Scottish Landform Example No. 35

Subglacial Landforms of the Tweed Palaeo-Ice Stream

JEREMY EVEREST, TOM BRADWELL & NICK GOLLEDGE

British Geological Survey, West Mains Road, Edinburgh EH9 3LA

Background

Ice streams are bodies of fast-flowing ice that move at much greater velocity than the surrounding ice sheet (Paterson, 1994; Hambrey, 1994). They are the most dynamic component of modern ice sheets, and as such are important drivers of ice-sheet evolution (Stokes & Clark, 1999; Bennett, 2003; Dowdeswell *et al*., 2004). Empirical studies in Antarctica, for example, have shown that ice streams account for more than 90% of mass transfer within the ice sheet (Bamber *et al*., 2000). Moreover, modern ice streams leave behind characteristic landform assemblages when they retreat (Stokes & Clark, 2001; Ó Cofaigh *et al*., 2002; Dowdeswell *et al*., 2004). These landsystems or landform assemblages, act as 'fingerprints' that can be compared with suites of landforms in formerly glaciated areas (Fig. 1). The accurate identification of palaeo-ice stream tracks in past glacial environments has aided our understanding of Pleistocene ice-sheet dynamics. This is becoming increasingly important as attempts are made to draw glaciological and climatological conclusions from refined ice-sheet reconstructions in deglaciated regions such as Scotland.

Ice streams are known to have existed in the British Ice Sheet (BIS) during the last (Late Devensian) glaciation (Jamieson, 1906; Linton 1959, 1962; Sissons 1963; Knight *et al*., 1999). Some of these have formal names and are well established in the literature, such as the Irish Sea (Knight *et al*., 1999), Strathmore (Linton, 1959; Merritt *et al*., 2003), and Moray Firth (Merritt *et al*., 1995) ice streams. Others are less well established but have been tentatively identified – *e.g*. the North Sea (Eyles *et al*., 1994) and Tyne Gap (Beaumont, 1971) ice streams. More recently, palaeo-ice streams have been identified using the criteria outlined by Stokes and Clark (1999) in North Wales (Jansson & Glasser, 2005) and The Minch (Stoker & Bradwell, 2005).

Perhaps the best British example of a palaeo-ice stream track, however, exists in the drainage basin of the River Tweed, Berwickshire (Fig. 2). This landform assemblage was originally investigated by Clapperton (1970, 1971). Although he focused predominantly on the pattern of meltwater channels and their relation to deglaciation, Clapperton identified 'exceptionally elongated' subglacial landforms (1971:374) and inferred a strongly convergent ice-flow pattern along the Tweed Valley. He also deduced that the ice sheet must have been flowing 'quite rapidly' to produce the elongate landforms. Clapperton's observations clearly describe the signature of a palaeo-ice stream, his map of drumlins

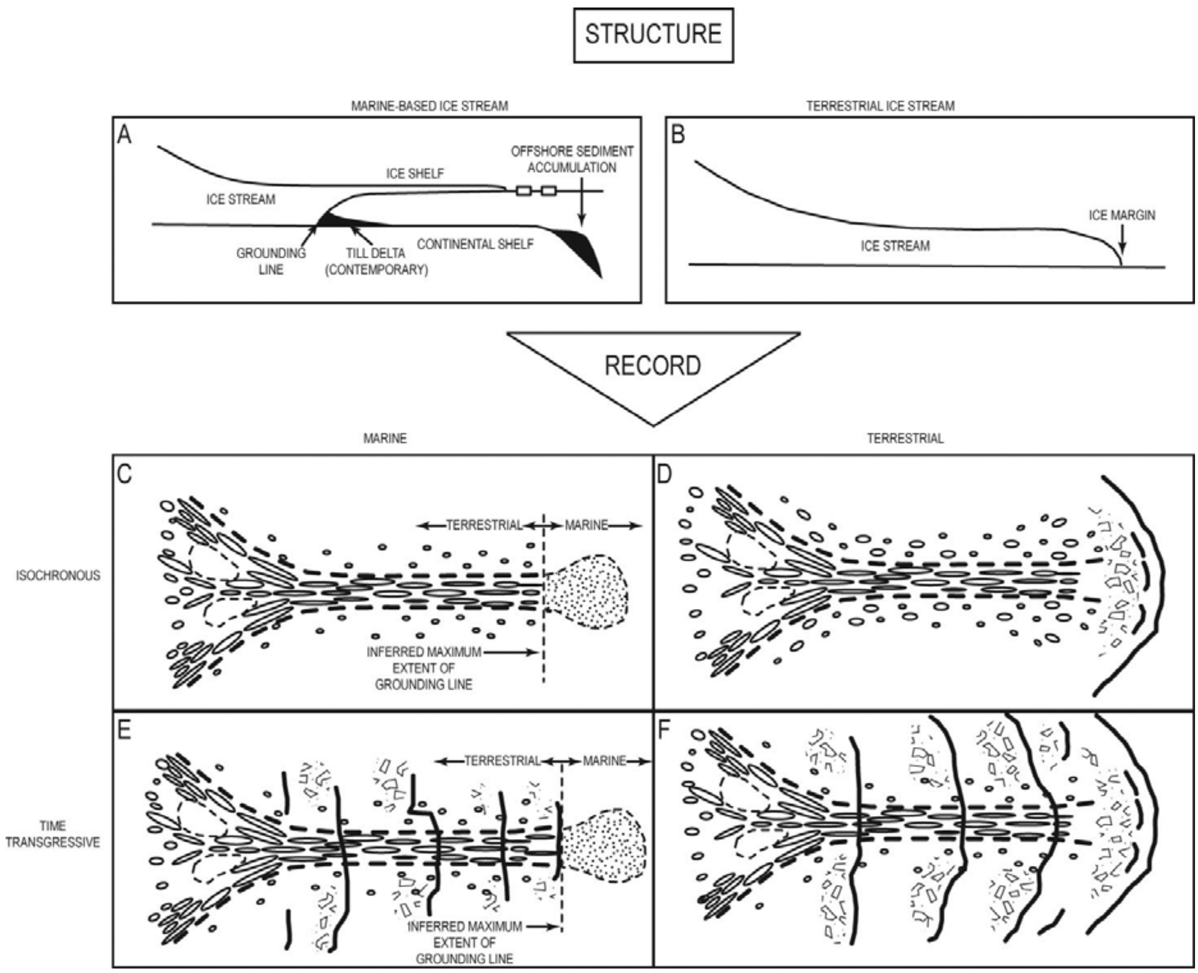

Fig. 1. Typical landsystem signatures produced by palaeo-ice streams (from Clark & Stokes, 2003).

and drumlinoid forms showing the width of the ice stream and its overall northeasterly flow (see Fig. 4 in Clapperton, 1970). This linework has since been captured digitally in the BRITICE glacial map and GIS compilation of Great Britain (Clark *et al*., 2004).

Numerous lines of geomorphological evidence have been used to identify the location of palaeo-ice streams. Stokes & Clark (1999) state that ice streams should be identifiable by a characteristic landsystem composed of a number of distinct geomorphological assemblages that match distinctive criteria. These criteria are listed in Table 1, together with details of their representation in the Tweed Valley. More traditional forms of geomorphological investigation are now being supplemented by the interpretation of remotely sensed data, and Geographical Information Systems (GIS) are now widely used to assimilate and interpret both raster and vector areal datasets at a variety of scales (Clark, 1997;

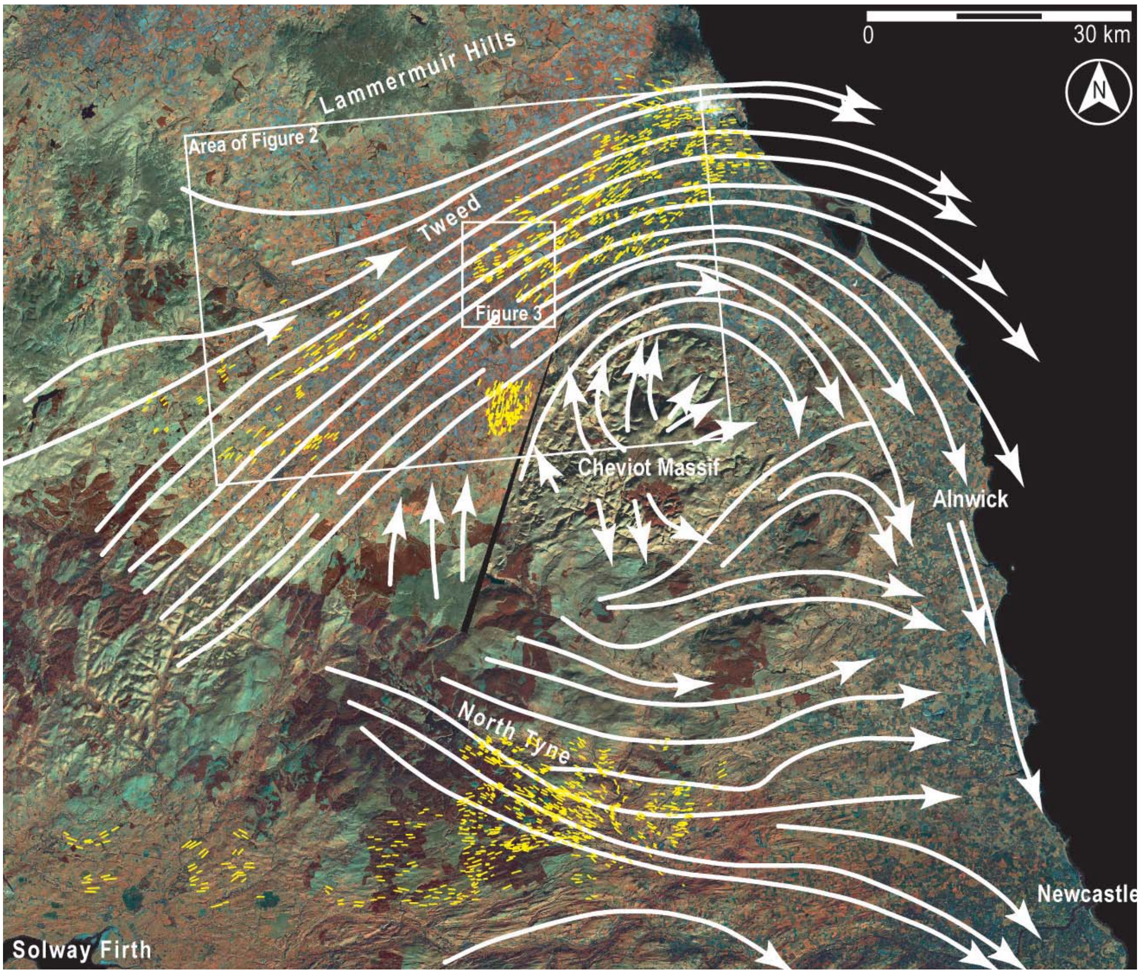

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Fig. 2. LANDSAT TM image (© NERC 2005) showing directions of former ice movement in the Tweed Valley and adjacent areas (from Clapperton, 1971). Previously mapped streamlined landforms (including drumlins, flutes and streamlined terrain) are also shown in yellow (taken from the BRITICE GIS; Clark *et al*., 2004). Black diagonal line (centre) is an artefact of image processing.

Stokes & Clark, 2003; Jansson & Glasser, 2005). Here we use ESRI ArcGIS 8.3 populated with Landsat TM 30 m resolution 7-band satellite imagery (Fig. 2), a 5-m vertical resolution Ordnance Survey-derived Digital Terrain Model (DTM) (Fig. 3), and a 1.2-m vertical resolution NextMap Digital Surface Model (DSM) (Fig. 4). Each dataset shows the elongate landforms of the study area at a different scale, highlighting the relationship between individual landforms and the palaeo-ice stream landsystem as a whole.

Table 1. Geomorphological criteria for a landsystem classification of ice streams (from Stokes & Clark, 1999). Examples from the Tweed palaeo-ice stream are also given.

Contemporary ice-stream characteristics	Proposed geomorphological signature	Tweed ice stream
Characteristic shape and dimensions	Characteristic shape and dimensions	>65 km long; 20 km wide
	Highly convergent flow patterns	Yes
Rapid velocity	Highly attenuated bedforms (length:width >10:1)	Up to 23:1
	Boothia-type erratic dispersal trains	Not seen
Sharply delineated margin	Abrupt lateral margins	Yes
	Lateral shear moraine	Not seen
Deformable bed conditions	Geotechnical evidence of pervasively deformed till	Up to 60 m of till (Clapperton, 1971); deformed
Focused sediment delivery	Submarine till delta or trough-mouth fan	Not seen

The Tweed Palaeo-Ice Stream

The datasets illustrated (Figs 2, 3 & 5) show that the Tweed Ice Stream produced a large number of highly elongate subglacial landforms in the area of low-lying topography between the Cheviot and Lammermuir Hills. The majority of these landforms can be classified as drumlins, megadrumlins and megaflutes (Fig. 5) and indicate ice-sheet flow-direction (*e.g*. Boulton, 1976; Clark, 1994). Furthermore, their degree of elongation is thought to reflect the relative velocity of ice flow (Stokes & Clark, 1999, 2002). The sub-parallel megadrumlins and megaflutes in the Tweed Valley (Fig. 3) form an assemblage describing generally northeastward and eastward flow, towards the present North Sea coast. Many of the individual bedforms have length to width (elongation) ratios of between 8:1 and 15:1, but in the vicinity of Kelso they reach elongations of 23:1 (Figs 3 & 4). These values are in excess of the 10:1 ratio suggested by Stokes & Clark (1999) as indicative of ice streaming (Table 1). Furthermore, the high degree of parallelism between landforms suggest that only one flow event is preserved in the geomorphic record; whilst the coherence of the overall landsystem gives it considerable 'glaciological plausibility' (*sensu* Clark 1997).

The flow set can be divided into an 'onset zone' in the west, and a 'trunk' covering much of the rest of the study area (Fig. 3). The onset zone is characterised by its sharp western boundary with non-streamlined topography, and the strongly convergent flow pattern seen in the bedform alignments. The trunk of the ice stream is exemplified by the highly parallel and densely packed megalineations in the low ground around the River Tweed (Figs 2 & 3). The lateral margins of the ice stream are marked by an abrupt transition to non-streamlined ground, for example on the flanks of the Cheviot Hills (Fig. 3). The former ice stream probably attained a maximum width in the onset zone of

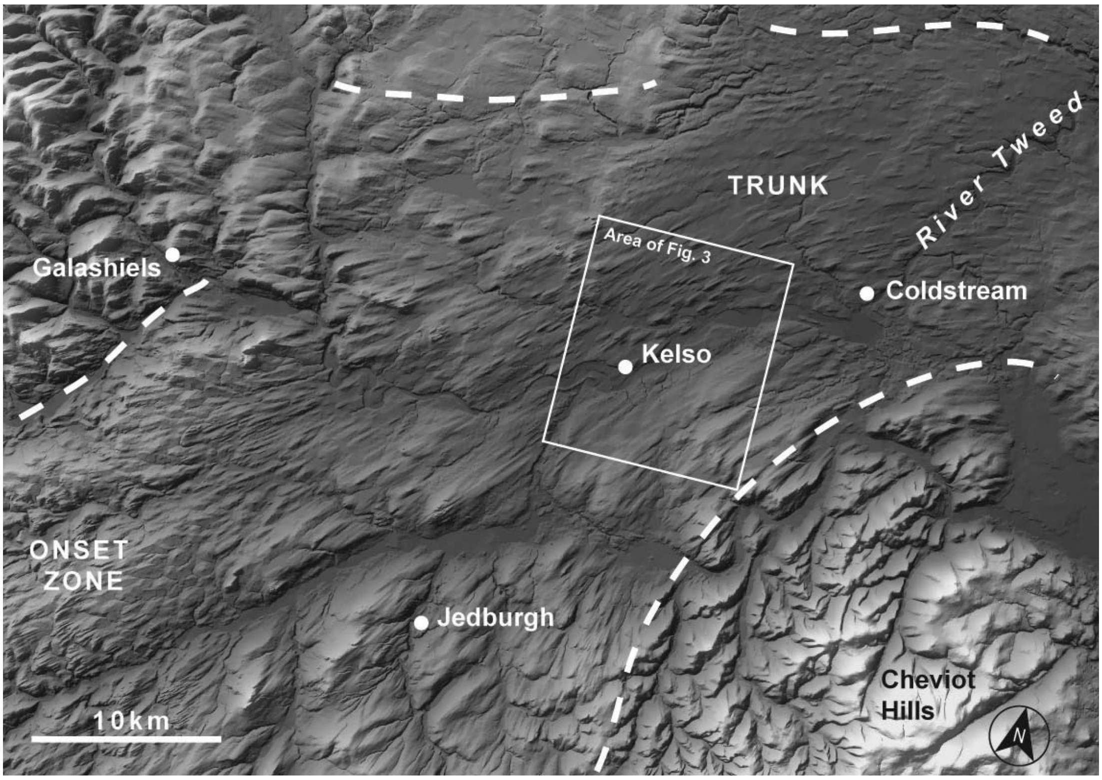

Fig. 3. 5-m vertical resolution OS-derived Digital Terrain Model (DTM) of the Tweed Valley (Ordnance Survey © Crown copyright 2003, license number GD272191/2003). Lighting from the north with 3× vertical exaggeration to highlight the streamlined landforms. White dashed lines indicate margins of palaeo-ice stream.

~40 km and narrowed to ~20 km in the trunk. Its onshore length was *c*. 65 km, although its total length may have been at least 100 km assuming that it terminated some distance offshore from the present coastline. The trunk of the ice stream overrode a deformable substrate of till resting on Lower Palaeozoic sedimentary strata. The glacial deposits in this area are known to be up to 60 m thick in places (Table 1, and Clapperton, 1971). It has been suggested that elevated porewater pressures beneath fast-flowing warm-based ice allow the ice to slide over its bed, streamlining the upper surface of the deformable till substrata (*e.g*. Clark, 1994; Benn & Evans, 1998).

Discussion

Ice streams are central to the dynamics of ice sheets (Stokes & Clark 1999; Bennett 2003), and have been identified in formerly glaciated parts of the world by numerous workers (eg. Andrews *et al*., 1985; Dyke & Morris, 1988; Punkari, 1995; Dongelmans, 1996; Stokes & Clark, 2002; Rise *et al*., 2004). Until

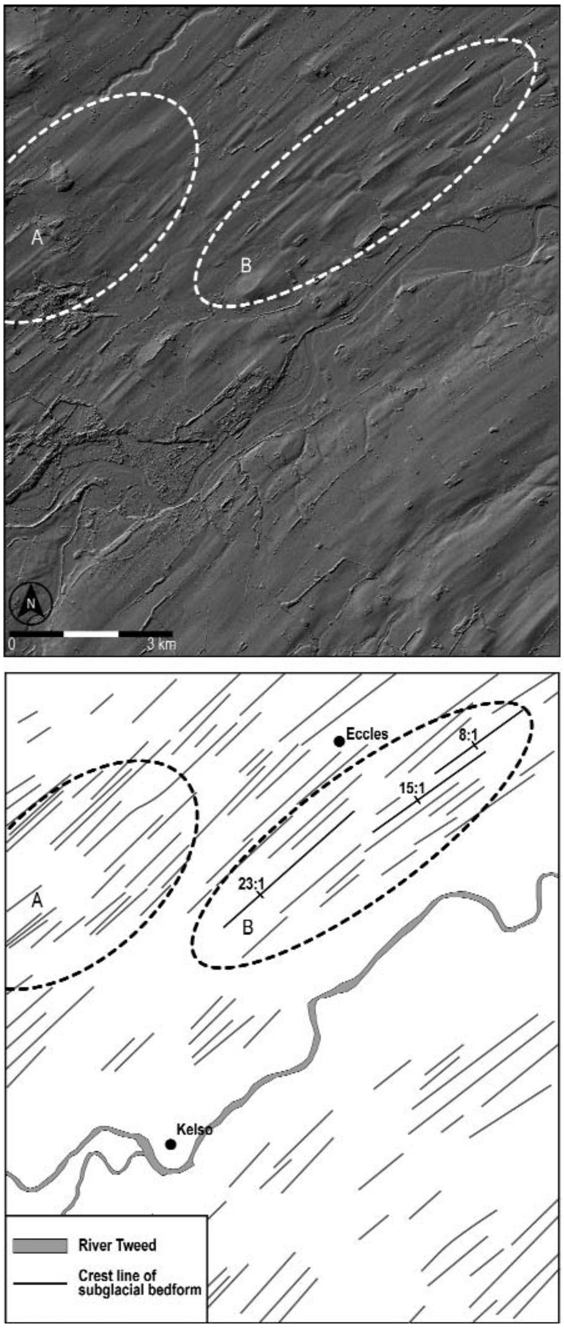

Fig. 4. Composite of tiles NT73 and NT72 from NEXTMap Digital Surface Model (DSM: 1.2 m vertical resolution) of the area around Kelso (NEXTMap Britain elevation data from Intermap Technologies). The image shows examples of highly elongated megalineations, interpreted as fast ice-flow indicators – ellipse A: strongly parallel fluted terrain; B: megadrumlins and megaflutes. The diagram highlights the high elongation ratios and NE orientation of the features.

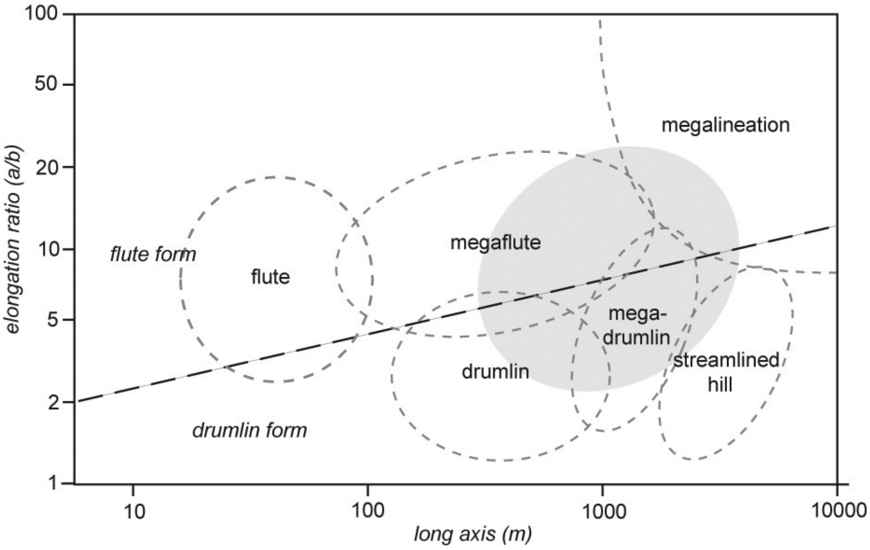

Fig. 5. The classification of subglacial landforms, based on the relationship between length and elongation ratio (modified from Rose, 1987). The shaded ellipse shows the approximate dimensions of landforms in the Tweed Valley.

relatively recently, however, little emphasis has been placed on recognising the signature of palaeo-ice streams on the British and Irish landmasses, despite their existence having been proposed almost 100 years ago (Jamieson, 1906). Within the last few years it has been recommended that large-scale glacial geomorphological features should be more accurately evaluated with a view to improving current palaeo-glaciological reconstructions (Clark *et al*., 2003, 2004). To this end, the use of remotely sensed imagery and digital GIS environments, together with the recognition of diagnostic landsystems, have enabled reappraisals of early work and allowed more focused assessments of key areas. As a result, the number of former ice streams identified in the British Isles has risen sharply since 2001 – to total eleven (Fig. 6).

The suite of subglacial landforms in Berwickshire represents one of the best terrestrial signatures of a palaeo-ice stream so far identified in Britain (Fig. 2). At its maximum, the Tweed Ice Stream would have drained ~3500 km^2 of the last British ice sheet, from the Lammermuir to the Cheviot Hills, before extending offshore as a grounded ice lobe. The identification of palaeo-ice streams such as this one has far-reaching implications for the last BIS. The presence of eleven palaeo-ice streams in the BIS suggests that many areas were more dynamic than previously thought, with fast-flowing zones and high mass turnover. As a consequence, these fast-flowing zones would probably have responded more rapidly to climatic and eustatic changes than slow-flowing sectors. Factors such as the size of ice-drainage basins, the position of ice divides and sources, and the stability of large portions of the ice sheet are also inextricably linked with the location and vigour of ice streams and will influence palaeo-glaciological

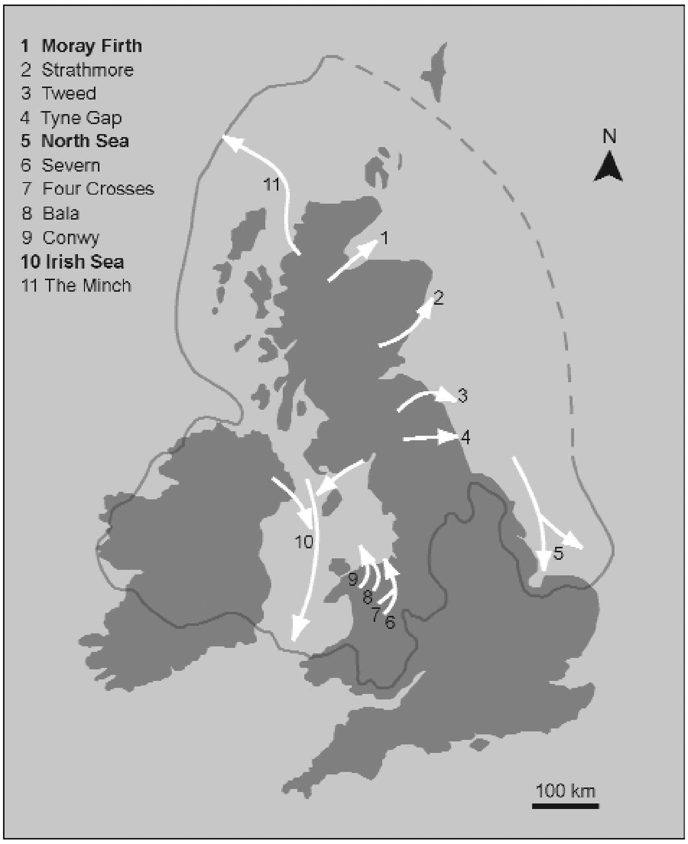

Fig. 6. Approximate locations and names of palaeo-ice streams so far identified in the British and Irish Ice Sheets. References are provided in the text. Stokes and Clark (2001) summarised evidence for three of these (bold). Ice-sheet maximum outline simplified from Boulton *et al*. (1977). Note that not all the ice streams may have operated at glacial maximum.

reconstructions (Paterson, 1994; Stokes & Clark, 1999; Bennett, 2003). Furthermore, the ability of ice streams to rapidly drain large areas of an ice sheet means that they act as a critical control on ice thickness, ice flow and, in marine settings, calving rates. Such spatial variability in ice-sheet behaviour may have significant implications for ice-sheet reconstructions and subsequent climatological inferences.

Presently, the timing of the fast ice-flow event in Berwickshire is unknown but almost certainly postdates the Last Glacial Maximum and may have occurred during a relatively late stage of deglaciation. Indeed, it may even have been instrumental in propagating deglaciation through enhanced drawdown of ice from the surrounding high ground, as postulated elsewhere (*e.g*. Stokes & Clark 2003; Clark *et al*., 2003).

Conclusions

The glacial landsystem in the Tweed valley represents the most complete terrestrial record of a palaeo-ice stream so far identified in Britain. Its recognition, along with other palaeo-ice streams, enables future reconstructions of the British Ice Sheet to be more accurately generated, thereby improving our understanding of Late Devensian palaeoclimate. The steadily accumulating inventory of palaeo-ice streams identified in Britain enables closer parallels to be drawn between present-day ice sheets and the last ice sheet to cover the British Isles.

Access

The subglacial bedforms and streamlined landscape of Berwickshire can be viewed from a number of locations. However, for a general overview of the terrain drive south along the A68 from Edinburgh and take the A697 to Wooler. The palaeo ice-stream terrain is exemplified in the megadrumlins and megaflutes between the Blackadder Water and the River Tweed. The twelve-mile section of road between Greenlaw and Coldstream cuts across the strike of the megalineations allowing their scale to be fully appreciated. Ordnance Survey Landranger map 73 (Kelso) covers the area with the most prominent streamlined landforms.

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