THE LAST GLACIATION OF SHETLAND, NORTH ATLANTIC

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ABSTRACT. Evidence relating to the extent, dynamics, and relative chronology of the last glaciation of the Shetland Islands, North Atlantic, is presented here, in an attempt to better illuminate some of the controversies that still surround the glacial history of the archipelago. We appraise previous interpretations and compare these earlier results with new evidence gleaned from the interpretation of a high resolution digital terrain model and from field reconnaissance. By employing a landsystems approach, we identify and describe three quite different assemblages of landscape features across the main islands of Mainland, Yell and Unst. Using the spatial interrelationship of these landsystems, an assessment of their constituent elements, and comparisons with similar features in other glaciated environments, we propose a simple model for the last glaciation of Shetland.

During an early glacial phase, a coalescent British and Scandinavian ice sheet flowed approximately east to west across Shetland. The terrestrial landforms created by this ice sheet in the north of Shetland suggest that it had corridors of relatively fast-flowing ice that were partially directed by bed topography, and that subsequent deglaciation was interrupted by at least one major stillstand. Evidence in the south of Shetland indicates the growth of a local ice cap of restricted extent that fed numerous radial outlet glaciers during, or after, ice-sheet deglaciation. Whilst the absolute age of these three landsystems remains uncertain, these new geomorphological and palaeoglaciological insights reconcile many of the ideas of earlier workers, and allow wider speculation regarding the dynamics of the former British ice sheet.

Key words: glaciation, Shetland, glacial landsystems, Scotland, North Atlantic

Introduction

The Shetland archipelago of Northern Scotland comprises over 100 islands, of which three main islands – Mainland, Yell, and Unst – account for the majority of land area. The islands occupy a distinctly maritime location in the North Atlantic north of the UK mainland at 60–61°N, roughly comparable to southern Norway or the southern tip of Greenland, and consequently the region is highly sensitive to climatic changes that may result from fluctuations in atmospheric or oceanic polar fronts (Gordon *et al.* 1993). The current climate is wet and moderately cool, with an annual precipitation of more than 1000 mm and a mean annual air temperature of around 7°C (Birnie 1993). Geologically the islands are extremely complex and host a considerable diversity of bedrock lithologies, predominantly metamorphic rocks but with plutonic igneous and sedimentary rocks also present. The relief of Mainland is largely governed by the resistant, approximately north–south trending, Scatsta Quartzitic Group (Mykura 1976), but the highest point of the archipelago is the granitic Ronas Hill (450 m) (Fig. 1).

Previous research

Despite more than a century of glacial research in Shetland, the pattern and chronology of former ice flow is still widely debated (Ross *et al.* 1993). Previous studies (Peach and Horne 1879, 1880; Hoppe 1965; Mykura 1976; Flinn 1983; Boulton *et al.* 1977, 1985; Carr *et al.* 2006) have employed geomorphological observations, stratigraphical relationships of glacial deposits, the directions of erratic carry and orientations of striations, and ice-sheet modelling, but the wealth of such evidence has led to highly divergent reconstructions and no clear agreement (Fig. 2A–F). Radiocarbon dates relating to deglaciation have done little to clarify the timing of glacial oscillations (Sutherland 1991), but recent uranium series disequilibrium and luminescence dates from Fugla Ness and Sel Ayre respectively appear to indicate that both localities preserve deposits of early or pre-Devensian age (Hall *et al.* 2002) (Fig. 1).

Initial mapping by Peach and Horne (1879)

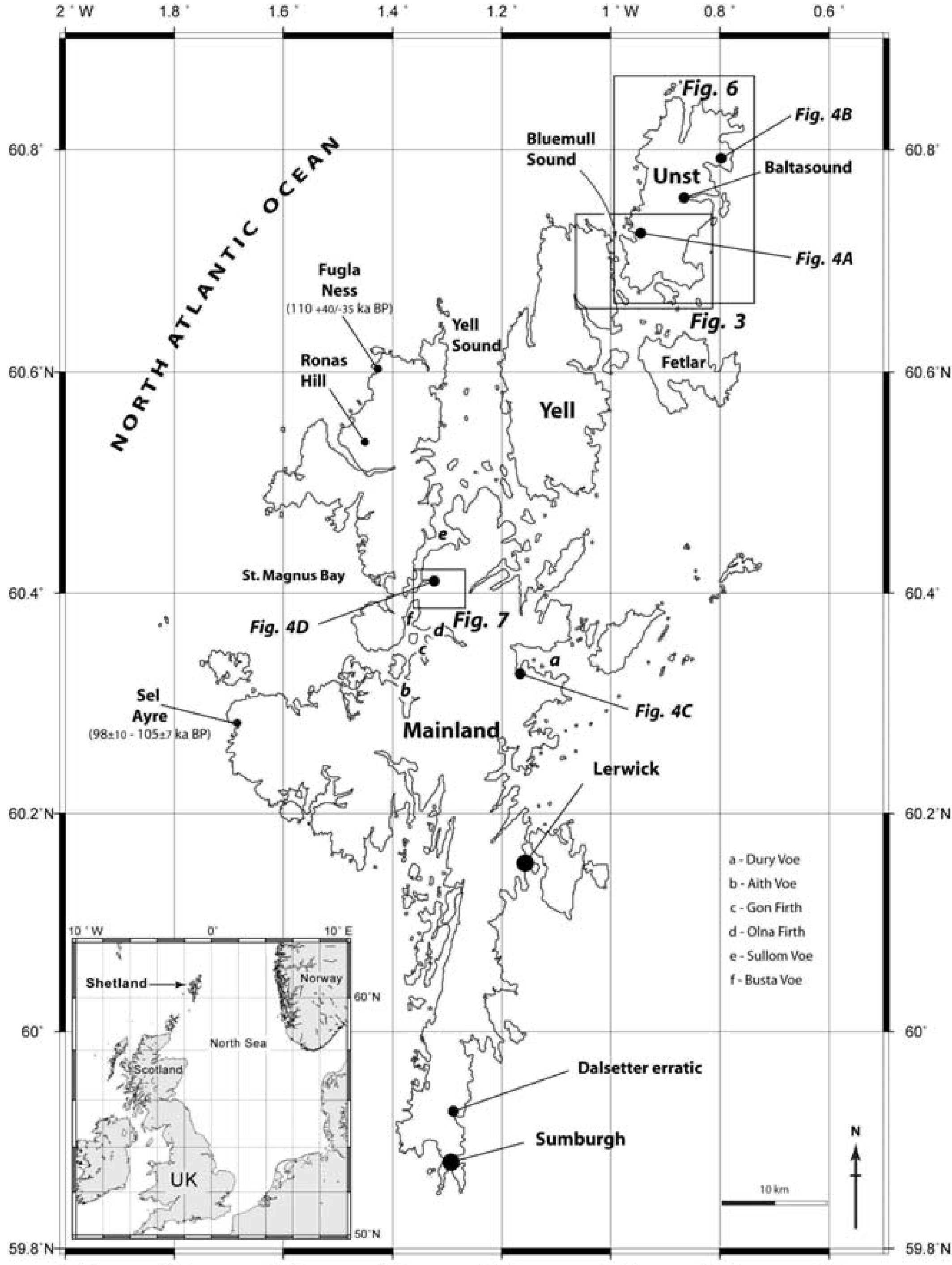

Fig. 1. The Shetland Islands, showing principal settlements and places mentioned in the text. Boxes show areas covered by subsequent figures. Inset shows North Sea context and proximity to southern Norway. Dates at Fugla Ness and Sel Ayre from Hall *et al.* (2002).

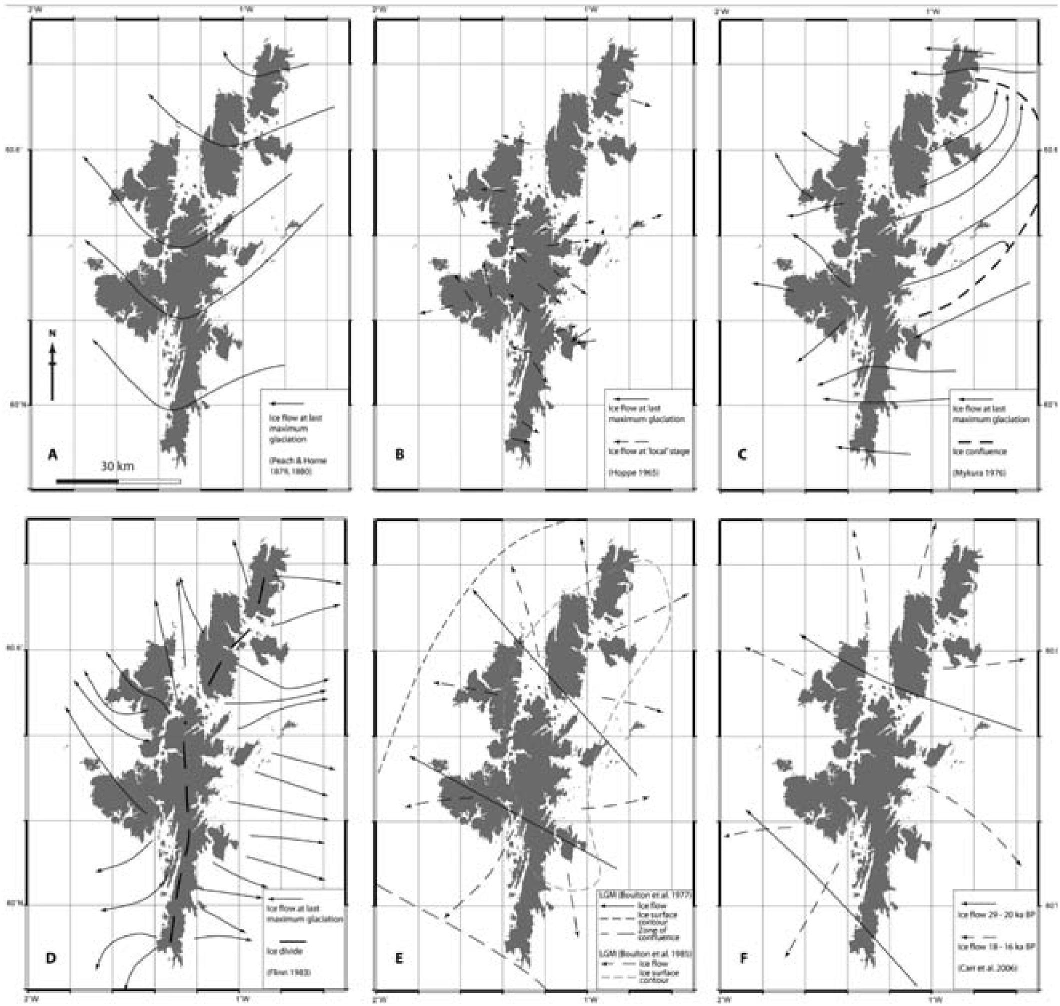

Fig. 2. Previous ice-flow reconstructions for Shetland: (A) Peach and Horne (1879, 1880); (B) Hoppe (1965); (C) Mykura (1976); (D) Flinn (1983); (E) Boulton *et al*. (1977, 1985); (F) Carr *et al.* (2006)

identified evidence for generally east-to-west flow of ice across the Shetland Islands, which was consequently interpreted as resulting from Scandinavian ice crossing the North Sea. The presence of at least one erratic of probable Norwegian origin, the Dalsetter tönsbergite erratic (Fig. 1), lent credence to this idea (Finlay 1928). This major ice sheet coalesced with that sourced from the Scottish mainland, the interplay between the ice masses giving rise to variations in local flow direction (Fig. 2A). Peach and Horne (1879) also noted local accumulations of moraines, and invoked these as evidence for a more restricted growth of ice subsequent to the ice-sheet phase. A reinterpretation of the area almost a century later led Hoppe (1965, 1974) to the conclusion that a local ice cap had been the more dominant agent in forming the glacial features of the landscape, and that radial flow from its centre on Mainland effectively erased most of the evidence of any earlier presence of Scandinavian ice (Fig. 2B).

Perhaps in an attempt to reconcile these differing views, Mykura (1976) presented a flowline reconstruction that incorporated elements of the radial, local ice flow with convergence of Scandinavian ice in the North Sea and east-to-west flow only across the northernmost part of Unst and the southern portion of Mainland (Fig. 2C). Early attempts

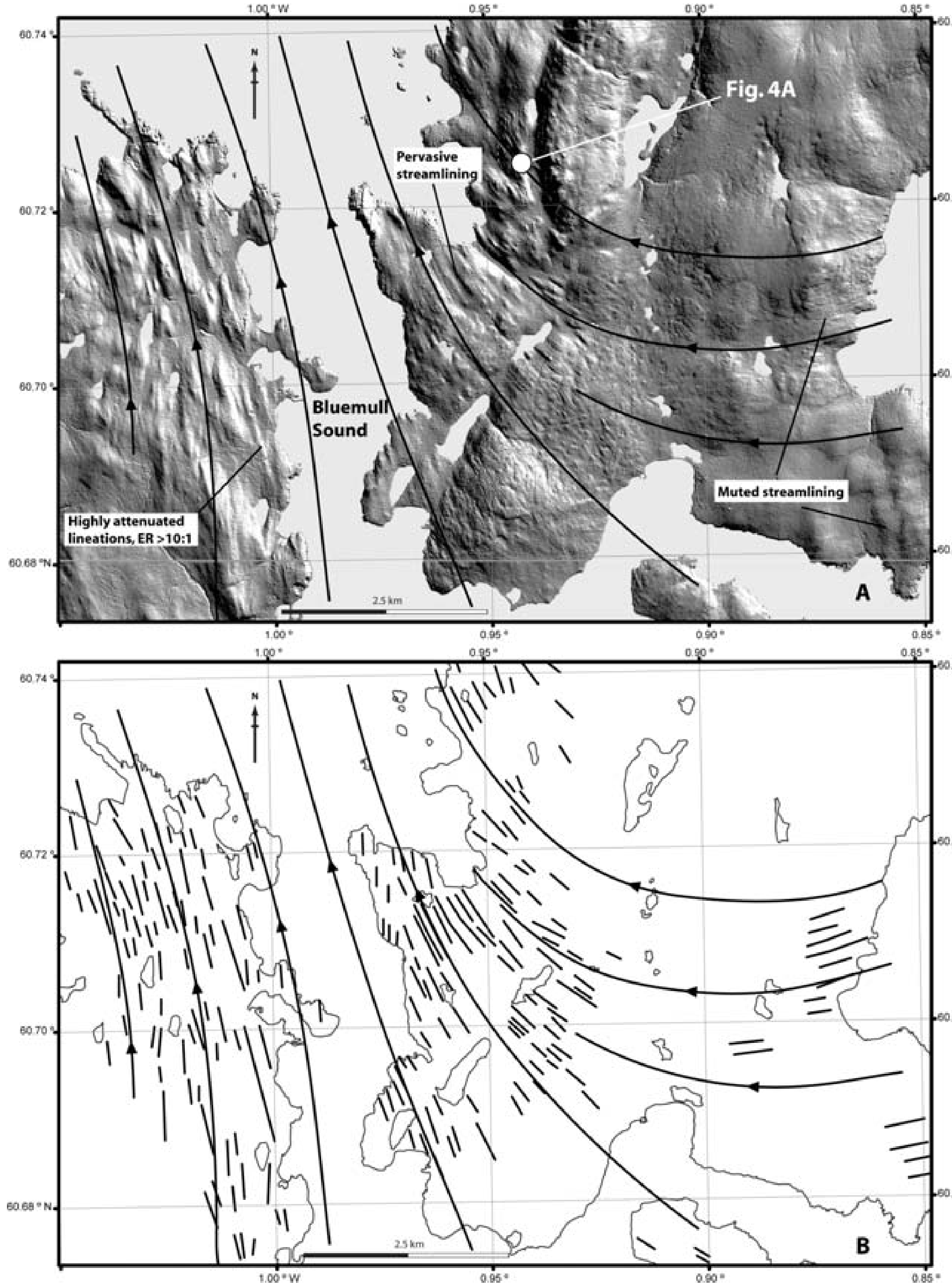

Fig. 3. A: Streamlined bedforms characteristic of Landsystem 1: note the strong, elongate features in the west and the more muted streamlining in the east. B: Digitally captured bedform crestlines from interpretation of the DTM. See Fig. 1 for context of location. NEXTMap hillshade DTM derived from Intermap Technologies high-resolution terrain data

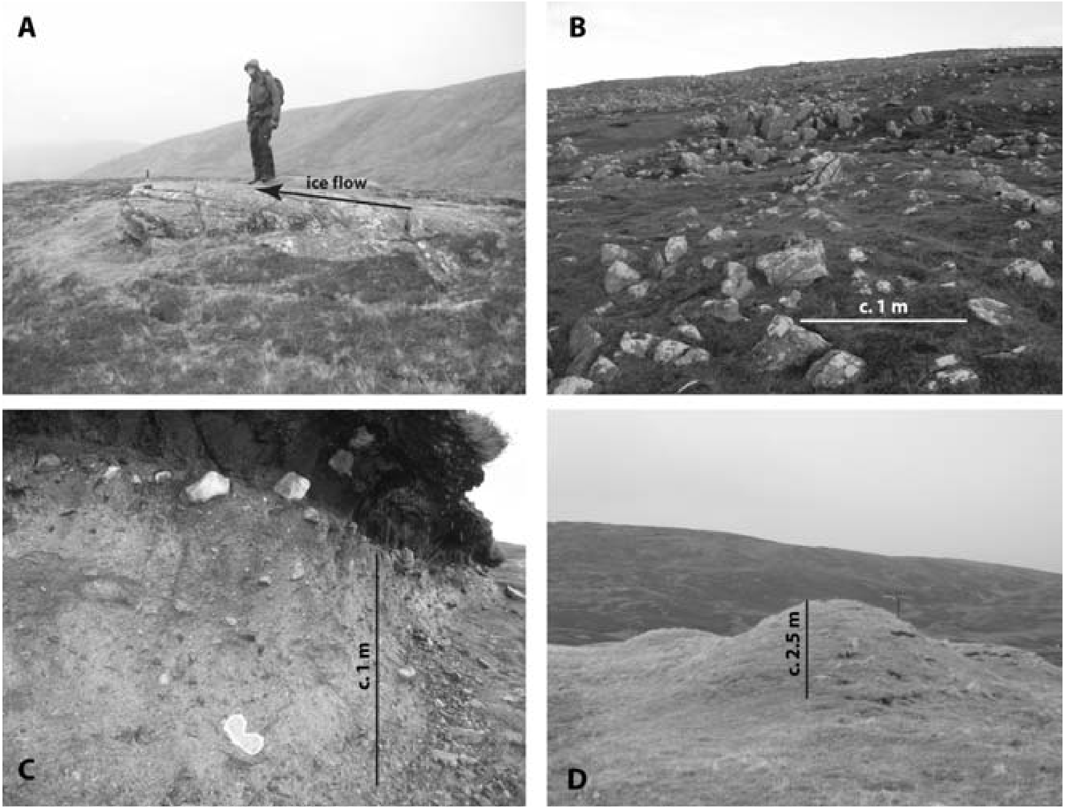

Fig. 4. A. Low roches moutonnée in southwest Unst, iceflow to northwest. B: Glacially disaggregated bedrock, Hill of Clibberswick, Unst. C: Subglacial till beneath peat, Mainland. D: 'Hummocky moraine' near Brae, Mainland. See Fig. 1 for locations

at ice-sheet modelling initially favoured a great thickness of northwestward flowing ice over Shetland, sourced from Scandinavia and confluent with the **BRITISH ICE SHEET (BIS)** (Boulton *et al.* 1977). Evidence for such extensive ice-sheet glaciation, as opposed to localized ice-cap glaciation, was dismissed by Flinn (1983), who instead proposed a local ice cap whose ice divides stretched the entire length of the three main islands (Fig. 2D). Further numerical modelling subsequently reproduced Flinn's empirical ice-cap reconstruction (Boulton *et al.* 1985), but positioned the former ice divide slightly to the east of the main axis of the island chain (Fig. 2E). A thorough study by Ross (1996) proposed that this eastward migration of the ice divide took place during the latter stages of glaciation, when ice sheet recession was at least partly influenced by calving losses associated with a rising sea level.

Marine studies have similarly provided a plethora of glacial reconstructions. Ehlers and Wingfield (1991) used seismic data to propose an extensive Late Devensian glaciation of the North Sea, most likely involving confluent British and Scandinavian ice, whilst Stoker and Holmes (1991) also presented compelling seismostratigraphic evidence for Late Devensian glaciation to near the shelf edge west of Shetland. Radiocarbon dates from shells and benthic foraminifera retrieved from boreholes in the North Sea subsequently constrained glaciation of the area to sometime prior to *c.* 22 ka ^{14}C BP, with subsequent open-water glacimarine conditions in the latter part of the Late Devensian (Sejrup *et al.* 1994). However, on the basis of numerous terrestrial and marine dates, Bowen *et al.* (2002) argued that any confluence of the British and Scandinavian ice sheets must have occurred around 40 ka BP, and that during the widely accepted **Last Glacial Maximum (LGM**; *c.* 22 ka BP) the BIS was considerably more restricted and certainly did not extend as far north as the Shetland Islands. Recent micromorphological evidence from glacigen-

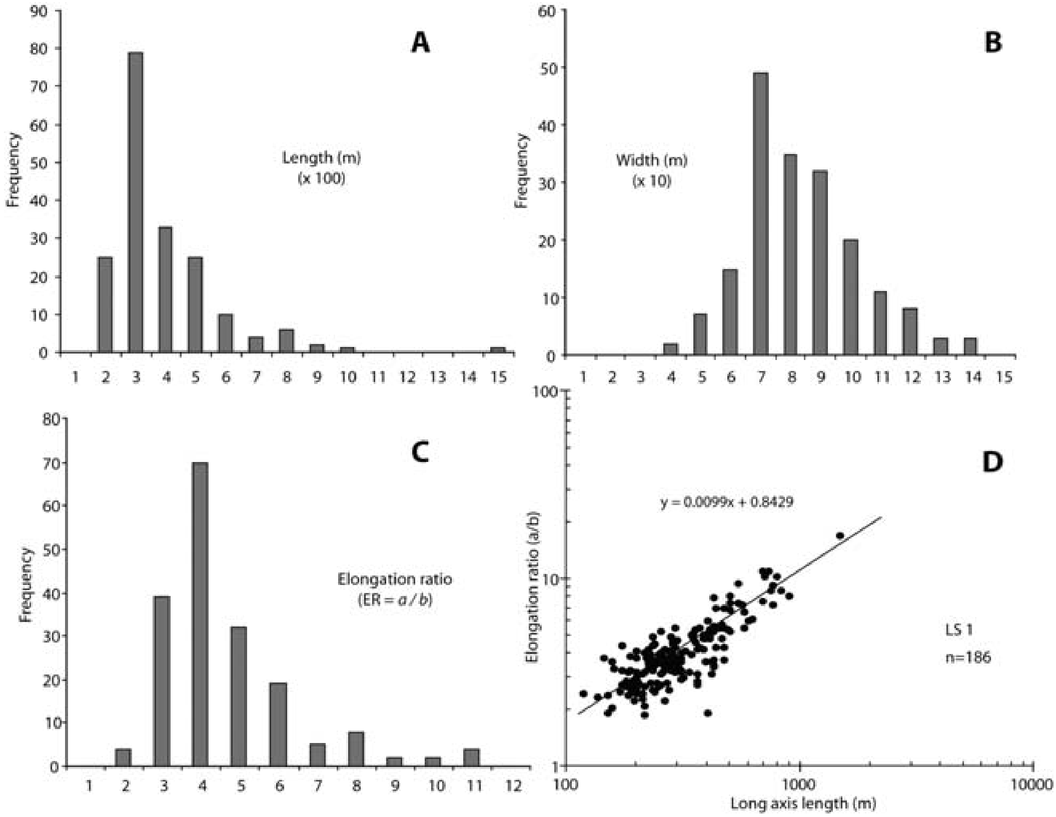

Fig. 5. Morphometric data for the 186 elements of Landsystem 1 (Fig. 3). A: Lengths (a); B: Widths (b); C: Elongation ratio a/b; D: relationship of elongation ratios of bedforms to bedform length

ic deposits of the North Sea (Carr *et al.* 2006) appears to question such a reconstruction, however, and indicates instead that Scandinavian ice overrode Shetland *c.* 29–20 ka BP, whilst later, radial flow of a local ice cap took place *c.* 18–16 ka BP (Fig. 2F). Perhaps the most convincing argument for an extensive, and probably confluent, Scandinavian ice sheet, however, comes from recent interpretations of 3D-seismic reflection data showing that the central North Sea hosted a major northwest-flowing ice stream during the Last Glacial Maximum (Graham *et al*. 2007).

Methods

In summarizing much of the earlier research, Ross *et al.* (1993) highlighted the lingering uncertainties of Shetland's glaciation and noted that any future research would have to address the pattern and chronology of ice flow, and the relative importance and style of glaciation of both local and Scandinavian ice. Here we present new interpretations for these problems, based on the interpretation of NEXTMap high-resolution (5 m × 5 m horizontal, 1.5 m vertical) **digitial terrain model (DTM)** for the whole archipelago, together with targetted field observations ('ground truthing') in parts of Mainland, Yell and Unst. Given the existing geological detail available in published maps, our primary emphasis was on improving the geomorphological component of the dataset through the use of this new topographic data.

Digital manipulation of the DTM in ESRI ArcGIS, particularly with respect to the angle of its illumination, has enabled clearer landform identification than hitherto possible, and allowed the capture of principal features in a spatially attributed geodatabase. This permits use of the DTM to derive vectorial and geometric data for individual features, which subsequently allow morphometric analyses to be employed in distinguishing between landform types and population groups. This ap-

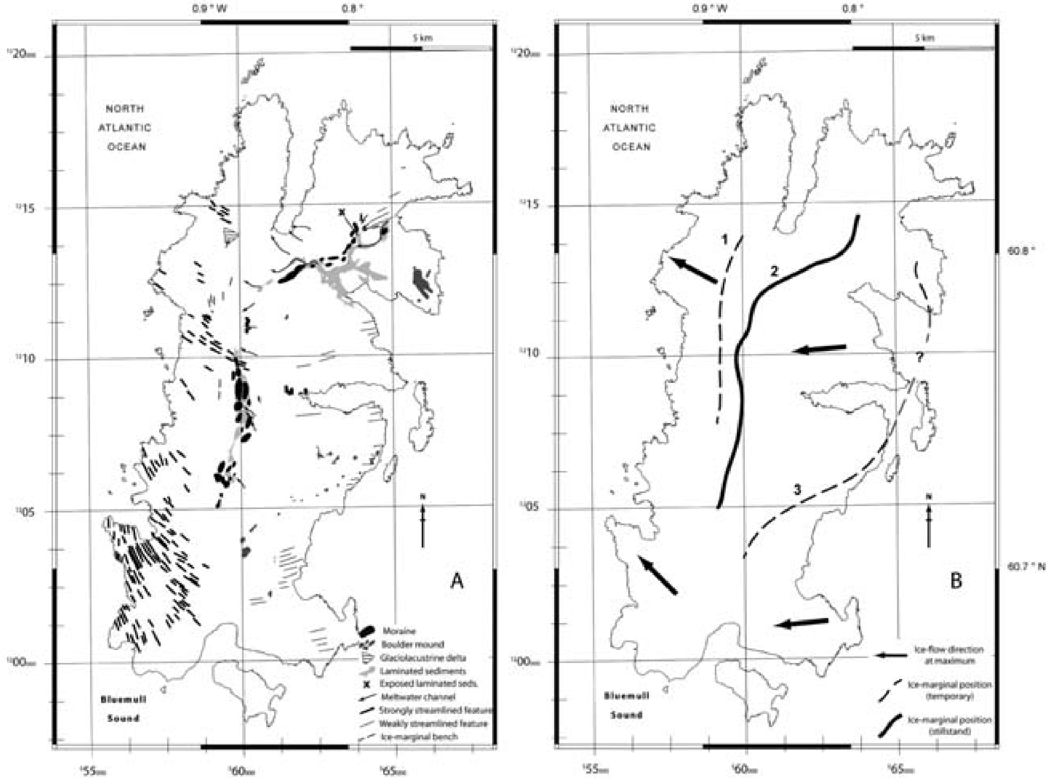

Fig. 6. (A) Key elements of Landsystem 2 in Unst; (B) interpreted ice-marginal positions. See Fig. 1 for context of location. Tick marks on western and southern borders show British National Grid coordinates; Latitude/Longitude shown on eastern and northern borders

proach to geomorphological mapping has been much advanced by the detailed and extensive work of e.g. Boulton and Clark (1990a,b) Clark (1993) Smith and Clark (2005). It is not without problems, however, particularly with respect to the azimuth bias introduced by angled illumination (Smith and Clark 2005). In an attempt to overcome this issue, we used both northwest and northeast-illuminated DTM's to identify and interpret glacial landforms, and endeavoured to avoid misidentification of bedrock structural features by following an approach similar to that employed elsewhere in Scotland (Golledge and Stoker 2006). Lineations interpreted from the DTM's are then used to reconstruct former ice flow patterns and ice marginal positions by process-form analogy with modern glacier systems (e.g. Evans 2003) and glaciological theory (e.g. Paterson 1994).

With the above in mind, the field mapping component of our investigations aimed primarily to validate the interpretation of the DTM, as well as to obtain specific lithological data for the mapped features, to take photographs and samples where appropriate, and to record any additional information that might inform the geological and palaeoglaciological interpretations. Where available, published 1:50 000 scale geological maps of Shetland (Institute of Geological Sciences 1978, 1982; British Geological Survey 1994, 2002) were interrogated, together with the unpublished larger scale field maps from which the published maps were derived. Large parts of Shetland are peat-covered (especially in Yell), and in such areas, ground truthing was restricted to point observations where glacial deposits were exposed beneath the peat, or where landforms were sufficiently large not to be masked by it. Thick peat cover also hampered survey in large parts of Mainland, and in many areas few glacial landforms could be discerned. By contrast, the island of Unst revealed an abundance of glacial sediments and landforms, so field observations were more detailed and extensive.

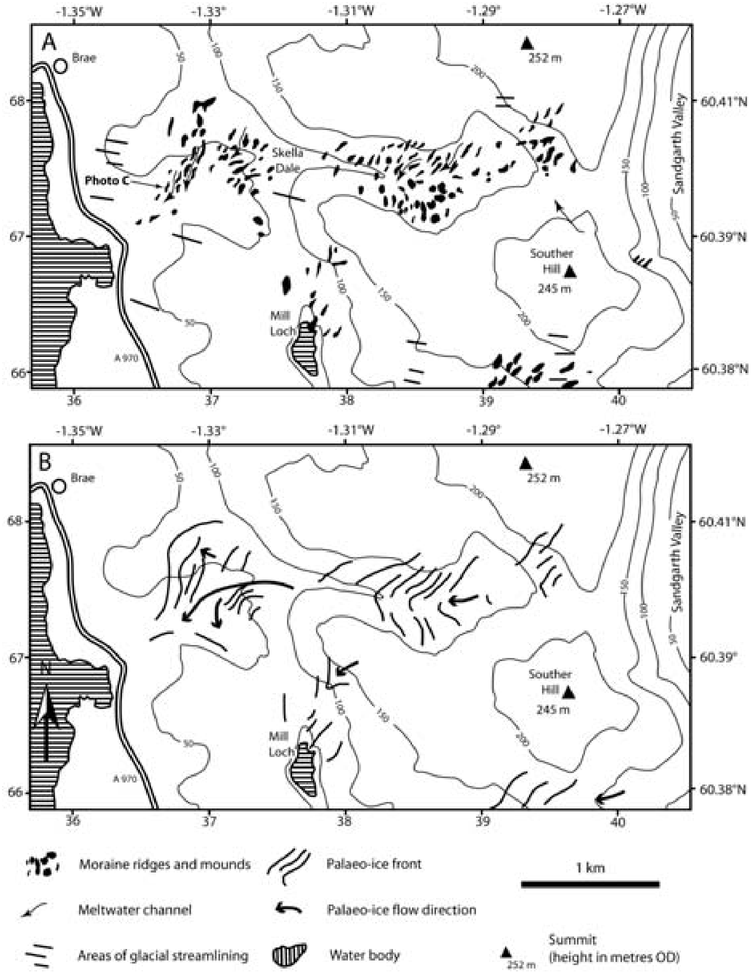

Fig. 7. (A) Moraine map of study area near Brae, Mainland. (B) Interpreted palaeoice fronts. See Fig. 1 for context of location. Tick marks on western and southern borders show British National Grid coordinates; Latitude/Longitude show on eastern and northern borders

Results

Elongate landforms (**elongation ratios (ER)** >5:1) and extensive areas of strongly ice-moulded, streamlined topography are evident in many areas of the Shetland archipelago. The hills that form the west of Unst show signs of streamlining along much of their length, but the largest areas, and best-developed individual features, occur mainly in the southwest of Unst, flanking Bluemull Sound (Fig. 3). Considerable streamlining also occurs on the western side of the sound, on Yell. In both areas a sharp boundary to the streamlined terrain is clearly evident, which together with variations in feature alignments gives an impression of convergent flow in this area. Field survey identified numerous roches moutonnée both on high ground (*c.* 200 m a.s.l.) and near to sea level (Fig. 4A). The northwesterly alignment of these streamlined rock outcrops is oblique to the generally north-northeast to southsouth-west strike of the principal bedrock schistocity.

One hundred and eighty-six crestlines were mapped in this area (Fig. 3), and their morphometries analysed in the GIS. Lengths range from *c.* 200–1500 m with a mode of 300 m (Fig. 5A), whereas widths range from approximately 40–140 m with a modal value of 70 m (Fig. 5B). Elongation ratios (a/b) of these features range from *c.* 1.5:1 to 11:1, with the majority clustering around 4:1 (Fig. 5C). Figure 5D shows that a positive correlation exists between ER and long axis length.

Strongly streamlined bedrock also occurs along the western margin of Yell, and in the northern coastal fringes of Mainland flanking Yell Sound, but is conspicuously absent from most of Mainland. More subdued streamlined bedrock is appar-

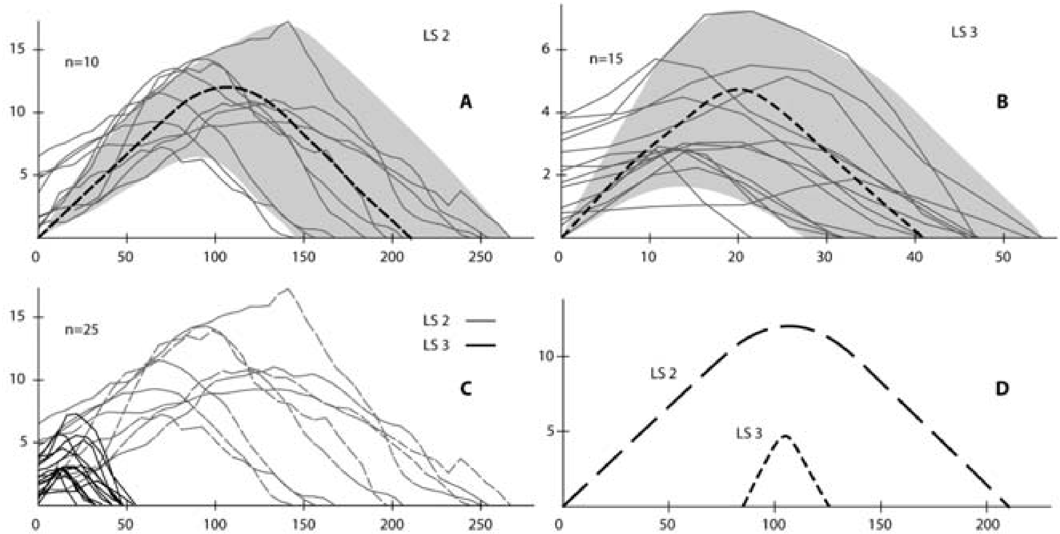

Fig. 8. (A) Profile data across LS2 moraines in Unst; shaded area shows envelope of maximum/minimum height and breadth of features; dashed line shows median profile. (B) Profile data across LS3 moraines in Mainland; shaded area shows envelope of maximum/minimum height and breadth of features; dashed line shows median profile. (C) Combined plot of LS2 and LS3 moraine profiles at same scale. (D) Median profiles of LS2 and LS3 moraines at same scale

ent in the east of Unst (Fig. 6), the southeast of Yell, and in scattered areas across Mainland. Glacially disturbed bedrock was seen in abundance on Hill of Clibberswick, Unst (Fig. 4B), where dislodged blocks appeared to show offset to the southwest. Erratics of this ultramafic bedrock also occur in the southwest of the island (British Geological Survey 2002).

Exposures of massive, matrix-supported diamicton up to 3 m thick, commonly overlying bedrock, were seen in scattered localities across Unst, Yell and Mainland, consistent with recent geological mapping (British Geological Survey 2002) (Fig. 4C). In Unst, roundcrested ridges up to 15 m high, several hundred metres long, and composed of diamicton are present around [HP635 135], [HP620 130], [HP600 090] and [HP603 074], some of which were formerly mapped as possible drumlins (British Geological Survey 2002). Collectively the mounds form an elongate, locally multiridged assemblage extending more than 10 km from north to south (Fig. 6); several have scattered subangular to subrounded erratics of vein quartz and granite on their crests.

Whereas other large moraines are generally absent, glacial disaggregation of bedrock outcrops in the east of Unst has produced abundant mounds of edge-rounded boulders of local lithologies around [HP660 125] (Hill of Clibberswick) and from [HP645 065] southwestwards to [HP600 040]. These 'morainic boulder ridges' (British Geological Survey 2002) were recently verified at Clibberswick. The previous mapping also identified meltwater channels, laminated sediments (interpreted as lacustrine deposits), and a glaciolacustrine delta in Unst. Our fieldwork verified that the meltwater channels commonly trend approximately normal to the overall alignment of the moraines, and identified laminated sediments between two of the morainic mounds at [HP6387 1404]. Ice-marginal benches forming a discontinous north–south aligned subhorizontal ridge on the hillside below the delta were identified from the DTM.

Assemblages of smaller, closely spaced ridges and mounds (Fig. 4D) occur in glens entering Dury Voe, Aith Voe, Gon Firth, Olna Firth, Sullom Voe and Busta Voe in northern central Mainland. Many of these landforms form arcuate chains that are convex down-valley, with the exception of those on the western side of Sullom Voe, where ridges arc up-valley. Particularly good examples of this landform-type are observed flanking the Skelladale Burn near Brae, where an extensive area of densely packed sharp-crested hummocks and ridges extend from near sea-level up to a col at approximately 200 m a.s.l. linking Skella Dale with the deep north–south trending Sandgarth Valley to the east (Fig. 7

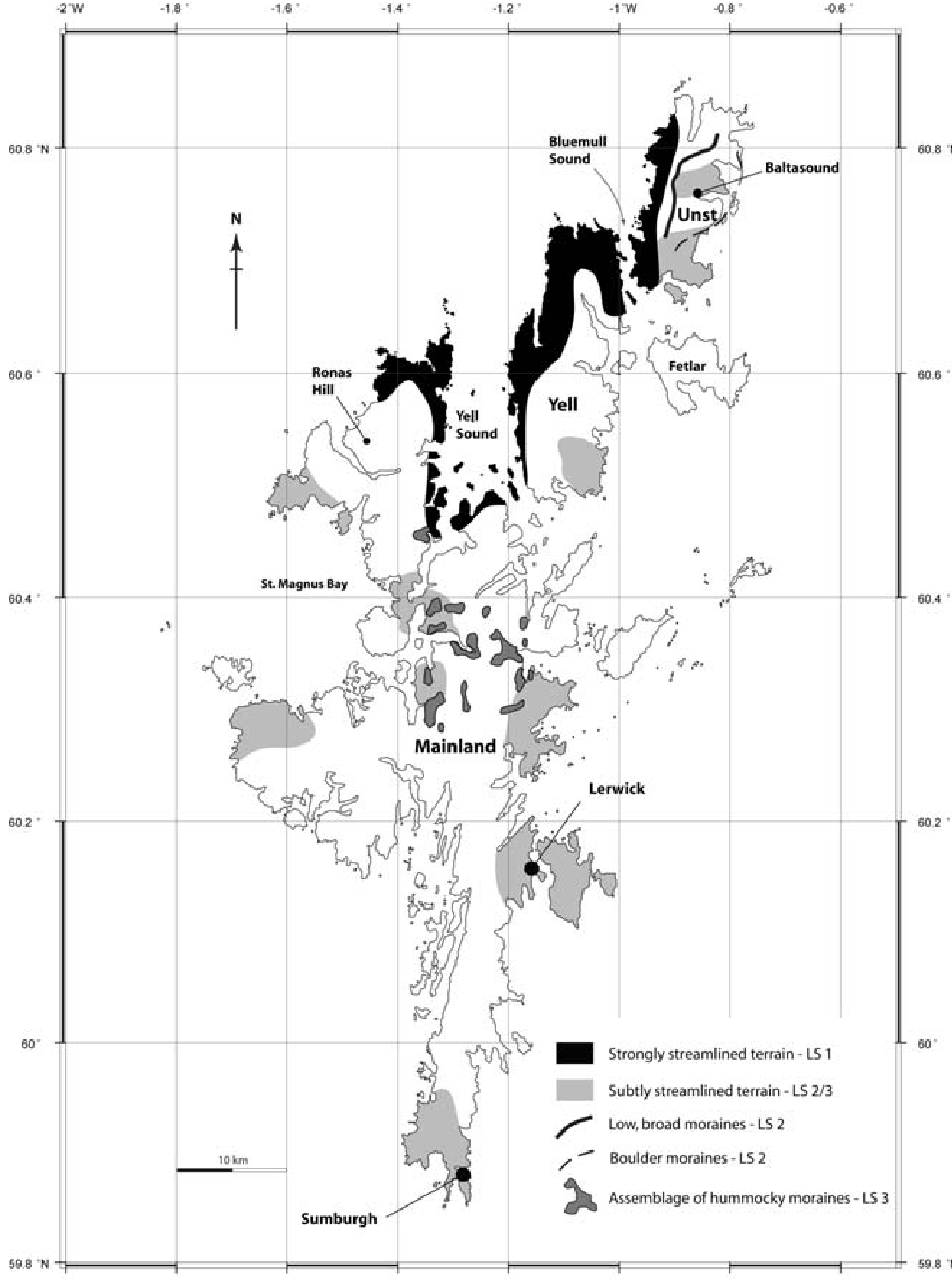

Fig. 9. Spatial distribution of landsystem elements across Shetland, based on published maps, recent mapping, and interpretation of a high-resolution DTM

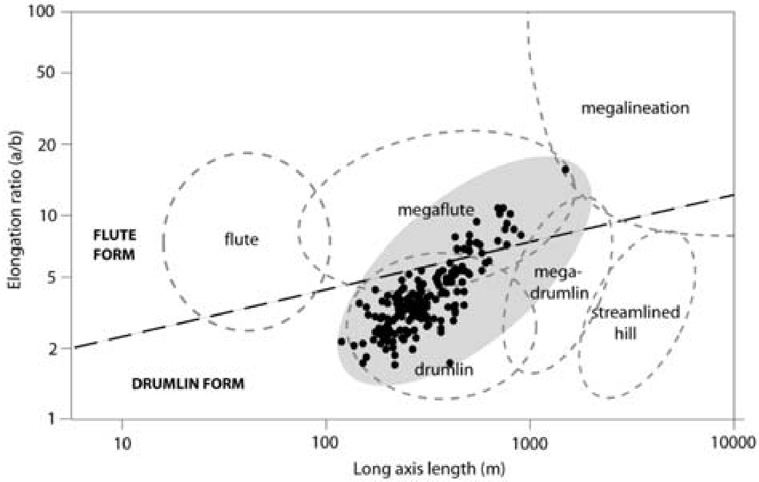

Fig. 10. Bedform data from Fig. 5 overlain on classification chart modified from Everest *et al.* (2005). Line separates drumlinoid forms from more elongate 'flute' type landforms.

A and C). The westernmost of the Skella Dale moraines form a coherent outer chain on the northern side of the valley, inside which morainic mounds and ridges are abundant and are separated by intervening meltwater channels. A number of scattered glacially transported boulders are present within the assemblage, in some instances lying perched on individual hummocks. A series of small transverse ridges, forming at least one cross-valley pair, are also evident trending downslope from higher ground towards Mill Loch in the south. Interpretation of the hill-shaded DTM identified that the Brae moraine assemblages occur within a larger area of muted streamlined terrain.

Cross-profile analysis (measured perpendicular to ridge axes) of a selection of the more elongate landforms in the Brae area reveals relatively consistent morphometry to the population. The width of individual elongated features discernable from the DTM ranges from 20 to 55 m, with a mean of *c.* 40 m, whereas their heights range from 2 to 7 m with a mean of *c.* 4.5 m (Fig. 8B). The mounds form a distinctly separate population from those described above from Unst, whose average width and height is *c.* 200 m and 12 m respectively. Figures 8C and D illustrate respectively: individual feature morphometries for both groups, and the mean geometry of the two populations, each plotted at the same scale for comparison.

Interpretation

In attempting to interpret the data we adopt a landsystems approach, in which areas of 'common terrain attributes' are delimited (Clark 1997; Stokes and Clark 1999; Evans 2003; Benn and Lukas 2006; Golledge 2007a). The recognition of areas exhibiting different terrain attributes – landsystems – also enables a relative event chronology to be proposed. We suggest that the landform–sediment assemblages described above can be classified into three different landsystems, defined by their contrasting geomorphological signatures. Landsystem 1 (LS1) is principally manifest as highly streamlined topography, Landsystem 2 (LS2) exhibits large-scale ice-marginal landforms and sediments as well as areas of muted streamlining, and Landsystem 3 (LS3) is mostly distinguished by locally concentrated nested groups of 'hummocky moraine', considerably smaller than the moraines of LS2. The general distribution of the landforms and sediments constituting each landsystem is summarized in Fig. 9.

Landsystem 1

Highly elongate landforms composed of bedrock or unconsolidated substrate are widely accepted as indicators of either prolonged or fast former ice flow (Hart 1999; Stokes and Clark 1999, 2002, 2003; Bradwell *et al.* 2007). Individual 'elements' of a large-scale streamlined landscape are commonly used to derive generalized flowlines that allow a regional ice-flow interpretation to be presented (Stokes and Clark 1999, 2001; Clark and Stokes 2003). Recognition and interpretation of such features in previously glaciated terrains is therefore highly instructive with respect to former ice-sheet

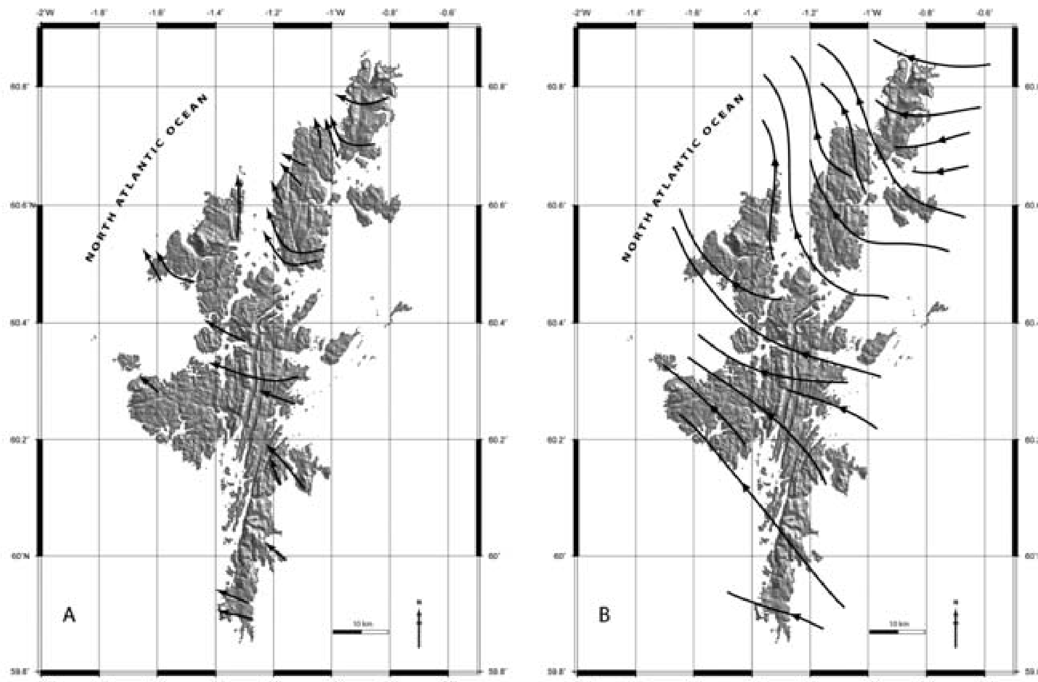

Fig. 11. (A) Interpreted streamlined bedforms; (B) generalized flowlines across Shetland during latter stages of ice-sheet overriding. Note localized topographically controlled deflection of general east–west flow. Nextmap hillshade DTM derived from Intermap Technologies high-resolution digital elevation data

behaviour, enabling new interpretations to be made in areas where controversies over the direction and style of ice flow still remain. A number of such studies have already focused on dynamic sectors of the former BIS (e.g. Everest *et al*. 2005; Jansson and Glasser 2005; Stoker and Bradwell 2005; Golledge and Stoker 2006), but none have yet specifically addressed Shetland.

Since the streamlined features in Shetland occur across different bedrock lithologies, trend oblique to primary foliation or strike, and form landsystem geometries consistent with those formed by streaming ice (Stokes and Clark 1999), we propose that the landforms reflect glacial genesis rather than inherited bedrock control. The elongate bedforms typical of LS1 show ERs typical of drumlins and megaflutes (Fig. 10), and thus we interpret this landform assemblage as indicative of relatively dynamic zones within the former ice sheet.

Streamlined landforms are best preserved in the north and west, but more subtle features in other areas show alignments consistent with their being part of the same episode, and enable a regional palaeoflow pattern to be approximated (Fig. 11). Areas of convergent flow (Figs 3 and 11A, B) appear to be largely associated with the location of topographic troughs, whereas divergent flow occurs around higher ground. Variability in flow direction is greatest in the north and least in the south, although this interpretation may partly be conditioned by the more limited evidence in the south. Nonetheless, it seems that the underlying topography, particularly that now below sea level, exerted at least some influence on former ice flow. Since the reconstructed flowsets cross the entire archipelago, the ice divide must have lain to the east of Shetland during this episode, as suggested by Ross (1996), with the former ice sheet surface declining towards the northwest. Formation of LS1 probably took place during a period of extensive glaciation when the overriding ice sheet was thick enough to cover the majority of hills in Shetland, requiring a minimum ice surface altitude of 200–300 m. Much of the streamlining generated during this stage is now muted, perhaps indicating further glacial erosion or cover by glacial substrates, suggesting that this episode was relatively early.

Landsystem 2

The landforms and sediments typical of LS2 (large moraines, meltwater channels, glaciolacustrine deposits) share similarities with those identified at the fringes of former ice sheets, such as the Laurentide Ice Sheet (Colgan *et al*. 2003). Such environments are characterized by: (1) sediment delivery to the proglacial zones via subglacial pathways, producing low, broad moraines and edge-rounded erratics; (2) limited accumulation and input of supraglacial debris; (3) ice movement through sliding, ploughing and deformation of an unconsolidated bed, and; (4) active recession of the ice margin.

Additionally, Golledge (2007b) demonstrated that populations of moraines that can be differentiated on both morphological and sedimentological grounds most probably relate to quite different palaeoglaciological environments, which in most cases reflect the chronology of their formation.

The morphometries of moraines identified in LS2 show consistency of height and breadth that is clearly distinct from those of LS3 moraines (Fig. 8), and the former are, without doubt, of an entirely different scale. In addition, the moraines in Unst (Fig. 6) form an arcuate complex that extends approximately 10 km from north to south. By analogy with moraines elsewhere in Scotland, and the criteria described in Golledge (2007b), we consider the cohesive diamicton-composed moraines incorporating subangular and subrounded clasts in Unst to be best interpreted as representative of a terrestrial ice-marginal position demarcating the edge of a retreating ice sheet. Although few exposures were seen in the Unst moraines, we may infer from the studies described above that features were probably formed primarily by meltout of debris-rich basal ice. The presence of scattered subangular and subrounded boulders on their crests may indicate subaerial deposition of englacial debris elevated from the bed to the glacier margin via compressive flow and associated thrusting (Sugden and John 1976; Colgan *et al.* 2003). Meltwater channels draining subglacially towards, and proglacially away from the ice margin attest to at least partially warm-based conditions during this stage. Glaciolacustrine deposits are commonly juxtaposed with moraines, and larger landforms such as the previously mapped delta (British Geological Survey 2002) may suggest that recession of the ice sheet was sufficiently gradual to allow ice-marginal lake formation. Preservation of LS2 landforms and sediments appears to be largely confined to central and eastern Unst, reflecting a period of formation after the pervasive streamlining phase of LS1, when ice was less extensive. Streamlining directions and the orientation of the moraine complex indicate that, although the ice sheet had receded by this time, the former ice divide still lay to the east of Shetland.

Landsystem 3

The moraines typical of Landsystem 3 are morphometrically of a very different scale from those in Landsystem 2, and are thus considered to represent a separate population (Fig. 8). The assemblages of mounds and ridges in northern central Mainland are comparable in pattern and morphology to 'hummocky moraine' described elsewhere in Britain (e.g. Benn 1992; Bennett and Boulton 1993; Lukas 2005; Benn and Lukas 2006). While early studies of these steep-sided moundy deposits favoured formation by in situ ice stagnation (Sissons 1967, 1974, 1976), more recent research has shown that this landform type is characteristic of deposition by active, oscillating glacier margins (Lukas 2005; Benn and Lukas 2006). Such studies demonstrate that individual chains of moraine mounds can be used to approximate palaeo-icefronts. If the moraines in our study area can be interpreted in a similar way, they indicate that the Brae moraines were produced during a period of active glacier retreat with numerous small oscillations (Fig. 7B). This active retreat continued up-valley onto higher ground and through the col towards the deep Sandgarth Valley. A similar pattern of incremental ice-retreat occurred in several locations in northern central mainland (Fig. 9), perhaps indicating that these glens supported outlet glaciers sourced from a small, central source. The presence of moraines arcing up into the valley of Sealt Burn, on the western side of Sullom Voe, perhaps suggests that this landsystem may be more extensive below current sea-level.

Discussion

Comparison of the three landsystems described above with relict and modern glacial landsystems elsewhere permits glaciological inferences to be made about the style and relative timing of former ice-flow events in Shetland.

Streamlined landforms shown by LS1 imply the former presence in parts of Shetland of relatively fast flowing portions of the former BIS, although little evidence exists to infer the presence of discrete ice streams sensu stricto. The reconstructed pattern of ice flow indicates that the ice sheet was sourced to the east of Shetland and flowed to the west and northwest. This general pattern, and the implied thickness of ice necessary to overwhelm much of the topography, points to a former ice sheet margin well beyond the present coast of Shetland, probably near the continental shelf edge. A marginal position on the West Shetland Shelf is entirely consistent with seismostratigraphic reconstructions for the area (Stoker and Holmes 1991). The direction of flow is most easily accounted for by confluence of the BIS with the Scandinavian ice sheet, the latter deflecting the flow of the former. Whilst there is some support for such a scenario, the timing of this configuration is widely debated ranging from Last Glacial Maximum (*c.* 22 ka BP; Ehlers and Wingfield 1991; Graham *et al.* 2007) to MIS 2 (early Late Devensian, *c.* 25–29 ka BP; Sejrup *et al.* 2003, 2005; Carr *et al.* 2006) to Mid-Devensian (*c.* 40 ka BP; Bowen *et al.* 2002) to pre-Devensian (Lonergan *et al.* 2006). Despite lingering uncertainty regarding the absolute age of this confluence, it nonetheless seems reasonable to infer that LS1 records the earliest of the glacial events described here.

Partial masking of LS1 in many areas, either by erosion of features or by deposition of covering substrate, suggests that Landsystem 2 relates to a later event. Not all elements of LS1 are overprinted, however, and the distribution of both the highly streamlined and the more subdued streamlined terrain appears to be governed more by the horizontal extent of ice during the later episode, rather than by the vertical extent. LS2 also includes the large, diamicton-composed mounds seen most clearly in Unst (Fig. 6). Their size, composition, morphometry and presence of edge-rounded surface erratics are consistent with an interpretation as moraines formed at the margin of an ice sheet, rather than an ice cap or valley glacier (Colgan *et al.* 2003; Golledge 2007a). We suggest that the multiridged moraine complex in Unst therefore marks the former position of an ice sheet margin, perhaps during a stillstand or minor readvance that punctuated overall recession. The ice was topographically constrained by the hills on the west side of Unst, implying thinner ice than gave rise to LS1. Pinned in this way, the ice would have flowed with considerably reduced velocity and may, as a consequence, have infilled or smoothed the older LS1 streamlined bedforms.

During this period of margin stabilization it would be likely for ephemeral ice marginal ponds to develop. The laminated sediments seen in close proximity to the Unst moraine may therefore be glaciolacustrine in origin, rather than lacustrine, as previously inferred (British Geological Survey 2002). Meltwater channels flowing subglacially towards, and proglacially away from the former ice margin may have fed and drained these lakes, respectively. Subsequent recession of the ice margin, particularly its thinning over higher ground, may be recorded in the extensive areas of disaggregated bedrock in the east of Unst. The detached blocks reflect the very limited transport efficacy of the thinning ice during it last movements in the area. Evidence for LS2 elsewhere in Shetland is far more limited, represented solely by a small number of ice-sheet moraines in the north and east of Mainland. Whether the restricted occurrence of LS2 features reflects localized formation or subsequent removal is unclear.

Landsystem 3 is limited in its distribution, and probably reflects moraine formation at the margins of outlet glaciers from a local ice cap on Shetland Mainland (Ross 1996). This ice cap would need to have been >200 m thick in order to overwhelm the north–south bedrock ridges that dominate the topography. No plateaux exist in this area of Mainland, thus its seems unlikely that a plateau icefield could develop. Instead, we propose that the linear hills of northern Mainland supported a relatively thick ice cap whose surface was sufficiently high to enable non-topographic ice flow even during deglaciation. Abundant moraines formed by outlet glaciers from this ice cap suggest the presence of a large volume of material (per unit area) available for transport. Ballantyne (2002) suggested that large volumes of debris would be more likely to occur following prolonged interstadial weathering, rather than at the closing stages of a glaciation, thus implying formation of these features during a readvance, such as took place during the Younger Dryas.

Benn and Lukas (2006) argue that such landforms reflect palaeoclimatic and palaeoglaciological conditions that were unique to the high mass turnover scenario that is thought to have characterized the Younger Dryas in Scotland. The extent of ice in Shetland during the Younger Dryas has previously been assumed to have been very restricted, however, and limited to only a small number of corrie glaciers (Mykura 1976; Sutherland 1991). Furthermore, hummocky moraine assemblages similar to LS3 described here have been shown elsewhere in Britain to have formed both during the Younger

Dryas (or Loch Lomond) Stadial (Walker *et al.* 1988; Ballantyne 1989), and also during Late Devensian glacier advances or stillstands (Clapperton *et al.* 1975; Everest and Kubik 2006). Although no absolute dates have yet been published for the hummocky moraine landsystem in Shetland, the relative sharpness of the moraines compared to the muted streamlined terrain that dominates the surrounding area strongly suggests that formation of these features was nonetheless the most recent of the events described here.

In summary, it is clear that three separate groups of associated landforms and sediments exist in Shetland, and can be interpreted as reflecting (1) an early, extensive, glaciation that flowed across the archipelago from east to west, (2) a stillstand of the ice sheet as it retreated to the southeast, and (3) the later regrowth or readvance of an independent ice cap on Mainland. This reconstructed event chronology, based on a morphometric landsystems approach, casts new light on previous theories. Peach and Horne (1879) accurately identified the flow pattern of the earliest, most expansive phase of glaciation, whilst Hoppe (1965) provided more detailed information with regard to directions of later ice flow. Mykura (1976) attempted to resolve the two dominant flow patterns into one episode, but in failing to appreciate the diachroneity of landform genesis, produced a glacier reconstruction that in some areas lacks plausibility. Likewise the radial LGM ice-flow pattern proposed by Flinn (1983) is, in part, inconsistent with the field evidence described above, and also with his own mapping (British Geological Survey 2002) in which landforms mapped as drumlins lie directly beneath, and parallel to, his reconstructed ice divide. Although ice divide migration might vindicate such an interpretation, the ice cap described by Flinn (1983) is so narrow that this seems unlikely. Previously reported evidence of eastward ice flow in Shetland therefore seems most likely to be a combination of misinterpreted ice flow direction in the north (particularly in Unst), and correctly interpreted eastward erratic dispersal further south. This latter event probably took place not at LGM, as formerly proposed, but instead during the last of the three stages described here. The interpretation presented here, based on new datasets and the application of new techniques, largely agrees with conclusions presented by Ross (1996). In this paper we have built on these and other ideas and have developed a coherent and testable event chronology for the last glaciation of Shetland.

Conclusions

Interpretation of new datasets and the application of a 'landsystem' method to an area of Scotland that has a widely debated glacial history has allowed new insights to be presented with regard to both the style, and the chronology, of its former glaciation. Three contrasting glacial landsystems are present on the Shetland archipelago, reflecting the different stages in its most recent glaciation as well as the contrasting roles of British and Scandinavian ice. The earliest set of features comprises streamlined landforms typical of zones of relatively fast ice flow, which appear to cross the landmass from approximately east to west. A second landsystem composed of ice-marginal drainage features, large rounded moraines, and subdued subglacial streamlining dominates much of Unst, and probably relates to a stage of ice-sheet stillstand or readvance during overall recession. The third landsystem occurs only on Mainland, and is characterized by landform assemblages typical of local ice-cap-style glaciation.

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