidence relating to the final demise of the SIS after ~14.7 ka has been largely removed or buried by readvance of ice during the Younger Dryas Stade.

There has been recurrent debate as to whether glacier ice persisted in the Scottish Highlands throughout the Lateglacial Interstade, or whether it vanished completely under the warmer interstadial climate (Fig. 26). Some authors have suggested that the evidence of Lateglacial pollen sites near the centres of ice dispersal (for example at Loch Etteridge and Callander) indicates that Scotland was completely deglaciated during the Lateglacial Interstadial (e.g. Sissons 1974). Others have argued for ice survival in favourable locations (e.g. Sutherland 1984; Clapperton 1997). Definitive evidence has proved elusive. The modelling experiments of Hubbard *et al.* (2009) suggest that ice was present in the western Grampians at 13.8 ka, after the warmest part of the interstade, and formed the core of the ice cap that expanded during the Younger Dryas. Finlayson *et al.* (2011) showed that the Beinn Dearg massif in NW Scotland remained an important centre of ice dispersal during SIS deglaciation, and speculated that the eastern part of the massif may have retained a thin ice cap throughout the Lateglacial Interstade, but their evidence appears inconclusive. Moreover, the TCN ages of ~16 ka obtained for erratics on the summit plateaux of mountains in Wester Ross (Fabel *et al.* 2012) demonstrate that these plateaux were ice-free long before the Lateglacial Interstade and remained so until the present.

Of relevance to this debate is the provenance of ice-rafted debris in a core from the St Kilda basin on the Hebridean Shelf. Small *et al.* (2013a) dated an episode of high IRD flux in this core to the Older Dryas climatic reversal (GI-1d) of ~14.1–13.9 ka. However, contrasts in the rutile age spectra for this IRD and those provided by detrital rutile in the alluvial deposits of rivers draining Moinian and Dalradian terranes in the Highlands established that some of the IRD is of distal (Laurentian) provenance. The absence of Moinian rutiles suggests minimal (if any) input from tidewater-terminating glaciers in the NW Highlands at this time, though a contribution from the SW Highlands cannot be ruled out on the basis of this evidence (Small *et al.* 2013b).

Given the rapid warming at the onset of the Lateglacial Interstade (Fig. 26) it seems inevitable that the glaciers still occupying the glens and fjords of the Highlands experienced marked negative mass balance, a rapid rise in equilibrium line altitudes and uninterrupted ice-margin retreat. Survival of high-level plateau ice caps and even corrie glaciers during the interstade is much more likely, but remains to be convincingly demonstrated.

10. Conclusions

The following conclusions arise from this brief review. Most should be regarded as provisional, as the rapidity of recent developments suggests that our understanding of the complex evolution of the SIS is likely to be radically improved within the coming decades.

- The SIS expanded from a limited ice cap with tidewater margins after ~35–32 ka.
- Initial expansion was dominated by ice nourished in the Scottish Highlands, with the later development of a major ice centre (or centres) in the Southern Uplands. The Outer Hebrides, Skye, Mull, the Cairngorms, Shetland and probably Arran developed independent ice centres that persisted throughout the last glacial cycle, diverting the flow of Highland ice.
- Net expansion was accompanied by ice-divide migration and switching flow directions, and punctuated by localised retreat. Ice from the Highlands initially flowed into the Irish Midlands

and ISB until expansion of Southern Uplands ice formed an ice divide across the North Channel. In consequence, only ice from Galloway continued to feed into the ISB, and ice from the SW Highlands was diverted W across the Malin Shelf and E across the Midland Valley. Southern Uplands ice fed into the Tweed and Tyne Valleys. Moray Firth ice initially moved SW across parts of Buchan into the NSB, then swung NE across Caithness and Orkney.

- Eastward-moving Scottish Ice met the FIS in the NSB, forming either a NW-aligned convergence zone, or a migratory ice divide stretching from Scotland to SW Norway. To the west, ice movement was dominated by flow SW around the Outer Hebrides Ice Cap across the southern Hebrides Shelf, westward flow of Outer Hebrides ice, NW flow of ice from the North Minch and surrounding coasts, and probably westward flow of Shetland ice.
- Most accounts place the W and NW terminus of the SIS at the Atlantic Shelf break, on the evidence provided by shelf-edge moraines and sedimentation on shelf-edge fans. The ice sheet failed to reach St Kilda, however, and stratigraphic evidence suggests that the outer northern Hebridean Shelf remained beyond the ice sheet. This implies that westward advance of the SIS was not everywhere terminated by calving in deep water.
- The timing of the LLGM in different sectors fed by Scottish ice was diachronous. The Hebrides and Minch Ice Streams probably reached their maximum extents within the period 30–27 ka. The Irish Sea Ice Stream probably culminated at ~25 ka, and the maximum extent of the North Sea Lobe down the western NSB was not achieved until 22–21 ka.
- The SIS overtopped all Scottish mountains, but pre-existing blockfields on many summit plateaux were preserved under cold-based ice. Estimates of the maximum altitude of the SIS vary widely (1400–2500 m relative to present sea level) but numerical modelling suggests that the maximum altitude fluctuated during successive 'binge and purge' cycles.
- Most of the mass of the mature ice sheet was discharged by fast-flowing ice streams identified from geomorphological evidence. Terrestrial ice streams drained the SIS down the Tyne and Tweed Valleys and Strathmore into the NSB. The Hebrides, Malin Sea ('North Channel'), Irish Sea, Moray Firth and Minch Ice Streams drained ice from present land areas across the adjacent shelves. The timing and persistence (or otherwise) of such ice streams remains to be established.
- The pattern of ice-sheet retreat on the Shetland and northern Hebrides shelves and parts of the NSB has been reconstructed from the evidence provided by nested submarine moraine banks. These suggest oscillating retreat of the northern SIS to an Orkney-Shetland ice centre, very early deglaciation of Cape Wrath and early development of a marine embayment in the North Minch. The available dating evidence suggests that Orkney and Shetland were largely deglaciated at 17–16 ka.
- The pattern of deglaciation in the NSB is uncertain and all proposed scenarios vitiate some radiocarbon dating evidence. Several authors have proposed decoupling of the SIS and FIS along a marine embayment that progressively extended from N of Shetland via the Witch Ground Basin to eastern Scotland. A recent proposal is that decoupling was initiated by drawdown of the Norwegian Channel Ice Stream and debuttressing of the SIS margin. The timing of decoupling has been variously placed between ~27 ka and ~18.5 ka. There is greater

agreement that retreat of the SIS margin in the NSB was interrupted by readvances, two of which have been dated to ~17.5 ka and ~16.2 ka.

- The southern ISB was deglaciated by ~21 ka, but deglaciation of the northern ISB was interrupted by at least two readvances. Decoupling of the SIS and Irish Ice sheet probably occurred between ~16.5 and ~16.0 ka, and was succeeded by readvance of Scottish ice into northern Ireland (the East Antrim Coastal Readvance).
- TCN ages suggest that the southernmost Outer Hebrides may have been deglaciated by ~19 ka, though most dates for this sector suggest deglaciation by 17.3–16.3 ka. South Harris was deglaciated by ~17.9 ka, though ice probably persisted in the mountains of North Harris until ~16 ka.
- Retreat of the Hebrides Ice Stream probably occurred along deep troughs N and S of the Tiree-Coll platform, progressively severing the Outer Hebrides Ice Cap from mainland ice. Tiree was deglaciated at ~20.6 ka, after which ice streaming in this sector was probably transient.
- In NW Scotland, Cape Wrath probably experienced very early deglaciation. Mountain summits in Wester Ross protruded above the thinning ice sheet by ~16.0 ka, and dating of the WRR places the ice margin across peninsulas of Wester Ross at ~15.3 ka. Farther S, the ice margin retreated E along the Sound of Raasay at 16.5–16.0 ka, and decoupling of mainland ice from Skye was followed by readvances of the Skye Ice Cap, the more recent of which may correlate with the WRR. SW Mull was deglaciated at ~17.5 ka, western Jura at ~16.5 ka.
- In NE Scotland, available evidence suggests deglaciation of much of Caithness within the period 17.5–17.0 ka. Deglaciation of the southern coast Moray Firth probably began as early as ~17.7 ka but was interrupted by readvances of uncertain age.
- In E Scotland, radiocarbon dates from raised marine muds suggest deglaciation at or before 21–20 ka, but are difficult to reconcile with the wider chronological evidence. Other ages from the glacimarine Errol Clay Formation in the Tay estuary and Howe of Fife imply deglaciation around or before ~16.5 ka. The status of proposed readvances in this area has been contested.
- Strathspey ice retreated across the northern flank of the Cairngorms within the period 16.5–15.5 ka, and the upper Spey valley was deglaciated by the latter date.
- In southern Scotland, ice had retreated to the Solway lowlands by ~16.4–15.7 ka, and had probably disappeared from all low ground by ~15.0 ka.
- On the Highland edge near Callander, the ice margin retreated to within the limits of Younger Dryas glaciation by 15.2 ka, implying that the entire central and eastern Midland Valley was ice-free at this time.
- The timing of deglaciation of the Firth of Clyde is uncertain, but available evidence suggests that the inner Clyde estuary and Glasgow area were deglaciated at ~14.7 ka. This date marks the onset of rapid interstadial warming, and it is likely that there ensued uninterrupted retreat of glaciers still occupying the fjords and glens of the Highlands. It is uncertain whether fragments of the SIS persisted throughout the Lateglacial Interstade to feed the growth of the glaciers that culminated during the Younger Dryas Stade.

- The SIS lost most of its mass under varying stadial conditions prior to ~14.7 ka, not in response to rapid warming at the onset of the Lateglacial Interstade.

11. Acknowledgements

We thank Tom Bradwell, Chris Clark, Andrew Finlayson, Anna Hughes, Jon Merritt, Stephen Livingstone and Hans-Petter Sejrup for providing figures that are reproduced here, Adrian Hall for informed commentary on a draft of the paper, Derek Fabel and Anna Hughes for constructive reviews, and John Gordon for thorough copy-editing. We particularly thank Graeme Sandeman for preparing all figures for publication.

12. References

Austin, W. E. N., Telford, R. J., Ninnemann, U. S., Brown, L., Wilson, L. J., Small, D. P. & Bryant, C. L. 2011. North Atlantic reservoir ages linked to high Younger Dryas atmospheric radiocarbon concentrations. *Global and Planetary Change* **79,** 226–233.

Bailey, E. B., Clough, C. T., Wright, W. B., Richey, J. E. & Wilson, G. V. 1924. *The Tertiary and post-Tertiary geology of Mull, Loch Aline and Oban.* Memoir of the Geological Survey. Edinburgh: HMSO.

Balco, G., Stone, J. O., Lifton, N. A. & Dunai, T. J. 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. *Quaternary Geochronology* **3**, 174–195.

Ballantyne, C. K. 1999. Maximum altitude of Late Devensian glaciation on the Isle of Mull and Isle of Jura. *Scottish Journal of Geology* **35,** 97–106.

Ballantyne, C. K. 2010. Extent and deglacial chronology of the last British-Irish Ice Sheet: implications of surface exposure dating using cosmogenic isotopes. *Journal of Quaternary Science* **25,** 515–534.

Ballantyne, C. K., McCarroll, D., Nesje, A. & Dahl, S. O. 1997. Periglacial trimlines, former nunataks and the dimensions of the last ice sheet in Wester Ross, North-West Scotland. *Journal of Quaternary Science* **12,** 225–238.

Ballantyne, C. K., McCarroll, D., Nesje, A., Dahl, S.O. & Stone, J.O. 1998a. The last ice sheet in north-west Scotland: reconstruction and implications. *Quaternary Science Reviews* **17,** 1149–1184.

Ballantyne, C. K., McCarroll, D., Nesje, A., Dahl, S. O., Stone, J. O. & Fifield, L. K. 1998b. High-resolution reconstruction of the last ice sheet in NW Scotland. *Terra Nova* **10,** 63–67.

Ballantyne, C. K., McCarroll, D. & Stone, J. O. 2007. The Donegal ice dome, northwest Ireland: dimensions and chronology. *Journal of Quaternary Science* **22,** 773–783.

Ballantyne, C. K., Schnabel, C. & Xu, S. 2009a. Readvance of the last British-Irish Ice Sheet during Greenland Interstadial 1 (GI-1): the Wester Ross Readvance, NW Scotland. *Quaternary Science Reviews* **28,** 783–789.

Ballantyne, C. K., Schnabel, C. & Xu, S. 2009b. Exposure dating and reinterpretation of coarse debris accumulations ('rock glaciers') in the Cairngorm Mountains, Scotland. *Journal of Quaternary Science* **24,** 19–31.

Ballantyne, C. K., Rinterknecht, V. & Gheorghiu, D. M. 2013. Deglaciation chronology of the Galloway Hills Ice Centre, SW Scotland. *Journal of Quaternary Science* **28,** 412–420.

Ballantyne, C. K., Wilson, P., Gheorghiu, D. and Rodés, À. 2014. Enhanced rock-slope failure following ice-sheet deglaciation: timing and causes. *Earth Surface Processes and Landforms* **39,** 900–913.

Ballantyne, C. K., Benn, D. I., Bradwell, T. & Small, D. 2016. The glacial history of the Isle of Skye 1: the last ice sheet. *In* Ballantyne, C. K. & Lowe, J. J. (eds) *The Quaternary of Skye: Field Guide,* 12–22. London: Quaternary Research Association.

Ballantyne, C. K., Fabel, D., Gheorghiu, D., Rodés, Á., Shanks, R. & Xu, S. 2017. Late Quaternary glaciation in the Hebrides sector of the continental shelf: cosmogenic nuclide dating of glacial events on the St Kilda archipelago. *Boreas* DOI: 10.1111/bor.12242.

Ballantyne, C. K. & Hall, A. M. 2008. The altitude of the last ice sheet in Caithness and east Sutherland. *Scottish Journal of Geology* **44,** 169–181.

Ballantyne, C. K. & Hallam, G.E. 2001. Maximum altitude of Late Devensian glaciation on South Uist, Outer Hebrides, Scotland. *Proceedings of the Geologists' Association* **112,** 155–167.

Ballantyne, C. K. & McCarroll, D. 1995. The vertical dimension of Late Devensian glaciation on the mountains of Harris and SE Lewis, Outer Hebrides, Scotland. *Journal of Quaternary Science* **10,** 211–223.

Ballantyne, C. K. & McCarroll, D. 1997. Maximum altitude of the Late Devensian ice sheet on the Isle of Rum. *Scottish Journal of Geology* **33,** 183–186.

Ballantyne, C. K. and Ó Cofaigh, C. 2017: The last Irish Ice Sheet: extent and chronology. *In* Coxon, P., McCarron, S. & Mitchell, F. (eds) *Advances in Irish Quaternary Studies,* 101–149. Atlantis Advances in Quaternary Science **1,** Paris: Atlantis.

Ballantyne, C. K. & Stone, J. O. 2012. Did large ice caps persist on low ground in north-west Scotland during the Lateglacial Interstade? *Journal of Quaternary Science* **27,** 297–306.

Ballantyne, C. K. & Stone, J. O. 2015. Trimlines, blockfields and the vertical extent of the last ice sheet in southern Ireland. *Boreas* **44,** 277–287.

Baltzer, A., Holmes, R. & Evans, D. 1998. Debris flows on the Sula Sgeir Fan, NW of Scotland. *Geological Society, London, Special Publications* **129,** 105–115.

Baltzer, A., Bates, R., Mokeddem, Z., Clet-Pellerin, M., Walter-Simonnet, A. V., Bonnot-Courtois, C. & Austin, W. E. N. 2010. Using seismic facies and pollen analyses to evaluate climatically driven change in a Scottish sea loch (fjord) over the last 20 ka. *Geological Society, London, Special Publications* **344,** 355–369.

Bateman, M. D., Buckland, P. C., Whyte, M. A., Ashurst, P. A., Boulter, C. & Panagiotakopulu, E. 2011. Re-evaluation of the Last Glacial Maximum typesite at Dimlington, U.K. *Boreas* **40,** 573–584.

Bateman, M. D., Evans, D. J. A., Roberts, D. H., Medialdea, A., Ely, J. & Clark, C.D. 2017. The timing and consequences of the blockage of the Humber Gap by the last British-Irish Ice Sheet. *Boreas* DOI: 10.1111/bor. 12256.

Benn, D. I. 1997. Glacier fluctuations in western Scotland. *Quaternary International* **38,** 137–147.

Benn, D. I. & Evans, D. J. A. 2010. *Glaciers and Glaciation.* Second Edition. London: Hodder.

Bennett M. R. 2003. Ice streams as the arteries of an ice sheet: their mechanics, stability and significance. *Earth-Science Reviews* **61,** 309–339.

Bentley, C. R. 1987. Antarctic ice streams: a review. *Journal of Geophysical Research* **92,** 8843–8858.

Birnie, J. K. 2000. Devensian Lateglacial palaeoecological changes in Shetland. *Boreas* **29,** 205–218.

Bishop, W. W. & Coope, G. R. 1977. Stratigraphical and faunal evidence for Lateglacial and Early Flandrian environments in south-west Scotland. *In* Gray, J. M. & Lowe, J. J. (eds) *Studies in the Scottish Lateglacial Environment,* 61–88. Oxford: Pergamon Press.

Boomer, I., von Grafenstein, U. & Moss, A. 2012. Lateglacial to early Holocene multiproxy record from Loch Assynt, NW Scotland. *Proceedings of the Geologists' Association* **123,** 109–116.

Bos, J. A. A., Dickson, J. H., Coope, G. R. & Jardine, W. G. 2004. Flora, fauna and climate of Scotland during the Weichselian Middle Pleniglacial: palynological, macrofossil and coleopteran investigations. *Palaeogeography, Palaeoclimatology, Palaeoecology* **204,** 65–100.

Boulton, G. S., Jones, A. S., Clayton, K. M. & Kenning, M. J. 1977. A British ice-sheet model and patterns of glacial erosion and deposition in Britain. *In* Shotton, F. W. (ed) *British Quaternary Studies: Recent Advances,* 231–246. Oxford: Clarendon Press.

Boulton, G. S., Smith, G. D., Jones, A. S. & Newsome, J. 1985. Glacial geology and glaciology of the last mid-latitude ice sheets. *Journal of the Geological Society, London* **142,** 447–474.

Boulton, G. S., Peacock, J. D. & Sutherland, D. G. 1991. Quaternary. *In* Craig, G. Y. (ed.) Geology *of Scotland,* 503–543. 3rd edition. London: The Geological Society.

Boulton, G. S. & Hagdorn, M. 2006. Glaciology of the British Isles Ice Sheet during the last glacial cycle: form, flow, streams and lobes. *Quaternary Science Reviews* **25,** 3359–3390.

Bowen, D. Q., Rose, J., McCabe, A. M. & Sutherland, D. G. 1986. Correlation of Quaternary glaciations in England, Ireland, Scotland and Wales*. Quaternary Science Reviews* **5**, 299–340.

Bowen, D. Q., Phillips, F. M., McCabe, A. M., Knutz, C. & Sykes, G. A. 2002. New data for the Last Glacial Maximum in Great Britain and Ireland*. Quaternary Science Reviews* **21,** 89–102.

Bradwell, T. 2013. Identifying palaeo-ice-stream tributaries on hard beds: mapping glacial bedforms and erosion zones in NW Scotland. *Geomorphology* **201,** 397–414.

Bradwell, T., Stoker, M. S. & Larter, R. 2007. Geomorphological signature and flow dynamics of the Minch palaeo-ice stream, northwest Scotland. *Journal of Quaternary Science* **22,** 609–617.

Bradwell, T., Fabel, D., Stoker, M., Mathers, H., McHargue, L. & Howe J. 2008a. Ice caps existed throughout the Lateglacial Interstadial in northern Scotland. *Journal of Quaternary Science* **23,** 401–407.

Bradwell, T., Stoker, M. S., Golledge, N. R., Wilson, C. K., Merritt, J. W., Long, D., Everest, J. D., Hestvik, O. B., Stevenson, A. G., Hubbard, A. L., Finlayson, A. G. & Mathers, H. E. 2008b. The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth-Science Reviews* **88,** 207–226.

Bradwell, T., Stoker, M. S. & Krabbendam, M. 2008c. Megagrooves and streamlined bedrock in NW Scotland: the role of ice streams in landscape evolution. *Geomorphology* **97,** 135–156.

Bradwell, T. & Stoker, M. S. 2015a. Asymmetric ice-sheet retreat pattern around northern Scotland revealed by marine geophysical surveys. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh* **105,** 297–322.

Bradwell, T. & Stoker, M. S. 2015b. Submarine sediment and landform record of a palaeo-ice stream within the last British-Irish Ice Sheet. *Boreas* **44,** 255–276.

Brazier, V., Kirkbride, M. P. & Gordon, J. E. 1998. Active ice-sheet deglaciation and ice-dammed lakes in the northern Cairngorm Mountains, Scotland. *Boreas* **27,** 297–310.

Briner, J. P., Goehring, B. M., Mangerud, J. & Svendsen, J. I. 2016. The deep accumulation of ^{10}Be at Utsira, southwestern Norway: implications for cosmogenic nuclide exposure dating in peripheral ice sheet landscapes. *Geophysical Research Letters* **43,** 9121–9129.

Brooks, S. J., Davies, K. L., Mather, K. A., Matthews, I. P. & Lowe, J. J. 2016. Chironomid-inferred summer temperatures for the Last Glacial-Interglacial Transition from a lake sediment sequence in Muir Park Reservoir, west-central Scotland. *Journal of Quaternary Science* **31,** 214–224.

Brooks, S. J., Matthews, I. P., Birks, H. H. & Birks, H. J. B. 2012. High resolution late-glacial and early Holocene summer air temperatures from Scotland inferred from chironomid midge assemblages. *Quaternary Science Reviews* **41,** 67–82.

Brooks, S. J. & Birks, H. J. B. 2000. Chironomid-inferred late-glacial air temperatures at Whitrig Bog, south-east Scotland. *Journal of Quaternary Science* **15,** 759–764.

Brown, E. J., Rose, J., Coope, G. R. & Lowe, J. J. 2007. An MIS 3 age organic deposit from Balglass Burn, central Scotland: palaeoenvironmental significance and implications for the timing of the onset of the LGM ice sheet in the vicinity of the British Isles. *Journal of Quaternary Science* **22,** 295–308.

Brown, I. M. 1993. Pattern of deglaciation of the last (Late Devensian) ice sheet: evidence from ice-marginal deposits in the Dee valley, northeast Scotland. *Journal of Quaternary Science* **8,** 235–250.

Carr, S. J., Holmes, R., van der Meer, J. J. M. & Rose, J. 2006. The Last Glacial Maximum in the North Sea Basin: micromorphological evidence of extensive glaciation. *Journal of Quaternary Science* **21,** 131–153.

Carr, S.J. & Hiemstra, J.F. 2013. Sedimentary evidence against a local ice cap on the Shetland Isles at the Last Glacial Maximum. *Proceedings of the Geologists' Association* **124**, 484–502.

Chiverrell, R. C., Thrasher, I., Thomas, G., Lang, A., Scourse, J. D., McCarroll, D., Clark, C. D., Ó Cofaigh, C., Evans, D. J. A. & Ballantyne, C. K. 2013. Bayesian modelling of the retreat of the Irish Sea Ice Stream (ISIS). *Journal of Quaternary Science* **28,** 200–209.

Chiverrell, R. C. & Thomas G. S. P. 2010. Extent and timing of the Last Glacial Maximum (LGM) in Britain and Ireland: a review. *Journal of Quaternary Science* **25,** 535–549.

Clapperton, C. M. 1997. Greenland ice cores and North Atlantic sediments: implications for the last glaciation in Scotland. *In* Gordon, J. E. (ed.) *Reflections on the Ice Age in Scotland,* 45–58. Glasgow: Scottish Association of Geography Teachers and Scottish Natural Heritage.

Clark, C. D., Evans, D. J. A., Khatwa, A., Bradwell, T., Jordan, C. J., Marsh, S. H., Mitchell, W. A. & Bateman, M. D. 2004. BRITICE: map and GIS database of landforms and features related to the last British Ice Sheet. *Boreas* **33,** 359–375.

Clark, C. D., Hughes, A. L. C., Greenwood, S. L., Jordan, C. & Sejrup, H. P. 2012. Pattern and timing of retreat of the last British-Irish Ice Sheet. *Quaternary Science Reviews* **44,** 112–146.

Clark, C. D., Ely, J. C., Greenwood, S. L., Hughes, A. L. C., Meehan, R., Barr, I. D., Bateman, M. D., Bradwell, T., Doole, J., Evans, D. J. A., Jordan, C. J., Monteys, X., Pellicer, X. M. & Sheehy, M. 2017. BRITICE Glacial Map, version 2: a map and GIS database of glacial landforms of the last Britsh-Irish Ice Sheet. *Boreas* DOI: 10.1111/bor.12273.

Clark, J., McCabe, A., Schnabel, C., Clark, P. U., Freeman, S., Maden, C. & Xu, S. 2009. ^{10}Be chronology of the last deglaciation of County Donegal, northwestern Ireland. *Boreas* **38,** 111–118.

Clark, P. U., McCabe, A. M., Mix, A. C. & Weaver, A. J. 2004. Rapid rise of sea level 19,000 years ago and its global implications. *Science* **304,** 1141–1144.

Clark, P. U., Dyke, A. S., Shakun, J., Carlson, A. E., Clark, J., Wohlfarth, B., Mitrovica, J. X., Hostetler, S. W. & McCabe, A. M. 2009. The Last Glacial Maximum. *Science* **325,** 710–714.

Coward, M. P. 1977. Anomalous glacial erratics in the southern part of the Outer Hebrides. *Scottish Journal of Geology* **13,** 185–188.

Cullingford, R. A. 1977. Lateglacial raised shorelines and deglaciation in the Earn-Tay area. *In* Gray, J. M. & Lowe, J. J. (eds) *Studies in the Scottish Lateglacial Environment,* 15–32. Oxford: Pergamon.

Cullingford, R. A. & Smith, D. E. 1966. Late-glacial shorelines in eastern Fife. *Transactions of the Institute of British Geographers* **39,** 21–38.

Cullingford, R. A. & Smith, D. E. 1980. Late Devensian raised shorelines in Angus and Kincardineshire, Scotland. *Boreas* **9,** 21–38.

Dahl, S. O., Ballantyne, C.K., McCarroll, D. & Nesje, A. 1996. Maximum altitude of Devensian glaciation on the Isle of Skye. *Scottish Journal of Geology* **32,** 107–115.

Davies, B. J., Roberts, D. H., Bridgland, D. R., Ó Cofaigh, C. & Riding, J. B. 2011. Provenance and depositional environments of Quaternary sediments in the western North Sea Basin. *Journal of Quaternary Science* **26,** 59–75.

Daves, H. C., Dobson, M. R. & Whittington, R. J. 1984. A revised seismic stratigraphy for Quaternary deposits on the inner continental shelf west of Scotland between 55°30'N and 57°30'N, *Boreas* **13,** 49–66.

Dove, D., Arosio, R., Finlayson, A., Bradwell, T. & Howe, J. A. 2015. Submarine glacial landforms record Late Pleistocene ice-sheet dynamics, Inner Hebrides, Scotland. *Quaternary Science Reviews* **123,** 76–90.

Dove, D., Finlayson, A., Bradwell, T., Howe, J. A. & Arioso, R. 2016. Deglacial landform assemblage records fast ice-flow and retreat, Inner Hebrides, Scotland. *Geological Society, London, Memoirs* **46,** 135–138.

Dunlop, P., Shannon, R., McCabe, A. M., Quinn, R. & Doyle, E. 2010. Marine geophysical evidence for ice-sheet extension and recession on the Malin Shelf: new evidence for the western limits of the British-Irish Ice Sheet. *Marine Geology* **276,** 86–99.

Evans, D. J. A., Clark, C. D. & Mitchell, W. A. 2005. The last British Ice Sheet: a review of the evidence utilised in the compilation of the glacial map of Britain. *Earth Science Reviews* **70,** 253–312.

Evans, D. J. A., Livingstone, S. J., Vieli, A. & Ó Cofaigh, C. 2009. The palaeoglaciology of the central sector of the British and Irish Ice Sheet: reconciling glaciology and preliminary ice-sheet modelling. *Quaternary Science Reviews* **28,** 739–757.

Everest, J. D., Bradwell, T. & Golledge, N.R. 2005. Subglacial landforms of the Tweed palaeo-ice stream. *Scottish Geographical Journal* **121,** 163–173.

Everest, J. D., Bradwell, T., Fogwill, C. J. & Kubik, P. 2006. Cosmogenic ^{10}Be constraints for the Wester Ross Readvance moraine: insights into British ice-sheet behaviour. *Geografiska Annaler* **88A,** 9–17.

Everest, J. D., Bradwell, T., Stoker, M. & Dewey, S. 2013. New age constraints for the maximum extent of the last British-Irish Ice Sheet (NW sector). *Journal of Quaternary Science* **28,** 2–7.

Everest, J. D. & Golledge, N. R. 2004. Dating deglaciation in Strathspey and the Cairngorm Mountains. *In* Lukas, S., Merritt, J. W. & Mitchell, W. A. *The Quaternary of the Central Grampian Highlands: Field Guide,* 50–57. Cambridge: Quaternary Research Association.

Everest, J. D. & Kubik, P. W. 2006. The deglaciation of eastern Scotland: cosmogenic ^{10}Be evidence for a Lateglacial stillstand. *Journal of Quaternary Science* **21**, 95–104.

Fabel, D., Ballantyne, C. K. & Xu, S. 2012. Trimlines, blockfields, mountain-top erratics and the vertical dimensions of the last British-Irish Ice Sheet in NW Scotland. *Quaternary Science Reviews* **55,** 91–102.

Finlayson, A., Merritt, J., Browne, M., Merritt, J., McMillan, A. & Whitbread, K. 2010. Ice sheet advance, dynamics and decay configurations: evidence from west central Scotland. *Quaternary Science Reviews* **29,** 969–968.

Finlayson, A., Golledge, N., Bradwell, T. & Fabel, D. 2011. Evolution of a Lateglacial mountain icecap in northern Scotland. *Boreas* **40,** 536–554.

Finlayson, A., Fabel, D., Bradwell, T. & Sugden, D. E. 2014. Growth and decay of a marine terminating sector of the last British-Irish Ice Sheet: a geomorphological reconstruction. *Quaternary Science Reviews* **83,** 28–45.

FitzPatrick, E. A. 1965. An interglacial soil at Teindland, Morayshire. *Nature* **207,** 621–622.

Flinn D. 1977. The erosional history of Shetland: a review. *Proceedings of the Geologists' Association* **88,** 129–146,

Flinn, D. 1978a. The most recent glaciation of the Orkney-Shetland channel and adjacent regions. *Scottish Journal of Geology* **14,** 109–123.

Flinn, D. 1978b. The glaciation of the Outer Hebrides. *Geological Journal* **13,** 195–199.

Flinn, D. 2009. The omission of conflicting evidence from the paper by Golledge et al. (2008). *Geografiska Annaler* **91A,** 253–256.

Fretwell, P. T., Smith, D. E. & Harrison, S. 2008. The Last Glacial Maximum British-Irish Ice Sheet: a reconstruction using digital terrain mapping. *Journal of Quaternary Science* **23,** 241–248.

Fyfe, J. A., Long, D. & Evans, D. 1993. The geology of the Malin-Hebrides sea area. *British Geological Survey, United Kingdom Offshore Regional Report.* London: HMSO.

Geikie A. 1901. *The Scenery of Scotland.* 3rd Edition. London: Macmillan.

Geikie, J. 1876. *The Great Ice Age.* 2nd Edition. London: Daldy, Isbister & Co.

Geikie J. 1878. On the glacial phenomena of the Long Isle or Outer Hebrides. *Journal of the Geological Society of London* **34,** 819–866.

Geikie J. 1894. *The Great Ice Age.* 3rd Edition. London: Daldy, Isbister & Co.

Gemmell, A. M. D. 1973. The deglaciation of the Isle of Arran, Scotland. *Transactions of the Institute of British Geographers* **59,** 25–39.

Gheorghiu, D. M., Fabel, D., Hansom, J. D. & Xu, S. 2012. Lateglacial surface exposure dating in the Monadhliath Mountains, Central Highlands, Scotland. *Quaternary Science Reviews* **41,** 132–146.

Gibbard, P. L. & Clark, C. D. 2011. Pleistocene glacial limits in Great Britain. *Developments in Quaternary Science* **15,** 75–93.

Godard A. 1965. *Recherches de Géomorphologie en Écosse du Nord-Ouest.* Paris: Masson.

Golledge, N. R. 2002. Glaci-tectonic deformation of proglacial lake sediments in the Cairngorm Mountains. *Scottish Journal of Geology* **38,** 127–136.

Golledge, N. R. 2010. Glaciation of Scotland during the Younger Dryas stadial: a review. *Journal of Quaternary Science* **25,** 550–566.

Golledge, N. R. & Stoker, M. S. (2006) A palaeo-ice stream of the British ice sheet in eastern Scotland. *Boreas* **35,** 231–243.

Golledge, N. R., Finlayson, A., Bradwell, T. & Everest, J. D. 2008. The last glaciation of Shetland, North Atlantic. *Geografiska Annaler* **90A,** 37–53.

Gordon, J. E. & Sutherland, D. G. (eds) 1993. *Quaternary of Scotland.* London: Chapman & Hall.

Graham, A. G. C., Lonergan, L. & Stoker, M. S. 2007. Evidence for Late Pleistocene ice stream activity in the Witch Ground Basin, central North Sea, from 3D seismic reflection data. *Quaternary Science Reviews* 26, 627–643.

Graham, A. G. C., Lonergan, L. & Stoker, M. S. 2009. Seafloor glacial features reveal the extent and decay of the last British Ice Sheet, east of Scotland. *Journal of Quaternary Science* **24,** 117–138.

Graham, A. G. C., Lonergan, L. & Stoker, M. S. 2010. Depositional environments and chronology of Late Weichselian glaciation and deglaciation of the central North Sea. *Boreas* **39,** 471–491.

Graham, A. G. C., Stoker, M. S., Lonergan, L., Bradwell, T. & Stewart, M. A. 2011. The Pleistocene glaciations of the North Sea Basin. *In* Ehlers, J., Gibbard, P. L. & Hughes, P. D. (eds) *Quaternary Glaciations: Extent and Chronology: a Closer Look.* Developments in Quaternary Science **15,** 261–278. Amsterdam: Elsevier.

Greenwood, S. L. & Clark, C. D. 2009. Reconstruction of the last Irish Ice Sheet 1: changing flow geometries and ice flow dynamics deciphered from the glacial landform record. *Quaternary Science Reviews* **28,** 3085–3100.

Hall, A. M. 1995. Was all of Lewis glaciated in the Late Devensian? *Quaternary Newsletter* **76,** 1–7.

Hall, A. M. 1996. Quaternary geomorphology of the Outer Hebrides. *In* Gilbertson, D., Kent, M. & Grattan, J. (eds) *The Outer Hebrides: the Last 14,000 years,* 5–12. Sheffield: Sheffield Academic Press.

Hall, A. M. 2013. The last glaciation of Shetland: local ice cap or invasive ice sheet? *Norwegian Journal of Geology* **93,** 229–242.

Hall, A. M., Whittington, G., Duller, G. A. T. & Jarvis, J. 1995. Late Pleistocene environments in lower Strathspey, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **85,** 253–273.

Hall, A. M., Auton, C. A., Michie, U. McL, Pearson, S. G. & Riding, J. B. 2011. Switching flow patterns within the last ice sheet in northern Scotland. *Scottish Journal of Geology* **47,** 157–167.

Hall, A. M., Binnie, S. A., Sugden, D. E., Dunai, T. J. and Wood, C. 2016a. Late readvance and rapid final deglaciation of the last ice sheet in the Grampian Mountains, Scotland. *Journal of Quaternary Science* **31,** 869–878.

Hall, A. M., Riding, J. B. & Brown, J. F. 2016b. The last glaciation in Orkney, Scotland: glacial stratigraphy, event sequence and flow paths. *Scottish Journal of Geology* **52,** 90–101.

Hall, A. M. & Bent, A. J. A. 1990. The limits of the last British ice sheet in northern Scotland and the adjacent shelf. *Quaternary Newsletter* **61,** 2–12.

Hall, A. M. & Glasser, N. F. 2003. Reconstructing the basal thermal regime of an ice stream in a landscape of selective linear erosion: Glen Avon, Cairngorm Mountains, Scotland. *Boreas* **32,** 191–207.

Hall, A. M. & Jarvis, J. 1989. A preliminary report on the Late Devensian glaciomarine deposits around St Fergus, Grampian Region. *Quaternary Newsletter* **59,** 5–7.

Hall, A. M. & Phillips, W. M. 2006. Glacial modification of granite tors in the Cairngorms, Scotland. *Journal of Quaternary Science* **21,** 811–830.

Hall, A. M. & Riding, J. B. 2016. The last glaciation in Caithness, Scotland: revised till stratigraphy and ice-flow paths indicate multiple ice-flow phases. *Scottish Journal of Geology* **52,** 77–89.

Hall, A. M. & Whittington, G. W. 1989. Late Devensian glaciation of southern Caithness. *Scottish Journal of Geology* **25,** 307–324.

Hall, I. R., Moran, S. B., Zahn, R., Knutz, P. C., Shen, C. C. & Edwards, R. L. 2006. Accelerated drawdown of meridional overturning in the late-glacial Atlantic triggered by transient pre-H event freshwater perturbation. *Geophysical Research Letters* **33,** L16616.

Harkness, D. D. & Wilson, H. W. 1979. Scottish Universities Research and Reactor Centre Radiocarbon Measurements III. *Radiocarbon* **21,** 203–256.

Hibbert, F. D., Austin, W. E. N., Leng, M. J. & Gatliff, R. W. 2010. British Ice Sheet dynamics inferred from ice-rafted debris records spanning the last 175 000 years. *Journal of Quaternary Science* **25,** 461–482.

Hiemstra, J. F., Shakesby, R. A. & Vieli, A. 2015. Late Quaternary glaciation of the Hebrides sector of the continental shelf: was St Kilda over-run by the British-Irish Ice Sheet? *Boreas* **44,** 178–196.

Holmes, R. 1977. Quaternary deposits of the central North Sea. 5. The Quaternary geology of the UK sector of the North Sea between 56° and 58°N. *Institute of Geological Sciences Report* **77/14,** 50 pp.

Hopkinson, C. & Ballantyne, C. K. 2014. Age and origin of blockfields on Scottish mountains. *Scottish Geographical Journal* **130,** 116–141.

Howe, J. A., Dove, D., Bradwell, T. & Gafeira, J. 2012. Submarine geomorphology and glacial history of the Sea of the Hebrides, UK. *Marine Geology* **315–318,** 64–76.

Hubbard, A., Bradwell, T., Golledge, N., Hall, A. M., Patton, H., Sugden, D. E., Cooper, R. & Stoker, M. S. 2009. Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British-Irish ice sheet. *Quaternary Science Reviews* **28,** 758–776.

Hughes, A. L. C., Clark, C. D. & Jordan, C. J. 2010. Subglacial bedforms of the last British Ice Sheet. *Journal of Maps* **6,** 543–563.

Hughes, A. L. C., Greenwood, S. L. & Clark, C. D. 2011. Dating constraints on the last British-Irish Ice Sheet: a map and database. *Journal of Maps* **7,** 156–184.

Hughes, A. L. C., Clark, C. D. & Jordan, C. J. 2014. Flow pattern evolution of the last British Ice Sheet. *Quaternary Science Reviews* **89,** 148–168.

Hughes, A. L. C., Gyllencreutz, R., Lohne, Ø. S., Mangerud, J. & Svendsen, J. I. 2016. The last Eurasian ice sheets – a chronological database and time-slice reconstruction, DATED-1. *Boreas* **45,** 1–45.

Hulme, P. D. & Shirrifs, J. 1994. The Late-glacial and Holocene vegetation of the Lang Lochs Mire area, Gulberwick, Shetland: a pollen and macrofossil investigation. *New Phytologist* **128,** 793–806.

Jacobi, R. M., Rose, J., MacLeod, A. & Higham, T. F. G. 2009. Revised radiocarbon ages on woolly rhinoceros (*Coelodonta antiquitatis*) from western central Scotland: significance for timing the extinction of woolly rhinoceros in Britain and the onset of the LGM in central Scotland. *Quaternary Science Reviews* **28,** 2551–2556.

Kirk, W. & Godwin, H. 1963. A Late-glacial site at Loch Droma, Ross and Cromarty. *Transaction of the Royal Society of Edinburgh* **65,** 225–248.

Kirkbride, M. P. & Winkler, S. 2012. Correlation of Late Quaternary moraines: impact of climate variability, glacier response and chronological resolution. *Quaternary Science Reviews* **46,** 1–29.

Kleman, J. & Glasser, N. 2007. The subglacial thermal organization (STO) of ice sheets. *Quaternary Science Reviews* **26,** 585–597.

Knutz, P. C., Austin, W. E. N. & Jones, E. J. W. 2001. Millennial-scale depositional cycles related to British Ice Sheet variability and North Atlantic palaeocirculation since 45 kyr B.P., Barra Fan, U.K. margin. *Palaeoceanography* **16,** 53–64.

Knutz, P. C., Jones, E. J. W., Austin, W. E. N. & van Weering, T. C. E. 2002. Glacimarine slope sedimentation, contourite drifts and bottom current pathways on the Barra Fan, UK North Atlantic margin. *Marine Geology* **188,** 129–146.

Kroon, D., Shimmield, G., Austin, W. E. N., Derrick, S., Knutz, P. C. & Shimmield, G. 2000. Century- to millennial-scale sedimentological-geochemical records of glacial-Holocene sediment variations from the Barra Fan (NE Atlantic). *Journal of the Geological Society* **157,** 643–653.

Kuchar, J., Milne, G., Hubbard, A., Patton, H., Bradley, S., Shennan, I. & Edwards, R. 2012. Evaluation of a numerical model of the British-Irish ice sheet using relative sea-level data: implications for the interpretation of trimline observations. *Journal of Quaternary Science* **27,** 597–605.

Lambeck K. 1995. Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. *Journal of the Geological Society* **152,** 437–448.

Lang, B., Brooks, S. J., Bedford, A., Jones, R. T., Birks, H. J. B. & Marshal, J. 2010. Regional consistency in chironomid-inferred air temperatures from five sites in north-west England. *Quaternary Science Reviews* **29,** 1528–1538.

Lawson, T. J. 1990. Former ice movement in Assynt, Sutherland, as shown by the distribution of glacial erratics. *Scottish Journal of Geology* **26,** 25–33.

Lifton, N., Sato, T. & Dunai, T. J. 2014. Scaling in situ cosmogenic nuclide production rates using analytical approximations to atmospheric cosmic-ray fluxes. *Earth and Planetary Science Letters* **386**, 149–160.

Lisiecki, L. E. & Raymo, M. E. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ^{18}O records. *Paleoceanography* **20,** PA1003.

Livingstone, S. J., Ó Cofaigh, C. & Evans, D. J. A. 2008. Glacial geomorphology of the central sector of the last British-Irish Ice Sheet. *Journal of Maps* **4,** 358–377.

Livingstone, S. J., Evans, D. J. A. & Ó Cofaigh, C. 2010a. Re-advance of Scottish ice into the Solway lowlands (Cumbria, UK) during the Main Late Devensian deglaciation. *Quaternary Science Reviews* **29,** 2544–2570.

Livingstone, S. J., Ó Cofaigh, C. & Evans, D. J. A. 2010b. A major ice drainage pathway of the last British–Irish Ice Sheet: the Tyne Gap, northern England. *Journal of Quaternary Science* **25,** 354–370.

Livingstone, S. J., Evans, D. J. A., Ó Cofaigh, C., Davies, B. J., Merritt, J. W., Huddart, D., Mitchell, W. A., Roberts, D. H. & Yorke, L. 2012. Glaciodynamics of the central sector of the last British-Irish Ice Sheet in northern England. *Earth-Science Reviews* **111,** 25–55.

Livingstone, S. J., Roberts, D. H., Davies, B. J., Evans, D. J. A., Ó Cofaigh, C. & Gheorghiu, D. 2015. Late Devensian deglaciation of the Tyne Gap Palaeo-Ice Stream, northern England. *Journal of Quaternary Science* **30,** 790–804.

Lonergan, L., Maidment, S. C. R. & Collier, J. S. 2006. Pleistocene subglacial tunnel valleys in the central North Sea Basin: 3-D morphology and evolution. *Journal of Quaternary Science* **21,** 891–903.

Lowe, J. J. 1978. Radiocarbon-dated Lateglacial and early Flandrian pollen profiles from the Teith valley, Perthshire, Scotland. *Pollen et Spores* **20,** 367–397.

Marrero, S. M., Phillips, F. M., Borchers, B., Lifton, N., Aumer, R. & Balco, G. 2016a. Cosmogenic nuclide systematics and the CRONUScalc program. *Quaternary Geochronology* **31**, 160–187.

Marrero, S. M., Phillips, F. M., Caffee, M. W. & Gosse, J. C. 2016b. CRONUS-Earth cosmogenic ^{36}Cl calibration. *Quaternary Geochronology* **31**, 199–219.

McCabe, A. M., Knight, J. & McCarron, S. G. 1998. Evidence for Heinrich event 1 in the British Isles. *Journal of Quaternary Science* **13,** 549–568.

McCabe, A. M., Clark, P. U. & Clark, J. 2005. AMS ^{14}C dating of deglacial events in the Irish Sea Basin and other sectors of the British-Irish ice sheet. *Journal of the Geological Society, London* **160,** 847–855.

McCabe, A. M., Clark, P. U., Smith, D. E. & Dunlop, P. 2007. A revised model of the last deglaciation of eastern Scotland. *Journal of the Geological Society, London* **164,** 313–316.

McCabe, A. M. & Clark, P. U. 1998. Ice-sheet variability around the North Atlantic Ocean during the last deglaciation. *Nature* **392,** 373–377.

McCabe, A. M. & Ó Cofaigh, C. 1995. Late Pleistocene morainal bank facies at Greystones, eastern Ireland: an example of sedimentation during ice marginal re-equilibration in an isostatically depressed basin. *Sedimentology* **42,** 647–663.

McCabe, A. M. & Williams, G. D. 2012. Timing of the East Antrim Coastal Readvance: phase relationships between lowland Irish and upland Scottish ice sheets during the last glacial termination. *Quaternary Science Reviews* **58,** 18–29.

McCarroll, D., Ballantyne, C. K., Nesje, A. & Dahl, S. O. 1995. Nunataks of the last ice sheet in NW Scotland. *Boreas* **24,** 305–323.

McCarroll, D., Stone, J. O., Ballantyne, C. K., Scourse, J. D., Hiemstra, J. F., Evans, D. J. A. & Fifield, L. K. 2010. Exposure-age constraints on the extent, timing and rate of retreat of the last Irish Sea ice stream. *Quaternary Science Reviews* **29,** 1844–1852.

Merritt, J. W., Coope, G. R., Taylor, B. J. & Walker, M. J. C. 1990. Late Devensian organic deposits beneath till in the Teith Valley, Perthshire. *Scottish Journal of Geology* **26,** 15–24.

Merritt, J. W., Auton, C. A. & Firth, C. R. 1995. Ice-proximal glaciomarine sedimentation and sea-level change in the Inverness area, Scotland: a review of the deglaciation of a major ice stream of the British Late Devensian Ice Sheet. *Quaternary Science Reviews* **14,** 289–329.

Merritt, J. W., Auton, C. A., Connell, E. R., Hall, A. M. & Peacock, J. D. 2003. *Cainozoic Geology and Landscape Evolution of North-East Scotland.* Edinburgh: Memoir of the British Geological Survey.

Merritt, J. W., Connell, E. R. & Hall, A. M. 2017. Middle to Late Devensian glaciation of north-east Scotland: implications for the north-eastern quadrant of the last British-Irish ice sheet. *Journal of Quaternary Science* **32,** 276–294.

Merritt, J. W., Hall, A. M., Connell, E. R. & Gordon, J. E. 2018. Late Pleistocene sediments, landforms and events in Scotland: a review of the terrestrial record. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh* (this issue).

Merritt, J. W. & Auton, C. A. 2000. An outline of the lithostratigraphy and depositional history of Quaternary deposits in the Sellafield district, west Cumbria. *Proceedings of the Yorkshire Geological Society* **53,** 129–154.

Mitchell, W. A. 2007. Reconstructions of the Late Devensian (Dimlington Stadial) British-Irish Ice Sheet: the role of the upper Tees drumlin field, north Pennines, England. *Proceedings of the Yorkshire Geological Society* **56,** 221–234.

Mitchell, W. A. 2008. Quaternary geology of part of the Kale Water catchment, western Cheviot Hills, southern Scotland. *Scottish Journal of Geology* **44,** 51–63.

Nygård, A., Sejrup, H. P., Haflidason, H., Lekens, W. A. H., Clark, C. D. & Bigg, G. R. 2007. Extreme sediment and ice discharge from marine-based ice streams: new evidence from the North Sea. *Geology* **35,** 395–398.

Ó Cofaigh, C., Dunlop, P. & Benetti, S. 2012. Marine geophysical evidence for Late Pleistocene ice sheet extent and recession off northwest Ireland. *Quaternary Science Reviews* **44,** 147–159.

Paterson, I. B. 1974. The supposed Perth Readvance in the Perth district. *Scottish Journal of Geology* **10,** 53–66.

Patton, H., Hubbard, A., Bradwell, T., Glasser, N. F., Hambrey, M. J. & Clark, C. D. 2013. Rapid marine deglaciation: asynchronous retreat dynamics between the Irish Sea Ice Stream and terrestrial outlet glaciers. *Earth Surface Dynamics* **1,** 53–65.

Patton, H., Hubbard, A., Andreassen, K., Winsbarrow, M. & Stroeven, A.P. 2016. The build-up, configuration and dynamical sensitivity of the Eurasian ice-sheet complex to Late Weichselian climatic and oceanic forcing. *Quaternary Science Reviews* **153,** 97–121.

Peach, B. N. & Horne, J. 1879. The glaciation of the Shetland Isles. *Quarterly Journal of the Geological Society* **35,** 778–811.

Peach, B. N. & Horne, J. 1880. The glaciation of the Orkney Islands. *Quarterly Journal of the Geological Society* **36,** 648–663.

Peach, B. N. & Horne, J. 1881. The glaciation of Caithness. *Proceedings of the Royal Physical Society of Edinburgh* **6,** 316–352.

Peach, B. N. & Horne, J. 1910. The Scottish lakes in relation to the geological features of the country. *In* Murray, J. & Pullar, L. (eds) *Bathymetric Survey of the Scottish Fresh-water Lochs,* Volume 1, 439–513. Edinburgh: Challenger Office.

Peacock, J. D. 1975. Scottish late and post-glacial marine deposits. *In* Gemmell, A. M. D. (ed.) *Quaternary Studies in North-East Scotland,* 45–48. Aberdeen: University of Aberdeen.

Peacock, J. D. 1984. Quaternary geology of the Outer Hebrides. *British Geological Survey Reports* **16/2,** 26 pp.

Peacock, J. D. 1991. Glacial deposits of the Hebridean region. *In* Ehlers, J., Gibbard, P. L. & Rose, J. (eds) *Glacial Deposits of Great Britain and Ireland,* 109–119. Rotterdam: Balkema.

Peacock, J. D. 1995. Late Devensian to Early Holocene palaeoenvironmental changes in the Viking Bank area, northern North Sea. *Quaternary Science Reviews* **14,** 1029–1042.

Peacock, J. D. 1999. The pre-Windermere Interstadial (Late Devensian) raised marine strata of eastern Scotland and their macrofauna. *Quaternary Science Reviews* **18,** 1655–1686.

Peacock, J. D. 2003. Late Devensian marine deposits (Errol Clay Formation) at the Gallowflat Claypit, eastern Scotland: new evidence for the timing of ice recession in the Tay Estuary. *Scottish Journal of Geology* **39,** 1–10.

Peacock, J. D., Austin, W. E. N., Selby, I., Graham, F. D. K., Harland, R. & Wilkinson I.P. 1992. Late Devensian and Flandrian palaeoenvironmental changes on the Scottish continental shelf west of the Outer Hebrides. *Journal of Quaternary Science* **7,** 145–161.

Peacock, J. D., Armstrong, M., Browne, M. A. E., Golledge, N. R. & Stoker, M. S. 2007. Discussion on a revised model for the last deglaciation of eastern Scotland. *Journal of the Geological Society* **164,** 1261–1263.

Peacock, J. D., Horne, D. J. & Whittaker, J. E. 2012. Late Devensian evolution of the marine offshore environment of western Scotland. *Proceedings of the Geologists' Association* **123,** 419–437.

Peacock, J. D. & Harkness, D. D. 1990. Radiocarbon ages and the full-glacial to Holocene transition in seas adjacent to Scotland and southern Scandinavia: a review. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **81,** 385–396.

Peacock, J. D. & Long, D. 1994. Late-Devensian glaciation and deglaciation of Shetland. *Quaternary Newsletter* **74,** 16–21.

Peacock, J. D. & Ross, D. L. 1978. Anomalous glacial erratics in the southern part of the Outer Hebrides. *Scottish Journal of Geology* **14,** 263.

Peglar, S. 1979. A radiocarbon-dated pollen diagram from Loch of Winless, Caithness, north-east Scotland. *New Phytologist* **82,** 245–263.

Pennington, W. 1975. A chronostratigraphic comparison of Late Weichselian and Late Devensian sub-divisions, illustrated by two radiocarbon-dated profiles from western Britain. *Boreas* **4,** 157–171.

Pennington, W., Haworth, E. Y., Bonny, A.P. & Lishman, J. P. 1972. Lake sediments in northern Scotland. *Philosophical Transactions of the Royal Society* **B264,** 191–294.

Penny, L. F., Coope, G. R. & Catt, J. A. 1969. Age and insect fauna of the Dimlington Silts, East Yorkshire. *Nature* **224,** 65–67.

Peters, C., Walden, J. & Austin, W. E. N. 2008. Magnetic signature of European margin sediments: provenance of ice-rafted debris and the climatic response of the British ice sheet during Marine Isotope Stages 2 and 3. *Journal of Geophysical Research* **113,** F03007.

Peters, J. L., Benetti, S., Dunlop, P. & Ó Cofaigh, C. 2015: Maximum extent and dynamic behaviour of the last British–Irish Ice Sheet west of Ireland. *Quaternary Science Reviews* **128,** 48–68.

Phillips, W. M., Hall, A. M., Mottram, R., Fifield, L. K. & Sugden, D. E., 2006. Cosmogenic ^{10}Be and ^{26}Al exposure ages of tors and erratics, Cairngorm Mountains, Scotland: timescales for the development of a classic landscape of selective linear erosion. *Geomorphology* **73,** 222–245.

Phillips, W. M., Hall, A. M., Ballantyne, C. K., Binnie, S., Kubik P. & Freeman, S. 2008. Extent of the last ice sheet in northern Britain tested with cosmogenic ^{10}Be exposure ages. *Journal of Quaternary Science* **23,** 101–107.

Praeg, D., McCarron, S., Dove, D., Ó Cofaigh, C., Scott, G., Monteys, X., Facchin, L., Romeo, R. & Coxon, P. 2015. Seeking the seaward limits of the Irish Sea Ice Stream: glaciation of the Celtic Sea shelf edge at the last glacial maximum. *Quaternary Science Reviews* **111,** 107–112.

Rasmussen, S. O., Bigler, M., Blockley, S. P., Blunier, T., Buchart, S. L., Clausen, H. B., Cvijanovic, I., Dahl-Jensen, D., Johnsen, S. J., Fischer, H., Gkinis, V., Guillevic, M., Hoek, W. Z., Lowe, J. J., Pedro, J. B., Popp, T., Seierstad, I. K., Steffensen, J. P., Svensson, A. M., Vallelonga, B. O., Walker, M. J. C., Wheatley, J. J. & Winstrup, M. 2014. A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. *Quaternary Science Reviews* **106,** 14–28.

Reimer, P. J., Bard, E., Bayliss, A. *et al.* 2013. IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP. *Radiocarbon* **55**, 1869–1887.

Rignot, E., Mouginot, J. & Scheuchl, B. 2011. Ice flow of the Antarctic Ice Sheet. *Science* **333,** 1427–1429.

Rise, L. & Rokoengen, K. 1984. Surficial sediments in the Norwegian sector of the North Sea between 60°30'N and 62°N. *Marine Geology* **58,** 287–317.

Roberts, D. H., Dackombe, R. V. & Thomas, G. S. P. 2007. Palaeo-ice streaming in the central sector of the British-Irish Ice Sheet during the Last Glacial Maximum: evidence from the northern Irish Sea Basin. *Boreas* **36,** 115–129.

Roberts, D. H., Evans, D. J. A., Lodwick, J. & Cox, N. J. 2013. The subglacial and ice-marginal signature of the North Sea Lobe of the British-Irish Ice Sheet during the Last Glacial Maximum at Upgang, North Yorkshire, UK. *Proceedings of the Geologists' Association* **124,** 503–519.

Robinson, M. & Ballantyne, C. K. 1979. Evidence for a glacial readvance pre-dating the Loch Lomond Advance in Wester Ross. *Scottish Journal of Geology* **15,** 271–277.

Salt, K. E. & Evans, D. J. A. 2004. Superimposed subglacially streamlined landforms of southwest Scotland. *Scottish Geographical Journal* **120,** 133–147.

Schimmelpfennig, I., Benedetti, L., Finkel, R., Pik, R., Blard, P. H., Bourlès, D., Burnard, P. & Williams, A. 2009. Sources of in-situ ^{36}Cl in basaltic rocks. Implications for calibration of production rates. *Quaternary Geochronology* **4**, 441–461.

Scourse, J. D. & Furze, M. F. A. 2001. A critical review of the glacimarine model for Irish Sea deglaciation: evidence from southern Britain, the Celtic shelf and adjacent continental slope. *Journal of Quaternary Science* **16,** 419–434.

Scourse, J. D., Haapaniemi, A. I., Colmenero-Hidalgo, E., Peck, V. L., Hall, I. R., Austin, W. E. N., Knutz, P. C. & Zahn, R. 2009. Growth, dynamics and deglaciation of the last British-Irish ice sheet: the deep-sea ice-rafted detritus record. *Quaternary Science Reviews* **28,** 3066–3084.

Sejrup, H. P., Haflidason, H., Aarseth, I., King, E., Forsberg, C. F., Long, D. & Rokoengen, K. 1994. Late Weichselian glaciation history of the central North Sea. *Boreas* **23,** 1–13.

Sejrup, H. P., Hjelstuen, B. O., Dahlgren, K. I. T., Haflidason, H., Kuijpers, A., Nygård, A., Praeg, D., Stoker, M. S. & Vorren, T. O., 2005. Pleistocene glacial history of the NW European continental margin. *Marine and Petroleum Geology* **22,** 1111–1129.

Sejrup, H. P., Nygård, A., Hall, A. M. & Haflidason, H. 2009. Middle and Late Weichselian (Devensian) glaciation history of south-western Norway, North Sea and eastern UK. *Quaternary Science Reviews* **28,** 370–380.

Sejrup, H. P., Hjelstuen, B. O., Nygård, A., Haflidason, H. & Mardal, I. 2015. Late Devensian ice-marginal features in the central North Sea – processes and chronology. *Boreas* **44,** 1–13.

Sejrup, H. P., Clark, C. D. & Hjelstuen, B. O. 2016. Rapid ice sheet retreat triggered by ice stream debuttressing: evidence from the North Sea. *Geology* **44,** 355–358.

Selby, I. 1989. *Quaternary Geology of the Hebridean Continental Margin.* Unpublished PhD thesis, University of Nottingham.

Shennan, I., Peltier, W. R., Drummond, R. & Horton, B. 2002. Global to local scale parameters determining relative sea-level changes and the post glacial isostatic readjustment of Great Britain. *Quaternary Science Reviews* **21,** 397–408.

Simpson, J. B. 1933. The late-glacial readvance moraines of the highland border west of the River Tay. *Transactions of the Royal Society of Edinburgh* **57,** 633–645.

Sissons, J. B. 1963. The Perth Readvance in central Scotland. Part I. *Scottish Geographical Magazine* **79,** 151–163.

Sissons, J. B. 1964. The Perth Readvance in central Scotland. Part II. *Scottish Geographical Magazine* **80,** 28–36.

Sissons, J. B. 1967. *The Evolution of Scotland's Scenery.* Edinburgh: Oliver and Boyd, 259 pp.

Sissons, J. B. 1974. The Quaternary in Scotland: a review. *Scottish Journal of Geology* **10,** 311–337.

Sissons, J. B. 1981. The last Scottish ice-sheet: facts and speculative discussion. *Boreas* **10,** 1–17.

Sissons, J. B. 1983. The Quaternary geomorphology of the Inner Hebrides: a review and reassessment. *Proceedings of the Geologists' Association* **94,** 165–175.

Sissons, J. B., Smith, D. E. & Cullingford, R. A. 1966. Late-glacial and post-glacial shorelines in south-east Scotland. *Transactions of the Institute of British Geographers* **39,** 9–18.

Sissons, J. B. & Dawson, A. G. 1981. Former sea levels and ice limits in part of Wester Ross, North-West Scotland. *Proceedings of the Geologists' Association* **92,** 115–124.

Sissons, J. B. & Smith, D. E. 1965. Raised shorelines associated with the Perth Readvance in the Forth valley and their relation to glacial isostasy. *Transactions of the Royal Society of Edinburgh* **66,** 143–168.

Sissons, J. B. & Walker, M. J. C. 1974. Late glacial site in the central Grampian Highlands. *Nature* **249,** 822–824.

Small, D., Rinterknecht, V., Austin, W. E. N., Fabel, D., Miguens-Rodriguez, M. & Xu, S. 2012. *In situ* cosmogenic exposure ages from the Isle of Skye, northwest Scotland: implications for the timing of deglaciation and readvance from 15 to 11 ka. *Journal of Quaternary Science* **27,** 150–158.

Small, D., Austin, W. E. N. & Rinterknecht, V. 2013a. Freshwater influx, hydrographic reorganization and the dispersal of ice-rafted detritus in the sub-polar North Atlantic Ocean during the last deglaciation. *Journal of Quaternary Science* **28,** 527–535.

Small, D., Parrish, R., Austin, W. E. N., Cawood, P. A. & Rinterknecht, V. 2013b. Provenance of North Atlantic ice-rafted debris during the last deglaciation – a new application of U-Pb rutile and zircon geochronology. *Geology* **41,** 155–158.

Small, D., Rinterknecht, V., Austin, W. E. N., Bates, R., Benn, D. I., Scourse, J. D., Bourlès, D., ASTER Team & Hibbert, F. D. 2016. Implications of ^{36}Cl exposure ages from Skye, northwest Scotland for the timing of ice stream deglaciation and deglacial ice dynamics. *Quaternary Science Reviews* **150,** 130–145.

Small, D., Benetti, S., Dove, D., Ballantyne, C. K., Fabel, D., Clark, C. D., Gheorghiu, D. M., Newall, J. & Xu, S. 2017a. Cosmogenic exposure age constraints on deglaciation and flow behaviour of a marine-based ice stream in western Scotland, 21–16 ka. *Quaternary Science Reviews* **167,** 30–46.

Small, D., Clark, C. D., Chiverrell, R. C., Smedley, R. K., Bateman, M. D., Duller, G. A. T., Ely, J. C., Fabel, D., Medialdea, A. & Moreton, S. G. 2017b. Devising quality assurance procedures for assessment of legacy geochronological data relating to deglaciation of the last British-Irish Ice Sheet. *Earth-Science Reviews* **164,** 232–250.

Smedley, R. K., Chiverrell, R. C., Ballantyne, C. K. Burke, M. J., Clark, C. D., Duller, G. A. T., Fabel, D., McCarroll, D., Scourse, J. D., Small, D. & Thomas, G. S. P. 2017a. Internal dynamics condition centennial-scale oscillations in marine-based ice stream retreat. *Geology* In press.

Smedley, R. K., Scourse, J. D., Small, D., Hiemstra, J. F., Duller, G. A. T., Bateman, M. D., Burke, M. J., Chiverrell, R. C., Clark, C. D., Davies, S. M., Fabel, D., Gheorghiu, D. M., McCarroll, D., Medialdia, A. & Xu, S. 2017b. New age constraints for the limit of the British-Irish Ice Sheet on the Isles of Scilly. *Journal of Quaternary Science* 32, 48–62.

Stewart, H. A. *et al.* 2018. Quaternary stratigraphy of the shelves adjacent to Scotland (final authors and title to be determined). *Earth and Environmental Science Transactions of the Royal Society of Edinburgh.* This issue.

Stoker, M. S. 1995. The influence of glacigenic sedimentation on slope-apron development on the continental margin off Northwest Britain. *Journal of the Geological Society* **90,** 159–177.

Stoker, M. S. 2013. Cenozoic sedimentary rocks. *In* Hitchen, K. Johnson, H. & Gatliff, R. W. (eds) *Geology of the Rockall Basin and adjacent areas.* British Geological Survey Research Report **RR/12/03,** 159–177.

Stoker, M. S., Hitchen, K. & Graham, C. C. 1993. The geology of the Hebrides and West Shetland shelves, and adjacent deep-water areas. *British Geological Survey United Kingdom Offshore Regional Report.* London: HMSO, 149 pp.

Stoker, M. S., Leslie, A. B., Scott, W. D., Briden, J. C. Hine, N. M., Harland, R., Wilkinson, I. P., Evans, D. & Ardus, D. A. 1994. A record of late Cenozoic stratigraphy, sedimentation and climate change from the Hebrides Slope, NE Atlantic Ocean. *Journal of the Geological Society* **151,** 96–137.

Stoker, M. S., Bradwell, T., Wilson, C., Harper, C., Smith, D. & Brett, C. 2006. Pristine fjord landsystem revealed on the sea bed in the Summer Isles region, NW Scotland. *Scottish Journal of Geology* **42,** 89–99.

Stoker, M. S., Bradwell, T., Howe, J. A., Wilkinson, I. P. & McIntyre, K. 2009. Lateglacial ice-cap dynamics in NW Scotland: evidence from the fjords of the Summer Isles region. *Quaternary Science Reviews* **28,** 3161–3184.

Stoker M. S. & Bradwell T. 2005. The Minch palaeo-ice stream, NW sector of the British-Irish ice sheet. *Journal of the Geological Society, London* **163,** 425–428.

Stoker, M. S. & Holmes, R. 1991. Submarine end-moraines as indicators of Pleistocene ice-limits off northwest Britain. *Journal of the Geological Society, London* **148,** 431–434.

Stoker, M. S. & Varming, T. 2011. Cenozoic (sedimentary). *In* Ritchie, J. D., Ziska, H., Johnson, H. & Evans, D. (eds) *Geology of the Faroe-Shetland Basin and adjacent areas.* British Geological Survey Research Report **RR/11/01,** 151–208.

Stokes, C. R. & Clark, C. D. 1999. Geomorphological criteria for identifying Pleistocene ice streams. *Annals of Glaciology* **28,** 67–74.

Stokes, C. R. & Clark, C. D. 2001. Palaeo-ice streams *Quaternary Science Reviews* **20,** 1437–1457.

Stone, J. O., Ballantyne, C. K. & Fifield, L. K. 1998. Exposure dating and validation of periglacial weathering limits, northwest Scotland. *Geology* **26**, 587–590.

Stone, J. O. & Ballantyne, C. K. 2006. Dimensions and deglacial chronology of the Outer Hebrides Ice Cap, NW Scotland: implications of cosmic-ray exposure dating. *Journal of Quaternary Science* **21,** 75–84.

Stuiver, M., Reimer, P. J. & Reimer, R.W. 2016. CALIB 7.1. http://calib.org (accessed June 2017).

Sugden, D. E. 1970. Landforms of deglaciation in the Cairngorm Mountains, Scotland. *Transactions of the Institute of British Geographers* **51,** 79–92.

Sutherland, D. G. 1984. The Quaternary deposits and landforms of Scotland and the neighbouring shelves: a review. *Quaternary Science Reviews* **3**, 157–254.

Sutherland, D. G. 1986. A review of Scottish marine shell radiocarbon dates, their standardization and interpretation. *Scottish Journal of Geology* **22,** 145–164.

Sutherland, D. G., Ballantyne, C. K. & Walker, M. J. C. 1984. Late Quaternary glaciation and environmental change on St Kilda, Scotland, and their palaeoclimatic significance. *Boreas* **13,** 261–272.

Thomson, M. E. & Eden, R. A. 1977. Quaternary deposits of the central North Sea. 3. The Quaternary sequence in the west-central North Sea. *Institute of Geological Sciences Report* **77/12,** 18 pp.

Truffer, M. & Echelmeyer, K. A. 2003. Of isbrae and ice streams. *Annals of Glaciology* **36,** 66–72.

Turner, A. J., Woodward, J., Dunning, S. A., Shine, A. J., Stokes, C. R. & Ó Cofaigh, C. 2012. Geophysical surveys of the sediments of Loch Ness, Scotland: implications for the deglaciation of the Moray Firth Ice Stream, British-Irish Ice Sheet. *Journal of Quaternary Science* **27,** 221–232.

Tyrrell, G. W. 1928. *The Geology of Arran.* Memoir of the Geological Survey. Edinburgh: HMSO.

Von Weymarn, J. A. 1979: A new concept of glaciation in Lewis and Harris. *Proceedings of the Royal Society of Edinburgh* **77B,** 97–105.

Walker, M. J. C., Ballantyne, C. K., Lowe, J. J. & Sutherland, D. G. 1988. A reinterpretation of the Lateglacial environmental history of the Isle of Skye, Inner Hebrides, Scotland. *Journal of Quaternary Science* **3,** 135–146.

Walker, M. J. C. & Lowe, J. J. 1982. Lateglacial and Flandrian chronology of the Isle of Mull, Scotland. *Nature* **296,** 822–824.

Watson, J., Brooks, S. J., Whitehouse, N. J., Reimer, P. J., Birks, H. J. B. & Turney, C. 2010. Chironomid-inferred Late-glacial summer air temperatures from Lough Nadourcan, Co. Donegal, Ireland. *Journal of Quaternary Science* **25,** 1200–1210.

Whittington, G., Edwards, K. J. & Caseldine, C. J. 1991. Late- and post-glacial pollen-analytical and environmental data from a near-coastal site in north-east Fife, Scotland. *Review of Palaeobotany and Palynology* **68,** 65–85.

Whittington, G., Buckland, P., Edwards, K. J., Greenwood, M., Hall, A. M. & Robinson, M. 2003. Multiproxy Devensian Late-glacial and Holocene environmental records at an Atlantic coastal site in Shetland. *Journal of Quaternary Science* **18,** 151–168.

Whittington, G. & Hall, A. M. 2002. The Tolsta Interstadial, Scotland: a correlation with D-O cycles GI-8 to GI-5? *Quaternary Science Reviews* **21,** 901–915.

Wilson, L. J., Austin, W. E. N. & Jansen, E. 2002. The last British Ice Sheet: growth, maximum extent and deglaciation. *Polar Research* **21,** 243–250.

Wilson, L. J. & Austin, W. E. N. 2002. Millennial and sub-millennial scale variability in sediment colour from the Barra Fan, NW Scotland: implications for British Ice Sheet dynamics. *Journal of the Geological Society* **203,** 349–366.

Wright, W. B. 1914. *The Quaternary Ice Age.* London: MacMillan & Co.

Captions to Figures

Figure 1 Key locations mentioned in the text.

Figure 2 The last Scottish Ice Sheet as depicted by Peach & Horne (1910), who envisaged confluence of Scottish and Scandinavian ice in the North Sea Basin, northwestward deflection of ice from Eastern Scotland and the Moray Firth across Caithness and Orkney, and westward termination of the ice sheet at the Atlantic Shelf edge. The flow patterns were based only on terrestrial evidence (striae, erratic carry and lithostratigraphy) as no offshore information was available.

Figure 3 Changing views of the extent of the northern sector of the last British-Irish Ice Sheet. The dashed line represents the LGM limit of the last ice sheet depicted by Bowen *et al.* (1986, 2002). The solid line represents the approximate limit of the last ice sheet as depicted by Sejrup *et al.* (2005) S of 55°N and Bradwell *et al.* (2008b) N of 55°N.

Figure 4 Flowsets of the northern and central parts of the last ice sheet in Great Britain as interpreted by Hughes *et al.* (2014). Red flowsets are interpreted to be isochronous and those in other colours are inferred to be time-transgressive. Reproduced from Hughes *et al.* (2014) *Quaternary Science Reviews* **89,** 148–168, with permission from Elsevier. © 2014 Elsevier Ltd.

Figure 5 Stages in the growth of the last British Ice Sheet inferred by Hughes *et al.* (2014) from flowset and offshore evidence. Thick lines represent former ice divides or saddles, and thin lines represent flowlines inferred from flowsets and offshore landform data. Reproduced from Hughes *et al.* (2014) *Quaternary Science Reviews* **89,** 148–168, with permission from Elsevier. © 2014 Elsevier Ltd.

Figure 6 Stages in the evolution of the last ice sheet in west central Scotland identified by Finlayson *et al.* (2010). (a) Advance of ice from the SW Highlands across the Firth of Clyde, Ayrshire and the Midland Valley. (b) Establishment of an ice divide between the SW Highlands and western Southern Uplands results in eastward flow of ice across the Midland Valley. (c) Eastward migration of the ice divide results in dominantly westward ice movement, feeding the Hebrides Ice Stream. Reproduced from Finlayson *et al.* (2010) *Quaternary Science Reviews* **29,** 969–988, with permission from Elsevier. © 2009 NERC.

Figure 7 Ice flow in southern Scotland and northern England during the maximum expansion of the BIIS, as depicted by Livingstone *et al.* (2012). Thick dash-dotted lines represent ice divides, arrows indicate ice-flow vectors and dashed arrows in red indicate possible alternative ice-flow vectors. The inset shows location of this sector within the BIIS as depicted by Clark *et al.* (2012). Reproduced from Livingstone, S.J. *et al.* (2012) *Earth-Science Reviews* **111,** 25–55, with permission from Elsevier. © 2011 Elsevier B.V.

Figure 8 Sequential stages in the evolution of the eastern sector of the SIS as depicted by Merritt *et al.* (2017). (a) Southeastward diversion of Moray Firth ice from an ice divide linking Caithness and the Shetland Ice Cap. (b) Northwestward re-routing of Moray Firth ice by a receding ice shed linking Buchan and Shetland (position 1) that subsequently retreated to position 2. Dashed lines represent flow directions. Thick lines with open diamonds denote ice divides; those with filled ticks denote a receding ice shed. The red hexagon represents the position of the Witch Ground Basin. From Merritt *et al.* (2017) *Journal of Quaternary Science* **32,** 276–294. Copyright 2016 John Wiley & Sons, Ltd.

Figure 9 Confluence of the SIS and FIS in the NSB during the LLGM as depicted by Bradwell *et al.* (2008b), with hypothesized flow lines. Dark shading depicts the inferred confluence zone (CZ) and arrows show the orientations of mega-scale glacial lineations. Hatching represents the approximate areas occupied by shelf-edge fans. Also depicted is diversion of ice from western Scotland into the Minch and Hebrides Ice Streams by the Outer Hebrides Ice Cap. From Bradwell *et al.* (2008) *Earth-Science Reviews* **88,** 207–226. © 2008 NERC. Reproduced with permission from Elsevier B.V.

Figure 10 Merged onshore-offshore (topographic-bathymetric) surface model depicting the relief of Scotland north of the Southern Uplands and the adjacent continental shelf. Offshore data are derived from the Olex database (www.olex.no) and onshore relief from the NEXTMap Britain digital surface model (Intermap Technologies). Reproduced from Bradwell *et al.* (2008b) *Earth-Science Reviews* **88,** 207–226. © 2008 NERC. Reproduced with permission from Elsevier B.V.

Figure 11 Seafloor landforms on the Atlantic shelf and northern North Sea Basin mapped by Bradwell *et al.* (2008b) from the bathymetric data in Figure 10. Solid lines: ridges (moraines or moraine banks). Dashed lines: channels, interpreted as tunnel valleys excavated by subglacial meltwater. Reproduced from Bradwell *et al.* (2008b) *Earth-Science Reviews* **88,** 207–226. © 2008 NERC. Reproduced with permission from Elsevier B.V.

Figure 12 Reconstructed ice-margin positions around northern Scotland (coloured lines), interpreted from the alignment of submarine moraines by Bradwell & Stoker (2015a). Stages 1 and 2 are inferred to represent pre-MIS 3/2 moraines, and Stage 3 moraines are interpreted as the outermost Late Devensian moraines. Their interpretation of subsequent ice-sheet retreat (stages 4–10) implies early deglaciation of the northern Outer Hebrides and persistence of an ice cap centred on Orkney and Shetland after retreat of the ice margin to the present coast of NW Scotland. The dates depicted are selected (unrecalibrated) TCN ages. Reproduced from Bradwell, T. & Stoker, M. S. (2015) *Earth and Environmental Science Transactions of the Royal Society of Edinburgh* **105,** 297–322 with permission from Cambridge University Press.

Figure 13 (a) Striae on ice-moulded bedrock at 997 m altitude on Ben Challum, southern Grampians. (b) Quartzite erratic resting on ice-moulded sandstone bedrock at 860 m altitude on Beinn Damh, Wester Ross. (c) Granite tors rising above blockfield debris at the summit of Beinn Mheadhoin (1182 m), Cairngorm Mountains. (d) Periglacial blockfield of sandstone boulders at the summit (933 m) of Maol Cheann-dearg, Torridon. Quartzite erratics on the blockfield have produced cosmogenic ^{10}Be exposure ages of ~16 ka (Fabel *et al.* 2012), indicating that they were deposited by the last ice sheet.

Figure 14 TCN exposure ages obtained for high-level erratics and bedrock samples above and below trimlines in the Scottish Highlands. The shaded area represents the timing of the LGM (26.5–19.0 ka). Horizontal bars represent ±1σ uncertainties. Post-LGM exposure ages obtained for most high-level erratics demonstrate that mountain summits were over-run by the last ice sheet. Reproduced from Fabel *et al.* (2012) *Quaternary Science Reviews* **55,** 91–102. Reproduced with permission from Elsevier. © 2012 Elsevier B.V.

Figure 15 Main palaeoglaciological features of the Minch Ice Stream. White lines indicate proposed ice-stream tributaries and flowlines. Thick lines are inferred terminus positions proposed by Bradwell & Stoker (2015a), who considered that the outermost line probably represents a pre-MIS3/2 ice limit, but the inner lines represent Late Devensian ice margin positions. Hatching indicates an area of subglacial bedforms and iceberg scours, but lacking moraines. From Bradwell & Stoker (2015b) *Boreas* **44,** 255–276. © Boreas Collegium. Reproduced with permission from John Wiley & Sons Ltd.

Figure 16 Reconstruction of the pattern of retreat of the BIIS as depicted by Clark *et al.* (2012). Solid black lines record former ice margins based on landform evidence and dashed lines are interpolated or extrapolated ice margin positions. Reproduced from Clark *et al*. (2012) *Quaternary Science Reviews* **44,** 112–146, with permission from Elsevier. © 2010 Elsevier Ltd.

Figure 17 Reconstructions of successive ice-sheet configurations in the North Sea Basin (NSB) proposed by Sejrup *et al.* (2016). (a) Maximum configuration with an ice divide extending from NE Scotland to SW Norway and an ice-dammed lake in the southern NSB. (b) Initiation of ice-sheet collapse: expansion and acceleration of the Norwegian Channel Ice Stream (NCIS) (dark blue lines) causes drawdown of ice and destroys the ice divide. Grounding line retreat in the Norwegian Channel progressively debuttresses ice on either side. (c) Decoupling of the BIIS and FIS as the NCIS retreats, causing northward drainage of the ice-dammed lake. Red arrows indicate readvances of the BIIS, and black arrows indicate net westward retreat of the BIIS ice margin. Reproduced from Sejrup *et al.* (2016) *Geology* **44,** 355–358, with permission from the Geological Society of America.

Figure 18 Extent of the Scottish Readvance as represented by Livingstone *et al.* (2015). Only the ice limits south of the Solway Firth, along the Cumbrian coast and across the Isle of Man can be confidently identified. Purple areas represent proposed ice-dammed lakes. From Livingstone *et al.* (2015) *Journal of Quaternary Science* **30,** 790–804. © The authors. Reproduced with permission from John Wiley & Sons, Ltd.

Figure 19 Uncertainty-weighted means of terrestrial cosmogenic nuclide exposure ages indicating the timing of deglaciation, calibrated using the protocol outlined in section 2. Statistical outliers are excluded. Each age is followed by the full (± 1σ) uncertainty, and the number of individual ages in the sample is shown in brackets. Single ages on the Outer Hebrides are shown for completeness, but should be treated with caution.

Figure 20 Multibeam bathymetry of the seafloor in the vicinity of the Summer Isles, outer Loch Broom, showing multiple recessional moraines formed by readvances that interrupted ice margin retreat. From Bradwell *et al.* (2008a) *Journal of Quaternary Science* **23,** 401–407. © 2008 NERC. Reproduced with permission from John Wiley & Sons Ltd.

Figure 21 Wester Ross Readvance moraines. (a) The Applecross moraine crosses the photograph from left to right between the two lochans. (b) The central section of the Gairloch moraine, which is composed of Torridon Sandstone boulders and occasional Lewisian Gneiss erratics. The former glacier was located to the right (east) of the ridge.

Figure 22 Moraines marking the limits of the Wester Ross Readvance, showing the sites sampled by Bradwell *et al.* (2008a; sites 1, 2 and 4) and Ballantyne *et al.* (2009a; sites 3, 5, 6 and 7) for cosmogenic ^{10}Be exposure dating of boulders on moraines. From Ballantyne & Stone (2012), *Journal of Quaternary Science* **27,** 297–306. © 2011 John Wiley & Sons Ltd.

Figure 23 Summed normal kernel density estimates of recalibrated cosmogenic ^{10}Be exposure ages and their uncertainties for boulder samples from Wester Ross Readvance moraines. Upper line: all 22 samples; weighted mean age 15.28 ± 0.69 ka. Middle line: 14 ages originally reported by Ballantyne *et al.* (2009a); weighted mean age 15.31 ± 0.70 ka. Lower (dashed) line: 8 ages originally reported by Bradwell *et al.* (2008a); weighted mean age 15.23 ± 0.71 ka.

Figure 24 Key terrestrial and nearshore radiocarbon ages that constrain the timing of ice-sheet deglaciation, showing the extent of glacier ice during the Younger Dryas Stade (~12.9–11.7 ka). Ages are expressed as calibrated ± 1σ age ranges (cal ^{14}C ka). Most nearshore and coastal ages were obtained from molluscs or foraminifera, and inland ages represent the oldest date obtained from organic material in cores recovered from lakes or infilled depressions. For a few sites two or more ages have been aggregated and the combined ± 1σ age range is shown. All ages represent *minima* for deglaciation. Ages shown with a question mark may be too old.

Figure 25 (a) Pattern of ice movement in eastern Scotland following opening of a marine embayment to the Witch Ground Basin (red hexagon) depicted by Merritt *et al.* (2017). (b) Subsequent retreat of Strathmore ice and deglaciation of eastern Scotland depicted by the same authors. Dashed lines represent flow directions, and thick lines with open diamonds denote ice divides. From Merritt *et al.* (2017) *Journal of Quaternary Science* **32,** 276–294. Copyright © 2016 John Wiley & Sons, Ltd.

Figure 26 Key TCN (dots) and calibrated radiocarbon (vertical dashes) deglaciation ages plotted above the NGRIP ice core δ^{18}O record for the period 20–11 ka (Rasmussen *et al.* 2014), the associated ice core stages and mean July temperatures inferred from chironomid assemblages in SE Scotland (Brooks & Birks 2000). Horizontal lines are ± 1σ uncertainties. TCN ages represent the approximate timing of deglaciation but radiocarbon ages are minimal for the timing of deglaciation.

Table 1 Radiocarbon ages relating to the expansion of the last Scottish Ice Sheet

Site	Lab code	^{14}C age (years)	Calibrated age range (ka)	Sample and context
Balglass Burn, Campsie Fells, central Scotland[1]	CAMS 72403 to CAMS 72409	28,050 ± 160 to 34,480 ± 340	32.1–31.5 to 39.4–38.7	6 samples of coleopteran fragments or *Carex* fruits in glacitectonised organic deposit underlying till.
Sourlie, Ayrshire[2]	SRR-3023	29,900 ± 420	34.4–33.7	Reindeer antler in organic sediments overlain by till.
Sourlie, Ayrshire[2]	SRR-3146–SRR-3148	29,290 ± 350 to 33,270 ± 370	33.9–33.2 to 38.2–37.0	3 samples of plant debris or bulk organic matter from organic sediments overlain by till.
Wilderness Pit, Bishopbriggs[3]	OxA-19560	31,140 ± 170	35.3–34.9	Woolly rhinoceros bone in outwash overlain by till.
Hungryside, Bishopbriggs[3]	OxA-X-228-33	32,250 ± 700	37.1–35.3	Woolly rhinoceros bone in outwash overlain by till.
Tolsta Head, NE Lewis[4]	AA37779 to AA37781	28,680 ± 340 to 29,070 ± 360	33.4–32.3 to 33.7–32.9	Three bulk samples from organic sands and silts overlain by till.
Teindland, lower Strathspey[5]	NPL-78	28,140 ± 480	32.7–31.5	Organic soil under outwash sediments overlain by till.

Calibrated ages represent ±1σ range. Sources: 1. Brown *et al.* (2007). 2. Bos *et al.* (2004). 3. Jacobi *et al.* (2009). 4. Whittington & Hall (2002); the uppermost age in the Tolsta Head sequence may reflect contamination and is excluded. 5. FitzPatrick (1965); this date should be regarded as minimal (Sissons 1981; Hall *et al.* 1995).

Table 2 Time-slice reconstruction of SIS deglaciation (Clark *et al.* 2012; Hughes *et al.* 2016)

Time slice	Event
27 ka	Maximum extent of northern sector of BIIS, depicted at Atlantic shelf edge.
25 ka	Ice retreat after ~26 ka driven by rising sea level. Radiocarbon dates suggest deglaciation of central NSB, implying either decoupling of SIS and FIS or opening of a marine embayment from the north. (N.B. Sejrup *et al.* (2016) argued that the dates are invalid, removing the need for early deglaciation of the NSB).
24 ka	Limited ice retreat on Atlantic Shelf. Possible continued advance of the Irish Sea Ice Stream, though this may have culminated earlier (Smedley *et al.* 2017b).
23 ka	Decoupling of SIS and FIS in NSB proposed by Hughes *et al.* (2016). Oscillatory net retreat of a grounded calving margin in W and NW; development of multiple lobate readvance moraines, especially W of Orkney and N and E of Shetland.
22 ka	Rapid retreat of Irish Sea Ice Stream. Widening of embayment between SIS and FIS in northern NSB, though the two ice sheets may have been connected farther S.
21–20 ka	Ice-sheet thinning and net retreat in all sectors.
19 ka	Ice sheet 'in crisis'. Irish Sea largely deglaciated; development of autonomous Irish and British ice domes; evidence for deglaciation of part of E Scotland.
18 ka	Complete separation of FIS and SIS likely (Hughes *et al.* 2016). Reduction of ice cover in NSB.
17 ka	Ice cover restricted mainly to Ireland and Scotland, but with the North Sea Lobe still extending S to the Lincolnshire coast. Ice cover persists over most of mainland Scotland, Outer Hebrides, Orkney and Shetland and adjacent shelves but the North Minch is deglaciated. Ice margin oscillations and ice streaming at some coastal locations.
16 ka	Separation of Scottish and Irish Ice Sheets; remnant ice caps on Orkney, Shetland and Outer Hebrides. Readvance of Scottish ice into northern Ireland.
15 ka	Residual ice caps in W Highlands, W Southern Uplands, Shetland and Outer Hebrides. Lowland areas of Scotland deglaciated.

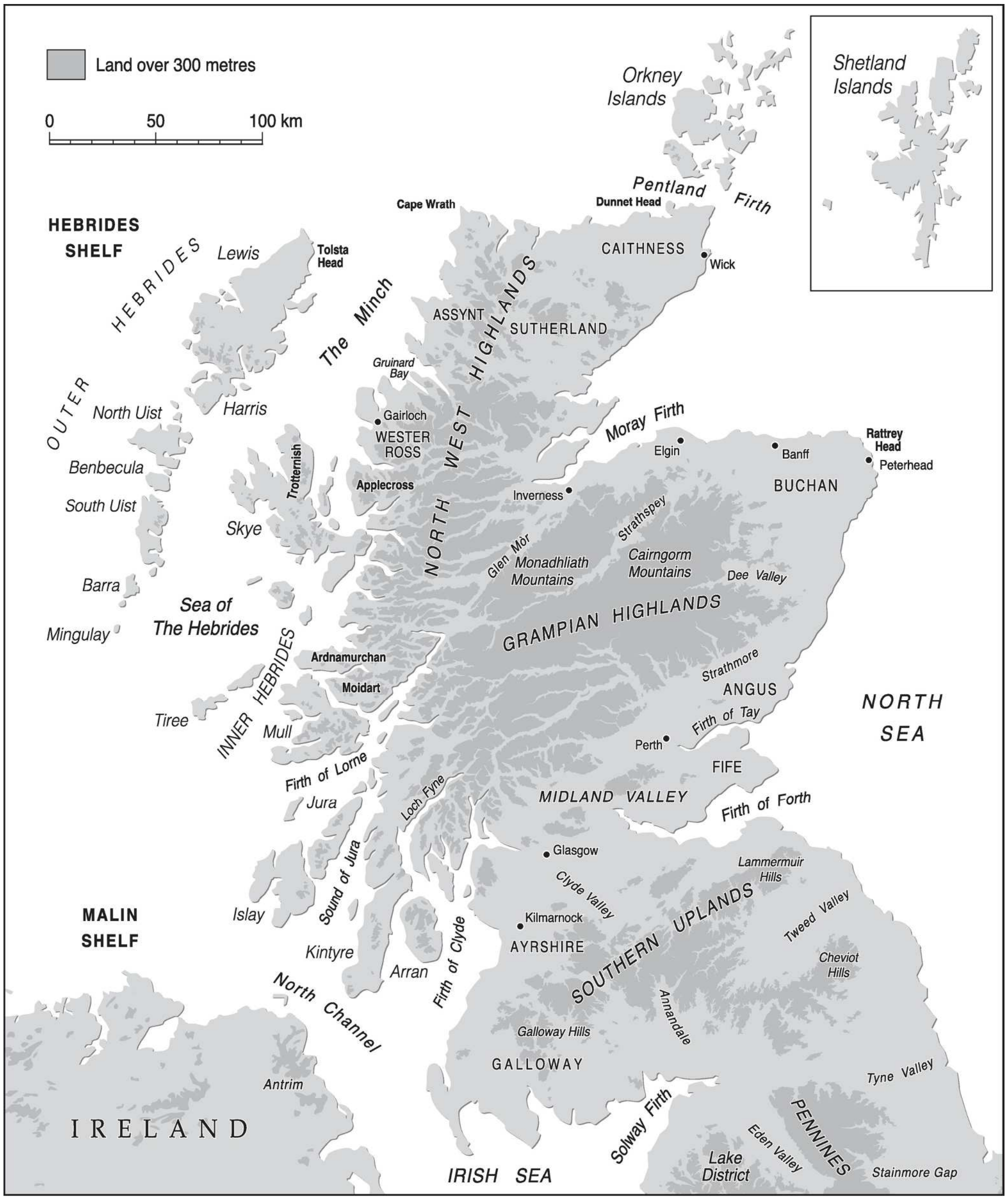

Figure 1 Key locations mentioned in the text.

196x233mm (300 x 300 DPI)

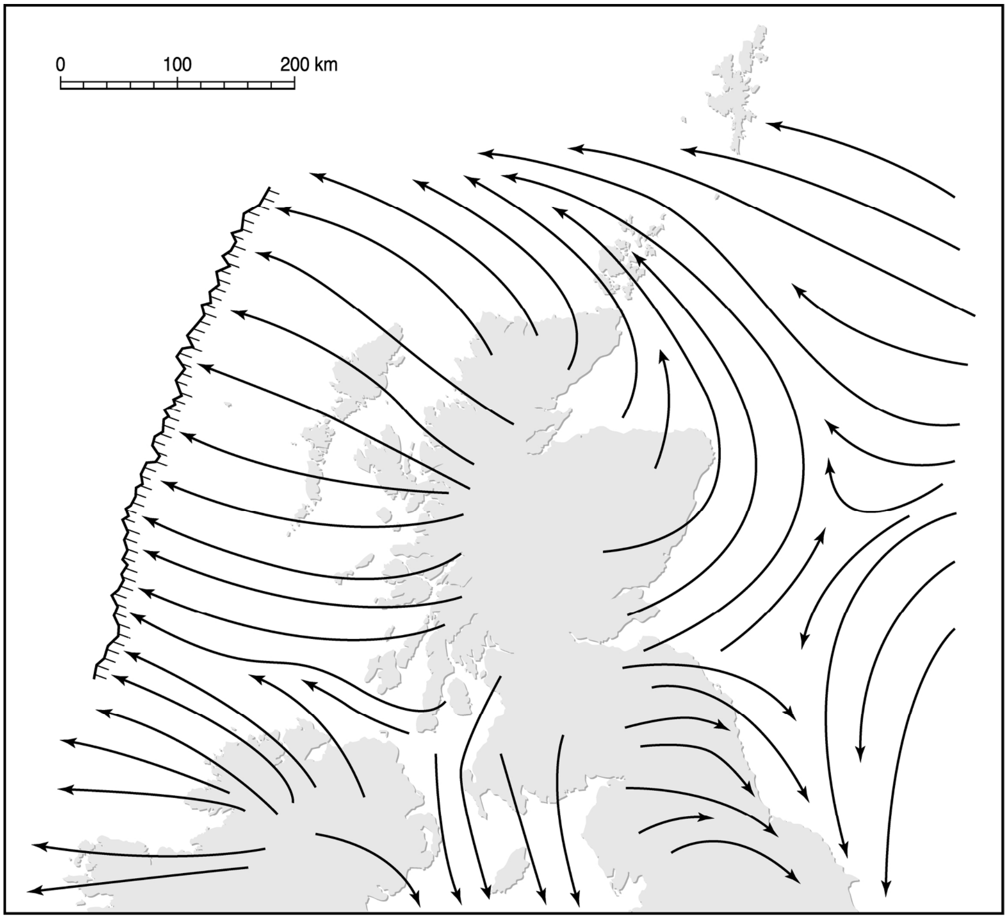

Figure 2 The last Scottish Ice Sheet as depicted by Peach & Horne (1910), who envisaged confluence of Scottish and Scandinavian ice in the North Sea Basin, northwestward deflection of ice from Eastern Scotland and the Moray Firth across Caithness and Orkney, and westward termination of the ice sheet at the Atlantic Shelf edge. The flow patterns were based only on terrestrial evidence (striae, erratic carry and lithostratigraphy) as no offshore information was available.

98x90mm (600 x 600 DPI)

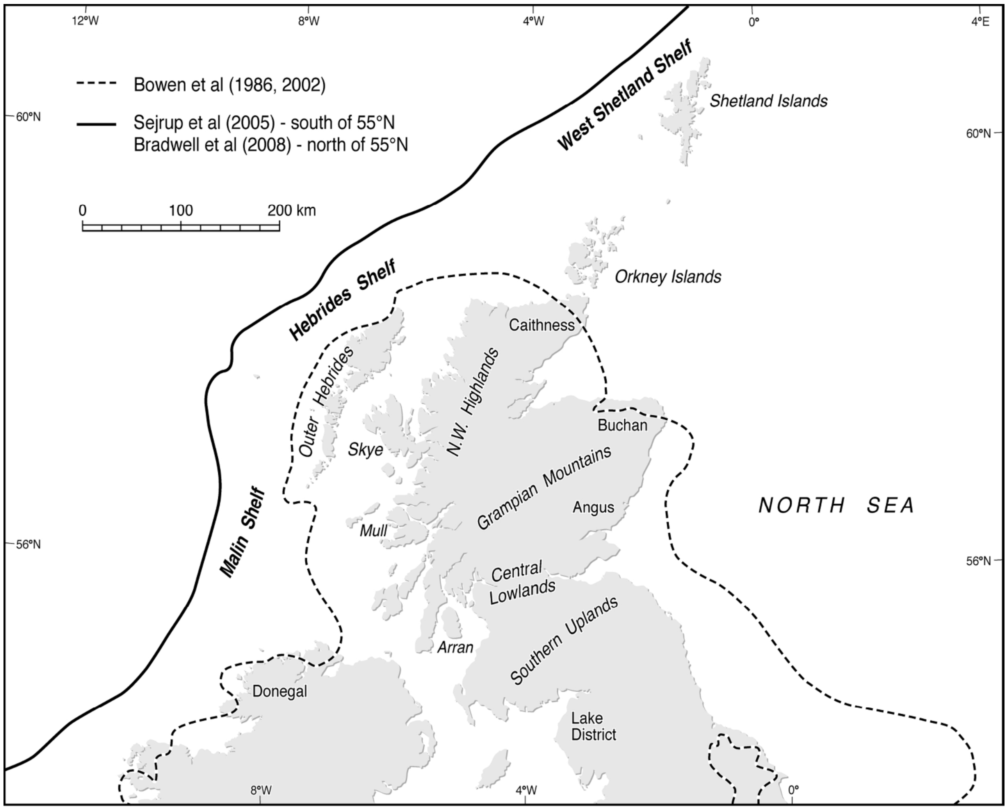

Figure 3 Changing views of the extent of the northern sector of the last British-Irish Ice Sheet. The dashed line represents the LGM limit of the last ice sheet depicted by Bowen et al. (1986, 2002). The solid line represents the approximate limit of the last ice sheet as depicted by Sejrup et al. (2005) S of 55°N and Bradwell et al. (2008b) N of 55°N.

103x83mm (600 x 600 DPI)

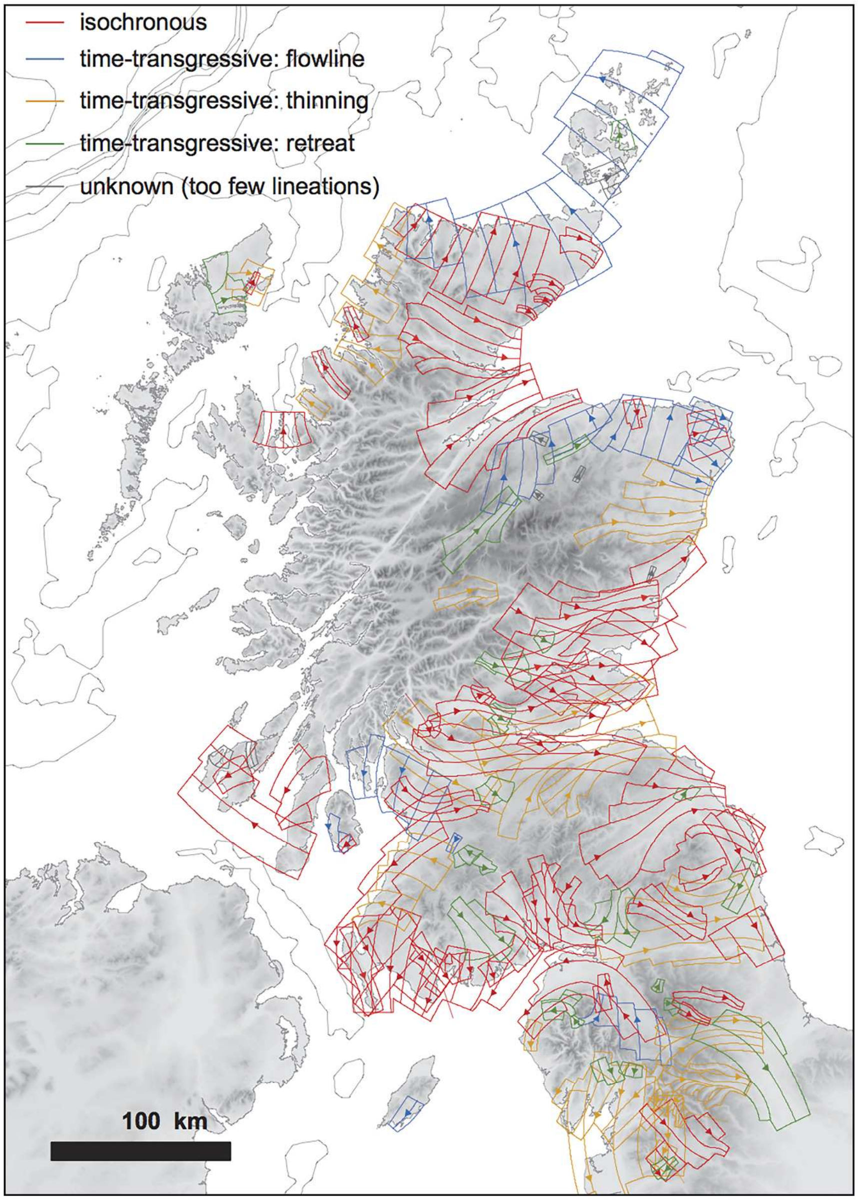

Figure 4 Flowsets of the northern and central parts of the last ice sheet in Great Britain as interpreted by Hughes et al. (2014). Red flowsets are interpreted to be isochronous and those in other colours are inferred to be time-transgressive. Reproduced from Hughes et al. (2014) Quaternary Science Reviews 89, 148–168, with permission from Elsevier. ☐ 2014 Elsevier Ltd.

249x348mm (300 x 300 DPI)

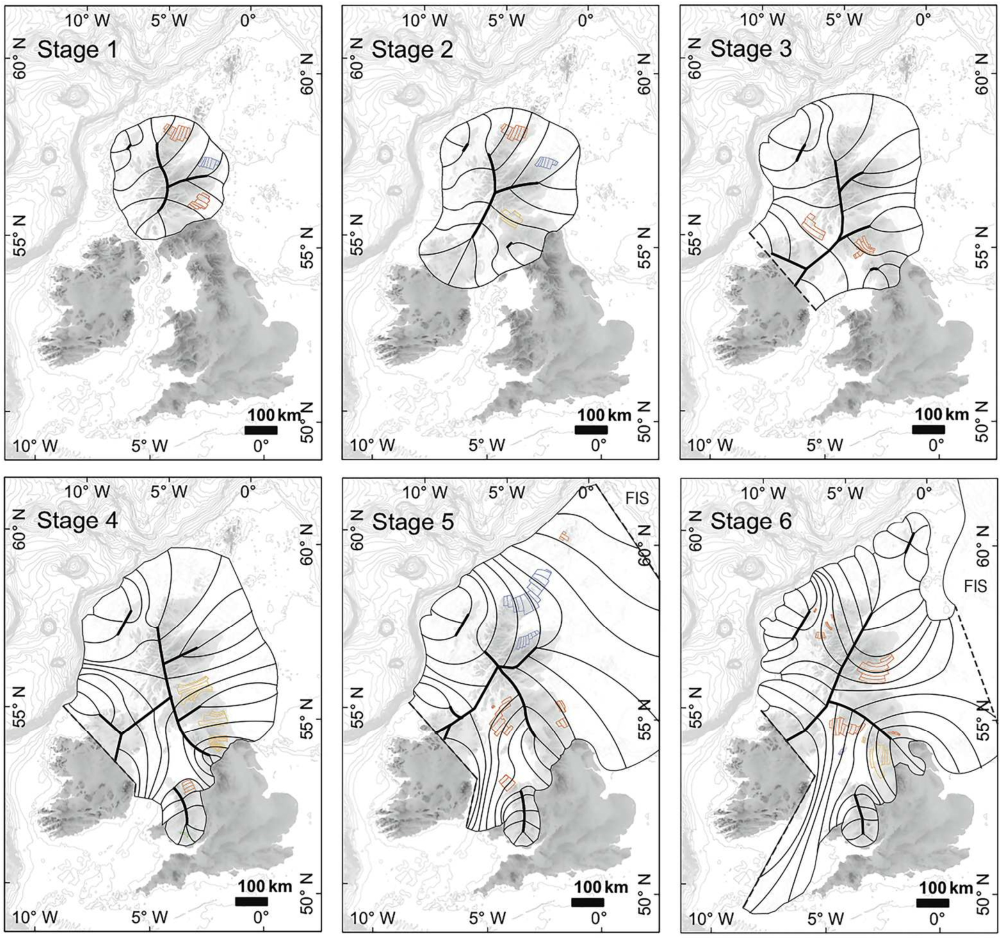

Figure 5 Stages in the growth of the last British Ice Sheet inferred by Hughes et al. (2014) from flowset and offshore evidence. Thick lines represent former ice divides or saddles, and thin lines represent flowlines inferred from flowsets and offshore landform data. Reproduced from Hughes et al. (2014) Quaternary Science Reviews 89, 148–168, with permission from Elsevier. ☐ 2014 Elsevier Ltd.

168x158mm (300 x 300 DPI)

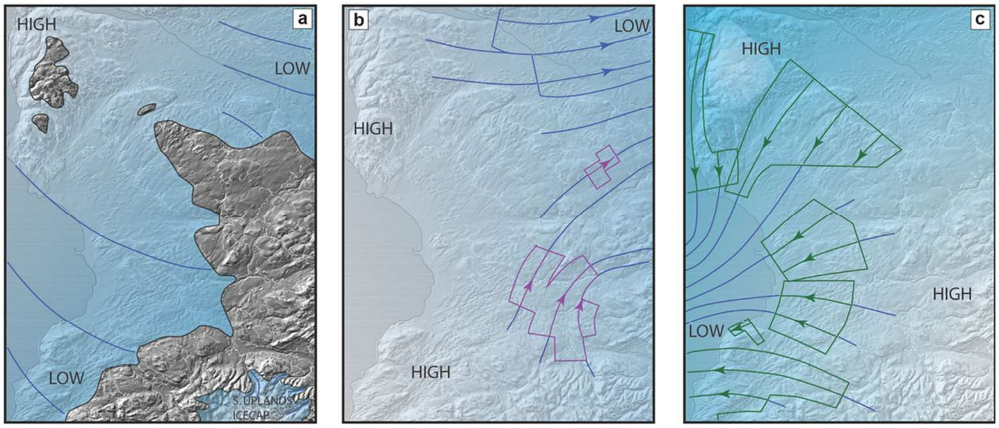

Figure 6 Stages in the evolution of the last ice sheet in west central Scotland identified by Finlayson et al. (2010). (a) Advance of ice from the SW Highlands across the Firth of Clyde, Ayrshire and the Midland Valley. (b) Establishment of an ice divide between the SW Highlands and western Southern Uplands results in eastward flow of ice across the Midland Valley. (c) Eastward migration of the ice divide results in dominantly westward ice movement, feeding the Hebrides Ice Stream. Reproduced from Finlayson et al. (2010) Quaternary Science Reviews 29, 969–988, with permission from Elsevier. ☐ 2009 NERC.

99x42mm (300 x 300 DPI)

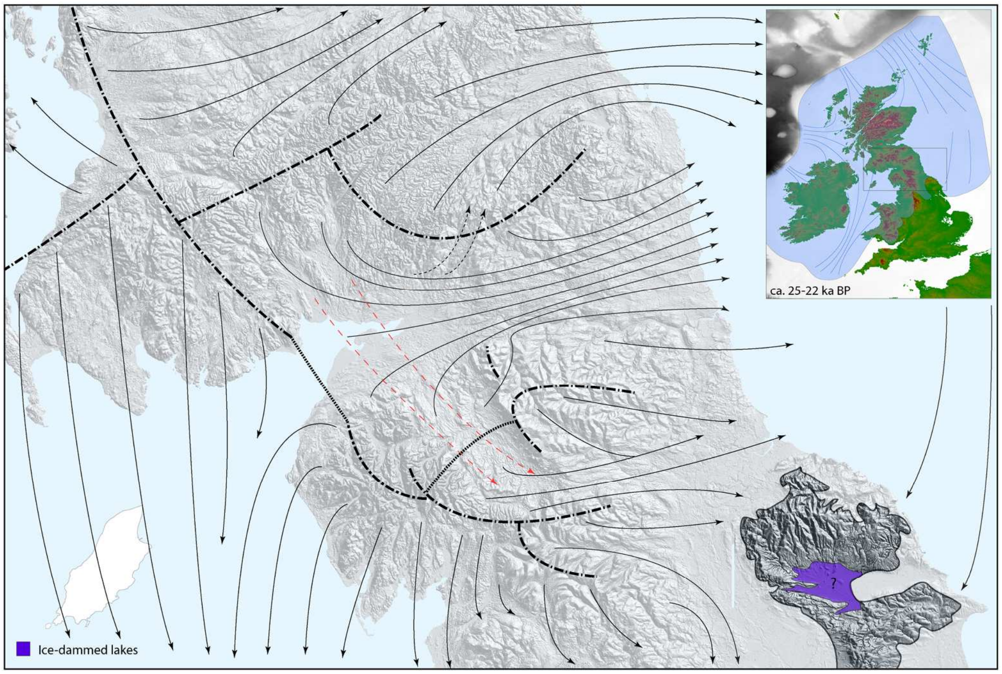

Figure 7 Ice flow in southern Scotland and northern England during the maximum expansion of the BIIS, as depicted by Livingstone et al. (2012). Thick dash-dotted lines represent ice divides, arrows indicate ice-flow vectors and dashed arrows in red indicate possible alternative ice-flow vectors. The inset shows location of this sector within the BIIS as depicted by Clark et al. (2012). Reproduced from Livingstone, S.J. et al. (2012) Earth-Science Reviews 111, 25–55, with permission from Elsevier. ☐ 2011 Elsevier B.V.

180x120mm (300 x 300 DPI)

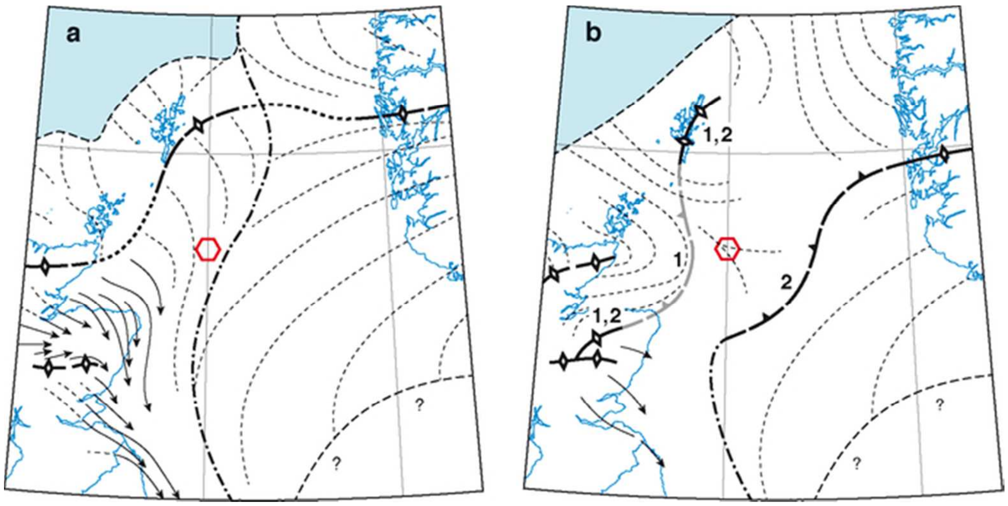

Figure 8 Sequential stages in the evolution of the eastern sector of the SIS as depicted by Merritt et al. (2017). (a) Southeastward diversion of Moray Firth ice from an ice divide linking Caithness and the Shetland Ice Cap. (b) Northwestward re-routing of Moray Firth ice by a receding ice shed linking Buchan and Shetland (position 1) that subsequently retreated to position 2. Dashed lines represent flow directions. Thick lines with open diamonds denote ice divides; those with filled ticks denote a receding ice shed. The red hexagon represents the position of the Witch Ground Basin. From Merritt et al. (2017) Journal of Quaternary Science 32, 276–294. Copyright 2016 John Wiley & Sons, Ltd.

58x28mm (300 x 300 DPI)

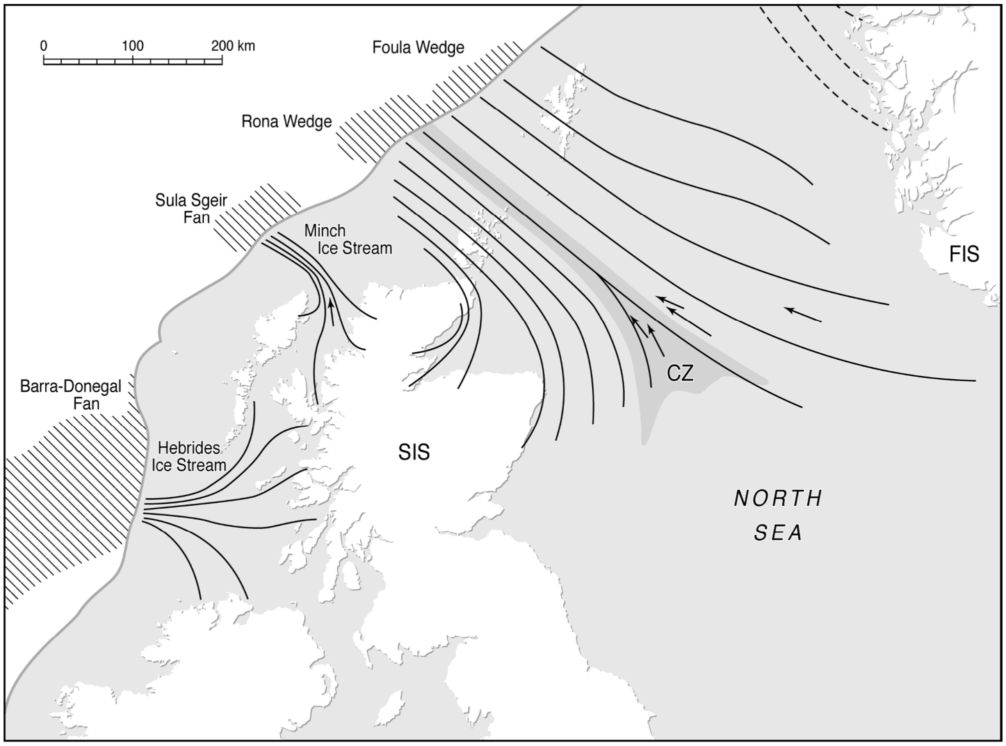

Figure 9 Confluence of the SIS and FIS in the NSB during the LLGM as depicted by Bradwell et al. (2008b), with hypothesized flow lines. Dark shading depicts the inferred confluence zone (CZ) and arrows show the orientations of mega-scale glacial lineations. Hatching represents the approximate areas occupied by shelf-edge fans. Also depicted is diversion of ice from western Scotland into the Minch and Hebrides Ice Streams by the Outer Hebrides Ice Cap. From Bradwell et al. (2008) Earth-Science Reviews 88, 207–226. ☐ 2008 NERC. Reproduced with permission from Elsevier B.V.

105x77mm (600 x 600 DPI)

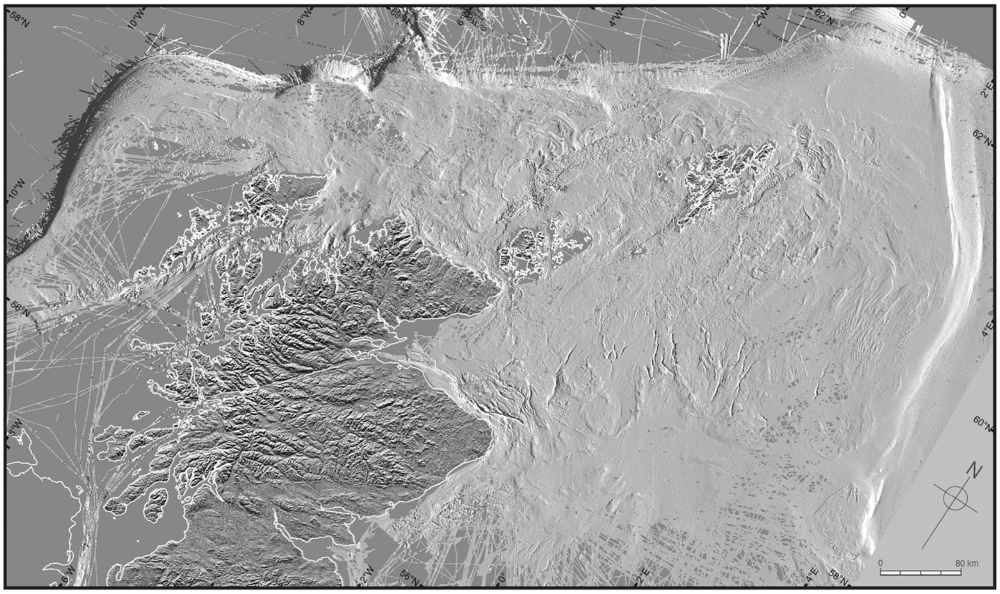

Figure 10 Merged onshore-offshore (topographic-bathymetric) surface model depicting the relief of Scotland north of the Southern Uplands and the adjacent continental shelf. Offshore data are derived from the Olex database (www.olex.no) and onshore relief from the NEXTMap Britain digital surface model (Intermap Technologies). Reproduced from Bradwell et al. (2008b) Earth-Science Reviews 88, 207–226. ☐ 2008 NERC. Reproduced with permission from Elsevier B.V.

133x79mm (300 x 300 DPI)

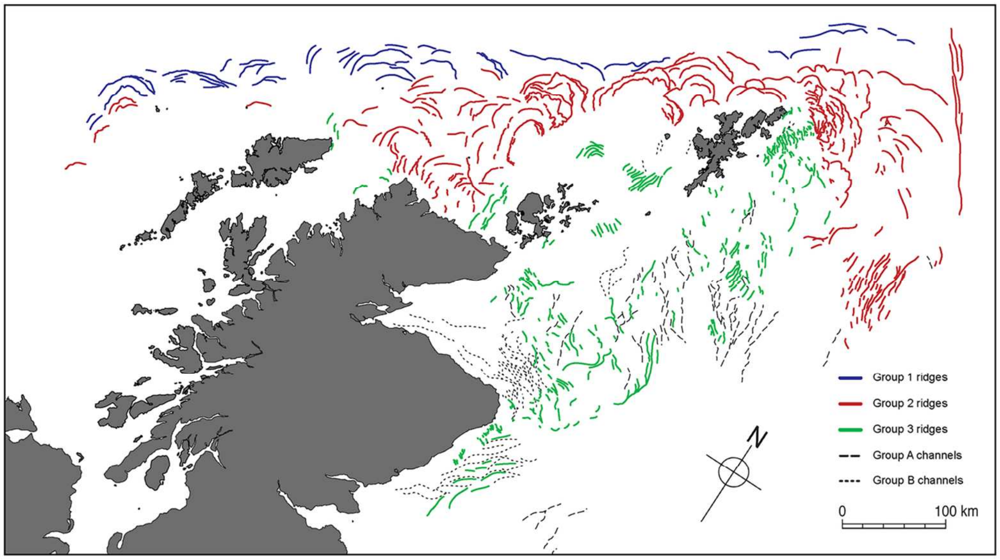

Figure 11 Seafloor landforms on the Atlantic shelf and northern North Sea Basin mapped by Bradwell et al. (2008b) from the bathymetric data in Figure 10. Solid lines: ridges (moraines or moraine banks). Dashed lines: channels, interpreted as tunnel valleys excavated by subglacial meltwater. Reproduced from Bradwell et al. (2008b) Earth-Science Reviews 88, 207–226. □ 2008 NERC. Reproduced with permission from Elsevier B.V.

123x69mm (300 x 300 DPI)

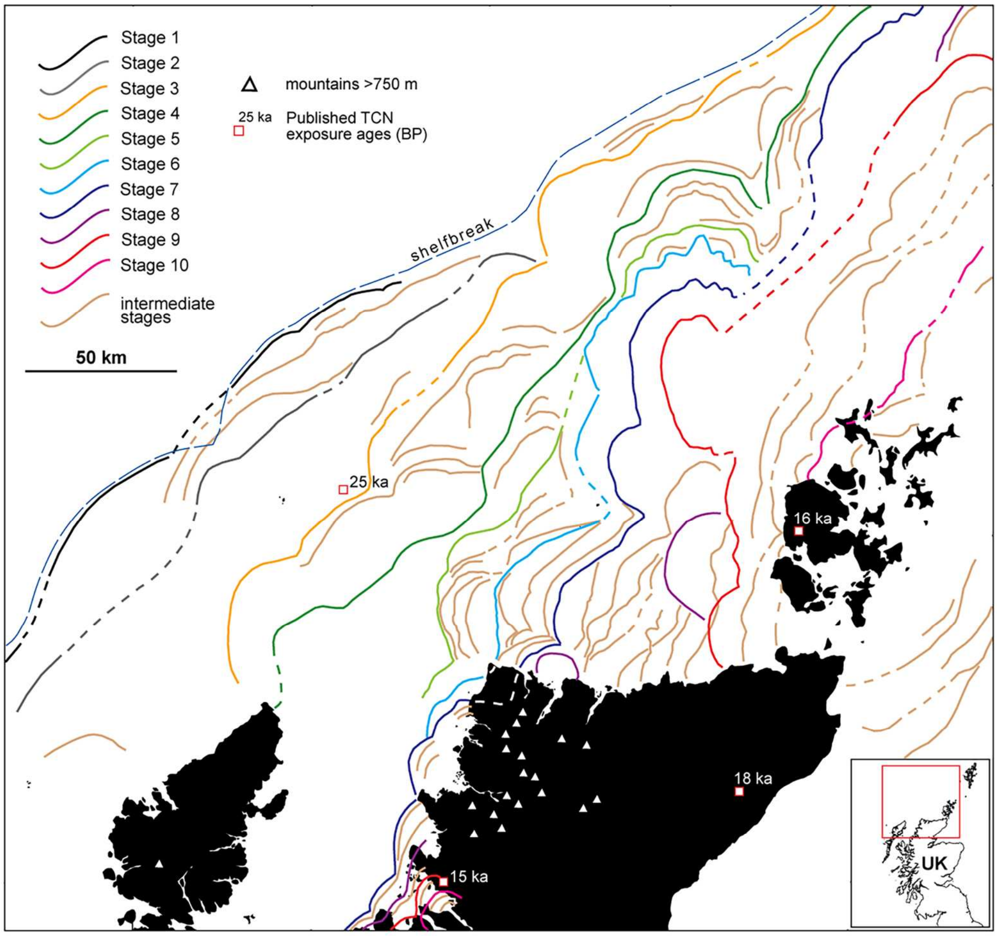

Figure 12 Reconstructed ice-margin positions around northern Scotland (coloured lines), interpreted from the alignment of submarine moraines by Bradwell & Stoker (2015a). Stages 1 and 2 are inferred to represent pre-MIS 3/2 moraines, and Stage 3 moraines are interpreted as the outermost Late Devensian moraines. Their interpretation of subsequent ice-sheet retreat (stages 4–10) implies early deglaciation of the northern Outer Hebrides and persistence of an ice cap centred on Orkney and Shetland after retreat of the ice margin to the present coast of NW Scotland. The dates depicted are selected (unrecalibrated) TCN ages. Reproduced from Bradwell, T. & Stoker, M. S. (2015) Earth and Environmental Science Transactions of the Royal Society of Edinburgh 105, 297–322 with permission from Cambridge University Press.

144x134mm (300 x 300 DPI)

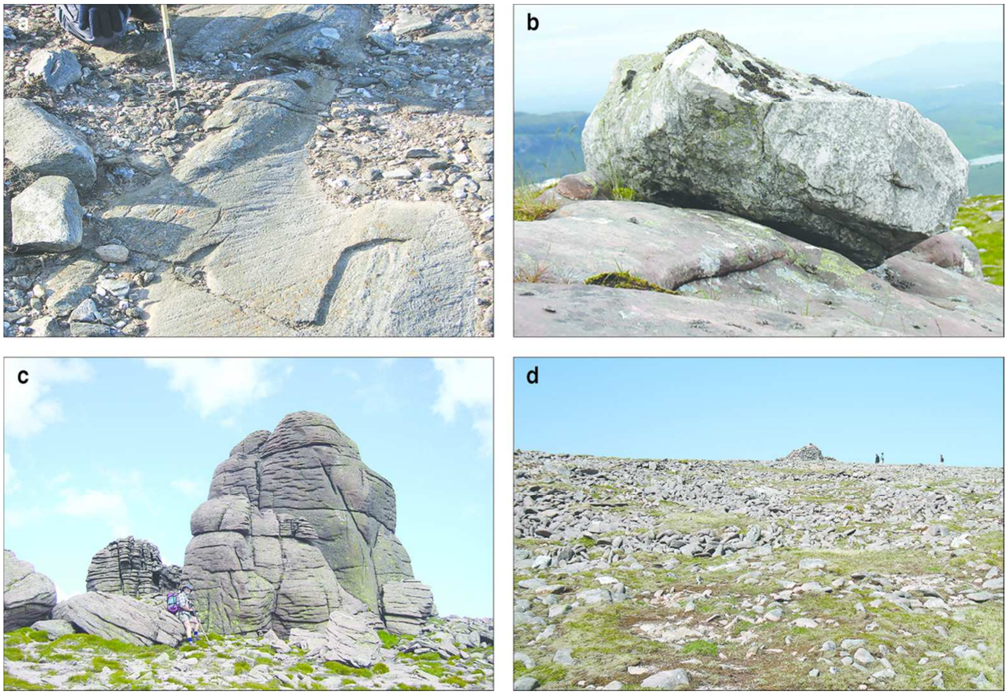

Figure 13 (a) Striae on ice-moulded bedrock at 997 m altitude on Ben Challum, southern Grampians. (b) Quartzite erratic resting on ice-moulded sandstone bedrock at 860 m altitude on Beinn Damh, Wester Ross. (c) Granite tors rising above blockfield debris at the summit of Beinn Mheadhoin (1182 m), Cairngorm Mountains. (d) Periglacial blockfield of sandstone boulders at the summit (933 m) of Maol Cheann-dearg, Torridon. Quartzite erratics on the blockfield have produced cosmogenic 10Be exposure ages of ~16 ka (Fabel et al. 2012), indicating that they were deposited by the last ice sheet.

103x70mm (300 x 300 DPI)

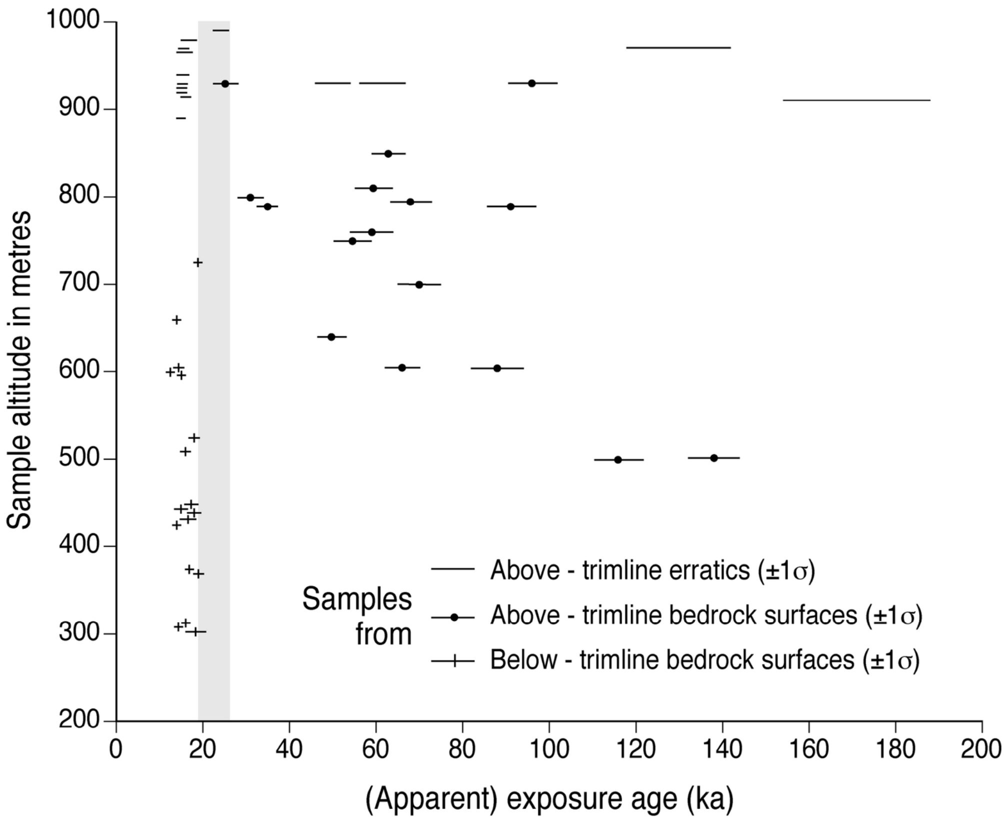

Figure 14 TCN exposure ages obtained for high-level erratics and bedrock samples above and below trimlines in the Scottish Highlands. The shaded area represents the timing of the LGM (26.5–19.0 ka). Horizontal bars represent ±1σ uncertainties. Post-LGM exposure ages obtained for most high-level erratics demonstrate that mountain summits were over-run by the last ice sheet. Reproduced from Fabel et al. (2012) Quaternary Science Reviews 55, 91–102. Reproduced with permission from Elsevier. ☐ 2012 Elsevier B.V.

74x62mm (600 x 600 DPI)

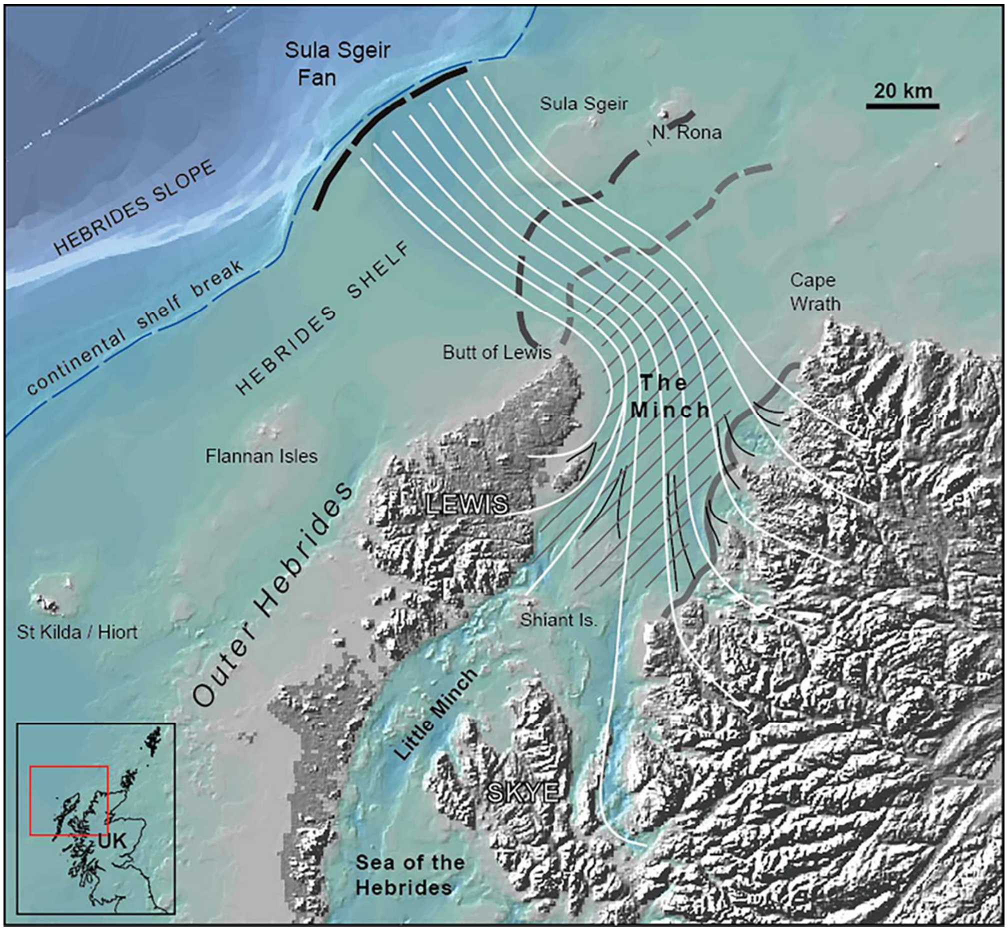

Figure 15 Main palaeoglaciological features of the Minch Ice Stream. White lines indicate proposed ice-stream tributaries and flowlines. Thick lines are inferred terminus positions proposed by Bradwell & Stoker (2015a), who considered that the outermost line probably represents a pre-MIS3/2 ice limit, but the inner lines represent Late Devensian ice margin positions. Hatching indicates an area of subglacial bedforms and iceberg scours, but lacking moraines. From Bradwell & Stoker (2015b) Boreas 44, 255–276. ☐ Boreas Collegium. Reproduced with permission from John Wiley & Sons Ltd.

93x86mm (300 x 300 DPI)

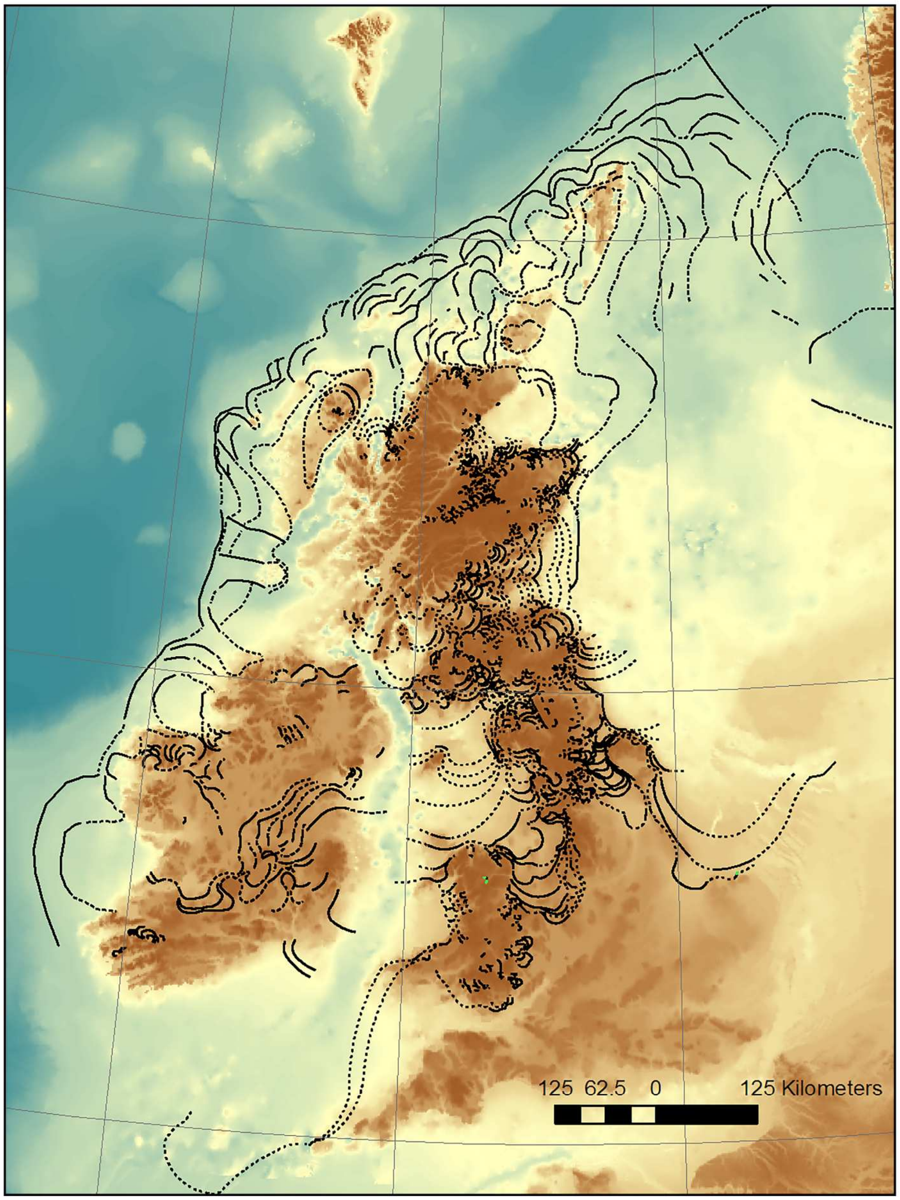

Figure 16 Reconstruction of the pattern of retreat of the BIIS as depicted by Clark et al. (2012). Solid black lines record former ice margins based on landform evidence and dashed lines are interpolated or extrapolated ice margin positions. Reproduced from Clark et al. (2012) Quaternary Science Reviews 44, 112–146, with permission from Elsevier. □ 2010 Elsevier Ltd.

195x260mm (300 x 300 DPI)

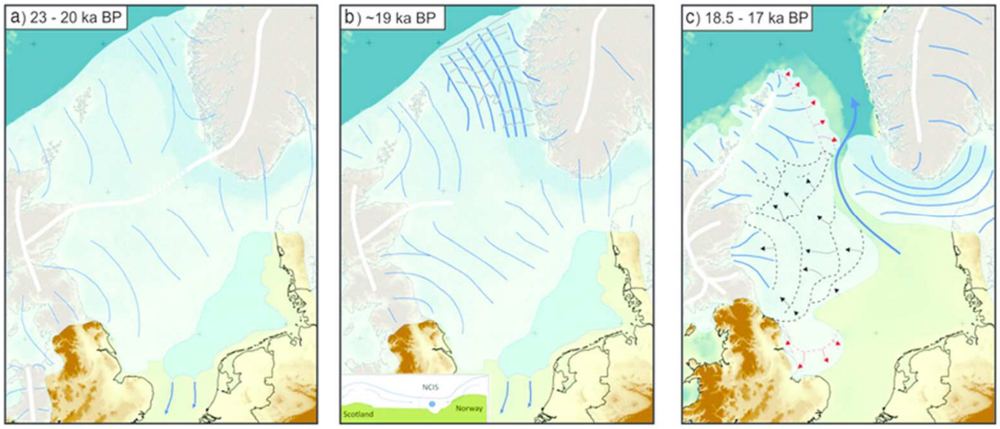

Figure 17 Reconstructions of successive ice-sheet configurations in the North Sea Basin (NSB) proposed by Sejrup et al. (2016). (a) Maximum configuration with an ice divide extending from NE Scotland to SW Norway and an ice-dammed lake in the southern NSB. (b) Initiation of ice-sheet collapse: expansion and acceleration of the Norwegian Channel Ice Stream (NCIS) (dark blue lines) causes drawdown of ice and destroys the ice divide. Grounding line retreat in the Norwegian Channel progressively debuttresses ice on either side. (c) Decoupling of the BIIS and FIS as the NCIS retreats, causing northward drainage of the ice-dammed lake. Red arrows indicate readvances of the BIIS, and black arrows indicate net westward retreat of the BIIS ice margin. Reproduced from Sejrup et al. (2016) Geology 44, 355–358, with permission from the Geological Society of America.

70x30mm (300 x 300 DPI)

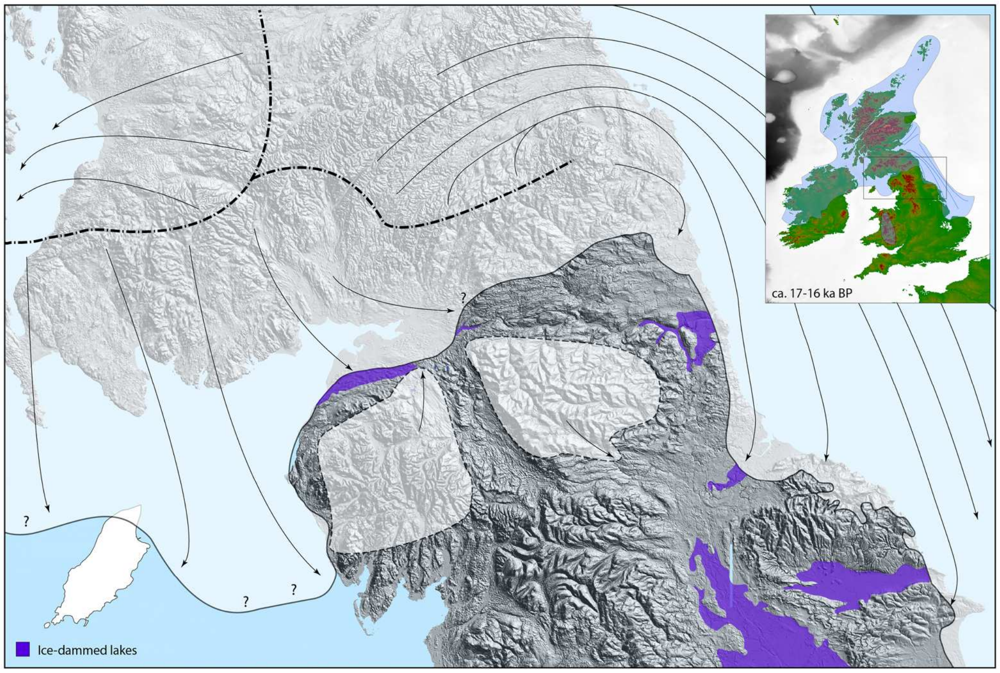

Figure 18 Extent of the Scottish Readvance as represented by Livingstone et al. (2015). Only the ice limits south of the Solway Firth, along the Cumbrian coast and across the Isle of Man can be confidently identified. Purple areas represent proposed ice-dammed lakes. From Livingstone et al. (2015) Journal of Quaternary Science 30, 790–¬804. □ The authors. Reproduced with permission from John Wiley & Sons, Ltd.

180x121mm (300 x 300 DPI)

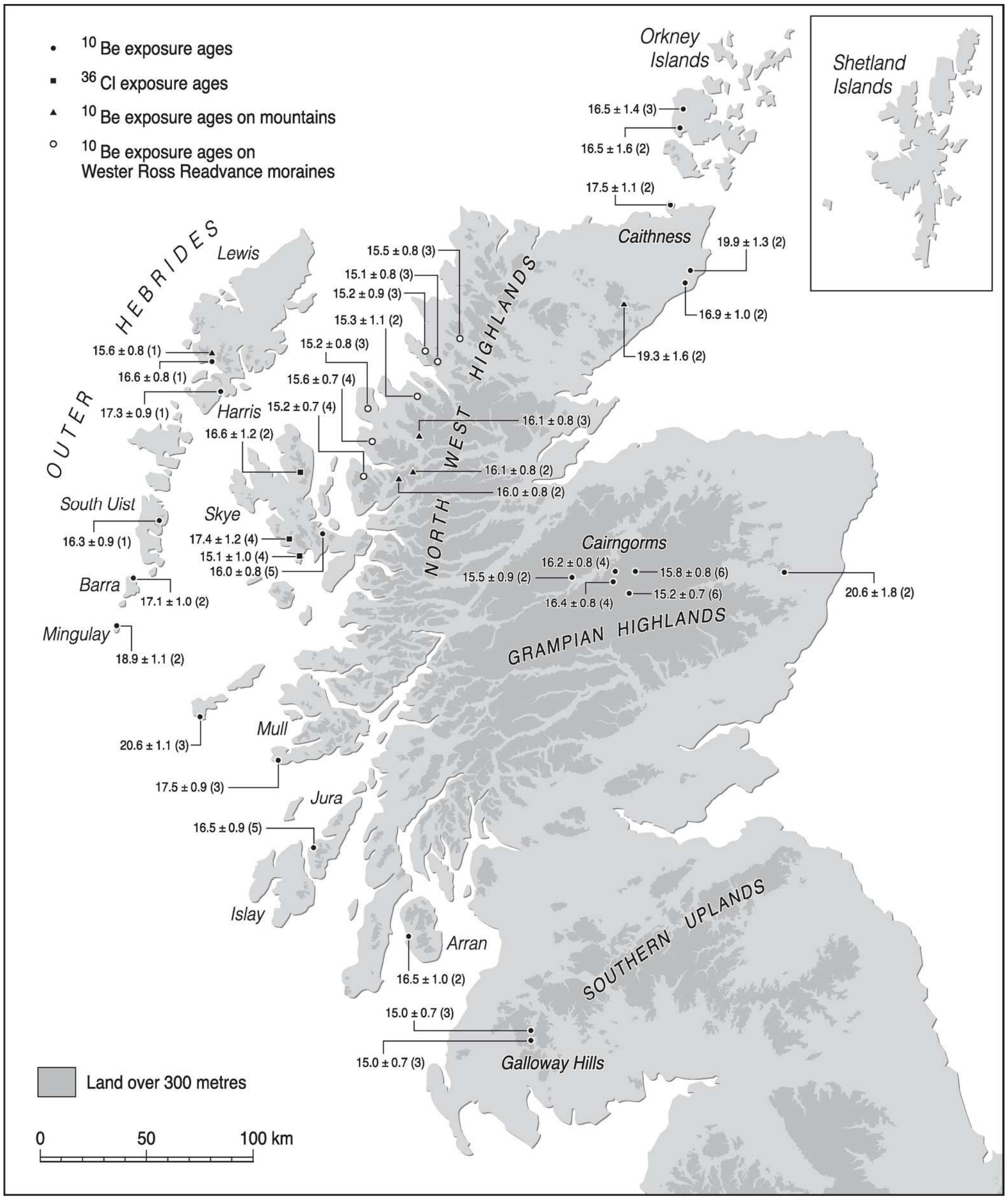

Figure 19 Uncertainty-weighted means of terrestrial cosmogenic nuclide exposure ages indicating the timing of deglaciation, calibrated using the protocol outlined in section 2. Statistical outliers are excluded. Each age is followed by the full (± 1σ) uncertainty, and the number of individual ages in the sample is shown in brackets. Single ages on the Outer Hebrides are shown for completeness, but should be treated with caution.

196x233mm (300 x 300 DPI)

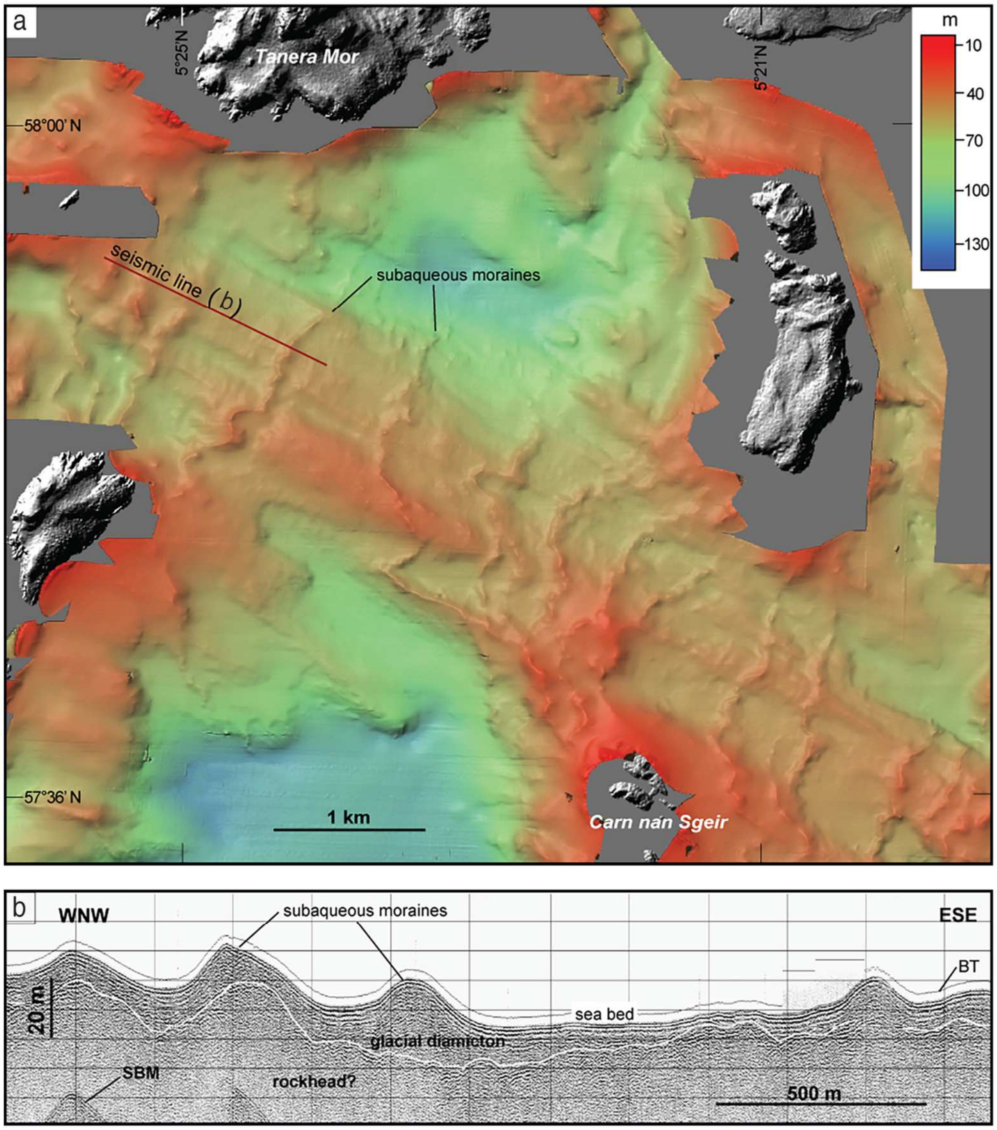

Figure 20 Multibeam bathymetry of the seafloor in the vicinity of the Summer Isles, outer Loch Broom, showing multiple recessional moraines formed by readvances that interrupted ice margin retreat. From Bradwell et al. (2008a) Journal of Quaternary Science 23, 401–407. ☐ 2008 NERC. Reproduced with permission from John Wiley & Sons Ltd.

143x161mm (300 x 300 DPI)

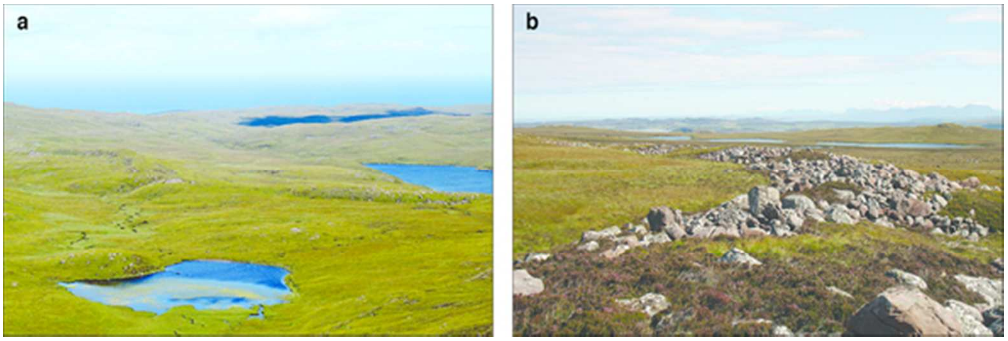

Figure 21 Wester Ross Readvance moraines. (a) The Applecross moraine crosses the photograph from left to right between the two lochans. (b) The central section of the Gairloch moraine, which is composed of Torridon Sandstone boulders and occasional Lewisian Gneiss erratics. The former glacier was located to the right (east) of the ridge.

50x16mm (300 x 300 DPI)

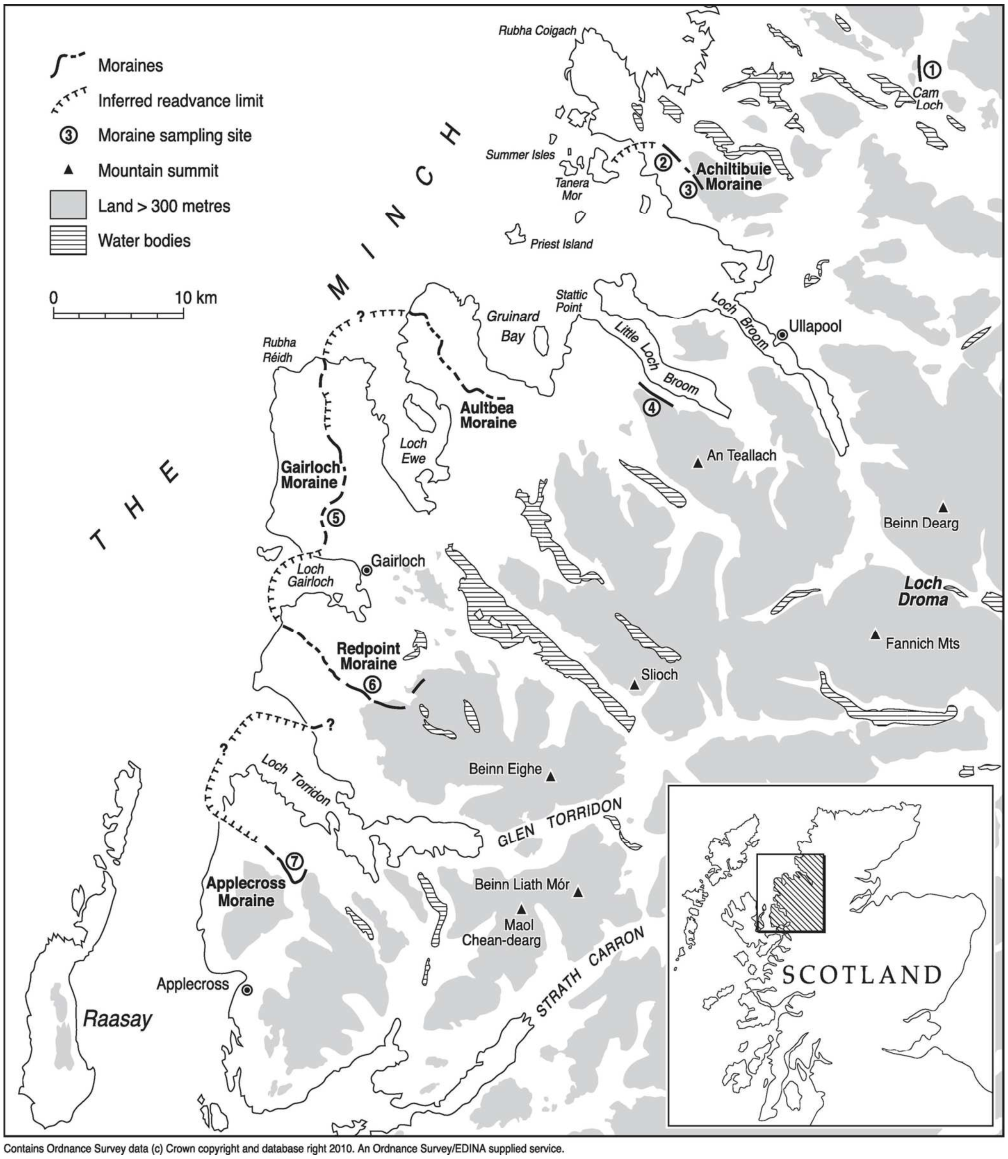

Figure 22 Moraines marking the limits of the Wester Ross Readvance, showing the sites sampled by Bradwell et al. (2008a; sites 1, 2 and 4) and Ballantyne et al. (2009a; sites 3, 5, 6 and 7) for cosmogenic 10Be exposure dating of boulders on moraines. From Ballantyne & Stone (2012), Journal of Quaternary Science 27, 297–306. ☐ 2011 John Wiley & Sons Ltd.

161x186mm (300 x 300 DPI)

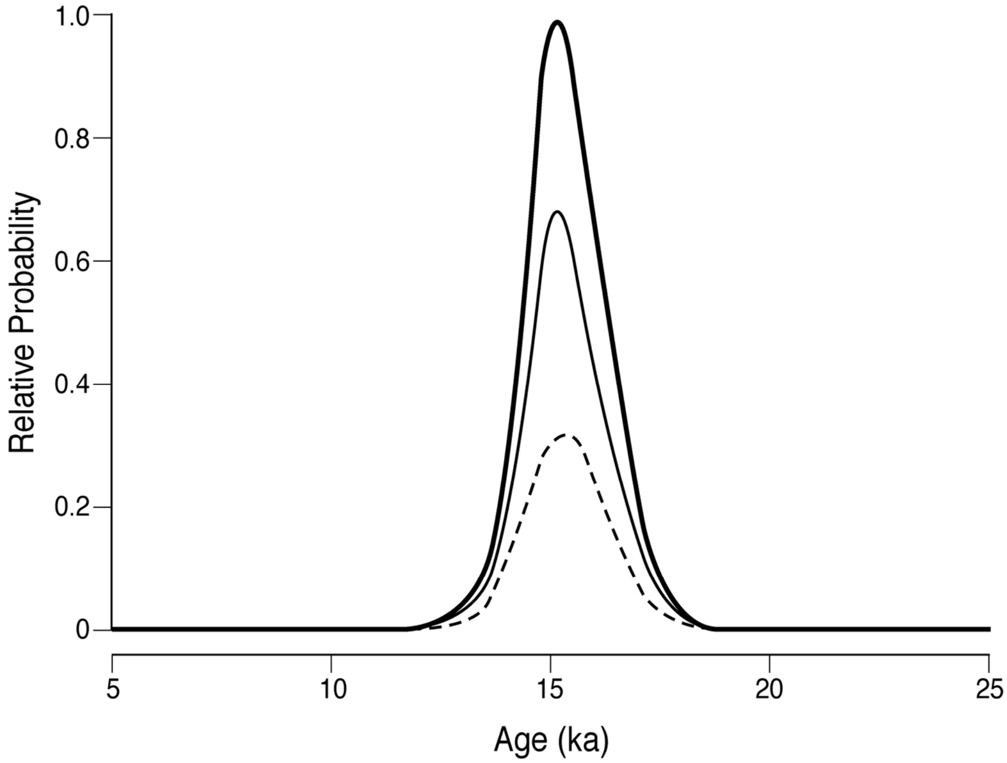

Figure 23 Summed normal kernel density estimates of recalibrated cosmogenic 10Be exposure ages and their uncertainties for boulder samples from Wester Ross Readvance moraines. Upper line: all 22 samples; weighted mean age 15.28 ± 0.69 ka. Middle line: 14 ages originally reported by Ballantyne et al. (2009a); weighted mean age 15.31 ± 0.70 ka. Lower (dashed) line: 8 ages originally reported by Bradwell et al. (2008a); weighted mean age 15.23 ± 0.71 ka.

67x51mm (600 x 600 DPI)

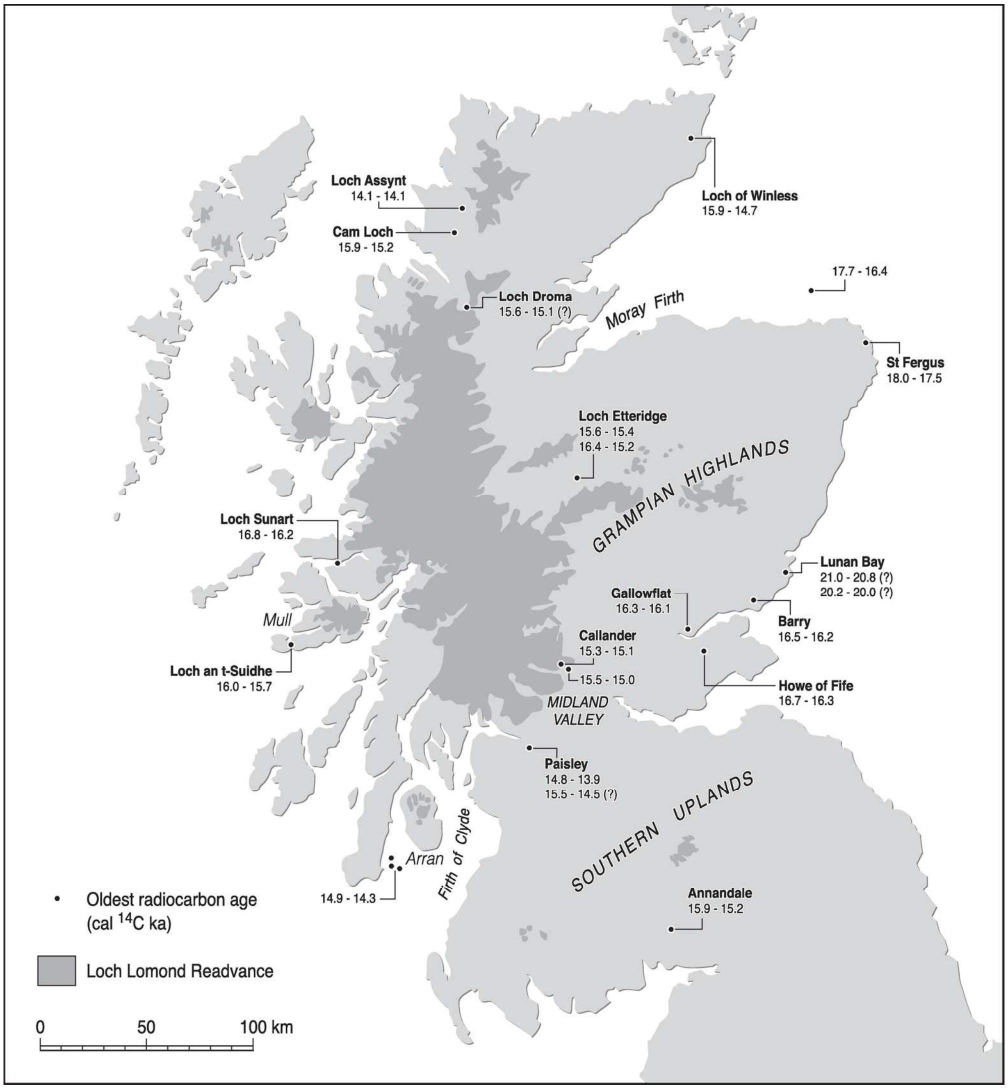

Figure 24 Key terrestrial and nearshore radiocarbon ages that constrain the timing of ice-sheet deglaciation, showing the extent of glacier ice during the Younger Dryas Stade (~12.9–11.7 ka). Ages are expressed as calibrated ± 1σ age ranges (cal 14C ka). Most nearshore and coastal ages were obtained from molluscs or foraminifera, and inland ages represent the oldest date obtained from organic material in cores recovered from lakes or infilled depressions. For a few sites two or more ages have been aggregated and the combined ± 1σ age range is shown. All ages represent minima for deglaciation. Ages shown with a question mark may be too old.

177x191mm (300 x 300 DPI)

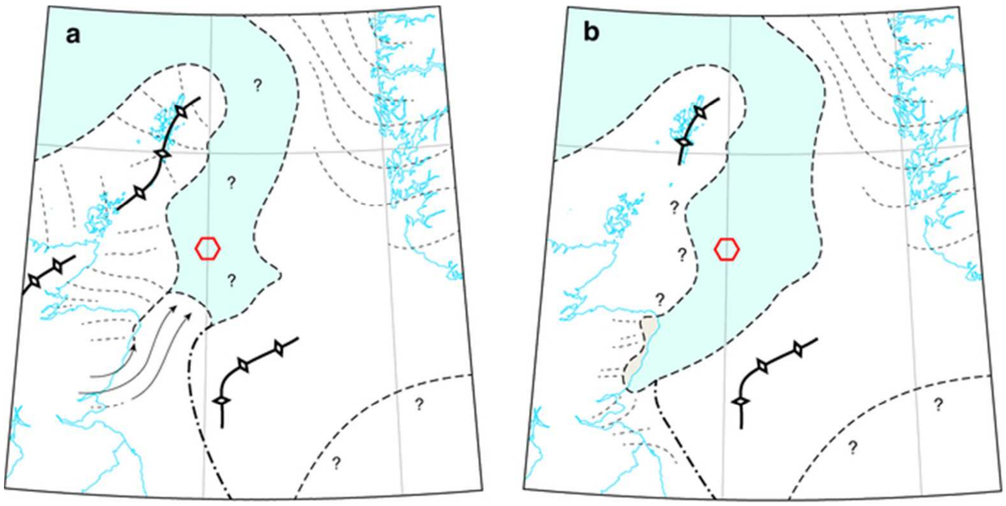

Figure 25 (a) Pattern of ice movement in eastern Scotland following opening of a marine embayment to the Witch Ground Basin (red hexagon) depicted by Merritt et al. (2017). (b) Subsequent retreat of Strathmore ice and deglaciation of eastern Scotland depicted by the same authors. Dashed lines represent flow directions, and thick lines with open diamonds denote ice divides. From Merritt et al. (2017) Journal of Quaternary Science 32, 276¬–294. Copyright ☐ 2016 John Wiley & Sons, Ltd.

58x29mm (300 x 300 DPI)

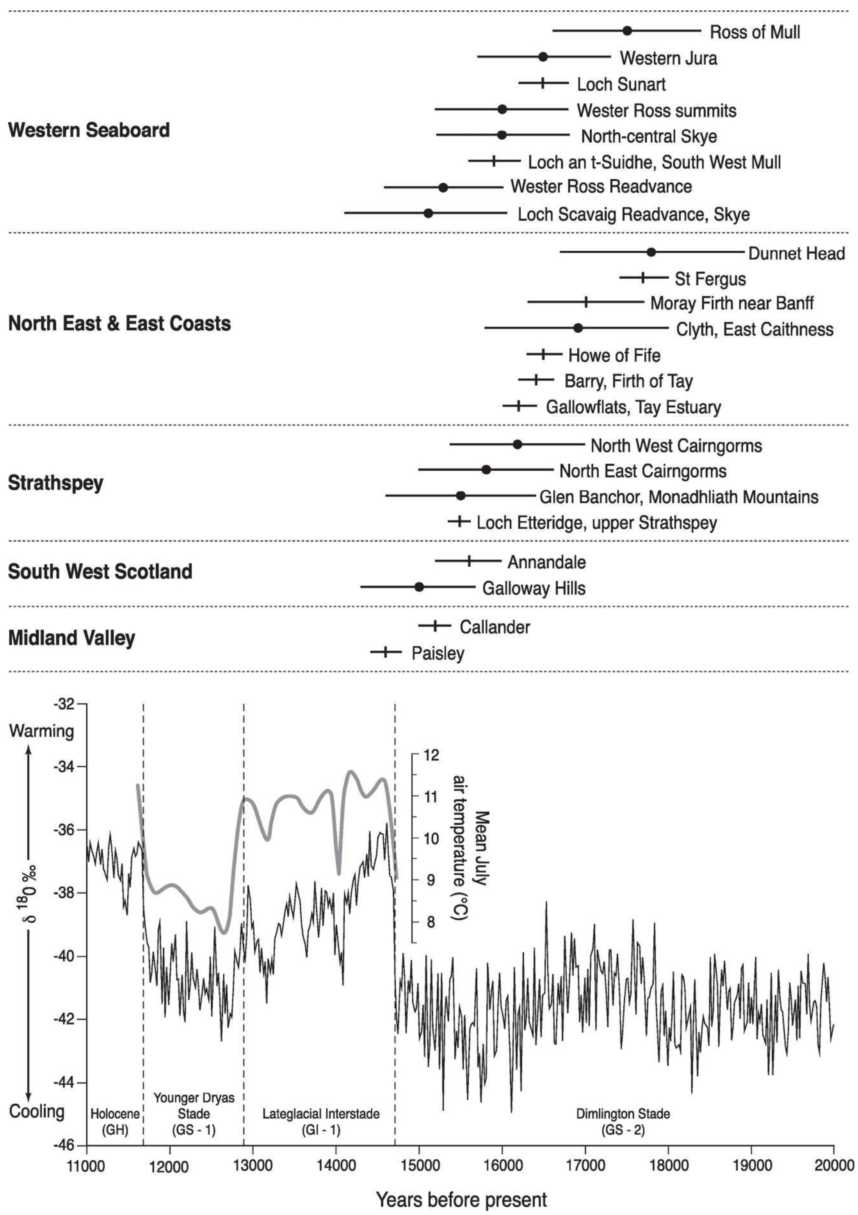

Figure 26 Key TCN (dots) and calibrated radiocarbon (vertical dashes) deglaciation ages plotted above the NGRIP ice core δ18O record for the period 20–11 ka (Rasmussen et al. 2014), the associated ice core stages and mean July temperatures inferred from chironomid assemblages in SE Scotland (Brooks & Birks 2000). Horizontal lines are ± 1σ uncertainties. TCN ages represent the approximate timing of deglaciation but radiocarbon ages are minimal for the timing of deglaciation.

184x261mm (300 x 300 DPI)