Journal of Maps

ISSN: (Print) 1744-5647 (Online) Journal homepage: http://www.tandfonline.com/loi/tjom20

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Journal of Maps, 2010, 543-563

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Abstract

Subglacial bedforms are a characteristic feature of formerly glaciated landscapes. Formed parallel (e.g. drumlins) or transverse (ribbed moraine) to ice flow their preserved distribution is a valuable record of ice sheet configuration. To date these landforms have been underused in Britain such that we have only a simple static view of the flow patterns of the last British Ice Sheet, with glimpses of complexity recorded in just a few locations. Arguably, this is because of the lack of a suitable, ice-sheet scale, map of subglacial bedform distribution. We present the first consistent and countrywide map of subglacial bedforms for Britain produced from systematic mapping. Individual landforms were mapped from relief-shaded renditions of high-resolution elevation data and Landsat TM imagery. The outline or crest-line of each bedform was manually captured by onscreen digitisation directly into a Geographic Information System (GIS) database. Over 39,000 landforms were identified revealing new lineation patterns, multiple instances of cross-cutting/superimposition, and adding additional detail to the known distribution established by local field surveys. A near complete representation of the British subglacial bedform population, the map is a major step towards a detailed model of British Ice Sheet configuration by providing a suitable basis for reconstructing the flow evolution at the ice sheet scale, and a geomorphological framework for the interpretation of sedimentological and stratigraphical data. The map is presented at a scale of 1:525,000.

(Received 2nd November 2009; Revised 18th May 2010; Accepted 12th August 2010)

ISSN 1744-5647
doi:10.4113/jom.2010.1111

1. Introduction

There have been nearly two centuries of interest in the glacial landscape of Britain, producing numerous papers and memoirs, and yet we have only a fairly simple picture of the flow configuration and evolution of the last British Ice Sheet (BIS) (Evans et al., 2005). This is in stark contrast to the situation for other, significantly larger, former ice sheets such as the Laurentide (Dyke and Prest, 1987; Clark et al., 2000) and Fennoscandian (Kleman et al., 1997). Furthermore, it limits our ability to investigate relationships with the climate changes of the last glacial cycle. Arguably, it is the lack of a comprehensive map of subglacial bedforms for the whole of the area covered by the former ice sheet, the basic starting point for any reconstruction of ice sheet flow configuration and evolution (Kleman and Borgström, 1996) that has led to the current situation. The results of over one hundred and fifty years of field mapping were summarised together for the first time in the Glacial Map of Britain and accompanying BRITICE Geographic Information System (GIS) database (Clark et al., 2004; Evans et al., 2005). This synthesis highlighted that, despite considerable detail of mapping in some areas, significant areas remain unmapped and the existing information is spatially fragmented or inconsistent in terms of mapping methodologies, scales, styles and terminology. This is problematic for resolving the form and dynamics of the ice sheet as a whole, because evidence on which to base and constrain models is spatially restricted and inconsistent. Beyond the difficulties this poses for a geomorphological reconstruction of the ice sheet, there is no spatial framework in which to connect or place information from sedimentological surveys or to test or validate the outputs of numerical modelling experiments.

Considering the volume of literature concerning British glacial history, the failure to produce a glacial map is intriguing. One explanation is that a once strong tradition of glacial geomorphological mapping in Britain, necessary for the incremental build up of information, waned, with less and less tendency to publish results, i.e. maps, in addition to interpretations. Another is that during the long time period (over 150 years) the focus, approach, and purpose of research has changed to reflect contemporary theories of landform genesis and observations of present day ice sheets. Early work focussed on mapping and recording striations and erratics (e.g. Goodchild, 1875; Tiddeman, 1872). From such work the broad flow patterns of the British Ice Sheet were established (Geikie, 1894) and despite detailed later landform mapping revealing considerable additional information at a number of locations (e.g. Raistrick, 1933; Trotter, 1929) and efforts to assimilate data (e.g. Sutherland, 1984), the flow pattern structure has remained relatively unchanged (e.g. Boulton et al., 1977; Charlesworth, 1957). Detailed mapping of drumlins at a local scale has revealed instances of superimposition and cross-cutting hinting at a more complex history than suggested by erratic transport paths alone (e.g. Letzer, 1987; Salt and Evans, 2005; Mitchell, 1994; 2007; Rose and Letzer, 1977). Unfortunately such mapping has not been extended over the country and the drumlin population of Britain has yet to be fully exploited for the determination of ice sheet configuration.

This paper presents the first systematic, countrywide mapping of subglacial bedforms for Britain conducted between 2004 and 2007. To achieve rapid, systematic, and consistent mapping over the whole country a remote sensing approach was adopted. Remote sensing data are now an established basis for glacial geomorphological mapping (e.g. Boulton and Clark, 1990a;b; Clark et al., 2000; Clark and Meehan, 2001; De Angelis, 2007; Dunlop and Clark, 2006; Hättestrand and Clark, 2006b; Jansson and Glasser, 2005; Jansson et al., 2002; 2003; Jordan, 1997; Smith and Clark, 2005; Stokes and Clark, 2003). A single observer can apply a well defined set of identification criteria to map large areas many times more quickly than can be achieved in the field, and the resulting maps can be directly incorporated into a Geographic Information System (GIS) for further analysis and checks against reference data such as geological maps (Clark, 1997). Indeed, the resolution of digital data sources is now such that remote mapping of landform morphology can match the detail achieved by field studies (Smith et al., 2006).

2. Methods

2.1 Primary data sources

The principle data source used for mapping was the NEXTMap Britain digital elevation model (DEM), from Intermap Technologies. The NEXTMap elevation data surpasses all other national datasets for detailed geomorphological mapping (Smith et al., 2006) with a horizontal resolution of 5 m and vertical resolution of $<$1 m (Figure 1). A discussion of the accuracy of the data is given by Dowman et al. (2003). A Landsat TM mosaic composed of cloud free winter images, collated by British Geological Survey (BGS) over a 15 year period, provided information on land cover (resolution 30 m). At the time of mapping the Isle of Man was not covered by the NEXTMap dataset and so this area was mapped from the Landsat TM mosaic and the Ordnance Survey (OS) Land-form PANORAMA DEM. This DEM has a grid size of 50 m and was derived from OS contour data. For copyright reasons the Isle of Man drumlins shown on the accompanying map were remapped using the 25 m resolution Landmap DEM. Solar relief-shaded visualisations of the elevation data were used to conduct mapping (e.g. Clark and Meehan, 2001). To avoid azimuth bias (Smith and Clark, 2005), a minimum of three relief-shaded visualisations were generated for each area of the country; two images with the sun placed in orthogonal positions, $045°$ (NE) and $315°$ (NW), and one with the sun placed at a solar elevation of $90°$ (i.e. 'overhead') (Figure 2). All images were vertically exaggerated four to five times and for the two orthogonal images solar elevation was set at $30°$ to enhance subtle features. To ensure geometric consistency all mapping and datasets were projected on British National Grid.

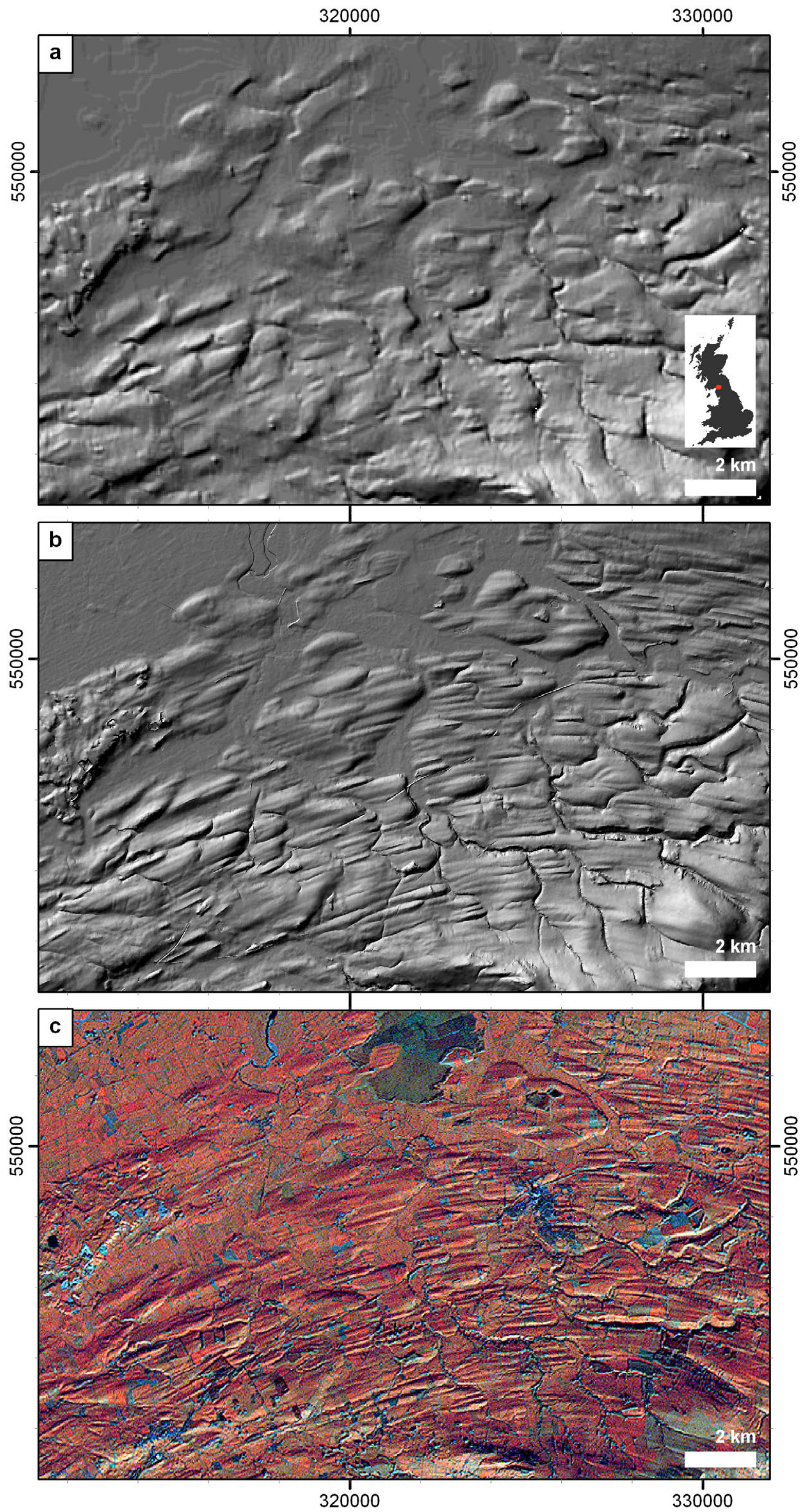

Figure 1. Example from part of the Solway lowlands' drumlin field west of Carlisle to show resolution of data sources used for mapping: a) OS PANORAMA LANDFORM DEM, 50 m resolution derived from 10 m contour data; b) NEXTMap DEM, 5 m resolution derived from InSAR measurements; and c) Cloud free Landsat TM colour composite image, 30 m resolution. Drumlin break-of-slope is clearly observable on the NEXTMap and Landsat data. Both DEMs are solar shaded from the NE. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC. British National Grid coordinates.

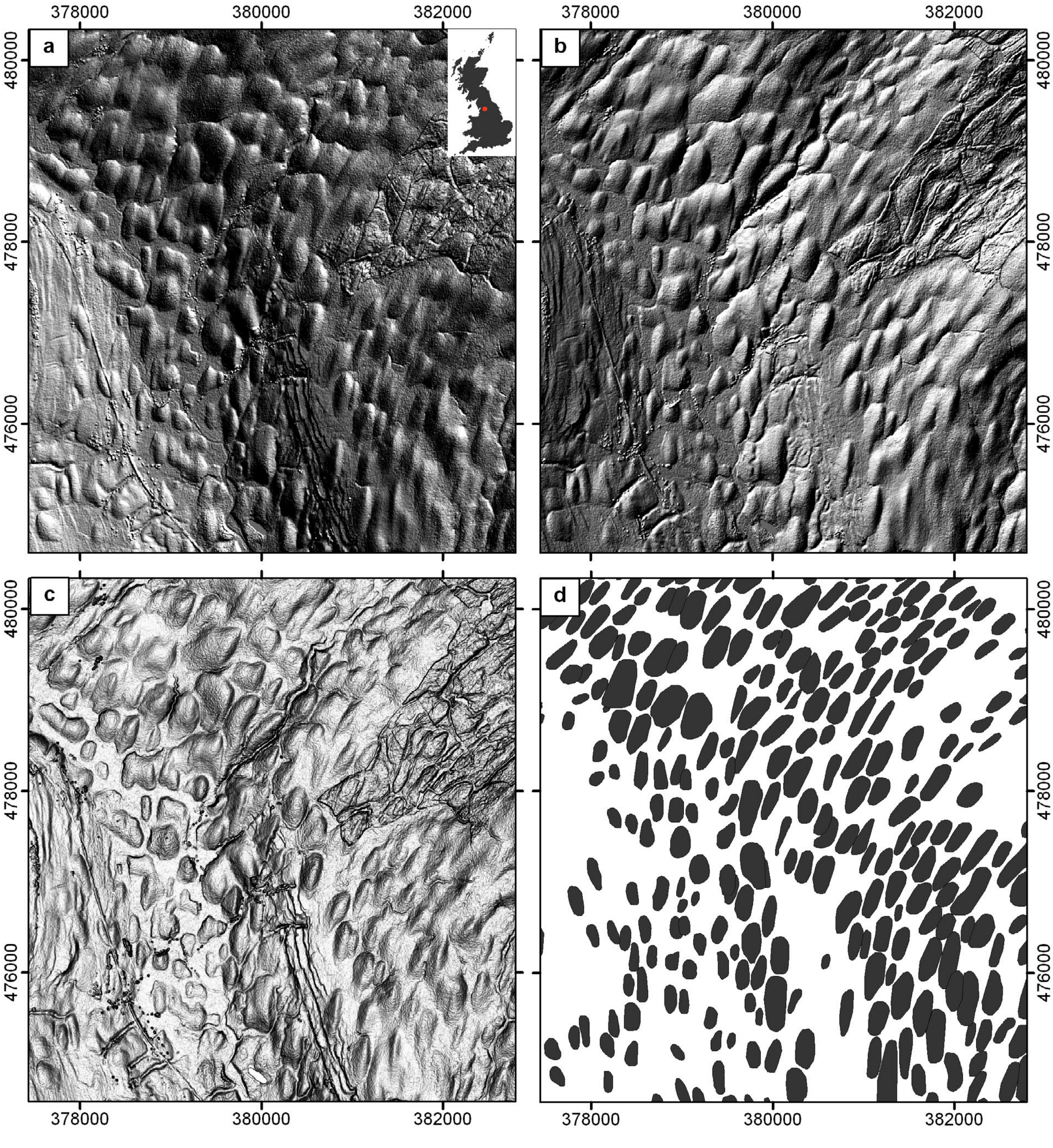

Figure 2. To avoid azimuth bias, a minimum of three relief-shaded visualisations were used in combination. In this example from Ribblesdale, western Pennines using the NEXTMap DEM: a) relief-shaded image illuminated from the NE; b) relief-shaded image illuminated from the NW; c) 'overhead' relief-shaded or gradient image (solar azimuth set at 0°); and d) mapped drumlin polygons. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC. British National Grid coordinates.

2.2 Mapping procedure

Mapping was achieved by visual identification (Table 1) and onscreen digitisation of each individual landform within a GIS environment. Four types of subglacial bedform were identified; drumlins, crag-and-tails, mega-scale glacial lineations (MSGL) and ribbed moraine. Flutes, narrow streamlined ridges, typically less than 3 m high and commonly observed at close to the front of present-day glaciers (Rose, 1987), were not observed. It is likely that any flutes that have survived post-glacial erosion (Rose, 1991) are below the resolution of the data. Streamlined bedrock was excluded because of the potential for misidentification with bedrock structure and the possibility that bedrock streamlining may be the cumulative result of several cycles of glaciation. Mapping style for each bedform type was determined by consideration of the most appropriate representation of landform size, orientation and shape, the resolution of the source data, and the need to complete mapping within a reasonable time frame (Table 1; Figure 3). Repeated passes of the entire glaciated area were made at a range of scales to capture the full spectrum of bedform sizes discernable on the DEM. The regional overview was invaluable for the initial identification of landforms, followed by scrutiny at a larger scale for precise mapping of each landform's shape at a scale of 1:20,000 to 1:10,000. Investigation extended beyond the generally accepted drift limit (as reproduced on the Glacial Map of Britain; Clark et al., 2004) to ensure that all of the former ice sheet bed was captured.

2.3 Ancillary data sources and mapping checks

BGS bedrock, structural, and superficial (drift) maps, OS topographic maps, and aerial photography were employed to check mapping quality. A drift thickness model for Britain derived from the BGS national borehole archive and the NEXTMap elevation data was consulted to differentiate streamlined drift features, such as drumlins, from streamlined bedrock (see Figure 5 in Clark et al., 2009). Digital topographic 1:50,000 scale OS maps were used to identify areas of forest and confirm locations of urban areas. Mapping was reviewed periodically by all of the authors and colleagues at the University of Sheffield. Although systematic field checking was not undertaken, field visits to the north Lake District and Vale of Eden in Cumbria at an early stage of mapping were conducted to confirm landform identifications.

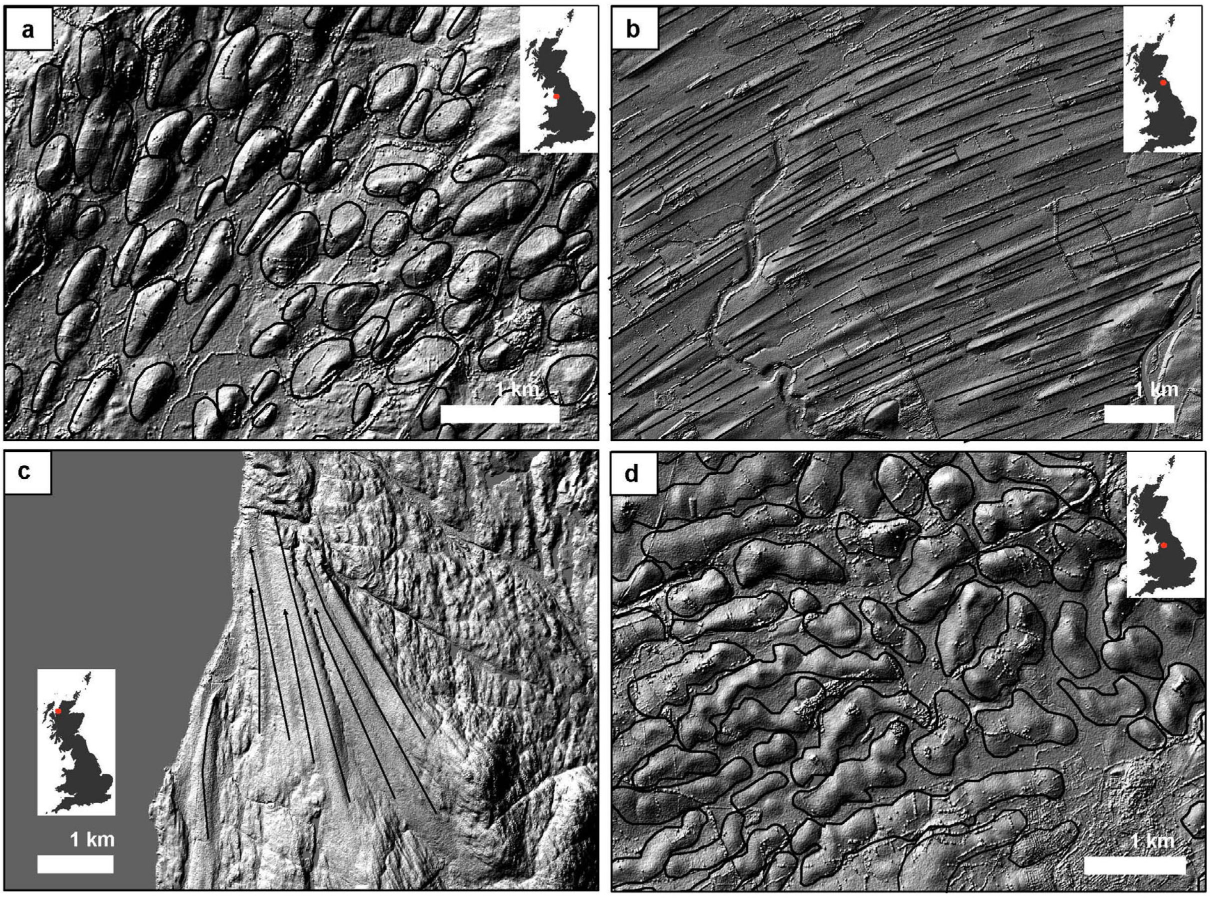

Figure 3. Style of mapping used for each landform type: a) break-of-slope outlines of drumlins close to Barrow-in-Furness, Morecambe Bay; b) mega-scale glacial lineations (MSGL) in the Tweed Basin and c) crag-and-tails close to Applecross, Wester Ross, NW Scotland are mapped along crest-lines;. d) ribbed moraine ridges north of the Forest of Bowland are mapped by break-of-slope. Map layers are shown superimposed on relief-shaded visualisations of DEM for illustration only. The outline of drumlins and ribbed moraine may not appear to coincide with the break-of-slope seen on the relief image. This is due to the azimuth bias problem of viewing from a single illumination direction. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC. British National Grid coordinates.

3. Map description

The map contains a total of 39,831 landforms, extending the locations of known subglacial bedform fields in Britain and adding considerable detail on bedform numbers, morphometries and spacing than documented by existing maps. To allow scrutiny of individual landforms the map is designed to be printed at a scale of 1:525,000. This requires the map to be 2A0 size (1189 by 1682 mm). The Glacial Map of Canada (Prest et al., 1968) and the Glacial Map of Britain (Clark et al., 2004; Evans et al., 2005) were used as templates for the map colours and design. The break-of-slope outline of drumlins is shown as filled black, crag-and-tails are shown as dark grey arrows pointing from crag to tail, MSGL are black crest-lines, and ribbed moraine is yellow (filled outlines or

Landform type	Identification characteristics and diagnostic criteria	Mapping style
Drumlin	Streamlined hill with long axis aligned in direction of ice flow. Commonly composed of till with a stoss and lee end. Generally occur in groups or fields. Direction of ice movement determined by the position of stoss end. Asymmetric plan form. Drumlins may be dissected or partially eroded by postglacial fluvial erosion.	Break-of-slope outline of individual landforms.
Crag-and-tail	Streamlined till tapers away from bedrock bump or crag in direction of ice flow. May be dissected or partially eroded by postglacial fluvial erosion. Also included are larger scale drift tails that follow bedrock escarpments.	Crest-line of individual landforms.
Mega-scale glacial lineation (MSGLs)	Highly attenuated streamlined landforms. Distinct from drumlins as have high elongation ratios and more symmetrical rectilinear plan in opposition to the classic 'basket of eggs' shape of drumlins. Generally long and commonly exhibit high levels of parallelism with neighbouring lineations. May be dissected or partially eroded by postglacial fluvial erosion.	Crest-line of individual landforms.
Ribbed (rogen) moraine	Groups of regularly spaced ridges composed of glacial sediments. Formed transverse to ice flow. Commonly superimposed by drumlins. Ridges may be dissected by post-glacial fluvial channels.	Break-of-slope outline (or crest-line) of individual ridges.

Table 1. Characteristics of subglacial bedforms used in identification and the mapping style for each type of landform. Definitions after Hättestrand and Clark (2006a) and De Angelis (2007).

ridge crest-lines). There has been no attempt at cartographic reduction and so outlines and crest-lines represent the actual area or length dimensions of individual features respectively. The elements of the map are described below.

3.1 Glacial Lineations: drumlins, crag-and-tails, and MSGL

The term glacial lineation refers to all variants of the subglacial bedform family that form parallel to ice flow (drumlins, crag-and-tails, and MSGL). Both the number and the overall distribution of lineations are greatly increased from that summarised in the Glacial Map of Britain, especially in Scotland. Three types of lineations were observed; 5,901 crag and tails, 258 MSGL crest-lines, and 37,115 drumlins, as opposed to the 5,956 drumlins in BRITICE. Lineations are widespread across the country but some clear patterns also emerge from the national coverage. The length, width, and elongation ratio of British drumlins is analysed in detail in Clark et al. (2009). There is considerable variety in drumlin morphometry within and between drumlin fields (Figure 4). Drumlin lengths range from 99 m to 6.9 km, with a mean length of 599 m (Clark et al., 2009). In general there is an even distribution of drumlin lengths across the country although clusters of similar lengths occur. For example Galloway appears to be home to mainly short (<400 m) drumlins and long drumlins (>2 km) are more frequent along major valleys leading to offshore bays (Moray Firth, Firth of Forth, Firth of Tay and Solway Firth). There are 133 instances of bedform superimposition; most commonly drumlins overlapping other drumlins or ribbed moraine ridges (Figure 5). Previously, superimposition has only been observed in two locations, the Vale of Eden, NW England and north of Glasgow in Scotland (Rose and Letzer, 1977; Rose, 1987). We can now see that a multi-temporal record of ice flow patterns is recorded across the British landscape. MSGLs, distinguished from drumlins on the basis of tendency towards a more rectilinear shape and higher elongation ratios (Table 1) only occur in the Tweed Basin, north of the Cheviot Hills where they form a strongly convergent pattern (Figure 6). The Tweed MSGLs are smaller than examples from other palaeo-ice sheets such as the Laurentide, ranging from 2 to 16.5 km long. Long lineations do occur in other areas (e.g. on Black Isle, at the head of the Moray Firth, NE Scotland, NH 65 59 and Strathmore north of the Sidlaw Hills, eastern Scotland, NO 42 55) but never in the same number or with the same distinctive rectilinear shape as in the Tweed Basin and are therefore not classified as MSGL. Crag and tails occur within and adjacent to drumlin fields, frequently fringing the boundaries. They are most common in Scotland. Lengths of drift tails range from 113 m to 8.2 km. Crag-and-tails occur as isolated features and as broad swaths of sediment in the lee of escarpments (e.g. the Sidlaw Hills, NO 32 35).

A striking observation from the map is that the distribution of bedforms clearly outlines the distribution of high ground; drumlin fields predominantly occur in lowland areas with the majority of upland areas, and areas with a high variability of topography, free of subglacial landforms, e.g. Southern Uplands, Scottish Highlands, Wales, Cumbrian Mountains and northern Pennines. Apparent topographic control on drumlin distribution is also observed at the local scale, most clearly exemplified by the deflection of drumlins around the Pentland and Lammermuir Hills, south of Edinburgh (NT 14 55). It is likely that this is, in part, a function of the distribution and thickness of glacial sediment. Nevertheless, drumlins do occasionally occur at high elevations, reaching 677 m east of the Vale of Eden (NY 79731 23849). This is indicative of ice flow independent of topography and that processes controlling drumlin formation were not always restricted to valley bottoms. The observation of high elevation drumlins in the north Pennines concurs with the field mapping of Mitchell (2007). Other gaps or 'holes' in the distribution of bedforms are coincident with the routes of major rivers, most notably the empty swaths running along the courses of the Rivers Kelvin, Clyde and Forth bisecting the drumlin field of the Central Lowlands of Scotland, north and south of the Campsie Fells. It is possible that drumlins close to the river courses have been buried by fluvial sedimentation (or removed by fluvial erosion) during the Holocene. An examination of these areas with ground-penetrating-radar would be useful to test these hypotheses. By qualitative assessment, the distribution of lineations does not appear to be controlled by geology since lineations occur across the country on a number of different rock types.

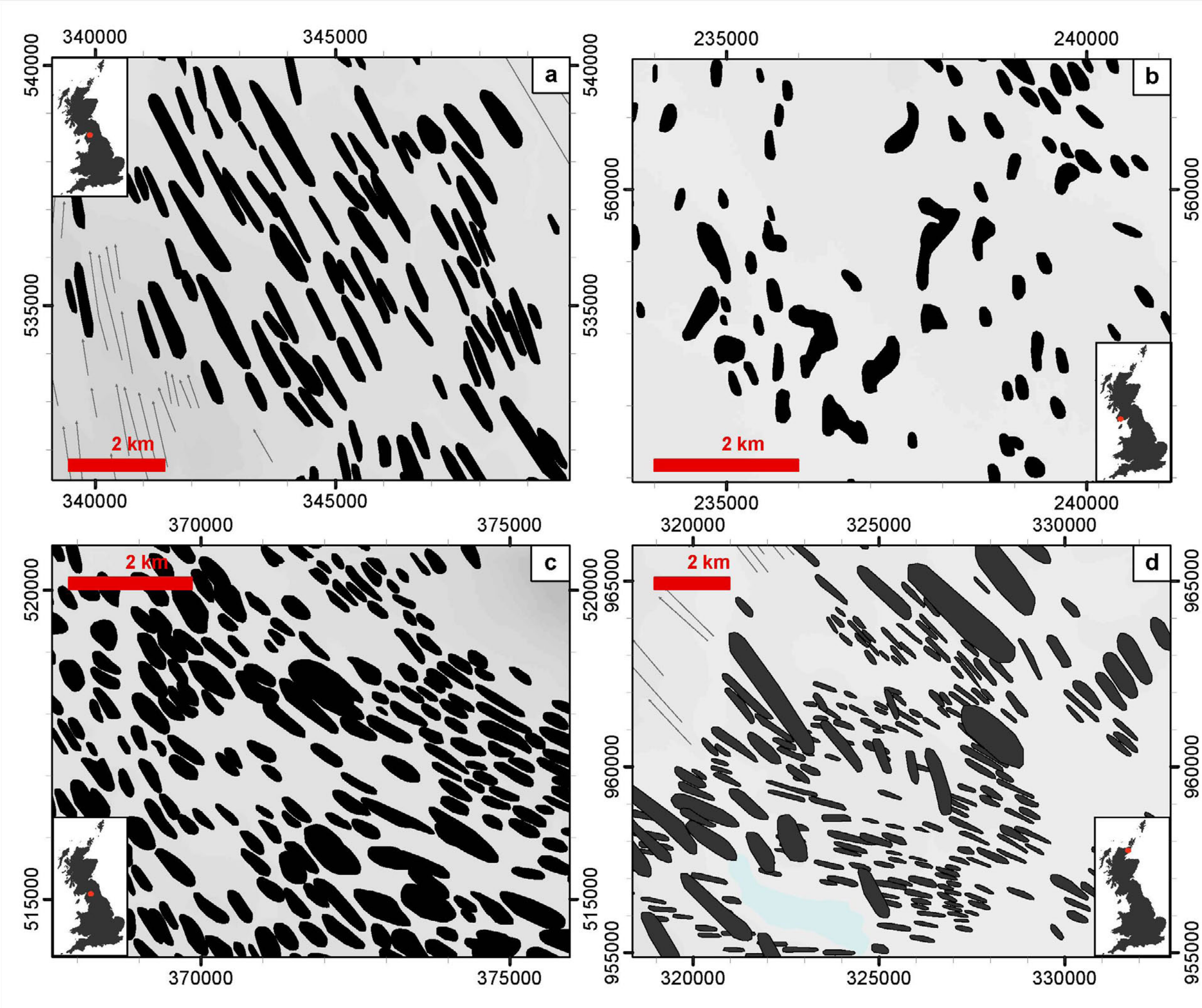

Figure 4. A range of morphometries are exhibited by the drumlins of Britain. For example; thin, elongate, 'spindle' shaped drumlins close to Penrith, Vale of Eden (a), irregular, 'tadpole' shaped drumlins in the Marchars of Galloway (b), classic ovoid shaped drumlins in the Vale of Eden (c), and in Caithness, NE Scotland two distinct populations of drumlins on the basis of length cross cut each other. British National Grid coordinates.

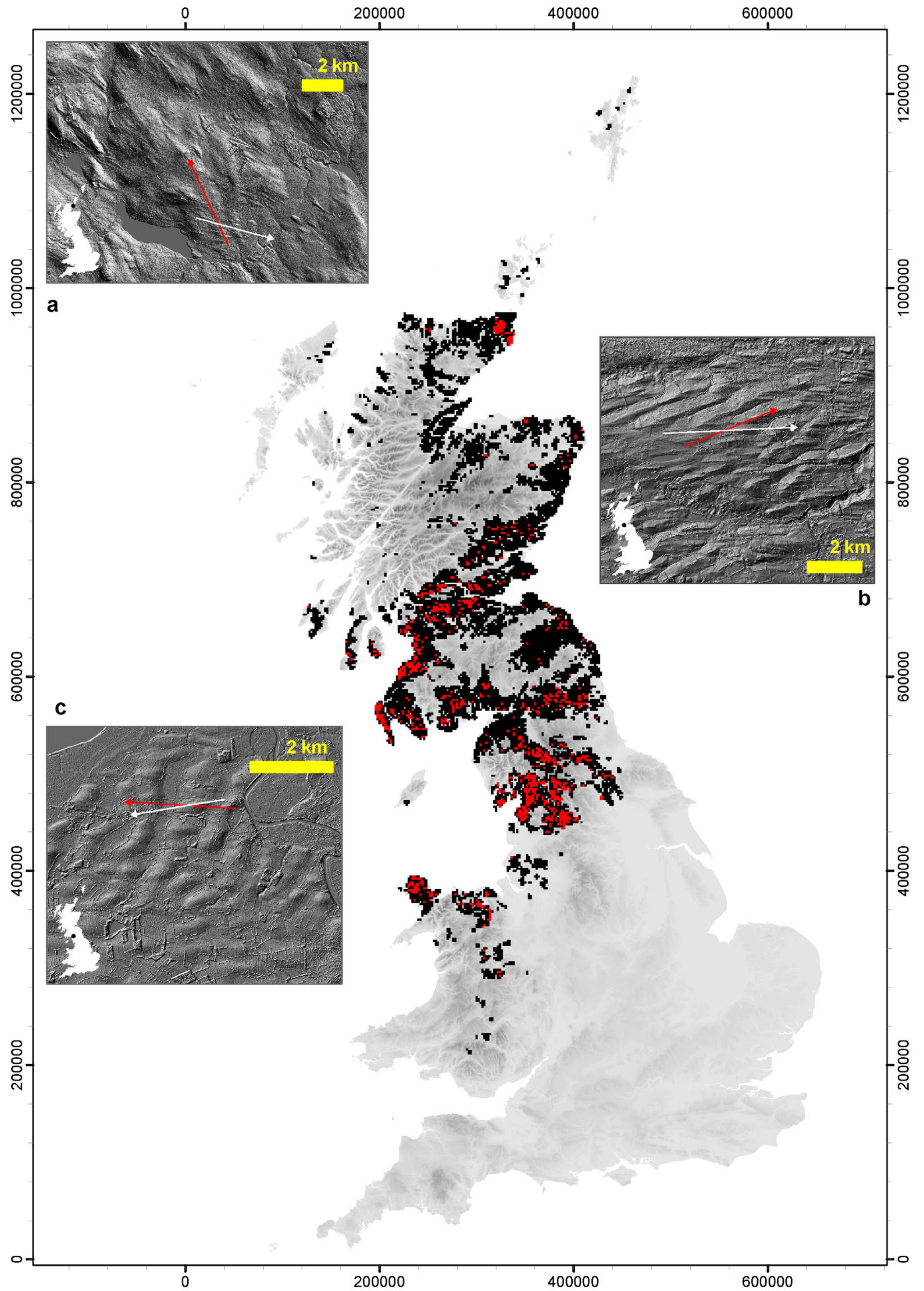

Figure 5. Mapping revealed multiple instances of cross-cutting bedform patterns and superimposition. The coverage of subglacial bedforms is shown generalised on a 2 x 2 km grid (black), instances of cross-cutting are shown in red. The inset maps are examples of types of superimposition: a) Drumlins orientated SSE-NNW are cross-cut by drumlins orientated broadly W-E in Caithness; b) Drumlins orientated WSW-ENE are superimposed by drumlins orientated W-E resulting in modification of the original WSW-ENE flow signature in the Midland Valley of Scotland; and c) ribbed moraine is overlain by drumlins in the Solway lowlands west of Carlisle. Arrows show direction of ice flow; red for underlying features, white for overlying.

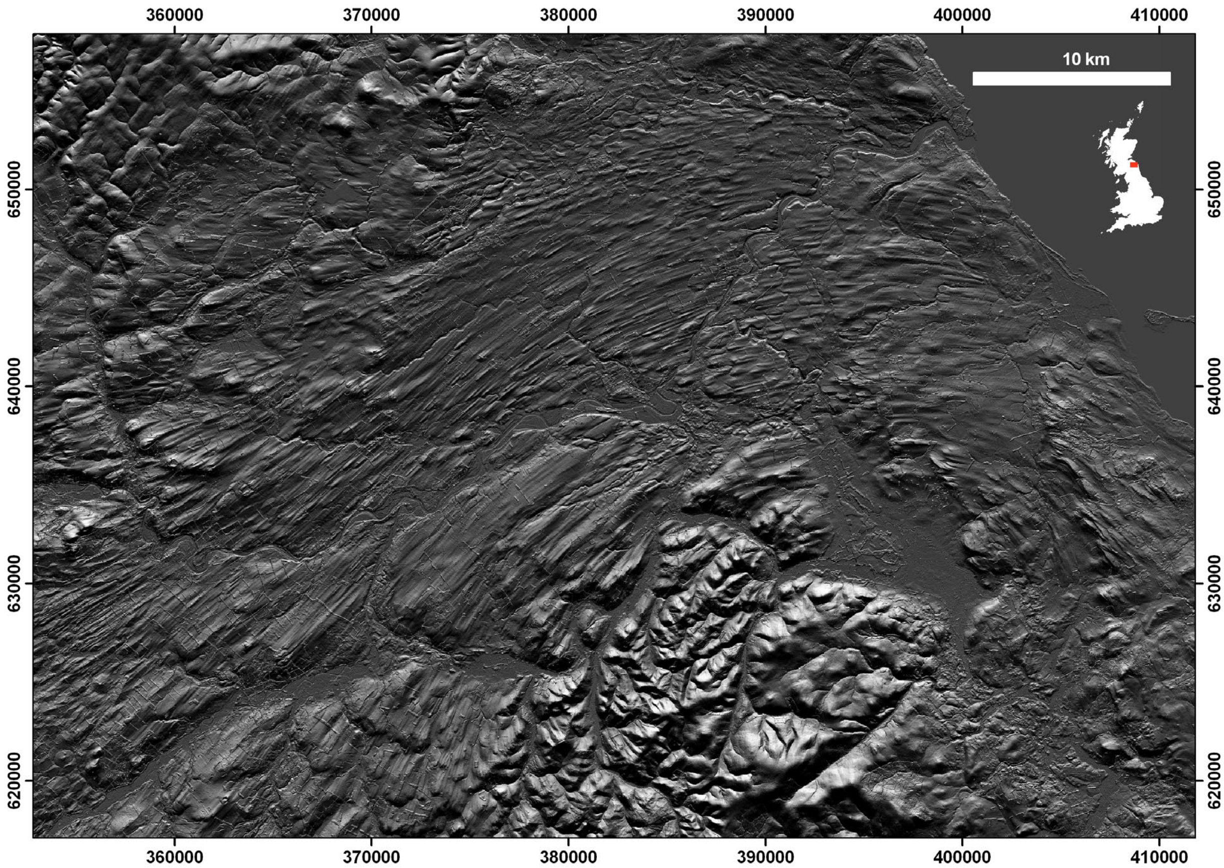

Figure 6. Relief-shaded (N) image of the Tweed basin. There are a suite of subglacial bedforms in the image documenting the route of a major ice flow terminating offshore (the Tweed Ice Stream, (Everest et al. 2005)). Most notably the Mega-Scale Glacial Lineations (MSGL) in the centre of the image. These MSGL are shorter than Canadian examples but have the same distinctive rectilinear elongated shape and form a distinctive convergent pattern bending around the Cheviots. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC. British National Grid coordinates.

3.2 Ribbed moraine

Ribbed moraine has rarely been observed in Britain in contrast to discoveries in neighbouring Ireland and beneath other palaeo-ice sheets (Smith, 2003; Dunlop and Clark, 2006; Finlayson and Bradwell, 2008). However, new mapping has revealed a total of 1,868 ribbed moraine ridges grouped into 19 separate patches or fields. The majority of these discovered or mapped as ribbed moraine rather than other landforms (e.g. drumlins, Figure 8) for the first time. Ribbed moraine fields are less expansive than those observed in Ireland (Greenwood and Clark, 2008). The only considerable area of ribbed moraine in Britain is north of the Southern Uplands in Ayrshire in western Scotland, where ridges cover an area of 750 km^2. Elsewhere, ribbed moraine exists in discrete patches (e.g. northern Scotland). Two main morphometries of ribbed moraine are identified: thin widely spaced ridges that are not overprinted and occur in valley bottoms (minor ribbed moraine after Dunlop and Clark (2006)), and broad flat ridges that are typically superimposed by drumlins and generally occur in low lying expansive settings (Figure 7). The first type of ribbed moraine appears to be exclusively restricted to Scottish locations. The second type occurs mainly in lowland locations and appears pushed up or stacked against topographic highs in Ayrshire (NS 41 21) and north and east of the Forest of Bowland, NW England (SD 66 71).

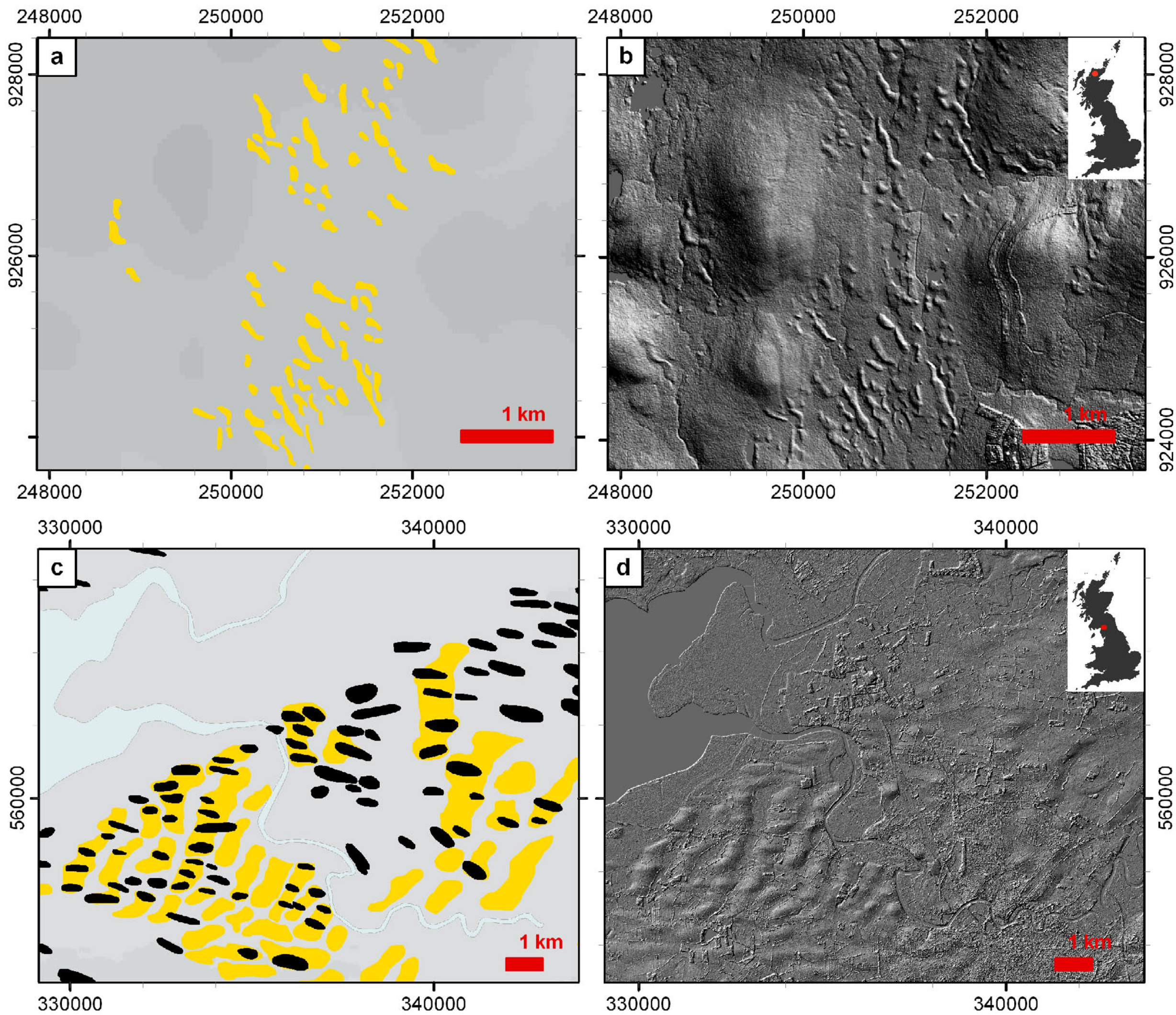

Figure 7. Two main types of ribbed moraine observed in Britain: thin widely spaced ridges constrained in bottom of valley in northern Scotland (a and b), broad closely spaced ridges superimposed and partly remoulded by drumlins in Solway lowlands (c and d). NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC. British National Grid coordinates.

3.3 Accuracy and map completeness

As mapping was conducted by a single observer the resulting maps are internally consistent in terms of bias due to skill and experience in landform identification. The main limitation of DEMs and satellite imagery for geomorphological mapping is that they do not provide information on the internal composition of landforms. A critical assumption is that landforms can be identified and classified on the basis of their morphology alone (Table 1). The whole country was systematically examined and therefore the absence of landforms is a reliable reflection of the paucity of identifiable subglacial bedforms in certain regions. It is notable that the area covered by the Loch Lomond Stadial ice cap in Scotland is virtually devoid of bedforms, with the exception of drumlin fields fringing the southern margin of Loch Lomond (and mapped in Rose, 1981; Smith et al., 2006; Rose and Smith, 2008). The rest of the area appears to be covered by hummocky glacial deposits or moraines, and it is probable that the region contains landforms that are below the resolution of the DEM. This interpretation requires analysis of higher resolution data and field visits.

Post-glacial modification of the subglacial landscape is apparent in places at the scale of individual landforms; meltwater and fluvial erosion has resulted in the truncation and/or bisection of drumlins and ribbed moraine ridges. Mapping reflects existing form. Drumlins and ribbed moraine ridges were mapped along the break-of-slope at the base of the drumlin or ridge. In some areas post-glacial deposition will have raised the level of the ground in the inter-drumlin/ridge hollow above the original base. It is assumed that postglacial deposition in inter-drumlin hollows will be equally distributed and so will only serve to reduce the overall size and not affect drumlin shape. The only way to confirm the level of the true drumlin base would be to use ground penetrating radar or invasive techniques such as boreholes or trenches to examine the underlying stratigraphy (impractical for this volume of data). The overall advantages of mapping break-of-slope were considered to outweigh minor errors due to post-glacial sedimentation. The high resolution of the primary data source enabled cultural features such as roads and urban areas to be easily identified and distinguished from glacial landforms, and this was confirmed by the use of topographic maps.

The new mapping presented is complementary to, and builds upon, previously published and predominantly field based mapping contained within the Glacial Map of Britain and BRITICE database. All landforms contained within the BRITICE database were remapped to ensure consistency of mapping style. New mapping typically replicates the existing distribution of features in the few areas where detailed field examination has been undertaken (Figure 4 in Clark et al. (2009) modified from Smith et al. (2006)). Although there are locations where information contained in BRITICE was interpreted differently (Figure 8). Notable divergences in interpretation occur in Easter Ross, NE Scotland (NH 880 800) where drumlins of Peacock (1984) are reinterpreted as crevasse-squeeze ridges, the Tweed Basin, Scottish Borders (NT 830 420) where drumlin

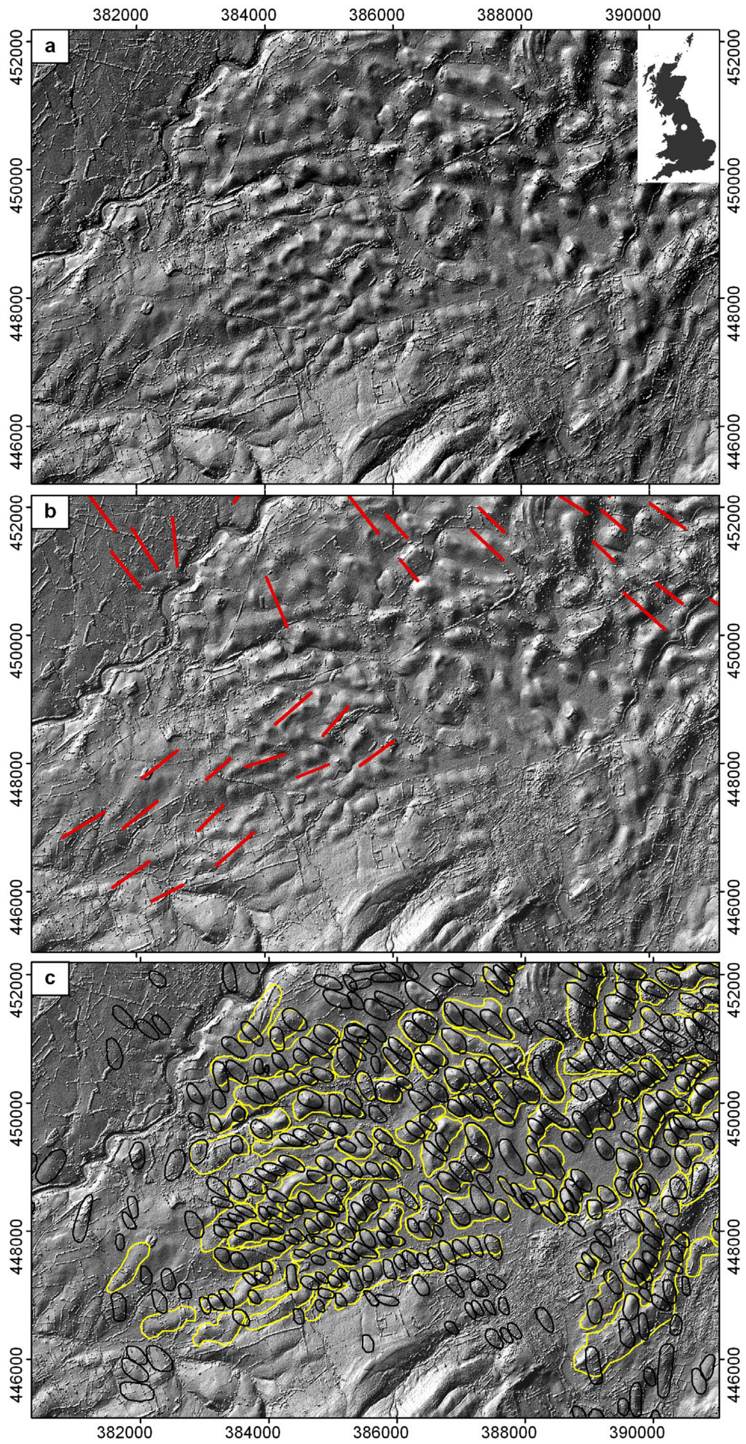

Figure 8. A rare example from the Yorkshire Dales of conflict between new mapping and that contained within the BRITICE dataset. NW relief-shaded image (a), is overlain by BRITICE drumlin layer (in this case the drumlins are from Raistrick (1933)) (b), and overlain by new mapping (c). Drumlins in black, ribbed moraine in yellow. Linear features visible in the relief shaded image are fences and hedgerows between fields demonstrating the high resolution of the digital elevation model (in the upper left corner of the image close to the river a railway line is also visible). The most striking difference is the dramatic increase in mapped bedforms. Ribbed moraine ridges are superimposed by drumlins both indicating ice flow towards the SE. South-westerly trending drumlins of Raistrick (1933) are reinterpreted as ribbed moraine ridges. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC. British National Grid coordinates.

orientation is about 30 degrees different to that of the drumlins mapped by Clapperton (1970) and east of the Forest of Bowland (SD 850 480) where drumlins (Raistrick, 1933) are reinterpreted as ribbed moraine (Figure 8).

It is estimated that approximately 90% of the total subglacial bedform population of Britain is now documented in map form. We estimate that the remaining 10% are either too subtle or small to be recognised clearly on the DEM. The map is therefore a good representation of the distribution and population of subglacial bedforms for Britain and thus a suitable basis for a reconstruction of ice flow patterns.

4. Summary

The accompanying map presents the results of the first consistent whole country mapping of subglacial bedforms for Britain. The map builds upon previous work conducted primarily by field investigations over the last two centuries of interest in the British glaciation and contained within the Glacial Map of Britain. It is estimated that the map is 90% complete and considered an accurate representation of the distribution and pattern of British subglacial bedforms. The mapped distribution has a number of implications for the nature of the last BIS.

The majority of mapped subglacial bedforms frame the distribution of high ground. This apparent topographic control on bedform distribution could suggest that the last BIS was relatively thin (relative to relief) throughout the glacial cycle, or that the majority of subglacial bedforms record the later, thinning, stages of the ice sheet. Alternatively, the paucity of bedforms at high elevations could indicate that some upland areas were covered by cold-based ice. However, as erosional bedforms, which predominantly occur at high elevations, have been excluded from this study as the potential product of multiple glaciations it is probable that the extent of warm based ice is underestimated. Investigations in the Cheviots, NE England (Mitchell, 2008) and parts of Wales (Jansson and Glasser, 2008) support the suggestion of pockets of cold based ice in upland areas. The relative lack of ribbed moraine in comparison to neighbouring Ireland is interesting considering that the British Isles were covered by a single ice mass. There is clear evidence of bedforms in Caithness and Buchan in Northeast Scotland, confirming that these areas were not ice free enclaves at the peak of the last glaciation, as recently demonstrated in the literature (Ballantyne, 2010).

The general pattern of lineations supports the known basic ice flow configuration of the last BIS; ice radiating out from multiple upland ice centres located on the western side of the country. However, superimposition and cross-cutting lineation patterns are also observed indicative of switching flow patterns and therefore supporting the concept of a dynamic, evolving ice sheet (Hubbard et al., 2009). The majority of drumlin fields document ice flow routed offshore through major valleys such as Strathmore and the Tweed Basin and deflected around minor upland areas such as the Cheviots and Lake District. A number of these locations demonstrating converging ice flow have been proposed as sites of palaeo-ice streams (Everest et al., 2005; Hughes, 2008; Golledge and Stoker, 2006).

Together with other palaeoglaciological information, the map formed the basis of the first geomorphologically based inversion reconstruction of the last BIS (Hughes, 2008). It is anticipated that the map will provide a framework for sedimentological studies to further constrain the temporal dynamics of the ice sheet in order to explore connections between ice sheet evolution and the climate changes of the last glacial cycle.

Software

Relief shaded visualisations of the NEXTMap dataset were produced using Erdas Imagine 8.6 and 8.7. On screen digitising of landform break-of-slope or crest-line was conducted in Erdas Imagine 8.6 and 8.7, and ArcMap 9.0 and 9.1. Checks with topographic and geological maps were conducted in ArcMap 9.0 and 9.1. The 3D visualisation tool in Imagine 8.7 was used to create 3D images to assess the landscape context. The map was produced in ArcGIS 9.2 and exported as a PDF.

Acknowledgements

This research was funded by a BGS NERC PhD studentship awarded to ALCH (NER/S /A/2004/12102). NEXTMap Britain elevation data from Intermap Technologies, Landsat TM imagery, 1:50,000 digital geological maps and drift thickness model data were provided under licence by British Geological Survey. Digital Ordnance Survey maps and the LANDFORM PANORAMA DEM were obtained under licence from EDINA. Landmap UK DEM copyright University of Manchester/University College London Year 2001. This paper is published with the permission of the Executive Director of the British Geological Survey (NERC).

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