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Megagrooves and streamlined bedrock in NW Scotland: the role of ice streams in landscape evolution

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Abstract

New multibeam bathymetry data, onshore high-resolution elevation data (NEXTMap) and fieldwork in the Ullapool area of NW Scotland reveal large-scale megagrooves and streamlined bedrock forms in a well-defined ~20-km wide zone. The landsystem is typical of a coherent flow corridor within a grounded ice sheet on bedrock-dominated terrain. We describe the morphology of the large-scale features, discuss their likely formation, and consider the wider implications for ice-sheet dynamics. Based on the strongly convergent bedform distribution, the presence of megagrooves and highly elongate bedrock forms, we interpret the erosional landscape to be the signature of a fast-flowing tributary that once fed the The Minch palaeo-ice stream – a major artery of the last British-Irish ice sheet. The exact genesis of bedrock megagrooves remains uncertain, although focused subglacial abrasion is likely to have carved most of the shallow, strongly parallel, features; whilst glacial meltwater may have carved or modified others. Bedform morphometry is used to discriminate zones reflecting the degree of glacial streamlining (elongation ratios <5:1 or >5:1). We interpret these zones to represent the transition from potentially cold-based slow ice-sheet flow to warm-based fast flow. Based on these results, and the presence of ribbed moraines, we suggest a bedform continuum model for onset zones of palaeo-ice streams on rigid beds. Rapid spatial bedform evolution is suggested to reflect an increase in subglacial erosive power that may be diagnostic of palaeo-ice-sheet thermal boundaries (i.e. from cold- to warm-based), and is also consistent with the expected downstream increase in ice velocity within an ice-stream onset zone. Finally, this study speculates on the role played by basal meltwater in ice-stream initiation and the role of ice streams and their tributaries in landscape evolution.

Keywords: palaeo-ice stream; onset zone; glacial lineations, NW Scotland

Introduction

Ice streams are the major conveyors within ice sheets. Often compared to arteries, they are vital components of large ice masses (e.g. Bentley, 1987; Paterson, 1994; Clark et al., 2003a). It has been estimated that ice streams are currently responsible for draining about 90% of the mass of the West Antarctic Ice Sheet (Bentley, 1987). Many ice streams past and present are marine-terminating, thus allowing them to act as intimate connections between the ice sheet and the ocean. It is this unique role that may well be responsible for initiating the abrupt climatic change seen towards the end of the Last Glacial Maximum in the Northern Hemisphere (e.g. Heinrich, 1988; Bond and Lotti, 1995; Andrews and MacLean, 2003). Since the existence of ice streams was confirmed in present-day ice sheets, some geologists and glaciologists have turned their attention to identifying the location of *palaeo-ice streams* in order to better understand their flow mechanics, and their effects on ice-sheet evolution and Quaternary climate change (e.g. Canals et al., 2000; Stokes and Clark, 2001; Andrews and MacLean, 2003).

Much of our understanding of palaeo-ice streams comes from subglacial bedforms and glacial sediments. The majority of these studies have addressed the role of soft sediments beneath fast flow zones, with much emphasis being placed on the presence of a 'deforming bed' as the major controlling factor on fast flow (e.g. Boulton and Hindmarsh, 1987; Hart and Smith, 1997; Stokes and Clark, 2001). In contrast, relatively little work has focused on the bedforms of ice streams flowing on rigid beds. These rigid beds are typified by ice sliding directly over hard, often crystalline, bedrock of low permeability (Menzies, 1989). Reasons for this relative neglect may be due to the erosional, sometimes ambiguous, nature of the evidence; complications caused by geological structure; and the tendency for bedrock features to form over several glacial cycles.

Empirical studies have proposed that there are two principal types of ice stream: *pure ice streams* and topographically controlled *isbraes* (Truffer and Echelmeyer, 2003). However, the two are seldom mutually exclusive and several authors have observed examples of the latter grading into the former with distance downstream. It is therefore likely that non-topographic, pure ice streams and isbrae-type ice streams form a glaciological continuum (Bamber et al., 2000; Stokes and Clark, 2001; Truffer and Echelmeyer, 2003).

This paper focuses on the erosional bedrock elements in the glacial landscape of NW Scotland, both on the terrestrial land surface and the present-day seabed, identified recently by the British Geological Survey (BGS). These landforms represent the signature of a large palaeo-ice stream in NW Scotland (Stoker and Bradwell, 2005; Bradwell et al., 2007). This fast flowing corridor of ice – The Minch ice stream – probably operated during the Late Devensian Glaciation (Marine Isotope Stage 2), drained much of the NW sector of the British-Irish ice sheet (~15,000 km^2) and was responsible for the deposition of the large Sula Sgeir fan on the continental shelf edge. (Fig. 1). This paper describes the morphology of the large-scale erosional features; considers likely formation mechanisms; and discusses the wider implications for ice-sheet dynamics and landscape evolution in NW Scotland.

Previous work using large-scale, bedrock forms to infer palaeo-ice flow dynamics

Glacially sculpted bedrock forms are commonly used to make qualitative palaeo-glaciological reconstructions. Small-scale glacial erosion features in bedrock (i.e. striae, chattermarks and p-forms, etc.) have been particularly well studied and provide much valuable information regarding conditions at the glacier bed (e.g. MacClintock, 1953; Iverson, 1990; Kor et al., 1991). However, only a few studies have attempted to make inferences about palaeo-ice-flow velocity based on medium- and large-scale glacially eroded bedrock features. These include key papers by Evans (1996), Hall and Glasser (2003), Jansson et al. (2003), and Roberts and Long (2005).

Evans (1996) showed how subtle differences in bedform morphology could be used as a proxy for subglacial pressure conditions. He found that symmetrical glacial bedforms (whalebacks) only formed beneath fast-flow zones, probably isbrae-type ice streams, where ice was thicker and bed separation was suppressed. Hall and Glasser (2003) used the degree of glacial erosion to reconstruct basal thermal regime in the Cairngorm Mountains, Scotland. Ice moulded roche-moutonnees occur close to undisturbed tors and blockfields, implying a relatively abrupt transition from frozen bed ice-sheet conditions to fast-flowing warm based ice. In northern Quebec, Canada, Jansson et al. (2003) mapped numerous erosional bedforms, including megadrumlins, grooved bedrock and large-scale crag-and-tail forms. They inferred several discrete palaeo-ice-flow sets based on the distribution of bedforms. Furthermore, Jansson et al. (2003) suggested that the high density and high elongation of drift and bedrock features indicated that the Ungava Bay area acted as the pathway of a major Laurentide ice stream. Roberts and Long (2005) examined glacial bedforms in gneissose bedrock adjacent to the fast-flowing Jakobshavns Isbrae in west Greenland. They found quantifiable differences in bedform morphology, both in terms of elongation and density, which led them to define the former limits of the isbrae. Roberts and Long (2005) deemed ice-sheet flow velocity to be more important than ice-sheet thickness in the generation of strongly streamlined erosional bedforms.

Other workers have used large-scale ice-directional features to make inferences about palaeo-ice-sheet velocities, but rarely distinguish between soft-sediment features and those formed in bedrock (e.g. Boulton and Clark, 1990; Clark, 1994; Stokes and Clark, 2002). Collectively, these highly elongate ice-directional landforms are known as 'mega-scale glacial lineations' (Clark, 1993). The formation of large-scale glacial lineations in soft till is unlikely to be caused by the same process responsible for the formation of similar-looking features in hard bedrock.

Study area

The study area covers approximately 600 km^2 and is centred on the area of landscape lineations occurring between Loch Broom and the Cromalt Hills, near Ullapool in NW Scotland (Fig. 2a). The area also includes much of Little Loch Broom, Loch Kanaird, the Summer Isles, the surrounding bays and headlands, and all the land immediately to the east within the district of Wester Ross (Fig. 2a). The study area comprises a broad topographic low flanked to the north by the mountains of Coigach (743 m ASL) and by the An Teallach massif (1060 m ASL) to the south. The Beinn Dearg massif (900–1080 m ASL) lies just to the southeast. Much of the land within the study area is below 300 m ASL; and much of the sea bed lies between 50-120 m below sea level. The watershed runs generally north-south along the highest ground, which in the centre of the study area is below 500 m (Beinn Donuill) (Fig. 2a). The area constitutes the widest breach (~20 km) in the Scottish Highlands mountain range.

The bedrock geology of the study area is varied and complex (Fig. 2a). The western part of the study area is dominated by coarse red, thick-bedded Torridonian sandstone of Neoproterozoic age. In places there are inliers of Archaean Lewisian gneisses, onto which the Torridonian sandstone was unconformably deposited. Just east and north of Ullapool is a thin strip of Cambro-Ordovician rocks, mainly quartz-arenite (‘quartzite’) with subordinate carbonate. Quartzite outcrops are commonly highly polished and possess good glacial striae. Small thrust slices of Lewisian gneiss occur adjacent to these rocks. The eastern part of the study area is dominated by psammite (metamorphosed sandstones) and subordinate semipelite (metamorphosed mudstone) of the Moine Supergroup, also of Neoproterozoic age (Trewin, 2002).

Glacial deposits are scarce in this part of NW Scotland. Thin patchy tills (<5 m thick) occur locally on gentle slopes; however, much of the Torridonian sandstone is a bare, glacially abraded bedrock surface (British Geological Survey, 1998). Read et al. (1926) found erratic boulders and glacial striae indicating that at maximum glaciation ice flowed from east to west, across the present-day watershed.

Methods and data collection

Onshore data collation

Satellite imagery (Landsat TM) was used to identify areas of large-scale lineations in NW Scotland that warranted further investigation. These lineations were subsequently mapped using a combination of 1:10,000-scale stereoscopic aerial photographs and high-resolution digital surface models (NEXTMap Britain) with 1-m resolution in the vertical plane and 2-m in the horizontal plane. NEXTMap is most useful at larger scales, with a wide field of view, typically >1:20,000. A geological field survey of the Loch Broom and Strathcanaird area was conducted between May 2004 and 2006. This included bedrock measurements, sediment distribution mapping, section logging and landform mapping at 1:10,000 scale where appropriate.

Offshore data collection

Multibeam swath bathymetry and boomer seismic data were collected in July 2005 (Stoker et al., 2006). The total extent of the offshore survey is ~225 km^2. Bathymetric data were acquired using a GeoSwath system operating at 125 kHz, mounted on a retractable bow pole on the R/V Calanus. Swath survey lines were run at a spacing of 200 m, thereby enabling swath overlap and full coverage bathymetry of the survey area. The data were collected on a GeoSwath computer with post-acquisition processing carried out on a separate workstation. Output was in the form of xyz data with a typical grid spacing of 3 m. The grid was converted into a depth-coloured shaded-relief image using Fledermaus (processing and visualization software) (Stoker et al., 2006). Seismic data were acquired using a BGS surface-towed boomer and hyrdrophone. The data were recorded and processed (Bandpass Filter 800-200 Hz) on a CODA DA200 seismic acquisition system and output as SEG-Y and TIFF format. Technical details of the offshore data collection are outlined in Stoker et al. (2006).

Image interpretation

When georectified and merged in a geospatial database (ArcGIS 9.0 (ESRI)), the seamless high-resolution surface model of the landscape and seabed can be viewed and interrogated (Fig. 2b). The use of three-dimensional NEXTMap and multibeam data allowed surface models to be illuminated and viewed from any angle thus enabling clear, accurate identification of landform morphology. The long axis of all glacial lineations (>100 m) within a ~600 km^2 area of land and seafloor were mapped digitally on screen (Fig. 2c). The data capture method used is similar to that outlined by Stokes and Clark (2003). Landform dimensions, such as length, height and elongation ration were measured digitally within the GIS.

The resulting landform map is based on mapping at a fixed scale of 1:30,000 (Fig. 2c). Although, in essence, the landform map is a remotely sensed interpretation of the ground, extensive field surveys between 2004-06 verified the inferences made from the digital datasets.

Results

The following section summarises the major geomorphological elements in the landscape of the Loch Broom–Summer Isles region. The descriptions combine the results of detailed BGS fieldwork, spanning 3 years, with new mapping based on recently acquired digital topography and bathymetry datasets (Fig. 2b).

Glacial lineations

The seamless onshore-offshore digital surface model reveals a remarkably coherent pattern of glacial lineations (Fig. 3). In this study the term 'lineations' encompasses a range of positive and negative landform elements. The pattern of glacial lineations in the Loch Broom–Summer Isles area can be grouped into a single, unambiguous, flow set (Fig. 3). The overall distribution of lineations is convergent from east to west; bunching in the central region around Strathcanaird and the mouth of Loch Broom – similar to bottleneck patterns of mega-scale glacial lineations reported elsewhere (e.g. Canals et al., 2000; Stokes and Clark, 2002). Morphometric analysis has been used to discriminate the landforms on the basis of elongation (i.e. length:width ratio). Generally, larger, more pronounced, more elongate forms occur in the central east-west zone of the study area; whilst smaller, less well-developed, less elongate features occur towards the north, south and eastern margins (Fig. 4). Landforms also show a general increase in length with distance along hypothesised palaeo-flow lines (Fig. 4). These finding are also in line with previous studies of glacial lineations, on the Canadian Shield and off Antarctica (e.g. Canals et al., 2000; Stokes and Clark, 2002; 2003; Jansson et al., 2003).

Based on landform morphology, we distinguish three zones within the study area (Fig. 4): Zone A has no elongate landforms; Zone B has subtle forms with low elongation ratios (<5:1); whilst Zone C has well-developed forms with high elongation ratios (>5:1). Smaller, low-elongation, landforms do occur within Zone C but highly elongate forms predominate. Although the boundaries between these zones are generally gradational, the zones have distinct spatial expression. On the basis of their overall distribution and spatial coherency, the landforms or lineations are interpreted to be subglacial bedforms, ranging in length from ~100 to ~6000 m.

Geological field mapping has shown that bedrock occurs at or near surface across ~90% of the study area above sea level (Fig. 2c). Isolated patches of till or morainic debris occur only as relatively narrow east-west trending strips, chiefly draped on Moine Supergroup psammites. Thus, almost all bedforms mapped onshore within the study area occur in bedrock and are therefore the product of glacial erosion (Fig. 2c). In the following descriptive section the bedforms are separated into three categories – (i) megagrooves, (ii) streamlined bedrock forms and (iii) streamlined glacial deposits.

(i) Megagrooves

Since the identification of bedrock megagrooves in Assynt, NW Scotland (Bradwell, 2005), several other areas of large-scale grooving have been identified onshore in the UK (Stoker and Bradwell, 2005; Golledge and Stoker, 2005; Bradwell et al., 2007). The area around Ullapool, extending offshore to the Summer Isles, is the largest area of bedrock grooving (~500 km^2) so far identified in Europe. Megagrooves are linear features with negative topographic expression, >100 m long and >1 m deep, cut in bedrock (Bradwell, 2005). 10-km long, 20-m deep examples have been reported from North America (Smith, 1948; Witkind, 1978).

Within the study area, the megagrooves are best developed onshore around the watershed between Loch Chroisg and Loch Achall, and immediately east of Beinn Donuill (Fig. 4). Here they are closely spaced, sub-parallel grooves ranging in length from 500 to 3000 m. Discontinuous features up to 5500 m in length have also been identified; however, most of the megagrooves around Beinn Donuill are between 1000–2500 m long and 50–100 m wide (Table 1). In the highest density area, east of Beinn Donuill, megagroove spacings are typically about 100 m (Fig. 4). Groove spacings generally decrease away from this central zone, although spacings of 100–200 m occur elsewhere in the study area.

Megagroove depths vary. Two kilometres east of Beinn Donuill, where the most striking grooves occur, average depths range from 10 to 15 m. Other grooves are less pronounced with peat-filled floors and are only ~5 m deep.

Broadly three types of megagroove occur, each with different cross-profiles: (i) parabolic megagrooves with steep concave sides and high width:depth ratios (~5–

10:1); (ii) v-shaped megagrooves with steep sides and low width:depth ratios (<5:1); (iii) asymmetric, bench-like megagrooves, with only one steep wall (Fig. 5). Shallow parabolic grooves are more common east of the watershed, whilst deeper v-shaped grooves are more common to the west. In places, individual megagrooves change from parabolic to v-shaped as they cross the watershed. The most pronounced bedrock grooves are deep gorge-like channels with width:depth ratios of <5:1 (Fig. 5). Some of these reach 25 m or more in depth.

Where the megagrooves are well defined and closely spaced the residual landforms are narrow elongate bedrock ridges akin to megaflutes, with elongation ratios ranging from 6–25:1 (Fig. 4). Where the megagrooves are weakly defined or discontinuous, for instance on the low ground around Allt Beinn Donuill, bedrock megadrumlins predominate (elongation ratios ~ 4–8:1).

Bedrock structure appears to control megagroove cross-profile asymmetry. The Moine psammite possesses a strong bedding-parallel, gently dipping schistosity. Where this bedding/schistosity outcrops parallel to ice flow, asymmetric megagrooves are particularly well developed. Also, finely spaced megagrooves are more commonly developed on Moine psammite than on Torridonian sandstone (cf. Figs. 2a, 2b). However, the development of megagrooves is not solely governed by bedrock, as they occur in varying degrees on Moine psammite, Torridonian sandstone and quartzite regardless of lithology and structure (Bradwell, 2005).

Occasional glacial striae were recorded on quartz veins within the megagrooves, indicating east-west ice flow. These veins typically stand 5-10 mm proud of the present rock face suggesting that the glacially abraded rock surface has been largely removed by postglacial weathering.

Large-scale linear erosional grooves also occur on the seafloor in the central part of the study area, between Cailleach Head and Tanera Mòr (Figs. 2b, 6). Seismic reflection profiles show that these features are cut in bedrock (Fig. 6), probably Torridon Group sandstone and Lewisian gneiss (British Geological Survey, 1998). The seafloor grooves are typically 1–4 km long and 50–250 m wide. The largest is ~6 km long, 500 m wide and 20-40 m deep (Table 1). The offshore megagrooves trend in a northwesterly direction, in places cutting across the structural grain of the Torridonian sandstone bedrock. On the seabed between Eilean Dubh and Horse Island, where the grooves are best developed, they have broad parabolic cross-profiles, typically with width:depth ratios of ~10:1 (Fig. 6). Many of the grooves have undulating long profiles. In planform the pattern of grooves delineate intervening bedrock ridges, resembling flutings and megadrumlins, with elongation ratios of 5–15:1. The large-scale erosional grooves on the seabed are similar in form, but have greater dimensions than, the bedrock megagrooves identified on the adjacent landmass (Table 1).

(ii) Streamlined bedrock forms

Large-scale crag and tails, rock drumlins, whalebacks and roches moutonnees all occur throughout the study area, giving the landscape a highly streamlined overall appearance. Field mapping has shown that glacial bedforms occur on a range of scales, from 1–3400 m (Table 1) with more elongate forms clustering in the central Zone C. Large-scale bedforms occur in the Torridonian sandstone, in lower Strathcanaird and on the southeastern flank of Ben Mor Coigach (Fig. 7). The NEXTMap data show that the long axes of these features trend southwest to west indicating the dominant, strongly convergent, palaeo-ice-flow direction (Fig. 7). Some of the largest bedforms are strongly streamlined, broadly symmetrical hills with glacially abraded surfaces on both up-ice and down-ice faces. Around Loch Kanaird good evidence of intimate ice-bedrock contact is seen on the outcrop scale. Ice-worn bedrock surfaces with well-developed, uni-directional striae indicate persistent flow in a west-southwesterly direction. Excellent examples of p-forms also occur within this area, typically on the metre scale, including longitudinal undercut channels, comma forms and smooth undulating surfaces (Fig. 7). P-forms are thought to form when debris-rich basal ice flows plastically around bedrock obstacles carving smooth, well-defined, depressions (Boulton, 1979). They may be indicative of suppressed bed separation beneath thick or fast-flowing ice (Evans, 1996; Roberts and Long, 2005).

Towards the margins of the flow set and on higher ground, stoss-and-lee forms predominate (Fig. 7). Field mapping on the higher elevation parts of Cailleach Head and around Bheinn Gobhlach identified well-developed stoss-and-lee forms ranging from 5–250 m in length. Although generally too small to show on the main map (Fig.

2c), these small- and medium-scale bedforms add to the strongly streamlined overall appearance of the landscape and are important for understanding subglacial dynamics. Stoss-lee forms with plucked faces are thought to be indicative of thinner ice prone to subglacial-cavity development (Benn and Evans, 1998; Roberts and Long, 2005). Examples of large-scale stoss-lee forms are also found amongst the Summer Isles. The northern islands, particularly Tanera Mòr and Tanera Beag exhibit strongly asymmetrical profiles in the direction of palaeo-ice-flow (Fig. 7). The Summer Isles probably represent the tops of large-scale streamlined hills and roche moutonnees (flyggbergs) – some with pronounced stoss-lee form. The multibeam bathymetry data shows other submerged streamlined bedforms of similar scale on the seabed, many apparently lacking plucked lee faces (Fig. 6). The similarity between the onshore and offshore geomorphology allows the bedforms to be interpreted as part of the same streamlined glacial landscape.

(iii) Streamlined glacial deposits

Field mapping has shown that the occurrence of glacial deposits is limited within the Loch Broom-Summer Isles region (Fig. 2c). Thick tills (>5 m) only occur in isolated localities, and collectively cover <5% of the land within the study area. The largest area of glacial diamicton occurs on the southern part of Cailleach Head and around Badcaul, either side of Little Loch Broom. Here tills blanket the underlying bedrock resulting in smooth apparently featureless slopes. However, the hill-shaded NEXTMap surface model highlights subtle lineations on the ground around the western end of Little Loch Broom (Fig. 2b). These glacial bedforms are up to 1500 long, 400 m wide, and trend broadly NW, in agreement with the surrounding streamlined bedrock features. Other small streamlined areas of till (<3 km^2) occur at Badidarroch, on the southern edge of the study area; on the southern flank of Glen Achall; and on the western slopes of Ben More Coigach (Fig. 2c). It is possible that the streamlining in these till-covered areas is merely due to glacial sediment being draped on a previously streamlined bedrock surface. However, field exposures at Badidarroch, reveal two well-consolidated tills; one immediately overlying the other. The upper reddish-brown till forms the streamlined present-day land surface and is therefore likely to have been deposited subglacially. The lower grey lodgement till at Badidarroch may relate to an earlier glacial advance.

Meltwater channels

Numerous large erosional meltwater channels dissect the landscape, both onshore and on the seafloor in the vicinity of the Summer Isles. These channels can be subtly distinguished on morphologically grounds from the more regular large-scale grooves. The channels are large (>100 m wide), deep (>20 m) chasms cut into bedrock, normally occurring in isolation (Fig. 8). They have steep v-shaped or box-section cross-profiles with low width:depth ratios (<5:1) and often exhibit a slightly sinuous plan form (Table 1). The best examples of large-scale meltwater channels occur just north of Ulapool, in the central part of the study area, where six large channels have been mapped (Fig. 8). The largest of these are Glutton in Strathcanaird, and An Strathan 2 km north of Ullapool. The rock walls of both these channels are ornamented with water-worn forms and erosional scour marks, up to 1.5 m in diameter (Fig. 8). The Glutton channel is over 1500 m long, ~200 m wide, and up to 55 m deep in places. Both channels now host only small misfit streams; and both clearly owe much to the power of glacial rivers. It is notable that some of the meltwater channels follow significant bedrock faults, such as at Glutton and Allt Garbh; whilst others, such as the An Strathan and Ullapool River channels, do not.

Similar-sized glacial meltwater channels are seen on the swath imagery (Fig. 9). One, 500 m east of Cailleach Head, forms a large submarine bedrock canyon, >30 m deep and 2 km long, with a steep up-and-down long profile and a single thalweg (Fig. 9a). A second large-scale channel starts 2 km east of Priest Island. It is 2.5 km long with a slightly sinuous course an undulating long profile (Fig. 9b). In cross profile the channel is steep sided with a wide flat floor. Judging by their low width:depth ratios (<5:1), sinuous unbranching nature, and up-and-down long profiles, both these erosional features are inferred to be large subglacial meltwater channels. They are similar in scale to those identified by Ó Cofaigh et al. (2002, 2005) off West Antarctica.

Ribbed moraines

In the Cromalt Hills on the gently eastward sloping flank of Meall a' Bhuirich Rapaig [NC 26 02], a group of low-elevation rounded ridges trend north-south, perpendicular to the regional pattern of streamlined bedforms (Figs. 2a, 2b). The ridges are typically around 500 m long, 50-100 m wide and generally <10 m high. They are probably composed of glacial diamicton, although no sediment exposures were seen in the field. The ridges are interpreted as a small field of ribbed moraines. Other, much more extensive, fields of ribbed (Rogen) moraines have been identified elsewhere in NW Scotland, 30 km to the east, around Invercassley and Loch Shin (Bradwell and Finlayson, 2006). The transverse ridges on Meall a' Bhuirich Rapaig are similar in size and morphology to ribbed moraines identified by Hättestrand (1997) in central Sweden.

Eskers

Superimposed on the streamlined bedforms, in the east of the study area [NC 247 977], is a well-preserved, sharp-crested, highly sinuous landform. This unbroken single ridge, >10 m high and over 800 m long, is composed principally of sorted sand and gravel and is interpreted as an esker relating to the Late Devensian ice sheet. A similar, poorly preserved, discontinuous feature lies 2 km to the northwest [NC 223 996].

Ice-marginal features

A distinctive suite of 15–20 ridges occurs on the sea bed, between Tanera Mòr and Cailleach Head. The ridges are superimposed on, but perpendicular to, the glacially streamlined bedforms (Fig. 6). Composed of glacial diamiction and interpreted as recessional moraines, they chart the punctuated retreat of a grounded ice-sheet margin across the Summer Isles region (Stoker et al., 2006).

Interpretation of the landform assemblage

The bedform distribution in the Loch Broom-Summer Isles region suggests that this zone of the ice sheet underwent strong flow convergence from east to west. The lack of elongate bedforms to the north and south of this ~20 km-wide zone gives the flow corridor abrupt lateral margins (Fig. 2c). The presence of the large Ben Mor Coigach and An Teallach massifs, either side of a wide topographic trough, would have helped to funnel the ice sheet and hence differentiate this flow corridor from neighbouring, sections of the ice sheet. This suggests that the flow corridor was influenced by the surrounding topography.

The nature of the bedforms can be used to infer palaeo-ice-sheet dynamics in this part of NW Scotland. Several studies have shown strong correlations between fast ice flow and highly elongate bedforms in numerous settings (Hart, 1999; Wellner et al., 2001; Stokes and Clark, 2002; Christoffersen et al., 2005). We interpret the highly elongate, strongly parallel, bedforms in the vicinity of Ullapool to be indicative of fast palaeo-ice flow (Fig. 2c). Examination of bedform morphometry across the fast-flow corridor shows a marked decrease in bedform elongation away from the central Zone C. The presence of large-scale bedrock flutings and roche moutonnees, with elongation ratios of >10:1, within Zone C suggests that this part of the ice sheet was faster flowing than areas to the north and south (Zone A), where elongate bedforms are lacking (Figs. 2c, 3). Furthermore, examination of bedform morphometry along a hypothesised palaeo-flow line shows bedform lengths generally increase in a down-ice direction (Fig. 3). All these findings are in line with geomorphological studies of other palaeo-ice streams (eg. Stokes and Clark, 2003) and consistent with velocity profiles from Antarctic ice streams (Whillans et al., 1993; Paterson, 1994).

Work in the wider area has shown that this fast-flow zone was probably only one of several in NW Scotland that fed into a large palaeo-ice stream flowing in The Minch, during the Late Devensian Glaciation (Fig. 1) (Stoker and Bradwell, 2005; Bradwell et al., 2007). On the basis of geomorphological evidence, we interpret the Ullapool ice-stream tributary as one of the main feeders into The Minch palaeo-ice stream.

Discussion

The discussion is divided into three parts: firstly, we contemplate the formation of certain large-scale glacial lineations in bedrock; secondly, we discuss the implications of the whole bedform assemblage for regional ice-sheet dynamics; finally, we put these interpretations in a wider context with a view to better understanding ice-stream initiation and glacial landscape evolution.

Landform genesis

The genesis of streamlined bedforms on rigid beds is a challenging topic. Unlike many of their counterparts in soft unlithifed sediment, glacial bedforms in bedrock are clearly the product of erosion. The mechanisms of subglacial erosion are well known (see Benn and Evans, 1998). Most streamlined bedrock forms (e.g. crag and tails, rock drumlins) are produced by preferential glacial erosion of the surrounding substrate to leave a prominent more resistant core aligned in the direction of ice flow (Sissons, 1971, Sugden and John, 1976; Sugden et al., 1992). But by what process are large-scale linear grooves carved in hard, seemingly uniform, bedrock? Four possible formation mechanisms are proposed:

1. Pure subglacial erosion (by abrasion and/or plucking)
2. Erosion by saturated till or subglacial ice-water slurry
3. Erosion by subglacial meltwater
4. Groove ploughing (*sensu* Clark et al., 2003b)

Bradwell (2005) suggested that megagrooves on quartzite dip slopes near Elphin in Assynt were probably the product of high-energy subglacial meltwater. However, in the light of new evidence presented here, it is worth reviewing the arguments again.

Large-scale bedrock grooves have been reported in other previously glaciated areas (Carney, 1910; Smith, 1948; Witkind, 1978). These workers concluded that the grooves formed as a result of mechanical abrasion under localized, particularly favourable, conditions at the base of the ice sheet. This mechanism of groove formation remains attractive and is the most commonly cited in the scientific literature (e.g. Boulton, 1979; Benn and Evans, 1998), although the precise mechanism for generating these particularly favourable conditions remains elusive.

Erosion of bedrock by saturated till or ice-water slurry has been advocated for the formation of certain small-scale p-forms (Gjessing, 1965), although it has not been strongly endorsed by the wider scientific community. This mechanism is unlikely to excavate megagrooves on the scale of the features under discussion (~100–5000 m).

Groove ploughing by basal-ice irregularities, as proposed by Tulacyzk et al. (2001) and elaborated by Clark et al., (2003b), has only been invoked to explain ridge-groove structures in till (i.e. soft deformable sediment). Few would argue that undulations in the base of the ice sheet are capable of ploughing grooves through hard bedrock. Perhaps unsurprisingly, mega-scale glacial lineations (*sensu* Stokes and Clark, 2001) have not yet been noted to occur in bedrock. This in itself represents a problematic aspect of the groove-ploughing hypothesis. However, the mechanism does invoke some intriguing questions surrounding the role played by basal-ice irregularities in sculpting the ice-sheet bed. We speculate that undulations set up at the ice sheet–bedrock interface, possibly in response to longitudinal driving-stress variations, may concentrate debris into linear bands. Several workers have reported the presence of flow-parallel debris bands near ice-stream beds, in the form of englacial flow stripes or debris-rich basal crevasses (Jezek and Bentley, 1983; Whillans et al., 1993; Catania et al., 2005). It is conceivable that focused glacial erosion by basal debris locked in flow-parallel bands is responsible for carving large-scale bedrock grooves.

The hypothesis that megagrooves are eroded by subglacial meltwater is less likely in the present study area than in the previous study area in Assynt (cf. Bradwell, 2005). The megagrooves east of Beinn Donuill are different in form to most of those identified in Assynt (see Table 1; cf. Bradwell, 2005). Most have wide parabolic cross-profiles, are shallow relative to their width (width:depth ratios >5:1), and are long, linear or curvilinear, features – in contrast to the deep, relatively short, gorge-like megagrooves at Elphin (Bradwell, 2005). Unfortunately, due to postglacial weathering of the psammite rock surfaces, any evidence of flowing water within the Ullapool megagrooves is lacking. These factors, combined with their strongly parallel, closely spaced, distribution, would all argue against a meltwater-carved origin for most of these megagrooves.

Both v-shaped and parabolic megagrooves clearly form part of the same landsystem. The occurrence of single megagrooves with parabolic cross-profiles to the east, and v-shaped to the west, of the watershed implies a complex formation mechanism. We suggest that the parabolic megagrooves, and the bench-like asymmetric grooves, were probably formed by focused subglacial abrasion. Whereas the v-shaped megagrooves were formed by subglacial meltwater, or were first carved by glacial erosion and subsequently modified by meltwater. Although some low-lying megagrooves may have been modified by proglacial subaerial meltwater during deglaciation, this is unlikely to have been the case for high-level megagrooves on the watershed around Beinn Donuill. However, the broadly similar scale of all onshore megagrooves and their subparallel ice-directed orientation strongly suggests synchronous formation beneath a coherent ice-flow corridor. These findings highlight the problem of equifinality when dealing with erosional landforms, especially when few modern analogues exist.

It is suggested that the generic term megagroove is reserved for all, large-scale, linear, erosional features with negative topographic expression conditioned by glaciation, regardless of their genesis – as used previously by Bradwell (2005) and Bradwell et al., (2007). Megagrooves should be >100 m in length and >1 m deep; currently no terminology exists for these features. Knowledge of genesis allows a sub-classification to be made: glacial megagrooves – those megagrooves where subglacial abrasion is the main erosional agent; and meltwater megagrooves – those formed chiefly by fluvioglacial erosion.

Bedform evolution: The signature of an ice-stream onset zone?

Ice-stream onset zones mark the transition from slow sheet flow to streaming flow. In present-day ice sheets, onset zones are defined as areas at the head of ice streams where ice velocities increase by an order of magnitude (Paterson, 1994). They are readily distinguishable in Antarctica by synthetic aperture radar measurements over time (Bamber et al., 2000). Several studies have shown that onset zones are conicident with a thermal boundary within the ice sheet, where cold slow-flowing ice becomes warmer, wet-based, and, hence, faster flowing (Engelhardt and Kamb, 1998; Bamber et al., 2000; Vaughan et al., 2006). Relatively few studies, to date, have identified palaeo-ice-stream onset zones in the landscape record.

Several authors have found that large-scale rock-cut grooves and meltwater channels occur in the onset zones of palaeo-ice streams (Shipp and Anderson, 1997; Ó Cofaigh et al., 2002; 2005; Evans et al., 2005). These features are part of a family of erosional bedforms, including large-scale grooves, scallops, rock drumlins and megaflutes, all intimately associated with the onset of streaming ice flow (Ó Cofaigh et al., 2002; Evans et al., 2005).

We suggest that the marginal zones of the Ullapool ice-stream tributary represent the geomorphological signature of ice-stream initiation. Collectively these regions are best described as a palaeoice stream [E1]onset zone. The marginal zone in the north, adjacent to Ben More Coigach, is narrow and parallel to palaeo-ice flow and probably represents a lateral shear margin. To the east, the marginal zone is transverse to palaeo-ice flow, and is generally wider and more diffuse; this may represent ice stream onset *sensu stricto.*

Focusing on the sharp northeastern margin, around the Cromalt Hills, a rapid spatial bedform transition occurs (Fig. 10). Where this transition is most pronounced the three zones of glacial streamlining (A–C) occur within a 2-km wide belt. In Zone A there is no evidence of glacial streamlining – we interpret this to be the slow sheet-flow zone (Fig. 10). Zone B consists of subtle streamlined forms with low elongation ratios (<5:1), interpreted as the transitional zone. Zone C consists of strongly streamlined bedforms with high elongation ratios (5–25:1), characteristic of streaming ice flow. In this area all three zones have clear and distinct spatial expression (Fig. 10). We suggest that this rapid bedform continuum is consistent with a velocity transition and may be diagnostic of palaeo-ice-stream onset zones.

The presence of a bedform continuum in bedrock also equates to an erosional transition, ranging from nil to high levels of subglacial erosion within a short distance (<2 km in places) (Fig. 11). We suggest that this erosional transition represents a thermal boundary at the palaeo-glacier bed; with erosion occurring under warm-based (thawed bed) conditions; and no erosion or preservation occurring under cold-based (frozen bed) conditions. This interpretation is supported by the presence of ribbed moraines in Zone A. These transverse ridges form in subglacial settings, probably at the thermal boundary within the glacier bed where changes in flow rate are greatest (Hättestrand, 1997; Hättestrand and Kleman, 1999). Furthermore, Zone A is also noted for its lack of meltwater channels, whilst Zone C exhibits many. The combined geomorphological evidence – ribbed moraines adjacent to a streamlined bedform continuum, along a well-defined ice-sheet flow line – strongly suggests the existence of a palaeo-ice sheet thermal boundary. The clarity of the landform evidence in the Cromalt Hills region of the study area, combined with the likely abrupt nature of this boundary, enables the palaeo-thermal boundary to be located, in places, to within 1–2 km.

Consideration of the flow set as a whole shows that the spatial density of elongate bedrock bedforms increases from Zone B to Zone C, a function of strong convergence towards the central zone. We suggest that this bedform density increase is also a function of subglacial erosive power and may reflect greater, more focused, erosion at higher ice-flow velocities (Fig. 11).

Many landscapes are the cumulative result of successive erosional events, be they glacial, fluvial or otherwise. However, it is possible that the megagrooves and other landforms in the study area formed during a single glacial event – the last ice-sheet glaciation to affect NW Scotland. Alternatively, it is conceivable that ice streams occurred in this position repeatedly during successive glaciations, and that the megagrooves are the cumulative result of several cycles of subglacial erosion.

In short, we cannot know for certain that the bedforms are contemporaneous in age; however, several key points suggest that they probably are. The last glaciation to affect this part of NW Scotland was the Late Devensian ice-sheet glaciation. The only evidence for subsequent glaciation in the study area, during the Younger Dryas, is restricted to corries on the northern side of Ben Mor Coigach (Sissons, 1977; Lawson, 1986). The ground in the eastern part of the study area, between Loch Broom and the Cromalt Hills displays only one discrete glacial landsystem, that of a westward-flowing and subsequently retreating ice sheet. Therefore, arguing that the streamlined bedform continuum is time transgressive represents unnecessary over-complication. The bedforms may have formed over several glacial cycles, but the coherence of the flow set and the highly elongate, strongly parallel morphology of the bedforms would favour a single-event origin. The fact that the megagrooves have not been even partially infilled with till suggests that they were actively forming during the last glaciation, and possibly relate to the latter stages of ice-sheet flow. Stratigraphically, only one thin, discontinuous till has been identified in this area, and all morainic deposits can be attributed to punctuated eastward retreat of the same ice-sheet (Stoker et al., 2006). The ribbed moraines are subglacial features showing no evidence of subsequent overprinting or drumlinisation, suggesting that they too relate to the last ice-sheet advance to affect the area. Without any other chronological evidence it is reasonable to assume that the surface bedforms are equivalent in age.

Wider Implications for Landscape Evolution

Considering the wider implications of this work, it is clear that ice streams and isbraes are central to landscape evolution in mountainous areas, as illustrated in NW Scotland. It is notable that the location of the Ullapool palaeo-ice-stream tributary coincides with one of the largest topographic breaches through the Scottish Highland Mountains. Large stable ice streams, chiefly controlled by topography, such as The Minch palaeo-ice stream, exert a fundamental control on glacial erosion patterns. Their role may be a self-reinforcing one. Ice streams are highly erosive, highly mobile, ice-sheet corridors that only initiate where certain basal thermal conditions are satisfied (Bentley, 1987; Engelhardt et al., 1990; Bindschadler et al., 2000). If these thermal conditions at the kilometre scale are mainly governed by topography, as has been suggested (Glasser, 1995; Truffer and Echelmeyer, 2003; Hall and Glasser, 2003), we might expect ice-stream initiation to occur in certain locations over successive glaciations. This would set up a positive feedback effect within the glacial erosion cycle – whereby one ice stream lowers the land surface within a relatively narrow corridor, only for a second ice stream to utilise the same flow path during a subsequent glaciation. This argument is not new, it merely reinforces the theory of selective glacial erosion proposed by Sugden (1968). On this basis we might be able to predict the location of palaeo-ice stream tributaries in topographic breaches through mountainous terrain – a theory borne out by findings from West Antarctica (Joughin et al., 1999; Bamber et al., 2000)

The high frequency and large size of meltwater channels in the Ullapool area shows that subglacial meltwater has played a primary role in shaping the bedrock landscape. The presence of numerous meltwater channels within a zone of fast palaeo-ice-flow may not be coincidence. Meltwater generation is thought to be greatest beneath ice-stream tributaries where ice is often thicker and driving stresses are higher than in the main ice-stream trunk (McIntyre, 1985; Joughin et al., 2003). Could the onset of fast flow on rigid beds be critically determined by the presence of basal meltwater? The existence of subglacial meltwater along an ice-sheet thermal boundary is implicit. On hard impervious bedrock this meltwater is quickly put under high effective pressure – a mechanism known to instigate basal sliding and rapid ice flow (e.g. Kamb et al., 1985; Engelhardt and Kamb, 1998; Kamb, 2001). Subglacial sheet flows and water films are inherently unstable and are thought to re-organise into channels at the ice-sheet bed (Walder, 1982; Fountain and Walder, 1998). The occurrence of numerous rock-cut channels in the Ullapool region is consistent with this model. Their large size may be testament to the erosive power of the meltwater over a sustained period of time. The subparallel non-arborescent distribution pattern of these channels is also consistent with subglacial drainage networks postulated for ice streams on rigid beds (Fountain and Walder, 1998). Such channel networks result in distributed high-pressure drainage systems thought to increase basal sliding and facilitate rapid ice flow (e.g. Alley, 1989, Engelhardt and Kamb, 1998; Zwally et al., 2002). We therefore suggest that the location of an ice-stream onset zone and the presence of high-pressure basal meltwater along a subglacial thermal boundary are inextricably linked.

Conclusions

Our main conclusions are summarised as follows:

1. Onshore high-resolution NEXTMap surface elevation models in combination with fieldwork and offshore multibeam imagery have revealed the geomorphological signature of a coherent ice-sheet flow corridor in the Loch Broom–Summer Isles region of NW Scotland. Large-scale, closely spaced, glacial lineations – including megagrooves and elongate streamlined bedrock forms – occur both onshore, in a broad topographic breach, and offshore around the Summer Isles. The overall bottleneck distribution pattern of bedforms within a 20-km wide zone suggests convergent, accelerating westward ice flow. This fast-flow corridor represents a tributary of the The Minch palaeo-ice stream, a major artery of the last British-Irish ice sheet.
2. The size of the bedforms in the Loch Broom-Summer Isles area increase from east to west, along palaeo-ice-sheet flow lines. Bedform elongation ratios are also related to palaeo-ice-flow. Shorter, more subtly streamlined forms (elongation ratio <5:1) occur upstream and around the margins of the flow corridor; whilst highly elongate well developed bedforms (elongation ratio >5:1) only occur within the central portion of the flow corridor and further downstream. We interpret this bedform distribution to represent a transition

from slow sheet flow to fast streaming flow. We suggest that this bedform pattern is indicative of a palaeo-ice stream onset zone. Furthermore, we suggest that palaeo-ice-sheet thermal boundaries (i.e. from cold-based to warm-based) may be distinguishable on the basis of a rapid spatial bedform continuum.

3. Based on our results we propose a bedform continuum on rigid beds within the onset zones of palaeo-ice streams. We suggest that bedform elongation and bedform density can be used as a proxy for subglacial erosive power and are proportional to palaeo-ice-flow velocity. Subglacial erosive power within ice streams may become more focused with distance downstream.
4. The exact mechanism of megagroove formation is uncertain. Good evidence points toward the role of subglacial meltwater in carving certain deep megagrooves (width:depth ratio <5:1) (Bradwell, 2005). However, focused subglacial abrasion is envisaged to have formed the majority of megagrooves in the Loch Broom–Summer Isles region, particularly those with broad parabolic cross-profiles (width:depth ratio >5:1). Two genetic sub-categories of megagroove are defined: glacial megagrooves and meltwater megagrooves, although distinction may not always be possible.

Some wider implications of this work are also summarised below:

1. Ice streams play an important role in landscape evolution. Their presence, often determined by topography, sets up a positive feedback system over several glacial erosion cycles. Ice-stream onset is initiated in topographic settings where basal thermal conditions are conducive for streaming to occur. This onset may perpetuate the erosion cycle, with ice-stream tributaries – focused erosion corridors – choosing the same path in subsequent glaciations.
2. We speculate that the onset of fast ice-sheet flow on rigid beds may be intimately associated with the presence of high-pressure basal meltwater along ice-sheet thermal boundaries.

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Figure Captions:

Figure 1: Location of the study area in NW Scotland (box labelled Fig.2), showing reconstructed path of The Minch palaeo-ice stream (grey shading). Thick black lines are hypothesised flow paths; thin lines are inferred onset-zone catchments. Dashed line shows probable limit of grounded British-Irish ice sheet at last glacial maximum (LGM). AT – An Teallach massif; BD – Beinn Dearg massif (modified from Bradwell et al., 2007).

Figure 2a: Simplified bedrock geology of the study area. Location of other figures and places referred to in the text are also shown.

Figure 2b: Merged multibeam swath image (bathymetric data) and shaded NEXTMap image (land surface elevation data) for the Loch Broom–Summer Isles region of NW Scotland (see scale bar on Figure 6 for water depths).

Figure 2c: Map of glacial lineations in the study area. To aid comparison with other studies only elongate positive features are shown. Each line represents the long axis of an individual landform (>100 m). However, some generalization occurs in the highest density areas. Grey shading shows the distribution of glacial diamicton, chiefly till, above sea level. The lineations have been interpreted as a single coherent flow set (thin lines with arrows) recording the overall palaeo-ice-flow direction. Thick lines indicate the margins of the flow set.

Figure 3: (a) Landscape classification map, subdivided on the basis of glacial lineation morphology. Zone A: no elongate bedforms. Zone B: subtle bedforms with low elongation ratios (<5:1). Zone C: well-developed bedforms with high elongation ratios (>5:1). (b) Plot of bedform elongation ratio against distance at right angles to the flow set, measured from the northern margin. Blue circles – east; pink squares – west, mainly offshore. (c) Plot of bedform length against distance along a 30-km flow line.

Figure 4: (a) NEXTMap image in the central zone of the study area, between Loch Achall in the south (just off the image) and Loch a' Chroisg. Letters indicate position of photographs of Figure 5. (b) Geomorphological map of megagrooves distribution . Thin lines are parabolic megagrooves; thick lines are deep, v-shaped megagrooves (width:depth ratio <5:1); grey shading denotes residual bedrock drumlinoid ridges. Not all drumlinoid ridges are shown, for the sake of clarity.

Figure 5: Photographs of megagrooves near Beinn Donuill in cross profile and in oblique view (see Figure 4 for locations). (a & b) Examples of deep gorge-like megagrooves with width:depth ratios <5:1; (a) is steep sided and parabolic, whilst (b) is v-shaped in cross profile. (c, d & e). Examples of broader megagrooves with width:depth ratios >5:1; all have wide parabolic cross-profiles. The water-filled overdeepening in (e) is shallow and estimated to have a maximum depth of ~6 m. (b, d & e) taken looking in the direction of palaeo-ice flow. (f). Oblique view of well-developed, closely spaced megagrooves ~2 km east of Beinn Donuill. Palaeo-ice flow from left to right (east to west).

Figure 6: (a) Multibeam swath imagery of the seabed between Horse Island and Eilean Dubh, showing offshore megagrooves. Note also the well-preserved ice-sheet moraines, transverse to the grooving. Colour bar shows depth scale in metres. (b) Geomorphological cross-profile, across the line A-B, showing the typical morphology of the grooves. Note the broad parabolic cross profiles (width:depth generally >10:1). Horizontal scale ~10x vertical scale. Constructed using Fledermaus™ visualization software. (c) BGS boomer seismic profile 05/04-17 along the line C-D, showing bedrock occurring at the seabed across the grooved area. SBM = sea-bed multiple.

Figure 7: Large-scale streamlined bedrock forms. (a) NEXTMap image of strongly streamlined bedrock terrain around Loch Kanaird, showing locations of photos (b)-(e). (b) Glacially abraded slab of Torridon Group sandstone in Strathcanaird, showing strong unidirectional striae trending 260°. Arrow indicates direction of palaeo-ice flow. (c) Well-developed p-forms and mamillated rock outcrops close to sea level, Loch Kanaird. Palaeo-ice flow away from the observer. (d) Ice-worn streamlined hills, resembling large whalebacks, on the southern flank of Ben More Coigach. Note the rounded form and absence of plucked lee slopes. (e) Ben More Coigach viewed from the south. The mountain is composed entirely of Torridon Group sandstone and exhibits all three landform zones – Zone A occurs above ~400 m; Zone C occurs below ~250 m. (f) The Summer Isles viewed from the north. The islands represent the tops of large drowned stoss-lee forms, with pronounced asymmetry in the direction of palaeo-ice flow. (g) Glacially streamlined bedrock (Torridon Group sandstone) on the flanks of Beinn Gobhlach, Loch Broom; medium-scale stoss-lee forms with high elongation ratios. Viewed from the north.

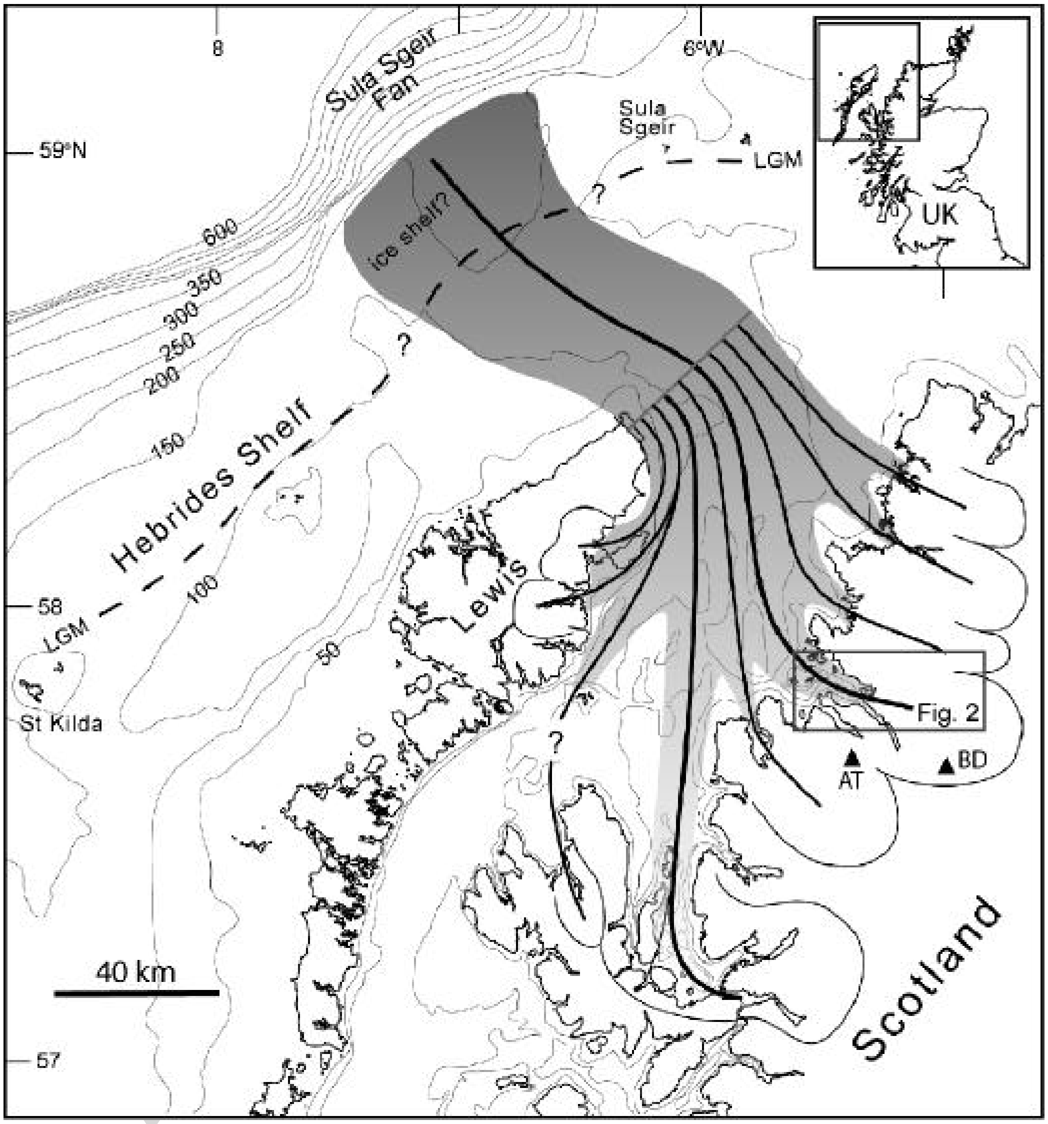
Figure 8: Large-scale meltwater channels. (a) NEXTMap image of area immediately north of Ullapool showing the distribution of large glacial meltwater channels cut in bedrock, numbered 1-6. MG = area of well-developed megagrooves. (b) Looking northeast along the

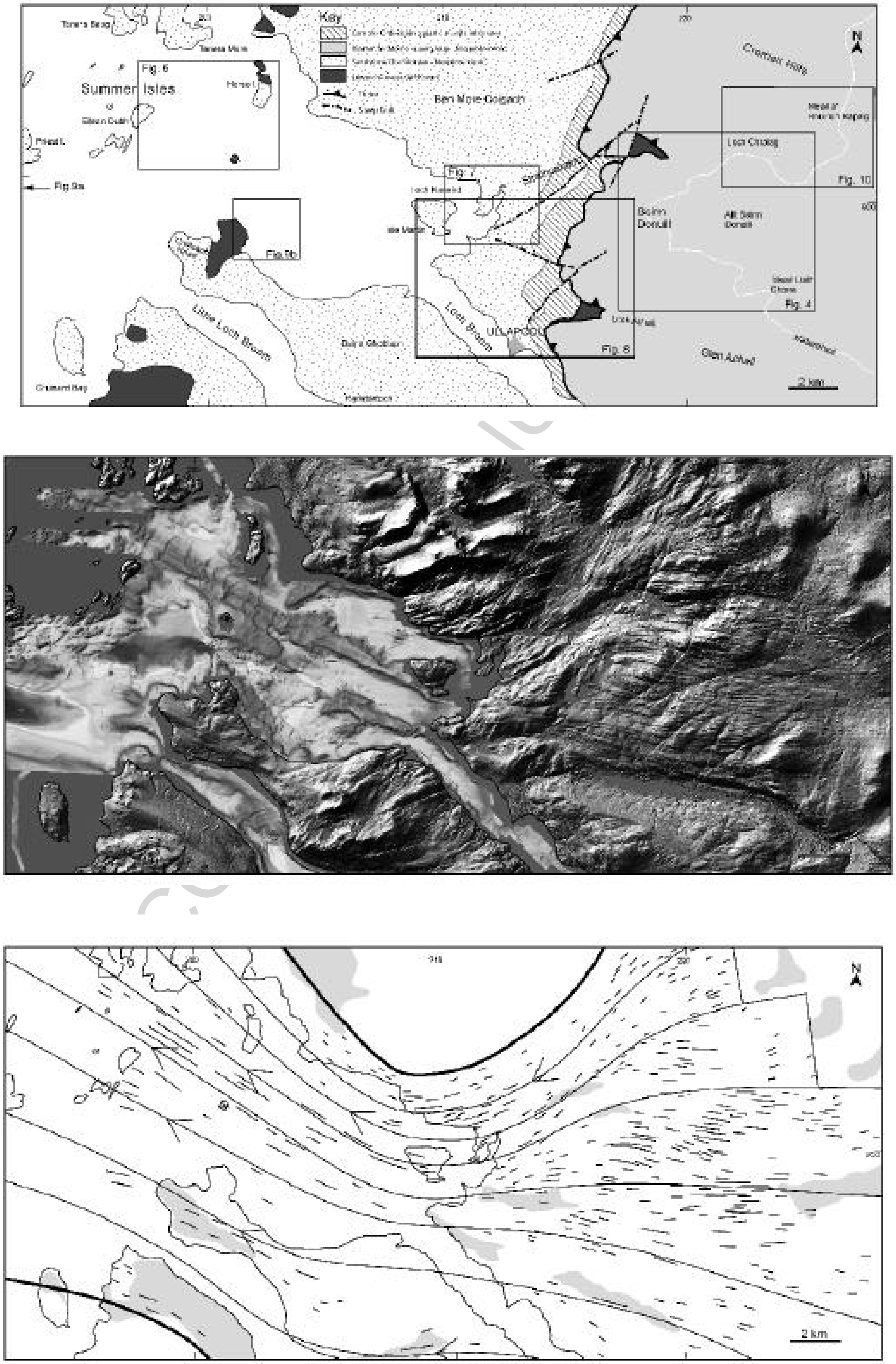
Glutton meltwater channel. Note the steep sides and low width:depth ratio (~4:1). (c) Sculpted, water-worn bedrock on the sides of the An Strathan meltwater channel. Flow was from left to right. (d) Small-scale half-channel (p-form) carved by glacial meltwater flowing in An Strathan channel. (e) Allt Garbh meltwater channel, 3.5 km north of Ullapool. The gorge is 30–40 m deep and only 60-80 m wide. (f) Glac Mhor meltwater channel cut in quartzite escarpment, Ullapool.

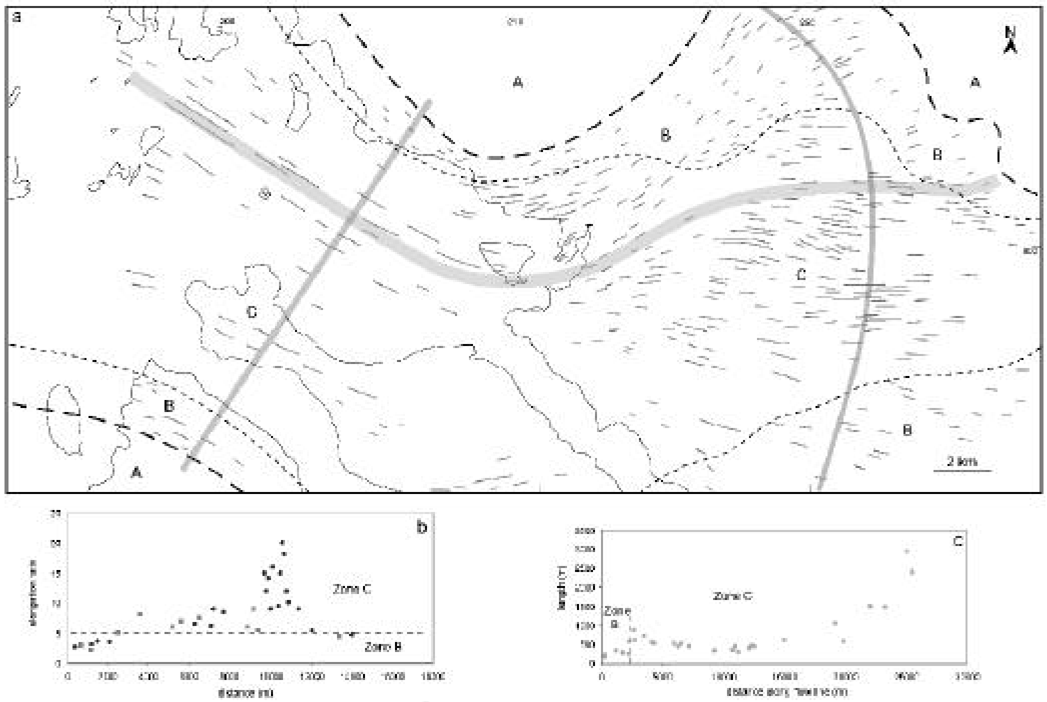
Figure 9: Multibeam swath imagery of large meltwater channels on the seabed in the vicinity of the Summer Isles. (a) off Cailleach Head. (b) ~1 km west of Priest Island. Note the up-and-down long profiles and deep narrow cross-profiles of both channels.

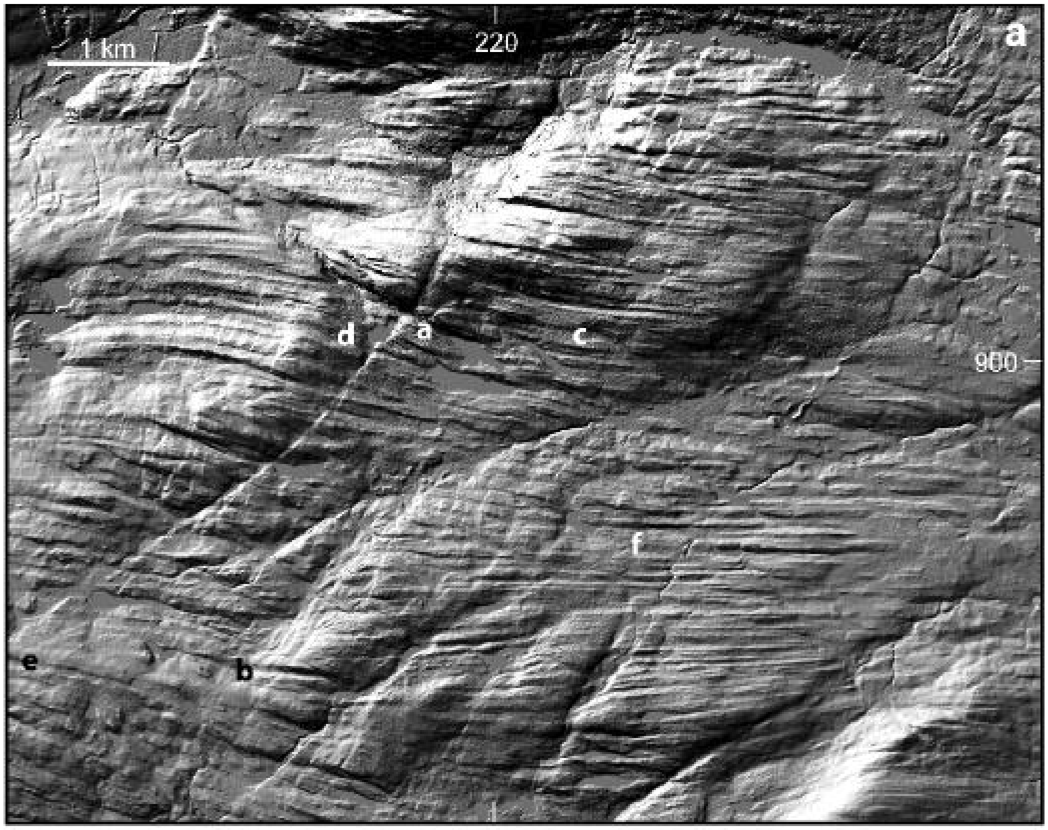
Figure 10: (a) NEXTMap image and (b) geomorphological map of bedform distribution and landform zones at the northeast margin of the flow set, adjacent to the Cromalt Hills. A = zone of no glacial streamlining; B = subtle streamlined forms; C = zone of strong glacial streamlining. RM = ribbed moraines.

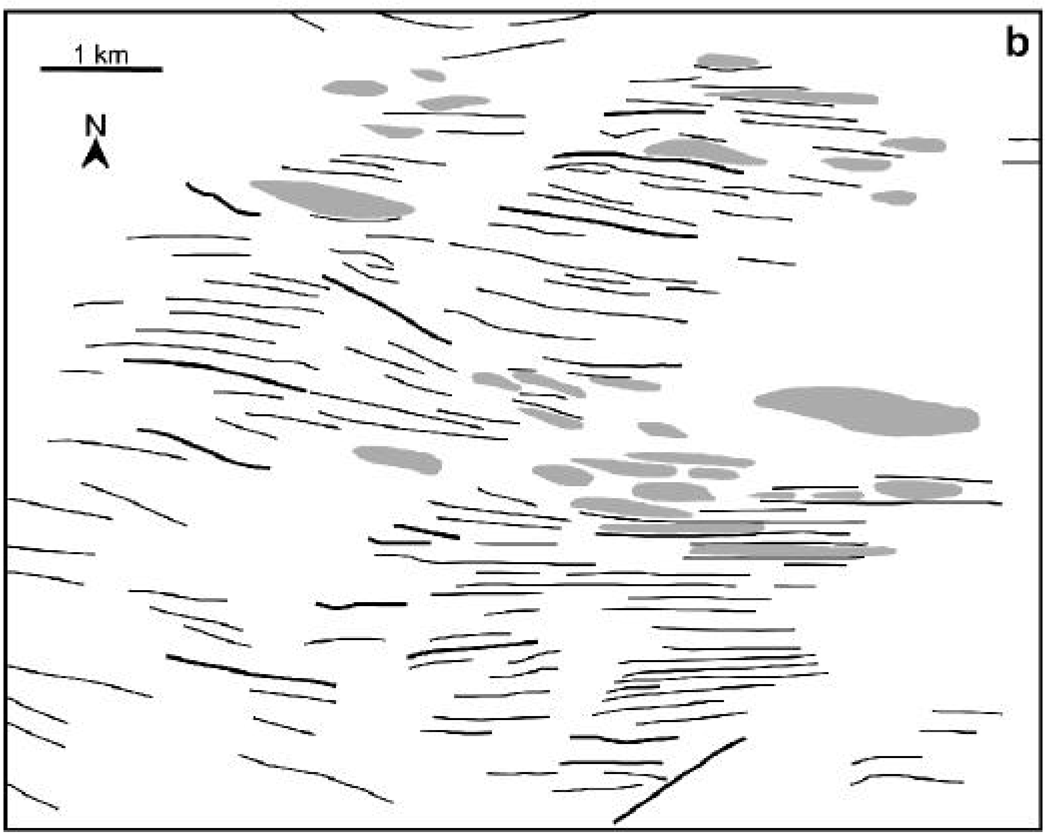
Figure 11: Diagram showing idealized bedform continuum in bedrock, along a flow line across a palaeo-ice stream onset zone. The diagram illustrates the relationship between the degree of landscape streamlining (Zones A–C) and ice-sheet flow and basal thermal regime. The upper half of the diagram relates to bedform morphology; the lower half relates to bedform density, in a down-ice direction. This rapid spatial bedform continuum (10^3–10^4 m) can be used to make inferences about the basal thermal regime, ice-flow velocity and subglacial erosive power of palaeo-ice sheets.

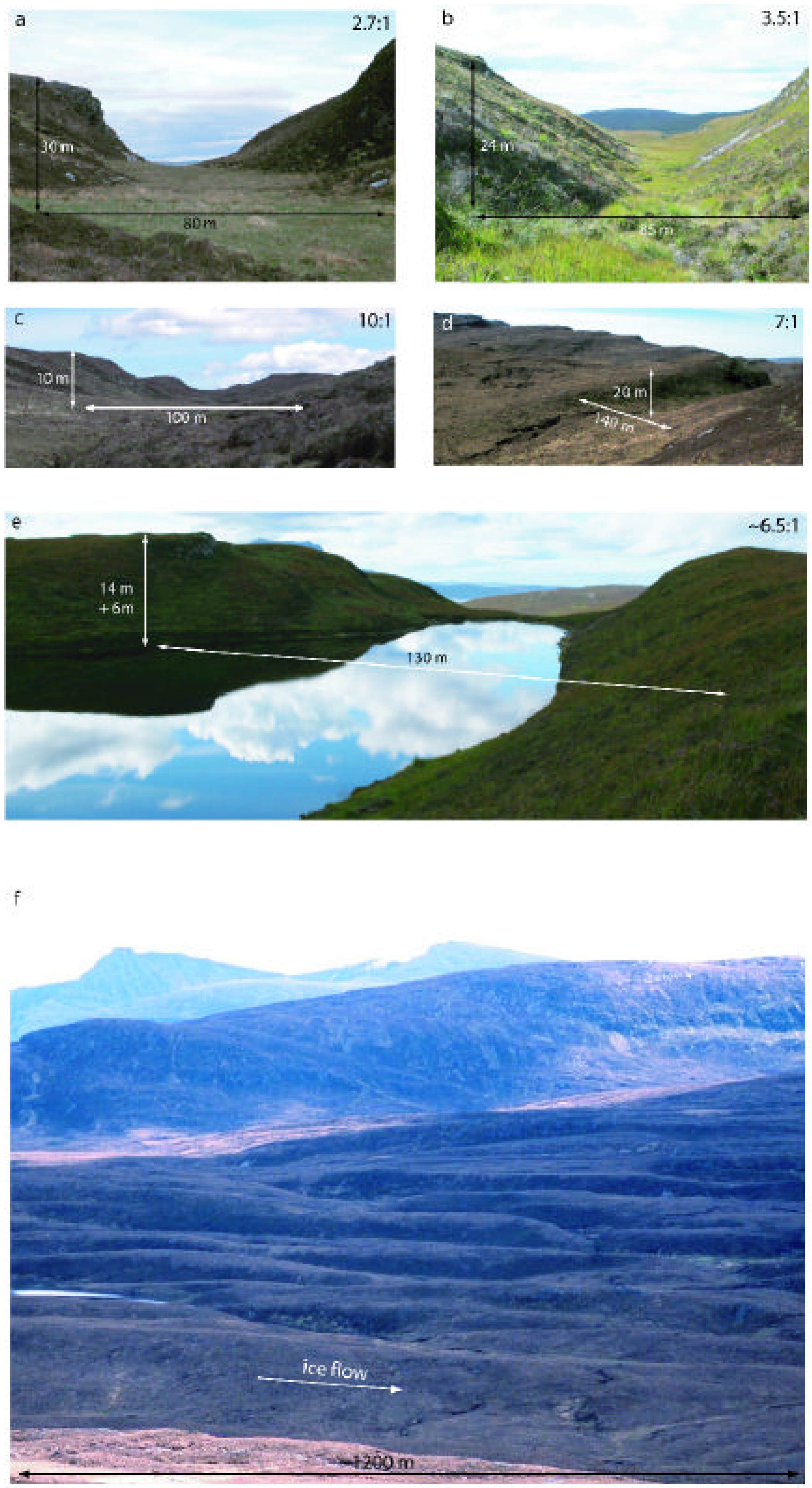

8
6°W
59°N
58
57
Sula Sgeir Fan
Sula Sgeir
LGM
?
ice shelf?
600
350
300
250
200
150
100
50
Hebrides Shelf
Lewis
St Kilda
UK
Fig. 2
AT
BD
40 km
Scotland

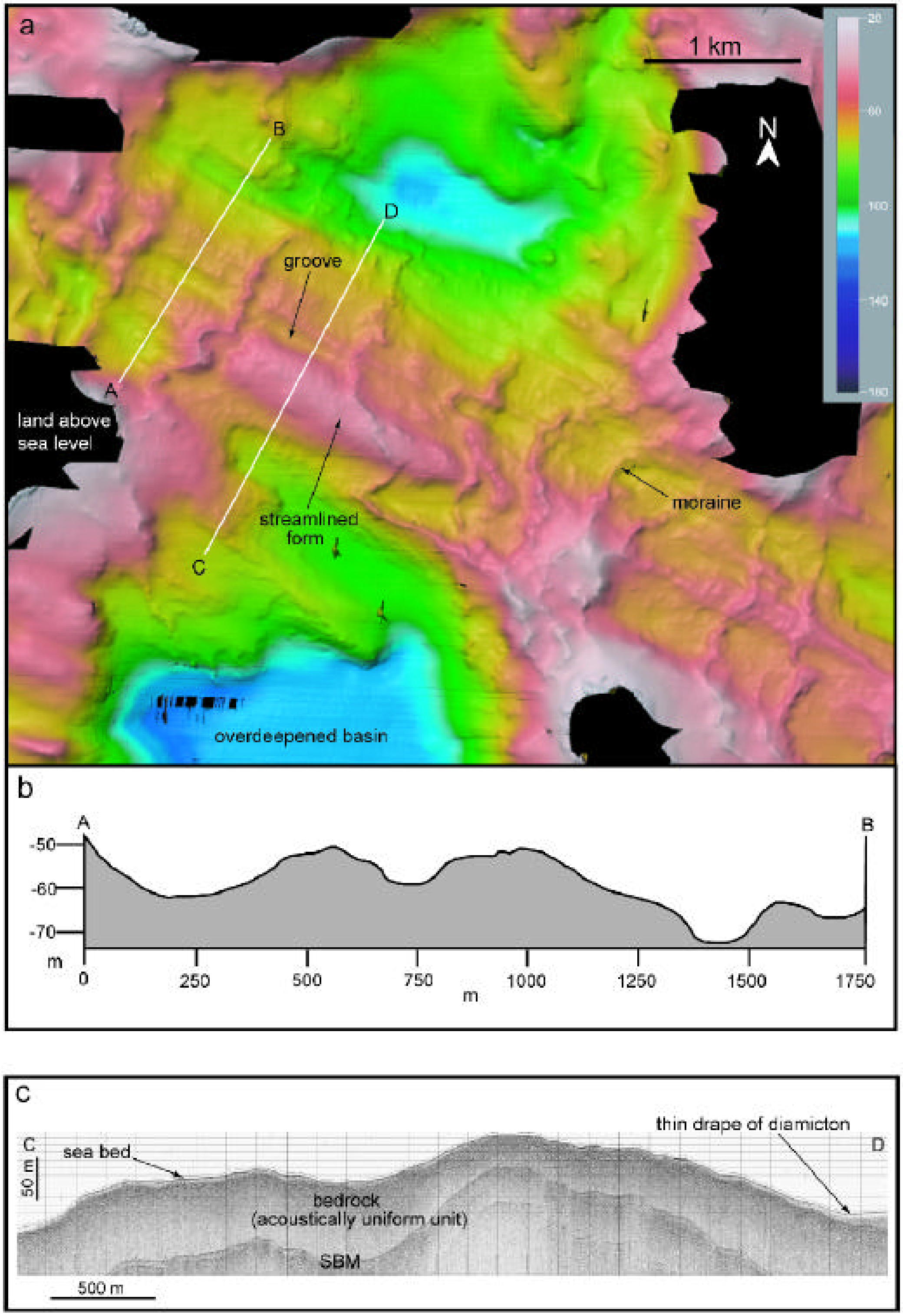

Key
Summer Isles
Fig. 6
Fig. 7
Fig. 8
Fig. 4
Fig. 10
Ben More Coigach
Cromalt Hills
Loch Achall
Beinn Donuill
Little Loch Broom
Loch Broom
ULLAPOOL
Glen Achall
N
2 km

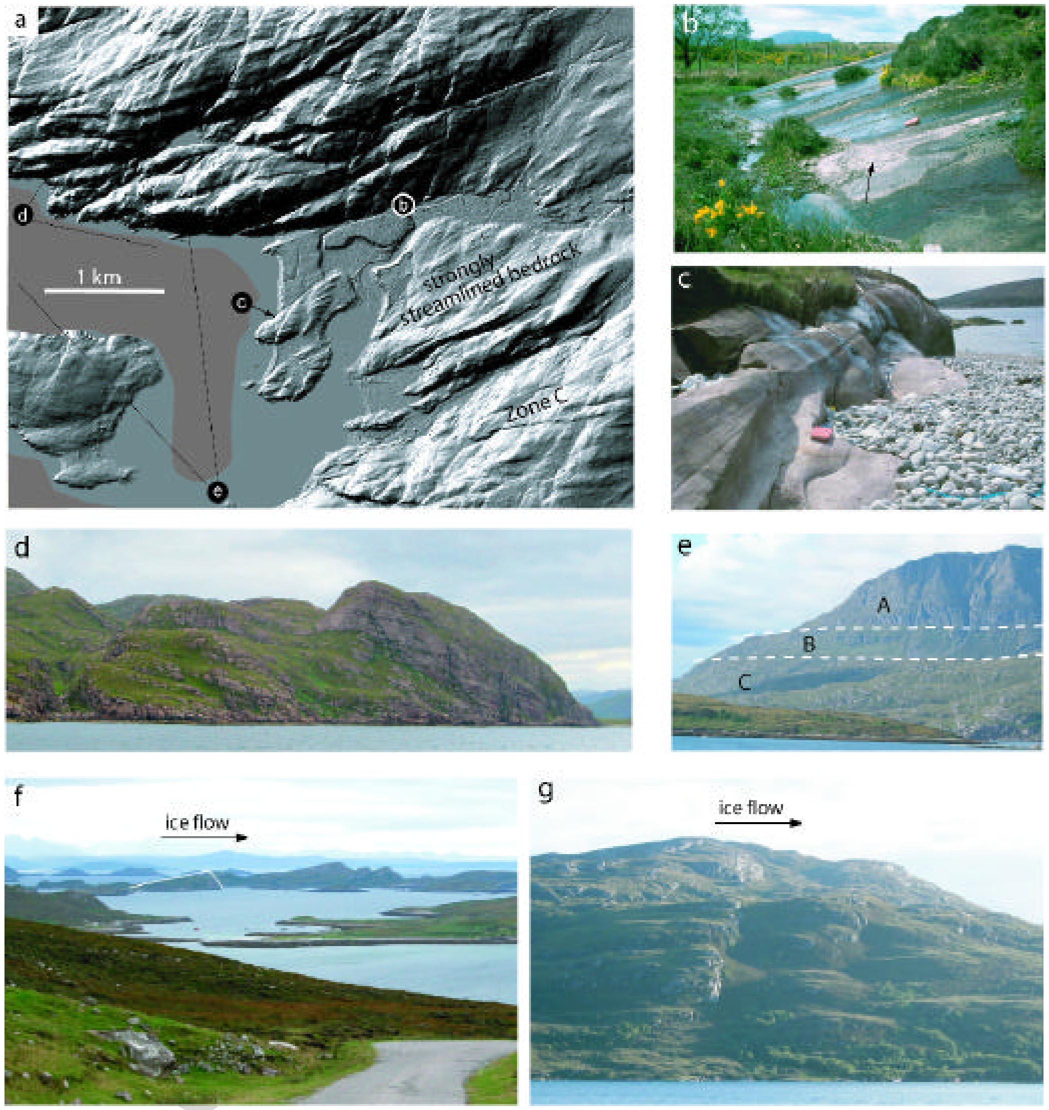

a
N
A
B
C
2 km
b
Zone C
Zone B
distance (m)
c
Zone C
Zone B

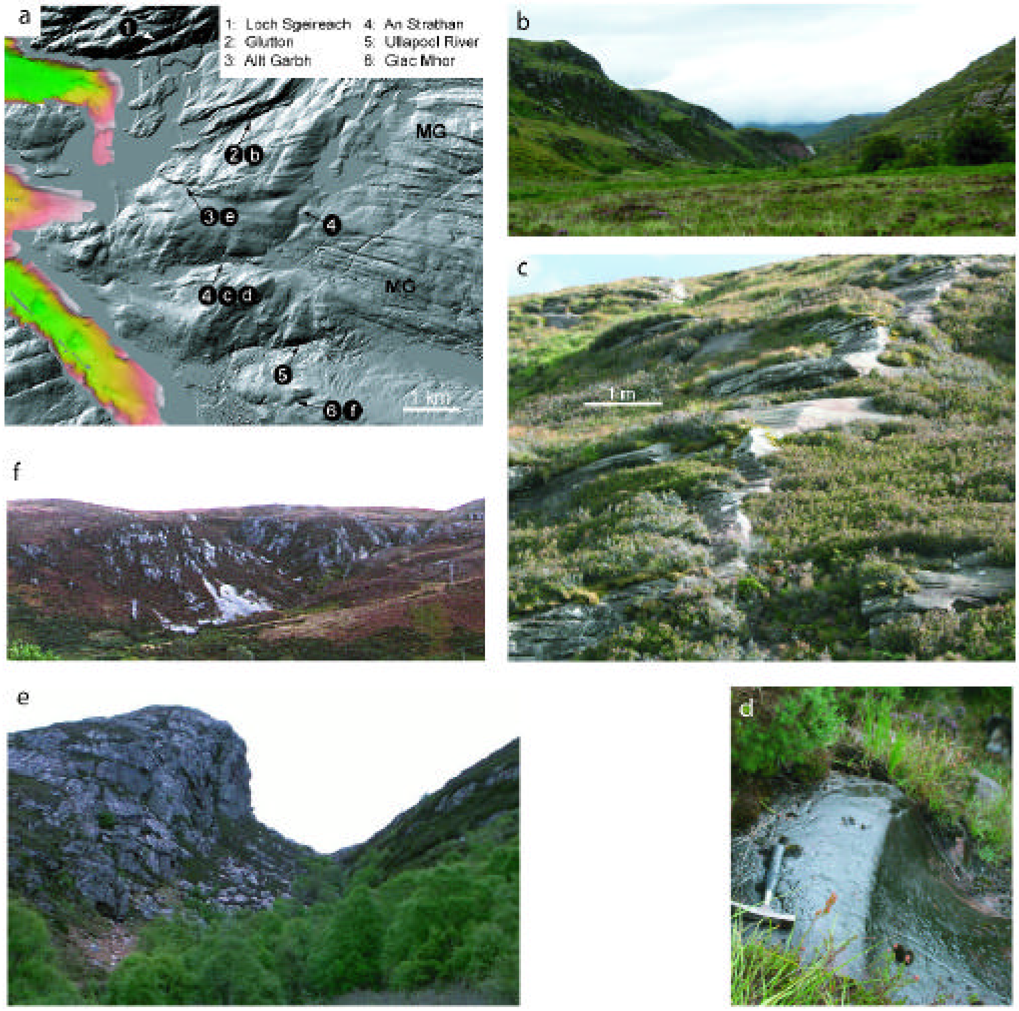

1 km
220
a
d
a
c
900
f
e
b

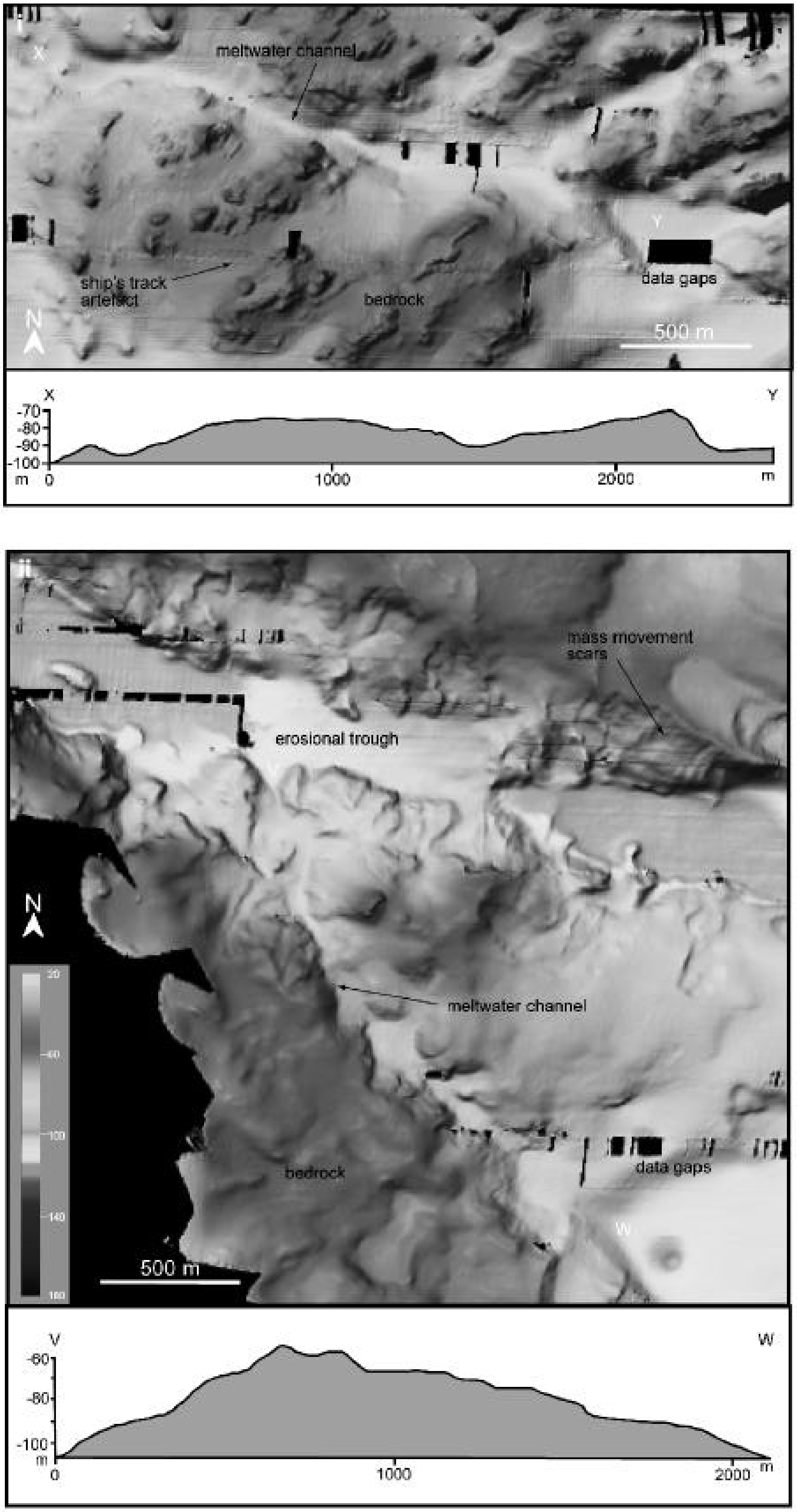

1 km
N
b

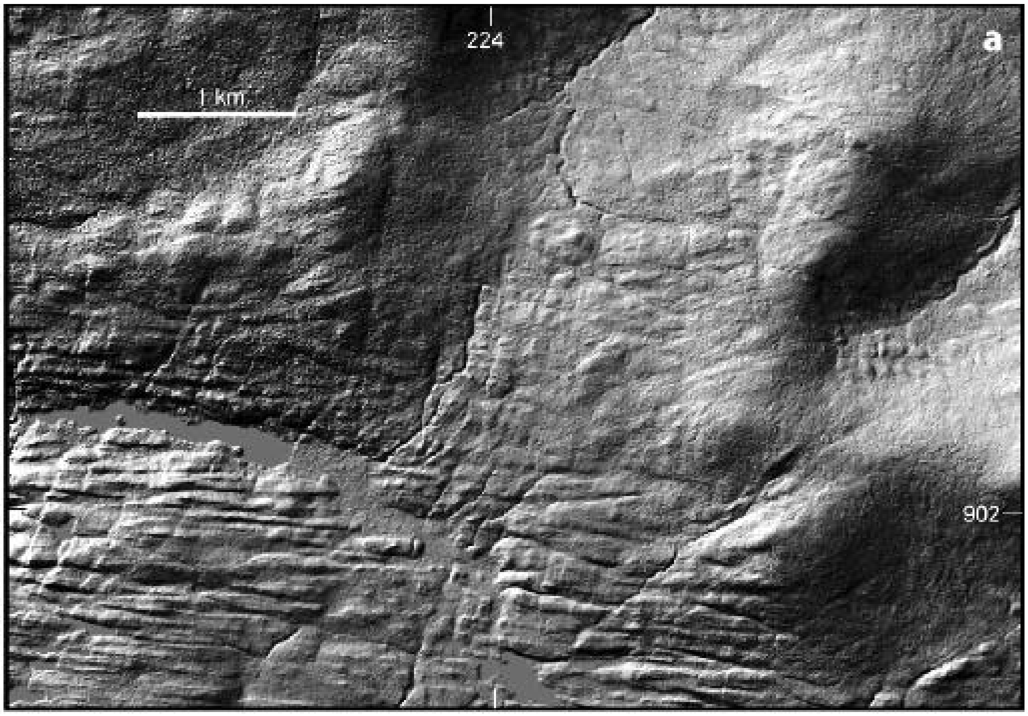

a
2.7:1
30 m
80 m
b
3.5:1
24 m
85 m
c
10:1
10 m
100 m
d
7:1
20 m
140 m
e
~6.5:1
14 m
+6m
130 m
f
ice flow
~1200 m

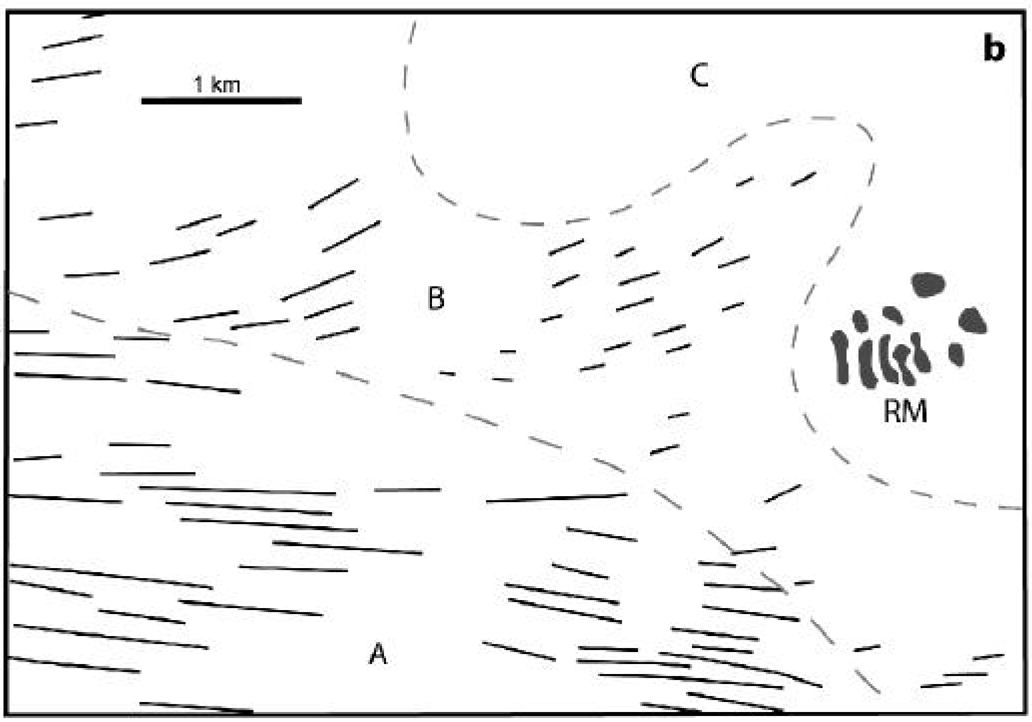

a
1 km
N
B
D
groove
A
land above
sea level
streamlined
form
moraine
C
overdeepened basin
b
A
B
-50
-60
-70
m
0
250
500
750
1000
1250
1500
1750
m
c
thin drape of diamicton
C
D
sea bed
50 m
bedrock
(acoustically uniform unit)
SBM
500 m

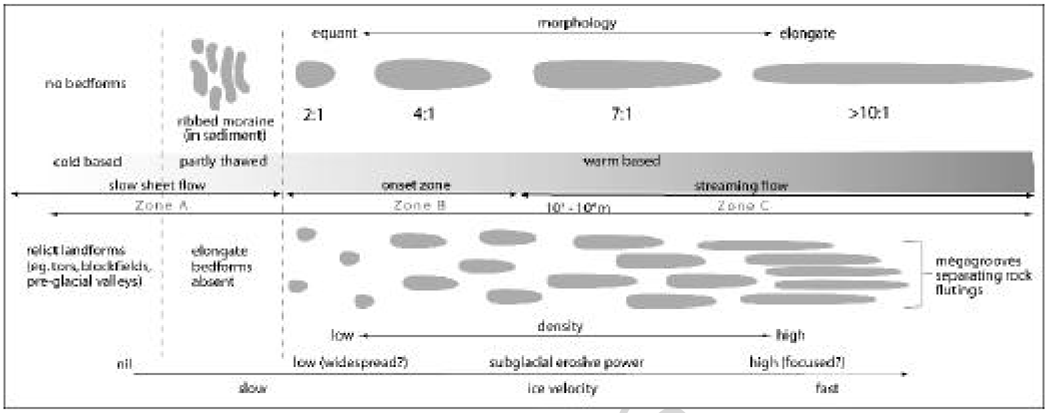

a
b
c
d
e
1 km
strongly streamlined bedrock
Zone C
A
B
C
f
g
ice flow
ice flow


a
1: Loch Sgeireach
2: Glutton
3: Allt Garbh
4: An Strathan
5: Ullapool River
6: Glac Mhor
MG
MG
1 km
b
c
1 m
d
e
f


i
X
meltwater channel
Y
ship's track artefact
bedrock
data gaps
N
500 m
X
Y
-70
-80
-90
-100
m
0
1000
2000
m
ii
mass movement scars
erosional trough
V
N
meltwater channel
bedrock
data gaps
W
500 m
V
W
-60
-80
-100
m
0
1000
2000
m


224
a
1 km
902


b
1 km
C
B
RM
A


morphology
equant
elongate
no bedforms
ribbed moraine
(in sediment)
2:1
4:1
7:1
>10:1
cold based
partly thawed
warm based
slow sheet flow
onset zone
streaming flow
Zone A
Zone B
Zone C
relict landforms
(eg. tors, blockfields,
pre-glacial valleys)
elongate
bedforms
absent
megagrooves
separating rock
flutings
low
density
high
nil
low (widespread?)
subglacial erosive power
high (focused?)
slow
ice velocity
fast