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Pattern and timing of retreat of the last British-Irish Ice Sheet.

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Abstract

During the last glacial the ice sheet that subsumed most of Britain, Ireland and the North Sea attained its maximum extent by 27 ka BP and with an ice volume sufficient to raise global sea level by ca. 2.5 m when it melted. We reconstruct the demise of this British-Irish Ice Sheet (BIIS) and present palaeoglaciological maps of retreat stages between 27 – 15 ka BP. The whole land area was investigated using remote sensing data and we present maps of moraines, meltwater channels, eskers, and drumlins and a methodology of how to interpret and bring them together. For the continental shelf, numerous large moraines were discovered recording an extensive pattern of retreat stretching from SW Ireland to the Shetland Isles. From an integration of this new mapping of glacial geomorphology (> 26,000 landforms) with previously published evidence, compiled in the BRITICE database, we derive a pattern of retreat for the whole BIIS. We review and compile relevant dates (881 examples) that constrain the timing of retreat. All data are held within a Geographic Information System (GIS), and are deciphered to produce a best-estimate of the combined pattern and timing of retreat.

Pattern information reveals an ice sheet mainly comprised of a shelf-parallel configuration from SW Ireland to NE Scotland but it spread far enough to the south to incorporate outlying ice domes over Wales, the Lake District and Kerry. Final disintegration was into a number of separate ice caps, rather than reduction as a single mass, and paradoxically, retreat was not always back to high ground. By 23 ka BP ice withdrew along its northern boundaries at the same time as the southern margins were expanding, including transient ice streaming down the Irish Sea and advances of lobes in the Cheshire Basin, Vale of York and east coast of England. Ice divides migrated south. By 19 ka the ice sheet was in crisis with widespread marine-based ice losses, particularly in the northern North Sea and the Irish Sea. Considerable dynamic-thinning occurred during this phase. Final collapse of all marine sectors occurred by 17 ka BP and with most margins beginning to back-step onshore. Disintegration of the North Sea 'ice bridge' between Britain and Norway remains loosely constrained in time but the possibility of catastrophic collapse of this sector is highlighted. The North Channel and Irish Sea ice streams had finally cleaved the ice sheet into separate Irish and Scottish ice sheets by 16 ka BP. Rates of ice loss were found to vary widely over space and time (e.g. 65 - 260 km^3 per year). The role of ice streams and calving losses of marine-based sectors are examined. Retreat rates of up to ca. 150 ma^{-1} were found for some ice stream margins.

That large parts (2/3) of the BIIS were marine-based, drained by ice streams, and possibly with fringing ice shelves in places, makes it a useful analogue for the West Antarctic Ice Sheet (WAIS). This is especially so because the BIIS deglaciated in response to rising temperatures and a rising sea level (driven by melting of other ice masses) which are the current forcings that might cause collapse of the WAIS. Our reconstruction, when viewed from the opposite perspective, documents when fresh land became exposed for exploitation by plants, animals and Man, and records for how long such land has been available for soil and geochemical development and ecological succession.

1. Introduction

During the global Last Glacial Maximum (gLGM), traditionally defined as occurring ~21,000 years ago, large ice sheets existed in the mid to high latitudes of the northern hemisphere, sufficient in volume to lower eustatic sea level by 130 m. Increasing levels of northern hemisphere solar insolation are thought to be the trigger for their deglaciation, which commenced between 20 and 19 ka BP (P.U. Clark et al., 2009). Whilst external forcing is required to initiate deglaciation on a global scale, the processes involved in amplifying change to produce retreat is likely a complex combination of factors, including the ice-albedo feedback to warming, rising sea levels promoting increased ice calving flux, the operation of ice streams, changes in sea surface temperatures and atmospheric levels of CO_2 amongst others. Untangling these factors and understanding the controls and processes that cause individual ice sheets to reduce in size has now become a major goal for the scientific community (e.g. PALSEA (PALeo SEA level working group) 2010), strongly motivated by societal needs to know how the Antarctic and Greenland Ice Sheets will proceed on their current deglacial trends and how these will impact on sea level in a warming world. If the pattern and rate of retreat of Quaternary ice sheets can be reconstructed, they offer a powerful tool for advancing knowledge of the mechanisms of ice mass loss. If existing numerical ice sheet models cannot adequately capture and explain known patterns and timings of retreat then it is fair to presume that they are lacking an important ingredient and therefore not yet fit for making robust predictions. Good constraints on a diminishing palaeo-ice sheet therefore provide an excellent resource for testing models. Alternatively, given that we know that existing models perform well with regard to climate forcing but relatively poorly to sea level controls (due to insufficient physical understanding about ice streams, iceberg calving and grounding line dynamics, for example), then data on ice sheet retreat could be used to help develop an improved modelling approach.

The British-Irish Ice Sheet (BIIS) is useful in the context of the above argument because it is relatively small and therefore presents a modest computational effort for any modelling experiments. It is challenging because its small size yields a rapid response to changes in boundary conditions (high dynamism) and it is positioned in a part of the world (adjacent to the gulf stream branch of the thermohaline circulation) that has experienced large and rapid oscillations during the Quaternary, and it is known to have been drained by several vigorous ice streams. We should therefore expect it to be one of the world's most rapidly changing and dynamic of ice sheets and thus to provide an exacting test of any ice sheet model.

Over the last decade the maximum reconstructed extent of the BIIS has been considerably revised from a mostly terrestrially-constrained and smaller ice sheet (ca. 357,000 km^2) to a version twice as large in areal extent (ca. 840,000 km^2) and covering extensive areas of current seafloor including the North Sea and continental shelves of Britain and Ireland (Fig. 1). That large parts of the BIIS were marine-based (estimated 300,000 km^3 of ice on the British and Irish continental shelves and over the North Sea), drained by ice streams, and likely with fringing ice shelves in places, makes it a useful analogue of the West Antarctic Ice Sheet (WAIS), but at one third of its volume. Retreat would have been accomplished at first by marine-terminating margins until such time as these back-

stepped onto land, yielding a dramatic change in the processes of ice loss and presumably a change in the rate of retreat. How might ice streams have influenced this retreat pattern and rate? Furthermore the BIIS deglaciated in response to rising temperatures but also due to a rising sea level (driven by melting of other ice masses) which are the current forcings that we fear might cause rapid shrinkage of the WAIS (Bamber et al., 2009).

Constraints on the retreat of the BIIS have relevance also to fields beyond glaciology and Quaternary science; for example, when did fresh land become exposed for exploitation by plants, animals and Man, and how long has such land been available for soil and geochemical development and ecological succession? When and for how long were 'land bridges' open between Ireland, Britain and continental Europe for migration of species?

The BIIS has been widely investigated and modelled but, surprisingly, a systematic synthesis of its pattern and timing of retreat has not been compiled beyond very generalised accounts of the whole ice sheet (e.g. Andersen, 1981; Boulton, et al., 1985; 1991; Sejrup, et al. 2005) or more detailed but regional investigations of various sectors of the ice sheet (e.g. Bradwell et al., 2008a; Brown, 1993; Charlesworth, 1924, 1926; Colhoun, 1970; Delaney, 2002; Embleton, 1961; Everest and Kubik, 2006; Knight, 2003a,b; Lafferty et al., 2006; McCabe and Clark, 1998, 2003; Meehan, 1999; McCabe et al., 2007b; Merritt et al., 1995; Mitchell, 2008; Sejrup, et al. 2009). Since ice sheets leave behind a fragmentary record of their activity, which is then incompletely sampled by geoscientists, and of which only a small fraction is subjected to geochronometric dating, then we will always have an incomplete knowledge of the time-space envelope of ice sheet retreat. Although we have only a partial understanding of Earth-system ice and climate interactions, we possess a strong desire to link any reconstructed changes in the ice sheet to known or posited climate fluctuations. If we are to avoid too much conjecture and wishful event-matching, clearly the magnitude of the task demands a systematic and cautious approach.

In this paper we summarise our new mapping of glacial landforms (especially moraines and meltwater channels), merge it with a large body of published work and, together, use the data (including drumlins, eskers and ice dammed lakes) to derive a pattern of retreat. We review and compile relevant dates for the region (881 examples) that constrain the timing of retreat. All data are held within a Geographic Information System (GIS), and are then deciphered to produce a best-estimate of the combined pattern and timing of retreat of the ice sheet. The data, method and results are presented and it is emphasised that this is almost certainly not the complete picture, but provides a framework of what is known.

If we were fortunate to have many thousands of geochronometric dates recording the onset of ice free conditions spread evenly over the bed of the ice sheet then a simple analysis should reveal the combined retreat pattern and timing. Given a much lower number and uneven spread of dates, as will be seen later, then the most appropriate approach is to make the best use of existing dates by applying them to an independently defined pattern of retreat. How such a pattern is derived is first discussed, followed by an

introduction to our dating-database, integration of the two and then finally, a synthesis yielding maps of ice sheet retreat.

2. Mapping and compiling the pattern of retreat

Given a reconstructed maximum ice sheet extent (e.g. Fig. 1) and a known bed topography, one could simply draw shrinking and concentric margin positions on the assumption that as climate warmed then ice at lower elevations melted first and the overall pattern was retreat back to the higher ground. Some early generalised patterns of ice retreat likely took such an approach (e.g. Andersen, 1981), and in part may have 'guessed correctly'. However given that we know that ice sheets lose mass not just by melting from spatially-uniform warmer temperatures but also via the activity of ice streams, and, once these become established, they preferentially drain some sectors at the expense of others (e.g. Vaughan et al., 2008), we should therefore consider that retreat might not proceed simply. Given an urgent need to know how ice streams assist in terminating ice sheets and the need for robust data on ice sheet retreat for informing modelling then it is imperative that we attempt to build and refine the retreat pattern and timing on a strong base of evidence, with as few a priori assumptions as possible. For this reason we chose to amass much new geomorphological evidence and to independently reconstruct retreat from different lines of evidence, which are subsequently brought together and compared to discover where corroboration (and contradiction) occurs. By this means we can assess the confidence of the ensuing reconstruction. The following lines of evidence were mapped, compiled in a GIS and used to generate patterns of retreat;

- Moraines (including ice contact landforms and sediments), which provide direct evidence of a palaeo-margin position and its orientation.
- Lateral meltwater channels, which record actual margin positions and are often found as a flight of channels documenting ice thinning down the flank of a hill (cf. Greenwood et al. 2007), thus providing the same marginal information as moraines.
- Eskers, which allow us to infer the orientation of the back-stepping palaeo-margin and thus a retreat pattern. This is based on the knowledge that water drainage is driven primarily by ice surface slope and should therefore exit the ice sheet roughly orthogonal to the margin.
- Subglacial meltwater channels, which similar to eskers, must mostly record the direction of ice surface slope close to the margin and therefore the direction and orientation of retreat. This presumes that most preserved subglacial meltwater channels are cut close behind the deglaciating margin (i.e. within say 15 km).
- Drumlins, which record ice flow and by careful analysis of their pattern and context, some drumlin fields (or flow sets) can be confidently inferred to have been generated during retreat (see later and Clark, 1999; Greenwood and Clark, 2009a).
- Ice-dammed lakes. Where glacial lake deposits have been described, the relationship of the lake position to the surrounding topography permits the approximate location of the requisite ice dam to be deduced (e.g. C.D. Clark et al., 2004a).

Moraines, eskers, meltwater channels and drumlins were mapped by visual interpretation of Digital Elevation Models (DEMs) and satellite images. The resolution (pixel size) of the data sources ranged between 2.5 and 90 m. Detailed methods and the results of mapping have already been reported in Greenwood and Clark (2008) and Hughes et al. (in press) and so are not repeated here. Evidence for ice dammed lakes and the required dam positions were taken from the BRITICE compilation (C.D. Clark et al., 2004a; Evans et al., 2005) drawn from the wider literature. New systematic mapping of moraines was conducted for the continental shelf region using the Olex bathymetric database (www.olex.no) which is a DEM compilation of depth soundings taken by fishing vessels. Bradwell et al. (2008a) describe this database and present extensive maps of moraines surrounding northern Scotland. We extend this work by investigating and mapping down the west coasts of Scotland and Ireland to complete mapping for the whole of the glaciated continental shelf (Fig. 2). To the north and northeast of Scotland we mostly adopt the mapping of Bradwell et al. (2008a) but vary it very slightly where our interpretations differ.

2.1 Moraines

Moraines mapped for the onshore (Fig. 3) and offshore areas (Fig. 2) are summarised in Figure 4 with a notable increase in the spread and number of moraines compared to previous records (compare with BRITICE map, C.D. Clark et al., 2004a). Their distribution unequivocally demonstrates that glaciation of Britain and Ireland extended offshore and as far as the continental shelf edge. This extent of glaciation was first envisaged in a reconstruction by Geikie (1894) although this was presumably something of a conjecture given the lack of evidence available at the time. Since then however, and given a lack of direct evidence for extensive ice, most reconstructions concluded that the BIIS was restricted to the present-day landmasses with only limited excursions offshore (e.g. Charlesworth 1928; McCabe 1985; Bowen et al., 1986; 2002; Ballantyne et al., 1998a; and reviewed in C.D. Clark et al., 2004b). More recently a range of evidence and arguments have been used to infer ice extending to the shelf break. Some submarine evidence off the Irish west coast (Haflidason et al., 1997) and analogy with what had been discovered on the Norwegian shelf led Sejrup et al. (2005; 2009) to draw the margin at the shelf edge from SW Ireland all the way past Scotland and linking up with the Fennoscandian Ice Sheet. Discovery of ice-rafted debris in the North Atlantic from source areas in Britain and Ireland (Scourse et al., 2009) requires that the BIIS made it to marine margins (necessary for the calving of icebergs) in at least some places (e.g. Hall and McCave, 1998; Scourse et al., 2000; Knutz et al., 2001, 2002; Wilson et al., 2002; Peck et al., 2006, 2007). Bradwell et al. (2008a) used the Olex bathymetric data to discover and map the suite of offshore moraines surrounding Scotland, and Ballantyne (in press) reviewed the debates about ice extent and used cosmogenic exposure dating to investigate the long-standing putative ice free enclaves (cf. Charlesworth, 1957) in Scotland and Ireland, concluding that they were in fact ice covered during the last glaciation. Ó Cofaigh et al. (in press) re-examined the chronostratigraphy of key glacial and marine deposits in southern Ireland and used optically stimulated luminescence (OSL) dates to demonstrate that southern Ireland was covered by ice during the last (Midlandian) glaciation, as previously postulated by Warren (1992), and that the earlier ideas of this landscape as part of the previous (Munsterian) glaciation (e.g. Charlesworth, 1928;

McCabe, 1987) are spurious. Taken together, and with the discovery of moraines at or close to the shelf break almost continuously from SW Ireland to the Shetland Isles (Fig. 4), it is clear that the BIIS certainly extended to the shelf break and that it most likely did so during the last (Oxygen Isotope Stage 2) glaciation. We note however that none of the offshore moraines have been directly dated and it might be that some (or all) of them relate to previous glacials or indeed multiple occupancies. As with many other palaeo-ice sheets the largest moraine systems are found at or close to the maximum extent and with numerous smaller examples that are most easily interpreted as stillstands during recession. Irrespective of uncertainty with regard to timing, the overall moraine pattern of the BIIS (Fig. 4) is a rich resource for constraining retreat patterns.

2.2 Eskers, meltwater channels and ice dammed lakes.
Evidence for subglacial and proglacial water activity are brought together in Figure 5. The meltwater channels were further subdivided into lateral or subglacial varieties according to their relationship with local topography in order to use them to reconstruct retreat patterns (methods reported in Greenwood et al., 2007). Around 20,000 meltwater channels are identified and 3000 fragments of esker ridges. As expected, eskers are mostly confined to lowland regions and meltwater channels avoid the more rugged uplands. Margin positions for ice-dammed lakes in Britain have been compiled using documented evidence for glaciolacustrine sediments, primarily the superficial or 'drift' maps of the British Geological Survey (e.g. Clark et al., 2004a). This remains to be done for Ireland.

 2.3 Drumlins
Britain and Ireland have an extensive record of subglacial bedforms, mostly drumlins but also ribbed moraine and mega-scale glacial lineations. Mapping of bedforms for both landmasses has now been completed (Greenwood and Clark, 2008; Hughes et al., in press) and drumlin patterns organised into flow sets (e.g. Greenwood and Clark, 2009a) from which the changes in ice sheet flow geometry have been reconstructed (Greenwood and Clark, 2009b). Given the palimpsest nature of drumlin patterns it is clear that they can be generated during the build up, maximal stages or retreat phase of the ice sheet. In this paper we separate out those flow sets that pertain to retreat. As documented in Clark (1999) and Greenwood and Clark (2009a), it is thought possible to achieve this by closely examining the nature of parallel conformity and cross-cutting of drumlins within a flow set and by association of the flow set with moraines, eskers and meltwater channels (Kleman et al., 2006). Essentially it is argued that drumlins which formed close behind a steadily retreating ice margin leave behind a smudged and discordant geomorphological signature that allows them to be recognised as an assemblage distinct from other palaeo-glaciological contexts (Fig. 6). Flow sets interpreted to record such retreat signatures are shown in Figure 7.

2.4 Deriving a pattern of retreat
To combine all lines of evidence, and synthesise the information they provide regarding palaeo-margin positions and retreat pattern, we adopted a two-stage process. For each line of evidence (moraines, eskers, meltwater channels, ice-dammed lakes and drumlin patterns) we independently reconstructed the retreat pattern that most faithfully fits the

6

data. This allowed us to examine where different lines of evidence were corroborative and where they conflicted, and thereby we could assess levels of confidence in our final, combined retreat pattern. Margin positions were defined as appropriate given the orientation of the feature of interest, paying close attention to local topography. Figure 8 presents four, independent retreat maps for mainland Britain based on eskers, meltwater channels, ice-dammed lakes and moraines.

Our second stage of interpretation was to bring these retreat patterns together (illustrated in Fig. 9). This was approached on a region by region basis; the multiple lines of evidence were assessed and a series of successive palaeo-margins drawn that best accommodate all the evidence. At this (local) scale of analysis judicious use of topography helped inform the likely pattern of retreat, for example up a valley or around an isolated hill. Reference to topography was also used to establish wider (regional) links between spatially separate local patterns. We emphasise that such links are conjectural interpretations based upon how we intuitively expect ice margin retreat to respond to the topographic context. New landform or stratigraphic evidence is required in these locations and may challenge and require changes to our reconstructed patterns. Figure 10 emphasises such uncertainties and illustrates how mistakes (or more generously - oversimplifications) may occur in this method. Where data 'blanks' were large, no interpolation was attempted and these areas were left blank. The most crucial links that were sought were between Britain, Ireland and the offshore area. Mapping and derivation of a retreat pattern for these three regions were initially performed separately (and by different authors). Strong links were evident and easily reconstructed between Ireland and its continental shelf, and between Scotland and its surrounding seas, but the linkages between Ireland and Britain (across the Irish Sea) and between Britain and Fennoscandia (across the North Sea) require further evidence and were left blank.

2.5 The pattern of BIIS retreat

Based on the above analysis, independent retreat maps from different lines of evidence are presented for mainland Britain in Figure 8. In Ireland, the smaller land area and perhaps less abundant landform evidence permitted us to synthesise a retreat pattern as a single map (Fig. 11). Our final, combined retreat map for the BIIS is presented in Figure 12. This map represents the first assessment of ice margin positions of the BIIS based on fully documented geomorphological/geological evidence.

Overall, Figure 8 shows that the different lines of evidence yield remarkably, and reassuringly, similar patterns. Many elements of retreat are common to all landform records. There is a very clear role of offshore ice. Along the length of the eastern English coast eskers document retreat towards the north and northeast away from high ground. An esker close to Flamborough Head records retreat towards the SE from the Yorkshire Wolds. The direction of retreat of these eskers requires a North Sea ice presence (and see Evans and Thomson, in press). Esker patterns suggest initial retreat from the maximum ice limit in the Cheshire Plain in a NNW direction; the Cheshire Plain also contains one of the most complete records of retreat indicated by moraines, which document retreat back into the Irish Sea. Retreat in offshore directions is also found close to Stranraer and on the northern Irish coast, where moraines indicate retreat towards the North Channel;

and moraines on the Holderness coast indicate ice presence in the southern North Sea. Furthermore, the locations of several ice-dammed lakes are testament to the persistent influence of offshore ice after deglaciation of inland areas. For example, ice along the NE coast of England created lakes in the Tees, Wear and Humber, ice in the Irish Sea dammed lakes in the western Lake District, and lakes were impounded in Buchan in NE Scotland by ice at the northern and eastern coasts.

Meltwater channels additionally demonstrate that onshore, not all ice retreat proceeds towards the highest ground. In fact, the high ground in many parts of the country deglaciated before ice in the lowlands, indicative of a thin ice sheet. For example, ice thinned and retreated around the Forest of Bowland in Lancashire as it retreated northwards. Lateral channels running along the Pennine escarpment in the Vale of Eden suggest that ice remained in the valley after Pennine summits had deglaciated. Likewise, lateral channels on the edges of the Cumbrian Mountains suggest that Lake District peaks were ice free before the Irish Sea ice had retreated. Lateral channels on the southern flanks of the Pennines in Derbyshire and Lancashire record thinning of ice in the Cheshire Plain. Ice retreating up the Firth of Forth and Tweed basins split around the Lammermuir Hills. Similarly ice retreating NW into the Scottish Highlands was diverted around the Campsie Fells and Ochill Hills. In northern Scotland, ice retreated along valleys towards ice centres in the southern Grampians and Rannoch. The pattern also indicates the significance of offshore ice. Lateral channels running broadly W-E along the Nairnshire-Buchan coast of Scotland indicate the westward retreat of a lobe of ice emanating from the Moray Firth, after inland ice from the Grampians had retreated away from the coast. Interestingly, in Ireland, there are fewer examples of lateral flights of meltwater channels, but nonetheless some record ice thinning, lobate development and the upland emergence of Slieve Bloom, the Ox Mountains and the Malin Head Peninsula (see Fig. 11).

Much is revealed from the pattern of retreat shown in Figure 12. Large moraines on the continental shelf clearly indicate that grounded ice reached the shelf edge and with numerous stillstand positions as it withdrew. Such is the detail, that retreat of many individual lobes can be traced. We consider their timing and degree of synchronicity below (section 3.1). The suture zone in the North Sea where Norwegian and British ice unzipped during deglaciation is revealed (Fig. 13). The ice sheet wide retreat pattern shows how various ice domes comprising the BIIS became separate ice caps (e.g. Kerry, Welsh, Lake District, Southern Uplands) as the main ice sheet thinned and withdrew. Locations where such partitioning occurred are now well defined. Of perhaps greatest surprise is that the ice sheet eventually shrank to a 'sausage-shaped' configuration running SW to NE from Ireland across the Highlands of Scotland and to the Shetland Isles, and leaving Welsh and English ice caps as satellite entities. The dominance of this 'shelf-parallel configuration' is further emphasised by the occurrence of lowland and marine lobes which clearly emanated from it and at one time surrounded and subsumed the autonomous ice masses residing over Wales and the Lake District and Pennines.

3. The tempo of retreat

In order to apply timing constraints to the pattern we built a database of published dates. A search of the literature revealed some 882 dates of relevance to the ice sheet, which were examined and entered as attributed points in the GIS (Fig. 14) with an associated spreadsheet table. Information on the nature the of dates and stratigraphic position were recorded (see Table 1), and it was decided, on the basis of the author's descriptions in each paper, whether the date constrained ice advance (e.g. sample below a till or other glacial deposit), retreat (deglacial, on a till or in Lateglacial sediments) or margin (date close to palaeo-margin, e.g. cosmogenic isotope date on a moraine). Further categories were ice free (used where the wider stratigraphic position is unknown such as for animal remains in a cave), exposure time (for cosmogenic isotope exposure dates of surfaces with no evidence of glacial erosion or no information is provided) and high sea level stand (for dates for high sea level coupled with no stratigraphic information) . In order to consider radiocarbon dates alongside those obtained by other methods they were calibrated to calendar ages using the Fairbanks online calibration tool and calibration curve (the Fairbanks0107 calibration in Fairbanks et al., (2005)). This choice was to permit calibration over the full time period without any 'jump' introduced by changing from one calibration curve to another. A marine reservoir correction of 400 years was applied where appropriate. Full details of calibration and date collation including the full database is given in Hughes et al., (submitted). Once all dates were calibrated and reduced to these six categories, they could be visualised in the GIS to aid reconstruction. All ages cited herein are thus reported as calendar ages, and all ages based on radiocarbon dates follow our calibration scheme (see above), not the original authors'. First we must define the maximum extent of ice and then apply the database of dates to the previously-defined pattern of retreat to yield isochrones of the shrinking ice sheet.

3. 1 Timing of the maximum extent
Unfortunately none of the newly discovered moraines which run around the shelf edge from SW Ireland to the Shetland Isles (Fig. 4) have been directly dated. However, as noted earlier, moraines of this size and freshness have elsewhere (e.g. Canada, US, and Fennoscandia) usually been found to be from the last glacial when dated. A more convincing argument for this timing comes from analysis of ice-rafted debris (IRD) concentrations found in cores taken from the trough mouth fans and the seafloor adjacent and beyond the continental shelf edge (Scourse et al., 2009 and references therein). Although there is some uncertainty in how to interpret increases in IRD flux within a core (possibilities include ice advance, retreat, increase in ice streaming, or changes in debris load), leading to varying interpretations (reviewed and explained in Scourse et al., 2009), the first occurrence of significant concentrations of IRD within a core can be taken to indicate that the adjacent ice sheet must, somewhere, have reached a marine-terminating margin from which icebergs were calved. Scourse et al. (2009) report a 'pronounced increase' in IRD at the Rosemary Bank and Barra-Donegal Fan at 29 ka, which requires that the ice sheet must have grown into the sea, but we know not where or how large the marine-terminating margin needs to be. However, it is reasonable to presume that the margin was advancing across the shelf to the NW of Scotland and elsewhere around much of the ice sheet perimeter at this time. By 27 ka BP, Wilson et al., (2002) have demonstrated that ice must have reached the shelf edge in at least one location because the Barra-Donegal trough mouth fan was being fed with new material. Further south,

along the western Irish margin, IRD fluxes also occur at 27 ka BP (Peck et al., 2006; Scourse et al., 2009). The requisite ice fronts to feed debris-laden icebergs may have existed just at some places along the margin, perhaps as over-extended and isolated lobes (cf. ice streams), or the margin may have reached the shelf edge everywhere from SW Ireland to the Shetlands. The map of moraines on the shelf (Fig. 4) and palaeo-margin patterns we have reconstructed (Fig. 12) appear to indicate the latter scenario because moraines can be traced almost continuously along most of the shelf edge. We thus take the simplest inference that ice reached the shelf edge everywhere by 27 ka BP along the whole boundary from SW Ireland to the Shetlands. This is consistent with the interpretation of Bradwell et al. (2008a), who reconstruct ice at the shelf-break from Scotland and across the North Sea to Norway between 30 – 25 ka and follows the reconstruction of Sejrup et al. (1994, 2005, 2009).

The north and western maximum extent of the BIIS, as reported above, is shown in Figure 15. The moraines at the shelf-break are clearly now submerged (in excess of 140 m below present day sea level), and we now consider the depth of water at the appropriate time slice. Eustatic sea level (from Thompson and Goldstein, 2006) was at -112 m at 27 ka, and we mark this contour on Figure 15 to crudely record the palaeo-coastline at this time. At most places along the shelf the moraines and our maximum extent show ice to have advanced up to 60 km beyond this palaeo-coastline, and therefore to be grounded in the sea. Glacioisostatic loading would serve to lower the shelf elevation, and relative sea level would be higher and the palaeo-coastline would move inwards towards the present day coast by the appropriate amount. Brooks et al. (2008) model relative sea level at this time for around the west coast of Ireland in the order of -20 m, which would move the palaeo-coastline in Figure 15 to very close to the present day coastline. It is thus clear that at 27 ka BP and at the glacial maximum that most of the shelf remained below sea level (in spite of the global lowering) and the ice margins can therefore confidently be considered as marine-based, and prone to calving.

That the maximum extent of ice was attained to the west and north of the British Isles at a time when global sea level was still lowering and prior to the main period of intense glaciation (i.e. the 'traditional' global LGM at 21 ka BP) is curious (why so early?). We interpret this to indicate that nourishment of the BIIS was sufficient for continued growth to the west and north and was merely curtailed by the shelf-edge and waters too deep for grounded ice; the BIIS would have advanced further if the shelf was more extensive. If true, this adds further support to the argument for continuous and complete ice cover along the shelf. However, until such time as the moraines on the shelf are directly dated, this remains an inference and one that is convenient for us to define the maximum extent in this sector and to start the retreat pattern from. We note however recent analysis of sea level records (Peltier and Fairbanks, 2006) has demonstrated that the global LGM should be considered to be some five thousand years earlier than traditionally assumed, with the ultimate sea level low-stand at 26 ka BP, and individual palaeo-ice sheets contributing to this slightly out of phase (P.U. Clark, et al. 2009). This makes the advance of the BIIS to the shelf edge by 27 ka much less surprising. We presume that ice remained at the shelf edge from 27 ka through to the global LGM and the sea level low-stand at 26 ka and

that retreat from this position was likely driven by rising sea levels (again, this interpretation needs testing by dating the moraines).

Continuing anticlockwise around the margin, ice was at the southern Welsh limit by 23 ka BP (Phillips et al., 1994; range 25.2-21.2 ka). Advance dates from the Isles of Scilly suggest that the islands were reached after c. 25 ka BP (range 26.9-24.6 ka) (Scourse, 2006). This is consistent with dates from the Celtic Sea placing ice advance after 24.2 ka BP (Ó Cofaigh and Evans, 2007). For the rest of the southern margin the picture is more complex. The youngest date for advance into the Cheshire Plain suggests that ice advanced inland here after 27 ka BP (Bateman pers. comm. 2009; range 29-25 ka). However, a woolly mammoth bone dated to between 20.0-22.9 ka BP (Rowlands, 1971; Bowen, 1974) lying below Irish Sea till could be used to suggest that Irish Sea ice did not advance up the Vale of Clywdd, and potentially the Cheshire Plain, until after 21 ka BP. Although this date is significantly younger than the advance dates in the Cheshire Plain, such a situation is not inconsistent with them. Alternative scenarios include: a) incursion of ice into the Vale of Clywdd was initially prevented by the presence of Welsh sourced ice; b) the location existed as an ice free enclave until 21 ka BP; c) the bone date is unreliable or the date reflects an oscillation of the ice margin in this region around 21 ka BP.

Ice advanced down the Vale of York after 23.3 ka BP (Bateman et al., 2008; range 24.8-21.8 ka) but had retreated to the north by 20.5 ka BP (range 21.7- 19.3 ka). Dates from Dimlington on Holderness suggest ice did not reach the eastern English coastline until after 22 ka BP (Penny et al., 1969; range 22.5-21.3 ka) and dates from inland Lincolnshire suggest ice did not progress inland until after c. 17 ka BP (Wintle and Catt, 1985; range 19.1-14.9 ka). Ice at this position at this time is consistent with a recently published age for a beach deposit (16.6 ka BP, Bateman et al., 2008; range 17.8-15.4) related to Glacial Lake Humber, the existence of which requires ice damming the Humber Gap. This new date is significantly younger than the previously quoted maximum age for Lake Humber of 26.2 ka BP (Gaunt, 1974; 1976; range 28.1-24.2 ka) and inconsistent with a more recent date for deposition of sands into Lake Humber at c. 22 ka BP (Murton et al., 2009) that is difficult to reconcile with the Dimlington date for ice first reaching the eastern coast. It is suggested that the dates at these sites could reflect oscillations of the ice margin, including sporadic damming of the Humber Gap. In the absence of deglacial dates preceding the 'young' advance dates it not possible to confirm this.

If all of the above dates are accepted there are two possible interpretations: 1. Ice did not reach eastern England or the Cheshire Plain until after 17 and 21 ka BP respectively; 2. The dates reflect oscillations of the ice margin within the last glaciation. This implies advance into the Cheshire Plain after 27 ka BP, followed by retreat to an unknown position north of Wales before 21 ka BP and a subsequent readvance south after 21 ka BP. This could reflect oscillations of the Irish Sea glacier during uncoupling with Welsh ice. In eastern England, the dates could be interpreted as advance after 25 ka BP (Ventris, 1985) followed by retreat to an unknown offshore position, followed by a readvance at least as far as Dimlington after 22 ka BP, with ice reaching the Lincolnshire Wolds after

17 ka BP. Possible surging of this ice margin is discussed in Evans and Thomson (in press). The Dimlington dates have been invoked to support a contemporaneous readvance of the British Ice Sheet with the Tampen readvance of the Scandinavian Ice Sheet (Sejrup, et al. 1994; Carr, 2004).

In summary, the maximum extent and thus the starting points for retreat are different at different parts of the margin. Retreat from the continental shelf edge is taken to be from 26 ka BP and from the southern limit at 23-20 ka BP in the Scilly Isles, 25-21 ka BP in South Wales and the Cheshire Plain, 23-21 ka BP in the Vale of York and 19-15 ka BP along the eastern English coastline. Figure 15 shows the maximum limits marked with a date or range of dates suggested by the chronology described above.

3.2 Chronology of retreat.
The dates were brought together with the geomorphologically-defined retreat pattern and information on timing transferred to the palaeo-margins to produce isochrones (see Fig. 16). This was not always a simple matter; sometimes the inferred linkages (i.e. dashed lines) between known palaeo-margins required adjustment, and sometimes some dates could not be incorporated. Our aim was to satisfy as much of the pattern information and as many of the dates as possible in the simplest way possible, whilst maintaining a glaciologically plausible ice sheet. Occasionally, minor re-advances of the margin were required to satisfy the geomorphology or disposition of the advance-retreat dates. We emphasise however, that we deliberately sought a conservative reconstruction of the ice sheet, only incorporating re-advances where absolutely required by the data, rather than adding all of the many reported re-advances from the literature. We do this for two reasons. Firstly, given that the ice sheet has yet to have had a fully documented reconstruction of retreat, we wish to make a systematic and cautious synthesis onto which more complex interactions can be built or refined at a later date; let's build the house before we fit the windows. Secondly, whilst authors are free to interpret their own evidence as they wish, our reading of many papers reporting readvances is that the evidence only indicates a small distance of over-riding by ice (hundreds of metres or kilometres rather than many tens of kilometres) and consequently, until the magnitude of actual readvance is known, we treat these as minor oscillations below the scale of our analysis. We intend publishing the map and dating database in full elsewhere (Hughes et al., submitted), so that others may choose to reconstruct elements differently and to permit modification as more evidence becomes available.

In trying to optimise the pattern and dating constraints to yield a plausible looking ice sheet, we find that whilst many variations are possible they can be distilled into two scenarios which are the same for Ireland and Britain (i.e. the patterns and dates work well together here) but are distinguished by different behaviour with regard to break-up of the North Sea ice cover. We therefore present two scenarios of ice sheet retreat.

3.3 Scenario One: Early and complete break-up of North Sea ice and a surge lobe down the east coast of England.

Isochrones of retreat are shown in Figure 17. Over Britain and Ireland, as the ice sheet shrank back from the continental shelf, it reduced in size and reconfigured its shape, eventually fragmenting into a number of separate ice masses over some centres of high ground. The style and rate of retreat are discussed later. In synthesising available dates and patterns for the North Sea with those of the east coast of Scotland and England, our first scenario builds a retreat sequence as displayed in Figure 17. Essentially this is a merging of the more recent acknowledgment of North Sea ice cover (Sejrup et al., 1994; 2009; Carr et al., 2006) with the long-held view (as far back as Charlesworth (1957) through to Boulton and Hagdorn (2006) and Davies et al., (2009)) of a surge lobe down the east coast of England. Although built from scratch here, Scenario One best follows from the trajectory of argument in the literature and we therefore see it is as very much the traditional view. We suspect that its widespread acceptance and popularity in the literature is a product of a longstanding paradigm of an ice free North Sea: a surge lobe was the only reasonable explanation for the carriage of erratics and provenance of Pennine and Scottish till emplaced on the east coast of Yorkshire and Lincolnshire, with clear evidence of ice pushing onshore from the sea (see Davies et al., 2009 and references therein). Given more recent acceptance of a confluent BIIS – FIS, our Scenario One tries to reconcile North Sea ice cover with the 'traditional' east coast surge lobe.

We reconstruct an early separation of British and Norwegian ice prior to 25 ka BP, and almost complete deglaciation of the North Sea by 23 ka followed by a dramatic surge of some 400 km at 17 ka. Whilst the geomorphology and the dating constraints permit such a scenario, there remain grounds for questioning its plausibility. The lobe appears glaciologically unlikely over such an extended distance and it is rather strangely directed southwards hugging the coast, rather than following the lower elevation bathymetry eastwards into the North Sea. Arguments about the position of an isostatic forebulge in the North Sea (Jim Rose, Pers. Comm. 2009) might help explain the southern trajectory of such a lobe. Recently acquired deglacial dates in northern England (e.g. dates close to Lake Windermere (Ballantyne et al., 2009a) and from the Yorkshire Dales (Vincent et al., in press; Telfer et al., 2009) make this scenario more problematic than had earlier been thought because much of northern England was ice free prior to the time of the supposed surge, making the source area rather limited. That ice existed so far south and at such a late stage in glaciation is not in question as there is much sedimentological and lithological information and good evidence for the timing as discussed earlier in section 3.1. We do, however, question the 'traditional' ice sheet geometry invoked to account for the evidence.

3.4 Scenario two: Two stage deglaciation of the North Sea with a persistent ice dome in the south.
An alternative reconstruction (Fig. 17) that satisfies the retreat patterns and timings comprises North Sea ice cover which broke up initially only in the north leaving a more persistent ice dome or rise over the southern North Sea. This dome of ice was responsible for the southern extent of ice in eastern England late on in glaciation (ca. 17 ka), deflecting ice that originated from Scotland and northern England onshore down the east coast. Such a scenario envisages a saddle between a Southern Upland dome and a dome of ice over the shallow southern North Sea. The lithology of tills and erratic travel that

have bemused palaeoglaciologists for so long on the east coast can be explained by multistage transport, (i.e. not transported by a single flowline in one go), first offshore (into the North Sea Sector of the ice sheet) and then onshore by flow deflection from the ice dome. The appeal of this model is that an extreme surge of an east coast lobe is not required. We argue that our Scenario Two is actually the more reasonable reconstruction of the data, especially if one recognises that the long history of papers that invoked an east coast lobe did so when there was an absence of evidence for North Sea ice cover at the time. Whilst this scenario is a logical outcome of the synthesis of the data, we accept that ice cover remaining over the southern North Sea for so long is a contentious proposal; we have no actual evidence from this specific region to say that it did, and the southern limit of ice in the North Sea is not known (Carr, 2004). That we reconstruct a dome here should not be taken to imply it was a preferential source of precipitation, but rather that it became a residual dome or rise because of evacuation of ice from the deeper parts of the sea (Norwegian Channel and Fladen Deep).The model urgently needs testing with marine investigations in the area. Although considering much earlier (Middle Pleistocene) episodes of ice sheet activity, Lee et al., (2002) muse over the same problem with regard to ice moving onshore in eastern England and propose that a huge piedmont lobe emanating from northern England might have been sufficient. For the Late Devensian however, such a lobe is precluded because of ice-free dates in northern England.

4.0 Palaeoglaciology of the retreating ice sheet
Ice sheet history is described using the following time slices each of which has an accompanying map; 27, 23, 19, 18, 17, 16 and 15 ka BP (Fig. 18). The margins come from the preceding analysis. The flow geometry and ice divide positions are necessarily partly schematic and to some extent supported by ice flow data such as from subglacial bedforms (Greenwood and Clark, 2009a,b; Hughes et al., in press) and erratic transport paths (C.D. Clark et al., 2004a). In Figure 18 and the narrative below we use the Scenario Two geometry for deglaciation of the North Sea, and we illustrate and describe the alternative (Scenario One Fig. 19) in a later section (4.8). Note that they only differ with regard to the North Sea. In compressing ice sheet history into just seven time slices we inevitably lose some of the changes that occur in between these steps, such as the splitting of the Welsh Ice Cap and various oscillations of ice margins as adjacent domes uncouple from each other. A narrative is provided exploring the changing configuration and dynamics of the shrinking ice sheet and pointing out some of the evidence base that belongs to each episode. We also highlight evidence that does not fit so well with our synthesis and where improvements are required.

4.1 Maximum extent - 27 ka BP
Contrary to the traditional view of the maximum extent of the BIIS at around 21 ka BP, it is found to reach its maximum areal extent by 27 ka BP, preceding the global LGM, which is now placed according to sea level estimates (Peltier and Fairbanks, 2006) at 26 ka BP. For a small and presumably well nourished ice sheet perhaps this is not surprising especially given its proximity to moisture-bearing westerly winds. The ice sheet had reached the continental shelf edge in all sectors of its western and northern margins, between SW Ireland and Norway, and with a fully glaciated North Sea. We presume that ice cover was mostly initiated over the uplands of Britain and Norway and steadily spread

to lower ground. Eventually the North Sea would have received opposing lobes of grounded ice meeting in the middle and which merged and rose in elevation to yield a saddle. Our map thus has a saddle over the North and Irish Seas, with ice divides positioned over high ground. According to marine records (Lekens et al., 2009) the Norwegian Channel Ice Stream (NCIS) had yet to reach full vigour (we thus map it in an embryonic state). It is important for ice sheet development that this had not yet happened otherwise its considerable drainage would have hindered advance of Norwegian ice far enough out into the North Sea so as to accomplish confluence with British ice. This is because the ice stream effectively blocks, or captures, passage of Norwegian ice that could have travelled further west. An alternative view, if glaciologically plausible, is that the western boundary of the NCIS had a distributary function with ice leaving the main trunk and flowing towards the west. Ice streams such as the Minch and NCIS are marked and come from an excellent evidence base (Bradwell et al,. 2007; Stoker and Bradwell, 2005; Sejrup et al., 2003), but we also mark ice streams in other places based on the position of shelf-edge fans (requiring profligate sediment delivery) and prominent troughs (e.g. the North Channel between Ireland and Scotland) that should have received fast ice flow given the surrounding ice sheet configuration. The Mega-Scale Glacial Lineations (MSGLs) reported by Graham et al. (2007) in the Witch Ground Basin of the North Sea and interpreted to record a NW flowing ice stream, likely fits in this stage, feeding ice to the margin near the Shetland shelf. The main BIIS had a combined divide running from Ireland across to Scotland and with two satellite domes, namely covering Wales and the Outer Hebrides and which appear to have existed as autonomous ice masses throughout glaciation. According to our model the Shetland Isles were subsumed by regional ice rather than supporting their own dome (see Golledge et al., 2008a and Flinn, 2009) at this stage, but the reverse happened later on in time.

The evidence base for this time slice was earlier presented in Figure 15 and Section 3.1. A number of difficulties remain and which question aspects of our reconstruction. Limited ice extent in Scotland around 32 ka BP is suggested by radiocarbon dates from a number of sites (Tolsta Interstadial = Whittington and Hall, 2002). The youngest date for build up in Scotland is a radiocarbon date from reindeer remains at 29.5 ka BP but the reliability of dates from this site (Reindeer Cave, Inchnadamph; Lawson, 1984) have been questioned (Bradwell et al., 2008a) in light of new ultrafiltration techniques for radiocarbon dating of ancient bone (Higham et al., 2006). However, if these dates hold then it does not give much time for the ice sheet to build up and reach the shelf edge by 27 ka BP as we reconstruct (based on IRD records, see earlier). Also, it could be argued that Irish Sea ice did not enter the Cheshire Plain and Vale of Clywdd until after 21 ka, in which case the 27 ka limit should be offshore from the Cheshire coast. This is based on a bone dated to 21.4 +/-1.7 ka (Rowlands, 1971; Bowen, 1974) found under Irish Sea till at Tremeirchion Caves in the Vale of Clywdd. As far we know there is absolutely no evidence for the southern limit of ice in the North Sea, but given glaciation to the north, a margin must have existed and we merely place it between the main Stationary Line of Denmark (Houmark-Nielsen, 2004) and Skipsea Till evidence in eastern England, and just south of the Dogger Bank.

 4.2 Asymmetric behaviour: northern retreat and southern advance - 23 ka BP.

An ice-free date in the North Sea at 25 ka BP requires that ice loss has commenced by this time and that at least a marine embayment opens up here, starting the unzipping process of Celtic and Viking ice. We reconstruct a minor ice rise to the east of this embayment, likely a residual product of drawdown and lowering of ice though the embayment and via the NCIS. The Moray Firth and Strathmore Ice Streams (Merritt et al., 1995; Golledge and Stoker, 2006) are reconstructed as being active in this phase and were likely prompted by the opening of the calving bay. The arrangement of the Moray Firth Ice Stream, the calving bay and the NCIS is consistent with the reconstruction of Bradwell et al., (2008a).

Although no dates yet exist we presume that retreat across the continental shelf was driven by globally rising sea levels from 26 ka BP onwards and that retreat was steady rather than abrupt or by 'float-off'. This is because the moraine patterns show an incremental back-stepping arrangement, in contrast to patterns on some other continental shelves from which more rapid retreat can be inferred (cf. Dowdeswell et al., 2009). We thus incrementally back-step the margin across the shelf, using the moraine positions and in keeping with the dating constraints onshore and with the morainal banks west of St Kilda which are dated to 26.6 ka BP (Peacock et al., 1992). Once retreated back from the shelf edge moraine shapes and configurations show that the ice margin became crenulate with multiple lobes. Sea level records indicate that it remained a marine calving margin which is consistent with IRD input to the Barra Fan until ca. 17 ka BP (Kroon et al., 2000; Knutz et al., 2001). Overall, the northern margins thus lost ice at this time and the NCIS is known to have started one of its purging phases (Lekens et al., 2009), so plenty of icebergs were released to the ocean.

In contrast to ice losses in the north, the southern margin experienced several advances, most notably by the Irish Sea Ice Stream down as far as the Scilly Isles (reconstructed as a 300 km advance). Advances are also reconstructed in the Cheshire basin (55 km) and Vale of York (130 km). We reconstruct ice starting to approach the east Lincolnshire coast as a precursor to ice incursion here dated to c. 21 ka at Dimlington (Penny et al., 1969). We imply an expansion south from the hypothesised North Sea ice dome and so ice movement directly from Britain is not required to satisfy these dates. These readvances along much of the southern ice sheet margin occurred whilst northern sectors were commencing retreat. The body of the ice sheet therefore moved towards the south, and its attainment of maximum extent and commencement of retreat were both asymmetric and asynchronous across different sectors of the margin.

While Celtic Sea ice advanced we expect ice to have started thinning in elevation over Ireland, and so we reconstruct an independent ice dome emerging over the hills of SW Ireland. A trans Irish - British ice divide is reconstructed but the saddle between the countries, over the North Channel, progressively lowered as the North Channel and Irish Sea ice streams continued to export ice mass. The extent and timing of the Irish Sea Ice Stream are constrained by Ó Cofaigh and Evans (2007) and Scourse (2006) and indicate the advance of ice after 24.2 ka BP. In Ireland some problematic dates exist for our reconstruction, notably the cosmogenic dates reported in Bowen et al. (2002) that indicate 'early' deglaciation of parts of mainland Ireland in conflict with our synthesis.

Many of these dates however, have been questioned by others using cosmogenic and radiocarbon methods (Ballantyne et al., 2007; 2008; Ballantyne in press; Ó Cofaigh and Evans, 2007; J. Clark et al., 2009a). These authors all suggest cosmogenic inheritance for the dates reported in Bowen et al. (2002) producing artificially old dates for younger events. Deglacial ages between 28.9 and 25.9 ka BP have also been reported by McCabe et al., (2007a) from marine muds on the north Mayo coast, but we note that the same authors (J. Clark et al., 2009b) prefer to cite the later age of 20.1 – 19.4 ka BP (McCabe et al., 2005) for the timing of initial deglaciation of the Mayo coast.

4.3 Ice streams cleave the ice sheet into autonomous Irish and British domes - 19 ka BP
The BIIS including North Sea ice cover has now reduced to 84 % of the extent it had at 27 ka BP, mostly by shrinking on the continental shelf and by enlargement of the marine embayment in the North Sea. The eastern part of this embayment (i.e. Norwegian ice) is reported (Sejrup et al., 2009) to have experienced a retreat and readvance, the Tampen Re-advance of 22 to 19 ka BP, although the distance of this margin oscillation is not known (we show it as a re-advance in Scenario One and more simply as a late-retreat in Scenario Two, Fig. 17). In our reconstruction, the marine embayment has enlarged to an extent that it has also deglaciated part of the (present day) land surface in east Scotland (to conform to marine mud dates (20 ka BP) at the coast in Lunan Bay; McCabe et al., 2007c). These dates appear anomalously early in comparison to surrounding information. We can accommodate it by producing the large embayment in our reconstruction, but it is questionable. Peacock et al. (2007) specifically question the basis for the proposed Lunan Bay re-advance and Sejrup et al. (2009) comment on how it appears incompatible with adjacent younger ages of deglaciation provided by cosmogenic techniques (Phillips et al, 2008).

Timing of ice withdrawal from the Irish Sea Basin remains one of least certain elements of BIIS history (and our reconstruction). Irish Sea ice was at the Scilly Isles at 23 – 24 ka BP (Scourse et al., 2009) and is required to retreat extremely rapidly in order satisfy ice free dates (glaciomarine muds) on the Irish County Down coast of 19.7 to 19.2 ka BP. We thus have to reconstruct rapid margin retreat, which is to be expected of an over-extended and presumably thin Irish Sea lobe. We configure it as retreating to a position pinned between the County Down coast and the Isle of Man and with a calculated retreat rate of 145 metres/year although it possibly remained pinned at various constrictions (Pembroke-Ireland; Lleyn Peninsula –Ireland) for some time and thus had phases of even more rapid retreat. Such a rapid withdrawal and the timings are consistent with the analysis of Scourse et al., (2009) and Ó Cofaigh and Evans (2001; 2007). This also fits with Ó Cofaigh et al., (in press) who use dates above and below Irish Sea till to demonstrate the advance was short-lived. They interpret the advance to have been a surge event partly controlled by subglacial bed conditions rather than climate forcing. Over the Wicklow Mountains on the east coast of Ireland (around which our 19 ka isochrone bends (Figure 17)) Ballantyne et al., (2006) used cosmogenic exposure ages to reveal that the summits here have been ice free for 18 to 19 ka years, which is broadly consistent with our analysis.

Dates in NW Ireland (McCabe and P.U. Clark, 2003; McCabe et al., 2005; Ballantyne et al., 2007; J. Clark et al., 2009a) reveal that some coastal fringes became ice free in this stage and the geomorphology allows us to satisfy these constraints whilst reconstructing ice lobes still extending out into the major bays. There is scant dating information to reconstruct ice margin withdrawal across southern Ireland though the geomorphology gives an indication of margin shape. Whilst we found that the putative Southern Irish End Moraine (Charlesworth, 1928) does not really exist as a continuous morphological feature (i.e. moraine), its supposed position likely marks the limit of other ice-marginal assemblages and we place our 19 ka limit along this approximate line. To the north of our margin (in Wicklow) Ballantyne et al. (2006) used exposure dates from glaciated summits to indicate that ice was thinning at 19 ka BP, and so is consistent with our reconstruction. In SW Ireland we reconstruct separation of a Kerry-Cork ice cap from the main ice sheet. Local stratigraphic and sedimentological information suggests that ice flowed north and west over the peninsulas of west Kerry from a local source subsequent to earlier coverage of the main ice sheet (Lewis, 1974; Warren, 1991; Ó Cofaigh et al., 2008), and was followed by retreat into the major valleys of the MacGillycuddy's Reeks and surrounding mountains (e.g. Warren, 1988, 1991). There is little chronological control on this separation, but many moraines that could be targeted. Several dates reported in Bowen et al. (2002) are in conflict with our model as they argue for ice having reached this stage by 22-20 ka BP (e.g. in Kerry/Cork, SW Clare, Galway Bay) and for greater ice loss by our 19 ka timeslice. We note (see above) that several dates reported in Bowen et al. (2002) have been found to be anomalous (Ballantyne et al., 2007, 2008; Ó Cofaigh and Evans, 2007; Ó Cofaigh et al., in press; J. Clark et al., 2009a) and these authors have cited likely cosmogenic nuclide inheritance and a poorly defined stratigraphic context or a specific nature of the dated samples.

The calving bay retreating in the Irish Sea had separated Welsh from Irish ice, and we place the margin as pinned between the Lleyn Peninsula of North Wales and County Down of Ireland. This satisfies dates (Foster, 1968; 1970) indicating decoupling of Welsh and Irish ice from 20 ka BP onwards. The Welsh Ice Cap retreated from the southern limit, consistent with cosmogenic dates from South Wales (Phillips et al. 1994), but advanced to the west and east because the buttressing effect of Cheshire Plain and Irish Sea lobes had been removed. Ice retreated from the maximum limit in the Vale of York, to at least north of Ferrybridge by 20 ka (Bateman et al. 2008). Where dating constraints do not exist we assume retreat more rapidly from low-lying areas, such as in the Cheshire Plain. Recently published luminescence dates on loessic silts close to Morecambe Bay suggest that the northern Irish Sea had deglaciated before 19.3 ka BP (Telfer et al., 2009); our reconstruction is compatible with the age range of these dates (16.7-21.9). New cosmogenic dates on erratic boulders suggest that the Yorkshire Dales were deglaciated above at least 280 m by c. 18 ka BP (Vincent et al., in press), which is also compatible given a thinning ice sheet that first exposes high ground.

By 19 ka, ice had withdrawn from terrestrial portions in the south of Ireland, Wales and England, and the Irish Sea Ice Stream had likely undergone significant and rapid retreat. The activity of presumed ice streams operating in the confluence between Ireland and Britain are reconstructed to have significantly lowered ice sheet elevation, particularly

over the North Channel where an ice divide was previously hosted, and to have undergone dramatic margin retreat, producing autonomous Irish and British ice domes with independent ice divides.

4.4 Major marine sector breaks up and northern North Sea loses its ice - 18 ka BP.
Following dramatic loss of Irish Sea ice during the previous stage (above), by 18 ka there was a wholesale loss of ice cover over the northern North Sea and retreat of the Norwegian Channel Ice Stream of over 400 km. We presume that these events are largely sea level driven. In this reconstruction a residual ice dome, or rise, persists over the southern North Sea. As noted earlier (Section 3.4) this dome has little basis in evidence from the North Sea (there is virtually none for this region), but an ice mass is required in order to penetrate onshore down the east coast of England and at this late stage in glaciation (see Scenario One; Section 3.3 for the alternative).

The BIIS continued its demise leaving behind a separate Welsh Ice Cap and with a notable reorganisation of the flow geometry over Ireland with ice divides migrating westwards (Greenwood and Clark, 2009ab). This migration may have been in response to the dramatic purging of ice from the east coast by the Irish Sea Ice Stream and continued migration away from the residual saddle. The BIIS now had its main axis configured SW to NE from SW Ireland to the Shetland Isles, and roughly parallel to the continental shelf edge. This might be a reflection of proximity to moisture sources or, more likely in our model, as a consequence of the purging of ice from ice stream activity and calving bays in both the Irish Sea and northern North Sea. The latter effect thus appears to have unzipped the ice sheet through its middle leaving a residual ice mass over the southern North Sea. Although there is no direct dating control, we presume that the Kerry-Cork ice cap has by now been reduced to cirque and valley glaciers.

4.5 Final collapse of all marine sectors, with margin oscillations and minor ice streaming at the coastline - 17 ka BP.
Ice has now been lost from nearly all of the continental shelf areas and finally collapsed completely in the North Sea. There is very little pattern or timing information from the floor of the North Sea that permits us to plot the retreating margins here and so the large lobes depicted at this stage are conjectural and reflect an intermediate stage between complete and no ice cover. Ice still moved onshore in Lincolnshire at this time to fulfil the dating constraint (Bateman et al., 2008), but is drawn as two lobes because this is where the low ground and slopes should have directed them. It might be that once all North Sea ice was lost (perhaps catastrophically, by 'float-off' or break up?) that the previously buttressed BIIS surged offshore producing something like the lobes we depict. A minor readvance (of at least 50 km) from the Shetland – Orkney ice mass into the Witch Ground Basin of the North Sea is depicted following Sejrup et al. (2009) and may be a part of this readjustment. Alternatively it could be part of a climate-induced oscillation associated with the Heinrich- 1 Event. Ice had retreated inland from the NE coast of Buchan allowing ice from the Moray Firth and Strathmore Ice Streams to advance onshore. Our landform evidence shows this clearly and is consistent with dates

and geomorphological/stratigraphic evidence (Merritt et al., 2003) for ice advance to the Buchan coast after 18 ka BP.

Of the known ice streams, the Strathmore Ice Stream (Golledge and Stoker, 2006) is reconstructed as operating at this time and contributing to a north-flowing lobe that is required by the geomorphological evidence along the coast south of Aberdeen. Other small ice streams likely existed, but we have little basis for adding them. Evidence exists (Everest et al., 2005) for an ice stream track running down the Tweed valley in NE England and draining to the coast. This might have contributed to the large offshore lobes, but we have not included it as it more likely operated at a later stage (it is quite small) and between our 17 and 16 ka time slices.

Apart from the large and presumably thin ice lobes (if they existed) extending into the North Sea, the main mass of the BIIS ran along the NW periphery of the landmass with most of England and half of Ireland deglaciated. By this time the Lake District is ice free to satisfy dates for the onset of organic sedimentation at Lake Windermere (Pennington, 1977; Coope and Pennington, 1977) and loess deposits and cosmogenic isotope dates in the Yorkshire Dales (Telfer et al., 2009; Vincent et al. in press). Ice had retreated further up the Irish Sea to the Isle of Man. A much reduced Welsh Ice Cap was isolated from the main ice sheet and is schematised here but was likely reduced to ice fields on the major summits, and with small valley glaciers. In Scotland we envisage a relatively thin ice sheet at this stage with some of the major summits of Skye, Lewis and Caithness emerging as nunataks.

In NW Ireland the ice margin is well fixed in time. Dates from McCabe and P.U.Clark (2003) suggest the ice margin was still in close proximity to the coast, as we depict it here. Our landform patterns show that as ice thinned around Malin Head it split into two lobes in Loughs Swilly (W) and Foyle (E) as deglaciation ensued from 17-16 ka BP. Three exposure dates from the NW Donegal coast (16.6, 16.3, 15.9; Ballantyne et al., 2007) indicate that the ice margin lingered near the present-day coastline after initially impinging back on the shoreline at ~19.3 ka (J. Clark et al., 2009a). In western Ireland lobes in Donegal Bay, Clew Bay and Galway Bay drew back towards the present-day shore. Over central-southern Ireland dating control is severely limited (Ahlberg et al., 1996; Bowen et al., 2002; Diefendorf et al., 2006), but there is a wealth of pattern information provided by landforms. Retreat from the putative Southern Ireland End Moraine (Charlesworth, 1928), is reconstructed as a series of lowland lobes in Limerick, Laois and Kildare, separated by the emergent higher ground of the Silvermine Mountains, Castlecomer Plateau, Slieve Bloom, and eventually the Slieve Aughty Mountains. Esker systems mark a suture zone along a corridor from County Offaly to the Ox Mountains, which reflect the 'unzipping' of two main ice domes pinned in the W and the NE from 17 – 16 ka BP.

On the east coast of Ireland (Counties Down and Louth) a series of dates (McCabe and Haynes, 1996; McCabe and Clark, 1998; PU Clark et al., 2004; McCabe et al., 2005, 2007b) have been used to reconstruct re-advances of the margin between 19 and 15.5 ka BP, and one of which (Killard Point Stadial) was initially linked to the Heinrich 1 cooling

event (McCabe and PU Clark, 1998; McCabe et al., 1998). The most recent synthesis (McCabe et al., 2007b) reports withdrawal of ice onshore prior to 18.2 ka (Cooley Point Interstadial) followed by an advance into Dundalk Bay (18.2 to 17.4 ka BP; Clogher Head Stadial), then retreat back onshore by 17.4 ka BP (Linns Interstadial) and further re-advance into the bay (Killard Point Stadial) between 17.2 and 16.6 ka BP. Final retreat onshore (Rough Island) is achieved by ~15.5 ka BP. We have not incorporated these ice margin dynamics in the vicinity of Dundalk Bay because they are below the resolution of our ice sheet wide analysis and the selected timeslices (Figs. 17 &18). Our ice limits at 17 and 16 ka BP are, however, broadly consistent with these deglaciation dynamics and ages. We note that the spatial distribution of dated sites only constrains the magnitude of these retreat – readvance cycles (i.e. distance) to ~15 km, rather than pan ice sheet re-advances of climatic significance.

4.6 Separation of Irish and Scottish ice sheets - 16 ka BP.
The Scottish and Irish components of the ice sheet have by now decoupled over the North Channel. Shetland and Orkney also supported separate ice masses and Welsh ice had probably disappeared. Interestingly, Peacock (1995) reports proximal glaciomarine sediments some 130 km east of Shetland (on the Viking Bank) and dated at 15.5 to 13.5 ka BP. Given that the NCIS was already deglaciated, the only source of proximal ice for these sediments would have been from the Shetland Isles, and there is a possibility, worth further investigation, that a major and very late readvance of Shetland ice occurred. Maybe this was associated with the Fladen readvance reported by Sejrup et al. (2009). However we have not included a readvance to the Viking Bank because it does comply with other dates and because Peacock himself (1995) preferred to invoke transport by sea ice. Dates from the southeast coast of Shetland suggest deglaciation by 14 ka BP (Phillips et al,. 2008), therefore the Shetland Ice Cap margin is placed roughly along the coastline.

Ice retreated to the Cairngorm Mountains and Spey-Cairngorm ice started to decouple, as suggested by OSL dates from glaciolacustrine sediments (Everest and Golledge, 2004). Ice retreated rapidly in Strathmore to accommodate the youngest suggested ages for the Errol Beds formation (Peacock, 2002). Caithness was now ice free (Phillips et al. 2008). Elsewhere in Scotland the ice is inferred to be close to the present day coastline. The Wester Ross moraine (Ballantyne et al., 2009b; Everest et al., 2006) had previously been dated as 17 to 15 ka BP, but more recent work, using cosmogenic techniques, places the moraine later, at 14 to 13.5 ka BP (Ballantyne et al., 2009b). This is in agreement with dates further north (Bradwell et al., 2008b) which have been taken to indicate a large Late Glacial ice cap at this time. Our margin at 16 and 15 ka time slices reflects this. A small ice mass is maintained in the Southern Uplands on the basis of the retreat pattern reconstructed from geomorphology. There are only a few dates from the Central Valley of Scotland (Bishop and Coope, 1977) and these all suggest that this region was ice free by 15 ka BP.

From 17 to 16 ka BP retreat of ice in the North Channel (between Ireland and southern Scotland) separated Irish from British ice and at some point in this transition a lobe of Scottish ice impinged on the north Irish coast producing the well known Armoy Moraine (Synge 1968). The west to east unzipping along the North Channel meant that Irish ice

reoriented into lobes draining through Loughs Swilly and then Foyle. In County Mayo, we confirm identification and interpretation of the Tawnywaddyduff moraine of J. Clark et al. (2009b) and, based on nested moraines and the disposition of meltwater channels flanking the Ox Mountains, we depict the onshore retreat of the ice margin as a series of lowland lobes separated by the high ground of the Nephin Beg range, the Ox Mountains and the mountains north of Sligo Bay. Cosmogenic exposure ages from the north shore of Clew Bay and from the Ox Mountains (J. Clark et al., 2009b) constrain the timing of this configuration to ~16 ka BP. This timing is broadly consistent with Ballantyne et al. (2008); the latter requires slightly further retreat south of Clew Bay by this time, though the ages for this area reported by Ballantyne et al. (2008) fall within the broad range in J. Clark et al. (2009b). Within the bounds of the errors and uncertainties in the cosmogenic method (cf. Ballantyne, 2010), our reconstruction is consistent with the dating record. We do not find any basis, either geomorphological, stratigraphical or chronological, for explaining this ice margin as a re-advance limit (J. Clark et al., 2009b), although of course, it might have been. Instead, we note that the ice margin remains close to the west coast for a considerable period after initial ice free enclaves appear (19 ka), likely pinned by high ground between retreating ice lobes. From 16 ka BP the Irish Ice Sheet continued its separation into two small remnant masses – western and northern – parting around the Ox Mountains and along the suture line identified earlier towards the central lowland eskers. This pattern is reconstructed from the disposition of drumlins, eskers and meltwater channels, with little further dating evidence to constrain final deglaciation once the ice sheet had fully retreated onshore.

4.7 Final demise - 15 ka BP
Immediately prior to the Late Glacial Interstadial (14.7 to 12.9 ka BP) ice extent is reconstructed as mostly restricted to the NW Highlands of Scotland, westernmost Southern Uplands and minor ice caps on Shetland, Orkney and the Outer Hebrides, and in Ireland to the uplands of Counties Sligo and Donegal and Connemara . The outline of the NW Highland ice cap has been partly constrained by assumed similarity with the subsequent Loch Lomond Stadial extent which is well known (Sissons, 1979). On the basis of a dense number of dates from Southern Scotland (e.g. Bishop and Dickson, 1970; Browne and Graham, 1981; Browne et al., 1983; Holloway et al., 2002; Lowe, 1978; Rose, 1980; Simpson, 1933; Vasari, 1977) the margins of the Loch Lomond Stadial Ice Cap were reached by c. 14 ka BP, and recent analysis suggests (Bradwell et al., 2008b) that for western Scotland there was no ice-free episode during the subsequent Late Glacial Interstadial prior to the Younger Dryas chronozone (12.9 – 11.5 ka BP). So whilst we stop our timeslices at 15 ka BP, it is likely that a NW Highland ice cap persisted right through into the Younger Dryas (likely expanding at this time) and met its final demise by around 11.5 ka BP (Lowe et al. 1999; Golledge et al. 2007, 2008b).

Information from landform patterns in Ireland indicates that ice finally retreated from the NW coast and up into the valleys of the Donegal Mountains. The rest of the remnant northern dome at 16 ka BP accomplished rapid retreat on its north and eastern flanks, as recorded by eskers and meltwater channels, such that it's ice divide migrated SW. Final disappearance of ice is constrained (i.e. youngest possible age of deglaciation) by dates of ~15.5 ka BP at Rough Island (McCabe and Clark, 1998; McCabe et al., 2007c), 14.4 ka

BP at Sluggan Bog (Smith and Goddard, 1991; Lowe et al., 2004) and 15.1-13.2 ka BP on Mweelrea, Connemara (Ballantyne et al., 2008).

4.8 Palaeoglaciology of Scenario One: Early and complete break up of North Sea Ice
There is not much evidence to constrain the pattern and timing of ice loss over the North Sea, i.e. distinguishing between our two scenarios (Fig. 17), so we here also illustrate (Fig. 19) the scenario in which the whole of North Sea ice cover is lost in a single, perhaps catastrophic, episode. Ice-free dates in the Fladen Basin of the northern North Sea require that grounded ice had retreated from this area by 25 ka BP (Sejrup et al., 1994). This constraint can be satisfied by a marine embayment over the area and with stable ice cover remaining over the southern North Sea (i.e. depicted in Scenario Two and Fig. 18). Alternatively, we may consider that at this time there was loss of grounded ice from the whole North Sea and a breaching of the 'ice bridge'. Given that this sector of the ice sheet is marine-based then it was clearly susceptible to very rapid deglaciation by iceberg calving or by floatation as sea levels rose, and so this remains a serious possibility and of great significance given current concerns about currently deglaciating marine- based ice sheet sectors in Antarctica.

In this scenario the saddle between British and Norwegian ice is presumed to have lowered and then the ice separated some time after 25 ka BP. Further evidence is required to constrain the rapidity of ice loss; was it a single, perhaps catastrophic event or did it proceed by steady or stepped retreat? We should also wonder as to the mechanism of break up and the culpability of sea level rise. The Norwegian Channel Ice Stream continued to operate after separation and up until at least 19 ka BP, which means that its western margin was probably unbounded by ice, or at least, with no feeding ice source (Fig. 19). From the perspective of ice streams operating today, this is an unusual configuration, and we query its plausibility. However, by now the ice stream had carved a deep trough which may explain the configuration as this would have routed its flow. The Moray Firth Ice Stream is also reconstructed to have been active in this phase.

Later on, by 19 ka BP we reconstruct margin advances on both sides of the North Sea based on seismic evidence and dates (Nygård et al. 2004; Nygård et al. submitted, Sejrup et al. 2009). The Tampen Advance requires that ice was supplied from overspilling the NCIS onto the North Sea Plateau. The actual distance of these readvances is poorly constrained and we do not yet know it they were a response to the loss of buttressing of inland ice by North Sea ice, or as a consequence of short-lived climate events, or just by changes internal to the ice sheet (e.g. change in bed properties). By 17 ka the Norwegian Channel and Moray Firth ice streams are reconstructed to have shutdown and the Strathmore Ice Stream to have advanced. The deglaciation of the NCIS is one of the best dated events in this history. The previously discussed (section 3.3) surge lobe or ice stream down the east coast of England is required to satisfy dated advances onshore as late as 17 ka. If a glaciologically plausible event, this must surely have been a short-lived surge presumably triggered internally rather than as a response to a cooling.

5. **Discussion**

Our reconstruction is consistent with the record of ice-rafted detritus from the BIIS as synthesised by Scourse et al., (2009), in terms of the first-order appearance and demise of marine-terminating margins. It would be illuminating to see if the ice losses implied by our reconstruction would satisfy the IRD fluxes at various times during deglaciation, or whether these must be explained by significant readvances.

5.1 North Sea Ice

The largest uncertainty regarding deglaciation is of the North Sea area; when did the 'ice bridge' break up, and was it a single, perhaps catastrophic event or a more measured reduction? Our two scenarios explored the main possibilities regarding the timing of separation. When British and Norwegian ice was confluent, a large lake should have formed in the southern North Sea, because the confluent ice would have prevented any northward escape of meltwater and river discharges from the Rhine and Thames and other rivers draining into the basin. The shallowing at the English Channel would have provided a topographic barrier that acted as an overflow for the impounded lake (cf. Valentin, 1957; Clark et al., 2004c; Toucanne et al., 2010). We schematically illustrate such a lake position in Figure 18, and estimate it as around 1300 km^3 in volume. Toucanne et al. (2010) have analysed sediments that passed through the southern North Sea basin (i.e., the lake) and spilled through the Fleuve Manche (Channel River) out to the Bay of Biscay. On the basis of their evidence and dating control they argue for a 'profound change of the glacial conditions in the North Sea Basin around 18 ka' (Toucanne et al., 2010, p470.) and hypothesise that this is the time for separation between British and Norwegian ice, once more permitting water outflow northwards rather than via its diverted route down the Fleuve Manche. This is exactly as we had independently reconstructed in our Scenario Two (a late breakup of an ice dome over the southern North Sea at 18 ka BP), and thus adds some weight to the likelihood of this scenario.

We hypothesise that as ice elevations lowered during deglaciation that water from the ice-dammed lake may have penetrated beneath the ice, producing subglacial channels which grew and catastrophically destroyed the 'ice bridge' between Britain and Norway. Some of the tunnel valleys of the North Sea might be the erosional record of such an event (cf. Wingfield, 1990). If such a disintegration happened then a large volume of icebergs and fresh water would have abruptly entered the North Atlantic with the potential to influence salinity, ocean overturning and regional climate (Clark et al., 2004c). A similar situation involving catastrophic break-up has been proposed for the drainage of Lake Agassiz through an ice dam of the Laurentide Ice Sheet (Clarke et al., 2004). Evidence for a strong flux of meltwater from the North Sea to the Norwegian Sea close to H3 time (Lekens et al., 2006) could be related to such a break up.

5.2 Rates of retreat

Using the palaeo-glaciological maps of the specified time-slices we can assess the area and volume loss of the ice sheet through time (Fig. 20). Ice covered area was measured from the GIS files, and ice volumes were estimated using the relationship reported by Paterson (1972) which was empirically derived from a variety of modern ice sheets and ice caps; $logV = 1.23(logA-1)$, where V and A are volume and area respectively and measured in km units. According to this method of estimation the maximum area of the

ice sheet attained at 27 ka BP was 840,000 km^2 and with a volume of 1,120,000 km^3, inclusive of the whole BIIS and all North Sea ice, but excluding ice over present day Norway. Note the volume estimate is indicative as it is only crudely derived, and would vary widely according to actual ice thicknesses and dome configurations – it translates into a notional global sea level change of around 2.5 metres.

According to the reconstruction, the rate of ice loss (volume) was slow (65 km^3 per year) whilst retreating back from the shelf edge, and then more rapid (at 260 km^3 per year) once the margins approached modern shorelines after 17 ka BP (note the less steep curve in Fig. 20 for the marine sectors), an apparent contradiction of the hypothesis of unstable marine-based ice sheets. We caution, however, in drawing too strong a conclusion from this given the very poor timing constraints for the marine sectors. It is interesting to note that the two main pulses of ice loss (27 to 25 ka and 17 to 16 ka) in Figure 20 broadly correspond to Heinrich Events 2 and 1, but again much better timing constraints would be required to take this further. The contrast in retreat between the shelf versus terrestrial sectors is also expressed in a NW – SE asymmetry of retreat rates that is evident in the maps (Figures 17 and 18) and displayed and perhaps explained in Figure 21. Isochrones are closest together (slowest rates of retreat) along the continental shelf margin and widely spaced over the south-eastern sectors. We suggest that strong purging of ice when calving margins existed could have substantially lowered ice elevations onshore, preconditioning it for rapid retreat later. Thus, although the margins retreated slowly across the continental shelf, considerable ice mass loss was probably accomplished at these times through thinning. Such thinning at a time when equilibrium line altitudes were presumably rising would place the ice sheet in a position of strongly negative mass balance and promote rapid retreat. The thinning is supported by the earlier mentioned characteristics of retreat that were found in the uplands of Britain and Ireland, with landform signatures often indicating ice thinning, exposing summits whilst lowlands were still glaciated, rather than of simple margin retreat. Other factors that may have contributed to the asymmetry of retreat could be the continued nourishment of ice by proximity to moisture of the NW sectors, or a steeper original NW profile may have existed because ice extent was curtailed too soon by the shelf edge, with a more gentle SE profile, thus conducive to more rapid retreat of thin SE lobes.

Initially, it might be assumed that ice streaming accelerates ice margin retreat. However, from the general finding mentioned above, it seems more sensible to suppose that ice streaming accelerates ice mass loss (through interior thinning), but not necessarily rates of actual margin retreat, at least initially. Retreat rates along transects along the main ice stream trunks and for eight inter-stream locations were calculated (Fig. 22). Although there is great variability it is generally the case that ice streams retreated more rapidly (17.5 ma^{-1}) than for inter-stream areas (9 ma^{-1}), and with some very high retreat rates for the Irish Sea (147 ma^{-1}) and Moray Firth (149 ma^{-1}) Ice Streams. That nearly all of the ice streams retreated faster than the inter-stream areas implies that the ice streams were in active operation (i.e. fast flow) during retreat, rather than having switched off earlier. If they had switched off then ice elevations would have equalized (between stream and inter-stream areas) and the retreat rates should be more similar, or indeed slower, because ice streams tend to occur in troughs with thicker ice. We thus interpret the retreat

isochrones as indicating that ice streams purged large volumes of ice, significantly thinning the ice sheet but reducing its areal extent only slowly, and that the ice streams continued to operate throughout deglaciation with their margins eventually back-stepping rapidly. It is interesting that there are two modes of ice stream retreat rates (Fig. 22); extremely fast (ca. 148 ma^{-1}) for the Irish Sea and Moray Firth Ice Streams versus relatively slow (17.5 ma^{-1}) for the others, and we speculate that this reflects the difference between transitory and regulatory ice stream functioning, respectively. Transitory (or surging) ice streams over-extend themselves, are short-lived and thin and thus retreat rapidly. Regulatory ice streams operate for much longer and remain in balance with regard to discharge and feeding of ice through the onset areas. No evidence has been found (yet) for a terrestrially-terminating ice stream such as have been found in the Laurentide Ice Sheet (Stokes and Clark, 2003; Evans et al., 2008), and so we presume that major streaming terminated once the calving margins were lost. We regard the above analysis (Fig. 22) and its interpretation as hypotheses rather than robust conclusions because of weak time control on the marine margins and ice streams. Retreat rates identified here fall within the range of those observed for modern ice streams in West Antarctica (McMurdo ~ 120 ma^{-1}; Ice Stream C ~ 30 ma^{-1}; Ice Stream B ~ 450 ma^{-1}; Conway et al., 1999).

5.3 Readvances

The ice sheet wide scale of our analysis and its emphasis on landforms rather than sediment stratigraphy means that we have not reconstructed many margin readvances, yet intuitively, given documented millennial scale climate oscillations (Dansgaard-Oeschger and Heinrich Events) one might expect the ice sheet to have experienced frequent readvances, during cool episodes, within the overall retreat. Such behaviour is emphasised in the climate-forced numerical ice sheet modelling of Hubbard et al., (2009), for example, where it was found that the BIIS became phase-locked to the rapid climate oscillations of the Greenland ice core record, reflecting the forcing of the model by this temperature record. We could thus expect there to be numerous climate-driven readvances in the sedimentary record. Further, from the modelling experiments of Boulton and Hagdorn (2006), we might expect to find some 'unforced' readvances driven purely by internal glaciological oscillations. Some of our difficulties in reconstructing a retreat pattern that satisfies all dates and all elements of the pattern could arguably arise from a lack of knowledge of readvances. Of course, it is also likely that some dates or parts of the pattern might be wrong. As noted earlier, we chose not to incorporate putative readvances reported in the literature mostly because they were below the resolution of our analysis and also because the distance of retreat and then readvance is either small (kilometres), unspecified, or restricted to tidewater outlet glacier situations, which might be expected to experience frequent, but small oscillations. Clearly ice sheet scale readvances (over say 50 km and for large tracts of the margin) are crucial for understanding ice - climate – ocean interactions, and they deserve considerable attention. Our reconstruction is best thought of as the coarse spatial and temporal scale upon which these ice sheet scale readvances can be superimposed, once adequately constrained.

5.4 Numerical ice sheet models

There have been two recent numerical experiments of the BIIS (Boulton and Hagdorn 2006; Hubbard et al., 2009), both of which used a forward modelling approach, driving the mass balance of the ice sheet by climate fluctuations derived from a Greenland ice core, but differed in model design and the approach to the forward runs. One explored the large parameter space of boundary conditions producing hundreds of simulations from which promising versions (in terms of matches to evidence) were illustrated (Hubbard et al., 2009). The other took some boundary conditions as fixed and adjusted the others in order to find simulations that resembled the reality recorded by evidence (Boulton and Hagdorn, 2006). Both models are remarkably similar with regards to growth initiating and spreading from Scotland and in the LGM extent reached, but on this latter point we should remember that these are the simulations chosen or adjusted, presumably to match known LGM conditions. The Boulton and Hagdorn (2006) model simulated a single ice mass expanding, whereas the Hubbard et al. (2009) model simulations were sensitive to ice caps developing on highlands such as in SW Ireland and Wales, and that became subsumed by the main ice sheet. Curiously, this latter style is much less marked during the retreat, yet a key feature of our reconstruction. Both models simulate many aspects of our reconstruction such as the broad disposition of ice divides and major ice streams, but they appear to grow too slowly with very little ice extent at 27 to 24 ka BP when we have reconstructed maximal extents. This must surely imply that the imposed climates used for the British Isles, modulated from the Greenland record, must be inappropriate in some way. Whilst we earlier expressed some caution regarding the plausibility of the surge lobe or ice stream down the east coast of England, both models produce a muted version of this. Of great interest also is that in the Boulton and Hagdorn (2006) model, for their simulation of the North Sea ice evolution, we note that flow along the NCIS is reproduced but also ice flow spanning out from its trunk and to the west to nourish central North Sea ice, something that we earlier questioned. Such is the complexity of climate drivers, model formulations and specific simulations and the complexity of the evidence database with alternative scenarios and interpretations, that we take the model-data comparisons no further here. They require a full and systematic analysis to do both approaches justice. It is clear, however, that model and data approaches have now matured to a level where detailed comparison is warranted, and instead of our cursory maximum limits and disposition of ice divides approach, that one based on quantitative adherence to key goals should be attempted. To what extent are the marginal retreat patterns reproduced? Can the sequencing of ice flow directional changes be simulated? A GIS approach to assess the performance of numerical models along the lines advocated by Napieralski, et al. (2007), appears sensible, but is a major task.

6. **Summary and conclusions**

The whole of the land area of Britain and Ireland was systematically investigated using high resolution remote sensing data, and we have presented mapping results of moraines, meltwater channels (lateral and subglacial), eskers, and drumlins and a methodology of how to interpret and bring them together. We believe that our mapping is near complete and that most of the available landform evidence is now captured. Submarine areas received less attention because of patchy data availability especially for the Irish and North seas. However, for the continental shelf we have discovered and mapped numerous large moraines, recording an extensive pattern of retreat stretching from SW Ireland to

the Shetland Isles. On the basis of an integration of this new mapping of glacial geomorphology (> 26,000 landforms) with previously published evidence, compiled in the BRITICE database, we now believe that most of the pattern information on the shrinking ice sheet is captured (Fig. 12). Given that our methodology included deriving patterns of retreat from independent lines of evidence (e.g. moraines versus ice dammed lake positions), and that they mostly matched up extremely well (Fig. 8) gives us a high level of confidence in the robustness of the overall pattern we have derived. At a local-scale and where we have gaps, we expect further work can make useful refinements and additions, but we doubt there will be many surprises at the ice sheet scale. Conclusions that can be drawn from the pattern include:

- Unequivocal evidence for glaciation to the continental shelf edge all the way from SW Ireland to the Shetland Isles. From the large sediment volumes comprising the moraines the residence time for ice on the shelf must have been considerable.
- Rather than viewing the ice sheet as comprising autonomous British and Irish Ice Sheets that joined briefly at the peak of glaciation, the pattern demonstrates much stronger integration, and that for most of its history a genuinely combined ice sheet existed. A sausage-shaped ice sheet running from SW Ireland to NE Scotland (a 'shelf-parallel configuration') dominates the history and at maximal extent spread far enough to the south and east to incorporate outlying ice domes such as over Wales, the Lake District, and Kerry. The ice sheet is thus best viewed as an Irish-Scottish ice sheet with satellite domes in England and Wales and SW Ireland.
- Final disintegration of the BIIS was into component ice caps, rather than as a single ice mass. This is analogous to the incomplete deglaciation of Iceland into the numerous remnant ice caps that still exist.
- The style of retreat was highly lobate, suggestive of thin ice lobes and low basal shear stresses.
- A strong signal of ice sheet thinning is revealed by summits appearing as nunataks some distance behind the ice sheet margins. Such patterns were often difficult to resolve because the amplitude of topography was of a similar order to that of likely ice sheet thickness, creating a complexity beyond the monotonic retreat patterns that are typically experienced in flatter terrains such as on the Canadian or Fennoscandian shields. The BIIS is inferred to have lost considerable volume by extensive thinning, prior to areal reduction.
- Contrary to tempting presumptions, ice did not always retreat to the nearest high ground. Examples include retreat of the southern margin back into the Irish Sea from the Cheshire Plain, and back into the North Sea from the east coast of England.
- In the North Sea, moraine patterns reveal the suture zone where British and Norwegian ice separated.

To attach information on timing to the pattern of retreat, a database of 882 dates was compiled from the literature, tabulated in the GIS, and classified into the following categories: advance, deglacial, margin, ice free, exposure time, and high sea level stand. Once calibrated, the dates were visualised in the GIS along with the pattern information

and isochrones of the shrinking ice sheet were developed (Figure 17) from which palaeo -glaciological maps at a range of time slices were produced (Figure 18). Conclusions that can be drawn from the combined pattern and timing information include:

- As with other palaeo-ice sheets, and contrary to many earlier presumptions, the ice sheet reached its maximum extent at different times in different sectors. The disparity between continental shelf maximum extent as early as 27 ka against the southern limit extent of around 23 ka might simply be because the ice sheet may have continued expanding to the north and west if it had not run out of continental shelf and reached water too deep for grounding. The NW margin is thus a 'truncated maximum' extent.

- The ice sheet is reconstructed as attaining its maximum areal extent of 840,000 km^2 by 27 ka BP and with a volume of 1,120,000 km^3, inclusive of the whole BIIS and all North Sea ice, but excluding ice over present day Norway. The volume is a only a crude estimate and translates into a notional global sea level change of around 2.5 metres. The land area of the British Isles represents about one third of the ice sheet area, emphasising that the ice sheet was strongly marine-based.

- There is not enough pattern and timing information to adequately constrain retreat of North Sea ice and its interaction with British ice and we therefore present two scenarios; an early complete collapse and a later two stage disintegration. Further investigations are required and the possibility of catastrophic collapse of this marine sector is highlighted.

- From its maximum extent the ice sheet is reconstructed to have started withdrawing along its northern boundaries at the same time as the southern margins were still expanding, including the dramatic surge or transient ice streaming of the Irish Sea Ice Stream and advances of lobes in the Cheshire Basin, Vale of York and east coast of England. Ice divides migrated south, and British and Irish ice was very much part of an integrated ice sheet at this time (27 to 23 ka BP). By 19 ka the ice sheet was in crisis with widespread marine-based ice losses, particularly in the northern North Sea and the Irish Sea. It is during this phase that considerable thinning of the ice sheet is inferred from retreat-rate data and the geomorphology of inland retreat patterns. By 18 ka the 'shelf-parallel configuration' is again emphasised with the southern margin having left behind separate Kerry and Welsh ice caps, and by now ice was mostly restricted to the land masses of Ireland-Scotland with a remaining marine-based portion over the Orkney-Shetland isles. In one of our scenarios, the southern North Sea remained glaciated. Final collapse of all marine sectors occurred by 17 ka BP and with most margins having back-stepped onshore. Some minor and presumably transient ice streaming occurred draining to coasts and in one of our scenarios a major surge lobe was experienced on the east coast of England. The North Channel and Irish Sea ice streams had by now effectively cleaved the ice sheet into almost separate Irish and Scottish ice sheets, which is reconstructed to have finally taken place by 16 ka BP.

- The rate of ice loss (volume) was slow (65 km^3 per year) when the ice sheet was retreating back from the shelf edge and then more rapid (at 260 km^3 per year) once the margins approached modern shorelines, in seeming contradiction of the

hypothesis of unstable marine-based ice sheets. We caution, however, in drawing too strong a conclusion from this given the very poor timing constraints for the marine sectors. It is interesting to note that the two main pulses of ice loss (27 to 25 ka and 17 to 16 ka) broadly correspond to Heinrich Events 2 and 1, but again much better timing constraints are required.

- The above retreat rate paradox might be explained if vigorous purging of ice occurred when calving margins existed, substantially lowering interior ice elevations which preconditioned (by thinning) the ice sheet for later rapid retreat.

- Ice streams were found to have retreat rates that fall within the ranges reported for Antarctica. It is generally the case that the ice streams retreated more rapidly (17.5 ma^{-1}) than for inter-stream areas (9 ma^{-1}), and with some very high retreat rates for the Irish Sea (147 ma^{-1}) and Moray Firth (149 ma^{-1}) Ice Streams. We speculate that these two modes of ice stream retreat rates reflect the difference between transitory and regulatory ice stream functioning. Transitory (or surging) ice streams over extend themselves, are short-lived and thin and thus retreat rapidly. Regulatory ice streams operate for much longer and remain in balance with regard to discharge and feeding of ice through the onset areas.

- Preliminary comparison of our reconstruction with two recent numerical ice sheet models reveal some broad similarities in terms of extent and positions of ice divides but large differences in the timing of maximum extent and retreat phases. We suggest that the imposed climates chosen for the British Isles and how they are modulated from the Greenland ice core record must be inappropriate in some way. Further data-model investigations are warranted with regard to why some of the detailed patterns of retreat are at variance. We presume that much could be learnt with regard to the validity of calving laws and the balance between ice thinning and areal retreat and the effect of topography on ice sheet dynamics.

Now that we know the pattern of retreat, in theory, a smaller number of dates are required to constrain ice sheet demise because the pattern naturally interpolates between point data, and it can be used to impose an effort-effective sampling strategy. Note that the ad hoc collection of dating sites (Fig. 14) has thus far tended to oversample some locations because of the availability of stratigraphic sections, for example at coasts, whereas huge areas remain blank. The map of isochrones (Figure 17) could be used to target specific sites for dating investigations to reduce uncertainty or could be treated as hypotheses for testing and challenging. However, many hundreds of new dates are required, especially in the marine sectors, the southern North Sea, and inland away from coasts. It is likely that as the understanding and technology of dating progresses, many of the dates we have relied on could in the future be retired, with concomitant changes in our analysis of timing. We also note that increasingly large numbers of samples are being dated at individual sites in order to derive a single age and yet much of BIIS history hinges on single dates in many locations.

We regard the reconstructed pattern as the major accomplishment of this work and a robust constraint on ice sheet retreat and note that the dating control is only partial and subject to change. We hope that presenting this framework of retreat motivates renewed vigour in collecting geochronometric information such that the BIIS might become one

the best-constrained palaeo-ice sheets and thus a critical test of ice sheet modelling experiments to better inform future ice sheet demise and sea level rise, and as a platform for understanding ice – climate - ocean interactions.

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References

Ahlberg, K., Almgren, E., Wright, H.E., Ito, E., Hobbie, S. 1996. Oxygen-isotope record of Late-Glacial climatic change in western Ireland. Boreas, 25, 4, 257-270.

Andersen, B.G., 1981. Late Weichselian Ice Sheets in Eurasia and Greenland. In Denton, G. H. and Hughes, T.J. (eds.) The Last Great Ice Sheets. John Wiley and Sons.

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

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

Ballantyne, C.K., McCarroll, D. and Stone, J.O. 2006. Vertical dimensions and age of the Wicklow Mountains ice dome, Eastern Ireland, and implications for the extent of the last Irish ice sheet. Quaternary Science Reviews, 25, 2048-2058.

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

Ballantyne, C.K., Stone, J.O. and McCarroll, D. 2008. Dimensions and chronology of the last ice sheet in Western Ireland. Quaternary Science Reviews, 27, 185-200.

Ballantyne , C.K., Stone, J.O., Fifield, L.K. 2009a. Glaciation and deglaciation of the SW Lake District, England: implications of cosmogenic 36Cl exposure dating. Proceedings of the Geologists' Association, 120, 139-144.

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

Bamber, J.L., Riva, R.E.M., Vermeersen, B.L.A., LeBrocq, A.M. 2009. Reassessment of the Potential Sea-Level Rise from a Collapse of the West Antarctic Ice Sheet. Science **324** (5929), 901. [DOI: 10.1126/science.1169335]

Bateman, M.D., Buckland, P.C., Chase, B., Frederick, C.D., Gaunt, G.D. 2008. The Late Devensian proglacial Lake Humber: new evidence from littoral deposits east of Ferrybridge, Yorkshire, England. Boreas, 37, 195-210.

Bishop, W.W., Dickson, J.H. 1970. Radiocarbon dates related to the Scottish late-glacial sea in the Firth of Clyde, Nature, 227, 480-482.

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. Pergamon Press, Oxford.

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

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 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. (3rd ed.), London, The Geological Society.

Bowen, D.Q. 1974. The Quaternary of Wales. In Owen, T.R. (ed.), The upper palaeozoic and post palaeozoic rocks of Wales.University of Wales Press, Cardiff, 373– 426.

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, P.C., Sykes, G.A. 2002. New data for the Last Glacial Maximum in Great Britain and Ireland. Quaternary Science Reviews, 21, 89-101.

Bradwell, T., Stoker, M. , 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., 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. 2008a. The northern sector of the last British Ice Sheet: Maximum extent and demise. Earth-Science Reviews, 88, 207-226.

Bradwell, T., Fabel, D., Stoker, M., Mathers, H., McHargue, L. , Howe, J. 2008b. Ice caps existed throughout the Late glacial interstadial in northern Scotland. Journal of Quaternary Science, 23, 401-407.

Brooks , A. J., Bradley, S.L., Edwards, R.J., Milne, G.A., Horton, B., Shennan, I. 2008. Postglacial relative sea-level observations from Ireland and their role in glacial rebound modelling. Journal of Quaternary Science, 23, 175-192.

Brown, I.M. 1993. Pattern of deglaciation of the last (Late Devensian) Scottish Ice-Sheet – evidence from ice-marginal deposits in the Dee Valley, Northeast Scotland. Journal of Quaternary Science, 8, 235-250.

Browne, M.A.E., Graham, D.K. 1981. Glaciomarine deposits of the Loch Lomond stadial glacier in the Vale of Leven between Dumbarton and Balloch, west-central Scotland. Quaternary Newsletter, 34, 1-7.

Browne, M.A.E., McMillan, A.A., Hall, I.H.S. 1983. Blocks of marine clay in till near Helensburgh, Strathclyde. Scottish Journal of Geology, 19, 321-325.

Carr, S. 2004. The North Sea basin. In Ehlers, J. , Gibbard, P.L. (eds.) Quaternary Glaciations - extent and chronology. Elsevier.

Carr, S., 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.

Charlesworth, J.K. 1924. Stages in the dissolution of the last ice sheet in Ireland and the Irish Sea. Proceedings of the Royal Irish Academy. Section B: Biological, Geological, and Chemical Science, 73, 79-86.

Charlesworth, J.K. 1926. The readvance, marginal kame-moraine of the south of Scotland, and some later stages of retreat. Transactions of the Royal Society of Edinburgh, 55, 25-50.

Charlesworth, J.K. 1928. The Glacial Retreat from Central and Southern Ireland. Quarterly Journal of the Geological Society, 84, 293-344.

Charlesworth, J.K. 1957. The Quaternary Era, London, Arnold.

Clark, C.D. 1999. Glaciodynamic context of subglacial bedform generation and preservation. Annals of Glaciology, 28, 23-32.

Clark, C.D., Evans, D.J., Khatwa, A., Bradwell, T., Jordan, C.J., Marsh, S.H., Mitchell, W.A. , Bateman, M.D. 2004a. Map and GIS database of glacial landforms and features related to the last British Ice Sheet. Boreas, 33, 359-375.

Clark, C.D., Gibbard, P.L. , Rose, J. 2004b. Pleistocene glacial limits in England, Scotland and Wales. In Ehlers, J. , Gibbard, P.L. (eds.) Quaternary Glaciations: Extent and Chronology. Elsevier.

Clark, C.D., Sejrup, H-P., Bigg, G.R., Stoker, M., Lonergan, L., Raunholm, S., Haflidason, H. 2004c. Did the punctuated demise of glacial ice in the North Sea affect thermohaline circulation of the ocean? EOS, Transactions, American Geophysical Union, 85, number 31, 293.

Clark, J., McCabe, A.M., Schnabel, C., Clark, P.U., Freeman, S., Maden, C., Xu, S. 2009a. [10]Be chronology of the last deglaciation of County Donegal, northwestern Ireland. Boreas, 38, 111-118.

Clark, J., McCabe, A.M., Schnabel, C., Clark, P.U., McCarron, S., Freeman, S., Maden, C., Xu, S. 2009b. Cosmogenic [10]Be chronology of the last deglaciation of western Ireland, and implications for sensitivity of the Irish Ice Sheet to climate change. Geological Society of America, Bulletin, 121, 1-2, 3-16.

Clark, P.U., McCabe, A.M., Mix, A.C., Weaver, A.J. 2004. Paleoclimate: Rapid Rise of Sea Level 19,000 Years Ago and Its Global Implications. Science, 304, 1141-1143.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., McCabe, A.M., 2009. The last glacial maximum. Science, 325, 710- 713.

Clarke, G.K.C., Leverington, D.W., Teller, J.T., Dyke, A.S., 2004. Paleohydraulics of the last outburst flood from glacial Lake Agassiz and the 8200 BP cold event. Quaternary Science Reviews, 23, 3-4, 389-407.

Colhoun, E.A. 1970. On the nature of the glaciation and final deglaciation of the Sperrin Mountains and adjacent areas in the North of Ireland. Irish Geography, 6, 2, 162-185.

Coope, G.R. , Pennington, W. 1977. The Windermere Interstadial of the late Devensian, Philosophical Transactions of the Royal Society of London. B 280, 337–339.

Conway, H., Hall, B.L., Denton, G.H., Gades, A.M., Waddington, E.D. 1999. Past and future grounding-line retreat of the West Antarctic Ice Sheet. Science, 286, 280-283.

Davies, B.J., Bridgland, D.R., Roberts, D.H., Ó Cofaigh, C., Pawley, S.M., Candy, I., Demarchi, B., Penkman, K.E.H. and Austin, W.E.N.. 2009. The age and stratigraphic context of the Easington Raised Beach, County Durham, UK. Proceedings of the Geologists Association, 120, 183-198.

Delaney, C. 2002. Sedimentology of a glaciofluvial landsystem, Lough Ree area, Central Ireland: implications for ice margin characteristics during Devensian deglaciation. Sedimentary Geology, 149, 1-3, 111-126.

Diefendorf, A.F., Patterson, W.P., Mullins, H.T., Tibert, N., Martini, A. 2006. Evidence for high frequency late Glacial to mid-Holocene (16,800 to 5500 cal yr B.P.) climate variability from oxygen isotope values of Lough Inchiquin, Ireland. Quaternary Research 65, 1, 78-86.

Dowdeswell, J.A., Ottesen, D., Evans, J., Ó Cofaigh, C., Anderson, J.B., 2009. Submarine glacial landforms and rates of ice-stream collapse. Geology, 36, 819-822.

Embleton, C. 1961. The geomorphology of the Vale of Conway, North Wales, with particular reference to its deglaciation. Transactions of the Institute of British Geographers, 29, 47-70.

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., Clark, C.D., Rea, B.R. 2008. Landform and sediment imprints of fast glacier flow in the southwest Laurentide Ice Sheet. Journal of Quaternary Science, 23(3), 249- 272.

Evans, D.J.A., and Thomson, S.A. in press. Glacial sediments and landforms of Holderness, eastern England: A glacial depositional model for the North Sea Lobe of the British-Irish Ice Sheet. Earth Science Reviews.

Everest, J., Golledge, N.R.G. 2004. Dating deglaciation in Strathspecy and the Carirngorm Mountains. In Lukas, S., Merritt, J. W., Mitchell, W.A. (eds.) the Quaternary of the central Grampian Highlands: Field Guide. Cambridge, Quaternary Research Association.

Everest, J., Bradwell, T., Golledge, N. 2005. Subglacial Landforms of the Tweed Palaeo-Ice Stream. Scottish Geographical Journal, 121, 163-174.

Everest, J.D., Kubik, P. 2006. The deglaciation of eastern Scotland: cosmogenic [10]Be evidence for a Lateglacial stillstand. Journal of Quaternary Science, 21, 95-104.

Everest, J., Bradwell, T., Fogwill, C.J. , Kubik, P.W. 2006. Cosmogenic [10]Be age constraints for the Wester Ross readvance moraine: insights into British Ice-Sheet behaviour. Geografiska Annaler Series A, 88, 9-17.

Fairbanks, R.G., Mortlock, R.A., Chiu, T.C., Cao, L., Kaplan, A., Guilderson, T.P., Fairbanks, T.W., Bloom, A.L., Grootes, P.M. , Nadeau, M.J. 2005. Radiocarbon calibration curve spanning 0 to 50,000 years BP based on paired 230Th/234U/238U and 14C dates on pristine corals. Quaternary Science Reviews, 24, 1781-1796.

Flinn, D. 2009. The omission of conflicting evidence from the paper by Golledge et al. 2008.. Geografiska Annaler, 91, A (4), 253 – 256.

Foster, H.D. 1968. The Glaciation of the Harlech Dome. Unpublished Ph.D. thesis, University of London.

Foster, H.D., 1970. Establishing the age and geomorphological significance of sorted stone stripes in the Rhinog Mountains, North Wales. Geografiska Annaler, 52A, 96– 102.

Gaunt, G.D. 1974. A radiocarbon date relating to Lake Humber, Proceedings of the Yorkshire Geological Society 40, 195–197.

Gaunt, G.D. 1976. The Devensian maximum ice limit in the Vale of York. Proceedings of the Yorkshire Geological Society, 40, 631-637.

Geikie, J. 1894. The Great Ice Age and its relation to the antiquity of man, London, Edward Stanford.

Golledge, N.R. , Stoker, M. 2006. A palaeo-ice stream of the British Ice Sheet in eastern Scotland. Boreas, 35, 231-243.

Golledge, N.R., Fabel, D., Everest, J.D., Freeman, S. , Binnie, S. 2007. First cosmogenic [10]Be age constraint on the timing of Younger Dryas glaciation and ice cap thickness, western Scottish Highlands. Journal of Quaternary Science, 22, 785-791.

Golledge, N.R., Finlayson, A., Bradwell, T., Everest, J.D. 2008a. The Last Glaciation of Shetland, North Atlantic. Geografiska Annaler Series A, 90, 37-53.

Golledge, N.R. Hubbard, A., Sugden, D.E. 2008b. High-resolution numerical simulation of Younger Dryas glaciation in Scotland. Quaternary Science Reviews, 27, 888-904.

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 seismic reflection data. Quaternary Science Reviews, 26, 627-643.

Greenwood, S.L., Clark, C.D. 2008. Subglacial bedforms of the Irish Ice Sheet. Journal of Maps, 2008, 332-357.

Greenwood, S.L., Clark, C.D., 2009a. Reconstructing 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.

Greenwood, S.L., Clark, C.D., 2009b. Reconstructing the last Irish Ice Sheet 2: a geomorphologically-driven model of ice sheet growth, retreat and dynamics. Quaternary Science Reviews, 28, 3101 – 3123.

Greenwood, S.L., Clark, C.D. , Hughes, A.L.C. 2007. Formalising an inversion methodology for reconstructing ice-sheet retreat patterns from meltwater channels: application to the British Ice Sheet. Journal of Quaternary Science, 22, 637-645.

Haflidason, H., King, E.L., Kristensen, D.K., Helland, E., Duffy, M., Scourse, J.D., Austin, W.E.N., Sejrup, H.P. 1997. Marine geological/geophysical cruise report on the western Irish margin: Donegal Bay, Clew Bay, Galway Bay, Irish shelf and Rockall Trough. University of Bergen, Bergen.

Hall, I.R., McCave, I.N. 1998. Late Glacial to Recent accumulation fluxes of sediments at the shelf edge and slope of NW Europe, 48-50°N. In Stoker, M.S., Evans, D., Cramp, A. (ed.) Geological Processes of Continental Margins: Sedimentation, Mass-Wasting and Stability. Geological Society, London. pp339-350.

Higham, T.F.G., Jacobi, R.M., Ramsey, C.B. 2006. AMS radiocarbon dating of ancient bone using ultrafiltration. Radiocarbon, 48, 179-195.

Holloway, L.K., Peacock, J.D., Smith, D.E., Wood, A.M. 2002. A Windermere Interstadial marine sequence: environmental and relative sea level interpretations for the western Forth Valley, Scotland. Scottish Journal of Geology, 38, 41-54.

Houmark-Nielsen, M. 2004. The Pleistocene of Denmark: a review of stratigraphy and glaciation history. In Ehlers, J. , Gibbard, P. (eds.) Quaternary Glaciations - Extent and Chronology, Part 1: Europe. Amsterdam, Elsevier.

Hubbard, A., Bradwell, T., Golledge, N.R., 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.LC., Clark, C.D., Jordan, C.J. In press. Subglacial bedform map of Britain. Journal of Maps.

Hughes, A.L.C., Greenwood, S.L. and Clark, C.D. (submitted). Dating constraints on the last British-Irish Ice Sheet: a map and database. Journal of Maps.

Kleman, J., Hättestrand, C., Stroeven, A.P., Jansson, K.N., De Angelis, H. , Borgström, I. 2006. Reconstruction of paleo-ice sheets-inversion of their glacial geomorphological record. In Knight, P.G. (ed.) Glacier science and environmental change. Oxford, Blackwell Science Ltd.

Knight, J. 2003a. Geomorphic and sedimentary evidence for patterns of late Midlandian ice retreat in the Tempo Valley, north-central Ireland. Irish Geography, 36, 2, 127-144.

Knight, J. 2003b. Geomorphic evidence for patterns of late Midlandian ice advance and retreat in the Omagh Basin. Irish Geography 36, 1, 1-22.

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 paleocirculation since 45 kyr BP, Barra Fan, U.K. margin. Paleoceanography, 16, 53-64.

Knutz, P.C., Hall, I.R., Zahn, R., Rasmussen, T.L., Kuijpers, A., Moros, M., Shackleton, N.J. 2002. Multidecadal ocean variability and NW European ice sheet surges during the last deglaciation. Geochemistry, Geophysics, Geosystems, 3, 1077.

Knutz, P.C., Zahn, R, Hall, I.R. 2007. Centennial-scale variability of the British Ice Sheet: Implications for climate forcing and Atlantic meridional overturning circulation during the last deglaciation. Paleoceanography, 22, PA1207.

Kroon, D., Shimmield, G., Austin, W.E., Derrick, S., Knutz, P. , Shimmield, T. 2000. Century-to millennial-scale sedimentological-geochemical records of the glacial-Holocene sediment variations from the Barra Fan (NE Atlantic) Journal- Geological Society London, 157, 643-654.

Lafferty, B., Quinn, R., Breen, C. 2006. Subglacial imprints associated with the isolation and decay of an ice mass in the Lower Lough Erne basin, Co. Fermanagh, NW Ireland. Journal of the Geological Society, London, 163, 421-430.

Lawson, T.J. 1984. Reindeer in the Scottish Quaternary. Quaternary Newsletter, 42, 1–7.

Lee, J.R., Rose, J., Riding, J.B., Moorlock, B.S.M., Hamblin, R.J.O. 2002. Testing the case for a Middle Pleistocene Scandinavian glaciation in Eastern England: evidence for a Scottish ice source for tills within the Corton Formation of East Anglia, UK. Boreas, 31, 345-355.

Lekens , W.A.H., Haflidason, H., Sejrup, H.P., Nygard, A., Richter, T., Vogt, C., Frederichs, T. 2009. Sedimentation history of the northern North Sea margin during the last 150 ka. Quaternary Science Reviews, 28, 469-483.

Lewis, C.A. 1974. The glaciations of the Dingle Peninsula, County Kerry. Scientific Proceedings of the Royal Dublin Society, A5, 207, 235.

Lowe, J.J. 1978. Radiocarbon dated late glacial and early Flandrian pollen profiles from the Teith Valley, Perthshire, Scotland. Pollen et Spores, 20, 367-397.

Lowe, J.J., Birks, H.H., Brooks, S.J., Coope, G.R., Harkness, D.D., Mayle, F.E., Sheldrick, C., Turney, C.S.M., Walker, M.J.C. 1999. The chronology of palaeoenvironmental changes during the Last Glacial-Holocene transition: towards and event stratigraphy for the British Isles. Journal of the Geological Society, London, 156, 397-410.

Lowe, J.J., Walker, M.J.C., Scott, E.M., Harkness, D.D., Bryant, C.L., Davies, S.M. 2004. A coherent high-precision radiocarbon chronology for the Late-glacial sequence at Sluggan Bog, Co. Antrim, Northern Ireland. Journal of Quaternary Science, 19, 2, 147-158.

McCabe, A.M. 1985. Glacial geomorphology. In Edwards, K.J., Warren, W.P. (ed.) The Quaternary History of Ireland. Academic Press Inc, London. pp67-93.

McCabe, A.M. 1987. Quaternary Deposits and Glacial Stratigraphy in Ireland. Quaternary Science Reviews, 6, 259-299.

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., Clark, P.U. 2003. Deglacial chronology from County Donegal, Ireland: implications for deglaciation of the British-Irish Ice Sheet. Journal of the Geological Society, London, 160, 6, 847-856.

McCabe, A.M., Haynes, J.R. 1996. A late Pleistocene intertidal boulder pavement from an isostatically emergent coast, Dundalk Bay, eastern Ireland. Earth Surface Processes and Landforms, 21, 555-572.

McCabe, A.M., Knight, J., McCarron, S.G. 1998. Evidence for Heinrich event 1 in the British Isles. Journal of Quaternary Science, 13, 6, 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. Quaternary Science Reviews, 24, 1673-1690.

McCabe, A.M., Clark, P.U., Clark, J. 2007a. Radiocarbon constraints on the history of the western Irish ice sheet prior to the Last Glacial Maximum. Geology, 35, 147-150.

McCabe, A.M., Clark, P.U., Clark, J., Dunlop, P. 2007b. Radiocarbon constraints on readvances of the British-Irish Ice Sheet in the northern Irish Sea Basin during the last deglaciation. Quaternary Science Reviews, 26, 1204-1211.

McCabe, A.M., Knight, J.K., McCarron, S. 2007c. A revised model of the last deglaciation of eastern Scotland. Journal of the Geological Society London, 164, 313-316.

Meehan, R.T. 1999. Directions of ice flow during the last glaciation in counties Meath, Westmeath and Cavan. Irish Geography 32, 1, 26-51.

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. (eds.) 2003. Cainozoic geology and landscape evolution of north-east Scotland. British Geological Survey.

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.

Murton, D.K., Pawley, S.W., Murton, J.B. 2009. Sedimentology and luminescence ages of Glacial Lake Humber deposits in the central Vale of York. Proceedings of the Geologists Association. 120, 209-222.

Napieralski, J., Hubbard, A., Li, Y., Harbor, J., Stroeven, A.P., Kleman, J., Alm, G., Jansson, K.N. 2007. Towards a GIS assessment of numerical ice-sheet model performance using geomorphological data. Journal of Glaciology, 53, 71-83.

Nygård, A., Sejrup, H.P., Haflidason, H., Cecchi, M., Ottesen, D. 2004. Deglaciation history of the southwestern Fennoscandian Ice Sheet between 15 and 13 14C ka BP. Boreas, 33, 1-17.

Ó Cofaigh, C., Evans, D.J.A. 2001. Sedimentary evidence for deforming bed conditions associated with a grounded Irish Sea glacier, southern Ireland. Journal of Quaternary Science, 16, 5, 435-454.

Ó Cofaigh, C., Evans, D.J.A. 2007. Radiocarbon constraints on the age of the maximum advance of the British-Irish Ice Sheet in the Celtic Sea. Quaternary Science Reviews, 26, 1197-1203.

Ó Cofaigh, C., Evans, D.J.A., Hiemstra, J. 2008. Till sedimentology and stratigraphy on the Dingle Peninsula, SW Ireland: implications for Late Quaternary regional ice flow patterns. Proceedings of the Geologists' Association, 119, 137-152.

Ó Cofaigh, C., Telfer, M.W., Bailey, R.M., Evans, D.J.A. In press. Late Pleistocene chronostratigraphy and ice sheet limits, southern Ireland. Quaternary Science Reviews.

PALSEA (PALeo SEA level working group., 2010. The sea-level conundrum: case studies from palaeo-archives. Journal of Quaternary Science, 25, 19-25.

Paterson, W.S.B. 1972. The Physics of Glaciers, Pergammon Press, Oxford.

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. 2002. Macrofauna and palaeoenvironment of marine strata of Windermere Interstadial age on the east coast of Scotland. Scottish Journal of Geology, 38, 31-40.

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 in the Scottish continental shelf west of the Outer Hebrides. Journal of Quaternary Science, 7, 145–61.

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 By McCabe, A.M., Clark, P.U., Smith, D.E. , Dunlop, P. Journal of the Geological Society, 164, 2007, 313 316. Journal of the Geological Society, 164, 1261-1263.

Peck, V.L. Hall, I.R., Zahn, R., Elderfield, H., Grousset, F., Hemming, S.R., Scourse, J.D. 2006. High resolution evidence for linkages between NW European ice sheet instability and Atlantic meridional overturning circulation. Earth and Planetary Science Letters, 243, 475-488.

Peck, V.L., Hall, I.R., Zahn, R., Grousset, S.R., Hemming, S.R., Scourse, J.D. 2007. The relationship of Heinrich events and their European precursors over the past 60 ka BP: a multi-proxy ice-rafted debris provenance study in the North East Atlantic. Quaternary Science Reviews, 26, 862-875.

Peltier, W.G., Fairbanks, R.G., 2006. Global ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. Quaternary Science Reviews. 25, 3322-3337.

Pennington W., 1977. The Late Devensian flora and vegetation of Britain. Philosophical Transactions of the Royal Society of London, Series B, 280: 247–271.

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

Phillips, F.M., Bowen, D.Q. , Elmore, D. 1994. Surface exposure dating of glacial features in Great Britain using cosmogenic chlorine-36: preliminary results. Mineralogical Magazine 58A, 722–723.

Phillips, W.M., Hall, A.M., Ballantyne, C.K., Binnie, S., Kubik, P.W. , Freeman, S. 2008. Extent of the last ice sheet in northern Scotland tested with cosmogenic [10]Be exposure ages. Journal of Quaternary Science, 23, 101-107.

Rose, J, 1980. Rhu. In Jardine, W.G. (ed.) Glasgow Region Field Guide, Quaternary Research Association.

Rowlands, B.M., 1971. Radiocarbon evidence of the age of an Irish Sea glaciation in the Vale of Clwyd. Nature-Physical Science, 230, 9– 11.

Scourse, J.D. (ed.) 2006. The Isles of Scilly. Field Guide. Quaternary Research Association.

Scourse, J.D., Hall, I.R., McCave, I.N., Young, J.R., Sugdon, C. 2000. The origin of Heinrich layers: evidence from H2 for European precursor events. Earth and Planetary Science Letters, 182, 2, 187-195.

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 detritis 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 northern North Sea. Boreas, 23, 1-13.

Sejrup, H.P., Larsen, E., Haflidason, H., Berstad, I.M., Hjelstuen, B.O., Jonsdottir, H.E., King, E.L., Landvik, J., Longva, O., Nygard, A., Ottesen, D., Raunholm, S., Rise, L. Stalsberg, K. 2003. Configuration, history and impact of the Norwegian Channel Ice Stream. Boreas, 32, 18-36.

Sejrup, H.P., Hjelstuen, B.O., Dahlgren, K.I.T., Haflidason, H., Kuijpers, A., Nygard, A., Praeg, D., Stoker, M.S. , Vorren, T.O. 2005. Pleistocene glacial history of the NW European continental margin. Marine and Petroleum Geology, 22, 111-1129.

Sejrup, H.P., Nygard, 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.

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, 633-646.

Sissons, J.B. 1979. The Loch Lomond Stadial in the British Isles. Nature, 280, 199-203.

Smith, A.G., Goddard, I.C. 1991. A 12 500 year record of vegetational history at Sluggan Bog, Co. Antrim, N. Ireland (incorporating a pollen zone scheme for the non-specialist). New Phytologist, 118, 167-187.

Stokes, C.R. , Clark, C.D 2003.. The Dubawnt Lake Palaeo-Ice Stream: evidence for dynamic ice sheet behaviour on the Canadian Shield and insights regarding the controls on ice-stream location and vigour. Boreas, 32, 1, 263 – 279.

Stoker, M.S., Bradwell, T. 2005. the Minch palaeo-ice stream, NW sector of the British-Irish Ice Sheet. Journal of the Geological Society, 162, 425-428.

Stone, J.O. , Ballantyne, C.K. 2005. Dimensions and deglacial chronology of the Outer Hebrides Ice Cap, northwest Scotland: implications of cosmic ray exposure dating. Journal of Quaternary Science., 21 75-84.

Synge, F.M. 1968. The Glaciation of West Mayo. Irish Geography, 5, 372-386.

Telfer, M.W., Wilson, P., Lord, T.C. and Vincent, P.J. 2009. New constraints on the age of the last ice sheet glaciation in NW England using optically stimulated luminescence dating. Journal of Quaternary Science, 24, 906-915.

Thompson, W.G. , Goldstein, S.L. 2006. A radiometric calibration of the SPECMAP timescale. Quaternary Science Reviews, 25, 3207-3215.

Toucanne,S., Zaragosi,S., Bourillet, J.F., Marieu,V., Cremer,M., Kageyama,M., Vliet-Lanoe,B.V., Eynaud,F., Turon,J.L., Gibbard,P.L. 2010. The first estimation of Fleuve Manche palaeoriver discharge during the last deglaciation: Evidence for Fennoscandian ice sheet meltwater flow in the English Channel ca 20-18 ka ago, Earth and Planetary Science Letters, Volume 290, Issues 3-4, 20 February 2010, Pages 459-473.

Valentin, H., 1957. Glazialmorphologische Untersuchungen in Ostengland. Abhandlungen des Geographischen Institut der Freien Universitat Berlin 4. pp.1–86.

Vaughan, D.G., Corr, H.F., Smith, A.M., Pritchard, H.D., Shepherd, A. 2008. Flow-switching and water piracy between Rutford Ice Stream and Carlson Inlet, West Antarctica. Journal of Glaciology, 54, 184, 41-48.

Vasari, Y.N. 1977. Radiocarbon dating the Late Glacial and earlty Flandrian vegetational sucession in the Scottish Highlands and the Isle of Skye. In Gray, J.M. Lowe, J.J. (eds.) Studies in the Scottish Lateglacial Environment, Pergamon Press, London.

Ventris, P.A. 1985. Pleistocene environmental history of the Nar Valley, Norfolk. Unpublished Ph.D. thesis, University of Cambridge.

Vincent, P.J., Wilson, P., Lord, T.C., Schnabel, C. and Wilcken, K.M. In press. Cosmogenic isotope (^{36}Cl) surface exposure dating of the Norber erratics, Yorkshire Dales: further constraints on the timing of the LGM deglaciation in Britain. Proceedings of the Geologists Association.

Warren, W.P. 1988. The Pleistocene Geology and Geomorphology of Glen Behy, Co. Kerry. Irish Geography, 21, 1-10.

Warren, W.P. 1991. Glacial deposits of southwest Ireland. In Ehlers, J., Gibbard, P.L., Rose, J. (ed.) Glacial Deposits in Great Britain and Ireland. Balkema, Rotterdam. pp345-353.

Warren, W.P. 1992. Drumlin orientation and the pattern of glaciation in Ireland. Sveriges Geologiska Undersöking Research papers, Series. Ca.81, pp.359-366.

Whittington, G., Hall, A.M., 2002. The Tolsta Interstadial, Scotland: 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.

Wingfield, R.T.R. 1990. The origin of major incisions within the Pleistocene deposits of the North Sea. Marine Geology, 91, 31-52.

Wintle A.G. , Catt, J.A. 1985. Thermoluminescence dating of Dimlington Stadial deposits in eastern England, Boreas 14, 231–234.