eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Glacial geomorphology of the central sector of the last British-Irish Ice Sheet

Stephen J. Livingstone, Colm Ó Cofaigh and David J. A. Evans

Department of Geography, Durham University, South Road, Durham, DH1 3LE, UK;
s.j.livingstone@dur.ac.uk

Abstract:
We here present a glacial geomorphological map covering 11,800km^2, at a scale of 1:550,000, of the central sector of the last (Main Late Devensian) British-Irish Ice Sheet. The map is based on the 5m resolution NEXTMap dataset. Six landform types have been mapped; subglacial lineations, hummocky terrain, ribbed moraine, meltwater channels, eskers and glaciofluvial sediment accumulations. The subglacial lineations have been further sub-divided into a series of 'flow sets' based on their morphology, conformity and length. Over 9,000 individual landforms have been identified within the study area, concentrated predominantly in the lowlands of the Vale of Eden, Solway and over the Tyne and Stainmore Gaps. A palimpsest geomorphic signature characterised by cross-cutting flow-sets is interpreted as evidence that dynamic, multiphase ice flow occurred throughout the Main Late Devensian (marine isotope stage 2) in response to migrating ice dispersal centres and ice divides. A relative chronology has been constructed and interpreted, based on the complex, cross-cutting flow signatures displayed throughout the region.

Introduction:
The area formerly covered by the central sector of the last British-Irish Ice Sheet (BIIS) encompasses the Solway Lowlands, Vale of Eden, Stainmore and Tyne Gap regions (Fig. 1) and contains a complex palimpsest of subglacial bedforms formed during the Main Late Devensian (marine isotope stage 2) glaciation. Previous glacial geomorphological mapping of the region (e.g. Trotter, 1929; Hollingworth, 1931; Letzer, 1978; Smith, 2002) highlighted the complexity of landforms relating to competing ice dispersal centres in the Southern Uplands, Lake District, Irish Sea and Pennines. However, the compilation of data within the BRITICE project (Clark et al. 2004; Evans et al. 2005) revealed incomplete coverage and a lack of knowledge concerning the relative and absolute timing of Late Devensian glacial events in the central sector of the BIIS. This is important because the ice-flow from the central sector of the BIIS influenced and/or controlled flow in key areas of the ice sheet such as the Irish Sea basin (e.g. Roberts et al. 2007), the Southern Uplands (e.g. Salt, 2001) and the English east coast (e.g. Raistrick, 1931).

Palaeoglaciologists now routinely acknowledge that ice sheet flow during a glacial cycle can be highly dynamic (e.g. Dyke and Morris, 1988; Boulton and Clark 1990a, b; Clark, 1997, Clark and Meehan, 2001) with several phases of flow often being preserved as a series of cross-cutting and superimposed landforms. This paper presents the glacial landform evidence of the central sector of the BIIS during the Main Late Devensian focusing on the location of palaeo-ice divides, dispersal centres, flow trajectories and relative flow phasing through the mapping of subglacial bedforms and identification of cross-cutting relationships.

Methods

<u>Imagery:</u>
The glacial geomorphology was mapped using NEXTMap data, which covers all of England, Wales and Scotland. These data comprise a digital elevation model derived from airborne Interferometric Synthetic Aperture Radar (IFSAR), which has enabled rapid assessment of the geomorphology at high spatial resolutions. The data are organised into National Grid tiles of 10 x 10km based on Ordnance Survey co-ordinates. These data have been acquired by the British Geological Survey (BGS) for NERC and are archived at NERC Earth Observation Data Centre (NEODC). Two products of the NEXTMap data were used within this project; a digital surface model (dsm) and a digital terrain model enhanced (dtme) which has been manually edited to removed human features. Both datasets have a spatial resolution of 5m (http://www.neodc.rl.ac.uk/). In addition maps of the bedrock geology and superficial deposits (DiGMapGB-625 downloaded from the BGS) were overlain onto the dsm and dtme.

Smith and Clark (2005) and Smith and Wise (2007) identified a series of problems with mapping glacial landforms from remotely sensed datasets including azimuth biasing, relative size of bedforms and landform signal strength (the degree to which individual landforms can be distinguished from other features). It has been estimated by Smith et al., (2006) that NEXTMap provides the most complete dataset for mapping, but that, in comparison to field mapping only visualises about 50% of what is on the ground. The effect of light biasing has been lessened by repeated mapping from two orthogonal light directions and a 'bird's eye' view which reveals slope curvature by shading and flat areas as light (Smith and Clark, 2005).

<u>Mapped Landforms:</u>
The table below lists the glacial landforms which have been identified and mapped. Research theory, methodology and a descriptive overview of the landforms within the study area are all discussed in this section.

Landform type	Number mapped
Subglacial lineations	8050
Hummocky terrain	102
Ribbed moraine	18
Meltwater channels	800
Eskers	13
Glaciofluvial sediment accumulations	36

Table 1: mapped glacial landforms

<u>Subglacial lineations:</u>
Subglacial lineations are used to reconstruct the glaciodynamics of the BIIS with respect to ice flow orientations, directions and relative velocities (Clark, 1997). 8050 lineations have been mapped within the field area with coverage ubiquitous throughout the lowlands (predominantly below the 400m contour). The density of coverage varies, with sparse groups both in the deglacially dominated terrain of the

Solway Lowlands, and towards the eastern end of the Tyne Gap where they become more subdued. The most densely populated regions are within the Tyne Gap and Vale of Eden. An example of these data is presented in Figure 2A which shows a heavily lineated area in the Vale of Eden with a southeast to north-westerly orientation of lineations. Streamlined landforms include drumlins, flutes, crag-and-tails and lineations which are interpreted as forming subglacially, parallel to ice flow. These features can be either constructional (till deposition) or erosional (bedrock moulded, or till eroded). It is difficult to determine, based on the geomorphology alone, which category particular lineations belong too. However, when combined with the mapped superficial deposits (BGS DiGMapGB-625), areas of bedrock moulded lineations have been picked out, such as in the Tyne Gap. The lineations have been grouped into discrete 'flow sets', defined as a collection of glacial features formed during the same flow phase and under the same conditions (Clark, 1997, 1999). The flow sets are defined on the basis of conformity, length, parallelism and morphology (Clark, 1999). Figure 2B displays a series of cross-cutting 'flow sets' west of the Stainmore Gap. The direction of flow is identified by observation of the stoss (up-ice) and lee (down-ice) forms of drumlins. In this case (Fig. 2A) the steeper stoss ends to the southeast and tapered lee ends to the northwest indicate former ice flow was to the northwest. Elongation of the lineations has been quantified (length/width) thereby allowing an approximation of relative velocity which can be assessed both spatially and temporally (Stokes and Clark, 2001; Stokes and Clark, 2002).

Hummocky Terrain:
Subglacially formed hummocky terrain is identified as irregular morainic topography characterised by elongation ratios of ca. 1:1 and therefore, indistinct orientations (as illustrated in the Solway Lowlands; Fig. 2C). Hummocky terrain is commonly associated with stagnant down-wasting ice (e.g. Eyles et al., 1999; Boone and Eyles, 2001). The 102 mapped hummocky terrain landforms are situated within the Solway Lowlands, formed in close association with ribbed moraine, at the northern margin of a flow set arcing out into the Irish Sea Basin (see map, Fig. 2C). The sequence of subglacial hummocky terrain and ribbed moraine thus seems to depict the lateral margin of the flow set, where inferred ice flow velocities were significantly reduced.

Ribbed moraine:
Ribbed moraines are subglacial ridges formed transverse to ice flow. They display a wide range of shapes and patterns and often have drumlinised ridges and transitional associations with lineations (Dunlop and Clark, 2006). This is evident in figure 2D in the Solway Lowlands, east of Carlisle, where drumlins partially overprint the ribbed moraine and a northwards transition occurs between elongate lineations to the south, which grade into more subdued and less elongate lineations and then into ribbed moraine. This transition is evident further eastwards, where the drumlins grade into hummocky terrain (Fig. 2C).

Meltwater channels:
Meltwater channels are an important record of the pattern of ice sheet retreat. However, it is often difficult to distinguish between features produced predominantly by post-glacial fluvial activity, which now dominates, and the relict meltwater channels formed during deglaciation. Holocene activity has to a certain extent been influenced by relict channels with modern streams re-occupying previous meltwater channels. Furthermore, being able to elucidate whether meltwater channels formed

subglacially, proglacially or ice marginally is crucial in distinguishing different patterns of ice sheet retreat. Therefore, the interpretation of meltwater channels relies on identifying whether they formed sub-aerially, sub-marginally or sub-glacially, and also differentiating between fluvial and glacial channels. The criteria of Greenwood et al., (2007) are used for this. 800 meltwater channels have been mapped in the study area. Especially dense channel networks are mapped along the Pennine escarpment (Fig. 2E), the Penrith sandstone outcrop (Fig. 2E), the ridge running south-west of Appleby-Westmorland (see map), the northern slopes of the Pennines (see map) and to the north of the Lake District (see map). A series of distinctive drainage network morphologies are also displayed, ranging from dendritic systems (southern ridge of the Vale of Eden) to parallel channels (northern slopes of Alston Block), anastomosing arrangements (lower Tees valley), major spillways (Dalston Gap) and isolated channels (throughout Edenside and the Tyne Gap). Channels intimately linked to lineation patterns have also been noted in areas such as the North Tyne Valley while in other areas some channels are situated transverse to lineations (Solway Lowlands). Thus, the central sector of the BIIS was associated with a myriad of meltwater channels which have been classified and used to demarcate ice-marginal positions during deglaciation.

Eskers:
Eskers are elongate, sinuous ridges of glaciofluvial sand and gravel (e.g. Fig. 2F in the Lyne Valley), that generally form parallel to the direction of ice flow (Flint, 1971; Benn and Evans, 1998). This means they are normally concurrent with the lineations with which they are juxtaposed, although divergence can occur locally due to a time separation between the formation of the lineations and eskers (Kleman and Borgstrom, 1996). Eskers form time-transgressively, close to a retreating margin (Kleman and Borgstrom, 1996) either supraglacially, englacially or subglacially (Price, 1973). Well developed networks of eskers are normally restricted to wet-bedded areas of glaciers (Kleman and Borgstrom, 1996). Of the 13 eskers that have been mapped within the study area, 4 are intimately associated with glaciofluvial sediment accumulations, for example at the Holme St Cuthbert deltaic complex (Fig. 2H) and the Brampton kame belt (Fig. 2G) (Huddart and Glasser, 2002). Other examples of eskers within the field area demarcate complex patterns of lobate retreat and stagnation, such as around the Penrith sandstone outcrop (Trotter, 1929; Huddart and Glasser, 2002).

Glaciofluvial sediment accumulations:
Glaciofluvial sediment accumulations cover a wide range of discrete landforms including, sandur deposits, kame belts, relict deltas and outwash plains. 36 accumulations of sand and gravel have been mapped within the study area (based on both the morphology and the BGS map of superficial deposits). Ice contact deltas such as at Holme St Cuthbert and Baronwood (Huddart and Glasser, 2002) are characterised by a steep ice contact face and internally have distinctive sedimentology and stratigraphy (Fig. 2H; Holme St Cuthbert). The Brampton kame belt displays very irregular topography containing kettle holes, ridges and flat topped hills (Fig. 2G), indicating that formation occurred during a complex period of stagnant, in situ downwasting (Huddart and Glasser, 2002).

Identifying complex flow:

There is a wide body of literature which recognises crossing or superimposed lineations that have been preserved beneath ice sheets during the Quaternary (Boulton and Clark, 1990; Letzer, 1987; Rose, 1987; Rose and Letzer, 1977; Salt, 2001; Salt and Evans, 2004). These superimposed 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, 1990a, b; Clark, 1993). 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 geomorphological signatures. Cross-cutting, may also relate to formation during multiple glaciations although this is unlikely to be the case in the present study as the entire study area was glaciated during the Late Devensian (Evans et al., 2005). This is further supported by the stratigraphic evidence, with the majority of glacial deposits assigned to the waxing and waning of a single ice sheet (Huddart and Glasser, 2002; Stone et al., in press) and the absence of heavily weathered till suggests that the deposits are Devensian in age (Stone et al., in press). By unravelling the complex palimpsest signature, through cross-cutting relationships identified between 'flow sets', a model of dynamic, multiphase ice flow can be reconstructed throughout a single glacial cycle.

Complex flow has been identified throughout the central sector of the BIIS. The criteria of Clark (1997, 1999) have been employed, allowing flow sets to be determined based on parallel conformity, length and morphology. Within the study area flow sets have been grouped into 8 regional zones, plus a series of individual valley lineations, based on related cross-cutting associations. The regional zones have been further subdivided into a series of flow phases, demarcating the relative ages of the flow sets, using the procedure outlined by Clark (1997). The higher the number the older the relative age of the flow set. Flow sets lacking cross-cutting evidence are not assigned to a specific flow phase because a relative age cannot be accurately inferred. Figure 3A, in the lower Vale of Eden illustrates one example of cross-cutting, with initial flow (flow phase C.4, purple arrow) moving north-westwards out into the Irish Sea Basin. This is followed by a later movement, northwards into the Solway Lowlands (flow phase C.3, red arrow) which cuts across the earlier flow. Another example, west of Stainmore Gap (Fig. 3B), illustrates how superimposition of landforms can be utilised in reconstructing the ice sheet dynamics. Initial flow was easterly through the Stainmore Gap (flow phase D4.3, green arrow). This was followed by a north-westerly flow (flow phase D4.1, red arrow) which partially remoulded the large drumlin positioned in the middle of diagram 3B, resulting in four new, superimposed drumlins. Complex flow is not just constrained to cross-cutting lineations. For example, Figure 2H illustrates the Holme St. Cuthbert deltaic complex overlying south-westerly trending lineations, and the ribbed moraine nearby have been superimposed by drumlins (Fig. 2D) which depict a later flow phase.

Elongation ratios:
Elongation ratios (length/width) provide a method for estimating the relative velocity of ice flow throughout a glacial cycle. Stokes and Clark (2001, 2002) suggest that highly attenuated subglacial bedforms characterised by high elongation ratios reflect fast ice flow. However, absolute velocities cannot be calculated as the elongation ratios are also influenced by a number of other factors including sediment supply and

texture (Rose, 1987) and duration of flow (Dyke, and Morris, 1988) associated with formation. Elongation ratios across the study area fluctuate both between, and within, individual flow sets (table 2). Most of the lineations have low mean elongation ratios (of 2:1 to 3:1) which suggest low flow velocities. An example of high elongation ratios is observed in the arcuate series of lineations to the north of the Lake District which sweep into the Irish Sea Basin (Fig. 4). The high elongation ratios (over 5:1 and as high as 12:1) relative to other flow phases in the area suggest ice was being vigorously drawn-down into the Irish Sea Basin (Eyles and McCabe, 1989; Evans and Ó Cofaigh, 2003; Ó Cofaigh and Evans, 2007; Thomas and Chiverrell, 2007). Recognisable differences between bedrock-moulded lineations and till-cored lineations can also be identified when elongation ratio data is draped with the surficial geology. For example, in the Tyne Gap, bedrock moulded lineations tend to be 'stubbier' and less elongate. The lowest elongation ratios are in the Solway Lowlands, with hummocky terrain displaying no discernable elongation characteristics (ratio of 1:1), thus suggesting that ice was very slow moving or even stagnant.

Regional zone	Flow Phase	Flow Set	Frequency	Minimum ER	Maximum ER	Mean ER	Standard Deviation
A: Dumfries-shire	1	1.1	158	1.49	7.07	2.96	0.97
B1: Tyne Gap	1	1.1	29				
	2	2.1	59	1.19	3.53	2.18	0.56
		2.2	220	1.12	4.69	2.21	0.68
	3	3.1	609	1	7.76	2.52	0.94
		3.2	126	1.01	4.23	2.01	0.68
		3.3	26	1.2	2.82	1.92	0.38
	4	4.1	236	1.34	7.26	3.02	1.23
		4.2	472	1	7.33	2.4	0.99
		4.3	149	1.04	11.95	4.36	2.18
	5	5.1	329	1	9.91	2.72	1.33
	6	6.1	309	1.01	10.21	2.19	0.85
		6.2	161	1	9	2.29	1.12
		6.3	275	1.36	11.98	3.5	1.61
	7	7.1	125	1	5.45	2.24	0.88
		7.2	276	1.11	7.29	2.63	1.08
	4-7	8.1	19	1.23	4.99	2.66	0.96
	1-7	9.1	43				
B2: Tyne Gap	½	1.1	32	2.11	5.66	3.56	0.85
	½	1.2	60	1.11	5.45	2.44	0.86
C: Vale of Eden	1	1.1	116	1.21	4.84	2.17	0.6
	2	2.1	64	1.19	5.9	2.35	0.87
	3	3.1	653	1	6.78	2.94	1.01
		3.2	243	1.01	4.46	2.22	0.58
	4	4.1	573	1	11.73	3.23	1.61
	5	5.3	28	1.51	3.57	2.48	0.52
	1-2	6.1	48	1.04	2.91	1.9	0.42
		6.2	72	0.49	4.76	1.92	0.58
	1-4	7.1	13	1	5	2.69	0.99
	1-5	8.1	77	1	4.02	2.06	0.68
		8.2	50	1.42	3.84	2.15	0.58
D1: Stainmore	1	1.1	62	1	3.11	1.77	0.42
	2	2.1	134	1.03	3.95	1.96	0.53
	3	3.1	32	1.16	2.85	1.95	0.46
D2: Stainmore	1	1.1	84	1.25	4.46	2.24	0.69
D3: Stainmore	1	1.1	122	1.15	4.29	2.19	0.52
	2	2.1	25	1.36	2.91	1.83	0.34
		2.2	141	1.28	5.47	2.53	0.79
	3	3.1	25	1.28	1.88	1.49	0.18
D4: Stainmore	1	1.1	368	1.06	5.68	2.4	0.76
	2	2.1	406	1	9.25	2.42	0.94
	3	3.1	67	1.52	6.08	2.98	0.87
		3.2	85	1.22	5.46	2.45	0.69
		3.3	30	1.38	6.38	3.01	1.15
	4	4.1	21	1.24	3.95	2.24	0.71
	5	5.1	16	1.54	3.21	2.3	0.46
		5.2	13	1.78	4.88	2.86	0.76
		5.3	24	1.49	3.42	2.32	0.52

Table 2: Elongation ratios: statistics

Implications for BIIS flow dynamics:
The flow phases identified in the glacial geomorphological map have been used to reconstruct ice sheet dynamics within the central sector of the last British-Irish ice sheet during the Late Devensian (Fig. 5). Eight flow phases have been identified within the Lake District-Tyne Gap (LT) region. Initial ice flow phases are inferred to have occurred when ice was sufficiently thick for it to flow across the Pennines (LT1) and to spill eastwards across the Tyne Gap (LT2/3/4). The build-up of ice within the Irish Sea Basin (Eyles and McCabe, 1989; Scourse et al. 1990, 1991) would have inhibited the westwards movement of ice, while the gradual ice flow shift from north-east (LT1) to east (LT4) through the Tyne Gap reflects the gradual waning influence of the Lake District and Vale of Eden in-place of the Southern Uplands ice dispersal centre (LT5). A major flow switch occurred when ice drained westwards into the Irish Sea Basin (LT6) cutting off the Tyne Gap. This was probably associated with drawdown into the Irish Sea Ice Basin (Eyles and McCabe, 1989; Ó Cofaigh and Evans, 2007; Roberts et al., 2007). Superimposed on LT6 is a deltaic complex which delineates the limit of a south-easterly ice advance that crossed the Solway Firth (SF1) during or following LT7, LT8. These final two flow phases are characterised by topographically constrained flow lobes extending into the lowlands (LT7/8).

Four flow phases have been recognised within the Stainmore Gap (ST) region, characterised by an increasingly prevalent Tees Valley ice flow forcing ice south-eastwards towards the Vale of York (ST3/4). The Stainmore group are likely to have been formed relatively early in the Late Devensian based on the cross-cutting of flow set ST1 by LT7. Ice must have been sufficiently thick at ST1 for ice sourced in the Howgill Fells and Lake District to overtop the Stainmore col. Ice build-up probably resulted in an ice divide developing in the Vale of Eden between ice converging on both Stainmore and the Tyne Gap. The flow in the Vale of Eden (ES1) is difficult to interpret as despite showing no conceivable difference with LT7, it veers eastwards into the Stainmore Gap. Stoss and lee forms have also been interpreted as indicative of southerly flow (Hollingworth, 1931), although on the NEXTMap data this is hard to distinguish.

Ice moving southwards down the east coast (EC1) is unrelated to other flow sets within the area. However, the absence of any easterly orientated lineations within this region suggests that EC1 occurred after LT4, wiping away or covering evidence of the Tyne Gap ice flow.

Conclusions:
In summary, the presented geomorphological map illustrates the wide variety and complexity of landform deposition during the Main Late Devensian in the central sector of the British-Irish ice sheet. A palimpsest geomorphic signature, characterised by cross-cutting glacial landforms is interpreted as evidence for dynamic ice flow in response to migrating ice dispersal centres and ice divides. The variety of landforms details the evolving behaviour of the ice sheet through periods of both advance and decay. Based on this data, a relative chronology has been established which begins to reconstruct the glacial history throughout the Main Late Devensian, thus providing a framework for future analysis and interpretation.

Software:
The NEXTMap data was processed and digitised using ArcGIS 9.1 (ArcMap and ArcCatalogue). Adobe Illustrator CS was used in the production of the map.

Bibliography:
Benn, D. I. and Evans, D. J. A., (1998). Glaciers and Glaciation. Arnold, London.
Boone, S. J. and Eyles, N., (2001). Geotechnical model for Great Plains hummocky moraine formed by till deformation below stagnant ice. Geomorphology, 38; 109-124.
Boulton, G. S., and Clark, C. D., (1990a). The Laurentide ice sheet through the last glacial cycle: the topology of drift lineations as a key to the dynamic behaviour of former ice sheets. Transactions of the Royal Society of Edinburgh: Earth Sciences, 81; 327-347.
Boulton, G. S., and Clark, C. D., (1990b). A highly mobile Laurentide ice sheet revealed by satellite images of glacial lineations. Nature, 346; 813-817.
Clark, C. D., (1993). Mega-scale glacial lineations and cross-cutting ice flow landforms. Earth Surface Processes and Landforms, 18; 1-29.
Clark, C. D., (1997). Reconstructing the evolutionary dynamics of former ice sheets using multi-temporal evidence, Remote Sensing and GIS. Quaternary Science Reviews, 16; 1067-1092.
Clark, C. D., (1999). Glaciodynamic context of subglacial bedform generation and preservation. Annals of Glaciology, 28; 23-32.
Clark, C. D. and Meehan, R. T., (2001). Subglacial bedform geomorphology of the Irish ice sheet reveals major configuration changes during growth and decay. Journal of Quaternary Science, 16(5); 483-496.
Clark, C. D., Evans, D. J. A., Khatwa, A., Bradwell, T., Jordan, C. J., Marsh, S. H., Mitchell, W. A. and Bateman, M. D. (2004). Map and GIS database of glacial landforms and features related to the last British Ice Sheet. Boreas, 33; 359-375.
Clark, R., (2002). The Solway region in the Pleistocene. Proceedings of the Cumberland Geological Society, 6(4).
Dunlop, P. and Clark, C. D., (2006). The morphological characteristics of ribbed moraine. Quaternary Science Reviews, 25; 1668-1691.
Dyke, A. S., and Morris, T. F., (1988). Drumlin fields, dispersal trains and ice streams in Arctic Canada. Canadian Geographer, 32(1); 86-90.
Evans, D. J. A. and Ó Cofaigh (2003). Depositional evidence for marginal oscillations of the Irish Sea ice stream in south-east Ireland during the last glaciation. Boreas, 32; 76-101.
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.
Eyles, N., Boyce, J. I. and Barendregt, R. W., (1999). Hummocky moraine: sedimentary record of stagnant Laurentide Ice Sheet lobes resting on soft beds. Sedimentary Geology, 123; 163-174.

Eyles, N. and McCabe, A. M., (1989). The Late Devensian (<22,000 BP) Irish Sea Basin: the sedimentary record of a collapsed ice sheet margin. Quaternary Science Reviews, 8; 307-351.

Flint, R. F., (1971), Glacial and Quaternary Geology. Wiley, New York.

Greenwood S. L., Clark, C. D. and 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(6); 637-645.

Hollingworth, S. E., (1931). Glaciation of West Edenside and adjoining areas and the drumlins of Edenside and the Solway Plain. Quarterly Journal of the Geological Society of London, 87; 281-357.

Huddart, D. and Glasser, N. F., (2002). Quaternary of Northern England, Geological Conservation Review Series, No. 25. Joint Nature Conservation Committee, Peterborough, 745pp.

Kleman, J., (1994). Preservation of landforms under ice sheets and ice caps. Geomorphology 9; 19-32.

Kleman, J. and Borgström, I., (1996). Reconstruction of palaeo-ice sheets: the use of geomorphological data. Earth surface processes and landforms, 21; 893-909.

Letzer, J. M., (1978). The glacial geomorphology of the region bounded by Shap Fells, Stainmore and the Howgill Fells in East Cumbria. Unpublished MPhil thesis. University of London

Letzer, J. M., (1987). Drumlins of the South Vale of Eden, Cumbria, England. In Menzies, J. and Rose, J., (eds), 1987. Drumlin Symposium. Balkema, Rotterdam, pp. 323-334.

Ó Cofaigh, C. and 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.

Price, R. J., (1973). Glacial and fluvioglacial landforms. Oliver and Boyd, Edinburgh.

Raistrick, A., (1931). Glaciation. *Proceedings of the Geologists' Association*, 42(3); 281-291.

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

Rose, J., (1987). Drumlins as part of a glacier bedform continuum. In: Menzies, J. and Rose, J., (Eds), 1987. Drumlin Symposium. Balkema, Rotterdam, pp 103-116.

Rose, J., and Letzer, J. M., (1977). Superimposed drumlins. Journal of Glaciology, 18(80); 471-480.

Salt, K. E., (2001). Palaeo-ice sheet dynamics and depositional settings of the Late Devensian ice sheet in south-west Scotland. Unpublished PhD thesis.

Salt, K. E. and Evans, D. J. A., (2004). Superimposed subglacially streamlined landforms of southwest Scotland. Scottish Geographical Journal, 120(1+2); 133-147.

Scourse, J. D., Austin, W. E. N., Bateman, R. M., Catt, J. A., Evans, C. D. R., Robinson, J. E. and Young, J. R., (1990). Sedimentology and micropalaeontology of glacimarine sediments from the central and southwestern Celtic Sea. Special Publication of the Geological Society of London, 5; 329-347.

Scourse, J. D., Robinson, J. E. and Evans, C. D. R., (1991). Glaciation of the central and southwestern Celtic Sea. In Ehlers, J., Gibbard, P. L. and Rose, J (eds), Glacial deposits in Great Britain and Ireland, 301-310, Balkema, Rotterdam

Smith, M. J., (2002). Techniques for the geomorphological reconstructions of palaeo ice sheets from remotely sensed data. Unpublished PhD thesis, University of Sheffield.

Smith, M. J. and Clark, C. D., (2005). Methods for the visualisation of digital elevation models for landform mapping. Earth surface processes and landforms, 30; 885-900.

Smith, M.J., Rose, J. and Booth, S. (2006). Geomorphological mapping of glacial landforms from remotely sensed data: an evaluation of the principal data sources and an assessment of their quality. Geomorphology, 76; 148-165.

Smith, M. J. and Wise, S. M., (2007). Problems of bias in mapping linear landforms from satellite imagery. International Journal of Applied Earth Observation and Geoinformation, 9; 65-78.

Stokes, R. A., and Clark, C. D., (2001). Palaeo-ice streams. Quaternary Science Reviews 20; 1437-1457.

Stokes, R. A., and Clark, C. D., (2002). Are long subglacial bedforms indicative of fast ice flow? Boreas 31; 239-249.

Stone, P., Lawrence, D., Merritt, J. W. and Millward, D. (in press). British Regional Geology: Northern England (Third Edition). British Geological Survey, Nottingham.

Thomas, G. S. P. and Chiverrell, R. C., (2007). Structural and depositional evidence for repeated ice-marginal oscillation along the eastern margin of the Late Devensian Irish Sea Ice Stream. Quaternary Science Reviews, 26; 2375-2405.

Trotter, F. M., (1929). The Glaciation of East Edenside, the Alston Block and the Carlisle Plain. Quarterly Journal of the Geological Society of London, 85; 549-612.

http://www.neodc.rl.ac.uk/

Figures:

Figure 1:
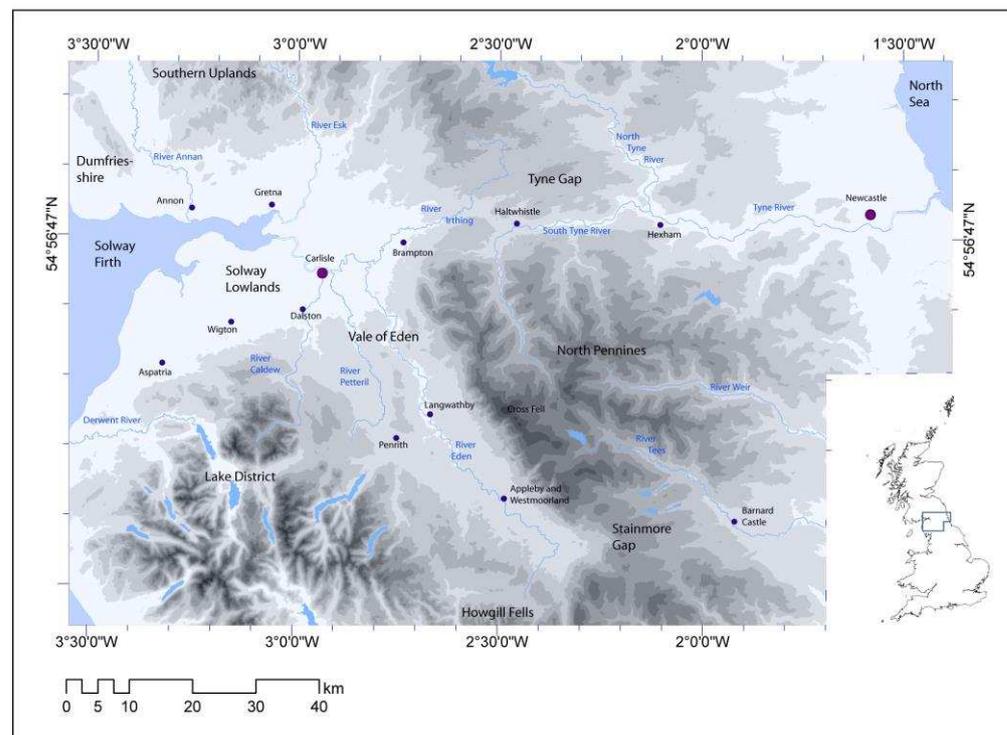
Location and topography of the study area. NEXTMap Britain data from Intermap Technologies Inc. were provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC).

Figure 2:
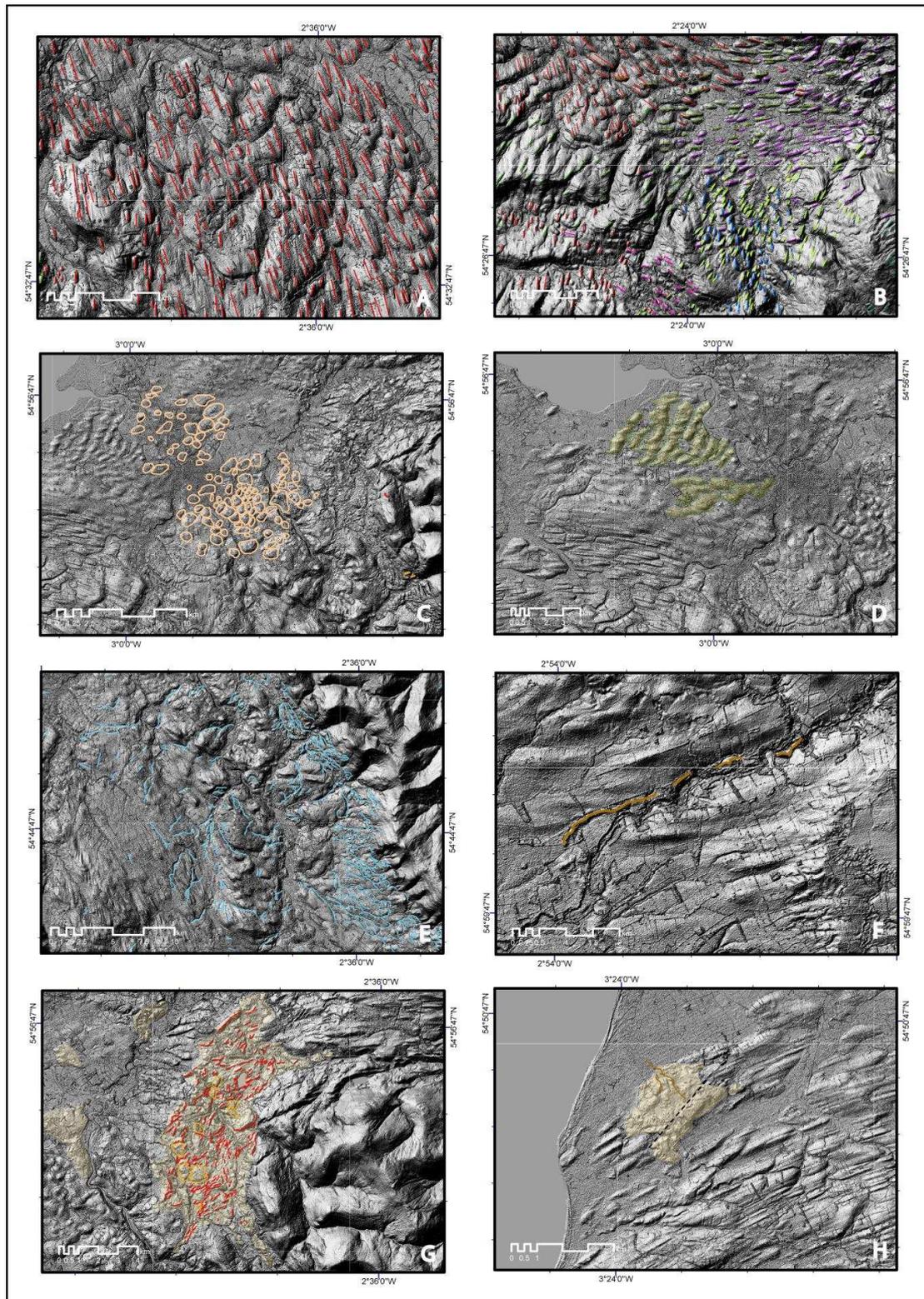
Examples of glacial landforms: 2A, SE-NW orientated drumlins in the Vale of Eden; 2B, A series of cross-cutting 'flow sets' to the southwest of the Stainmore Gap. Flow sets are distinguished based on the criteria of Clark (1999). 2C, hummocky moraine in the Solway Lowlands; 2D, Ribbed moraine with drumlinised ridges to the west of Carlisle; 2E, SE-NW parallel orientated meltwater channels on the Pennine

escarpment, probably formed at the ice margin due to progressive ice sheet surface lowering and a series of channels crossing the Penrith sandstone ridge related to a series of eskers and delta formations; 2F, sinuous, beaded esker in the Lyne Valley orientated in a SW-NE direction; 2G, Brampton Kame Belt 'hugging' the northwest corner of the Pennines and containing a series of SW-NE orientated ridges (red), flat topped hills (green polygons) and kettle holes; 2H, Ice contact delta at Holme St Cuthbert. The ice contact face is demarcated by the dotted black line, with eskers and dead ice features to the northwest indicating the ice marginal zone. The delta would have been fed by ice flow from the northwest. Relief shaded DEM (azimuth: 315). NEXTMap Britain data from Intermap Technologies Inc. were provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC).

Figure 3:
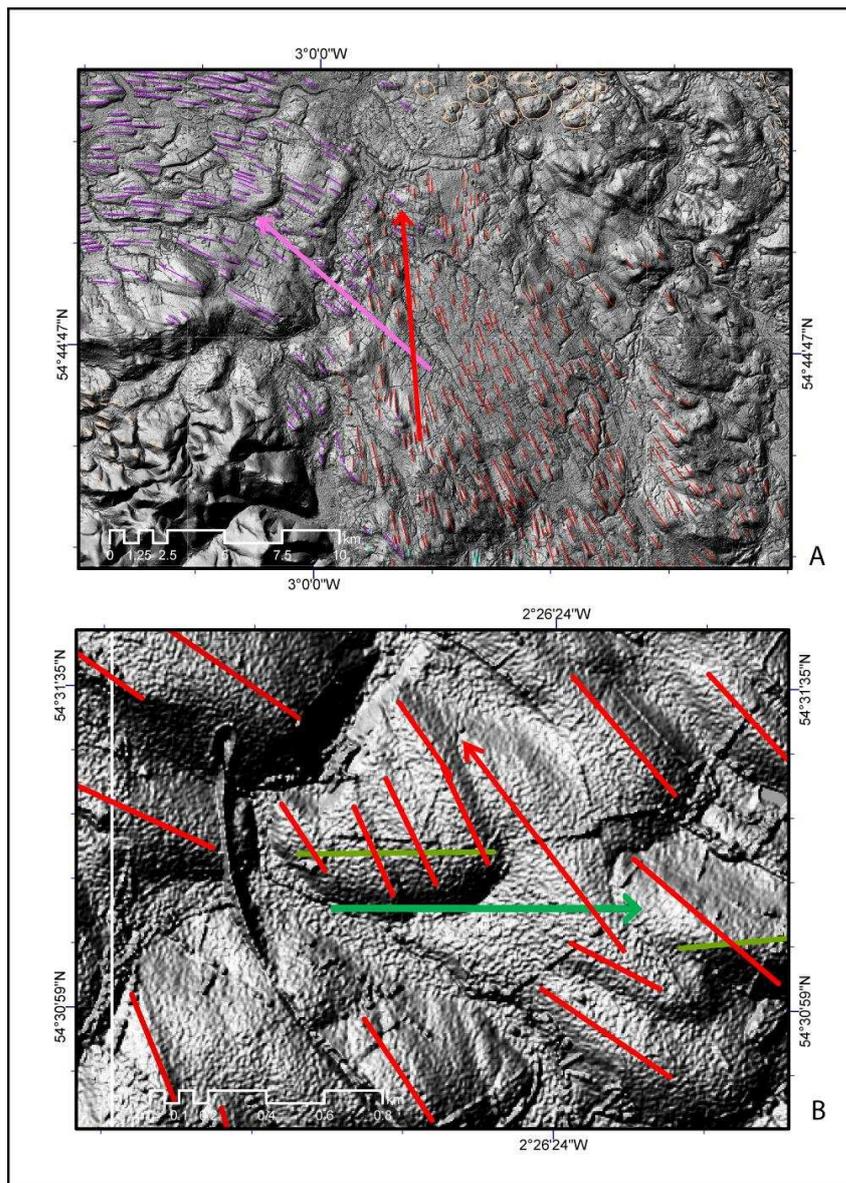
Examples of complex flow: 3A illustrates complex flow at a large scale between 2 flow sets (red and pink arrows/vectors). The earlier (pink arrow) phase was south-westerly, round the north of the Lake District. This was followed by a subsequent advance (red arrow) into the Solway Lowlands. 3B demonstrates superimposed drumlin formation just to the west of the Stainmore Gap, in the Vale of Eden. An initial easterly flow across Stainmore (green arrow) was followed by a north-westerly flow (red arrow) down the Vale of Eden towards the Solway Lowlands. The west-east orientated drumlin in the centre of the image has been superimposed by four smaller drumlins. Relief shaded DEM (azimuth: 315). NEXTMap Britain data from Intermap Technologies Inc. were provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC).

Figure 4:
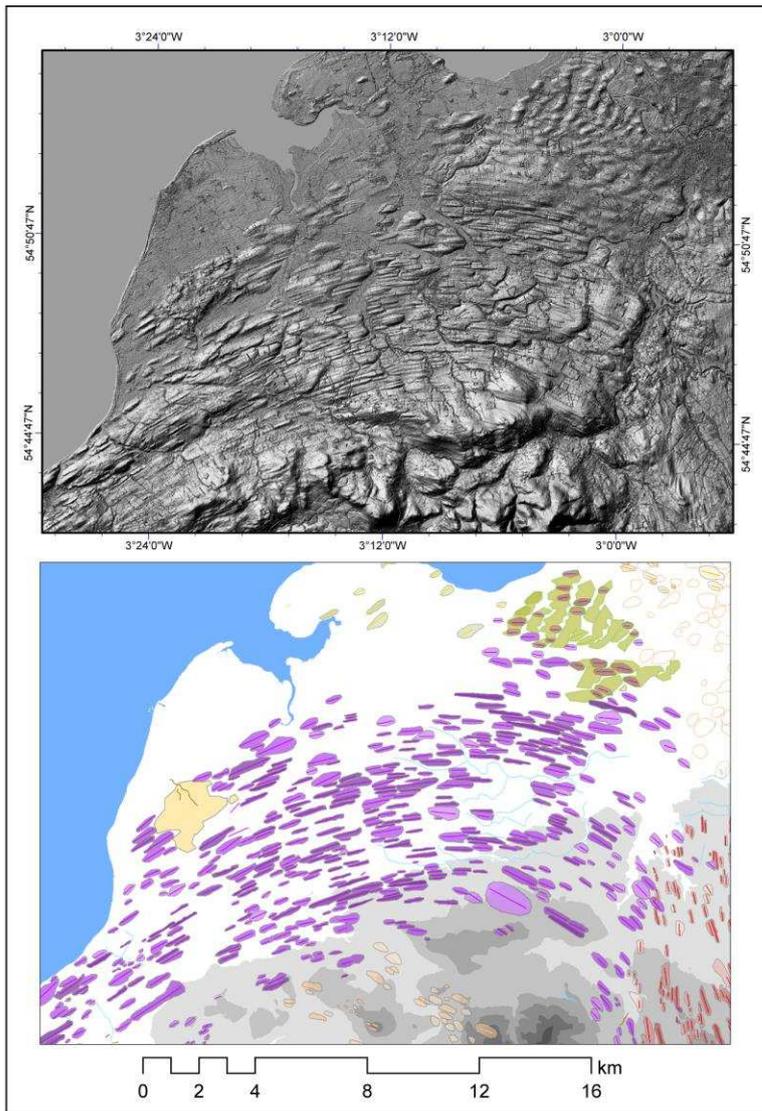
Ice streaming round the northern Lake District into the Irish Sea Basin. Relief shaded DEM (azimuth: 315). NEXTMap Britain data from Intermap Technologies Inc. were provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC).

Figure 5:
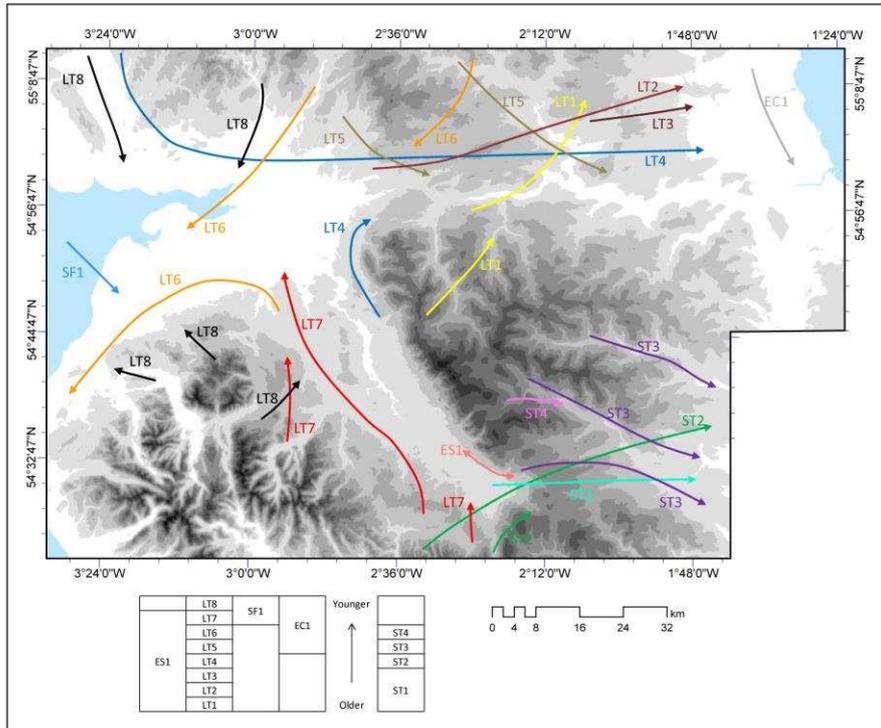
Generalised flow phases of ice dynamics in the central sector of the last BIIS during the Late Devensian. NEXTMap Britain data from Intermap Technologies Inc. were provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC).