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FIGURES – Clark et al, BIIS

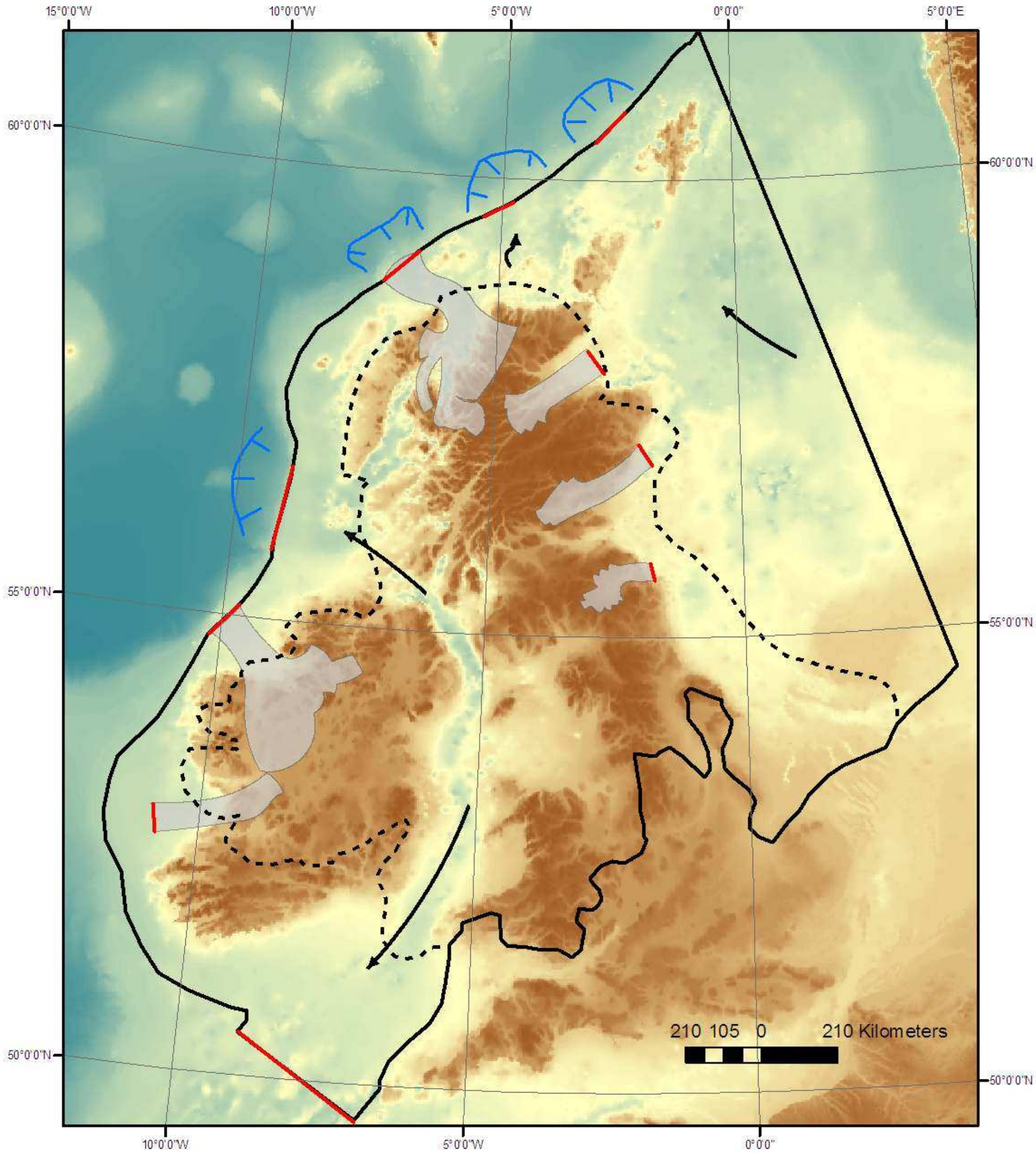


Figure 1.
Two end-member reconstructions of maximum extent of the British-Irish Ice sheet. The smaller (dashed) is the 'traditional' view that held sway for many decades and considered parts of Ireland and Scotland to be ice free at the LGM and with a very limited spread of ice beyond current coastlines, and is depicted here by the assessment of Bowen (1986). The larger extent (solid line) includes complete ice cover of Ireland and Scotland and with ice spreading to the continental shelf edge and covering the North Sea, confluent at some time with the Fennoscandian Ice Sheet. Whilst far from conclusively proven at all locations there is strong landform and ice-rafted debris evidence of ice reaching the shelf edge and some dating evidence to support this as being consistent with the last glaciation (see Sejrup *et al*., 2005; Ó Cofaigh and Evans, 2007; Bradwell *et al.,* 2008a; Ballantyne *et al*., 2009; Scourse *et al*., 2009; Ó Cofaigh *et al., in press*). We thus have a new depiction of the configuration of the BIIS that is twice as large as previously thought, and was actually a marine-based ice sheet and thus susceptible to sea level induced collapse and contained numerous ice streams to assist in its demise. The ice sheet was around 0.72 million km^2 in area and with a probable volume, using an estimation technique from Paterson (1972) of just below 800,000 km^3, around a third of the volume of the current West Antarctic Ice Sheet, for which it provides a useful analogue. Ice stream tracks, where known, are marked in grey, or by black arrows, and with red marks indicating their marine-terminating margins. Trough mouth fans are marked in blue.

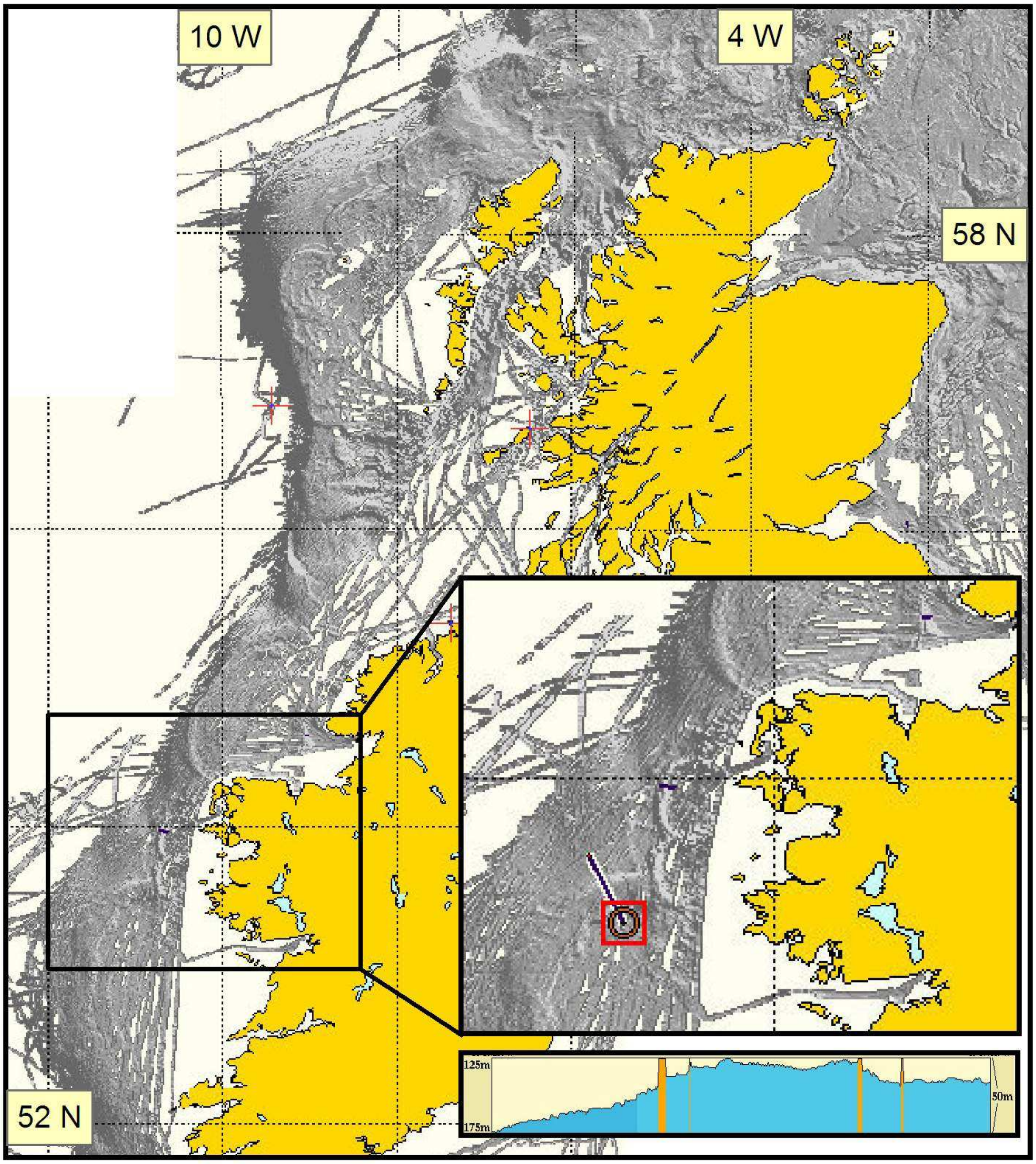


Figure 2.
Large moraines on the continental shelf surrounding Ireland and Scotland. They likely record considerable stillstand episodes of the ice margin at the LGM and at various retreat phases, (or some might record readvances). The inset shows, from north to south; a large (165 km long; 7 km wide) arcuate moraine of 10 to 20 m relief produced by ice emanating from Donegal Bay, two smaller arcuate moraines (ca. 7 km long and 30 m relief) offshore from Clew Bay and Connemara and that truncate each other and record less extensive ice margins, and the northern half of the largest moraine so far discovered for the BIIS (200 km long; up to 18 km wide and somewhat flat-topped) from ice emanating from Galway Bay. A topographic profile of this latter moraine is shown (transect position as annotated) indicating a relief of around 25 m. The image is a simulated solar-shaded rendition of the Olex bathymetric database comprising sonar measurements from fishing vessels. Moraines mapped from this data are shown in figure 4.

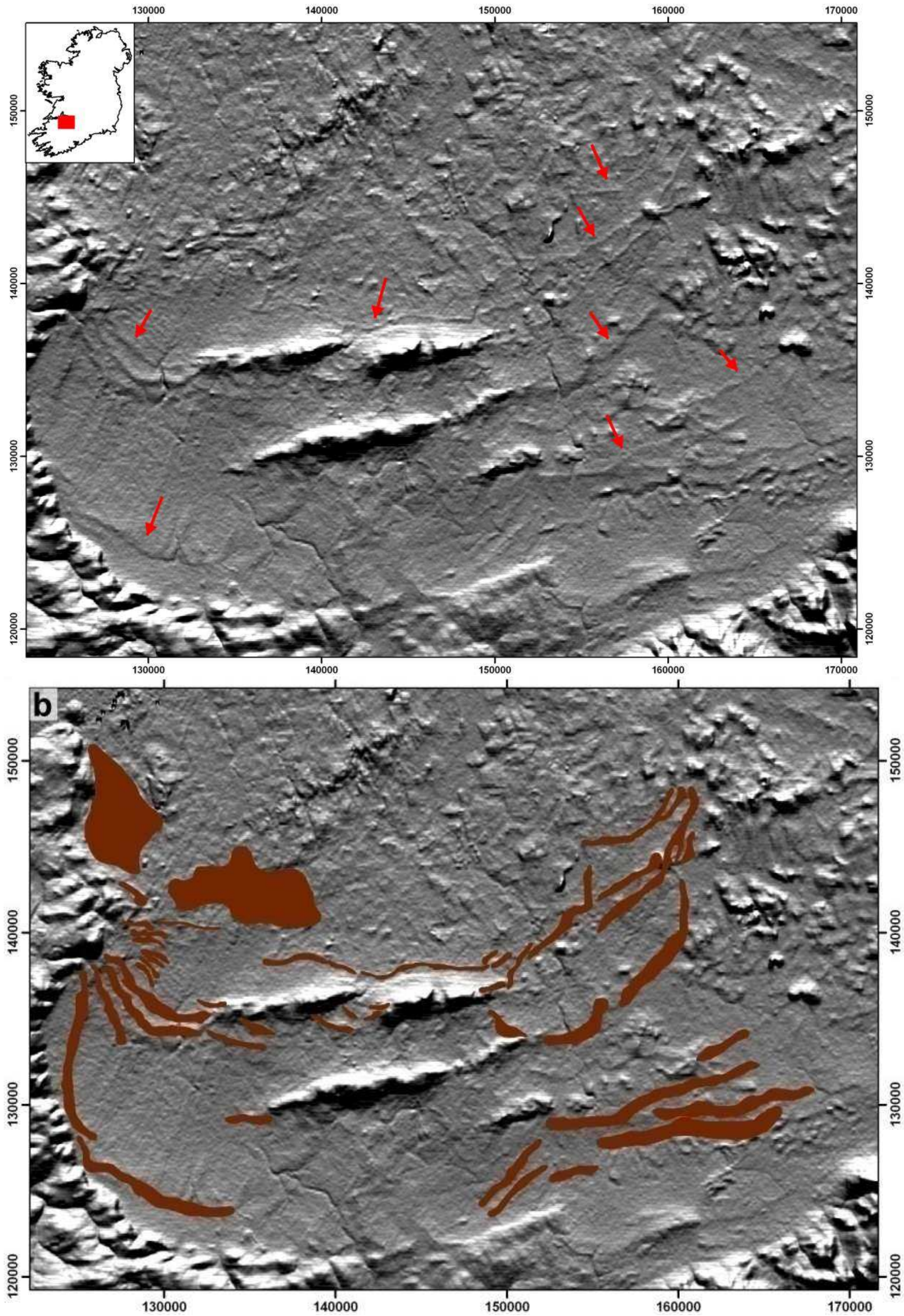


Figure 3.
Example of moraines mapped from a DEM for an onshore area in County Limerick, Ireland. A series of arcuate end moraines are annotated with red arrows in the upper panel and mapped in brown in the lower panel. The image is a solar shaded (SRTM) DEM with resolution of 90 m. Irish National Grid coordinates are indicated with labelling at 10 km intervals as a guide to the scale.

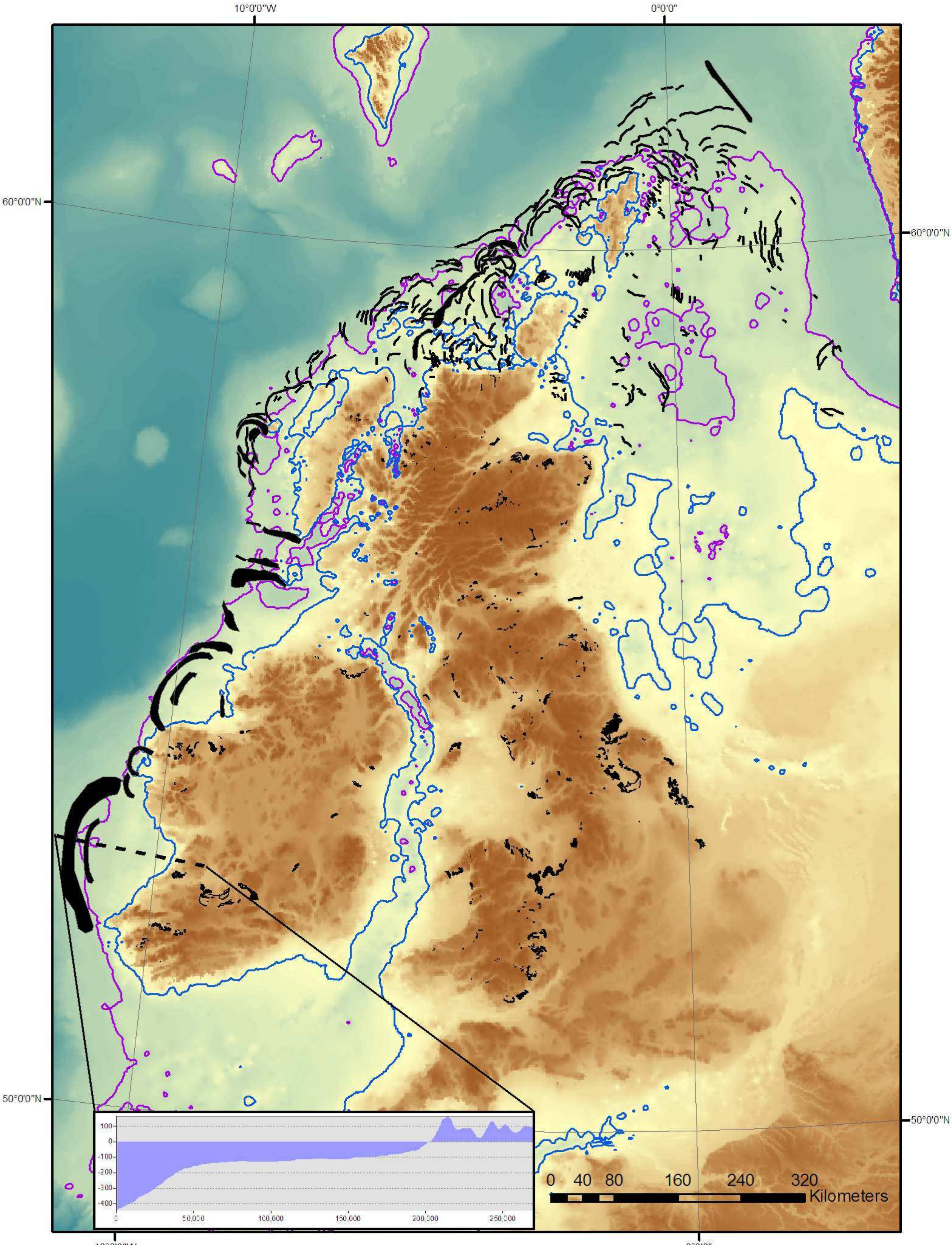


Figure 4.

GIS-compilation of all mapped moraines of the BIIS. See figures 2 and 3 for detailed zooms of selected areas and their appearance on DEMs. There are a total of 1480 moraines; 380 in Ireland; 785 in Britain; and 315 in the offshore areas. Larger moraines are mapped as areas and smaller ones as single lines along their crests. Submarine contours are at 70 m (blue) and 130 m (purple) below sea level. Inset shows elevation along a transect from the continental shelf edge through Galway Bay to the coastal Mountains.

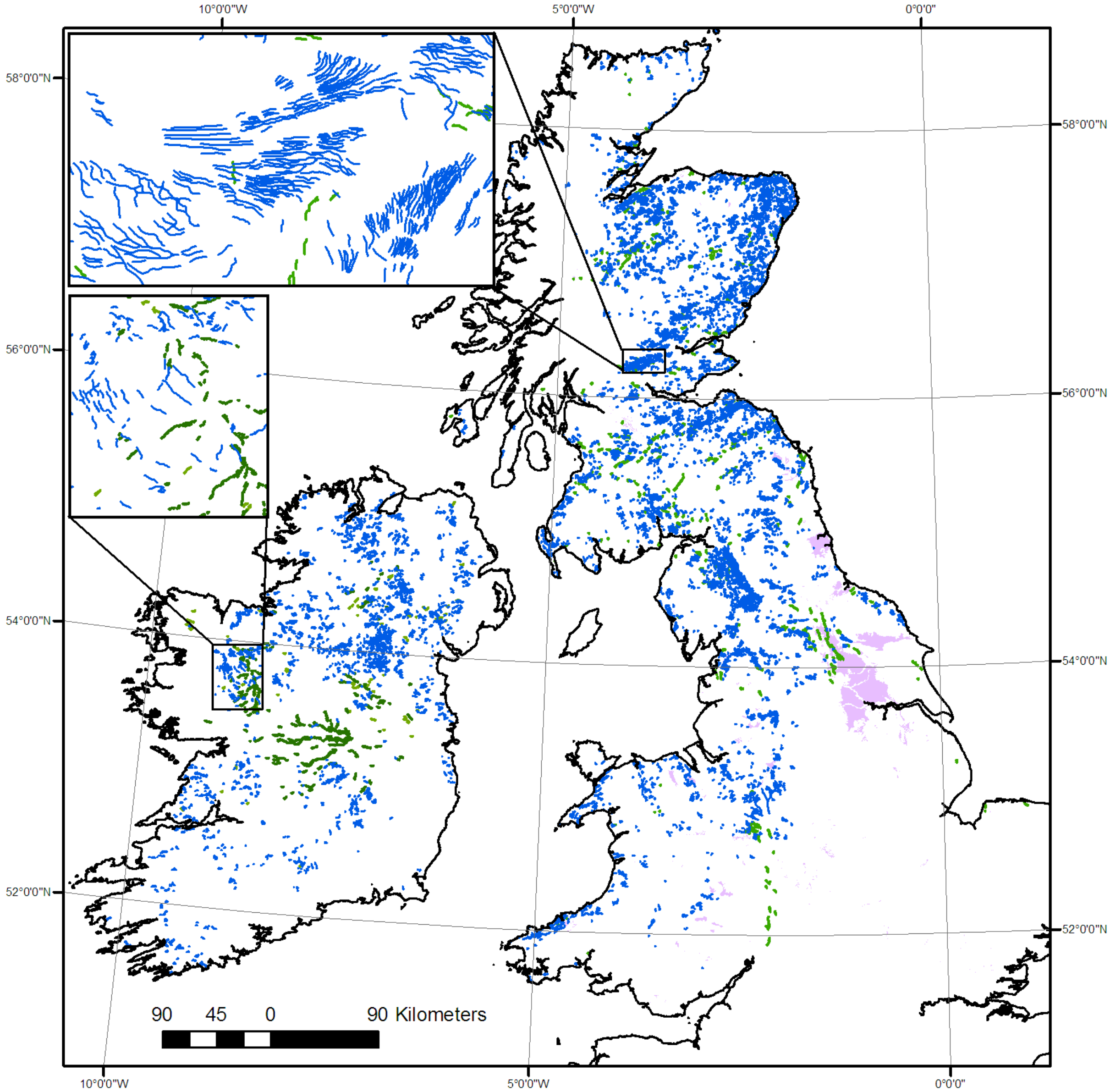


Figure 5.
Overview of the distribution and density of mapped meltwater channels (blue), eskers (green) and ice-dammed lake deposits (purple). Meltwater channels are further categorised into lateral and subglacial varieties (not shown here). The location of ice dammed lake deposits are taken from the wider literature and the BRITICE synthesis (C.D. Clark *et al* 2004a; Evans *et al,* 2005). Some information extends beyond the Dimlington Stadial ice margin. Zoomed insets show the level of detail in the maps.

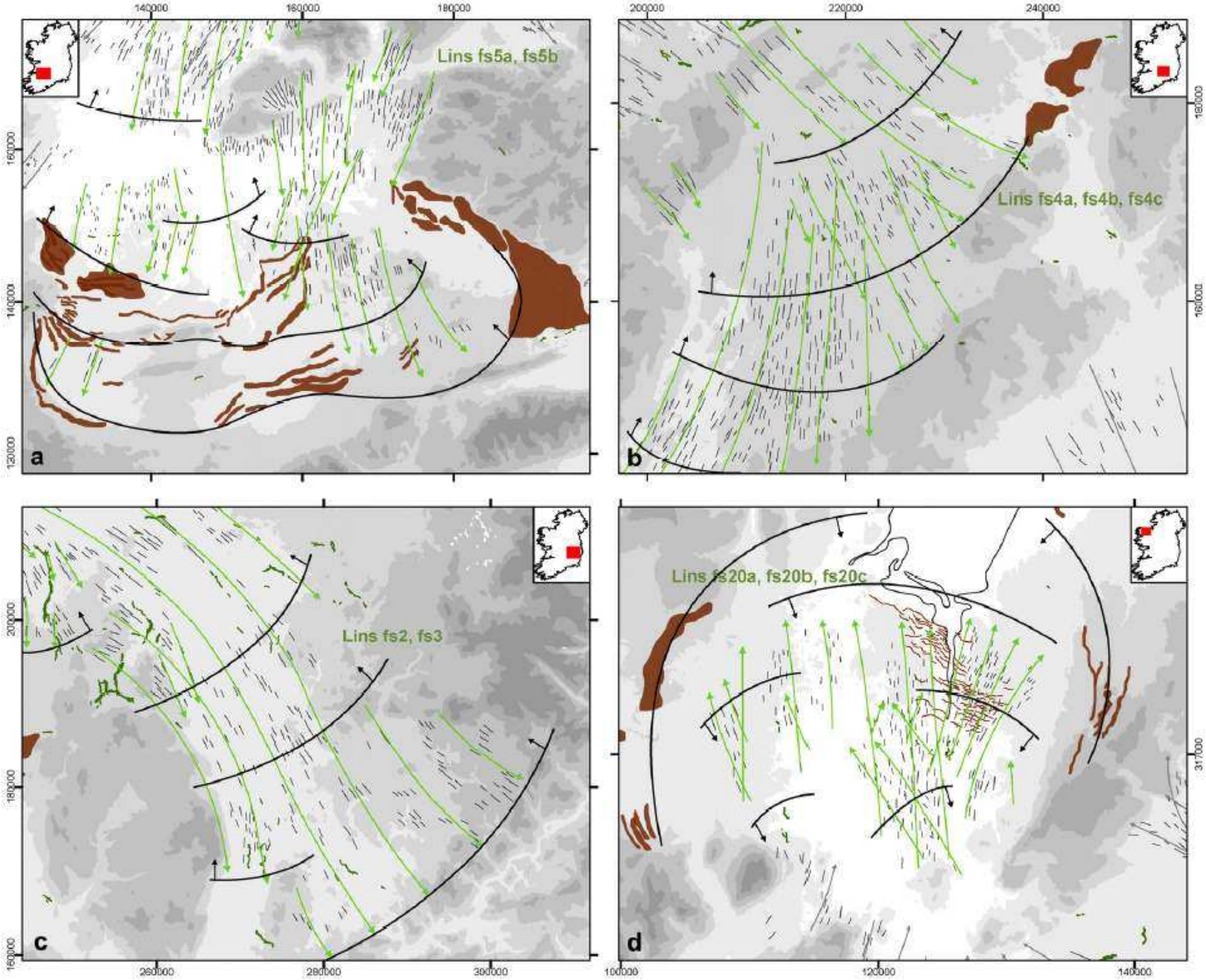


Figure 6.
Examples of drumlin patterns that have a geomorphological signature that permit us to deduce that they were formed during retreat of the ice margin, and thus become part of the evidence base for reconstructing patterns of margin retreat. In contrast to many (most?) drumlin patterns which show a high level of correspondence between neighbouring drumlins (similar size, spacing, and exactly parallel) these examples show spatial jumps in these measures and importantly, localised cross-cutting or discordances in orientation. We interpret this localised variation as arising from subtle changes in flow direction which is to be expected behind a back-stepping ice margin; a 'smudged' imprint. These examples also have moraines and/or eskers that further indicate that the record is of deglaciation. Drumlins are depicted as black lines along their crest, eskers as dark green; light green arrows summarise the geometry and direction of the flow set; moraines are brown; and the thick black lines are the reconstructed pattern of retreat.

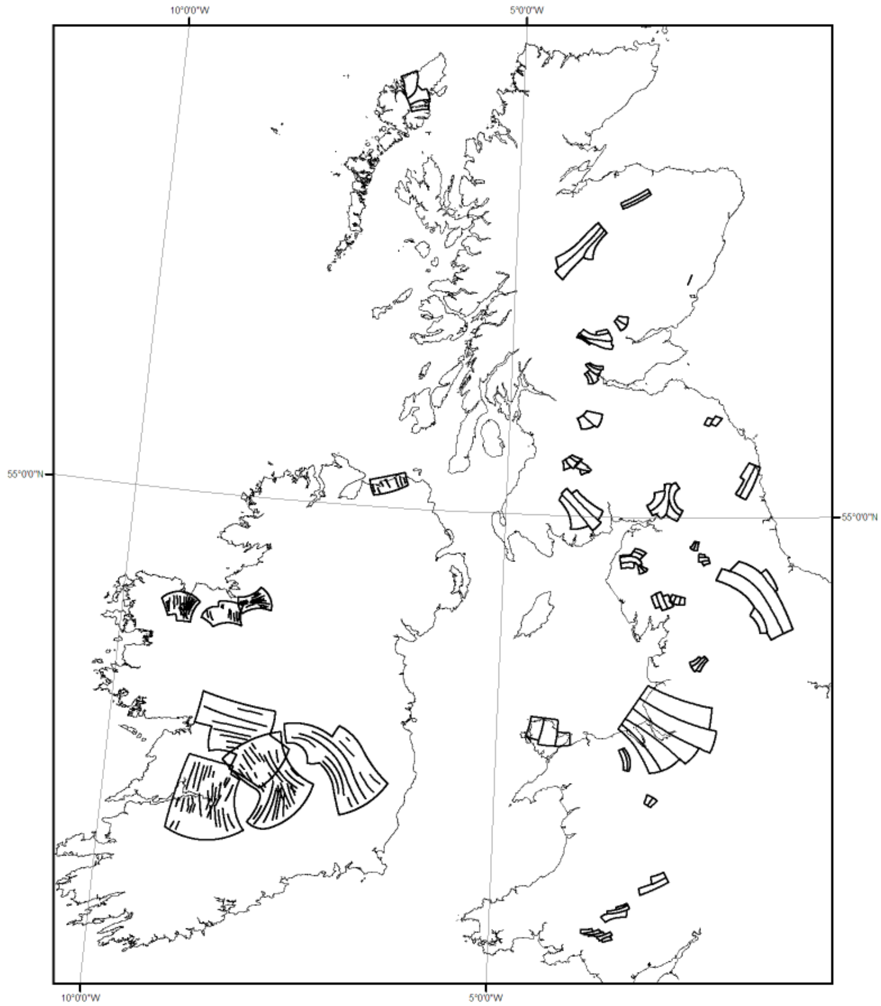
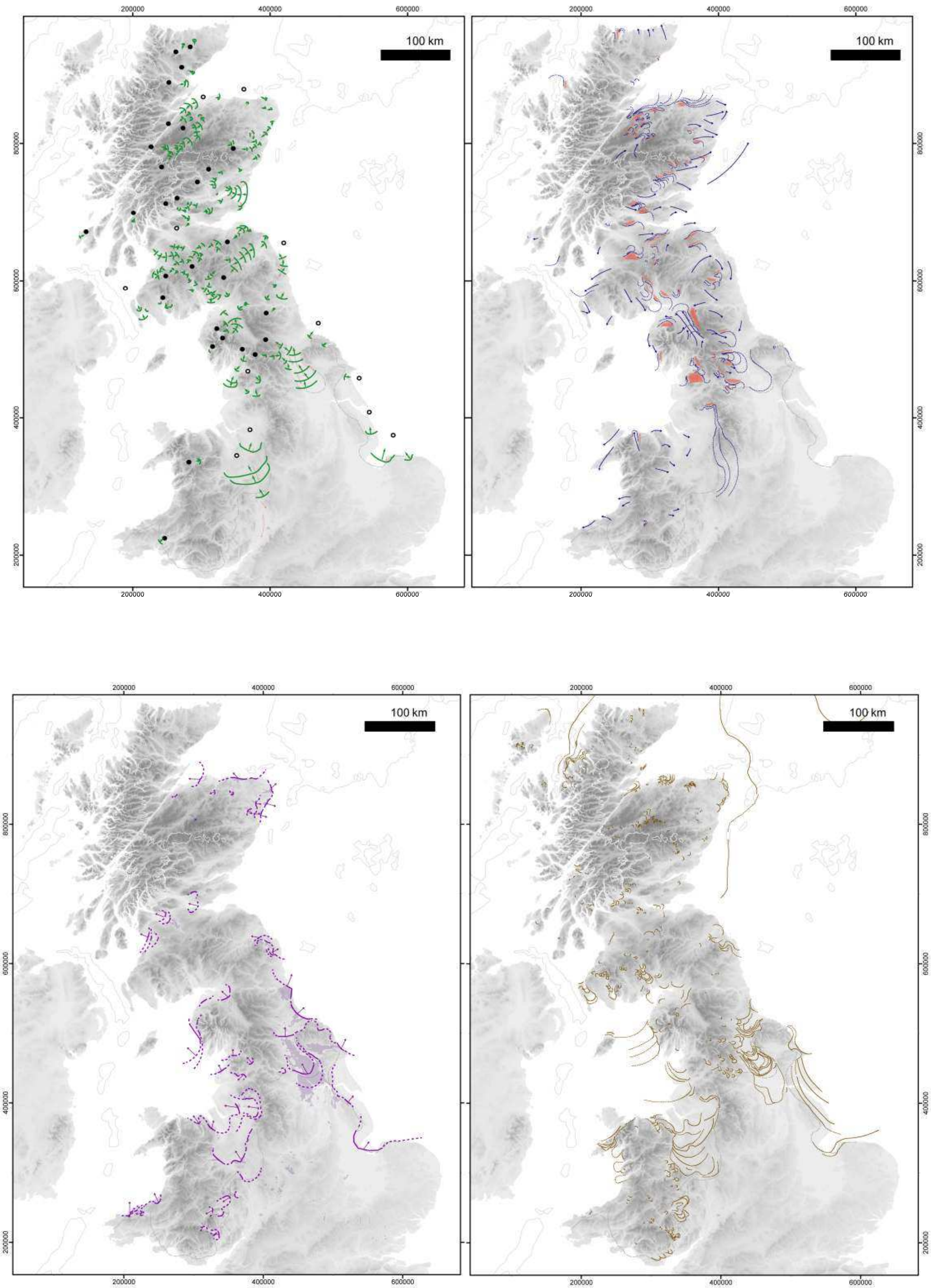


Figure 7.
Of the wider drumlin population of Britain and Ireland, and which have been grouped into flow sets (see Greenwood and Clark, 2008; 2009a; Hughes *et al.,* in press), those flow sets that are interpreted as recording successive margin retreat (i.e. time-transgressive flow sets) are illustrated here. See text for explanation. (The different style of cartography between Ireland and Britain has no significance).


100 km
100 km
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100 km
200000
400000
600000
800000

Figure 8.
Retreat patterns derived from each landform type; a) from eskers, b) from lateral and subglacial meltwater channels, c) from damming positions required to impound known ice dammed lakes and d) from moraines. Reassuringly, these independent lines of evidence mostly match up recording a similar direction and pattern of retreat. In a) successive margin retreat positions are drawn orthogonal to known eskers and arrows indicate the direction of retreat towards either an upland location (annotated by solid dot) or a lowland location (open dot). In b), solid blue lines indicate margin positions as indicated by lateral meltwater channels with dashed blue lines connecting these positions using their relationship with topography. Blue arrows record inferred ice surface slope (i.e. ice flow directions) derived from the position of subglacial meltwater channels. Red lines / patches mark locations that must have become ice free to enable the generation of lateral meltwater channels, and these therefore delineate high ground that emerged as nunataks during retreat. In c), schematic ice margins are drawn in positions required to dam known ice marginal lakes, with arrows indicating the direction of retreat. The location of glaciolacustrine sediments from British Geological Survey maps are shown in purple. In d), successive margin positions are generalised accounting for moraine positions (solid brown), and are connected (dashed brown line) where it was deemed logical to do so on the basis of topographic context. Bathymetric contour shown is -100 m.

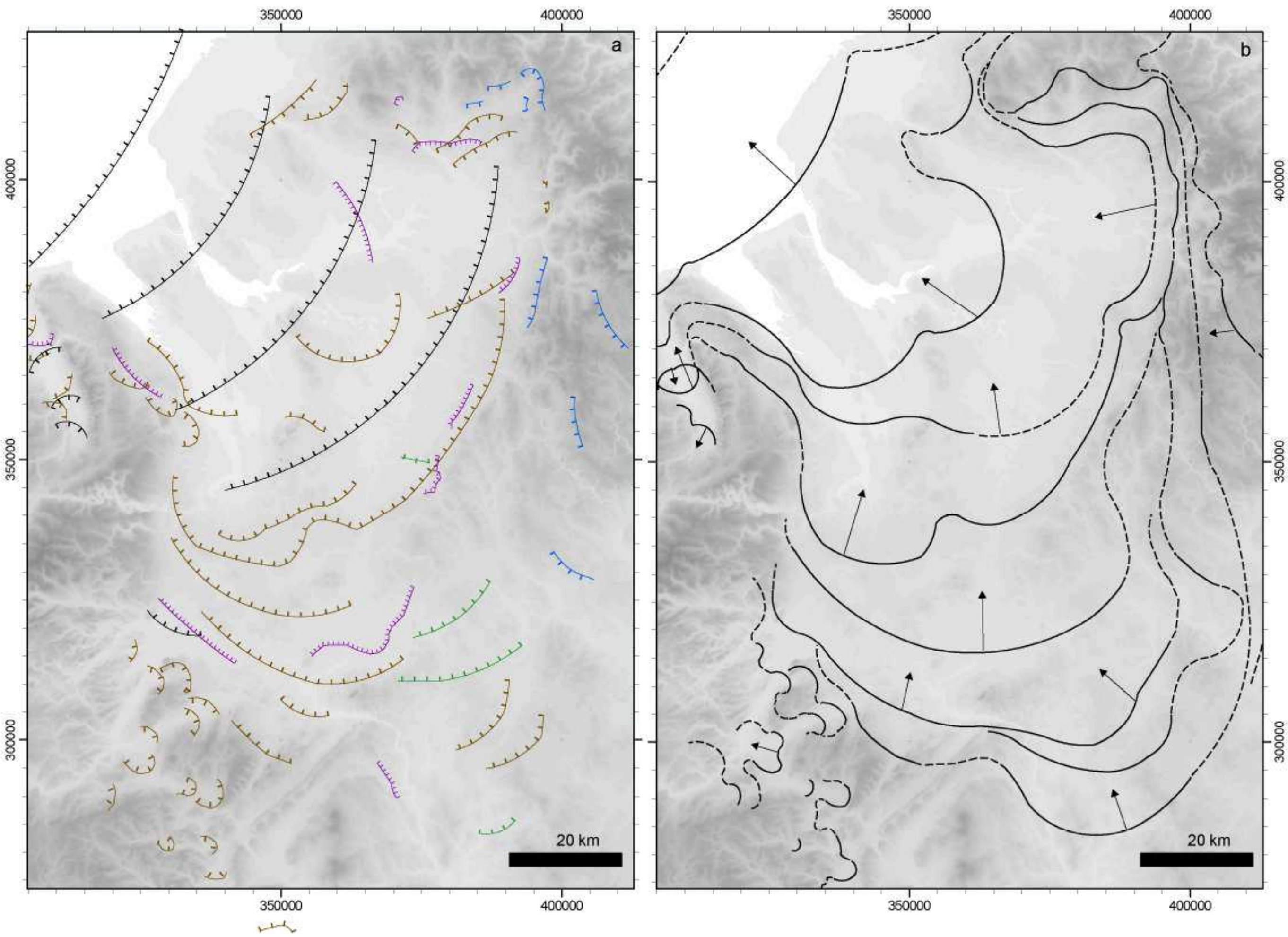

Figure 9.
Example to illustrate the synthesis of five independent lines of evidence to yield a single pattern of ice margin retreat; a) shows schematised margin positions underlain by a visualisation of topography. Hashes are on the ice-contact side of line. Information drawn from moraines are in brown, lake dams in purple, eskers in green, lateral meltwater channels in blue, and the retreat pattern from drumlins is black; b) is the synthesised retreat pattern with solid black lines corresponding to locations with evidence, dashed black lines as interpolations between these, and arrows indicating the direction of retreat. The evidence is mutually corroborative and documents retreat of a lobe of ice northwards out of the lowlands (Cheshire Plain) between the higher ground of Wales and the English Pennines. Welsh ice is seen to separate from the main lobe and to recess as a series of much smaller lobes into valleys to the west. In the Vale of Clywdd (in NW of image), the relative positions of moraines, lake deposits and drumlins lead to a reconstruction of retreat of Irish Sea ice leaving an ice free enclave between this mass and resident Welsh ice (permitting establishment of an ice dammed lake) followed by a minor expansion of Welsh ice.

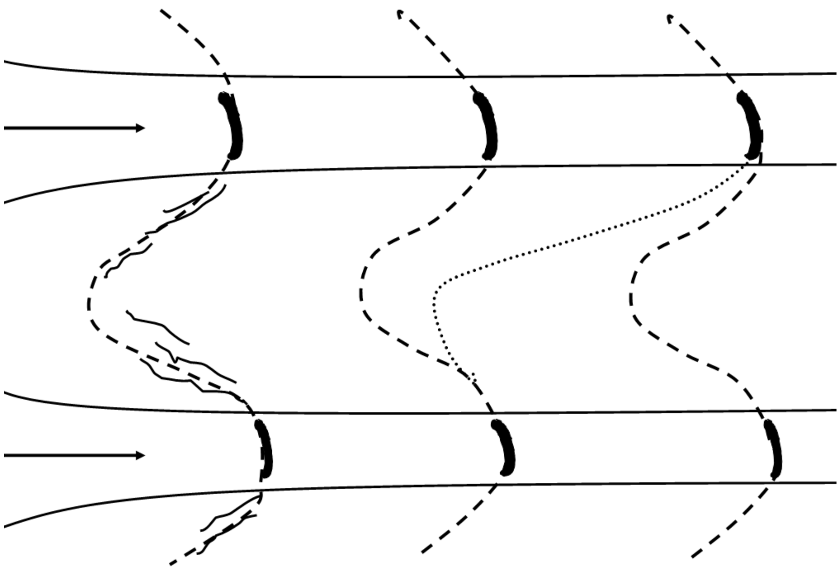

Figure 10
A schematic illustration of how interpolation between locations with evidence can lead to uncertainty in the pattern of retreat. Here are two trunk valleys draining ice to the east, each with a series of moraines. In the westernmost case some flights of lateral meltwater channels reasonably permit a connection between the two valleys and a robust reconstruction of a palaeo-margin. For the two sets of moraines further downstream, where there is no intervening evidence found, the simplest case is to interpolate directly between the valleys (allowing for the effect of topography on likely margin outline) yielding the dashed palaeo margins, but other possibilities exist; perhaps ice in the northern valley retreated much later (diagonal dotted line). The discovery of further landforms, stratigraphic control between the two valleys or direct dating of the moraines could resolve such problems.

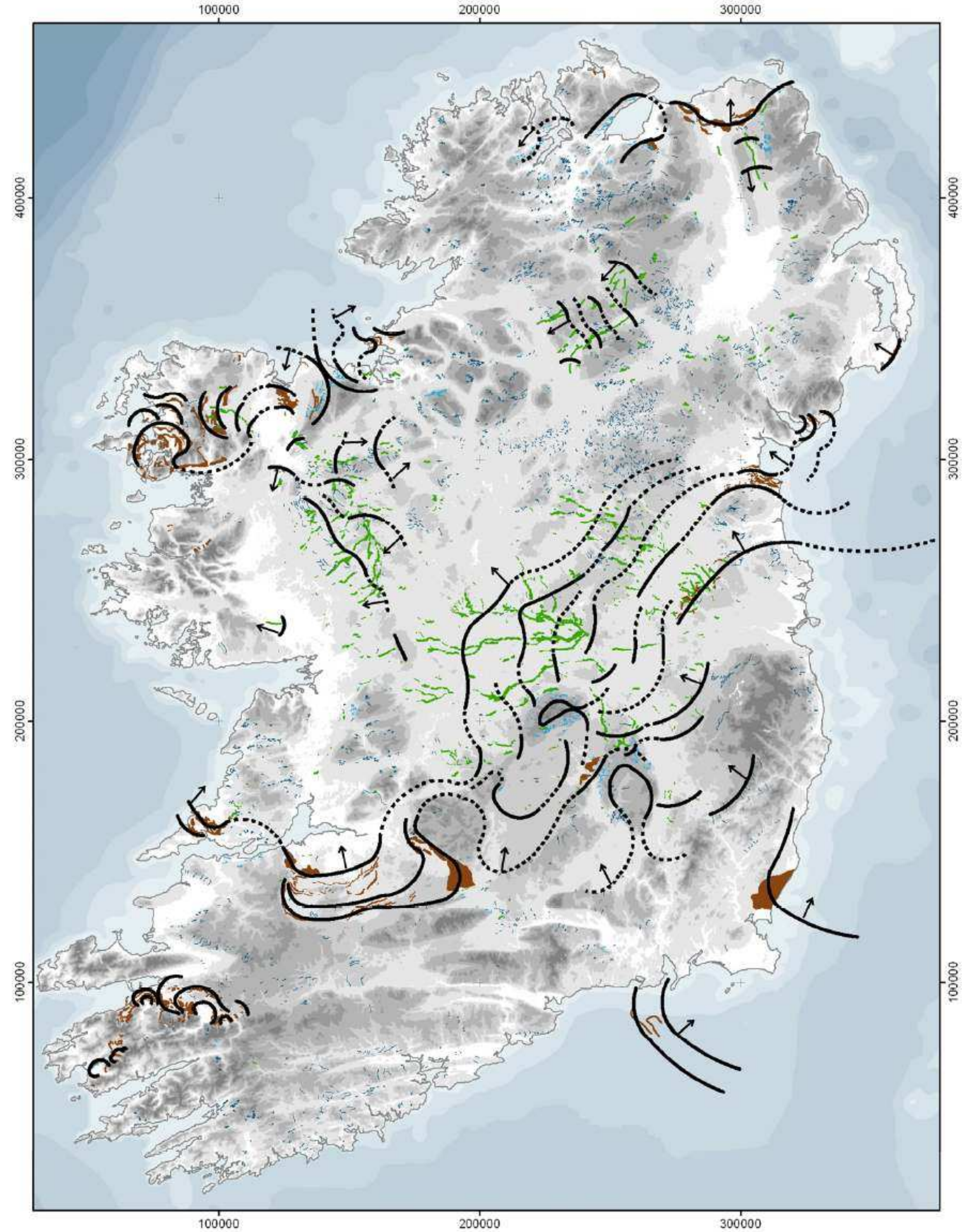

Figure 11.
Elements of the Irish retreat pattern derived from moraines (brown), eskers (green) and meltwater channels (blue). Solid black lines are reconstructed margin positions and dotted black lines are inferred to join these up. Note that, similar to Britain, a number of upland areas are shown to deglaciate prior to the adjacent lowlands (i.e. emergence of nunataks from a presumably thin ice sheet), and that retreat is not always to the uplands.

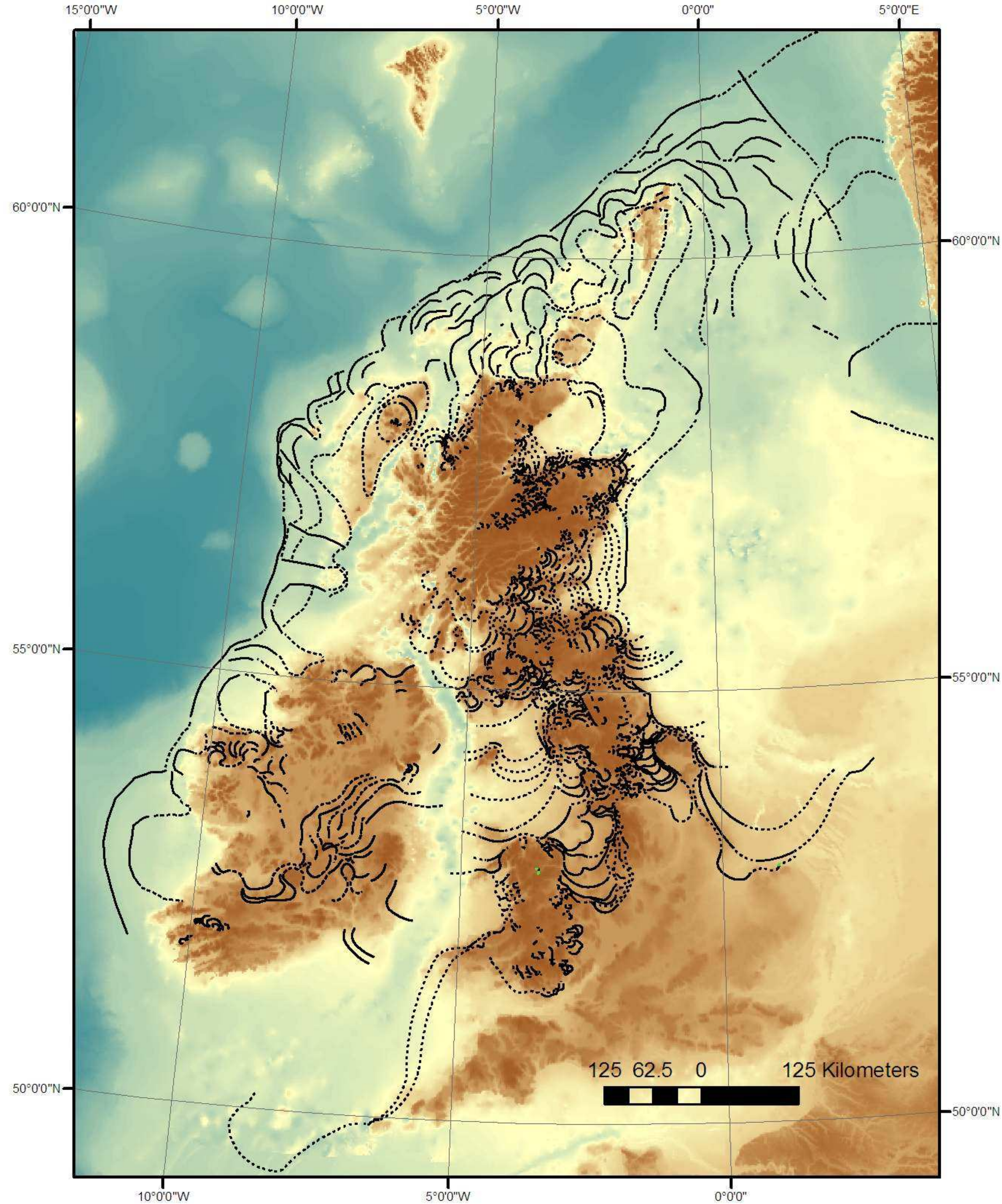

Figure 12.
Reconstruction of the pattern of retreat of the BIIS based on the disposition of moraines, meltwater channels, eskers, ice dammed lakes and drumlins and their relationship to the bed topography. Solid black lines record palaeo-margins with evidence and dotted lines are interpolations between them. There is no meaning implied in the spacing of successive margin positions, this merely reflects the data density and cartographic style. This reconstruction is based on over 26,000 newly mapped landforms as well as published information reported in the BRITICE compilation (C.D. Clark *et al.,* 2004a; Evans *et al*., 2005).

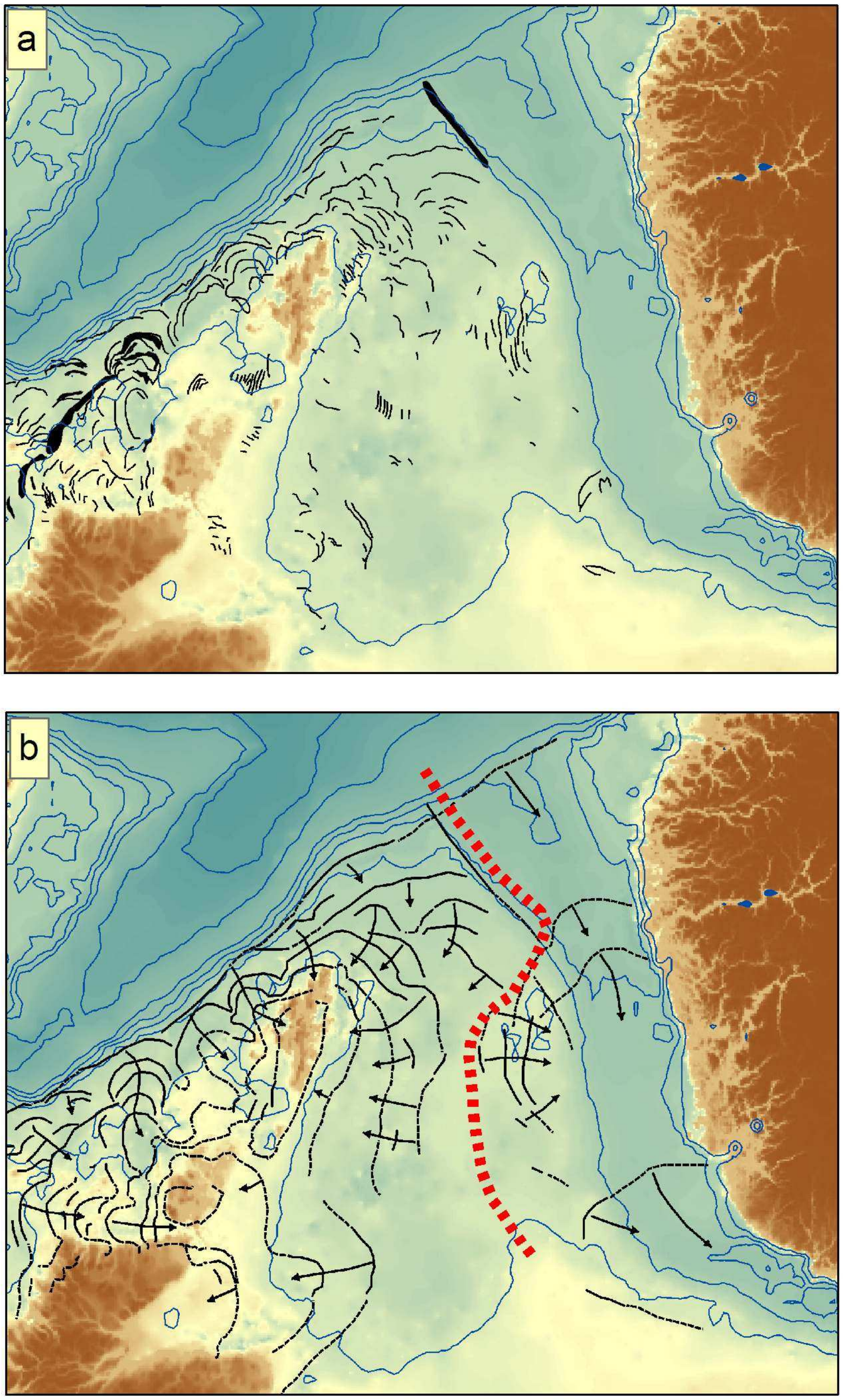

Figure 13.
Moraines (a), marked in black were used to define the pattern of retreat in the northern North Sea and define the suture zone (red in b) along which Norwegian and British ice finally separated.

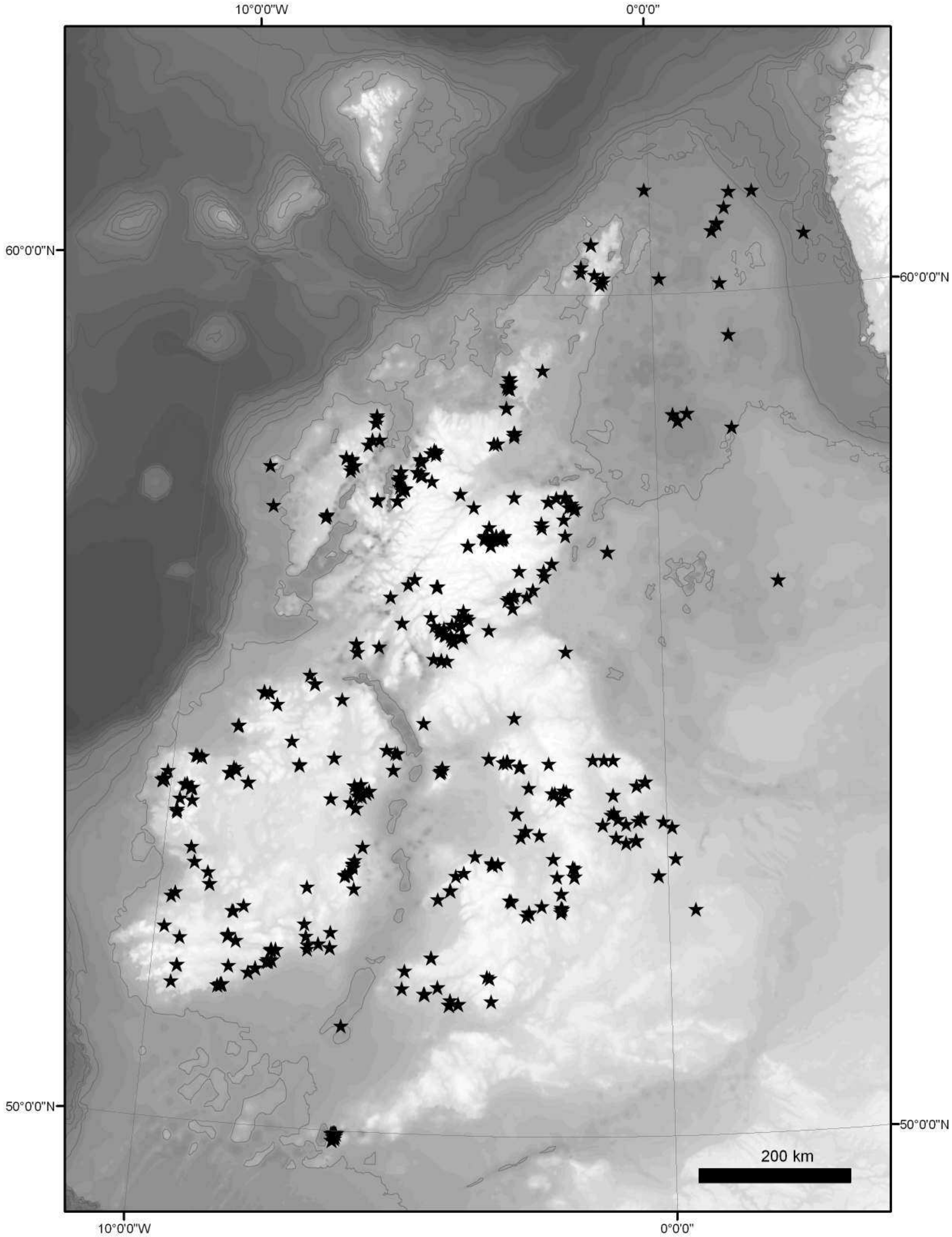

Figure 14.
The database of dates (n = 931) relevant to ice sheet history were derived from a search of the literature and entered into the GIS (see Table 1, for how the data are recorded). For some data points, in bog or ocean sediment cores for example, more than one date is recorded.

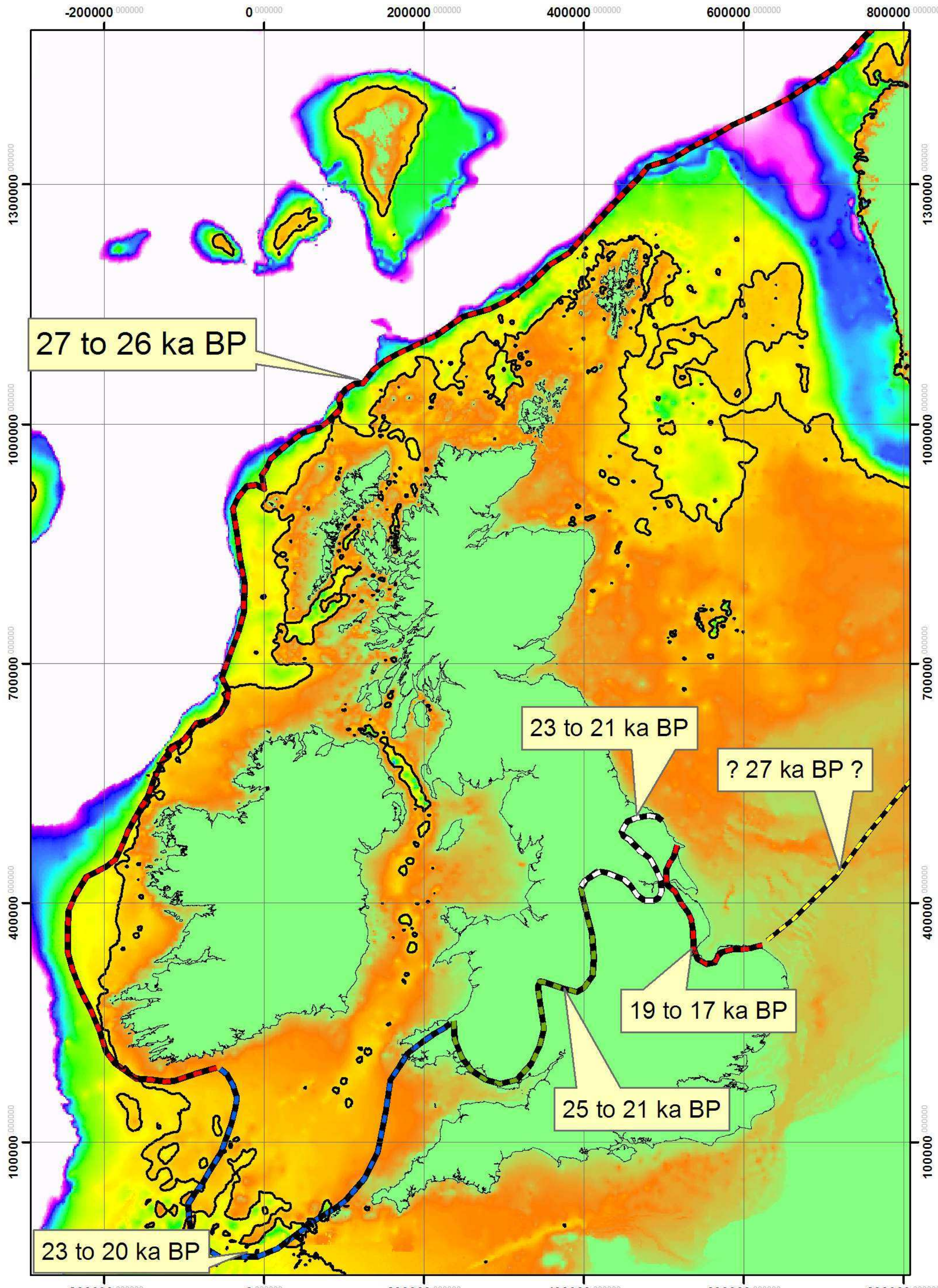

Figure 15.
Ice sheet maximum limits annotated according to when they were attained. The youngest *advance date* and the oldest *deglacial date* were used, where available, to attach a range of dates to each margin segment (coloured differently). Clearly the ice sheet reached its maximum extent at different times in different sectors. The disparity between continental shelf maximum extent reached as early as 27 ka BP against the southern limit of around 17 – 25 ka BP might be because the ice sheet attempted to continue expanding to the north and west but ran out of continental shelf and reached water too deep for grounding. Shelf bathymetry is shown from blue (-300 m) through yellows to brown (0 m), and the black contour marks the position of an estimated palaeo coastline at 27 ka BP accounting for eustatic lowering of sea level (but not glacioisostatic loading), see text.

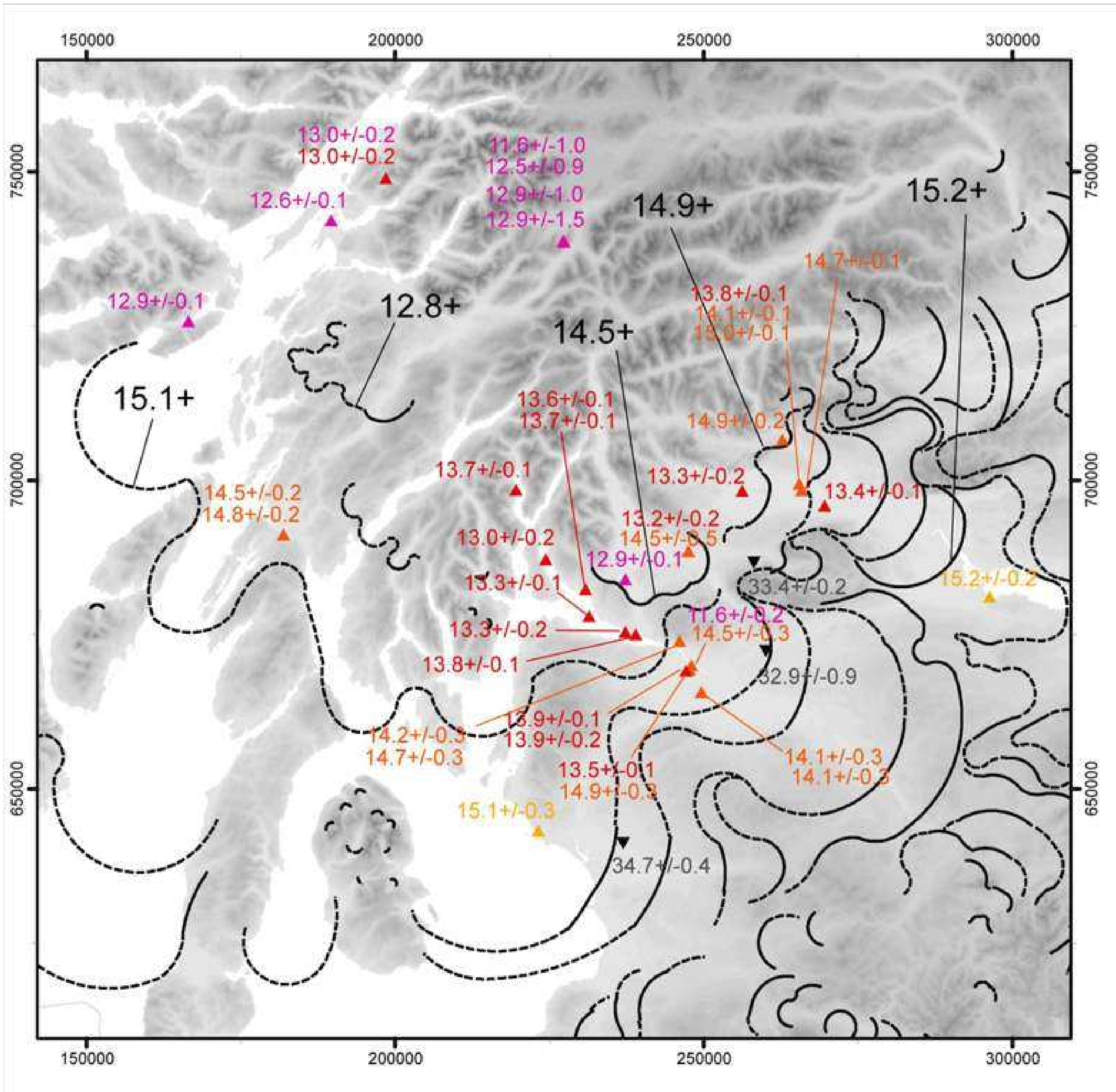

Figure 16.
Example of how the geomorphologically-defined pattern of retreat is brought together with dates to derive retreat isochrones. In this example in central Scotland, an age has been attached to ice margin positions where possible (black) using the relationship to the dated sites (colour). A positive sign following the value denotes a minimum age (the margin is at least this old). In this location all the dates are compatible and suggest that the ice sheet was in the vicinity of the Loch Lomond Stadial position by 14 ka BP.

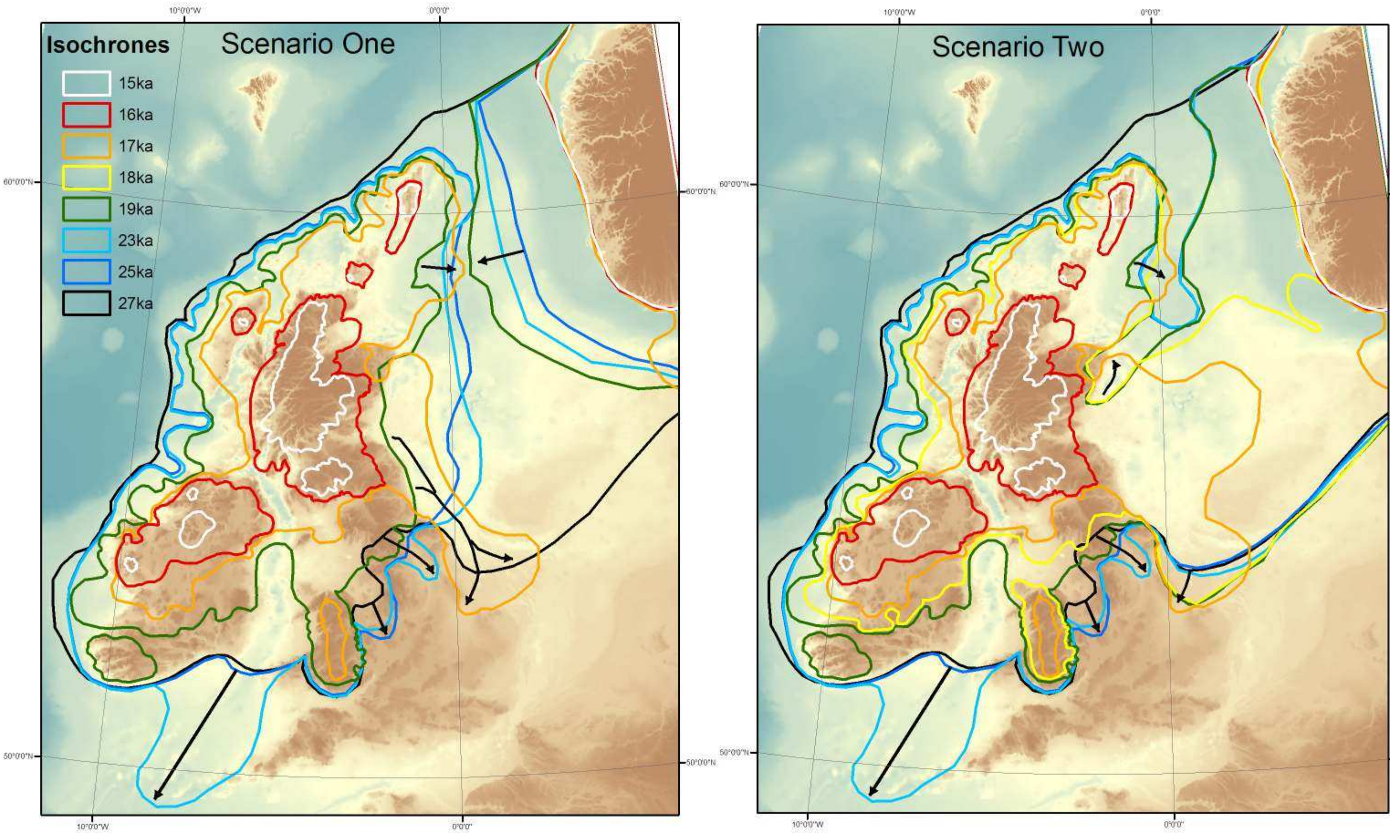

Figure 17.
Isochrones of ice retreat of the BIIS; successive margin positions in years ka BP. In synthesising and reconciling the timing constraints with the pattern of retreat we faced difficulties for the North Sea and the east coast of England and so present two scenarios. These are identical for Ireland and most of Britain but differ with regard to deglaciation of the North Sea. In ***Scenario One****; Early and complete break-up of North Sea ice and a surge lobe down the east coast of England* we also reconstruct the Tampen Re-advance of Norwegian ice. ***Scenario Two;*** *Two stage deglaciation of the North Sea with a persistent ice dome in the south*, adopts a more cautious view regarding the Tampen advance - it merely maintains its position. In both scenarios significant advances are marked with black arrows. Smaller re-advances are also discussed in the text but are below the resolution of this synthesis.

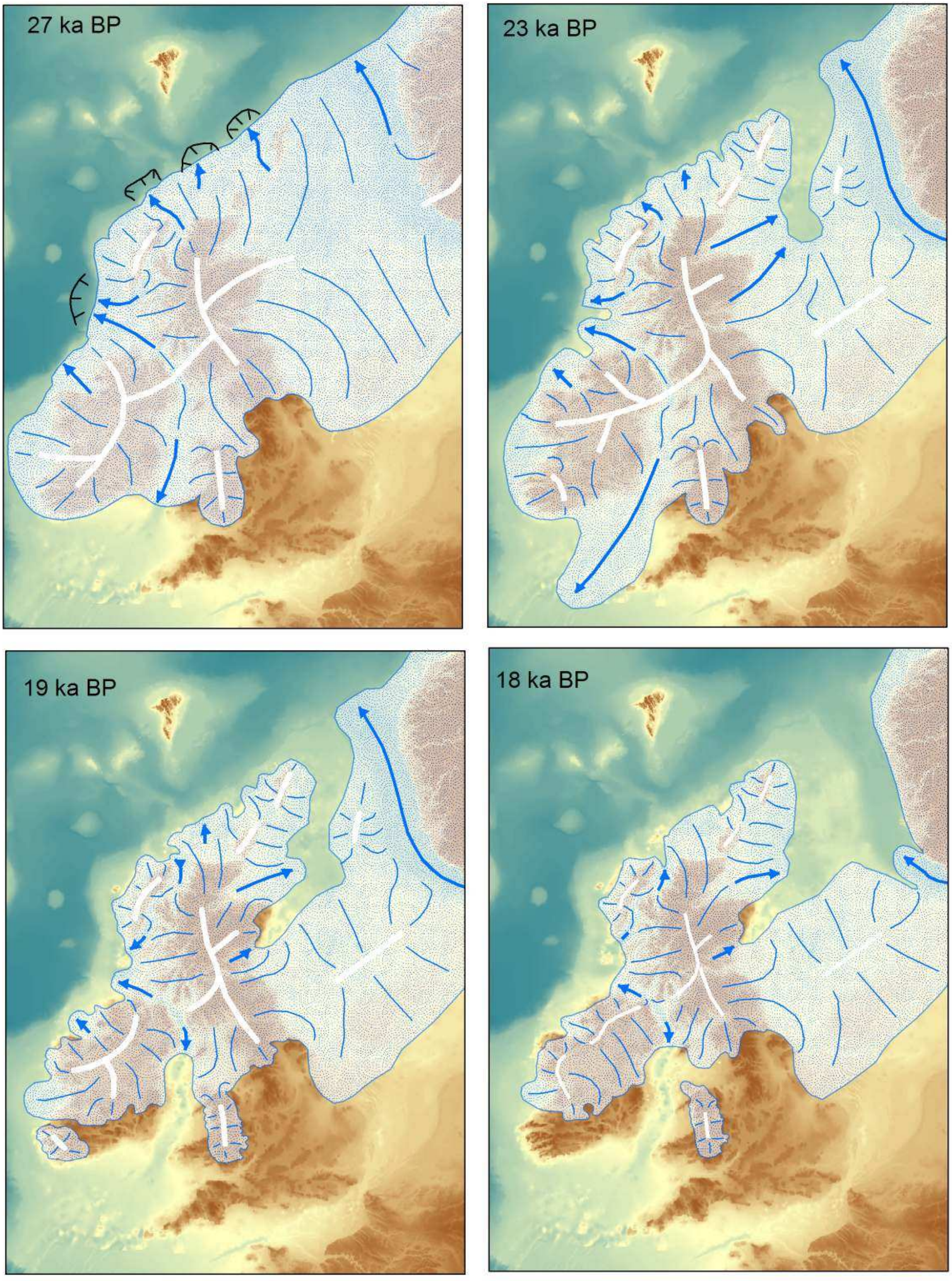

Figure 18….continued…

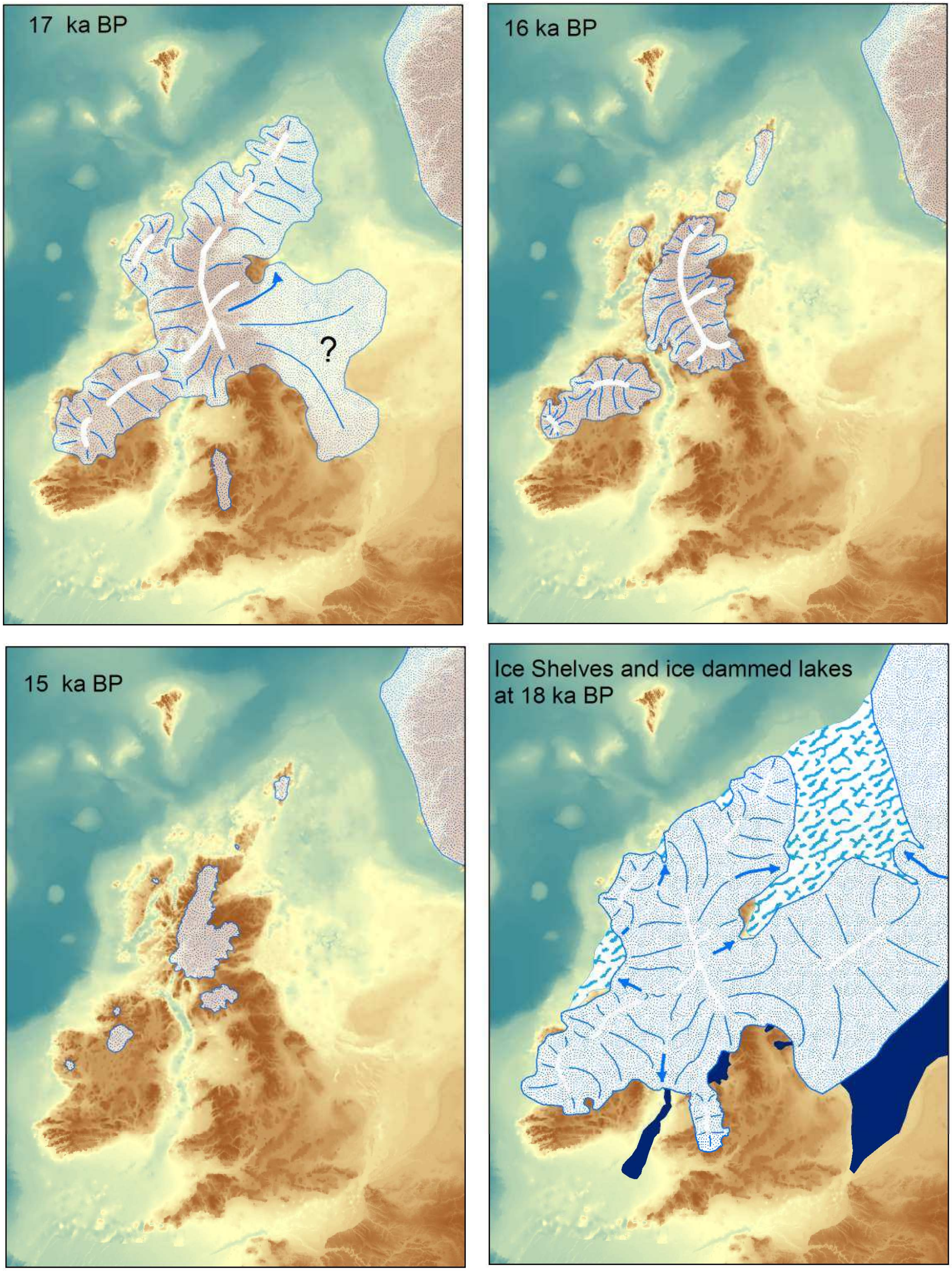

Figure 18….continued…

…continued..Figure 18
Reconstruction of the demise of the BIIS and North Sea ice cover. Note that the Faroe Islands were also glaciated but are not included in this reconstruction. Margins are based on the retreat analysis in this paper and the divide positions and flow configurations are partly based on flow evidence (Greenwood and Clark 2009a,b; Hughes *et al.,* in press) but are necessarily schematic for areas where this is unknown. Ice divides (white), ice streams (thick blue arrows) and sheet-flow geometry (thin blue) are shown. This reconstruction is of our scenario two (see text and figure 17) which has a persistent ice cover over the southern North Sea. See figures 17 and 19 for the alternative version of early break up of ice over the North Sea and a surge lobe down the east coast of England. The final panel of the figure schematically suggests that ice shelves (in white) likely existed in favourable locations during ice sheet retreat (here we show 18 ka BP) and also that certain margin positions should have dammed large proglacial lakes (blue) in topographic depressions with no external drainage.

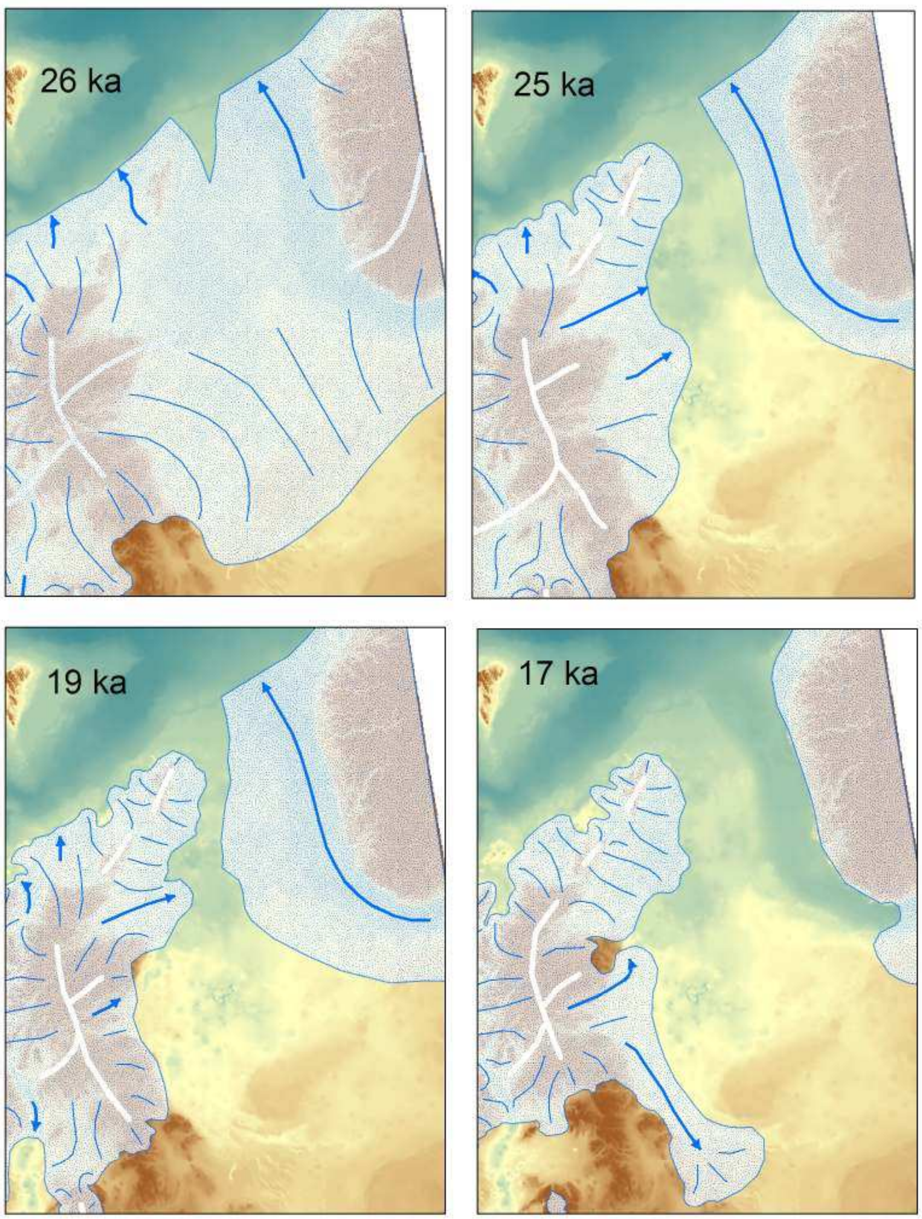

Figure 19.
Alternative reconstruction for deglaciation of the North Sea, derived from our scenario One (see text). The ‘ice bridge’ is breached (perhaps catastrophically) by 25 ka BP and the North Sea remains open but with readvances and surges on either side.

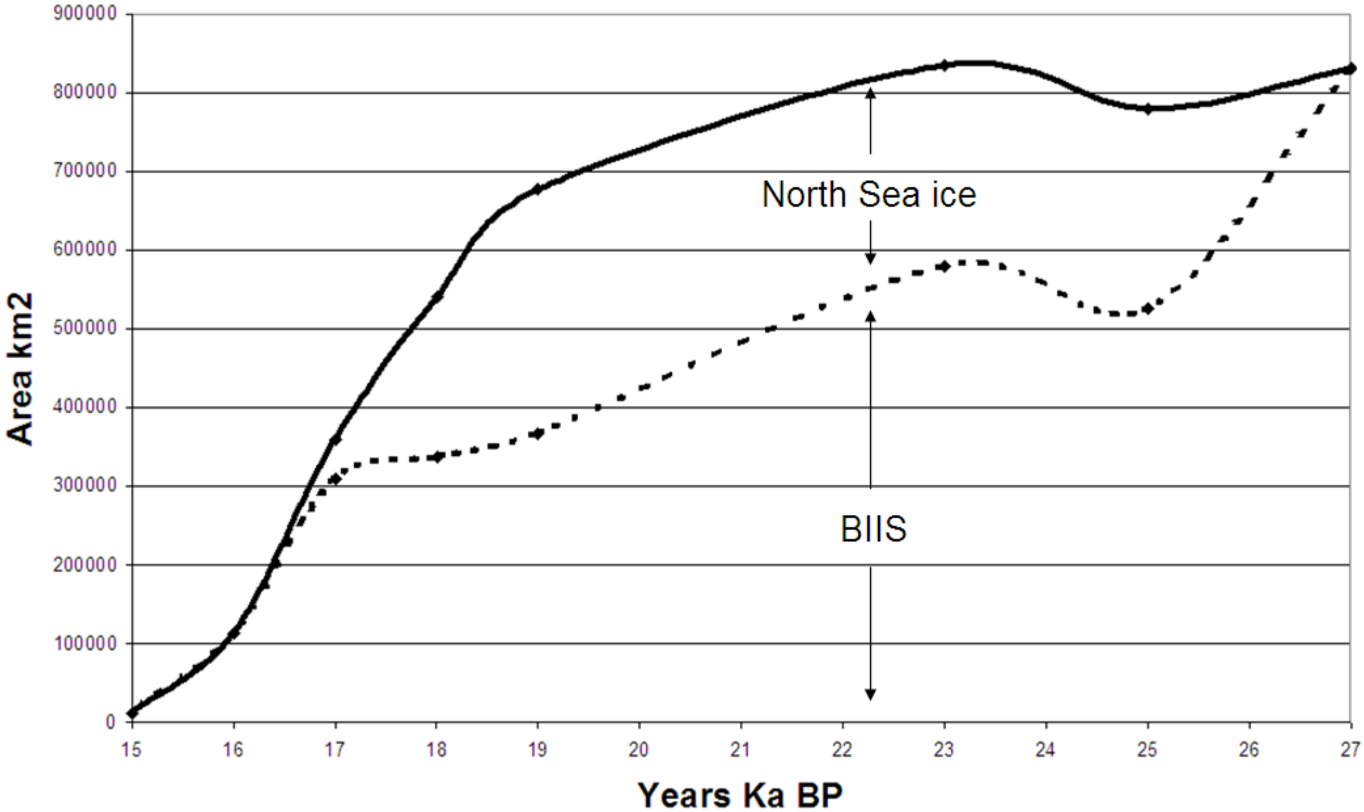

Figure 20.
Decline in ice sheet area through time, compiled from the reconstructed time slices. Solid black line is for the two-stage deglaciation with a persistent ice dome in the south of the North Sea (Scenario Two). This yields a slow deglaciation of the North Sea up until 18 ka and then a rapid and almost linear decline in ice sheet area. The dotted line is for the early and complete breakup of North Sea ice (Scenario One) which produces two pulses of ice loss (27 to 25 ka and 17 to 16 ka). The most rapid ice losses in both scenarios occur between 17 and 16 ka BP where final elements of continental shelf ice cover are lost. Note that uncertainty with regard to the timing of loss over the North Sea is large (area between two lines).

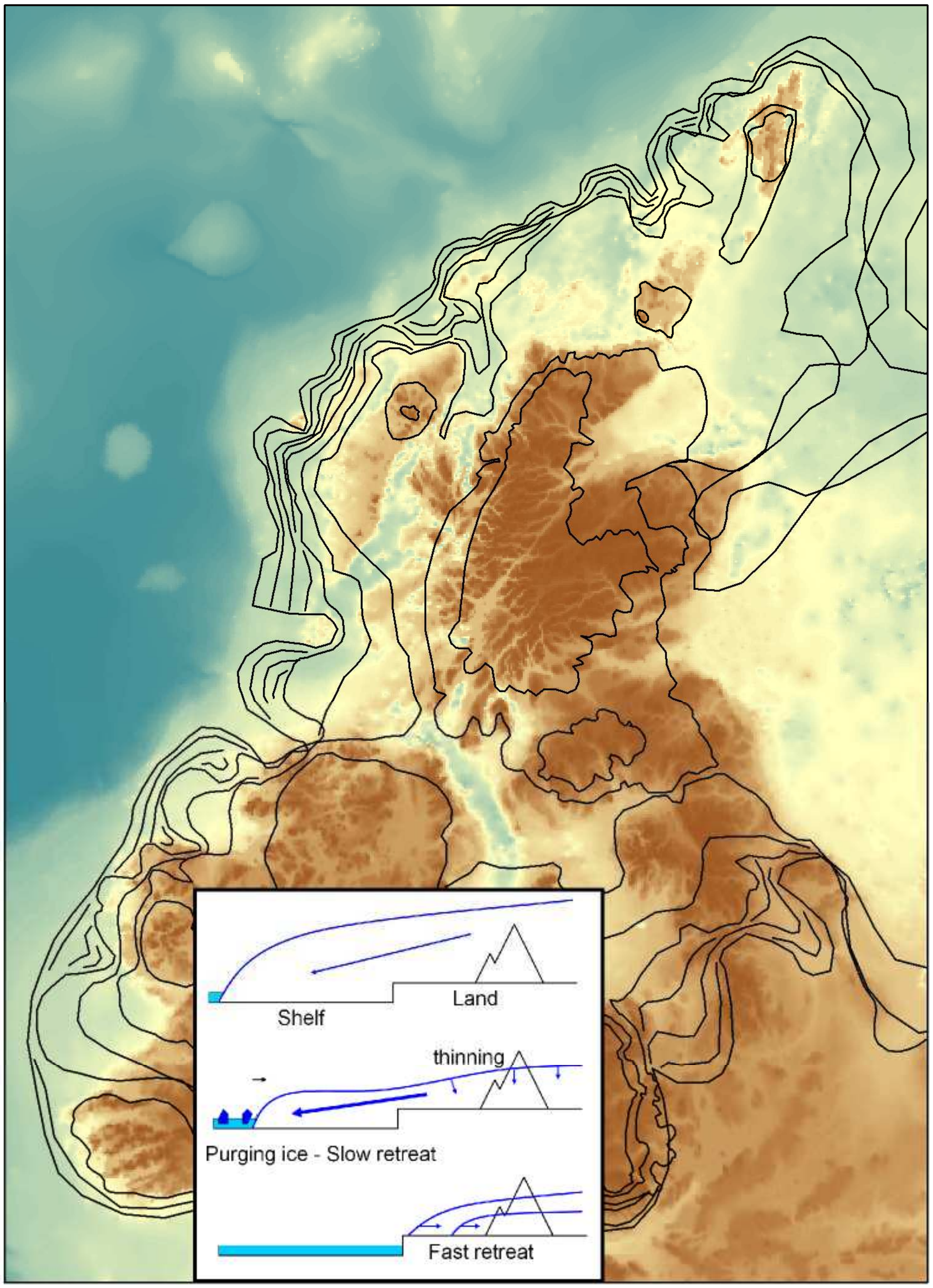

Figure 21.
Retreat pattern with interpolated 1 ka timesteps to illustrate the variability in rates of retreat. Note that retreat is reconstructed as being slow (close spacing of isochrones) on the continental shelf, in contrast to more rapid retreat onshore and at the southern margin. This is opposite to the oft-quoted rapidity of retreat for marine-based ice, and the paradox might be explained (see inset) by the purging of ice whilst calving margins existed which substantially lowered ice elevations onshore, preconditioning it for rapid retreat later.

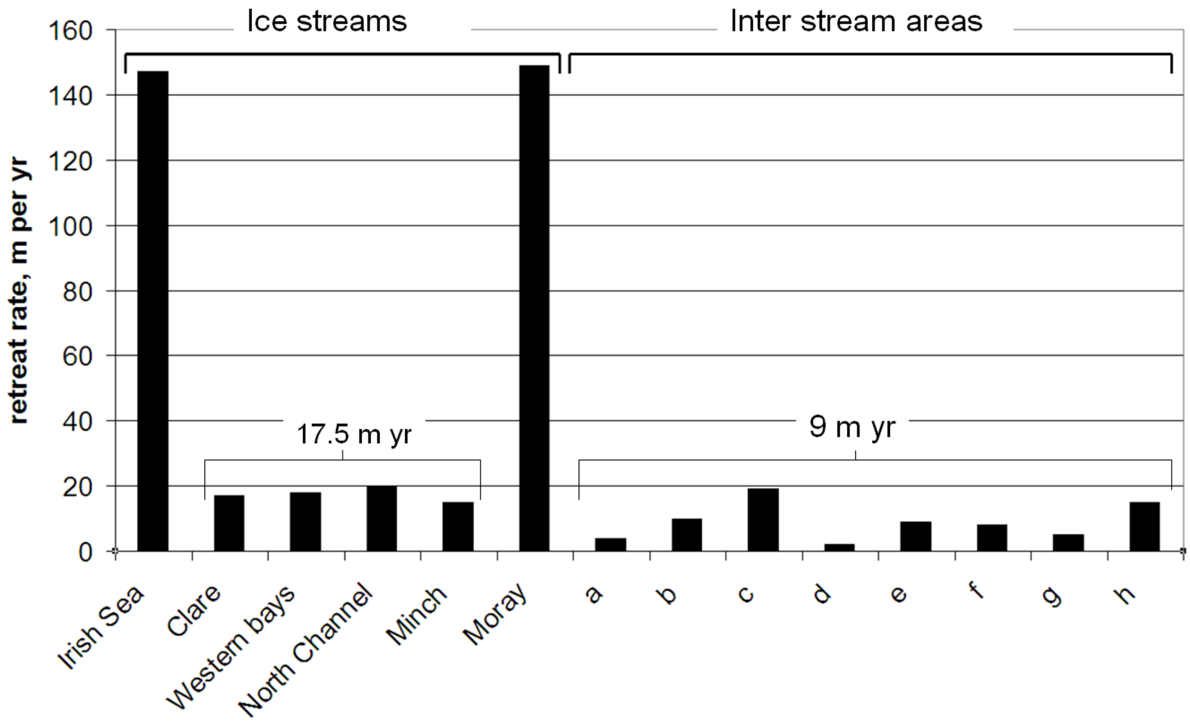

Figure 22.
Retreat rates (metres per year) of various margins around the ice sheet, derived from the reconstruction, ice streams as named and inter stream areas (a to h) as intermediate positions. Note that there are two modes of ice stream retreat rate, the Irish Sea and Moray Firth ice streams experienced rapid margin retreat in contrast to the others. Ice streams retreat rates generally exceed those for inter-stream margins.