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The palaeoglaciology of the central sector of the British and Irish Ice Sheet: reconciling glacial geomorphology and preliminary ice sheet modelling.

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Abstract

Digital elevation models of the area around the Solway Lowlands reveal complex subglacial bedform imprints relating the central sector of the LGM British and Irish Ice Sheet. Drumlin and lineation mapping in four case studies show that glacier flow directions switched significantly through time. These are summarized in four major flow phases in the region: Phase I flow was from a dominant Scottish dispersal centre, which transported Criffel granite erratics to the Eden Valley and forced Lake District ice eastwards over the Pennines at Stainmore; Phase II involved easterly flow of Lake District and Scottish ice through the Tyne Gap and Stainmore Gap with an ice divide located over the Solway Firth; Phase III was a dominant westerly flow from upland dispersal centres into the Solway lowlands and along the Solway Firth due to draw down of ice into the Irish Sea basin; Phase IV was characterised by unconstrained advance of Scottish ice across the Solway Firth. Forcing of a numerical model of ice sheet inception and decay by the Greenland ice core record facilitates an assessment of the potential for rapid ice flow directional switching during one glacial cycle. The model indicates that, after fluctuations of smaller radially flowing ice caps prior to 30kyBP, the ice sheet grows to produce an elongate, triangular-shaped dome over NW England and SW Scotland at the LGM at 19.5kyBP. Recession after 18.5kyBP displays a complex pattern of significant ice flow directional switches over relatively short timescales, complementing the geomorphologically-based assessments of palaeo-ice dynamics. The palaeoglaciological implications of this combined geomorphic and modeling approach are that: a) the central sector of the BIIS was as a major dispersal centre for only ca. 2.5ka after the LGM; b) the ice sheet had no real steady state and comprised constantly

migrating dispersal centres and ice divides; c) subglacial streamlining of flow sets was completed over short phases of fast flow activity, with some flow reversals taking place in less than 300 years.

Introduction

Recent modelling of the dynamics of the British and Irish Ice Sheet (BIIS) through the last glacial cycle has identified major dispersal centres and ice flow pathways (Boulton & Hagdorn 2006). Due to their spatial resolution, such models often fail to reconcile the temporal and spatial complexities of the glacial geomorphological evidence that documents regional ice sheet build up and decay. It is this complex geomorphic signature, particularly the subglacial bedform record, which provides us with an increasingly clear impression of the multiplicity of flow phases that characterized ice sheet evolution during the Last Glacial Maximum (LGM) (Punkari 1982, 1993; Boulton & Clark 1990a, b; Clark 1997; Clark et al. 2000; Clark & Meehan 2001). Although glacial bedform mapping in North America and Scandinavia has yielded significant advances in understanding the dynamic nature of ice sheet behaviour, the subglacial features of the British Isles have only recently been analysed systematically in areas of formerly complex ice sheet flow (e.g. Salt & Evans 2004). As a result numerical models of the BIIS (e.g. Boulton & Hagdorn 2006) do not focus on flow directional changes associated with multiple ice dispersal centres but rather give the impression that ice flowed from relatively static domes such as that over western Scotland.

We present initial geomorphological mapping and numerical modeling results from a project aiming to reconstruct the palaeoglaciology of the former centre of the BIIS. This focuses on the location of palaeo-ice divides, dispersal centres, flow trajectories and flow phasing through the mapping of subglacial bedforms and the identification of their cross-cutting relationships. Forcing of a numerical model of ice sheet inception and decay by the Greenland ice core record allows us to assess the potential for rapid ice flow directional switching during one glacial cycle. The ice flow trajectories reproduced by the model, while not exactly replicating the geomorphologically constrained flow phases, demonstrates the highly dynamic nature of ice sheet flow patterns, and emphasizes the short periods of time over which significant flow switches, some involving ice flow reversal, can take place at the centre of an ice sheet. Future applications of our data include usage in the testing of spatial and temporal variability of linkages between ice sheet behaviour, ocean/climate change, sea level rise and internal driving mechanisms (e.g. binge-purge cycles, topographic influences etc), especially when more complex boundary conditions (e.g. sea level rise) are incorporated into numerical models.

Previous palaeoglaciological reconstructions

The central sector of the former BIIS (Fig. 1) was a complex multi-sourced region of competing ice flows draining the Southern Uplands, Pennines, Lake District and the Irish Sea, resulting in the production of a complex geomorphic signature of flow dynamics. Early research recognized three phases of ice flow into the region, including an early "Scottish advance", a later "Main glaciation" and then a readvance phase (Trotter & Hollingworth, 1932). The early Scottish advance is recorded by a stratigraphically older reddish brown till containing Scottish erratics and documenting Scottish ice advance into the Tyne Gap and up Edenside as far as Stainmore, diverting Lake District ice over the Stainmore Gap (Trotter 1929; Hollingworth 1931; Huddart, 1970, 1971). The easterly ice flow direction across Stainmore is recorded by the unique Shap granite, Dufton Pike granite and Permian Brockram dispersal train (Trotter, 1929; Hollingworth, 1931). Easterly ice flow through the cols of Stainmore (533m) and Cold Fell (625m) required significant ice sheet thickening over the Southern Uplands and Lake District, whereas flow along the lower Tyne Gap (152m) appears to have been maintained throughout most of the last glaciation. Easterly flowing ice over the higher terrain to the east of Edenside (i.e. Cross Fell and surrounding summits) generally indicates that the region became a significant dispersal centre (Hollingworth, 1931).

The southerly flow of Scottish ice is reported to have been superseded by a northerly ice flow during the "Main Glaciation". Laminated clays at Langwathby (Fig. 2; Goodchild, 1875) between the deposits of the 'Scottish' and 'Main' glaciations suggest at least partial deglaciation of the area, although the magnitude of retreat is uncertain (Hollingworth, 1931). Lake District ice flowing northwards down the Vale of Eden is recorded stratigraphically by an extensive red, sandy till containing Borrowdale volcanics and Penrith sandstone. The northerly, down valley flow is indicated by the change in content of these erratics from 90% in the south to 85% in the north (Trotter, 1929). Additionally, drumlin orientations to the north of the Lake District were interpreted by Trotter (1929) and Hollingworth (1931) as evidence of Lake District ice flow into the Solway lowlands, where it was deflected west towards the Irish Sea because of “congestion” with Scottish ice to the north (Fig. 2).

A corridor of prominent streamlining occurs through the Tyne Gap (Johnson, 1952), where bedform lineation and elongation has been interpreted as the imprint of a former ice stream (Bouledrou, et al., 1988; Everest et al., 2005). Tributary ice flows from the south, west and north can also be identified in the bedform record but the sedimentary boundary between the Scottish and Lake District ice in the Tyne Gap is indistinct, and characterized by an increase in Lake District erratics (Borrowdale volcanics, Carrock Fell gabbro, Threlkeld microgranite and Penrith sandstone) towards the south (Trotter, 1929). Along its length from west to east the Tyne Gap is increasingly dominated by blue-grey, Scottish sourced till (Trotter, 1929), the drop off in Lake District erratics being interpreted by Dwerryhouse (1902) as a product of the influence of ice flowing south down the North Tyne.

The development of a separate Pennine icefield/dispersal centre during glaciation has been promoted by Dakyns et al. (1891), Dwerryhouse (1902), Vincent (1969) and Mitchell (2007) based upon the occurrence of a distinctive local till at Cross Fell, which documents flow from the Cross Fell plateau and down Edenside to coalesce with Lake District ice feeding into the Tyne Gap (Trotter 1929). This ice flow direction is difficult to reconcile with contemporary Eden ice flowing southward and over Stainmore and this, together with complex drumlin orientations in the Eden valley, compounded early attempts to reconstruct palaeo-ice flows (Hollingworth 1931; Clark 2002). For example, around Appleby, Hollingworth (1931) recognised drumlins with strikingly different flow directions (Fig. 2); west of Appleby movement was initially eastwards with an overprinted flow down Edenside, and east of Appleby there was an alignment that suggested ice flow towards Stainmore (Clark, 2002). Hollingworth (1931) proposed a “basal ice shed” in order to explain ice flowing in two different directions (Figure 2, lower). This is now known to be glaciological implausible, and Rose and Letzer (1977) were the first to suggest that the region contained overprinted subglacial bedforms that record shifting ice divides and migrating ice dispersal centres during a single glacial episode. The mobility of the local Pennine ice divide has similarly been charted by Mitchell (2007) based upon superimposed drumlins.

A further subglacial bedform enigma occurs in the Solway lowlands, into which ice flowed from the Scottish Southern Uplands and from the Lake District. Erratic trains, particularly from distinct granite outcrops around the Galloway area, indicate that ice radiated out from a Southern Upland dispersal centre and flowed down valleys such as the River Nith (Tipping, 1999). Grey-blue till, free of Lake District erratics, crops out in river sections of the Lyne, Irthing and Tipalt, marking the southern limit of Scottish ice at the southern edge of Bewcastle Fells. Subglacial bedforms appeared to indicate to early workers that the build up of ice in Edenside forced Scottish ice eastwards but itself flowed west (Fig. 2; Trotter, 1929), resulting in a palaeoglaciological reconstruction with the implausible scenario of contemporary ice flows in opposite directions. Recent developments in understanding spatial and temporal patterns in subglacial bedforms indicate that the enigmatic drumlins of NW England and SW Scotland are best understood when viewed as a landform palimpsest in which bedforms are overprinted (Mitchell & Clark 1994).

The concept of subglacial bedform overprinting is now widely accepted in the research field of palaeoglaciology and has been successfully applied to reconstructions of the Laurentide and Fennoscandinavian ice sheets (e.g. Boulton & Clark 1990a, b; Clark 1993, 1994, 1997; Kleman 1994; Kleman et al. 2006). Complex subglacial bedform palimpsests have been recognized in the British Isles in only a few locations since the work of Rose and Letzer (1977), for example by Clark and Meehan (2001) in Ireland and by Salt and Evans (2004) for the Southern Uplands ice dispersal centre where the subglacial bedforms are of multiple ages and have been superimposed or partially removed (Fig. 3). Salt and Evans (2004) provide evidence of four early, topographically unconstrained ice flow stages (A-D) and three late topographically constrained stages (E-G) for SW Scotland. It was the flows from the Southern Upland dispersal centre that impinged upon the Solway/Eden Valley area and these, from oldest to youngest, were: Stage A flow towards the southwest; pre-Stage B southerly flow; Stage B southwesterly flow; Stage C south-southwesterly flow; and Stages F and G when ice flowed down major valleys such as the Cree and Ken and along Loch Ryan to terminate somewhere in the Solway Firth. In addition some southeasterly regional flows of unknown relative age are apparent on the east side of the Southern Uplands (New Galloway district in Fig. 3). In NW England, overprinted drumlins have been used to verify the reversal of ice flow during the last glaciation in the Vale of Eden (Mitchell & Riley 2006) and to reconstruct ice divide migration over the western Pennines and Howgill Fells (Mitchell 1994). The potential for identifying further subglacial bedform complexity in the British Isles and employing it in palaeoglaciological reconstructions of the BIIS has been reviewed by Clark et al. (2006).

Because it contains a number of former upland ice dispersal centres that coalesced to form the core of the BIIS during the LGM, NW England potentially contains a complex record of flow phasing in its glacial landform-sediment assemblages (cf. Hollingworth 1931; Trotter & Hollingworth 1932). Salt and Evans (2004) identified superimposed multiple flow events to the north where Southern Upland ice competed with flow from the Scottish Highlands (Fig. 3), and there is no reason to believe that similar ice sheet flow complexity is not manifest in the subglacial bedform record over NW England, in part linked to the dynamics of ice over SW Scotland. This has been acknowledged by Merritt and Auton (2000) in their reconstruction of ice flow events along the Cumbria coast. They use a lithostratigraphic approach to identify oscillations of Scottish/Irish Sea ice and Lake District ice that were significant enough to allow the development of unglaciated enclaves and glacial lakes along the Cumbria coast through the later stages of the last glacial cycle. Significantly, two major readvances have been identified by Merritt and Auton (2000) at ca.17 ^{14}C ka BP or ca.19.5 cal ka BP (Gosforth Oscillation) and ca.14 ^{14}C ka BP or ca.16.8 cal ka BP (Scottish Readvance), although the chronological control on these events is equivocal.

More secure is the chronology on ice sheet maximum limits and readvances in the Irish Sea basin. Scourse (1991), Scourse and Furze (2001), Hiemstra et al. (2005) and Ó Cofaigh and Evans (2007) provide evidence that the BIIS reached the Scilly Isles and the south coast of Ireland after 20.2 ^{14}C ka BP (23.9 cal ka BP). To the north, McCabe and Clark (1998, 2003) and McCabe et al. (1998, 2005, 2007) have identified two subsequent readvances, the Clogher Head readvance between 15 and 14.2 ^{14}C ka BP (18.3-17.0 cal ka BP) and the Killard Point readvance after 14.2 ^{14}C ka BP (17.0 cal ka BP). The latter was a pan-Irish Sea response by the BIIS to Heinrich Event 1, which involved a readvance to the Bride Moraine on the Isle of Man. The northern plain of the Isle of Man contains evidence for repeated marginal oscillation during retreat, with the chronology for ice contact sediments of the Jurby and older Orrisdale Formations constrained by overlying organic materials (Thomas et al., 2004). Specifically, terrestrial plant remains from the basal layers of kettle basins date to the beginning of the late glacial interstadial at 14.0-14.4 and 14.2-15.0 cal. kyrs BP (Roberts et al., 2007). Cosmogenic nuclide dates on the Wester Ross Readvance moraine indicate that the ice sheet was onshore in NW Scotland during Heinrich event 1 (Everest et al. 2006). Although some local glacial stratigraphies clearly equate ice marginal readvances with global climate signals such as Heinrich events (McCabe 1996; McCabe et al. 1998), evidence for readvances is widespread around the Irish Sea Basin and many cannot be explained by external climate drivers (e.g. Thomas & Summers 1983; Evans & O Cofaigh 2003; Thomas et al. 2007).

Rationale and approach

Despite the success of McCabe and Clark (1998), McCabe et al. (1998, 1999, 2005) and P.U. Clark et al. (2004) in correlating palaeo-ice sheet marginal oscillations in NE Ireland with North Atlantic and even global climate-ocean events, the behaviour of the BIIS throughout the last glacial cycle is poorly understood, due to patchy and largely non-systematic mapping of glacial landforms (see C.D. Clark et al. 2004 and Evans et al., 2005 for a review) and a weakly constrained chronological control on glacial deposits/events. Although there have been some attempts to reconstruct the palaeoglaciology of the last BIIS (Boulton et al., 1977, 1985), these reconstructions have been based on either non-systematic mapping of spatially limited data, or inverse approaches using sea level histories (e.g. Shennan et al. 2002). Moreover, as McCabe et al. (2005) point out, these models are “static” because they are based on subglacial flowline indicators (bedforms) of mixed ages.

Some zones of former fast flow or ice streaming have been identified based on geomorphic criteria (Stokes & Clark 1999, 2001; Clark et al., 2004) and sedimentological evidence (e.g. Merritt et al., 1995; Evans & Ó Cofaigh 2003). It is also becoming clear that several generations of ice flow lineations exist and demonstrably cross-cut each other (e.g. Clark & Meehan 2001; Salt & Evans 2004). Despite some systematic attempts to map regional subglacial bedforms (e.g. Knight & McCabe 1997; McCabe et al. 1998, 1999; Clark & Meehan 2001; Salt & Evans 2004; Clark et al. 2006) our knowledge of BIIS palaeo-ice flow dynamics and their relationship to changes in ice sheet configuration and size remains at a relatively crude level compared to advances in research on the Laurentide and Scandinavian ice sheets. Although the BIIS has had a long history of research, previous work has predominantly concentrated on sediment stratigraphy and correlation, at the expense of investigations into spatial and temporal changes in ice-sheet dynamics. In order to resolve this and to elucidate BIIS interaction with ocean-atmosphere events over the last glacial cycle, systematic subglacial bedform and sediment mapping, constrained by robust ice-marginal chronologies, is crucial. This paper reports our attempts to identify and assess subglacial bedform overprinting at the former centre of the BIIS during the last glacial cycle with respect to the location of palaeo-ice divides, dispersal centres, flow trajectories and flow phasing. We specifically address the interactions between shifting ice masses in the three critical areas of ice buildup and dispersal (Southern Uplands, Lake District, Central Pennines) and establish their changing flow patterns and phasing. This has been achieved through reconciling the results of: a) the mapping of subglacial landforms; and b) the development of a numerically driven ice sheet model that depicts changing ice flow phases through the last glacial cycle; the model also provides a chronological framework for ice flow switching, because it is driven by the Greenland ice core record.

Subglacial bedform mapping involves the on-screen digitization of linear/streamlined landforms from NextMap Britain digital elevation model (DEM) data. This is a 5 m spatial resolution DEM derived using airborne interferometric synthetic aperture radar. Regional ice sheet flow phases are reconstructed through the identification of flow sets or assemblages of subglacially streamlined landforms that record a dominant ice flow direction. We employed the criteria of Clark (1997, 1999) and Salt & Evans (2004) to identify ice flow tracks/fans and palaeo-ice streams and determine temporal sequencing based upon overprinting. Based on the identification of their parallel conformity, length and morphology, glacial lineaments can be divided into "flow sets" (Fig. 4). A "flow set" can be defined as a collection of glacial features formed during the same flow phase and under the same conditions (Clark, 1999). Flow phase sequencing constitutes a relative chronology of ice flow events, because older flow sets are separated in time by those that overprint them. These superimposed or cross-cutting subglacial landforms survive because of the ability of ice sheets to preserve geomorphological flow features (Kleman, 1994). The co-existence of landforms superimposed at different orientations represents a palimpsest of different ice flow events and, therefore, a series of chronologically distinct relative flow phases (Boulton and Clark, 1990; Clark, 1993). Several assumptions form the basis for much of the interpretation (Kleman and Borgstrom, 1996): i) basal sliding requires a thawed bed; ii) lineations can only form if basal sliding occurs; iii) lineations are created in alignment to the local flow and perpendicular to the ice-surface contours at the time of creation; iv) frozen bed conditions inhibit re-arrangement of the subglacial landscape. In terms of ice flow evolution, cross cutting lineations can be interpreted in terms of migrating ice divides, ice stream activation and lobate retreat (Clark, 1997) all of which leave unique signatures (Fig. 5).

Smith et al. (2001, 2005) identified a series of problems with mapping glacial landforms from remote sensing datasets, including azimuth biasing, relative size of bedforms and landform signal strength (the degree to which individual landforms can be distinguished from other features). The glacial bedforms being mapped in this study are all distinctive landforms that are much larger than 5 m (the limit of the data resolution). The effect of light biasing has been lessened by repeated mapping from two orthogonal light directions (315º and 45º) and a 'bird's eye' view which reveals slope curvature by shading and flat areas as light (Smith et al., 2005).

Table 1 illustrates the glacial landforms which have been identified and mapped within the central sector of the BIIS.

Landform type	**Number mapped**
Subglacial lineations	8050
Hummocky moraine	102
Ribbed (Rogen) moraine	18
Meltwater channels	800
Eskers	13
Glaciofluvial sediment accumulations	36
Transverse ridges	3

Glacial landforms were mapped manually by on screen digitisation. A simple vector was used to digitise lineations, meltwater channels and eskers. Polygons were used to digitise hummocky moraine, ribbed (Rogen) moraine, glaciofluvial sediment accumulations, transverse ridges and the break of slope exhibited by subglacial lineations. Ground-truthing was carried out in areas of complexity to verify the mapped glacial landforms. Stoss and lee forms identified from the geomorphological mapping coupled with published erratic pathways (e.g. Goodchild, 1875; Trotter, 1929; Hollingworth, 1931) are used to interpret flow directions throughout the region.

We present local case studies of bedform overprinting in NW England as examples of the major changes in temporal ice sheet flow directions beneath the central sector of the BIIS. Regional maps of subglacial bedforms will be reported in later papers. Our results indicate significant changes in ice flow through time and a highly dynamic ice sheet dispersal centre, but due to a poorly constrained chronology for the region we can only speculate on the periods of time over which flow switching occurred. For this reason we ran a numerical model of ice sheet inception and decay for the British Isles driven by the Greenland ice core temperature record, in order to independently evaluate the potential for highly mobile ice sheet dispersal and basal flow paths.

Glacial geomorphology

We now present glacial geomorphological maps that demonstrate the complexity of ice flow in four locations around the study region. The major flow events in each location are placed in regional context with respect to changing ice sheet dispersal patterns. Each of these events can be placed into a relative age scheme based upon cross-cutting relationships, and these are then reconciled with the independently generated flow phases from our numerical modelling.

i) Eastward flowing ice in the Tyne Gap

The Tyne Gap (Figs. 1, 6a) has been interpreted as a potential eastwards flowing ice stream of the BIIS (Bouledrou et al. 1988; Everest et al. 2005) with a convergence zone generated by ice input from the Lake District and Southern Uplands (Trotter 1929) and a trunk zone demarcated by a smoothed corridor of terrain in which the W-E aligned bedrock structure has been accentuated by glacial streamlining. Geomorphological mapping of the area, coupled with erratic trains and stoss and lee forms indicates that ice flow is predominantly towards the east (Fig. 6a) but the visually striking appearance of the bedrock structure gives a false impression of W-E ice flow persistence through the last glacial cycle. Instead, a series of ice flow shifts are apparent in the overprinting of subglacial bedforms (Figs. 6b,c), suggesting a more dynamic flow pattern driven by the changing dominance of the competitive ice dispersal centres in the region. Cross-cutting patterns show that initial flow through the Tyne Gap was from the SW, from the Lake District (pink arrow, Fig. 6c). Flow then shifted to an easterly direction (green arrow and then blue arrow, Fig. 6c), indicating that ice dispersal was from the Solway lowlands and that Scottish, Southern Upland ice became more dominant. This increasing dominance of Scottish ice is evident in the final flow phase in the area, specifically down the North Tyne River from the NW, reflecting a northerly and easterly shift in the Southern Uplands ice dispersal centre (orange arrow, Fig. 6c). These flow phases help to explain the indistinct boundary between Scottish and Lake District erratics (Trotter, 1929). Ice flow through the Tyne Gap is likely to have occurred throughout all but the final phase drawdown into the Irish Sea.

ii) Opposed ice flow patterns in the Solway Lowlands

The Solway lowlands contains a complex palimpsest of cross-cutting subglacial bedforms (Figs. 1 & 7) indicative of major shifts in the competing ice dispersal centres of the region. The earliest flow phase is recorded by W-E orientated drumlins, indicative of ice dispersal from a westerly source and generated by the Southern Uplands. This flow direction must have been influenced by the presence of a strong ice dispersal centre of the Lake District and northern Pennines, because the Scottish ice was forced to flow east through the Tyne Gap (blue arrow, Fig. 7b,c). The corollary is that an ice divide straddled the outer Solway Firth. A subsequent switch in ice flow is recorded by NE-SW orientated drumlins (yellow arrow, Fig. 7b,c), indicating that ice was being drawn down into the Solway lowlands from southern Scotland. At this time dispersal centres were located over the highland terrain surrounding the Solway Lowlands and the Solway ice divide that was driving ice flow eastwards had dissipated. The final flow phase is recorded by NNE-SSW orientated drumlins, indicative of topographically controlled, deglacial flow from upland sources (grey arrow, Fig.7 b,c).

iii) Bedform overprinting in the Eden Valley

Although much of Edenside is dominated by a SE-NW orientated lineation pattern (Figs. 1 & 8a), erratic trains (Trotter 1929; Hollingworth 1931) and drumlin orientations (Letzer 1978; Mitchell & Clark 1994) reveal a complex ice flow history. In Figure 8b, mapping of stoss-and-lee drumlin forms reveals a predominantly north-westerly flow direction (red lines) in the area to the north and west of Appleby. This is in contrast to drumlin orientations to the area south and east of Appleby, towards the Stainmore Gap. Here the drumlin orientations indicate converging easterly flows (purple, green and blue lines, Fig. 8b) where ice was forced through the Stainmore Gap from the west. These two major flow phases, which have been recognised and grouped based upon the criteria of Clark (1999), are further sub-divided based upon their relative chronology. Superimposed drumlins (Fig. 8c) reveal that ice initially crossed Stainmore moving west to east. This was followed by a secondary movement in a north-west direction down Edenside towards the Solway lowlands. Drumlins deposited by the initial easterly flow are preserved in Stainmore but become increasingly rare to the west (Fig. 8b/c) where the later flow exerted a greater influence in remoulding the landscape. The northwesterly direction of the later stage of ice flow is consistent with inset sequences of glacifluvial deposits (kames; Huddart 1970) and meltwater erosional channels (Arthurton & Wadge 1981; Clark et al. 2006; Greenwood et al. 2007) that record a south-easterly recession direction by the last ice to occupy the Eden Valley.

iv) Late stage unconstrained flows in the Solway Firth

A very prominent late stage westerly flow of ice down the Solway Firth is documented by well developed drumlins on the lowlands that flank the northern Lake District (Figs. 1 & 9). The arcuate shape of the drumlin swarm associated with this westerly flow reveals that it was driven by ice flow down the Vale of Eden and driven by an ice divide that connected the Lake District and Pennine dispersal centres. Scottish ice must have been drawn down in the same direction at this time, because an easterly flow through the Tyne Gap would be glaciologically implausible. The strong westerly lineation pattern has been masked in the west by a large depositional landform in the vicinity of the town Aspatria (Fig. 9b, c). This landform comprises a flat-topped ridge which is separated from a heavily pitted terrain by a steep ice-contact NW face (black dashed line, Fig. 9c). A quarry in the flat-topped ridge displays Gilbert-type foreset beds with palaeo-current indicators that record palaeo-discharges from the NW. The heavily pitted terrain contains NW-SE trending esker ridges indicative of drainage through a former glacier snout towards the ice-contact slope of a delta (Huddart 1970). The delta foresets and pitted terrain are interpreted as the products of ice-marginal deposition into an ice-dammed lake, produced when Scottish, Southern Upland ice readvanced across the Solway Firth and blocked the local drainage off the northern slopes of the Lake District uplands (Huddart 1970, 1971, 1991). At this time ice flows in the region were driven by dispersal from upland terrains, which resulted in unconstrained advance into the surrounding lowlands. The resulting piedmont lobes were responsible for damming of glacial lakes in the Solway lowlands, as evidenced by extensive glacilacustrine sediments at the top of the Quaternary stratigraphic sequences in the region (Huddart 1971).

v) Regional summary of major ice flow phases

Based upon the four localised case studies above we identify four major flow phases in the region (Fig. 10), acknowledging that further intervening flow phases most likely exist and that not all regional flow phases are represented in every case study. Flow phase I identified predominantly from erratic trains in earlier work (e.g. Trotter, 1929), involved a dominant Scottish dispersal centre, as documented by the transport of Criffel granite erratics to the Eden Valley and the forcing of Lake District ice eastwards over Stainmore. This event is not recorded in the Tyne Gap record (Fig. 6) probably because later flows were also aligned W-E but we have indicated easterly flow through Tyne Gap at this time as this would be implicit in the regional flow patterns. Flow phase II involved easterly flow of Lake District and Scottish ice through the Tyne Gap and Stainmore Gap with an ice divide located over the Solway Firth. This explains the changing ice flow directions in the southern Vale of Eden and over the Tyne Gap. In the latter case, the shift of ice flow from northeasterly to easterly to southeasterly (Fig. 6) reflects the dissipation of the Solway Firth ice divide and the re-establishment of Scottish flows across the region, especially with the development of a north Tyne is flow. Flow phase III involves a dominant westerly flow from upland dispersal centres into the Solway lowlands and along the Solway Firth due to draw down of ice into the regional topographic low of the Irish Sea basin. This is recorded by strong lineation development in the Vale of Eden (Fig. 8), Solway lowlands (Fig. 7) and Solway Firth (Fig. 9). Finally, flow phase IV documents the unconstrained late advance of Scottish ice across the Solway Firth, clearly demarcated by the ice-contact delta at Aspatria but also probably recorded by localized valley constrained ice flows to the north of the Solway lowlands (Fig. 7b, c).

Ice flow reconstructions from numerical modelling

i) Model description

The model we develop here does not aim to reproduce an accurate reconstruction of BIIS history but rather allows us to investigate the effects of ice dynamics on ice sheet evolution and in particular their potential role in changing ice flow directions. Thus, the model includes the minimal requirements for a dynamic ice sheet model, specifically a 2-dimensional ice flow and free surface evolution. By ignoring temperature evolution within and at the base of the ice and any effects of longitudinal stresses our numerical ice sheet model is there for less sophisticated than previous attempts for modelling the BIIS or the Younger Dryas ice cap (Boulton and Hagdorn, 2006; Hubbard, 1999; Golledge et al., 2008).

A standard time-dependent 2-dimensional shallow ice approximation model (SIA) is used to simulate ice sheet evolution which is based on the 2-dimensional continuity equation for ice thickness. The flux in both horizontal directions is calculated using the SIA and Glen's flow law (Glen, 1955). At the bed, basal motion is either assumed to be zero or related to the basal shear stress to the power of 3 as similarly used for modelling the Loch Lomond Readvance by Hubbard (1999). A constant rate factor is used for the ice (isothermal) of $3.2 \cdot 10^{-24}$ $Pa^{-3}s^{-1}$ corresponding to an ice temperature of -2°C (Paterson and Budd, 1982) and an additional enhancement factor of 4 is applied to further soften the ice, as often used in ice sheet modelling (Ritz et al. 2001; Boulton and Hagdorn, 2006).

We account for the expected higher basal motion resulting from enhanced deformation of ocean sediments by enhancing the sliding coefficient in our sliding relation by a factor of 10 (from $6.4 \cdot 10^{-14}$ Pa^{-2} $a^{-1}m$ to $6.4 \cdot 10^{-13}$ Pa^{-2} $a^{-1}m$) in areas which are below sea level at present. Thus, for the same basal shear stress, the resulting sliding velocity over ocean areas is 10 times higher than over land-based areas. A simple local relaxation scheme is used for isostatic bedrock adjustment (Oerlemans 1980). At the marine boundary of the ice sheet a flotation criterion has been applied that basically removes any ice below flotation (Van der Veen 1996; Vieli et al. 2001).

The mass balance is calculated from considering the annual balance between accumulation and ablation. Ablation is calculated using a positive degree day model (Reeh, 1989) with a correction of temperature relative to the present day temperature (average from 1971-2000) to account for elevation changes of the ice sheet surface. Furthermore, temperature perturbations can be applied with time for forcing changes in mass balance.

Accumulation is estimated using the present day precipitation field (average from 1971-2000) as a reference and applying several corrections. Altitude and the prevailing wind direction from the west strongly affect the present precipitation pattern of the British Isles. These effects have been accounted by a correction for altitude change relative to the present surface elevation and a correction for the changing surface slope in the prevailing wind-direction, as used by Payne & Sugden (1990) for moisture calculations. A further correction is applied to account for the temperature dependency of precipitation as a result of reduced moisture content in the air with decreasing temperature (Marshall et al. 2002; Huybrechts et al. 1991). Overall, our model for mass balance involves 6 model parameters which have been chosen within the suggested values from the literature and if necessary have been further constrained by the basic tuning process below.

ii) Settings and tuning of model parameters

The horizontal grid-size is 10km and a time-step of 10 years has been used. The mean surface topography over each 10km x 10km grid cell has been taken as input surface topography and has been corrected by adding one standard deviation of each grid cell to correct for the smoothing effect in mountainous areas from the gridding processes. The prevailing wind-direction is assumed to be from 250 degrees (approximately WSW) and is kept constant over time. An implicit finite-difference scheme is used to predict the thickness evolution. The forcing in temperature anomaly (Fig. 11a) is derived from the $\delta^{18}O$ GRIP ice-core as provided for the EISMINT experiments (Dansgaard et al. 1993; Huybrechts 1998) and is used as input to determine mass balance. Sea level has been kept constant at current level over the whole model run period.

Using the GRIP ice core temperature-forcing, the model has been run over the last 43ky BP. The model parameters within the mass balance model, the rate factor and the sliding coefficient have then been tuned to match three main constraints: First, to match the extent of the Younger Dryas ice coverage; second, ice free conditions before the Younger Dryas event; and third an approximate agreement with the current knowledge of ice sheet extent (cf. Bowen et al. 2002; Clark et al. 2004; Evans et al. 2005; Ó Cofaigh & Evans 2007). This provided good constraints for most of the parameters within the model. We deliberately did not further tune the model to match specific evidence from geomorphology such as our observed flow direction sets (Fig. 6-10), because our aim was to independently investigate the effect of ice dynamics on flow directions rather than to reproduce the observations. The results are also in general agreement with earlier modelling reconstructions for the LGM (Boulton & Hagdorn 2006) and the Younger Dryas ice sheet (Hubbard 1999; Payne & Sugden 1990). An additional model run starting from 120ky BP also showed that the start point of 43ky is justified as it turned out to be ice free at that time. Also, the same model run with lower horizontal grid-resolution using 20km showed qualitatively very similar results.

iii) Results and discussion of modelling

The modelled history of the BIIS is summarized in terms of ice volume in Figure 11a and shows fluctuations of smaller ice caps before 30 ka BP, followed by a more or less continuous growth into an extensive LGM ice sheet. The forcing mechanism for this behaviour appears to be the length of the period of significantly lower temperatures; the model requires a long enough period of significantly lower temperatures to grow to its full LGM extent (Fig. 11). Most importantly with respect to NW England and SW Scotland, the model grows initially upland ice masses over the Lake District /Pennine area from which ice flows radially and then around 27 ka BP joins the Scottish ice cap (Fig. 12). The extensive period of continuously low temperatures from 26 to 19 ka BP then allows the ice sheet grow to its full LGM extent (Fig. 11 and 13a). The LGM-extent is reached at 19.5kyBP and is maintained for only 1000 years, with recession taking place after 18.5kyBP and then proceeding very rapidly over the next 2500years (Fig. 11 and 13). The recession from the LGM also displays a complex pattern (Fig. 14), with distinctly faster retreat rates in areas currently occupied by ocean and the development of several individual upland ice domes towards the end of deglaciation.

The modelled flow trajectories at different time slices during the recession from the LGM reveal significant ice flow directional switches over NW England/SW Scotland (Figs. 14 and 15). Particularly significant are the relatively short timescales (few hundreds of years) over which these shifts in flow pattern occur. The modelled retreat pattern and the ice flow trajectory changes seem to be a result of dynamical processes: firstly, the prescribed enhanced ocean area leads to a more efficient mass transfer and therefore preferential draw down of the ice surface over such areas; secondly, calving leads to accelerated retreat over marine over-deepenings; and thirdly, and important for the ice flow directions towards the end of the deglaciation, is the effect of the underlying bed topography once the ice sheet has thinned substantially. We have validated this positive relationship between ice flow acceleration and marine re-entrants by running additional models with the same, land-based sliding coefficient over land and ocean surfaces, and these have revealed far less variable retreat rates and less pronounced flow direction changes over time.

Due to the coarse resolution of the grid cells in our numerical ice sheet model, it is difficult to make firm conclusions on localized ice flow patterns in the region. However, changes in regional flow pathways are clearly reproduced by the model, highlighting the switches in basal ice flow trajectories that are associated with mobile ice divides. This mobility and flow switching allows us to have confidence in our reconstructions of rapid temporal overprinting of the subglacial bedforms of NW England and SW Scotland (cf. Salt & Evans 2002).

Some chronological control based on radiocarbon dated till stratigraphies (expressed from here on in calibrated years) around the Irish Sea Basin, the area into which the NW sector of the BIIS sheet was draining, allow us to independently reconcile the developmental stages of our sheet model. The southernmost limit ice sheet advance has been dated on the SE coast of Ireland by Ó Cofaigh and Evans (2007) at <23.9ka, when a large ice stream drained southwards down the Irish Sea Basin from the centre of the BIIS (Evans & Ó Cofaigh 2003; Boulton & Hagdorn 2006). By the time of the Clogher Head readvance at 18.3-17.0ka and the Killard Point Stadial some time after 17.0ka (McCabe & Clark 1998, 2003; McCabe et al. 1998, 2005, 2007), the ice sheet margin had receded to the northern end of the Irish Sea Basin and was fed by outlet lobes draining through the major re-entrants such as the Solway lowlands. At this time ice would have been streaming westwards from the upland dispersal centres in response to draw down into the deepening waters of the Irish Sea (cf. Eyles & McCabe 1989). Our numerical model depicts south-south westerly ice flow to ice margins lying over the Irish Sea basin during the 18.5 and 16.5ka time slices (Fig.13 and 14), the latter being located in the northern part of the basin in the vicinity of the Killard Point Stadial ice-marginal landforms and sediments. We therefore have confidence that our model, bearing in mind that it has a coarse spatial grid resolution, is a reasonable fit to the reconstructed late Quaternary history of the region. This allows us to make some realistic conclusions about rates of ice flow trajectory changes during the later stages of the last glacial cycle.

Integration of modelling and glacial geomorphology

Both palaeoglaciological reconstructions (e.g. Dyke & Morris 1988; Boulton & Clark 1990a, b; Clark 1993, 1997; Clark & Meehan 2001) and modern ice sheet observations (e.g. Bamber et al. 2000) have clearly demonstrated that basal flow can be complex and subject to significant switching over short timescales. This has been demonstrated also for the central part of the BIIS by Mitchell (1994, 2007), Salt and Evans (2002) and Mitchell & Riley (2006) and so it is unsurprising that the subglacial bedform record of NW England reflects the dynamic and mobile nature of the ice sheet during the last glacial cycle. This reflects the tendency for ice sheets to preserve geomorphological flow features (Kleman, 1994), revealing a palimpsest of cross-cutting relationships (Boulton & Clark 1990a, b; Clark 1993) and therefore, a series of flow phase relationships.

The ability to preserve landforms is pervasive within the ice-sheet system (Kleman, 1994) and occurs when basal shear stress is lower than bed strength (Clark 1999). This can relate to cold-based ice (Kleman & Borgstrom 1994), low velocity such as at ice divides, and shallowing of the deformation layer (Clark, 1999), as well as the period of time that the sediment is exposed to streamlining (Kleman & Borgstrom 1996). Kleman (1994) also infers that preservation of more robust landforms like drumlins can be ubiquitous with warm based conditions. In north-west Sweden Kleman (1992) was able to reconstruct a relative chronology and basal thermal regime history of flow events using morphological and cross-cutting criteria. Formation of composite subglacial landform assemblages has been recognised for a long time (Rose & Letzer 1977) and it is now recognised that cross-cutting refers to an intermediate stage in the complete re-organisation of the bed (Clark 1994). The frequently pervasive occurrence of such cross-cutting suggests that the erosive nature of ice sheets has been overestimated in the past, and ice in fact mainly re-distributes sediment to various levels of attenuation dependent on such factors as substrate rheology, basal thermal regime and duration of flow phases. However, deciphering the numerous and often rapid changes in ice flow directions during even one glacial cycle, due to the spatial and temporal variability in subglacial bedform modification, requires us to make difficult correlations between localized swarms of overprinted features. The large areas of lowland topography in NW England have imparted warm-based, sliding characteristics on large areas of the BIIS bed in the region, giving rise to a complex overprinted bedform signature from which we have deciphered regional flow complexities (Fig. 10). We now attempt to reconcile our ice flow phases with broader scale ice flow histories and our independently constructed numerical model. Given that bedform preservation will deteriorate with age, especially as similar ice flow trajectories have affected most areas in the study region more than once through the last glacial cycle, we have worked chronologically backwards through the numerical model when assigning relative ages to the bedform flow phases. In summary, all of our flow phases can be accommodated by the post 18.5ka BP period in the numerical model, although there is a possibility that some bedforms might have survived from previous flow phases.

Our numerical ice sheet model indicates that the BIIS developed an elongate, triangular-shaped dome at the LGM, centred over SW Scotland and widening towards the northern part of the Irish Sea basin and NW England and coalescing with the Irish sector of the ice sheet. The longest, N-S orientated ice divide on this dome migrated eastwards between 18.5 and 16.5ka to be located over the highlands of NW England and SW Scotland, where it was connected to residual Irish ice by a saddle over the north Irish Sea basin (Fig. 13).

Our modeled time slices of 18.5, 16.5, 16.0 and 15.7ka (Fig. 14 and 15) allow us to assess the impact of this ice divide shift on regional flow trajectories, although the coarse resolution of the underlying topographic grid restricts us from making firm correlations between model time slices and geomorphogically defined flow phases.

At 18.5ka, the westward location of the ice divide resulted in the driving of ice flow towards the east across the study region. This resulted in the incursion of Scottish ice into the northern Pennines and vigorous flow along the Tyne Gap. The easterly orientated bedforms of flow phases I through II (Fig. 10) were most likely moulded at this time, although the phase I southerly incursion of Scottish ice to the southern end of the Vale of Eden can not be accommodated in the modelled ice configuration, because Lake District ice is involved in the vigorous easterly flow. Rather, it is the later time slice at 16.5ka when the Lake District part of the dispersal centre initiates some radial flow over NW England and produces some southeasterly ice flow up the Vale of Eden. Although this could have potentially transported Scottish erratics southwards, it is most likely that the Scottish material had been delivered previously to the Solway lowlands from where it was then carried by more local ice; flow of Scottish ice up the Vale of Eden and through Stainmore is glaciologically implausible in our numerical model. Although we have no ages for the Scottish erratics in the Vale of Eden, they could have been transported initially to NW England during a previous glaciation (glacial lake sediments between Scottish and Eden Valley tills at Langwathby do record a break in ice coverage at some time) and/or during Salt and Evans's (2004) southerly and southeasterly flows. Even though some of Salt and Evans's (2004) flow stages may not date to the last glacial cycle, they can still be accommodated in our numerical ice sheet model. Specifically, the southeasterly flows on the east side of the Southern Uplands may relate to the 18.5ka time slice when the ice divide was driving regional Scottish ice in a southeasterly direction over the region; this was also a flow direction forced upon the Southern Uplands ice mass by the more powerful Highland ice flowing southwards from the Firth of Clyde (Salt & Evans 2004). This vigorous southerly flow of Highland ice is recorded on the Isle of Man, where Roberts et al. (2007) identify an early flow phase when Scottish Highland ice moved in a southeasterly direction, pinning Southern Uplands and Lake District ice masses against the Cumbrian coast. The later easterly migration of the Southern Uplands ice divide clearly initiated southerly to southwesterly flow over NW England until 16.0ka, explaining the development of subglacial bedforms during Stage A towards the southwest, pre-Stage B towards the south, Stage B towards the southwest and Stage C towards the south-southwest. This change if flow dominance is recorded also on the Isle of Man where Roberts et al. (2007) report a younger phase of south-westerly orientated striae, erratic trains and bedforms; the change in ice flow direction over the Isle of Man is accommodated in the 18.5 and 16.5ka time slices from our numerical model.

The flow of both Lake District and Scottish ice along the Tyne Gap during phase II is best replicated by the 16.5 and 16.0ka time slices. The likely changes in ice flow directions through phase II are recorded on the north side of the Tyne Gap where the shift of ice flow from northeasterly to easterly to southeasterly reflects changing dominance between Lake District and Scottish ice input to the regional easterly flow and also the dissipation of the Solway Firth ice divide and re-establishment of Scottish flows across the region. Our model, however, does not reproduce this particular flow shift, which may be due to the spatial and temporal resolution of the event. At 16.0ka the draw-down into the Solway Firth resulted in very vigorous ice streaming over the northern coastal fringes of the Lake District, giving rise to the production of the strongly drumlinized terrain associated with flow phase III.

The 15.7ka time slice shows not only an easterly migration of the main ice divide to the east of the Solway lowlands but also the establishment of localized upland dispersal centres from which ice flowed radially down the Eden Valley and the Southern Upland valleys into the fringes of the Solway lowlands (Stages F-G of Salt & Evans 2004). Ice margins at this time are recorded by significant ice-marginal landform-sediment assemblages in glaciated valley settings, such as those demarcating the Eden Valley glacier at the “Brampton kame belt” and associated Pennine escarpment meltwater channels (Arthurton & Wadge 1981; Clark et al. 2006; Greenwod et al. 2007). Overprinted drumlins have been used to verify the late reversal of ice flow in the Vale of Eden (Mitchell & Riley 2006) and to reconstruct the local ice divide migration over the western Pennines and Howgill Fells (Mitchell 1994). Either at this time or earlier (i.e. immediately after flow phase III), an uncontrained readvance of Scottish ice impinged upon the southern shore of the Solway Firth to construct the Aspatria ice-contact delta. Although we have assigned this flow phase IV, our numerical model does not replicate any such readvance, making it likely to be a late stage dynamic ice marginal response to rising sea levels and/or early dissipation of Lake District ice flow in the Firth. In the circumstances a surge origin can not be dismissed, explaining why the climatically driven model does not replicate phase IV. Moreover, Salt and Evans (2004) have previously identified a late stage readvance by Scottish ice into Loch Ryan (Stage G, "Stranraer Readvance"), indicating that pulsed recession/surging may have been a characteristic of the Highland ice as it retreated in contact with deepening marine water along the Scottish coast.

Our knowledge of the patterns of glacierization of landscapes with diverse topography allows us to make some realistic interpretations of the early stages of ice flow in the study region, which can in turn be reconciled with both existing data on erratic dispersal and our numerical model. The well established principle of "instantaneous glacierization" (Ives et al. 1975) implies that upland landscapes such as the Lake District fells, the North Pennine plateaux and the Southern Uplands will have developed an ice cover first, leading to the radial flow of valley glaciers into the lowlands of the Eden Valley, Tyne Gap and Solway Firth. This ice would have effectively drained unimpeded into the northern part of the Irish Sea Basin until Scottish Highland ice advanced far enough south to wrap around the Southern Uplands ice mass and up against the Cumbrian west coast, causing NW English/SW Scottish ice over the Solway to thicken as illustrated by the numerical modelling in Figure 12. This thickening would have caused regional ice flow to reverse, invigorating easterly flow along the Tyne Gap and forcing ice up the Eden Valley and over Stainmore, thereby wrapping around the plateau-based local ice of the Cross Fell area and forcing it to flow east (Mitchell 2007). During deglaciation this sequence of flow switching should logically be reversed, although some readvances may have resulted in localized flow adjustments as glacier margins were drawn down into proglacial lakes or the deepening sea. An example of the reversal of the ice sheet inception pattern is the final phase of deglaciation in the Eden Valley, which was characterized by ice recession southwards (our phase III) and onto the North Pennine/Cross Fell plateau, as documented by the inset lateral meltwater channels and kame terraces of the Melmerby-Brampton area (Arthurton & Wadge 1981; Clark et al. 2006; Greenwood et al. 2007).

Conclusions

A number of important conclusions have arisen from our dual approach to deciphering the palaeoglaciology of the central sector of the BIIS. Firstly, with respect to the glacial geomorphology of the region:

- Systematic mapping of subglacial bedforms from four case studies around NW England has identified overprinted subglacial bedforms, which relate to temporally superimposed flow sets indicative of complex ice sheet flow dynamics. The bedform signature of former ice sheet flow is of a complexity similar to that previously reported for the Southern Uplands (Salt & Evans 2004), immediately to the north of the study region but, more significantly, records reversals in glacier flow during glaciation.
- Large scale cross-cutting bedform patterns can only have been produced by significant shifts in ice dispersal centres through time and we have identified four major phases of regional ice flow in order to simply accommodate all the localized overprinting. Flow phase I involved dominant Scottish ice flow and the forcing of Lake District ice eastwards over Stainmore. Flow phase II involved more rigorous flow from the Lake District, Howgill and Pennine uplands, resulting in easterly flow of Eden Valley and Scottish ice through the Tyne Gap and Stainmore Gap with an ice divide located over the Solway Firth. Flow phase III involved a dominant westerly flow from all upland dispersal centres into the Solway lowlands and along the Solway Firth and this was locally masked by the deposition of an ice-marginal delta during flow phase IV when Scottish ice readvanced southeastwards across the Solway Firth.

Secondly, with respect to numerical ice sheet modelling we identified a number of significant factors that complement our geomorphologically-based assessments of palaeo-ice dynamics:

- Modelled ice sheet recession rates are very rapid, with the SW Scotland/NW England sector of the BIIS remaining as a major dispersal centre for only around 2,500 years after the LGM. Our model depicts a dynamic ice sheet with no real steady state and constantly migrating dispersal centres and ice divides. This dynamism is consistent with the ice flow phases recorded in the superimposed bedform record, and moreover implies that the subglacial streamlining of flow sets was most likely imprinted on the landscape over short phases of fast flow activity and during the recession from LGM, with some flow reversals taking place in less than 300 years.
- The modelled pattern of ice sheet recession reveals greater thinning over oceans and flat lying terrestrial areas and this in turn initiates rapidly evolving flow changes, particularly draw down into marine/estuarine re-entrants during overall ice sheet wastage.
- Our modelling has produced complex recession and flow change patterns with a very unsophisticated numerical ice sheet model and parameter setting and is governed entirely by internal flow dynamics. It has not been necessary to incorporate "on and off" switches for ice streaming nor have we needed to invoke a complex temperature evolution. It is as such a far simpler model than that of Boulton and Hagdorn (2006) but it still depicts the basic dynamic features necessary to explain the complex and enigmatic subglacial bedform signature of NW England.
- During the short and vigorous deglaciation depicted by our model, there is a strong potential to generate large volumes of meltwater, which in turn feedback into vigorous concurrent subglacial bedform modification and contribute to the carving of dense networks of glacifluvial meltwater drainage channels, such as those in the Vale of Eden.

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Figures

Figure 1: Location map of the central sector of the BIIS with areas covered by case studies located by boxes and names of sites mentioned in text. The research area includes the Southern Uplands, Lake District, Alston Block, Vale of Eden, Solway lowlands, Tyne Gap and Stainmore Gap.

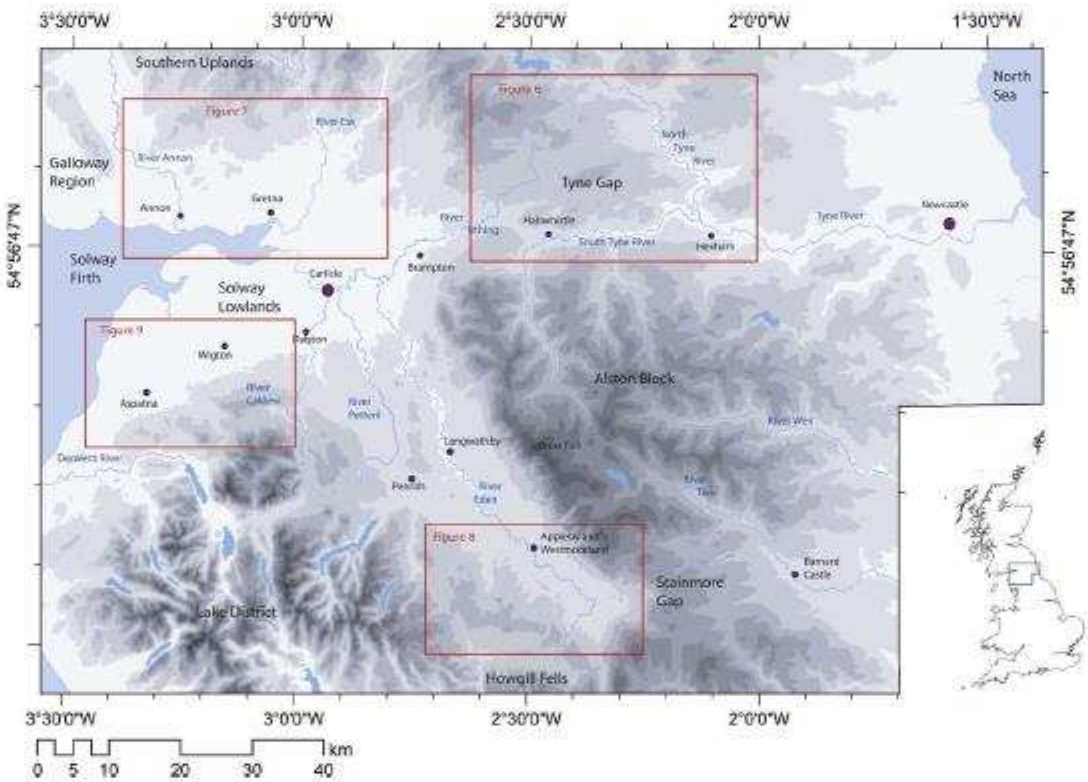


Figure 2: Early interpretations of glacier flow directions in the central BIIS based on Trotter (1929, above) and Hollingworth (1931, below).

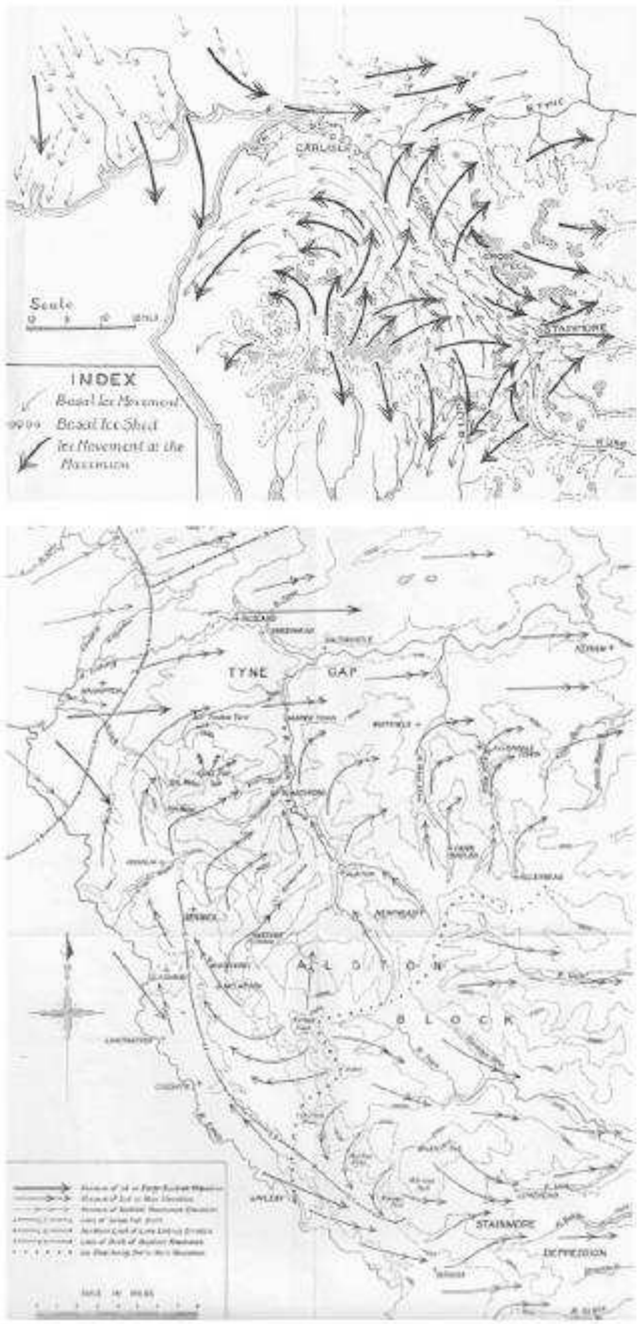


Figure 3: Map of cross-cutting flow sets in SW Scotland (from Salt & Evans 2004).

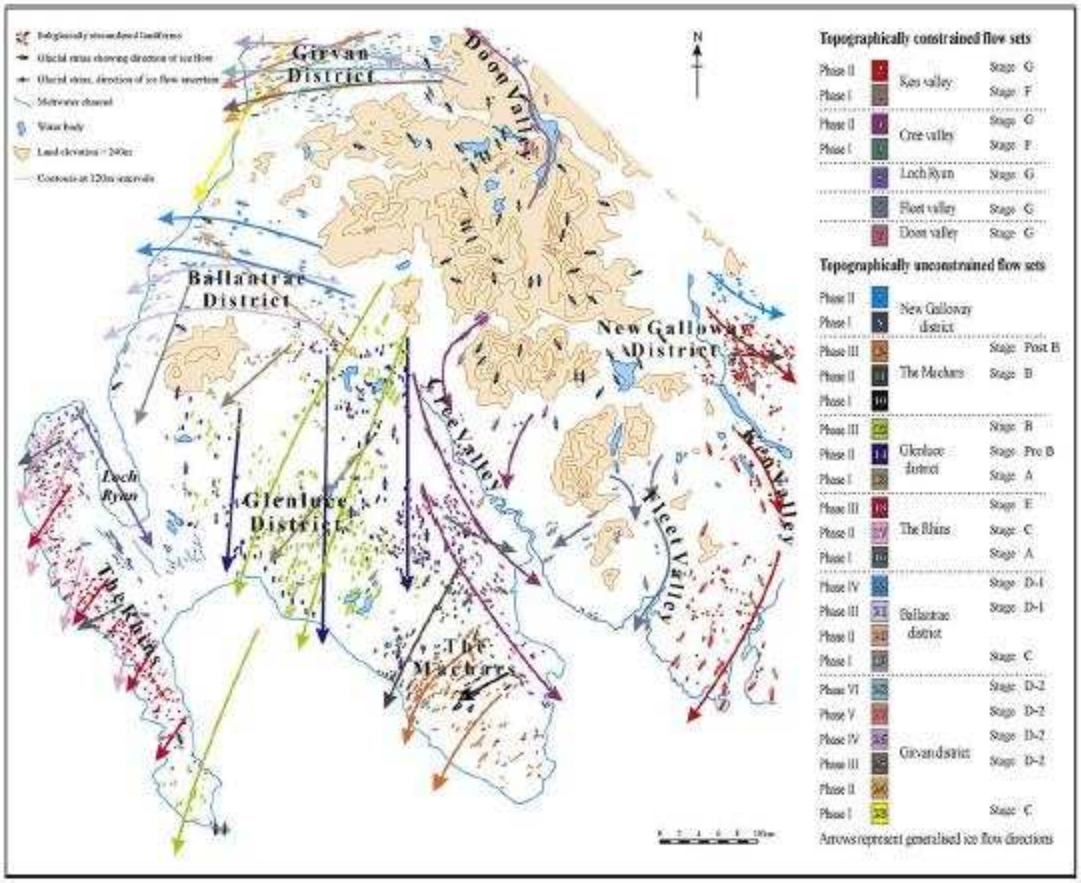


Figure 4: Schematic diagram to show the procedures employed in the grouping of subglacial flow sets: (a) the raw data showing lineation pattern of two separate sets of bedforms; (b) example of outdated attempts to interpret flow direction from lineations by blending the bedforms of two separate and overprinted ice flows; (c) example of more recent approach to separate the bedforms and interpret them as the products of two flow sets; (d) morphological criteria for flow set characterisation (from Clark 1997).

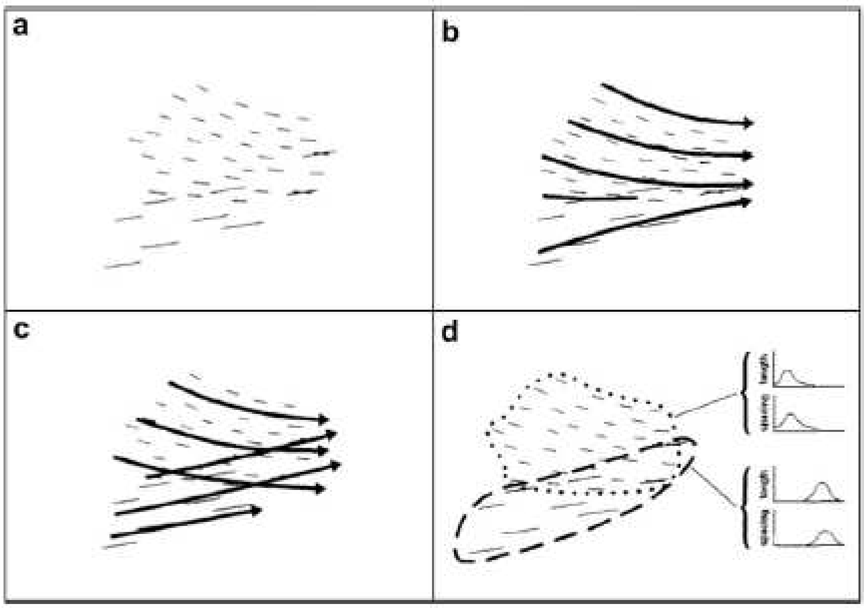


Figure 5: Three conceptual models of subglacial bedform overprinting (from Clark 1997). Upper diagram shows the impact of ice divide migrations through time, producing four cross-cutting flow sets at one example location. Middle diagram shows the imprints of ice stream flow, in trunk or onset zones. Lower diagram shows the impact of lobate margin recession.

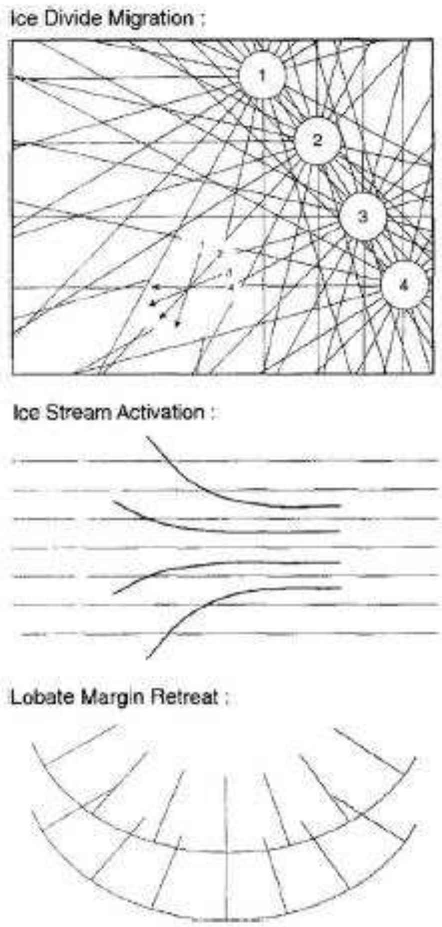


Figure 6: Glacial geomorphic evidence of eastward flowing ice in the Tyne Gap (for details see text). Illumination azimuth: 315º. NEXTMap Britain data from Intermap Technologies Inc were provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC).

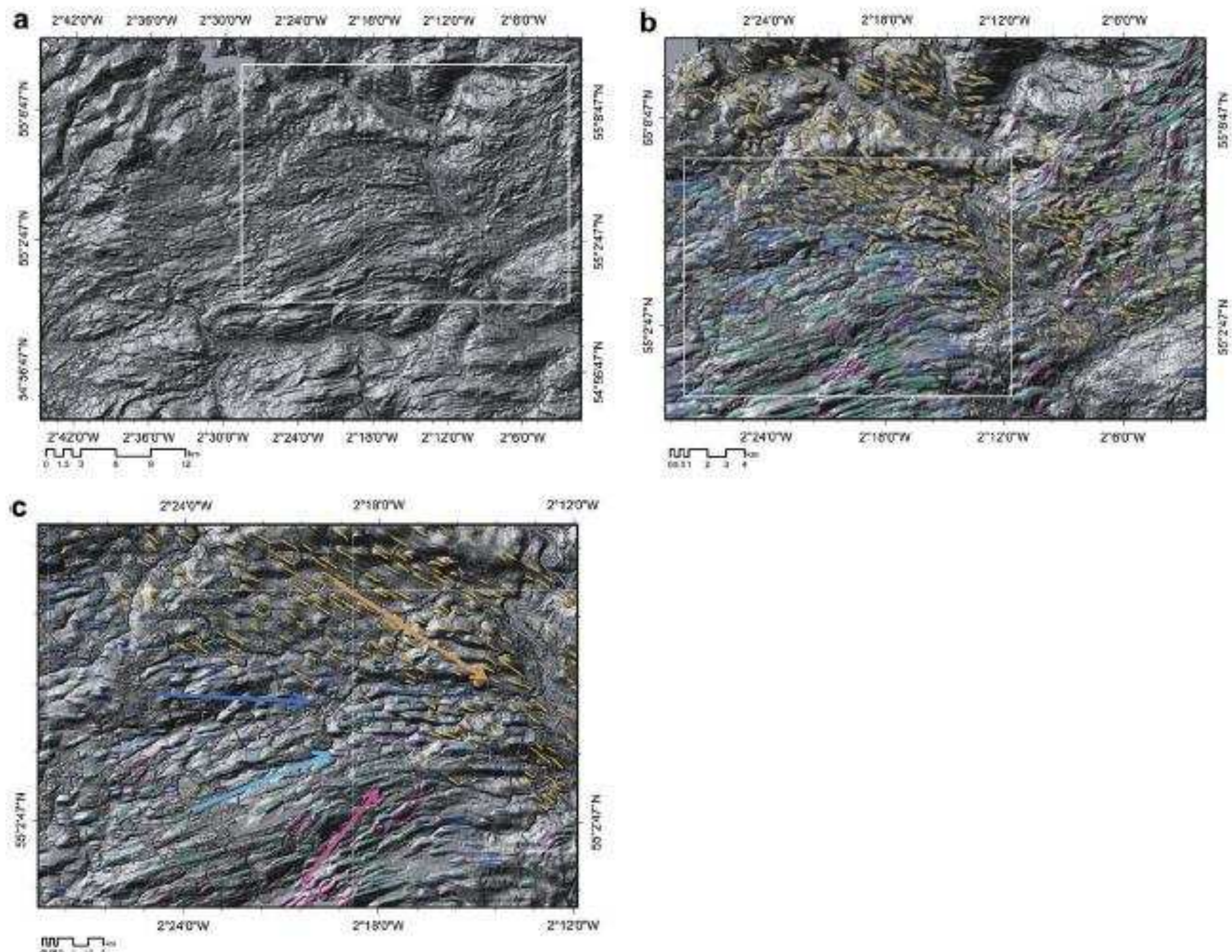


Figure 7: Glacial geomorphic evidence of opposed ice flow pattern in the Solway Lowlands (for details see text). Illumination azimuth: 315º. NEXTMap Britain data from Intermap Technologies Inc were provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC).

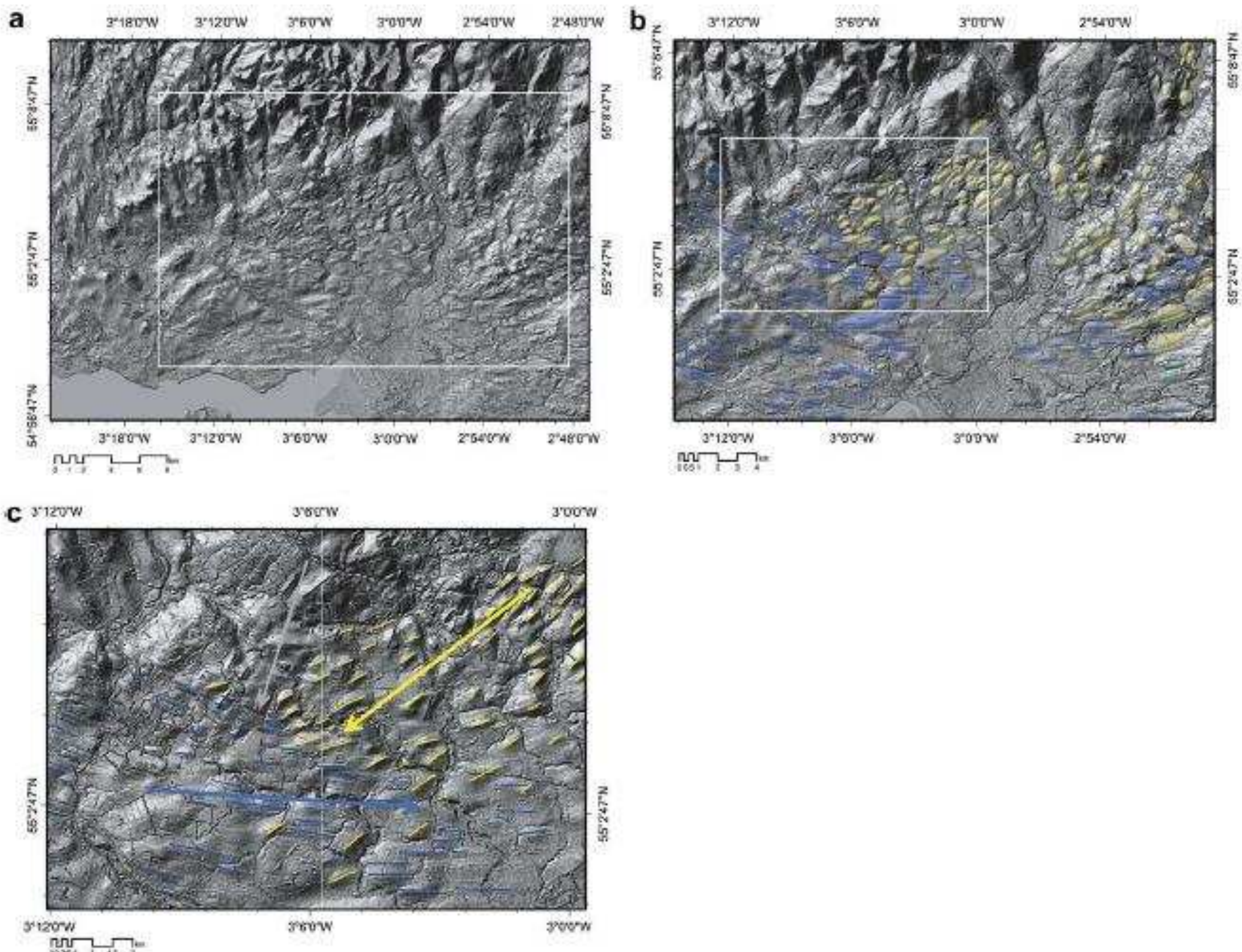


Figure 8: Glacial geomorphic evidence of bedform overprinting in the Eden Valley (for details see text). Illumination azimuth: 315º. NEXTMap Britain data from Intermap Technologies Inc were provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC).

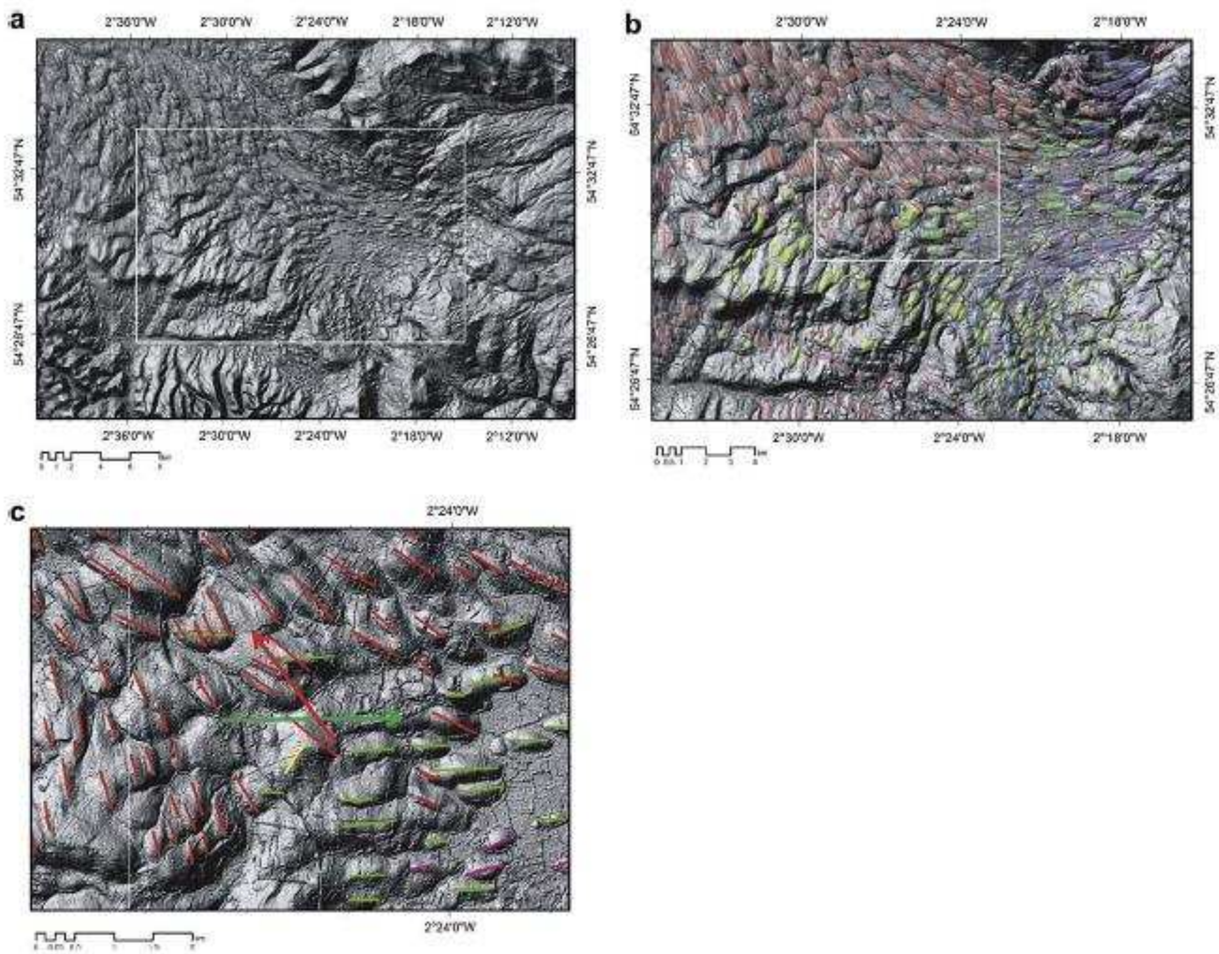


Figure 9: Glacial geomorphic evidence of late stage unconstrained flows in the Solway Firth (for details see text). Illumination azimuth: 315º. NEXTMap Britain data from Intermap Technologies Inc were provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC).

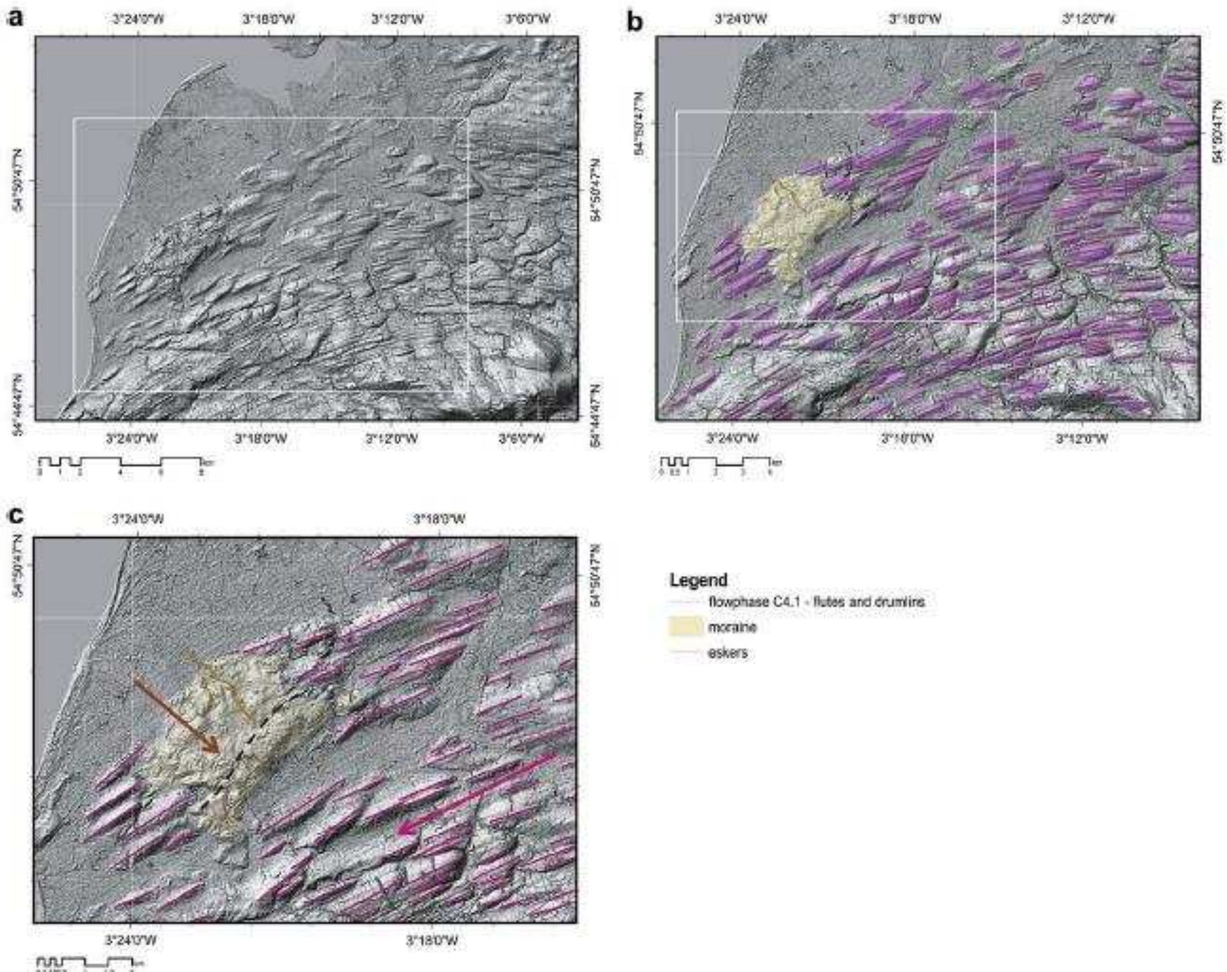


Figure 10: Summary maps of major flow events identified in the subglacial bedform mapping. Topography is derived from the SRTM dataset and the box represents the area of mapping.

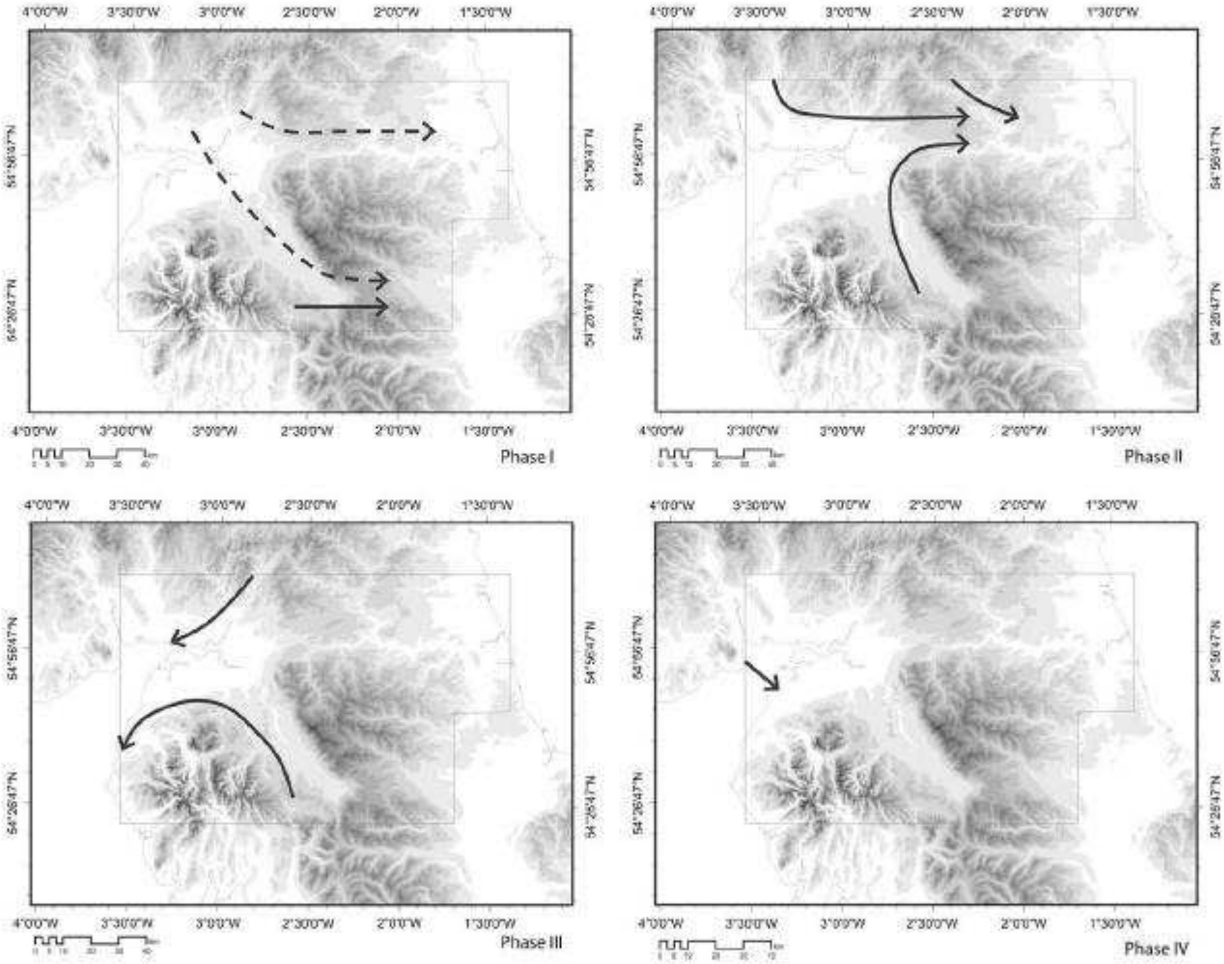


Figure 11: (a) Temperature anomaly from present with time derived from $\delta^{18}O$ ice core record (Daansgard et al 1993; Huybrechts 1997) which is used as forcing the mass balance input for the ice sheet model; (b) modelled ice sheet volume of the BIIS over the last 45 ka.

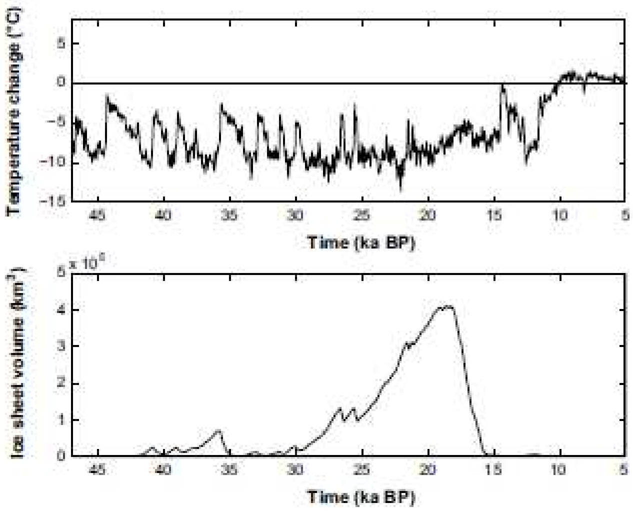


Figure 12: (a-d) Maps of modelled surface elevation (colours in m a.s.l.) and ice flow trajectories (black lines) of the BIIS during build up to the LGM, for the labelled calendar years before present, through the coalescence of upland icefields from 27.6 to 26 ka BP. The black rectangular frame indicates the outline of the zoomed area in figure (d) which shows a map of overlain flow trajectories from Figure (a-c): yellow lines = 27.6 ka BP, pink lines = 27.0 ka BP, blue lines = 26.0 ka BP. The brown areas indicate the present land surface.

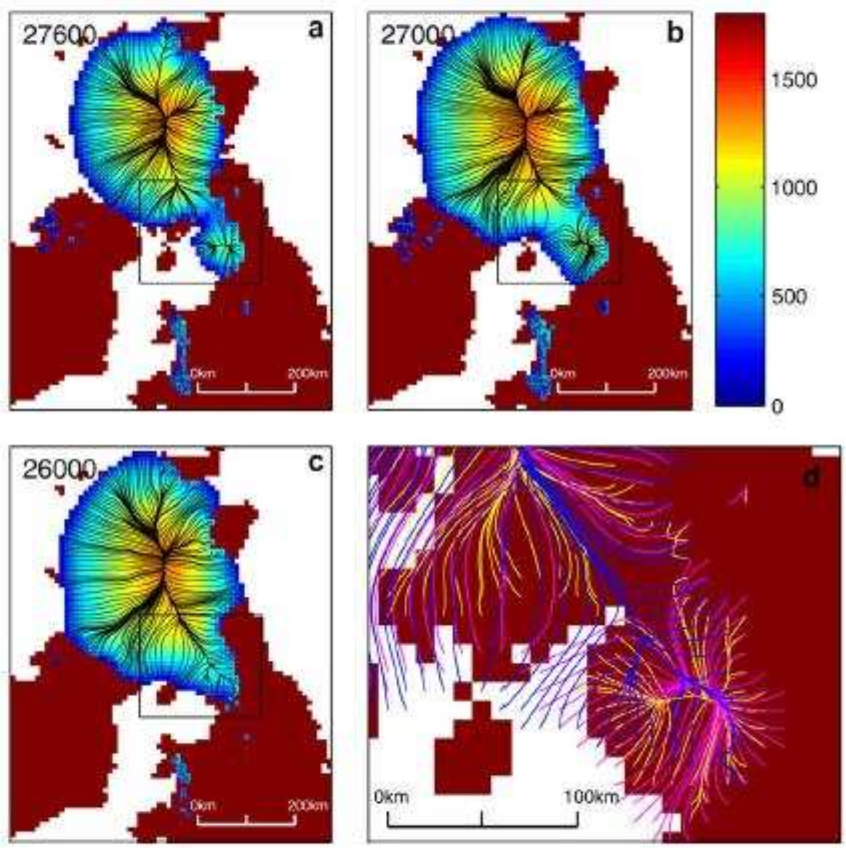
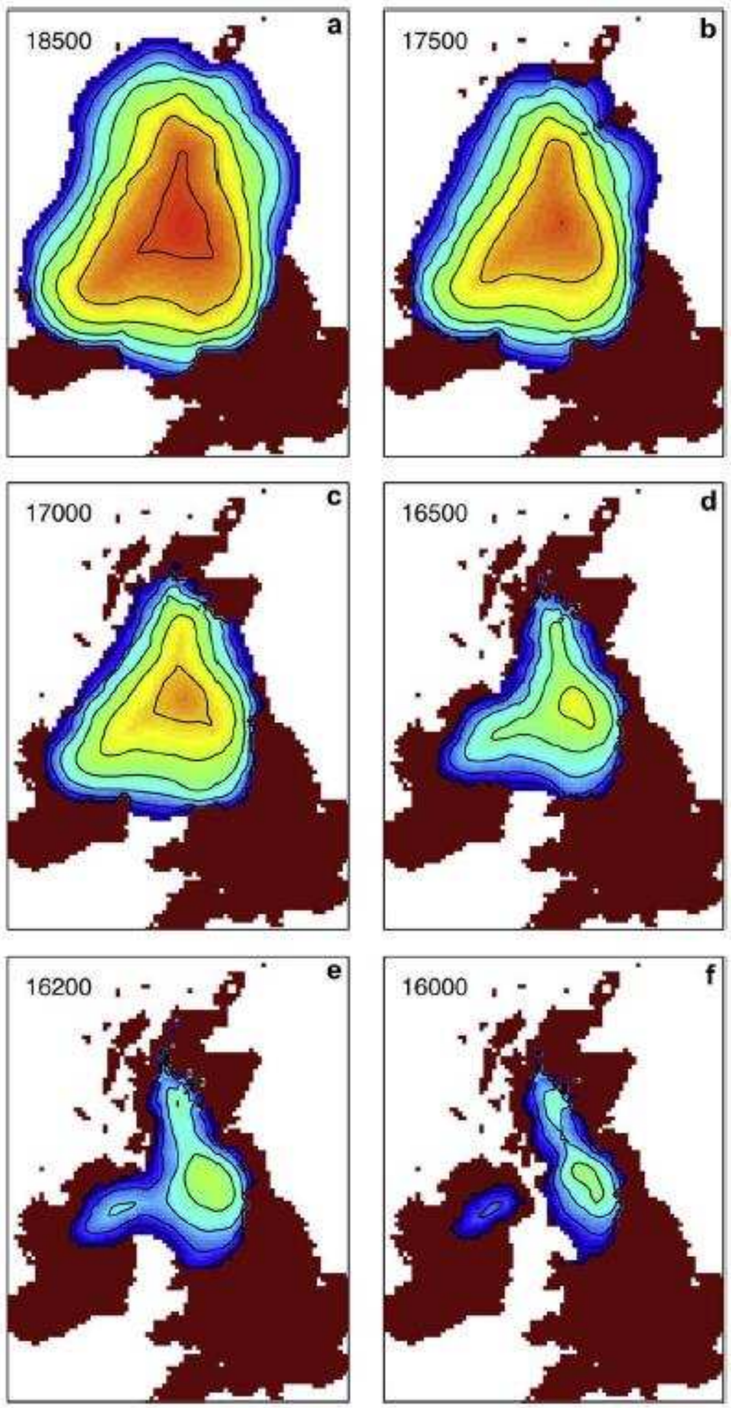


Figure 13: (a-i) Maps of modelled ice surface elevation (contours and colours in m a.s.l., 200m contour interval) of the BIIS during retreat from the LGM for the labelled years before present and postdating 18.5 ka BP. The brown areas indicate the present land surface.



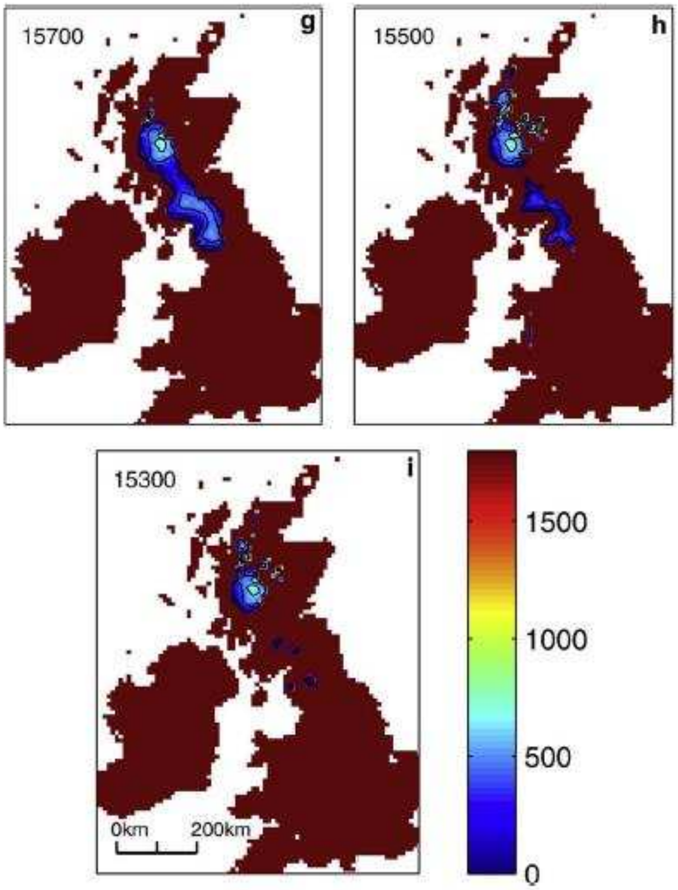


Fig. 13. (continued).

Figure 14: (a-d) Maps of modelled surface elevation (colours in m a.s.l.) and ice flow trajectories (black lines) during deglaciation of the BIIS for the labelled years before present. The black rectangular frame indicates the outline of the zoomed area in Figure 15.

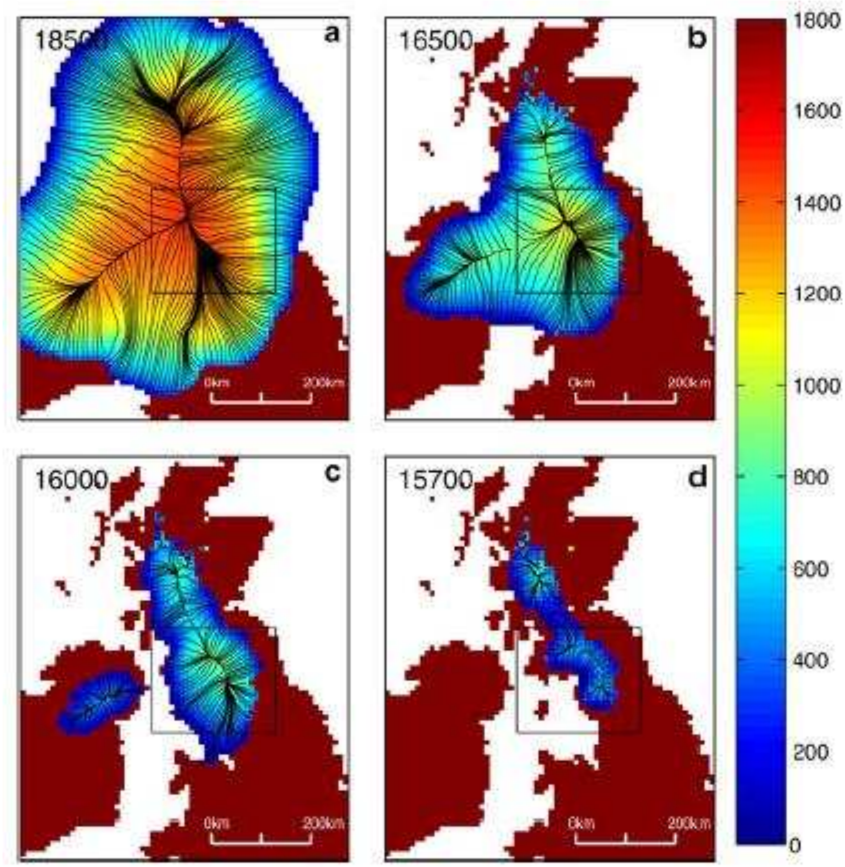


Figure 15: Map of overlain ice flow trajectories of the 4 flowsets for the different times slices in Figure 14: yellow lines = 18.5 ky BP, pink lines = 16.5 ky BP, green lines = 16.0 ky BP and blue lines = 15.7 ky BP.