The last glaciation of Shetland: local ice cap or invasive ice sheet?

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The question of whether the Shetland Islands were covered by an ice cap or by an ice sheet during the last glacial cycle (40–10 ka) remains unresolved. This paper addresses this problem using existing and new data on glacial erratic carry, striae, glacial lineaments and roche moutonnée asymmetry. Its focus is on eastern Shetland, where ice-cap and ice-sheet glaciation would lead to opposed ice-flow directions, towards and away from the North Sea. Evidence cited in support of ice-sheet glaciation of Shetland is questioned. The primary survey of striae correctly identified striae orientation but the direction of ice flow from striae on eastern Shetland was misinterpreted: it was not from, but towards the North Sea. Glacial lineaments interpolated to cross the spine of Shetland instead are discontinuous and diverge away from an axial ice-shed zone that lacks lineaments. Glacitectonic structures cited recently as evidence for westward flow of an ice sheet across eastern Shetland have been partly misinterpreted and other ice-flow indicators in the vicinity of key sites indicate former eastward ice flow towards the North Sea. Westward carry of erratics over short distances in N and S Shetland may be partly accounted for by shifts in ice sheds during ice-cap deglaciation. Collectively, the evidence for movement of the Fennoscandian ice sheet across Shetland is weak. Any ice-sheet incursion over Shetland occurred before the last glacial cycle. The cleansed ice-flow directional data for Shetland show a simple pattern of divergent ice flow from an axial ice-shed zone beneath an ice cap. The deglaciation sequence for the ice cap is evident from sea-bed moraine systems. The Shetland ice cap at the Last Glacial Maximum was substantial, attaining a thickness of 1 km and a diameter of >160 km. The ice cap was of sufficient size to restrain the Fennoscandian ice sheet on the western edge of the Norwegian Channel and to divert the British ice sheet over Orkney. Glacial landscapes on Shetland indicate that ice-cap glaciation has been the dominant mode of glaciation during the Pleistocene.

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Introduction

The late Derek Flinn published many papers and maps on the geology of the Shetland Islands. A part of his output was concerned with the glacial history of the archipelago (Flinn, 1964, 1967, 1970, 1973, 1977, 1978a, 1983, 1991, 1992, 2009a). Flinn consistently argued that the dominant mode of glaciation on Shetland, including during the last glacial cycle (40–10 ka), was by a local ice cap, whilst admitting the possibility that the islands also might have been overwhelmed by the Fennoscandian Ice Sheet at some earlier stage. This assessment contrasted sharply with the long-held view that ice-sheet glaciation had been dominant on Shetland (Croll, 1870; Horne, 1876; Peach & Horne, 1879), with a local ice cap being of importance only during deglaciation. Moreover, recent work on glacial bedforms on the sea floor (Bradwell et al., 2008; Graham et al., 2011), terrestrial glacial lineaments (Golledge et al., 2008) and terrestrial glacial sediments (Hiemstra & Carr, 2010; Carr & Hiemstra, 2013) has been interpreted as providing evidence for an overriding ice sheet moving across the islands towards the W during the Last Glacial Maximum (LGM) timed at ~27 ka (Clark et al., 2012). This recent work has tended to ignore or downplay evidence for ice-cap glaciation on Shetland from striae, erratic carry and other indicators assembled by Flinn and other workers (Hoppe, 1974; Mykura, 1976; Ross, 1996). Moreover, the latest reconstructions of the LGM extent and subsequent retreat stages of the British and Fennoscandian ice sheets based on sea-bed moraine systems in the northern North Sea also point to the development and decay of an ice cap on Shetland (Bradwell et al., 2008; Clark et al., 2012). The question of whether or not ice-cap or ice-sheet glaciation dominated on Shetland in the last and earlier glacial cycles thus remains open.

Shetland's position at the North Atlantic Ocean–North Sea interface is critical for understanding interactions between the northern sector of the British Ice Sheet (BIS) flowing out of the Moray Firth, the Fennoscandian Ice Sheet (FIS) moving across the bed of the northern North Sea and any radial flow of a local Shetland ice cap (SIC) (Fig. 1A). This review considers the patterns and dynamics of ice flow for the last glacial cycle on Shetland, with a focus on eastern Shetland (Fig. 1B) where ice-flow directions would be opposed beneath a local ice cap compared to an invasive ice sheet. The

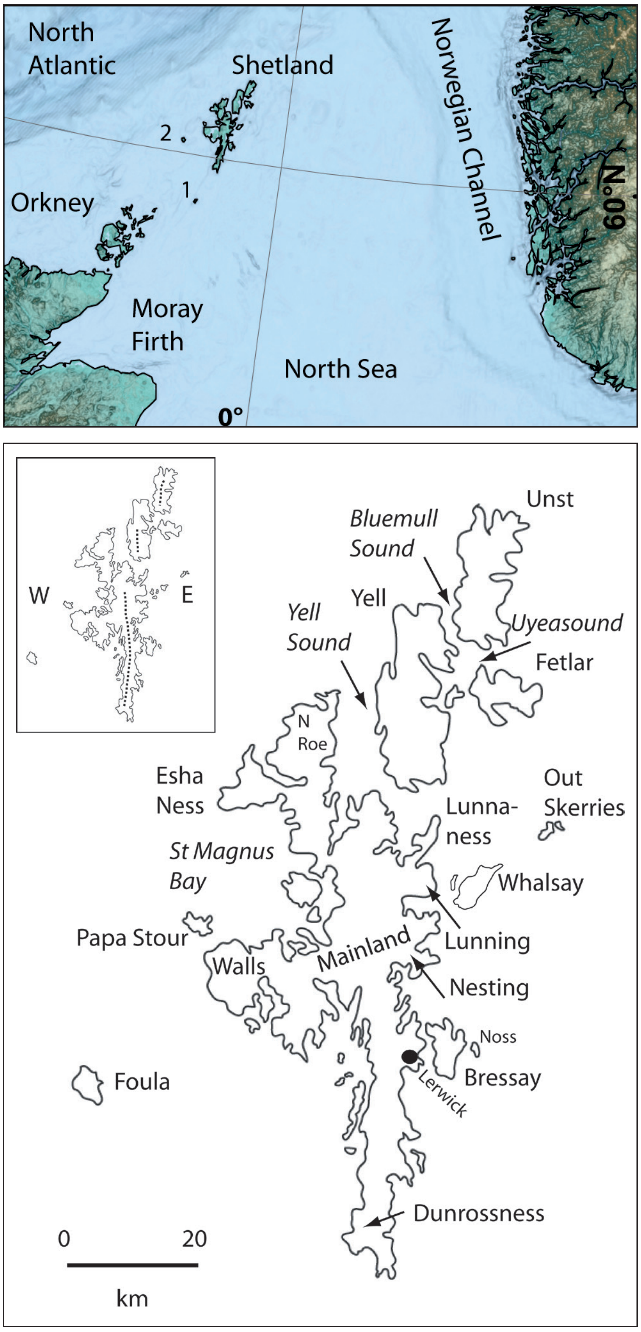


Figure 1. Location. (A) North Sea. 1. Fair Isle. 2. Foula. (B) Shetland localities. Inset shows the ice divide proposed by Flinn (1978a) that divides W and E Shetland in this paper.

reliability and interpretation of existing evidence from glacial lineaments, striae, glacitectonic fabrics and patterns of erratic carry is examined. New evidence based on air-photo interpretation is presented for roches moutonnées and used to clarify dominant ice-flow directions. The combined and verified dataset allows ice-flow patterns and glacier dynamics during the last glaciation to be reconstructed. Flinn's model of dominant ice-cap glaciation during the last glacial cycle is strongly supported by the terrestrial evidence on Shetland.

Geology, geomorphology and glacial sequence

The Shetland platform extends around 75 km to the west and 150 km to the east of the islands and separates the Mesozoic and Cenozoic sedimentary basins of the North Atlantic shelf from those of the northern North Sea (Fig. 2). Shetland comprises over 35 islands and the terrain of the archipelago typically shows a pronounced NNE–SSW grain that follows major structural trends. Metamorphic and sedimentary cover rocks are underlain by a Late Archaean basement interpreted as part of the Lewisian Gneiss Complex (Flinn, 2009b). The Caledonian metamorphic cover of Shetland is diverse and includes schistose and gneissic phyllites, pelites and psammites from the Moine and Dalradian (Mykura, 1976). Many acidic to ultrabasic plutonic complexes linked to the Caledonian Orogeny intrude these rocks. Devonian basins with sandstones, conglomerates and volcanic rocks locally overlie the metamorphic cover rocks and extend widely offshore. Permo–Triassic sandstones occur close inshore in St Magnus Bay and farther offshore in the East Fair Isle, Fetlar and Unst basins (Johnson et al., 1993).

The Shetland coast is submergent due to postglacial sea-level rise (Shennan & Horton, 2002). Offshore, water depths drop steeply to -80 to -100 m around many parts of the outer coast of Shetland. On land, peat cover is extensive and rests generally on thin till or bedrock. Consequently, little is known of the glacial history of Shetland before the last glacial cycle (Sutherland & Gordon, 1993). Organic deposits at Fugla Ness, North Roe, and Sel Ayre, Walls, are dated to Marine Isotope Stage (MIS) 5 and indicate that overlying tills are younger (Hall et al., 2002). Multiple diamicton layers occur at only a few sites on Shetland but none is firmly dated (Ross, 1996; Carr & Hiemstra, 2013). Deglaciation of Shetland Mainland was probably completed by ~13.0 ^{14}C kyr (Birnie & Harkness, 1993; Whittington et al., 2003), although assemblages of hummocky moraines may indicate renewed ice-cap glaciation on central Mainland during the Loch Lomond Stadial (Younger Dryas) (Golledge et al., 2008).

Methods and data validation

This review focuses on the eastern part of Shetland, here defined as the area lying east of the ice shed proposed by Flinn (1983) (Fig. 1B). Patterns of ice flow in western Shetland should be broadly similar under both ice-cap and ice-sheet conditions (Hoppe, 1974) and so offer only limited potential for distinguishing between these two styles of glaciation. In contrast, in eastern Shetland invasive flow beneath the FIS or BIS would be expected to produce a pattern of subparallel ice-flow lines from E to W, whereas a SIC would result in W to E ice flow away from an ice shed lying over the spine of the islands.

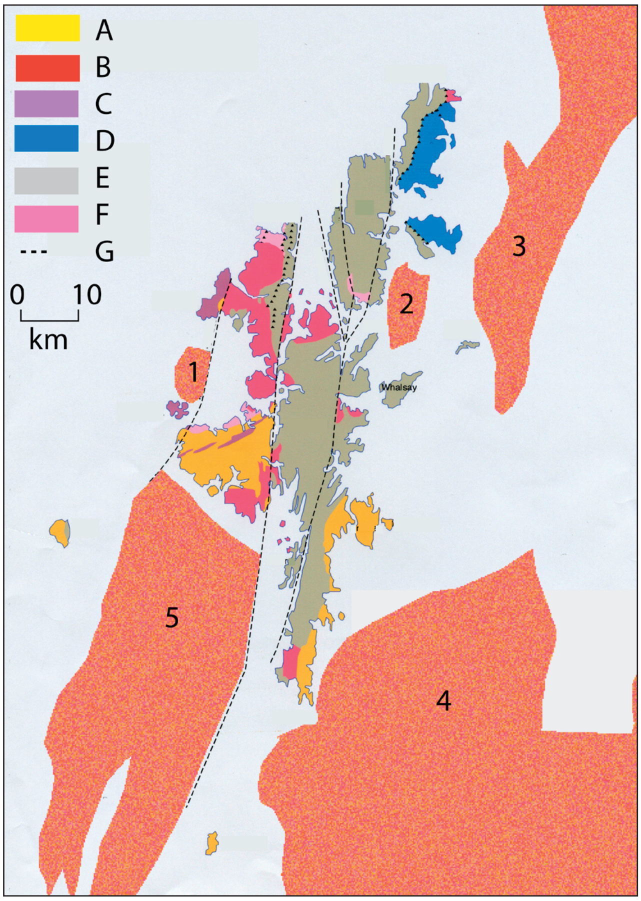


Figure 2. Geological sketch map. A – Devonian sandstones. B – Granite. C – Volcanic rocks. D – Basic and ultrabasic igneous rocks. E – Caledonian metamorphic rocks. F – Metamorphic gneissic basement. G – Faults and thrusts. Permo–Triassic sandstone basins offshore. 1 – St Magnus Bay. 2 – Fetlar. 3 – Unst. 4 – East Fair Isle. 5 – West Fair Isle.

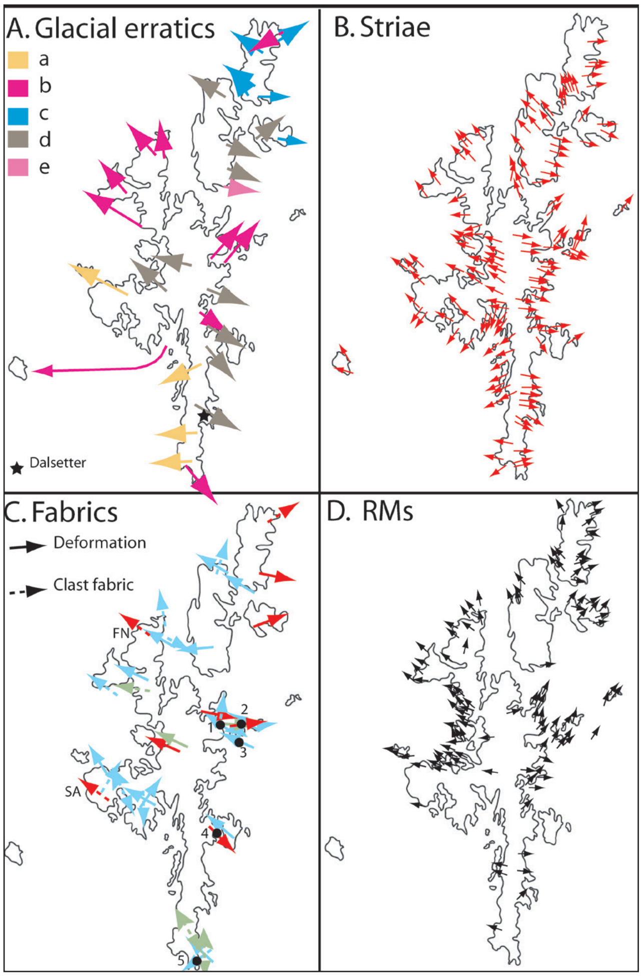


Figure 3. Ice-flow indicators. (A) Glacial erratics with direction of carry. Source rocks a – Devonian sandstone. b – granitic rocks. c – basic and ultrabasic rocks. d – Caledonian metamorphic rocks. e – gneissic basement rocks. Data from Robertson (1935), Chapelhowe (1965), Mykura (1976), Mykura & Phemister (1976), Flinn (1978a, 1994b, 2000), Hall et al. (1993b) and Ross (1996). (B) Striae. Data from Chapelhowe (1965), Flinn (1978b, 1983, 1994b, 2000), Sutherland (1991), Hall et al. (1993a, b), Ross et al. (1993) and Ross (1996). (C) Glacitectonic structures and fabrics. Data from Carr & Hiemstra (2013) (blue arrows), Ross (1996) (green arrows) and Hall (unpublished) (red arrows). Key sites in E Shetland. 1 – Vidlin Voe. 2 – The Bugg. 3 – Sand Wick. 4 – Breiwick. 5 – Sand of Hayes. SA – Sel Ayre. FN – Fugla Ness. (D) Roches moutonnées.

Directions and dynamics of former ice flow on Shetland can be reconstructed from a range of evidence: erratic carry, striae, glacitectonic fabrics, ice-moulded bedforms and landscapes of glacial erosion.

Indicator erratic carry

The geology of Shetland is complex (Fig. 2) and offers much potential for reconstructing patterns of glacial erratic transport. In this paper, existing data are compiled from Geological Survey records and other published sources (Fig. 3A). In addition, ground searches have been undertaken on the northern isles of Shetland to check for glacial erratics sourced from three distinctive rock types in areas east of the supposed ice-shed zone, namely the Skaw Granite in NE Unst, the ultramafic, mafic and pelitic rocks in S Unst and the Permo–Triassic red sandstone of the Fetlar basin (Fig. 2). Any movement of the FIS or BIS across Shetland during the last glacial cycle should have carried clasts of these rocks westward; conversely, any SIC should have carried these rocks eastward.

Striae

Striae provide evidence of the orientation of former ice flow but often not of its direction (Iverson, 1991). On Shetland, the direction of ice movement has been determined by supplementary observations of other glacier bedforms, including other microforms, such as steps and chattermarks, together with plucking at joints and larger stoss and lee forms (Hoppe, 1974; Flinn, 1994a, 2000, 2009b). Striae orientation with and without direction are recorded separately on Geological Survey maps but this study uses only direction data from the recent compilation of Carr & Hiemstra (2013),

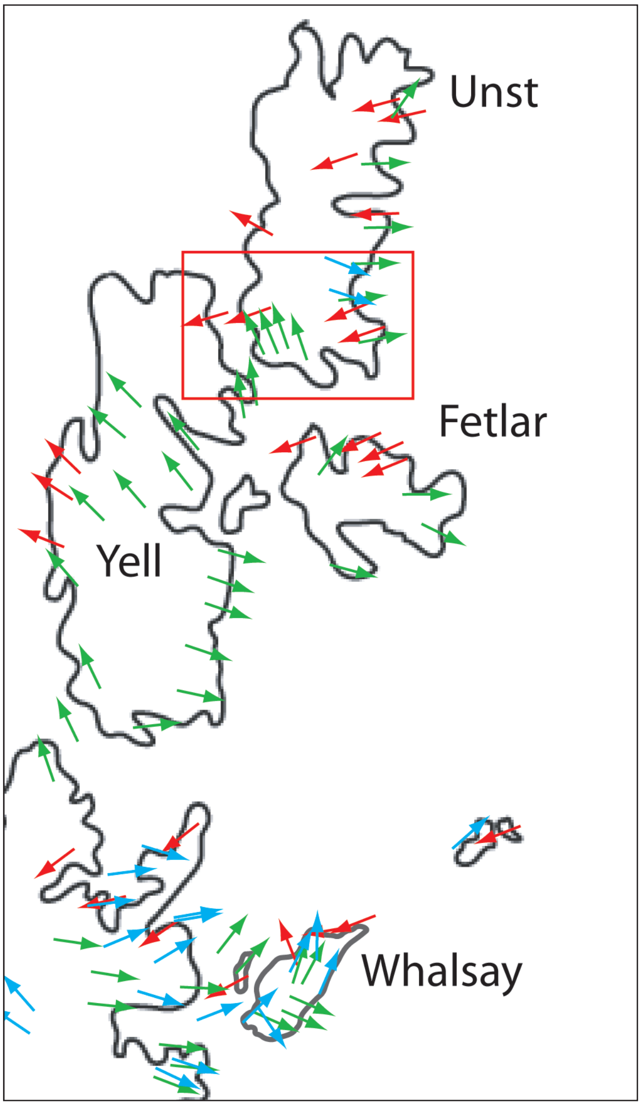


Figure 4. Striae patterns in NE Shetland as mapped by Peach & Horne (1879) (red arrows), Hoppe (1974) (blue arrows) and Flinn (1994b, 2000) (green arrows). Red box shows the area in Fig. 5.

with additions from Flinn (2000) and the author's observations (Figs. 3B, 4, 5). The observations of Peach & Horne (1879) are shown separately in order to highlight anomalous data in NE Shetland (Fig. 4).

Glacitectonic fabrics

Results from a recent detailed survey of glacitectonic and clast fabrics in tills at 17 sites on Shetland (Hiemstra & Carr, 2010; Carr & Hiemstra, 2013) are supplemented by existing and new data at sites for which data are available on till clast fabrics and glacitectonised bedrock (Fig. 3C). Glacitectonic fabric data are scarce in E Shetland due in part to the generally thin till cover. Findings from five key sites in Eastern Shetland reported by Carr & Hiemstra (2013) are examined and compared with evidence from other ice-flow indicators at and around these sites.

Streamlined bedforms

Glacially streamlined bedrock terrain includes elongate hills and ridges and intervening linear depressions (Krabbendam & Bradwell, 2011). On Shetland, streamlined bedforms were first identified by Flinn as *"air-photo striations"* on Fair Isle (Flinn, 1978a) and subsequently on Yell and Unst (Flinn, 1983, 1994a, b, 2000). Streamlined bedrock lineaments were recently mapped across Shetland from NextMap™ images (Golledge et al., 2008). These landforms record ice-flow orientation only and other indicators are needed to establish ice-flow direction (Flinn, 2009a). Here, published evidence from streamlining is combined with that from other ice-flow indicators across the supposed ice-shed zone in S Unst to establish directions of former ice flow (Fig. 5).

Roches moutonnées

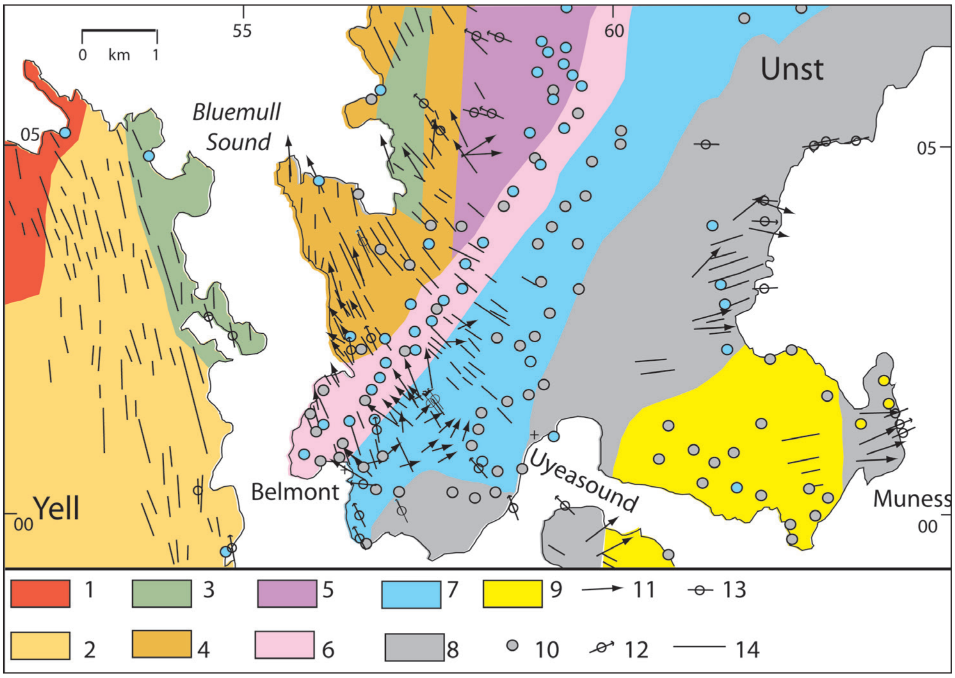
Roches moutonnées are typically developed in hard crystalline rocks where well–developed orthogonal fracture systems guide lee-side quarrying. The orientation and spacing of these fracture sets is an important control over the form of roches moutonnées (Gordon, 1981). Hence, whilst ice-moulded bedrock hills are generally aligned with the ice flow that shaped them, structural controls mean that the orientation of individual roches moutonnées can be an imprecise indicator of former ice-flow directions (Rastas & Seppälä, 1981). Nonetheless, erosion by plucking and abrasion is determined by basal ice dynamics and so the asymmetry of roches moutonnées is generally a good guide to the quadrant towards which the ice that shaped them was flowing (Glasser & Warren, 1990; Olvmo & Johannson, 2002). The stoss and lee form of roches moutonnées is a powerful discriminant of ice-flow direction when other indicators, such as striae or till fabrics, give only a flow orientation.

Around St Magnus Bay, roches moutonnées show consistent development of lee-side faces on the western or northwestern flanks of bedrock hills (Mykura & Phemister, 1976). Flow towards the W and NW is indicated (Fig. 3D) and consistent with evidence from other ice-flow indicators, notably subparallel striae and directions of erratic carry (Mykura & Phemister, 1976). This consistency confirms that roches moutonnées are valuable indicators of the general direction of former ice flow on Shetland. In eastern Shetland, roche moutonnée asymmetry provides important evidence as to whether former ice flow was from E to W (FIS or BIS) or from W to E (SIC). In this study, the direction of lee-side cliffs on asymmetric bedrock hills interpreted as roches moutonnées is mapped on Shetland from air photos in Bing™ and Google™ Maps (Figs. 3D, 5, 6).

Landscapes of glacial erosion

In glacial landscapes, the distribution of glacial and non-glacial landforms can provide important information

Figure 5. Ice-flow indicators in NE Yell and S Unst. 1 – Granite. 2 – Psammite and semipelite. 3 – Mylonites. 4 – Semipelite and psammite. 5 – Pelite. 6 – Graphitic and calcarerous pelite. 7 – Ultrabasic igneous rocks. 8 – Basic igneous rocks. 9 – Phyllite. 10 – Glacial erratics. Colour denotes lithology. 11 – Roche moutonnée. 12 – Striation with direction. 13 – Striation without direction. 14 – Glacial lineament. Data from Flinn (1994b, 2000), Golledge et al. (2008) and personal observations.



about patterns of glacial erosion that can be linked to former glacier dynamics and basal thermal regime (Hall & Glasser, 2003; Hall et al., 2013). Landscapes of glacial erosion on Shetland are identified by plotting features of limited glacial erosion (weak development of glacier bedforms, high-elevation blockfields and the survival of pockets of weathered rock or saprolite) and features of more advanced glacial erosion (knock and lochan terrain, streamlined bedrock and offshore deeps) (Fig. 7). As landscapes of glacial erosion are often products of multiple glacial phases (Hall & Sugden, 1987), the distribution of landform assemblages on Shetland provides insights into the relative importance of glacial erosion under ice caps and ice sheets in shaping Shetland. Ice-cap development on the N–S ridge of Shetland should result in zones of glacial erosion that indicate fast flow along depressions away from an axial ice-shed zone. In contrast, ice-sheet flow across Shetland should give generally E–W-oriented erosion zones that diverge around high ground.

Results

Indicator erratic carry

Patterns of erratic dispersal in W Shetland generally conform to patterns identified from other ice-flow indicators (Mykura & Phemister, 1976). Notable transport paths include carry of clasts of Spiggie Granite south to Fair Isle (Flinn, 1970; Hall, submitted) and west to Foula (Flinn, 1970, 1978a), Clousta volcanics northwest on to Papa Stour (Mykura & Phemister, 1976), Hillswick Granite northwest on to Esha Ness (Mykura & Phemister, 1976) and Ronas Hill Granite north-northwest to Fugla Ness (Hall et al., 1993b) (Fig. 3A).

In E Shetland, erratics carried from distinctive rocks that occur along or beyond the eastern coasts of these islands provide a key test of whether or not the FIS or BIS moved westward across the northern isles of Shetland.

Figure 6. Knock and lochan topography on E Shetland. Ice moulding on the Lunna peninsula, NE Mainland. Looking south towards Lunning and Whalsay. Peach & Horne (1879) proposed that ice moved across this area from left to right (NE to SW), but strong roche moutonnée asymmetry indicates instead ice moving right to left (SW-NE).

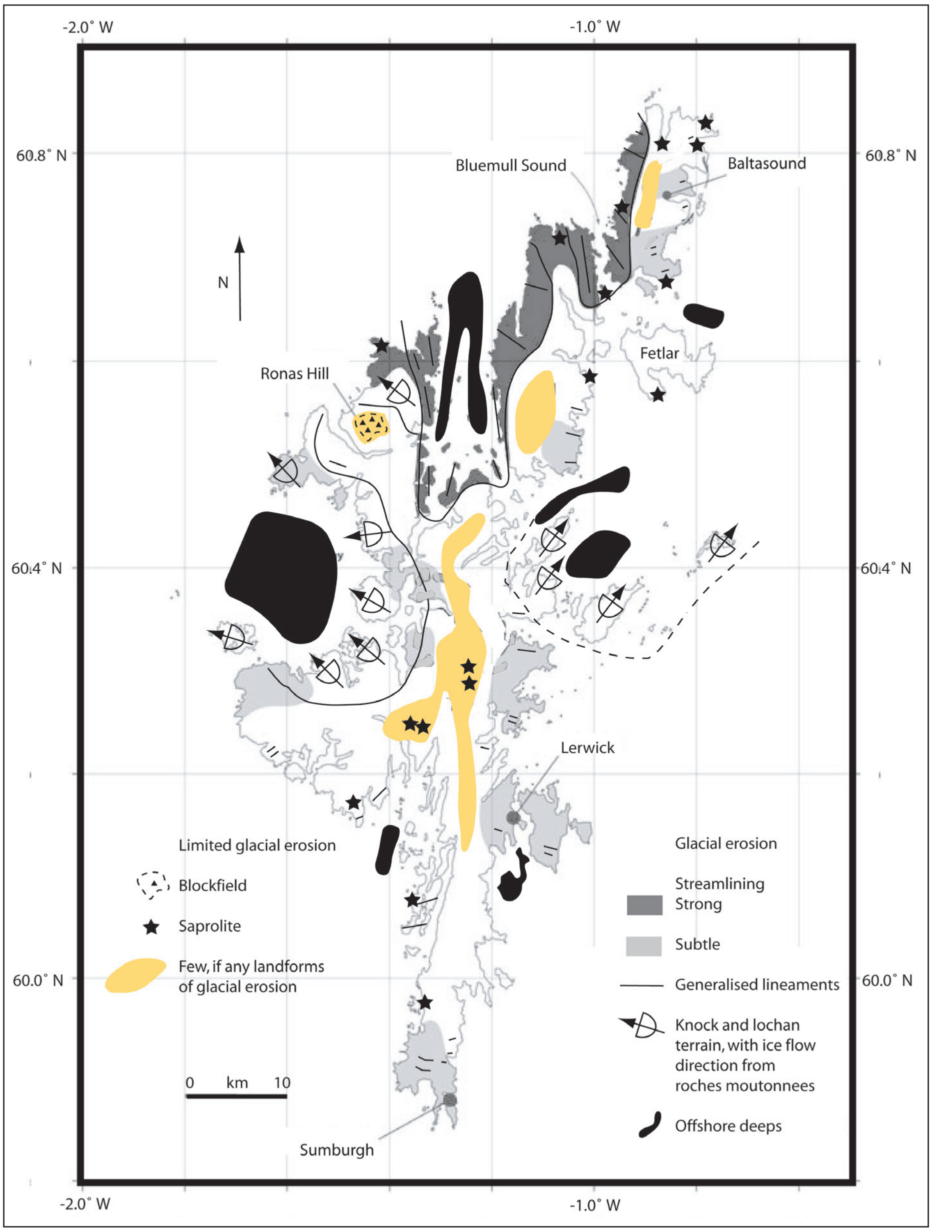


Figure 7. Landscapes of glacial erosion.

The offshore Permo–Triassic basins hold distinctive red sandstone beds (Johnson et al., 1993) and western basin margins approach to within a few km of the coasts of SE Yell and Lunna, Out Skerries and Dunrossness (Fig. 2). Permo–Triassic sandstones on the sea bed near Fair Isle and Foula have been eroded by ice to provide tills with a red brown matrix and containing sandstone clasts on these islands (Flinn, 1970, 1978a; Hall, submitted). Tills on or east of Permo–Triassic rocks beneath the seabed east of Shetland show similar colours (Long & Skinner, 1985). In contrast, no similar tills are recorded from sections on the east coast of Shetland. Moreover, no clasts of Permo–Triassic sandstone have been reported previously from east coast tills or storm beaches (Flinn, 1994a), although sandstone clasts do occur very rarely in storm beaches on E Fetlar, probably originally carried by ice moving to the NE along the northwest margin of the Fetlar basin.

A dominant opposite ice flow towards the E and NE is indicated by erratic patterns in NE Shetland (Fig. 3A). In NE Unst, large numbers of serpentinite clasts have been carried NE onto the Skaw Granite (Flinn, 2000). Across SE Unst, serpentinite and gabbro clasts have been carried E on to phyllite (Flinn, 2000) and phyllite clasts on to serpentinite at Muness (Fig. 5). In SE Yell, many clasts of the Houlland Lewisian outlier have been carried E (Flinn, 1994a). On Fetlar, granite gneiss clasts derived from the western Lamb Hoga peninsula have been carried E on to serpentinites and Funzie conglomerates (Flinn, 2000) without sign of any opposing westward carry (Ross, 1996). Farther south across Nesting, Lunning, Whalsay and Out Skerries, erratic carry is also invariably towards the E or NE (Robertson, 1935).

In central Mainland, no erratic blocks derived from a more easterly source than the Scallafield–Weisdale ridge of Mainland Shetland have been found on the Walls peninsula (Mykura & Phemister, 1976). On Bressay, metamorphic erratics derived from the W are not absent, as reported previously (Mykura, 1976), but are present (Peach & Horne, 1879) and found in tills and storm beaches along the northern coast of the island. From South Nesting to the south, the direction of erratic carry of metamorphic rocks on to Devonian sandstone shifts from E towards SE. Towards the southern tip of Mainland, many clasts of Spiggie Granite, serpentinite and metamorphic rocks from the west coast have been carried a few kilometres E and SE on to Devonian rocks (Fig. 3A).

Whilst the most abundant erratic clasts in E Shetland require eastward movement of ice, smaller numbers of erratics have been transported westward in both N and S Shetland (Fig. 3A). In N Shetland, clasts of the distinctive porphyritic Skaw Granite in N Unst are reported to occur west of the outcrop (Peach & Horne, 1879). Ground searches on the Hermaness and Saxa Vord promontories have failed to find any Skaw Granite clasts, even immediately west of the granite margin. However, a few clasts of sheared, gneissic granite with small pink phenocrysts that may represent a facies of the Skaw Granite, together with very rare sandstone clasts that resemble Devonian sandstones, are present in the storm beach at Burrafith. In W Unst, serpentinite erratics are found on the Valla Field ridge (Peach & Horne, 1879; Ross, 1996; Flinn, 2000) and serpentinite and gabbro erratics occur abundantly in till sections on the west coast (Peach & Horne, 1879). In the latter case, glacial streamlining indicates that the direction of carry is probably from the SE (Flinn, 2000) (Fig. 5). In S Shetland, a phase of ice flow to the W is also recognised across S Mainland from the carry of Devonian clasts on to metamorphic rocks (Mykura, 1976; Ross, 1996). A boulder of tønsbergite from Oslofjord in southern Norway (Le Bas, 1992) provides possible evidence of carry by the FIS. The boulder is now part of a field wall at Dalsetter in S Mainland (Fig. 3A), but there is circumstantial evidence that the Dalsetter erratic was extracted from till (Finlay, 1926), probably in a roadside pit close to its present location. It is possible also, however, that the block is a Norse introduction (Flinn, 1992). A search of the field walls in the surrounding 7 km^2 failed to find any other Norwegian erratic clasts (Ross, 1996) and none has been reported from till sections and storm beaches in S Mainland. If other Norwegian erratics are present then numbers must be very few.

In summary, the main carry of erratics was away from and not across the spine of Shetland. This pattern is consistent with ice flow beneath an ice cap. A subsidiary and perhaps earlier westward carry of small numbers of erratics across N and S Shetland also occurred. This subsidiary westward carry has been attributed previously to the passage of the Fennoscandian Ice Sheet (Mykura, 1976).

Striae

Large numbers of striae observations for E Shetland were made by Derek Flinn. His data are represented on unpublished (Flinn, 2009a) and published Geological Survey maps (Flinn, 1994b, 2000) and his observations have generally been confirmed by other geologists (Robertson, 1935; Hoppe, 1974; Mykura, 1976; Ross, 1996). One notable exception is represented by striae on the island of Noss, off Bressay, interpreted as indicating ice flow *from* the NE (Hoppe, 1974), but these striae were reinterpreted as indicating flow to the NE (Flinn, 1977). Striae data are also published on Geological Survey maps and in papers for the rest of Shetland (Mykura & Phemister, 1976; Flinn, 1978a; Ross, 1996). Crossing striae are recorded from North Roe (Chapelhowe, 1965; Hall et al., 1993b) and the Walls peninsula (Mykura & Phemister, 1976) and also on Bressay (Ross, 1996) and Whalsay (Fig. 3B). Crossing striae suggest that significant shifts took place in directions of ice flow during the last glaciation (Ross et al., 1993).

The directions of ice flow interpreted by Peach & Horne (1879) mainly from striae observations in E Shetland are often diametrically opposed to those of the first (Peach, 1865) and all subsequent (Flinn, 1978a, 1983, 1994a, 2000, 2009a) interpretations of striae on eastern Unst and Fetlar, Out Skerries, Whalsay and Lunna (Fig. 4). The direction of ice movement interpreted by Peach & Horne (1879) is also opposed to that indicated by roches moutonnées and glacial erratics (Fig. 3). This evidence implies that Peach & Horne correctly identified the orientation of striae in E Shetland, but misinterpreted the direction of ice movement.

Omission of the Peach & Horne striae data reveals a generally simple striae pattern on Shetland consistent with divergent ice flow from an axial ice shed within a Shetland ice cap (Hoppe, 1974; Flinn, 1978a) (Fig. 3B).

Glacitectonic fabrics

Carr & Hiemstra (2013) report glacitectonic fabric data for 17 sites on Shetland, mainly comprising shear structures and clast fabrics. Although results from individual sites in W Shetland show considerable internal variation (Fig. 3C), interpretations of ice-flow directions are generally consistent with other clast fabric measurements and with other ice-flow indicators (Fig. 3). Glacitectonic fabrics were investigated at only five sites in E Shetland, in part a reflection of the scarcity of thick glacial deposits in this sector. These key sites are examined in turn (Figs. 3C, 8).

At The Bugg, Whalsay, small bedrock steps suggest ice flow to the N or NW but shear structures in an overlying 0.5 m-thick lower diamicton unit were inclined to NNW, implying ice flow *to* SSE, and clast fabrics in an upper 1 m-thick diamicton unit suggest flow *to* the W or E (Carr & Hiemstra, 2013). Distinctive clasts in an

Figure 8. Glacitectonic structures in key sections in E Shetland. (A) The Bugg, Whalsay. Thin diamicton layers showing deformation of weathered calc schist bedrock and shear structures indicating former ice flow towards the NE or N. Hand trowel (circled) for scale. (B) Sand of Hayes, Dunrossness. Spiggie Granite lies ~1.5 km to the NW and large clasts are indicated (red outlines). Carry of clasts (black outlines) from distinctive units (dashed black lines) within the underlying Devonian Hayes Sandstone. Shear structures are indicated by dashed yellow lines. Geological hammer (circled) for scale. Former ice flow towards the SE.

upper red-brown diamicton were interpreted as spilite erratics derived from the seabed to the northeast near Out Skerries (Carr & Hiemstra, 2013), but probably have been misidentified as the red-brown diamicton is locally derived from a zone of weathered calc muscovite schist that lies at the bay head and that is quite distinct from the typical, grey, sandy diamicton found nearby (Fig. 8A). Shear structures, striae and granodiorite erratics observed in adjacent sections are consistent with ice flow *to* the N or NW.

At Sandwick, Whalsay, shears within bedrock suggest flow *from* the N or NW but the overlying 2.5 m-thick diamicton has no clear clast fabric (Carr & Hiemstra, 2013). Observations in adjacent sections around the bay, however, have identified shear structures and striae consistent with ice flow *to* the NE.

At Vidlin Voe on east Mainland, a lower diamicton unit shows fissility dipping towards SE, interpreted as indicating ice flow *towards* the NW, and a N–S clast fabric, but overlying diamictons show no clear clast fabrics (Carr & Hiemstra, 2013). Granodiorite clasts derived *from* the SW are, however, well represented in all diamictons at this site.

At Brei Wick, Lerwick, striae are oriented 150–330° but rock stoss and lee forms appear to suggest ice flow *to* the NW (Carr & Hiemstra, 2013) despite other striae in the vicinity having been interpreted as representing flow *from* the NW (Hoppe, 1974; Mykura, 1976). Moreover, weathered Devonian bedrock at this site has been transported *from* the NW to form the basal diamicton. Two overlying diamicts show shears dipping to the SE, interpreted as products of ice flow *to* the NW (Carr & Hiemstra, 2013), but each contains many Devonian conglomerate, breccia and arkose clasts with abundant granite debris that are derived *from* the NW. Schist erratics derived *from* the NW are also reported from the vicinity of the site (Ross, 1996).

At Sand of Hayes, S Mainland, a thin till layer shows an upper diamicton with shears that dip to the SE but with a NE–SW clast fabric, interpreted to indicate former ice flow to the NW (Carr & Hiemstra, 2013). The shears are picked out by stone lines and smeared diamicton lenses but in adjacent faces similar structures dip towards the NW (Fig. 8B) and so suggest flow *to* the SE. Moreover, the underlying rip-block diamicton shows turning and carry of sandstone blocks *toward* the E or SE. Ice movement *to* the E or SE is also consistent with striae directions and the abundance of Spiggie Granite debris, derived from outcrops lying ~1.5 km to the NW, as abundant clasts and matrix granules in both diamictons (Fig. 8B). The direction of ice flow at this site appears to be opposite to that reported by Carr & Hiemstra (2013).

Glacitectonic fabric data for E Shetland are interpreted as providing support for easterly movement of the FIS over these five sites (Carr & Hiemstra, 2013). However, the fabric data are not internally consistent and do not match other evidence from these sites and in their immediate surroundings. It is concluded that the glacitectonic structures as reported for E Shetland by Carr & Hiemstra (2013) do not provide reliable information on directions of former ice flow. Instead, the evidence from these five sites and others in E Shetland generally supports ice flow towards the North Sea.

Streamlined bedforms

Streamlined glacial bedforms are found widely on Shetland (Golledge et al., 2008) (Fig. 7). Streamlining is the most common glacier bedform on fine-grained metamorphic rocks and on Devonian sandstones, particularly where bedrock structures run parallel to former ice flow, as along the coast of Bluemull Sound (Flinn, 1994b). The most extensive and well developed areas of streamlined topography are developed along Yell and Bluemull Sounds (Fig. 7). Ridge alignment indicates ice flow into Yell and Unst Sounds, with a well-defined southern margin to streamlining around Yell Sound. Less distinct streamlining is found on either side of the proposed ice shed zone in C Mainland where there are few, if any landforms of glacial erosion. Streamlined bedrock ridges appear to be continuous across Dunrossness and indicate ice flow across S Mainland.

In S Unst, glacial lineaments on the southeast and southwest coasts are separated by a zone in the vicinity of Uyeasound where streamlining is absent or weakly developed (Golledge et al., 2008) (Fig. 5). Reconstructions based on streamlining which show continuous ice–flow lines from E to W and turning into Bluemull Sound (Golledge et al., 2008) overlook this 2–3 km-wide gap (Carr & Hiemstra, 2013). In SE Unst, however, directions of erratic carry, striae and roches moutonnées indicate ice–flow to the E (Fig. 5). Crossing ice flow sets in S Unst cannot be the product of a single phase of ice flow. The onset zone for fast–flowing ice moving N through Bluemull Sound appears to have shifted position and orientation through time.

Viewed for Shetland as a whole (Fig. 7), the pattern of glacial streamlining is consistent with divergent flow beneath a local ice cap. The absence of crossing lineaments, except in Dunrossness and on Fair Isle, is inconsistent with the passage of an erosive ice sheet over Shetland.

Roches moutonnées

The greatest concentrations of roches moutonnées are found around St Magnus Bay, off E Mainland on the islands of Out Skerries, Whalsay and on Lunna (Figs. 3D, 7). Maximum heights reach 60 m near Brae, but most hills are <20 m high.

In western Shetland, the orientation and asymmetry of roches moutonnées indicate ice flow to the W and NW, with only a weakly centripetal flow into St Magnus Bay (Fig. 3D). In contrast, in eastern Shetland roche moutonnée forms indicate a powerful flow of ice towards the NE over Lunna, Whalsay and Out Skerries (Figs 3D, 6). On Fetlar and over the eastern coast of Unst, flow was also *towards* the NE and E. Original interpretations by Peach & Horne (1879) of ice flow *from* the NE are not consistent with the disposition of stoss and lee bedrock forms in NE Shetland recognised previously (Robertson, 1935) and reported here (Figs. 3, 6).

The opposed orientations of roches moutonnées on the westand east coasts of Shetland indicate that the phase or phases of ice flow that shaped these bedrock forms took place beneath an ice cap. The pattern is not consistent with an ice sheet moving from E to W over Shetland because roches moutonnées are generally absent from the spine of Shetland and lee-side faces do not face west in E Shetland.

Landscapes of glacial erosion

Distinct zonation exists in the glacial landscapes on Shetland (Fig. 7). Knock and lochan topography (Linton, 1963), with its characteristic bare bedrock terrain dominated by roches moutonnées and lake-filled rock basins, occurs extensively on W and N Mainland (Fig. 6). Well-developed glacial streamlining around Yell and Bluemull Sounds indicates fast ice flow into these troughs. Wide areas of Shetland show more limited bedrock streamlining or the development of small groups of low roches moutonnées and widely spaced, shallow lake basins. This terrain reflects a lesser degree of glacial erosion. Along the spine of C Mainland, a belt <10 km wide shows few glacier bedforms and striae (Fig. 3B) and retains pockets of pre-glacial saprolite (Fig. 7), and represents a zone of low glacial erosion. Granite blockfields that have experienced little, if any glacial erosion are present at >250 m above sea level on Ronas Hill (Ball & Goodier, 1974; Veyret & Coque-Delhuille, 1991) (Fig. 7).

These contrasting glacial landscapes reflect geological, topographic and glaciological controls on glacial erosion. Knock and lochan topography is best developed on hard, massive gneiss, metagabbro and granite bedrock, whereas streamlined bedrock is associated with softer and more fractured phyllites, pelites and sandstones. Well-developed landforms of glacial erosion are generally absent from high ground, although the frequent location of saprolites on valley floors and in bays also implies limited glacial downcutting of some valleys. Areas of ice-moulded bedrock were shaped beneath fast-moving, warm-based ice, often draining via valleys towards offshore deeps. Areas of more limited glacial erosion exist where ice was slower moving. The patterns of glacial erosion are not consistent with dominant flow beneath the FIS or BIS as no N–S-oriented axial zone of limited erosion would exist on the islands under these circumstances. Instead, the zonation of glacial erosion on Shetland is consistent with development beneath one or more ice caps in which zones of contrasting basal thermal regimes, including the main ice shed, have retained rather fixed positions.

Discussion

Invasive ice sheet?

The question of whether or not ice-cap or ice-sheet glaciation dominated on Shetland in the last and earlier glacial cycles hinges on the interpretation of field evidence in E Shetland. Three main datasets have been presented in support of ice flow from E to W by the FIS or BIS across Shetland: (i) the patterns of striae, roches moutonnées and erratic carry reported by Peach & Horne (1879); (ii) glacitectonic structures identified in glacial diamictons by Carr & Hiemstra (2013) and (iii) glacial lineaments as interpreted by Golledge et al. (2008). Critical appraisal and results of wider field evidence presented above show that these datasets are either unreliable or may be interpreted differently.

The observations of Ben Peach and John Horne (Peach & Horne, 1879) in E Shetland were in conflict with the early reconnaissance work of Charles Peach (Peach, 1865) and were soon vigorously contested (Home, 1881). When Hoppe (1974, p. 198) later commented: *"Many of the observations cannot be duplicated and were probably* *erroneous for reasons that are not easily explained*", he was merely echoing the difficulty faced by later workers in replicating the observations of Peach & Horne. The data on striae, roches moutonnées and erratic carry assembled here for E Shetland are incompatible with Peach & Horne's observations (Figs. 3, 4). It is now clear that Peach & Horne's interpretation of the direction of ice flow in E Shetland was wrong. It can be suggested that this error stemmed from the overpowering influence of the prevailing late 19th century paradigm in the Geological Survey of Scotland that the glaciation of northern Caithness and Orkney involved diversion of the BIS moving out of the Moray Firth by the larger FIS moving across the North Sea (Croll, 1870, 1875; Geikie, 1877).

Despite long-standing concerns about its reliability, Peach & Horne's work has continued to influence recent thinking on ice configurations on Shetland (Golledge et al., 2008; Carr & Hiemstra, 2013). Glacitectonic fabrics reported for E Shetland by Carr & Hiemstra (2013) have been interpreted in terms of former ice flow *from* the E, with the striae data of Peach & Horne cited in support. It is shown above, however, that for each of the five thin diamicton sequences reported from E Shetland there are questions over interpretations of glacitectonic fabrics. Furthermore, other data for ice flow at and in the vicinity of these sites indicate instead a general movement of ice *to* the E in E Shetland. Glacial streamlining on Shetland as mapped by Golledge et al. (2008) supports the earlier observations of Flinn (1983, 1994a, b) but the direction of ice flow that produced the streamlining in E Shetland was *to* and not *from* the E (Fig. 3). Moreover, streamlining does not continue across the spine of the islands as indicated by the trend lines of Golledge et al. (2008). Instead, the pattern of streamlining, particularly when considered alongside the evidence from roches moutonnées (Fig. 5), indicates divergent flow away from an axial ice shed.

The likelihood of ice-sheet flow across Shetland from the North Sea can be tested in at least two other ways. Firstly, an erosive ice sheet moving from E to W across Shetland should have left roches moutonnées and streamlined bedrock extending across C Shetland from the east to the west coast. Erosion should have been most marked on N–S-oriented ridges that lie transverse to any ice-sheet flow because here ice would have been forced to move uphill. Instead, a zone of low erosion extends to ridge tops in C Shetland which, together with opposed roche moutonnée asymmetry on the west and east coasts, indicates divergent ice flow (Fig. 7). Secondly, material carried from the bed of the North Sea should be abundant in east coast tills on Shetland (Sutherland, 1991). On Orkney, where an ice sheet flowing out from the Moray Firth moved across these mainly low-lying islands (Peach & Horne, 1880), erratic material includes marine shell fragments and mud derived from older Pleistocene deposits, clasts of Palaeozoic and Mesozoic sedimentary rocks derived from offshore and erratic clasts derived from either southern Fennoscandia (FIS) or the Scottish mainland (BIS) (Mykura, 1976). On Shetland, in contrast, no shells are reported from east coast tills and these tills are dominantly sandy and dominated almost exclusively by clasts of Shetland rocks. Permo–Triassic material seems to be almost completely absent from Shetland tills, except on Foula and Fair Isle (Flinn, 1978b), despite the proximity of sedimentary basins to parts of the present east coast (Fig. 2). Only a single Norwegian erratic of uncertain stratigraphic context is known and no erratic material has been convincingly connected to sources in the rest of Scotland. Whilst it is conceivable that evidence of early ice-sheet incursions has been largely removed by later ice-cap glaciation, traces of ice flow across Shetland Mainland should still be present in the ice-shed zone of low ice-cap erosion but no such traces have been found.

The evidence of erratic carry west of the ice shed on Unst and in S Mainland has been repeatedly linked to the former flow of FIS (Mykura, 1976; Golledge et al., 2008; Carr & Hiemstra, 2013). On Unst, however, moraine systems and some erratic pathways may relate to the final retreat stages of an ice mass back towards the present line of the east coast rather than to earlier events (Golledge et al., 2008). There is possible evidence for an earlier phase of transport to the W of erratics of Skaw Granite but carry of basic and ultrabasic clasts towards Bluemull Sound also may be a product of ice flow beneath a Shetland ice cap. On S Mainland, the movement of Devonian erratics to the W almost certainly predates the final movement of ice towards the SE (Ross, 1996). Yet the lack of evidence for carry of Permo–Triassic material onshore from sedimentary basins just off the present east coast of Shetland implies that distances of erratic carry E across Unst and S Mainland were short.

Partly to account for this erratic distribution, Ross (1996) proposed that the ice shed within the SIC had shifted during deglaciation and that topographic control over ice flow had become stronger as the SIC thinned. Some support for an ice shed standing east of Unst comes from moraine systems formed during ice retreat (Golledge et al., 2008). The asymmetry of the SIC is also apparent from sea-bed moraine patterns (Bradwell et al., 2008; Clark et al., 2012) (Fig. 9A) and indicates that the ice shed must have lain a short distance east of Shetland at intervals during the last glacial cycle. Shifting ice sheds within the SIC remove the need to invoke ice-sheet glaciation to explain westward erratic carry on Unst and in S Mainland (Ross, 1996).

In summary, the evidence is weak for invasive ice-sheet glaciation of Shetland by the FIS or BIS during the last glacial cycle. If parts of Shetland were ever covered by the FIS or BIS then it is most likely that these parts would include the narrow extremities of N and S Shetland. In N Shetland, evidence is lacking of the former presence of the FIS from far-travelled erratics, heavy minerals or shell debris transported from the bed of the North Sea.

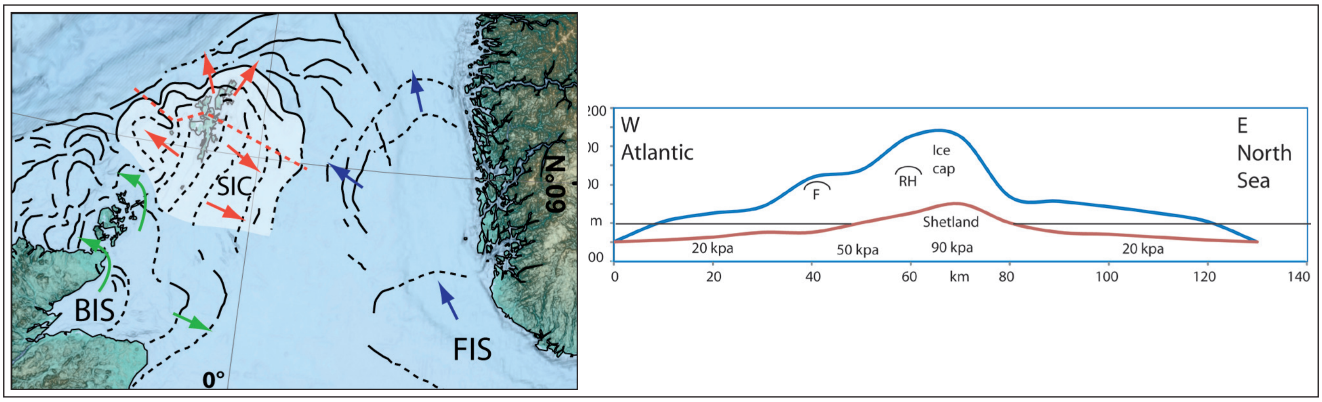


Figure 9. (A) Generalised flow patterns and ice extent in the northern North Sea during the last glacial cycle. Moraine ridges on the sea bed after Bradwell et al. (2008) and Clark et al. (2012). (B) Schematic profile of the Shetland ice cap at the LGM. Line of section shown in Fig. 9A. Values of basal shear stresses reflect variable bed materials. F – Foula. RH – Ronas Hill.

In S Shetland and towards the Orkney–Shetland channel, however, some of these traces begin to appear. Norwegian erratics are now known from tills and storm beaches on the Northern Isles of Orkney (Hall, unpublished), Fair Isle (Flinn, 1970, 1978a; Hall, submitted) and probably include the Dalsetter stone on S Shetland. Clasts of chalk flints and Late Jurassic–Early Cretaceous sedimentary rocks derived from the outer Moray Firth also occur widely in N Orkney (Peach & Horne, 1893), and a few are now known to occur as far north as Fair Isle (Hall, submitted). Pleistocene marine shell fragments occur in tills throughout Caithness (Peach & Horne, 1881) and Orkney (Peach & Horne, 1880) but have not yet been recorded farther north. The palynomorph content of tills may in future provide further information on long-distance transport of till matrix material in N Scotland (Hall et al., 2011). Collectively, this glacially transported material is consistent with former movement or movements of the FIS and BIS through the Orkney–Shetland Channel. These movements may not have been contemporaneous and the relative influence of the two ice sheets is unclear. Significantly, any such movement or movements are undated, although the disposition of moraine systems on the bed of the North Sea (Fig. 9) indicates that the FIS did not flow through the Orkney–Shetland Channel during the last glacial cycle.

Shetland ice cap?

In contrast, and as Flinn and others have long recognised, the evidence is strong for the former presence of an ice cap on Shetland. Across almost the entire east coast of Shetland, including the east coast of Unst, southeast Yell, Fetlar, Lunning, Nesting, Whalsay, Out Skerries and the east coast of S Mainland, evidence from glacial lineaments, roches moutonnées, glacial striae and erratic carry indicates a dominance of eastwards ice flow (Fig. 3). Ice-flow indicators, when viewed for Shetland as a whole, reveal divergent flow away from an axial ice-shed zone within an ice cap (Flinn, 1978a, 2009a). These flow patterns are not closely dated but striae patterns and the main carry of near-surface glacial erratics must relate to the last glacial cycle. Patterns of glacial erosion as indicated by glacier bedforms are also consistent with development beneath a SIC with variable ice-flow velocities during the last glacial cycle. Although roches moutonnées and other large erosional bedforms may be products of more than a single glacial cycle, it is clear that the dominant mode of glaciation on Shetland during at least the Late Pleistocene has been ice-cap glaciation.

The development of an independent ice cap on Shetland is a feature of recent glacial models for the BIS in the last glacial cycle between 40 and 10 ka. In simulations, the SIC builds up early and persists into the Lateglacial (Hubbard et al., 2009). Topography dictated that ice-cap build-up took place over C Shetland where Mainland reaches its greatest width (Ross, 1996). Moraine patterns on the neighbouring sea bed show ice retreat towards this core area during deglaciation (Clark et al., 2012). The former SIC was of considerable extent and thickness (Fig. 9). The SIC extended to the shelf edge west of Shetland at the LGM (Johnson et al., 1993; Bradwell et al., 2008). Sedimentological evidence for the SIC extending at least 75 km north and east of Shetland comes from heavy minerals (Beg, 1990) and till clast lithology (Long & Skinner, 1985; Peacock & Long, 1994; Ross, 1996). These Shetland-derived materials, together with sea-bed moraine systems (Clark et al., 2012), indicate that the former NW–SE extent of the SIC was at least 160 km (Fig. 9A). Till distribution indicates a minimum elevation of 300 m of the glacier surface on the outlying island of Foula (Milne, 1993). Fitting of an ice-cap profile across the deformable bed materials offshore Shetland and the rigid bed materials on Shetland (Ballantyne et al., 1998) suggests an ice thickness of ~1 km at around the time of the LGM (Fig. 9B). The last SIC was not local, small or thin. In Scotland, only the peripheral island groups of Shetland and the Outer Hebrides (Flinn, 1978b; Hall, 1996) supported independent ice caps during the last glacial cycle.

Conclusion

The question of whether or not Shetland was glaciated by a local ice cap or by an invasive Fennoscandian ice sheet has been debated since the 19th century. The key evidence to resolve this question lies in E Shetland where ice movements beneath an ice cap or an ice sheet would be diametrically opposed. Review of existing data indicates that striae evidence originally presented by Peach & Horne (1879) and interpreted to indicate ice-sheet flow from the North Sea conflicts with larger datasets assembled by all later workers in E Shetland that consistently show ice flow towards the North Sea. Glacial lineaments interpreted by Golledge et al. (2008) as indicating flow of the FIS across Shetland do not continue across the spine of the archipelago and instead developed by divergent flow beneath a Shetland ice cap. Glacitectonic structures and other ice-flow indicators recorded at five sites in E Shetland by Carr & Hiemstra (2013) and interpreted in terms of ice-sheet flow from the North Sea are unreliable, and other indicators at and adjacent to these sites indicate flow towards the North Sea. When these datasets are removed, the combined data from glacial erratics, striae, glacitectonic structures and roche moutonnée asymmetry indicate that during the last glacial cycle Shetland experienced radial ice flow beneath an ice cap. This conclusion is essentially the same as that reached by the late Derek Flinn based on his mapping over the last 50 years. Ice-cap glaciation is consistent with recent glacial models and with the pattern of deglaciation in the northern North Sea indicated by sea-bed moraines.

The FIS may have crossed all or parts of Shetland before 40 ka but the evidence is weak. Westward transport of glacial erratics over short distances occurred on Unst and across S Mainland, but may relate to localised shifts in the ice-shed zone of a Shetland ice cap rather than to ice-sheet incursion. The absence of material on Shetland derived from the bed of the North Sea, in particular Permo–Triassic sandstones found in basins close to the east coast and reworked Pleistocene marine sediment, is not consistent with the passage of Scandinavian ice. Movement of the FIS through the Orkney–Shetland Channel before the last glacial cycle is suggested, however, by small numbers of Norwegian erratics found on S Mainland, Fair Isle and N Orkney.

The dimensions of the Shetland ice cap as reconstructed from till lithology, moraine systems and ice-sheet profiles indicate that a substantial body of ice developed during the last glacial cycle, reaching a thickness of ~1 km and extending for >160 km from the Atlantic shelf edge towards the western edge of the Norwegian Channel. The SIC was sufficiently large not only to resist incursion by the Fennoscandian ice sheet but also to divert the British ice sheet across northern Orkney. The zonation of landscapes of glacial erosion on Shetland indicates that ice-cap glaciation is likely to have been the dominant mode of glaciation throughout long periods of the Pleistocene.

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