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Streamlined hard beds formed by palaeo-ice streams: A review

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ABSTRACT

Fast-flowing ice streams occur within modern ice sheets and also operated in Pleistocene ice sheets. The reconstruction of palaeo-ice streams normally relies on the mapping of mega-scale glacial lineations (MSGLs) and drumlins composed of soft sediment, mainly till. Analysis of new satellite imagery and digital terrain models, demonstrates the presence of large fields of kilometre-scale glacial lineations comprising rock drumlins, megagrooves and megaridges. In this paper we describe and analyse a number of such 'hard-bed' landform systems from the former Laurentide and British–Irish ice sheets, occurring in a variety of palaeo-ice stream settings. These are attributed to erosion of crystalline and sedimentary rock below fast flowing ice streams. Bedrock properties such as hardness, fracture spacing and bedding and their orientation with respect to ice flow have a profound effect on the occurrence and character of elongate rock bedforms. Elongate streamlined forms on hard crystalline rock, as on the Canadian Shield, only form under special circumstances; in contrast, sedimentary strata are highly susceptible to form streamlined hard beds, specifically if bedrock strike is parallel to ice flow. Large-scale elongate rock bedforms are erosional in origin, formed by preferentially focused abrasion or by lateral plucking, depending on bedrock type. Many palaeo-ice stream footprints previously mapped in the Laurentide Ice Sheet on the basis of soft-bed bedforms are shown to be significantly larger, extending up-ice across sedimentary strata and onto Precambrian crystalline rocks. Hard-bed streamlined forms further show that ice streaming does not necessitate a deformable bed, but can equally occur on smooth hard beds.

1. Introduction and scope

Ice streams have flow velocities many times greater than surrounding areas of sluggish or intermediate-velocity ice; they form the arteries of ice sheets and are crucial for regulating the flow dynamics of ice masses (e.g., Bentley, 1987; Joughin et al., 2001; Bennett, 2003; Rignot et al., 2011; Stokes et al., 2015). In modern ice sheets, ice streams can be mapped using direct satellite observations of surface ice velocities (e.g., Joughin et al., 2010; Rignot et al., 2011), whereas palaeo-ice streams in Pleistocene ice sheets can be reconstructed by mapping out their geomorphological footprints (Figs. 1, 2), consisting primarily of discrete flow sets of elongate bedforms such as mega-scale glacial lineations (MSGLs) (e.g., Clark, 1994; Patterson, 1997; Stokes and Clark, 2001, 2002, 2003; Everest et al., 2005; Golledge and Stoker, 2006; Hughes et al., 2014; Spagnolo et al., 2014). Within the former Laurentide Ice Sheet, for example, at least 100 such palaeo-ice streams have now been recognised (Margold et al., 2015).

Generally, MSGLs are implicitly or explicitly assumed to comprise unlithified, soft sediment (principally till) that has been modified subglacially into very long drumlins and megaridges, although the exact mechanism by which this happens (erosion, accretion, deformation or a combination of these) is still uncertain (e.g., Boyce and Eyles, 1991; Clark et al., 2003; Stokes et al., 2013; Spagnolo et al., 2014). However, increasing attention is being directed to elongate subglacial forms on bedrock surfaces, known as 'hard beds' (e.g., Bradwell et al., 2008a; Graham et al., 2009; Eyles and Putkinen, 2014). The geomorphological analysis of 'hard beds' is important given that large parts of the Northern Hemisphere Pleistocene ice sheets rested upon, and flowed across, hard beds composed largely of Precambrian shield rocks, flanked by Palaeozoic sedimentary strata. The same broad pattern is seen in Greenland and probably Antarctica (e.g., Goodwin, 1991; Livingstone et al., 2012). Analysis of hard-bed streamlined forms can aid in reconstructing palaeo-ice streams, assist in understanding the primary controls on ice streaming itself (see also discussions in Winsborrow et al., 2010; Livingstone et al., 2012) and has potential implications for the origin of MSGLs in general (Eyles et al., 2016).

In this paper we review selected hard-bed ice-stream landsystems, characterised by subglacially streamlined bedrock surfaces with abundant elongate rock bedforms. The primary aims of this paper are (i) to demonstrate that elongate rock bedforms are more common than previously thought, (ii) to show they occur in different palaeo-ice stream

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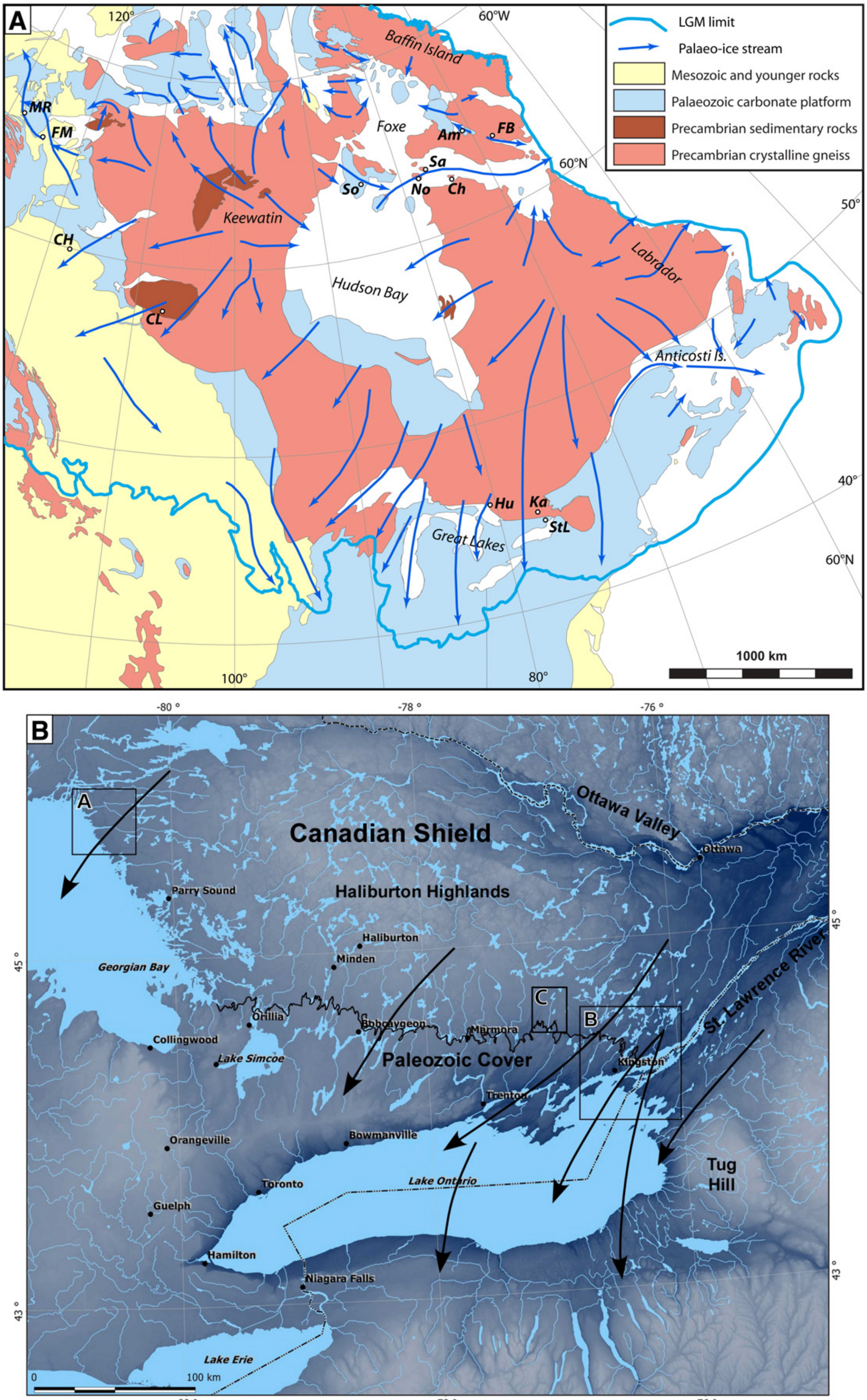


Fig. 1. (A) Laurentide Ice Sheet with reported palaeo-ice streams (schematic), simplified bedrock geology, extent at Last Glacial Maximum (LGM). Indicated study areas: Am = Lake Amadjuak; Ch = Charles Island; CH = Cameron Hills; CL = Cree Lake; FB = Frobisher Bay; FM = Franklin Mountains; Hu = Lake Huron; Ka = Kaladar; MR = Mackenzie River; No = Nottingham Island; Sa = Salisbury Island; So = Southampton Island; StL = St. Lawrence Platform. (B) Location map for streamlined bedrock in Ontario. Black zig-zag line is Shield–Platform boundary. Box A: locality of Lake Huron—Georgian Bay grooves (Section 5.1); box B: outline of Fig. 4; box C: outline of Fig. 5.

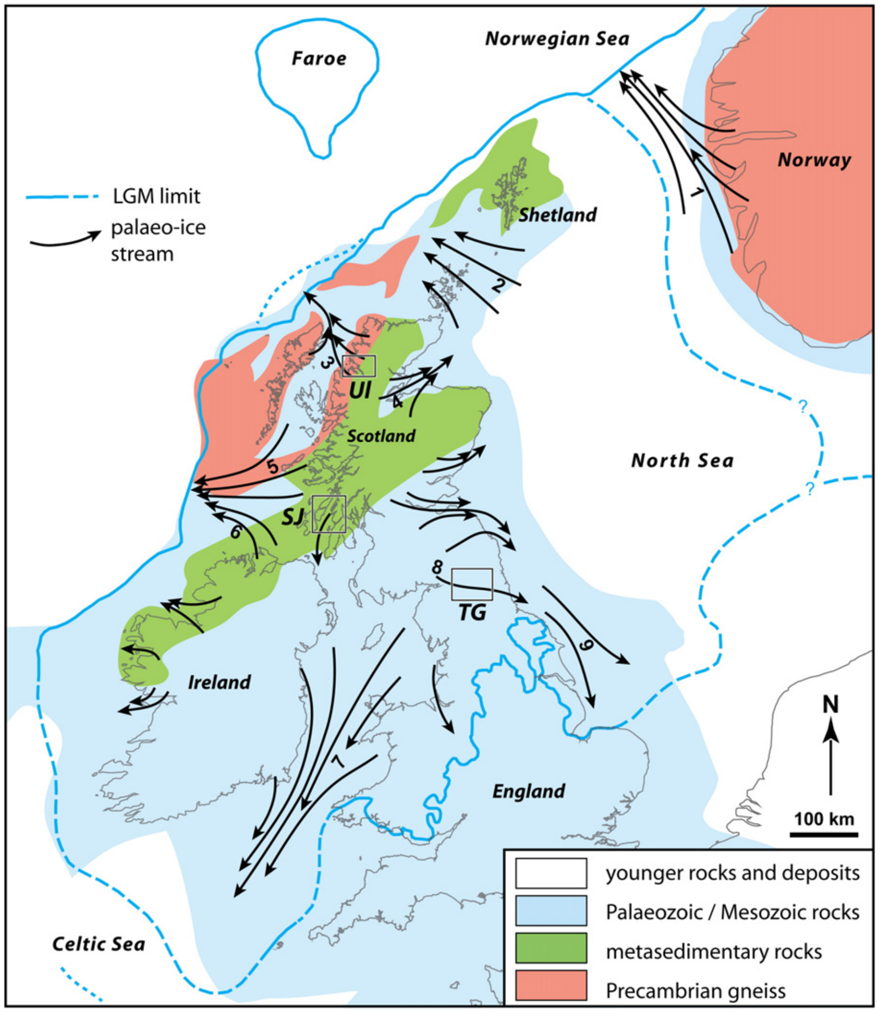


Fig. 2. British–Irish Ice Sheet with reported palaeo-ice streams, extent at Last Glacial Maximum (LGM) and simplified bedrock geology. Named palaeo-ice streams: 1. Norwegian Channel; 2. Orkney; 3. Minch; 4. Moray Firth; 5. Hebrides, 6. North Channel—Malin Shelf; 7. Irish Sea; 8. Tyne Gap; 9. North Sea lobe; after Everest et al. (2005); Bradwell et al. (2007, 2008b); Scourse et al. (2009); Livingstone et al. (2010); Dunlop et al. (2010); Hughes et al. (2014). LGM limit (dashed were uncertain; dotted where possibly floating) after Bradwell et al. (2008b) and Clark et al. (2012). Locations described in this paper: *Ul* = Ullapool; *SJ* = Sound of Jura; *TG* = Tyne Gap.

settings, (iii) to document the main types of elongate rock bedforms on different bedrock types, and (iv) to determine the principal effects of bedrock lithology and structure on their occurrence and characteristics. In Section 3 we describe the study methods, datasets used and the terminology of landforms used herein. The potential role of bedrock lithology and structures is then introduced. We describe a number of key landform sites, both previously analysed and newly discovered, from the former Laurentide and British–Irish ice sheets (Figs. 1, 2). In the discussion, we assess the role of bedrock structure and the relation between hard-bed and soft-bed streamlining; we propose possible formation mechanisms and discuss the implications for ice streaming on hard beds. This review should be seen as provisional in nature given that knowledge of new areas of bedrock streamlining is expanding rapidly as more detailed terrestrial digital terrain models (DTMs) and wider coverage of offshore swath bathymetry become available.

2. Previous work on elongate bedrock landforms

Previous work has considered the processes and rates of subglacial erosion on various rock substrates (e.g., White, 1972; Gravenor, 1975; Boulton, 1979) and the occurrence of whalebacks and roches moutonnées that occur in their thousands on glaciated rock surfaces (e.g., Rastas and Seppälä, 1981; Dionne, 1984; Glasser and Warren, 1990; Evans, 1996). The first detailed descriptions of metre-scale deep 'glacial grooves' in rock are found in the magnificently illustrated monograph 'The rock scorings of the great ice invasions' of Chamberlin (1888), which conclusively demonstrated that Canadian ice had invaded present day northeastern USA. The first kilometre-scale glacially cut megagrooves were described by Smith (1948) in the Northwest Territories of Canada and by Zumberge (1954) on Isle Royale in Lake Superior, USA. Medium-scale glacially eroded rock ridges were reported by Linton (1963) from the UK, and Funder (1978) and Roberts and Long (2005) described similar features from Greenland. Lesemann and Brennand (2009) and McClenagan (2013) mapped large-scale rock drumlins from western Canada but invoked erosion by catastrophic subglacial outburst floods (see Stumpf et al., 2014, for discussion). Elongate megagrooves, megaridges and rock drumlins are now increasingly being recognised on various bedrock types (e.g., Bradwell, 2005; Bradwell et al., 2008a; Eyles, 2012; Jakobsen, 2012; Eyles and Putkinen, 2014). Offshore, swath bathymetry has revealed elongate, streamlined bedrock features within the well-preserved footprints of palaeo-ice streams on the seabed off Antarctica (Graham et al., 2009; Livingstone et al., 2012), Canada (Shaw et al., 2006), Norway (Ottesen et al., 2008; Rydningen et al., 2013) and the British Isles (Bradwell and Stoker, 2015). Recently, elongate bedforms, interpreted as megagrooves in bedrock, have been imaged by radar at the base of the Greenland ice Sheet, adjacent to the Jakobshavn ice stream (Jezek et al., 2011).

3. Methods, datasets and terminology

Some sites of megagrooves and megaridges described here have been previously reported in the literature; others are described here for the first time. Most of our analyses are based upon remote sensing data, including Landsat 8 satellite imagery courtesy of US Geological Survey and NASA Shuttle Radar Topography Mission (SRTM) terrain model data (Global 1 Arc, Version 3 with 30 m resolution, after NASA JPL, 2013); and the NEXTMap (Intermap Technologies) DTM in the UK, an airborne-radar derived digital terrain data with a vertical and horizontal resolution of 1 and 5 m respectively. Offshore data sets include multibeam echosounder (swath) bathymetry (provided by the UK Maritime and Coastguard Agency) and British Geological Survey (BGS). The full extent of the former bed of the Laurentide Ice Sheet was initially surveyed using Google Earth imagery. Flow sets of megalineations were mapped in detail in ArcMap (ESRI) employing 30 m resolution multispectral Landsat Global Land Survey data. Simultaneously, 1:50,000 Canadian Digital Elevation Data (CDED) tiles from GeoBase were stitched together to create a uniform Mosaic Raster Dataset in ArcMap.

Fieldwork, with locally detailed geomorphological and geological observations, was carried out at around Lake Huron, on the St. Lawrence Platform and near Kaladar in Ontario (Canada) and near Ullapool (Scotland). For the other sites, various geological maps, the geological literature, and in some cases Google Maps Street View images were used to establish the geology of megalineated surfaces.

Glacial landform terminology is potentially contentious and will evolve as more and different examples of elongate bedrock landforms are discovered. The classification system used herein is simple (Table 1). For all features described below, the word 'rock' is omitted, except for *rock drumlin*, as the term 'drumlin' is commonly used for a form (largely) composed of soft sediment. If another particular feature is composed of soft sediment this will be explicitly mentioned. The separation between highly and medium elongate landforms uses the same criterion (elongation ratio of >1:10) that is widely used for separating soft-sediment drumlins from MSGLs (Stokes and Clark, 2002; Benn and Evans, 2010).

A bedrock surface comprising both megagrooves and megaridges is termed *megalineated*. If grooves and ridges alternate regularly in a continuous field, they can be regarded as some wave function, with attributes such as spacing (wavelength) and amplitude. Alternatively, grooves, ridges or rock drumlins can occur individually, with intervening flat areas in between. Ridge-and-grooves can be rounded to angular in cross-section, which has a potential bearing on formation mechanisms. Ridge-and-grooves are symmetric or asymmetric in cross section, commonly depending on rock type. Along its long axis, a groove can be straight or sinuous, although highly sinuous grooves are more likely to be formed by subglacial meltwater, as discussed in Section 10.3. Detailed quantitative morphometrics fall outside the scope of this paper, but all these attributes can potentially be quantified and analysed in a similar way as soft-sediment forms (e.g., Spagnolo et al., 2014).

4. Introduction to the role of bedrock type and structure

Primary lithological and structural properties such as rock hardness, fracture spacing, bedding and foliations have a profound effect on the character of subglacial rock bedforms (e.g., Gordon, 1981; Benn and Evans, 2010; Krabbendam and Bradwell, 2011; Krabbendam and Glasser, 2011; Hooyer et al., 2012; Lane et al., 2015) and thus also on the streamlined bedforms described here. Bedrock types are extremely variable across the beds of ancient and modern ice streams, potentially creating a complex mosaic of possible bedform types. However, at first order, a distinction can be made between nearly isotropic 'massive' rocks (typically gneisses and granitic rocks) versus strongly stratified sedimentary or metasedimentary rocks. Bedded successions may further show marked variations in properties from one bed to another (for instance a sandstone–shale–limestone sequence). Important also is the direction of bedding or layering with respect to ice flow, specifically whether bedrock strike is parallel, oblique or transverse to ice flow. If bedrock strike is transverse to ice flow it is furthermore relevant whether the rock strata dip down-ice or up-ice (e.g., Gordon, 1981; Lane et al., 2015). Some bedrock grooves are developed on a dipslope in which case the rock surface is typically very smooth and homogeneous.

At a continental scale (i.e., on the scale of large ice sheets) this lithological variation can be further simplified, potentially imparting a first-order bedrock control on ice sheet dynamics (Eyles, 2012). Thus, the central parts of the Laurentide, Fennoscandian and Greenland (but not the British–Irish) ice sheets are all characterised by shields of resistant Precambrian crystalline rocks, surrounded by less resistant, gently dipping Palaeozoic and Mesozoic sedimentary strata (e.g., Goodwin, 1991).

5. Laurentide Ice Sheet—Southern margin

In this section, examples are presented of hard-bed streamlining on the crystalline Canadian Shield, as well as on the surrounding Palaeozoic sedimentary strata. In North America, White (1972) identified what he called an 'arc of exhumation' around the margins of the Canadian Shield, characterised by several large and overdeepened lakes cut along the Shield–Platform boundary zone, where the Shield abruptly meets offlapping Cambrian–Devonian carbonate rocks. Gently-dipping, resistant limestone and dolostone strata commonly show a gentle cuesta and dip slope topography, which has been extensively modified by glacial erosion (Fig. 1). This boundary zone extends as a broad arc from the Arctic islands in the far north, to northwestern and central Canada, via the Great Lakes area into Maritime Canada. Palaeozoic strata also occur widely around Hudson Bay in the inner part of the Canadian Shield. In the Great Lakes area, the northern limit of Palaeozoic rocks has a distinct ragged 'zig-zag' planform (Fig. 1(B)), where north-facing limestone escarpments have been modified into bedrock megadrumlins (Eyles, 2012). Drumlinised outliers of Palaeozoic carbonates occur north of the boundary, part of once more extensive cover of limestone on Precambrian shield rocks and suggesting that glacial erosion played a major role in stripping Palaeozoic strata from the shield (Eyles, 2012; Eyles and Doughty, 2015). Widespread erosion of Palaeozoic carbonate surfaces is also recorded by extensive dispersal fans of carbonate-rich till from Hudson Bay carbonate platforms onto Shield rocks (Andrews and Miller, 1979; Dyke and Morris, 1988; Hicock et al., 1989; Dredge, 2000).

Table 1
Overview and explanation of terminology of elongate rock landforms used in this paper.

Feature	Description	Length	Elongation ratio
Groove	A highly elongate negative feature	<100 m	>1:10
Megagroove	A highly elongate negative feature	>100 m	>1:10
Megaridge	A positive feature, more elongate than a rock drumlin	>100 m	>1:10
Megalineation	A collective term for highly elongate positive and negative features	>100 m	>1:10
Rock drumlin	A positive streamlined feature, less elongate than a megaridge, and more gently dipping (<10° slopes) than a whaleback	n/a	<1:10
Whaleback	A positive streamlined feature, less elongate than a megaridge, and more steeply dipping (>10° slopes) than a rock drumlin	<100 m	<1:10
Megawhaleback	Like a whaleback but larger	>100 m	<1:10

5.1. Megagrooves cut in Canadian Shield gneiss, Lake Huron, Ontario

In the northern part of the Huron Basin in Ontario, Eyles (2012) recognised an extensive 'hard bed' terrain consisting of drumlins, megagrooves and megaridges on escarpments and dip slopes of Palaeozoic limestone (Fig. 1(B)). This streamlining is related to southwest-directed fast-flowing ice of the Saginaw–Huron Ice Stream (SHIS). Farther north and northeast, the upstream part of the SHIS can be extended onto the crystalline gneisses and granitic rocks of the Canadian Shield, exposed on the northern shores of Lake Huron (Georgian Bay). Our fieldwork in this area has revealed tracts of well exposed, well-developed glacial streamlining (Fig. 3). The best developed grooves occur on granulite gneiss (with granitic and other intrusive protoliths; Easton, 1992; Culshaw et al., 2004) that are relatively homogeneous compared to surrounding areas of more strongly foliated gneiss. Granulite gneiss typically underlie distinct 'peneplain' surfaces with relative relief amplitudes of less than 5 m, unlike the stronger, more undulatory relief amplitudes (>15 m) of surrounding strongly foliated gneisses. Granulite gneiss surfaces are grooved, whereas adjacent strongly foliated gneiss areas typically show whalebacks and roches moutonnées.

The grooves and megagrooves on the granulite gneiss (Fig. 3(B)) are typically 1–3 m deep, have a non-periodic wavelength of 2–10 m transverse to ice flow, and range in length from about ten to hundreds of metres. They have linear long axes and are symmetric in cross-section, with smooth and extensively striated surfaces. The abundance of striations also confirms that post-glacial modification by wave or shore-ice erosion was minor. Large (>30 cm) erratic boulders occur within many grooves (Fig. 3(B)); smaller debris has probably been removed by Holocene wave action. The regularity, surface smoothness and abundance of striations parallel to the grooves suggest an origin dominated by focussed subglacial abrasion (see Section 10.3). Shallow but long (c. 20 cm deep, 20–50 m long) grooves can be identified, independent from any bedrock structure (Fig. 3(C)), suggesting these may be incipient grooves formed by progressive enlargement of striations. Some sites suggest the importance of preferential glacial erosion along bedrock fractures oriented parallel to ice flow. Branching grooves diverge around large up-standing whalebacks which have a distinct drumlinoid form (Fig. 3(A)); some have longitudinal grooves down their centre lines recording the 'cloning' of smaller ridges from a large parent whaleback, as is typical of the transition from drumlins to megaridges cut in sediment or soft rock (Eyles et al., 2016).

The same area displays a wealth of bedforms cut into rock by subglacial meltwater. Straight megagrooves are locally associated with curvilinear 'gutters' cut by subglacial meltwaters. Various types of s-forms (sichelwannen, spindles, potholes, furrows, cavettos) have been described in detail by Kor et al. (1991). These features are curvilinear or sinuous on the metre-scale or less, and are commonly asymmetric in cross-section with locally steep or undercut margins. They are easily distinguished from the much more linear and symmetric megagrooves described here. Ongoing work suggests that glacial abrasion and meltwater erosion may have operated coevally at the base of the ice stream, as indicated by transitional or combined forms such as megagrooves with cavettos within them, or meltwater furrows that are straightened, have striae within them or were otherwise modified by glacial erosion. Overall, the Georgian Bay megagrooves are a good example of simple megagrooves in massive rocks that lack controlling bedrock heterogeneities.

5.2. Megagrooves on Palaeozoic carbonate, St. Lawrence Platform, Ontario

Much of central and eastern Ontario comprises offlapping, gently-dipping Cambro-Ordovician carbonates and sandstones of the St. Lawrence Platform (Figs. 1(B), 4(A)). On this platform, large areas are free of an appreciable glacial sediment cover and a streamlined, megalineated hard bed of escarpments and dip slopes is extensively exposed.

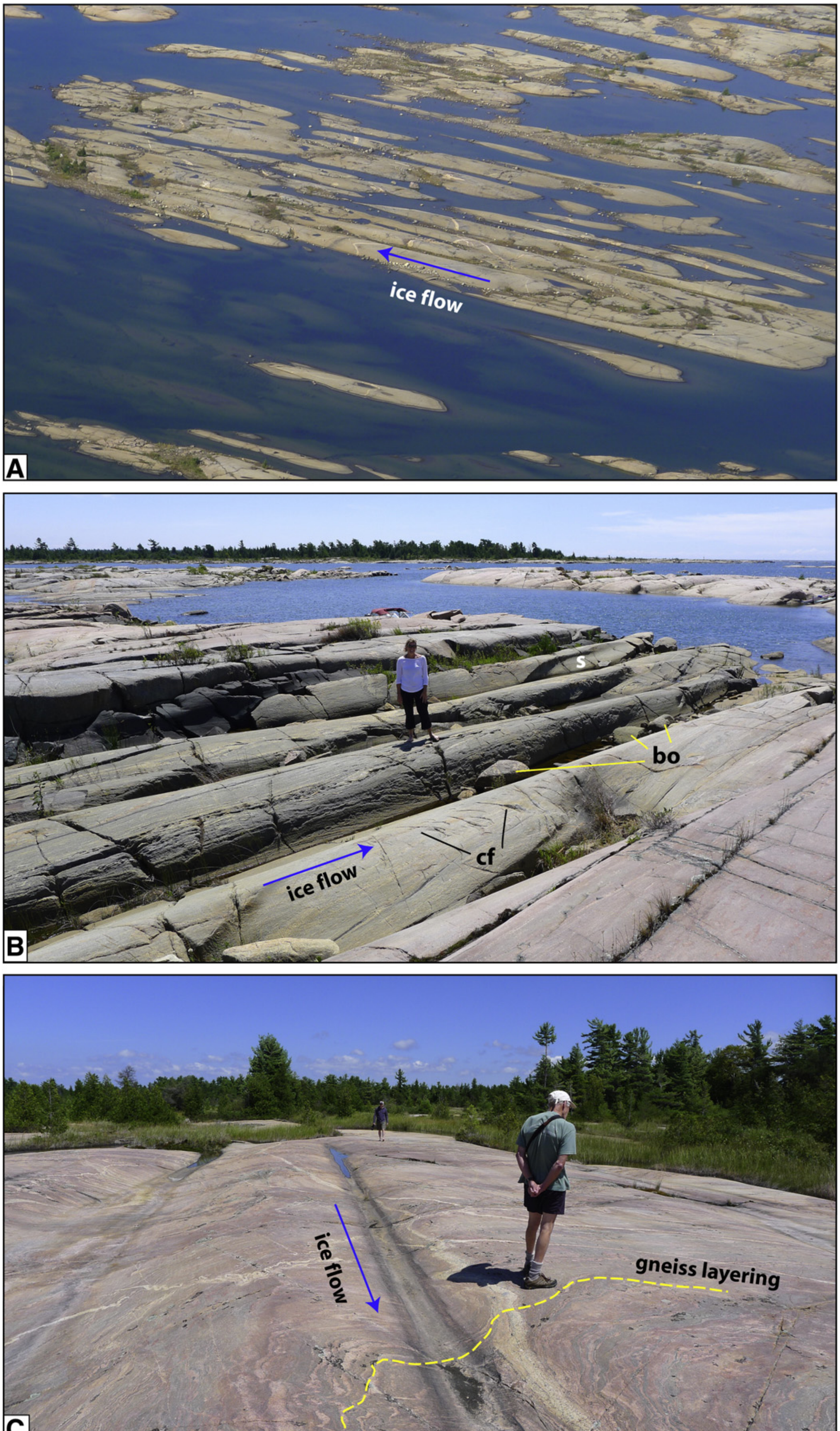
A key feature in the formation of a well-developed streamlined hard bed in Ontario is the presence of faults and fractures oriented largely parallel to ice flow. These underlie large (5–20 km long) funnel-like megagrooves ('through valleys') carved in Palaeozoic strata which focussed ice flow, and rounded off adjacent escarpment interfluves to form large finger-like rock drumlins or rock promontories (Fig. 4(A)). These rock promontories have steep, often stepped lateral margins reflecting the presence of thin shale interbeds in bedded and well-jointed limestones that show evidence of both abrasion and lateral plucking (Fig. 4(B); Section 10.3) in the manner described by Krabbendam and Bradwell (2011). This lateral erosion further widened the funnel-shaped megagrooves. The tops of rock promontories are typically very smooth limestone bedding planes (dipslopes), which are commonly striated and locally show shallow incipient grooves (Fig. 4(C)).

Very similar rock drumlin forms have been described from Manitoulin Island and Anticosti Island in the Gulf of St. Lawrence (Eyles, 2012; Eyles and Putkinen, 2014; see Fig. 1 for location). Megagrooved surfaces record streaming of basal debris around harder asperities (such as patch reefs protruding from bedding plane surfaces) or the progressive enlargement of long, deep striations. The presence of relatively high-strength basal debris (derived from the Shield; see gneiss erratic on Fig. 4(B)) aided abrasion of the softer sedimentary strata. The consistency of direction and linearity of the features demonstrate that subglacial erosion by fast ice flow across relatively homogeneous, gently dipping rock surfaces was a major factor in the formation of the elongate rock bedforms of the St. Lawrence Platform.

5.3. Megagrooves on metasedimentary gneiss, Kaladar, Ontario

Well-developed megagrooves on the Canadian Shield near the community of Kaladar in eastern Ontario (Fig. 5) provide an example of the contrasting geomorphic response arising from glacial erosion of diverse highly anisotropic (strongly layered) metasedimentary gneisses versus more isotropic granulite gneisses of the Huron Basin, described in Section 5.1. The Kaladar area was affected by the Ontario Ice Stream which flowed southwest from the Shield onto the St. Lawrence Platform (Section 5.2; Eyles and Doughty, 2015). The Kaladar megagroove field is about 100 km^2 in area and occurs in a strongly layered succession of marbles, calc-silicates, calcareous schist, psammitic and pelitic gneisses and schists, as well as harder mafic (metavolcanic) gneisses. These are part of the Mesoproterozoic Flinton Group, deformed and metamorphosed during the c. 1 Ga Grenville Orogeny (Easton, 1992). Some schistose and calcareous lithologies show local evidence of deep weathering in the form of regolith which has survived glacial stripping. The Flinton Group is bounded by more 'massive', isotropic granite and tonalite bodies (Fig. 5(A)). In contrast to these igneous rocks, the Flinton Group shows pronounced, layered differences in bedrock hardness and joint spacing. As a consequence, selective glacial erosion along the strike of weaker layers (typically marbles and schists) has created a distinct topographic grain where megagrooves follow the strike of the weaker units. In essence, glacial erosion has accentuated the pre-existing bedrock layering.

Fig. 3. Grooves cut by the Saginaw–Huron Ice Stream in granulite gneisses, Georgian Bay, north shore of Lake Huron, Ontario (location *Hu* on Fig. 1(A)). (A) Low level oblique air-photographs of megalineated bedrock near Key Harbour south of the mouth of the French River; blue flow arrow is about 500 m long, (45°51′11″N; 80°43′29″W). (B) Grooves in granulite gneiss at Painted Rocks, Georgian Bay (45°38′N, 80°35′W). Note boulders within grooves (bo) and crescentic fractures (cf) and possible s-from (s). View to south. (C) Shallow incipient grooves at Painted Rocks (45°38′N, 80°35′W). Groove developed independent from folded gneissosity (highlighted with yellow dashed line). View to NNE. All photos: Nick Eyles.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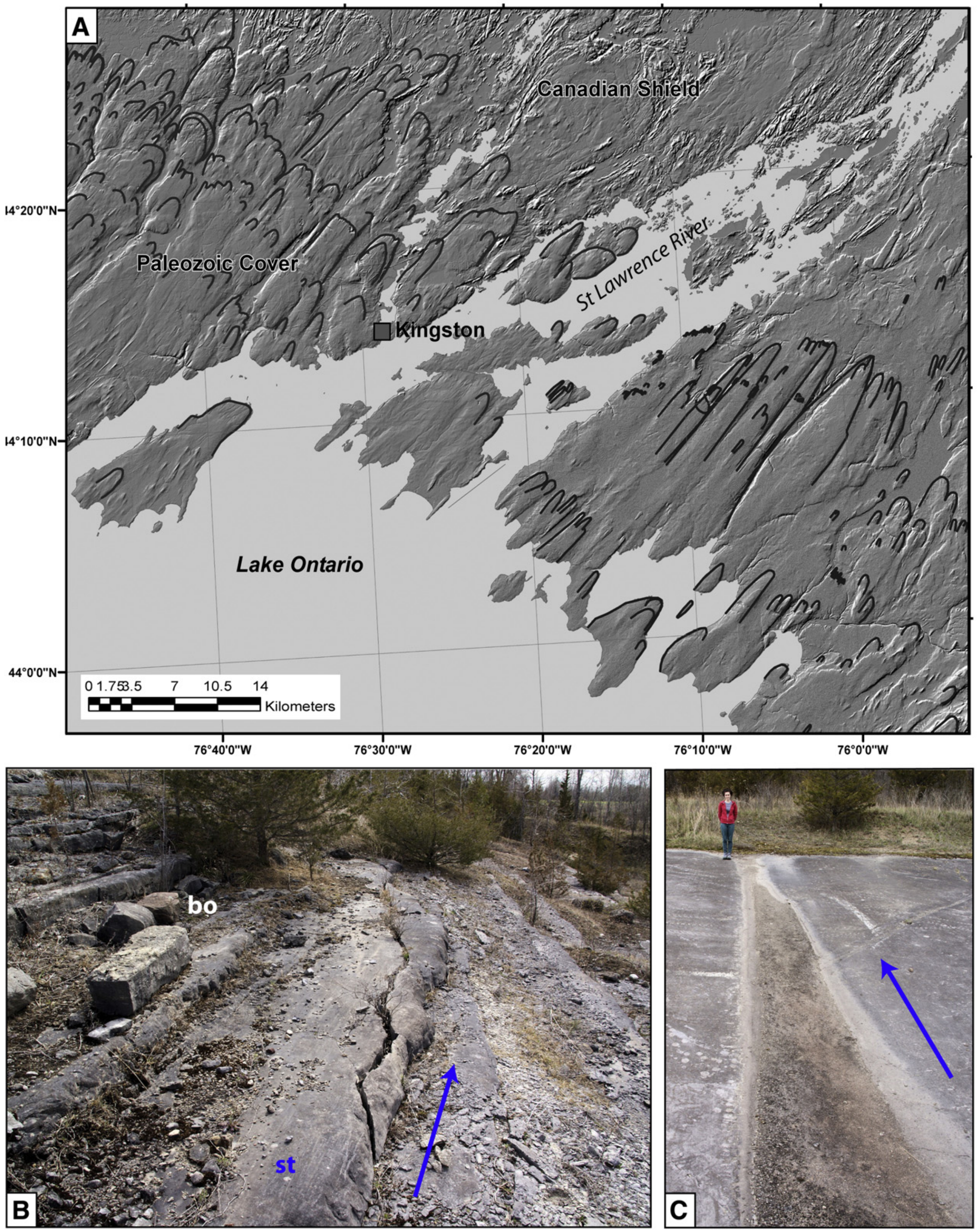

Fig. 4. (A) Prominent mega-rock drumlins separated by funnel-shaped through valleys on Palaeozoic carbonate rocks of the St. Lawrence Platform, resting on Canadian Shield in eastern Ontario (location *StL* on Fig. 1(A)). Elongation of rock drumlins increases towards the St. Lawrence River possibly reflecting faster ice flow along valley axis. DTM: NASA-SRTM. (NASA JPL, 2013)(B) Stepped lateral edge of 'through valley' megagroove. Rounded limestone surfaces with striae (st) suggest abrasion; note friable nature of thin bedded limestone and shale to right. Erratic of gneiss present (bo); Wilton Creek, 22 km west of Kingston (44°17′9″N, 76°46′25″W). (C) Incipient groove on smooth limestone bedding plane; 16 km west of Kingston (44°17′N, 76°41′W).

The megagrooves near Kaladar are much larger than those at Georgian Bay (Section 5.1), being tens of kilometres long, typically 10–30 m deep. Megagroove spacing ranges from 0.3 to 2 km. On the DTM, grooves are sinuous on a 10-kilometre scale and follow bedrock layering (Fig. 5(A), (B)). The cross-sectional shape of the grooves remains undetermined, as most grooves are partially filled with lakes or postglacial sediment. It is unlikely that flow of Laurentide ice was exactly parallel to the Kaladar grooves in all places at all times; instead it is likely that the Kaladar grooves formed parallel to pre-existing bedrock structure, rather than exactly parallel to ice flow. The relatively high

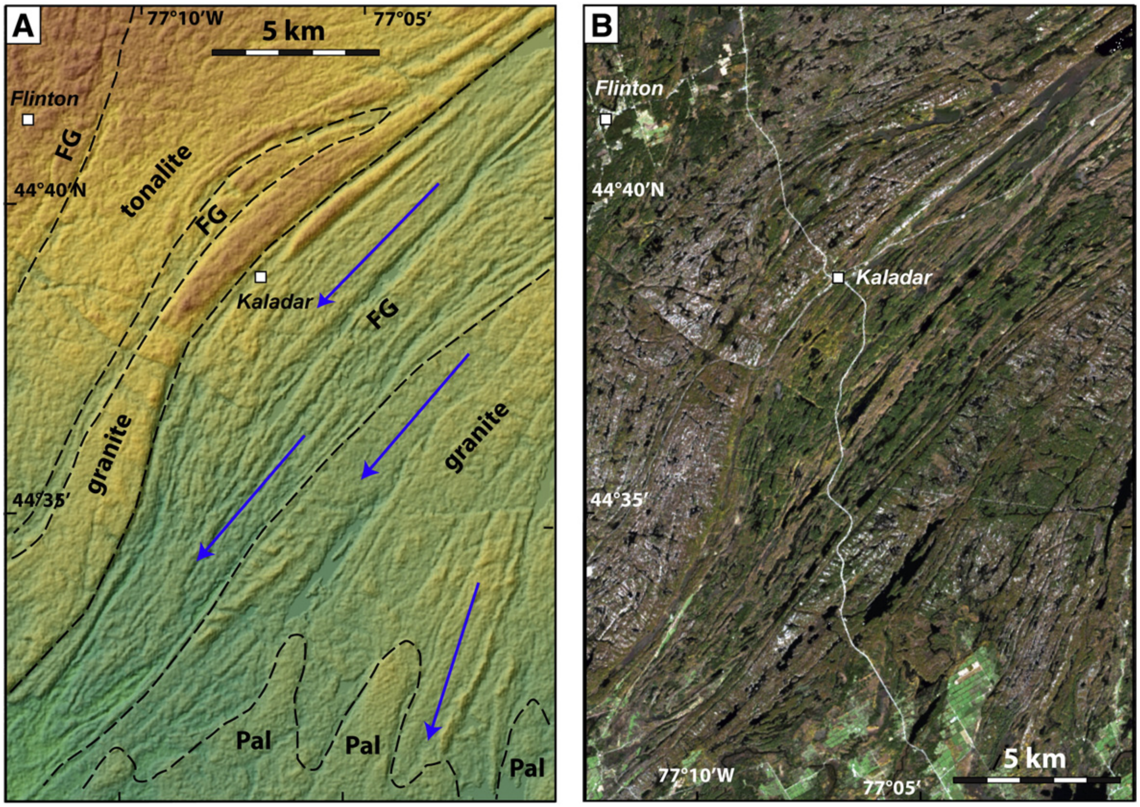

Fig. 5. Megalineated field near Kaladar, Canadian Shield, eastern Ontario (location *Ka* on Fig. 1(A)). (A) DTM (NASA—SRTM after NASA JPL, 2013) showing megagrooves developed in the metasedimentary Flinton Group (FG). High standing granite and tonalite areas do not show grooving. Edge of Palaeozoic carbonate strata (Pal) of the St. Lawrence Platform is shown in the south. Geological boundaries simplified after Easton (1992, p. 843). (B) Landsat image showing same area, showing grooves and ridges in higher resolution. Note difference between highly elongate lakes within outcrop of Flinton Group, and low elongation lakes in tonalite. Pale, poorly vegetated areas are underlain by granite and tonalite; cultivated fields are underlain by Palaeozoic carbonate rocks. Landsat imagery courtesy of US Geological Survey.

standing tonalite and granite areas, in contrast, do not show grooving, but instead comprise irregularly spaced whalebacks.

In summary, the Kaladar megagrooves are lithologically controlled and have been selectively excavated along the regionally sinuous strike of softer and more fractured rocks, and are very different from the straight grooves at Lake Huron that entirely ignore bedrock structure. The Kaladar megagrooves lie directly up-ice from the megagrooves and drumlins on the St. Lawrence Platform, formed by the Ontario Ice Stream. We suggest that the trace of the Ontario Ice Stream, or at least its onset zone, can thus be extended far onto the Canadian Shield (cf., Margold et al., 2015).

6. Laurentide Ice Sheet: Hudson Strait/Baffin Island sector

The Arctic Platform is a formerly continuous cover of thick Palaeozoic strata (e.g., Derby et al., 2012) that now comprises carbonate lowlands separated by prominent linear bulges (arches) of exposed Canadian Shield (Fig. 1(A)). The remnants of the Palaeozoic strata extend as an arcuate belt from Great Slave Lake in the far northwest, eastwards across the Canadian Arctic archipelago to Baffin Island and Foxe Basin (Dawes and Christie, 1991; Trettin, 1991). In northern Hudson Bay, Palaeozoic strata are exposed across the western half of Southampton Island and nearby Coats and Mansel islands.

The Hudson Strait Ice Stream has long been recognised as an important ice stream draining a significant portion of the Laurentide Ice Sheet, and responsible for the transport of material deposited as ice-rafted debris in Heinrich layers in Atlantic Ocean sediment cores (e.g., Andrews and Maclean, 2003). The primary source area for detrital carbonate found in these Heinrich Layers is thought to be the Palaeozoic limestone and oil shale outcrops around Hudson Bay (Hodell and Curtis, 2008; Naafs et al., 2011). Significant bedrock erosion must have occurred to produce this detritus. Up until now, the onshore geomorphological evidence of the Hudson Strait Ice Stream, based on soft-sediment landforms, has been regarded as 'scarce' (De Angelis and Kleman, 2007; Margold et al., 2015; Stokes et al., 2015).

6.1. Megagrooves on a carbonate platform, Baffin Island

On southern Baffin Island, a large expanse of glacially scoured, flat-lying Palaeozoic limestone largely devoid of glacial sediment occurs in a wide, fault-bounded trough near Amadjuak Lake (Fig. 6). Carbonates lie in faulted contact with Archaean basement to the south but overlie basement rocks farther north. Exceptionally well-developed megagrooves and megaridges occur south of Amadjuak Lake interspersed with rock drumlins (Fig. 6). The megagrooves are 2–8 km long, with a lateral spacing of c. 250 m. A number of elongate lakes partially occupy megagrooves. Several intervening megaridges extend as narrow, 1–3 km long peninsulas into Lake Amadjuak. This striking geomorphic surface was identified as an onset zone of a palaeo-ice stream, with ice flowing northwest into Foxe Basin during deglaciation (De Angelis and Kleman, 2007, 2008). However, given the overall south-eastwards ice flow in the region as a whole, the evidence for south-eastwards ice streaming in nearby Frobisher Bay (see Section 6.2) and the relatively low ground between Frobisher Bay and Foxe basin, it is probable that, prior to deglaciation of the Hudson Strait, ice flowed in the opposite direction, i.e., south-eastwards from Foxe Basin towards Frobisher Bay.

6.2. Streamlining on foliated gneisses, Frobisher Bay

High-resolution satellite imagery north of Frobisher Bay shows an extensive area of megalineated terrain (Fig. 7), developed on

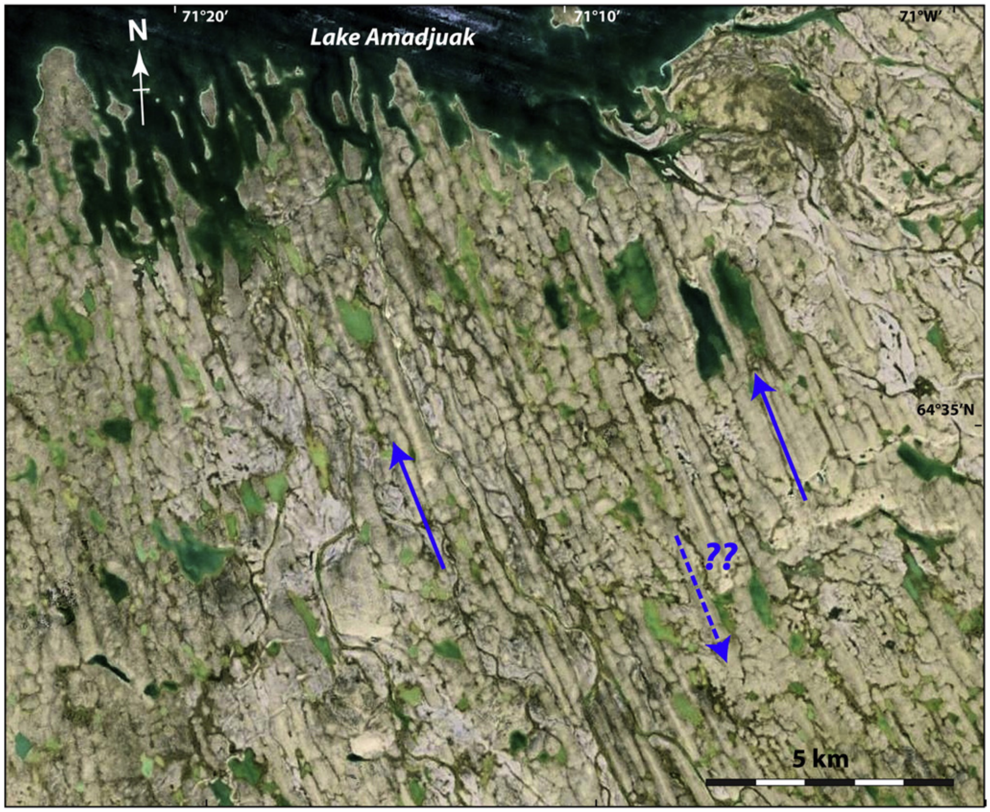

Fig. 6. Megalineated Palaeozoic carbonate bedrock on southern Baffin Island at Amadjuak Lake (location *Am* on Fig. 1(A)). Note lake elongation parallel to limestone ridges, and limestone ridges continuing onto Lake Amadjuak. Direction of deglaciation-related ice flow was to the NNW (De Angelis and Kleman, 2008), but earlier LGM-related SSE-directed ice flow towards Frobisher Bay may also have occurred. Landsat image courtesy of US Geological Survey.

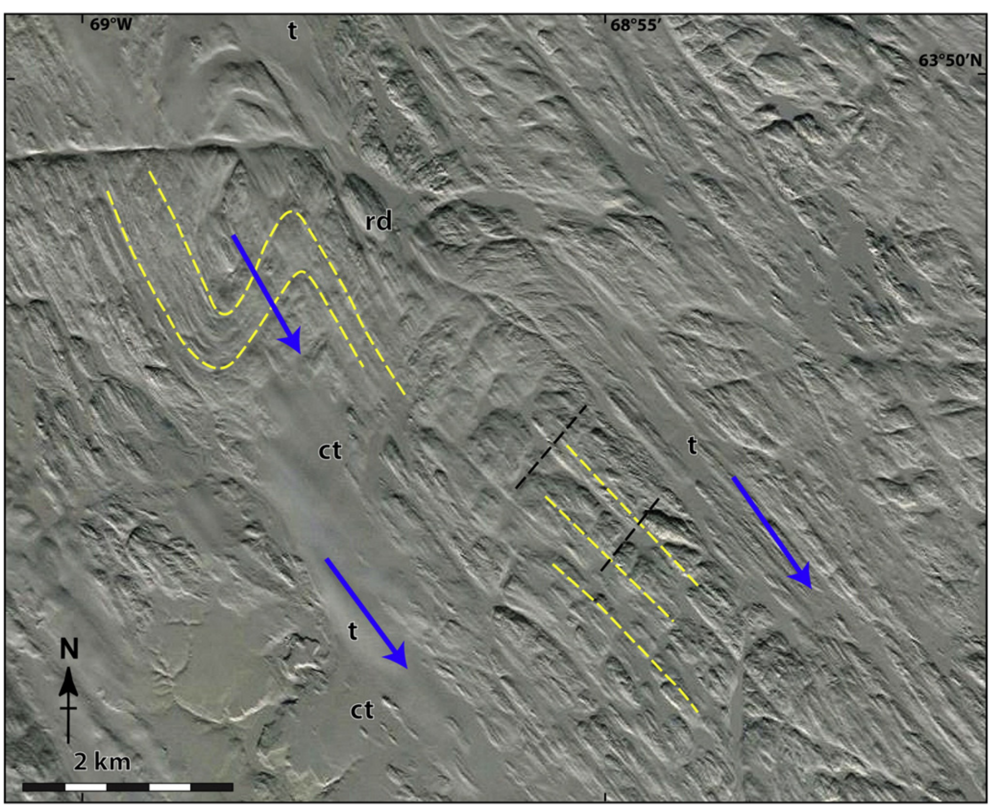

Fig. 7. Ridge-groove flow set north of Frobisher Bay (location *FB* on Fig. 1(A)). Ice flow was to the southeast. Megagrooves, megaridges and rock drumlins (rd) with superimposed megagrooves are developed in layered Palaeoproterozoic gneiss; note large-scale folding of bedrock layering (yellow dashed line) and fractures (black dashed lines) at high angles to bedrock strike. A thin veneer of till (t) occurs in places, and locally crag-and-tails (ct) occur. Landsat image; courtesy of Google Earth, retrieved August 2015.

Palaeoproterozoic orthogneisses and metasedimentary gneisses, that are strongly layered with a pronounced NW–SE strike (St-Onge et al., 2009, 2015). Parallel to this layering are ubiquitous elongate rock bedforms that appear to occur at two scales. Large-scale megagrooves are 100–500 m wide and >10 km long, extending across the area. Smaller scale (0.2–1 km long) elongate rock drumlins, megagrooves and ridges are superimposed on the larger scale megaridges-and-grooves. A thin, patchy veneer of glacial sediment is locally present (*t* on Fig. 7) and partially fills the megagrooves. Faint linear features in this sediment, as well as crag-and-tail features (*ct* on Fig. 7) are parallel to the dominant southeast-directed features, and confirm an origin by subglacial erosion. The entire field is at least 16 km wide and was likely carved by an ice stream that drained into Frobisher Bay. This Frobisher Bay ice stream was suggested by De Angelis and Kleman (2007) to be a long-lived, stable ice stream, although the above features were not mapped by these authors. In the northwestern part of the area, the layering is folded (highlighted in Fig. 7), resulting in a kilometre-scale swing in strike, so that ice flow was locally transverse to bedrock strike. Bedrock streamlined features are poorly developed in this area of strike-transverse flow, and till cover appears more widespread.

6.3. Streamlining on a carbonate platform, Southampton Island

Bare surfaces on Palaeozoic limestone on south-central Southampton Island (Fig. 8), together with those exposed on Coats Island also display megalineated rock surfaces. Bird (1953, p. 15) described the grooves on limestone on Southampton Island as 'generally 10 to 15 ft deep… about 300 yd wide… and 4 to 5 mi long' and being 'almost impossible to see even from the air' but they are clearly evident on satellite imagery (Fig. 8). The elongate features occur in a field 30 km wide and 40 km long, bound by two east-flowing esker ridges (Ross et al., 2011). NNE–SSW trending bedding traces can be seen on the imagery, being cross-cut by the NW–SE trending mega lineations, confirming the ridges and grooves are cut in bedrock. Similar linear bedrock features occur on carbonate rocks on Coats Island. On Nottingham Island and Salisbury Island, structurally controlled overdeepened linear basins and grooves on Archaean gneisses also show eastwards ice flow (Section 6.4). Collectively, these features record fast ice flow over a hard limestone bed at the base of the large long-lived, east-flowing Hudson Strait Ice Stream, and its onset zone (Ross et al., 2011). The flow set is consistent with soft-sediment MSGLs imaged on the Hudson Bay seafloor which are cross-cut by distinct and well-preserved iceberg scours (Ross et al., 2011).

6.4. Hudson Strait Ice Stream terrestrial footprint, Hudson Strait Islands

Nottingham, Salisbury and Charles Islands all lie in the path of the Hudson Strait Ice Stream and all are composed of shield gneisses, with a dense, complex pattern of fracture sets developed in multiple orientations (Fig. 9). The landscape here is thus a classic 'cnoc-and-lochan' landscape, with overdeepened lakes developed preferentially along fracture zones. In most glaciated gneiss terrains, overdeepened rock basins are entirely controlled by pre-existing fractures (Krabbendam and Bradwell, 2014) so that no dominant ice-flow direction can be inferred. Nevertheless, a clear groove–ridge landscape has developed on northern parts of Salisbury Island (Fig. 9(A)) with a continuous alternation of 2–10 km long megagrooves and megaridges. On central Nottingham Island (Fig. 9(B)) a multitude of lakes occurs, but east–west trending lakes are clearly dominant, being wider and longer than other fracture-controlled lakes with different orientations (see also Ross et al., 2011). In eastern Nottingham Island there are fewer lakes, but numerous east–west trending megaridges are present, with elongations ratios >10:1 (Ross et al., 2011). Farther east, Charles Island is almost completely covered by a ridge–groove landscape (Fig. 9(C)), with megagrooves and elongate lakes 5–10 km long. The elongation is so great (>1:20) that we suspect that the gneisses here possess a strong lithological layering subparallel to ice flow. Overall it appears that significant terrestrial streamlining did occur below the Hudson Strait Ice Stream, but the imprint was relatively subdued and inconspicuous due to the hard, resistant nature of the gneiss substrate.

7. Laurentide Ice Sheet—western margin

7.1. Megagrooves and bedrock strike, Mackenzie Corridor, Northwest Territories

The north-draining Mackenzie River Valley in western Canada was a major corridor for late Wisconsin ice flowing west from Keewatin to the

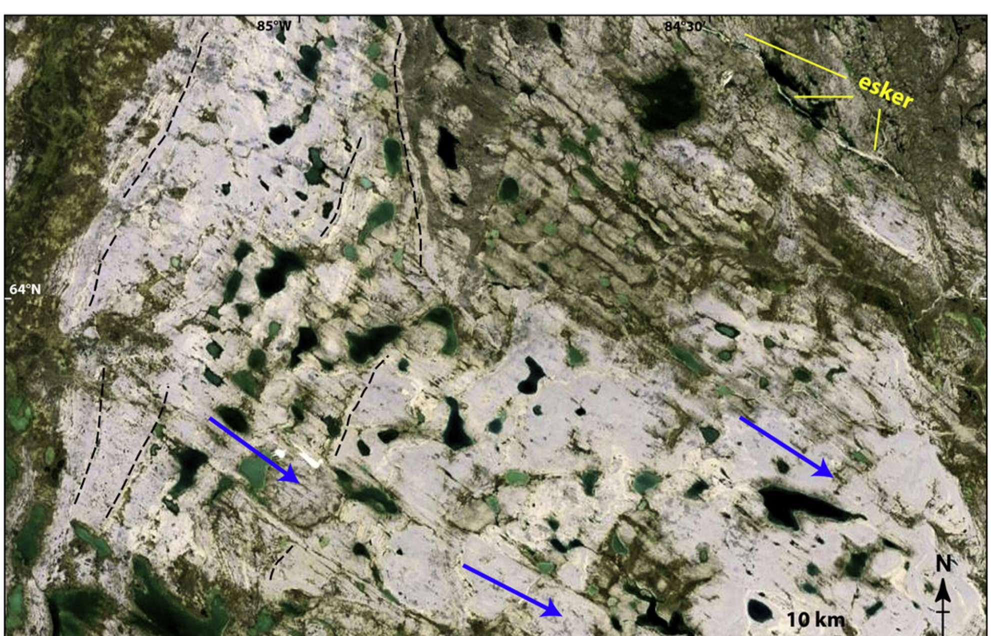

Fig. 8. Megalineated Palaeozoic carbonate surfaces on Southampton Island, northern Hudson Bay (location *So* on Fig. 1(A)). Ice flow was to the ESE. Bedrock strata highlighted in black dashed lines, representing very gently ESE dipping strata. Esker in NE corner of image mapped by Ross et al. (2011). Landsat image courtesy of Google Earth, retrieved August 2015.

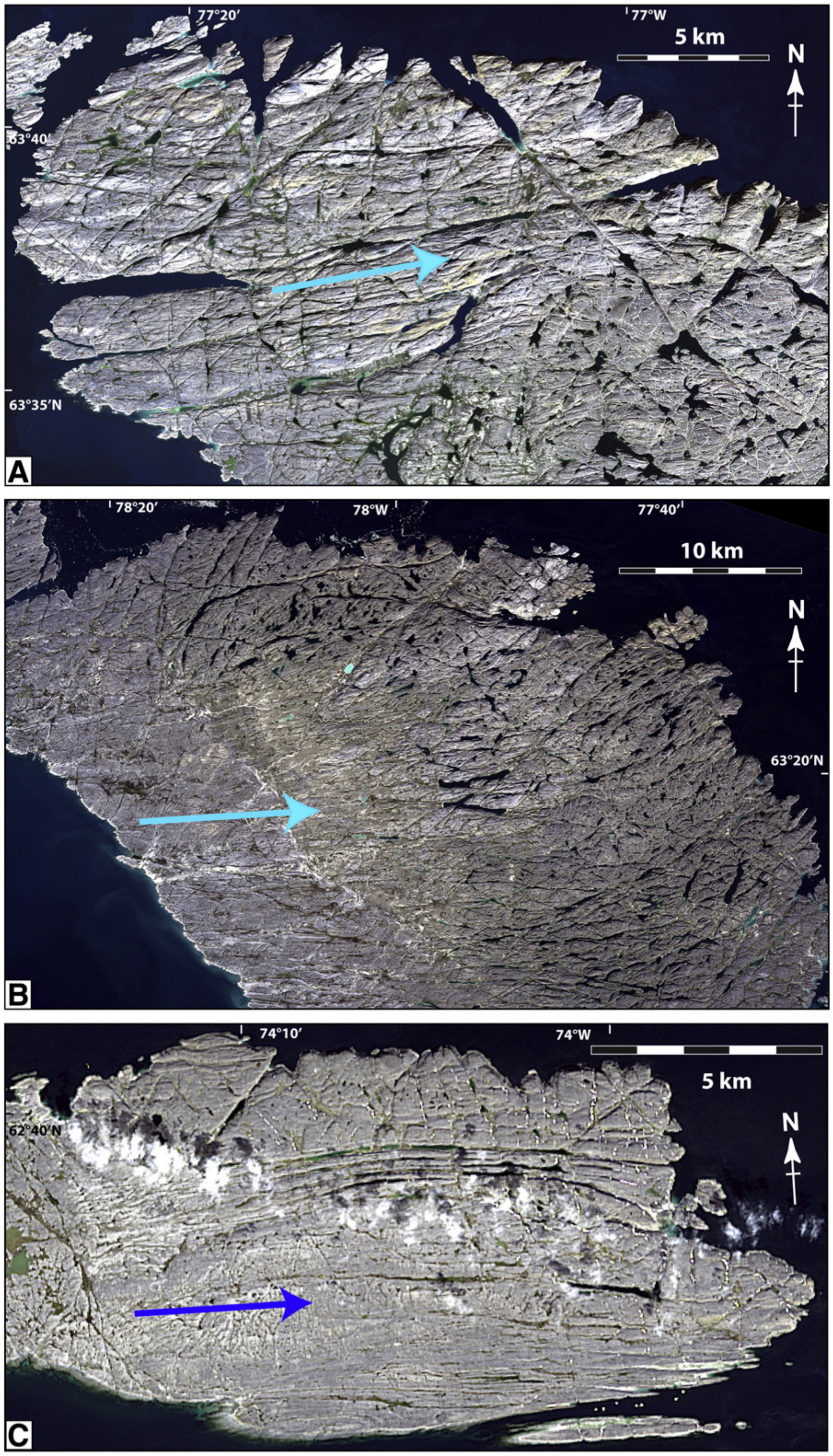

Fig. 9. Streamlined Archaean shield gneiss bedrock on islands in the Hudson Strait. (A) Northern part of Salisbury Island, with pronounced streamlining in the north contrasting with more random orientated bed forms in the central part. Location *Sa* on Fig. 1(A). (B) Nottingham Island, showing dominant east–west oriented overdeepened lakes. Location *No* on Fig. 1(A). (C) Pronounced elongate bedrock forms on Charles Island, Hudson Strait. Location *Ch* on Fig. 1(A). Landsat images courtesy of US Geological Survey.

Rocky Mountains and then being topographically steered north towards the Arctic Ocean (Dyke et al., 2002). The valley is parallel to the eastern edge of the northern Rocky Mountains (the Mackenzie Mountains) and flows between north–south-trending escarpments following the strikes of several tectonic (Laramide) thrust sheets of Palaeozoic strata (Morrow and Dubord, 1999). The most spectacular and well-known bedrock megagrooves in the Mackenzie Valley corridor occur over a cumulative area of some 150 km^2 between the Great Bear Lake and the Mackenzie River. They were first described by Smith (1948) and are cut into relatively homogeneous Silurian limestones and thin bedded to massive Devonian reef limestones, overthrust to the east with broad dip slopes dipping west or southwest to the Mackenzie River. Broadly speaking, megagrooves occur in two structural settings: transverse and parallel to strike.

Along the Great Bear River, west-directed ice flow was transverse to strike and crossed the north–south trending escarpments of the Franklin Range (Fig. 10(A)). East-facing scarps of the resistant Devonian limestone, oriented transverse to ice flow, have been rounded by glacial streamlining. Megagrooves cut into the crests of the escarpments and on west facing dip slopes are up to 11 km long, with an average depth of c. 15 m, but locally up to 45 m deep (Fig. 10(A); also Smith (1948) and Plate 2C therein). Shorter, discontinuous streamlined rock ridges are common and can be classed as rock drumlins and megaridges. Megagrooves are preferentially (but not exclusively) cut into heterogeneous brecciated and coralline Devonian limestone and are generally absent on thicker-bedded more massive and homogeneous limestones. Grooves are also poorly developed in areas where limestone is interbedded with sandstone and shale. Some kilometres west of the escarpment crest, bedrock megagrooves and megaridges merge into shallower but more elongate MSGLs on a flat plain: these are likely to be till-cored MSGLs, with the sediment presumably sourced from the erosion associated with bedrock groove formation. Thus here, both hard-bed

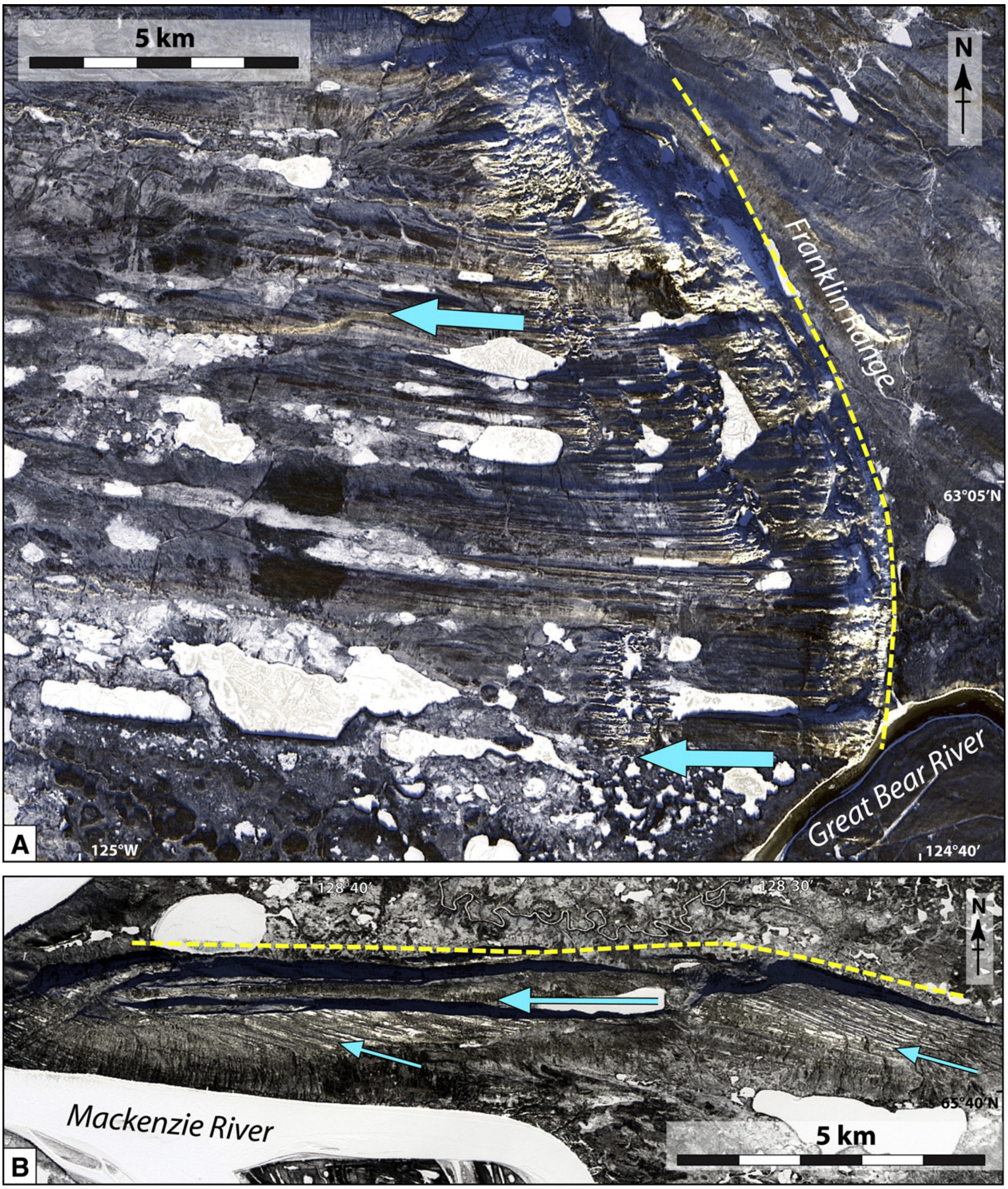

Fig. 10. Megalineated Palaeozoic carbonate bedrock along the Mackenzie Corridor, Northwest Territories. (A) Grooves developed transverse to north–south trending escarpments of Franklin Mountains, Bennet Field Airport, Great Bear River. Note change from hard-bed megalinations on escarpment to soft-bed MSGL's to the west. Location *FM* on Fig. 1(A).(B) Megagrooves parallel to east–west trending escarpments, with smaller-scale megagrooves at a small angle; Mackenzie River, east of Mountain River Airport. Location *MR* on Fig. 1(A). Blue arrows = inferred ice-flow direction; yellow dotted line = overall bedrock strike. Landsat images courtesy of US Geological Survey.

and soft-bed MSGLs in close association may have formed coevally. Soft-sediment MSGLs also occur just east of Norman Wells (65°19′N, 126°43′W) adjacent to the Mackenzie River, predominantly composed of outwash sediment.

Farther north along the Mackenzie River, the bedrock strike swings to east–west, so that overriding ice flow would have been sub-parallel to bedrock strike. The Imperial Hills is a particularly prominent glacially streamlined scarp that marks the exposed strike of thrust limestone packages. Just east of Mountain River Airport a series of prominent, 15-km long east–west-trending megaridges occur (Fig. 10(B)). The large-scale megaridges are asymmetric with steep north-facing rock escarpments and gently south-dipping dipslopes. On these dipslopes smaller-scale (c. 2 km long) megagrooves trend more towards the WNW. Thus, adjacent 'flow-sets' with different directions are evident here, where megagroove orientations in one flow set are offset from another set by as much as 15° (Fig. 10(B); see also Smith, 1948, and Plate 4 therein).

Smith (1948) suggested that megagrooves may have been deepened and widened by plucking of their margins, foreshadowing the recognition of 'lateral plucking' along the side slopes of megagrooves and ridges (see Bradwell et al., 2008a; Krabbendam and Bradwell, 2011). It is uncertain, however, how the grooves were initiated, since there megagrooves cut across local structures and no other obvious nucleation points occur up-ice (Smith, 1948).

7.2. Rock drumlins on Precambrian sandstone, Cree Lake, Saskatchewan

An extensive field of drumlins occurs in northwest Saskatchewan, Canada, largely covering the outcrop of the Palaeoproterozoic Athabasca Sandstone. Overall, this drumlin field shows southwest-directed ice flow (Fig. 11(A)), in a c. 250 km wide flow field crossing all of northwest Saskatchewan and includes the Livingston Lake drumlins, as described by Shaw and Kvill (1984). Many drumlins are composed of soft sediment, including till and glaciofluvial sediment (Shaw and Kvill, 1984). However, in the southeast part of the Athabasca basin, northwest of Cree Lake, a number of the drumlins are composed entirely of bedrock, separated by flat ground. Primary bedding traces can be traced on satellite imagery over several kilometres across drumlins and elongate ridges, and on the intervening flat ground surfaces (Fig. 11(B)–(D)). Thus, these landforms are entirely made up of bedrock. The rock drumlins are 0.2–2 km long, 100–300 m wide and the flats in between are 100–500 m wide. In some areas, the intervening flat ground is also grooved, with individual ridges 1–2 km long but less than 100 m wide; again the bedding traces can be seen to continue across the ridges/grooves (Fig. 11(D)). The bedrock strike is NW–SE, whereas the ice flow is to the southwest, crossing bedding traces at high angles: no obvious structural control on drumlin formation is evident. The Cree Lake rock drumlins occur within underformed Athabasca Group rocks, comprising sandstone, conglomerate and mudstone. The sandstones

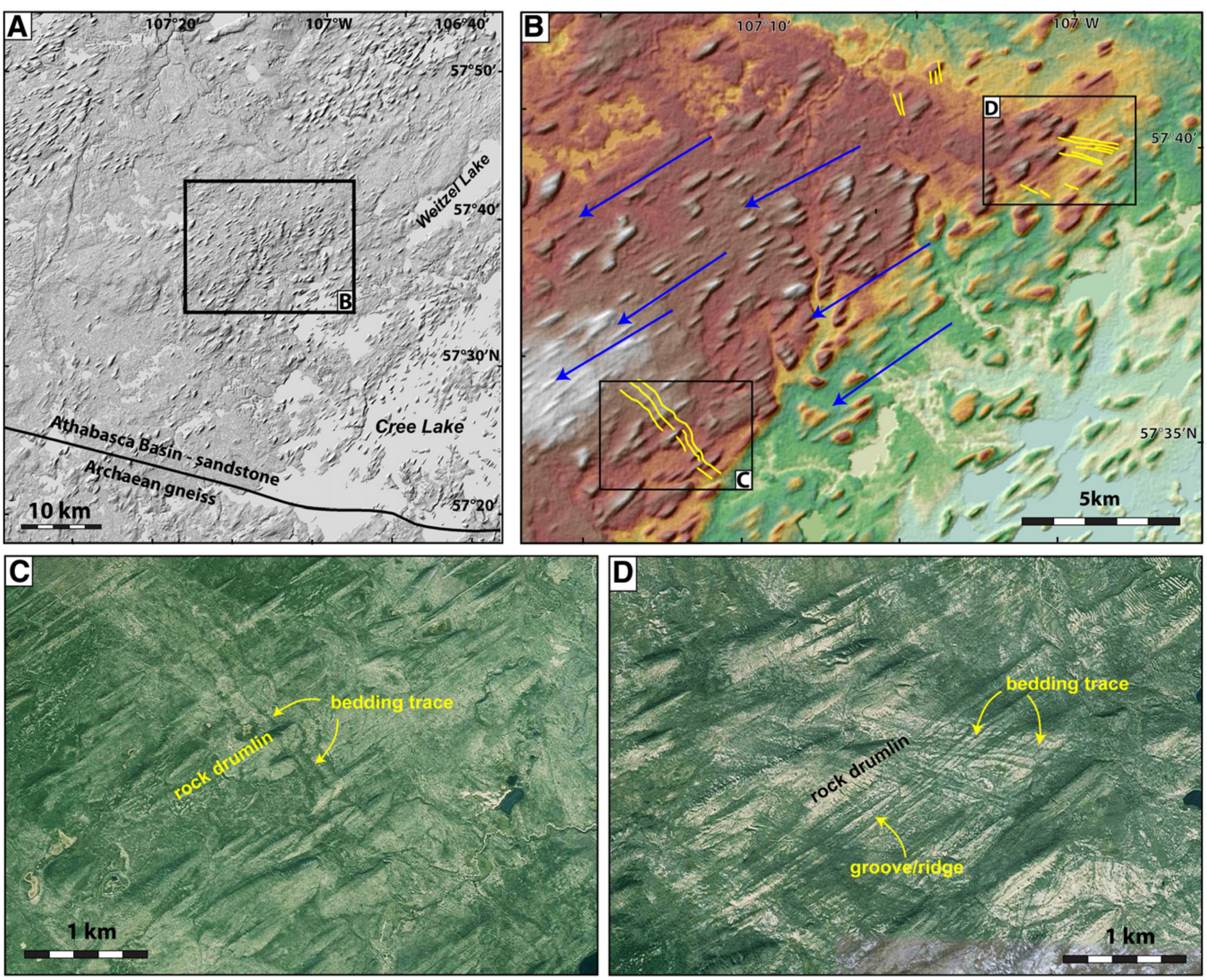

Fig. 11. (A) Setting of Cree Lake drumlins, NW Saskatchewan, location *CL* on Fig. 1(A). Southern limit of Precambrian sandstones of the Athabasca basin against Archaean gneisses of the Canadian Shield is indicated. (B) Detail of the Cree Lake Drumlins. Digitised bedding traces (yellow lines) overlain onto DTM (SRTM from NASA JPL, 2013); SW ice flow indicated with blue arrows. (C) and (D). SPOT satellite images, courtesy of Google Earth, showing bedding traces crossing drumlins and groove–ridges.

have a clay or chlorite matrix, are friable and have a high fracture density (Tremblay, 1982; Shaw and Kvill, 1984; Mwenifumbo et al., 2004), implying a high erodibility. The Cree Lake rock drumlins are identical in form to nearby soft-sediment drumlins, implying a common erosional origin. Although the precise erosion mechanism of the Cree Lake rock drumlins remains unclear, the general smoothness, at least at the resolution of the remote sensing imagery, suggests a strong component of abrasion, which is further discussed in Section 10.3.

7.3. Megagrooves on Mesozoic strata, Cameron Hills, Alberta

The Cameron Hills in northern Alberta provide an example of rock megalineations developed on poorly consolidated and clayey Mesozoic bedrock (Fig. 12). This has produced some of the most spectacular areas of streamlined forms anywhere in Canada. Several large upland areas (Swan Hills, Birch Mountains and Caribou Mountains) define the abrupt easternmost edge of the thick clastic infill of the Jurassic–Cretaceous Western Canada Sedimentary Basin. Broad river valleys (Peace, Athabasca and Wabasca) separating these uplands formed corridors hosting southwest flowing palaeo-ice streams now recorded by broad belts of drumlinised till and stagnation moraines (see Fenton and Pawlowicz, 2000; Fenton et al., 2013). The Cameron Hills Uplands is a massif some 100 km in length and 70 km wide, which during Pleistocene glaciations formed a major obstacle to southwest flowing Keewatin ice, with ice flow being diverted around its flanks. The distinctive keel-shaped planform of the Cameron Hills closely resembles the large mega-rock drumlins of the glacially streamlined promontories along the Niagara Escarpment in Ontario (Eyles, 2012). Thicker drumlinised till occurs in the lowlands surrounding the Cameron Hills (e.g., Paulen and Plouffe, 2009) but thins with increasing elevation, reflecting preferential deposition of subglacial sediment at lower elevations.

The upper surface of the Cameron Hills is extensively scored by very well developed megalineations (Fig. 12), developed probably on both soft sediment and bedrock, which here consists of relatively soft, poorly cemented Cretaceous shales and sandstones of the Fort St. John Group. Heavily vegetated elongate features on the satellite image are likely covered or composed of soft sediment, whereas pale grey/white surfaces are likely bare bedrock surfaces. Two flow sets of elongate features can be distinguished: a SSW trending set of elongate features (in the southeast corner of Fig. 12) appears to be dominated by soft sediment; these grooves ('MSGLs') are here densely spaced (c. 250 m) and 3–7 km long. The major WSW directed set is mainly cut into bedrock with minor till cover. The till cover is thin (<1 m) or absent over large areas and the same megagrooves, including numerous highly elongate 1–5 km long lakes, can be traced as continuous features from vegetated till-covered areas in the northeast, into areas of non-vegetated, exposed bedrock in the southwest. Hundreds of highly elongate megagrooves occur, with lengths exceeding 10 km, indicating dominant WSW-directed ice flow across the surface of the upland.

8. Cordilleran Ice Sheet: Nass and Skeena River, British Columbia

Extensive sets of long bedrock megagrooves and other elongate rock bedforms occur in the Nass and Skeena river valleys, within the rugged Cordillera of British Columbia. This area was not visited, and geological constraints are quoted from the literature, but the example is presented here as elongate rock bedforms developed in a strongly topographically controlled palaeo-ice stream environment (Fig. 13). Pronounced grooving occurs in a number of 5–30 km wide 'U-shaped' valleys or glacial troughs with wide, flattish floors (Fig. 13(A)). These 'U-shaped' trunk valleys contrast with narrower (1–3 km) 'V-shaped' side valleys, which lack wide flat floors. Although the narrow side valleys undoubtedly contained glaciers during glaciation they retained much of their dendritic and 'V-shaped' preglacial fluvial forms, suggesting limited glacial erosion. The trunk glacier following the Nass River valley was likely responsible for the ice-stream deposits found on Queen Charlotte Islands, farther downstream (see Hicock and Fuller, 1995).

The bedrock of the Nass and Skeena valleys (part of the Stikine Terrane) is dominated by a heterogeneous, strongly layered Jurassic–Cretaceous sequence (Bowser Basin) of shale, siltstone, limestone, sandstone, coal, conglomerate and some volcanic units, including basalt (Evenchick, 1987; Cookenboo and Bustin, 1989). On field photos in the literature (e.g., Cookenboo and Bustin, 1989) limestone and sandstone strata form small cliffs, whereas shale units appear very friable, typically covered in postglacial scree and with slopes lying at the approximate angle of repose. Thus the geological stratification translates

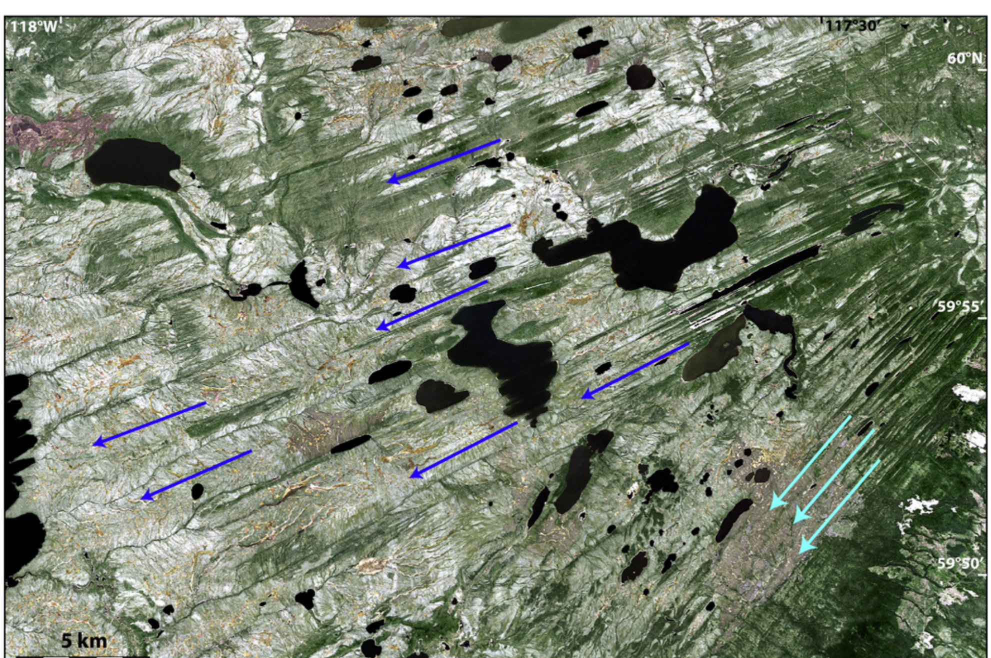

Fig. 12. Megalineated Mesozoic bedrock and till in the Cameron Hills, northern Alberta, location *CH* on Fig. 1(A). Two sets of elongate features are shown in pale blue and dark blue arrows respectively. Vegetated areas are interpreted to be till-covered, bare surfaces interpreted as bedrock dominated. Landsat images courtesy of US Geological Survey.

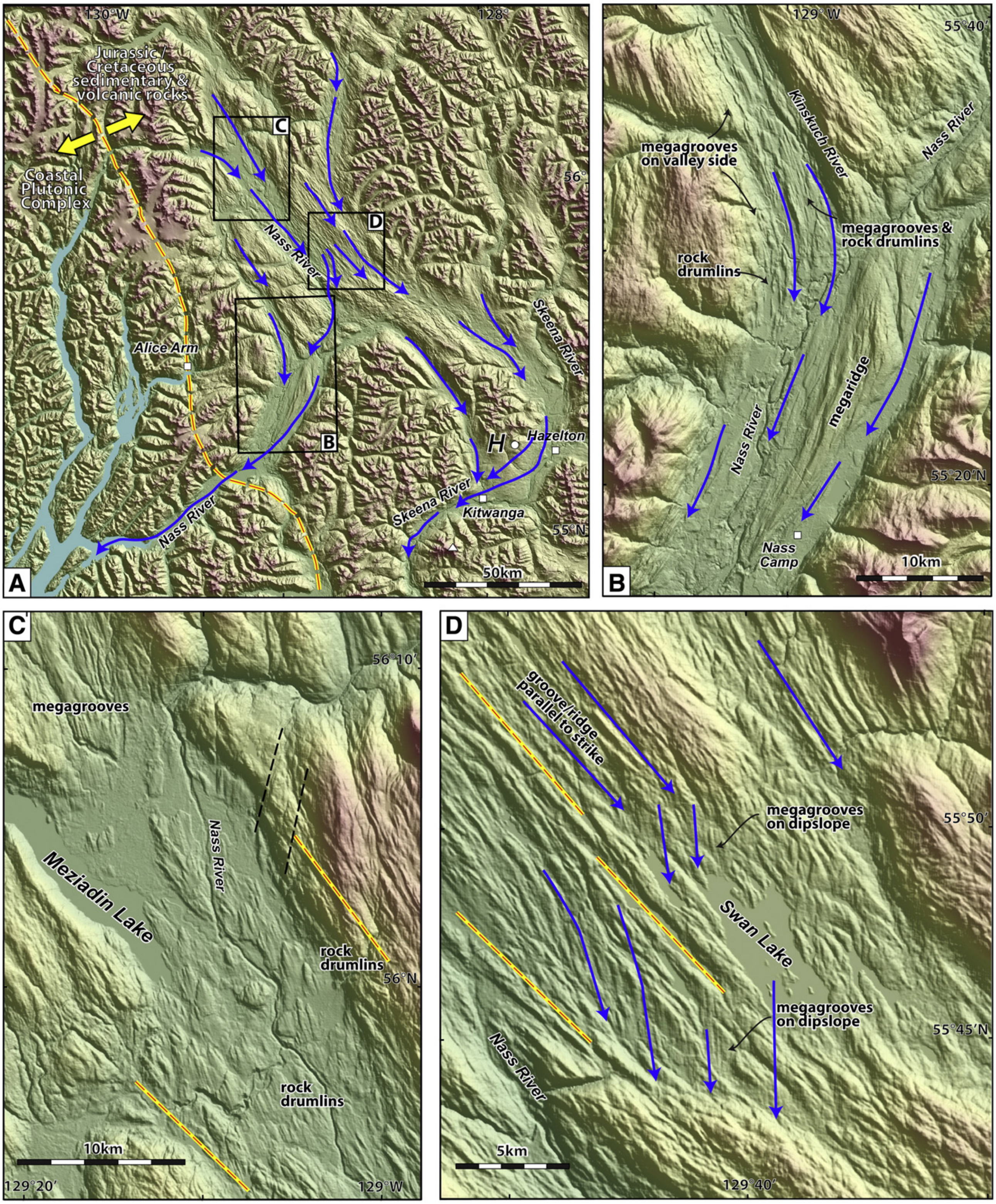

Fig. 13. (A) Overview of Nass River/Skeena River drainage areas, Canadian Cordillera, British Columbia. Ice flow via main trunk valleys indicated with blue arrows; boundary between sedimentary and plutonic rocks as yellow-red dashed line. Note difference in valley shape and width between the main trunk valleys, and the dendritic fluvial patterns still present in the smaller branch valleys. H = Hazelton hills—see Fig. 14. (B) Detail of Nass River valley. (C) Detail of Meziadin Lake area. (D) Detail of Swan Lake area. Blue arrows = ice flow; yellow-red lines = bedrock strike; black dashed lines = fractures. DTM from NASA SRTM (NASA JPL, 2013).

into pronounced differences in erodibility: some units, especially the shale/siltstone units appear highly erodible, whereas other units provided more massive layers. Between the Bowser Basin and the west coast is the Coastal Plutonic Complex, comprising much harder granitic rocks (e.g., Monger et al., 1982); this contrast is probably responsible for the narrowing of the Nass River valley towards the sea (Fig. 13(A)).

The trunk valleys in the area invariably show a pronounced bedrock streamlining with various types of elongate rock bedforms in different settings relative to former ice flow. Along the Kinskuch River valley, north of Nass Camp (Fig. 13(B)), megagrooves occur on the valley floor and along the valley sides. On the valley side, the megagrooves are clearly cut into bedrock. On the valley floor, ridge–groove complexes appear partially covered in soft sediment; possibly a hybrid form of rock drumlins and crag-and-tail features. In the main Nass River Valley, smaller scale grooves occur along the valley side. A large, 30 km long, 5 km wide megaridge occurs on the valley floor, with smaller grooves cut into it. This feature appears to be draped with soft sediment, but is almost certainly composed of bedrock, with grooving along the valley axis.

In the Meziadin Lake area (Fig. 13(C)), a field of 2–3 km long bullet-shaped rock drumlins occurs on the valley floor. The stoss-sides of these rock drumlins are markedly angular and appear to be controlled by NW–SE trending bedding planes, combined with a NNE–SSW trending fracture system. Just northeast of Meziadin Lake, there is a field of straight, linear grooves, some 2–3 km long. These grooves are cut by a meltwater channel (possibly subglacial), strongly suggesting the grooves are subglacial in origin. All these features are broadly aligned along the valley axis, and are assumed to be parallel to former ice flow.

In the Swan lake area, more complications occur (Fig. 13(D)). Bedrock strata strike NW–SE, with some southwest dipping dipslopes visible south of Swan Lake. Two sets of grooves occur here. The dominant ridge–groove forms are parallel to the NW–SE bedrock strike. These grooves are 1–5 km long and tens of metres deep. A more subtle set of straight grooves occur on the southwest dipping dipslopes; these groove are shallower, narrower and up to 2 km long and trend north–south. The two sets of grooves differ in trend by c. 35°. Two explanations are possible here. Firstly, ice flow may have switched from a mainly southeasterly direction, producing the strike-parallel megagrooves, to a southerly direction with the subtle dipslope megagrooves developed later. Alternatively, ice flow remained southwards throughout, with the dipslope megagrooves indicating regional ice flow, and the strike-parallel megagrooves developed oblique to ice flow, being strongly controlled by bedrock strike.

On a high resolution oblique view, a striking set of megagrooves can be seen on a hill WNW of Halzelton (Fig. 14). Megagrooves originate on a crest of an east-facing escarpment, and continue east for 0.5–1 km along the dipslope. The megagrooves are likely similar to the smaller set described above from the Swan Lake area. Overall, the Nass and Skeena rivers demonstrate the wide occurrence of megagrooves in topographically constrained ice streams.

9. British Ice Sheet

9.1. Megagrooves on foliated metasedimentary rocks, Ullapool, Northwest Scotland

Megagrooves in Northwest Scotland were first described from the Assynt area (Bradwell, 2005) and then near Ullapool (Bradwell et al., 2008a; Krabbendam and Bradwell, 2011). We focus here on the larger Ullapool field. The Ullapool megagrooves were cut by an ice-stream tributary flowing west through a c. 30 km-wide topographic breach between the Assynt and Fannich Massifs (Fig. 15(A)). This fast-flow corridor was one of several ice stream tributaries that coalesced to form the larger Minch Ice Stream system that drained the northwest sector of the British–Irish Ice Sheet (Bradwell et al., 2007). The Ullapool megagrooves occupy a field of approximately 6 by 10 km (Fig. 15(B)) and are cut into metamorphosed (amphibolite–facies) metasandstone of the Neoproterozoic Moine Supergroup (Strachan et al., 2010). These rocks possess a strong bedding and bedding-parallel foliation. However, all strata have similar properties, showing a very uniform lithology. Jointing is abundant, with a typical spacing of 10–30 cm (Krabbendam and Bradwell, 2011). The megagrooves are 1–4 km long, 2–20 m deep and 50–200 m apart (Fig. 15(B), (C)). Many are straight, although some curve gently on a kilometre-scale. Most megagrooves are angular and asymmetric in cross-section, with gently south-dipping dipslopes opposing steep north-facing rock steps that are parallel to strike and palaeo-ice flow. Some are U-shaped in cross-profile (see details in Bradwell et al., 2008a; Krabbendam and Bradwell, 2011). Notably, the megagrooves occur in part on an uphill slope with respect to regional ice flow, crossing the present-day watershed (Fig. 15(B)); V-shaped megagrooves occur just west of the watershed, suggesting a localised, perhaps later, component of subglacial meltwater erosion.

Overall, the structural control on megagroove occurrence around Ullapool is strong: most grooves are broadly parallel to bedrock strike (Fig. 15(B)) and the asymmetry of the grooves in cross-section is clearly

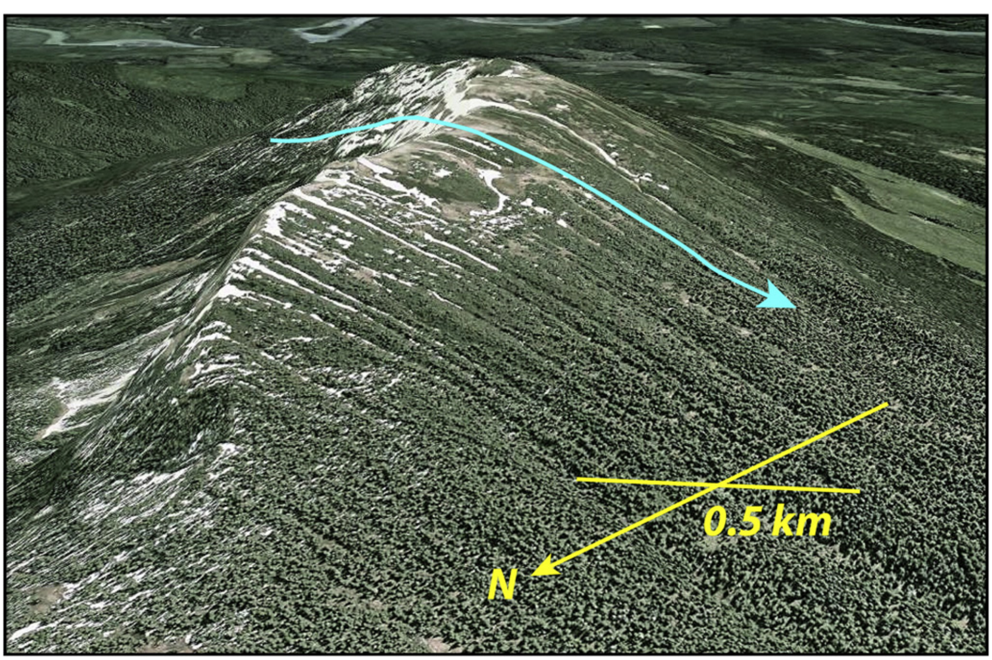

Fig. 14. Oblique view of subsidiary hill of Hazelton Peak, 10 km WSW of Hazelton, location *H* on Fig. 13(A). Megagrooves developed on crest and dipslope of escarpment, which faces against ice flow (blue arrow). Yellow bars are each c. 500 m. long. Oblique Google Earth image. Centre image is 55°16′25″N, 127°51′05″W. Landsat image courtesy of Google Earth, retrieved August 2015.

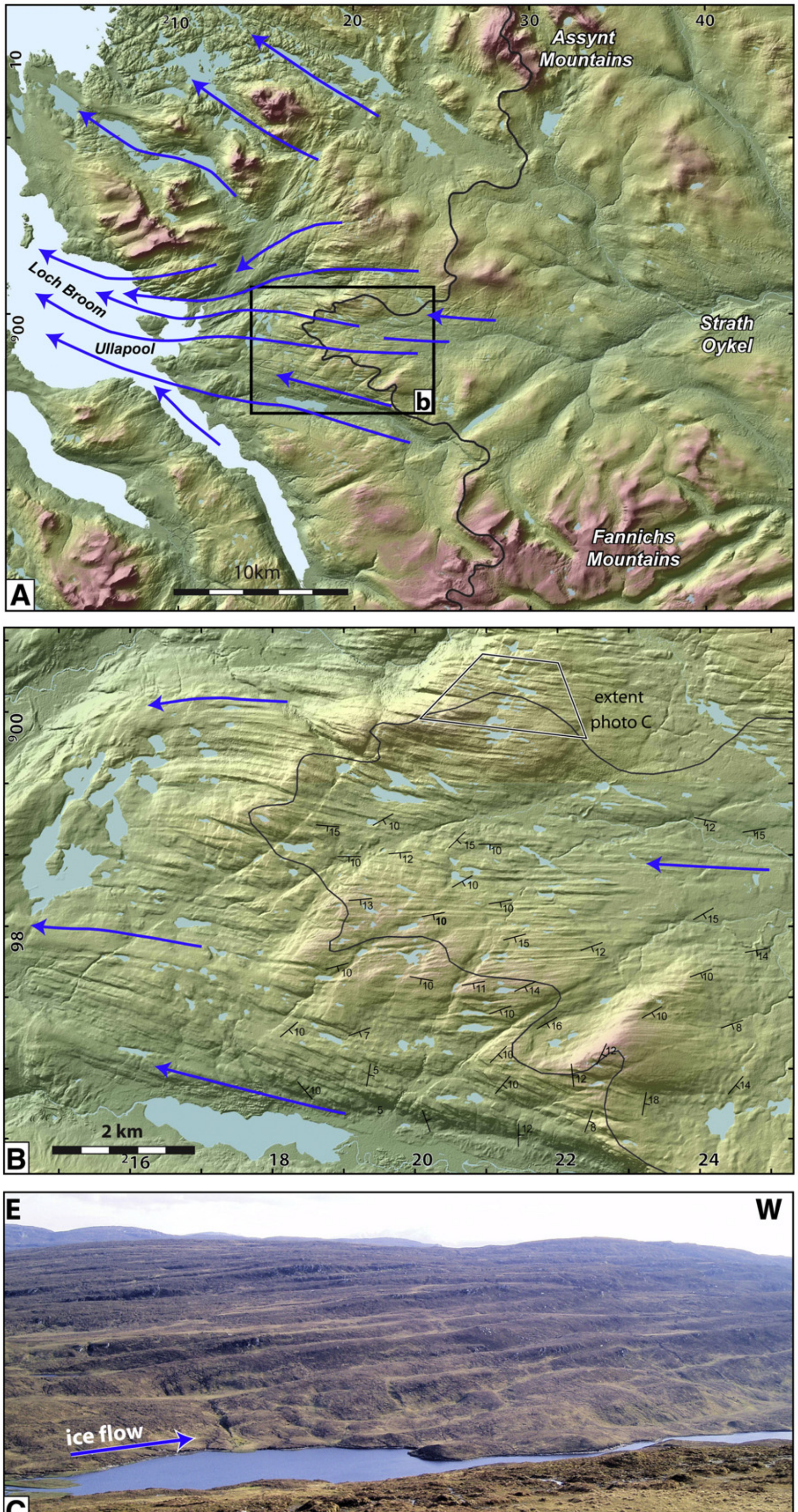

Fig. 15. (A) Setting of the Ullapool megagroove field, NW Highlands, Scotland, location *UL* on Fig. 2. Fast ice flow occurred through a breach in the watershed (black line) between the Assynt and the Fannich Mountains, both c. 1000 m high. The ice divide was positioned in Strath Oykel, or farther east. (B) Detailed DTM of the Ullapool megagroove field. Note slight sinuosity, and both uphill and downhill megagrooves. Strike and dip symbols show that ice flow was generally sub-parallel to strike (after Krabbendam and Bradwell, 2011). DTM and coloured altitude derived from NEXTMap Britain, Intermap Technologies. (C) Part of Ullapool megagroove field, looking south; ice flow was to the right (west). Width of view c. 2 km, height of exposed lateral rock steps between 5 and 20 m. Location see (B). BGS photo 595952.

the product of preferential glacial erosion of a stratified sequence. However, similar flaggy strata of the Moine Supergroup are widespread in the Northern Highlands (Strachan et al., 2010) but do not show megagrooves (Fig. 15(A)). This absence of glacial grooving is probably because the regional bedrock strike is generally north–south, transverse to westwards ice flow; only near Ullapool was fast ice flow parallel to strike. The strong anisotropy of the metasandstone, combined with a dense joint network and the blocky, angular nature of the steep megagroove walls, suggest that the dominant erosion mechanism was lateral plucking (Section 10.3; Krabbendam and Bradwell, 2011).

9.2. Onshore and offshore streamlining, Sound of Jura, west Scotland

The megalineated landform assemblage in and around the Sound of Jura in west Scotland (Fig. 16) is presented here as an example of a hard-bed ice stream assemblage that (i) is seen both onshore and offshore data; (ii) occurs in steeply dipping metasedimentary rocks; and (iii) shows how short-lived changes in ice-flow directions during deglaciation have little effect on earlier generated elongate rock bedforms. The megalineated topography of the Sound of Jura occurs in a package of Neoproterozoic metasedimentary and meta-volcanic rocks (Dalradian Supergroup) that were folded and metamorphosed to form the NE–SW trending Grampian Orogen during the Ordovician (e.g., Strachan et al., 2002). Due to this folding, the strata dips vary from gentle to steep (up to 60°–70°), but always maintain a NE–SW strike (Roberts and Treagus, 1977; British Geological Survey, 2003). Submarine glacial features in the outer Sound of Jura have recently been described by Dove et al. (2015); the glacial geomorphological evolution southeast of the Sound of Jura was analysed by Finlayson et al. (2014).

The Sound of Jura megagroove field is c. 40 km long and c. 15 km wide (Fig. 16(A)). To the northwest it is bound by the 300–700 m high hills of the island of Jura. The bedrock here is dominated by the Jura Quartzite and does not show strong streamlining even on low ground; instead a rugged 'cnoc-and-lochan' type terrain occurs. The southwest lateral limit is less well defined by the lower (200–450 m) hills of southern Knapdale and Kintyre; nevertheless a significant component of topographic steering is evident.

The inner Sound of Jura, probably comprising graphitic slate and calcareous semipelite, shows strong streamlining with numerous highly elongate megaridges developed. (On offshore swath bathymetry, seabed ridges are better defined than grooves, probably a function of postglacial marine sedimentation in the grooves and lack of subaerial weathering and erosion of the ridges.) The peninsulas on either side of Loch Sween comprise a mixed package of psammite (metasandstone), pelitic schist, and limestone with numerous amphibolite layers. This ground is intensely streamlined (Fig. 16(B), (C)), with 1–10 km long megaridges and megagrooves continuously alternating with spacings of 100–300 m and depths of 10–50 m. The megaridges are dominated by amphibolite whereas the megagrooves are dominated by other mentioned rock types (Fig. 16(B)). Evidently, the amphibolite was more resistant to erosion than the other lithologies, the preferential erosion of which resulted in the formation of the grooves. Overall, megagroove occurrence and orientation in the Sound of Jura is strongly controlled by bedrock layering.

Onshore, glacial striations from 1:10 560 scale geological maps (held in BGS archives) were digitised, as well as a number of ridges and grooves (Fig. 16(C), (D)). The ridges and grooves have a very consistent orientation between 200° and 220° but the orientation of the glacial striae varies widely between 210° and 280° (Fig. 16(D)). Striae measured within grooves are more commonly SSW oriented, sub-parallel to the overall ridge–groove orientation, whereas striae on the ridges have more westwards orientations, at high angle to the ridge–groove elongation. Working on the Mull of Kintyre southeast of the Sound of Jura, Finlayson et al. (2014) document switching ice-flow directions with a lateglacial westwards directed flow, spilling over from Loch Fyne farther east. Notably, this late stage westwards ice-flow direction switch produced striations and till fabrics (Finlayson et al., 2014), but did not significantly affect the overall ridge–groove landscape, which instead appears to document cumulative SSW-directed ice-sheet flow over one (or more) glaciations.

In the inner Sound of Jura, a c. 15 km long, 2 km wide overdeepened rock basin occurs parallel to bedrock strike (Fig. 16(A), (C)); the floor of this basin also contains ridges, although these are partially infilled by postglacial marine sediments. Farther south in the outer Sound of Jura, a second basin occurs (Fig. 16(A), (E)), where bedrock landforms are progressively buried beneath glacial sediment and the hard-bed megalineated topography gradually changes into a 'mixed-bed' of crag-and-tails and, close to the southernmost edge of the dataset, drumlins with continuous till cover (see also Dove et al., 2015). Although the drumlins and crag-and-tails are broadly parallel to bedrock grooves and ridges (confirming overall SSW-directed ice flow) some deviations occur. East of the basin centre, drumlins and crag-and-tails are truly parallel to grooves and ridges. However, in the bedrock high in between the two basins, ice flow (to 190°–210°) was at a c. 20°–30° angle to the dominant bedrock ridges, which here trend c. 235°. Sharply defined channels, possibly following a set of north–south trending fractures, cross-cut the ridges and connect the two basins; whether these channels are eroded by ice or meltwater erosion is not clear, although their alignment with small crag-and-tails suggests dominant ice flow through these channels. Thus, bedrock ridges and grooves developed here at a c. 25°–30° angle to the dominant ice flow. A further observation is that west of the basin centre, ridge–groove terrain changes southwards into a landscape of isolated rock drumlins with little sediment cover.

Overall, the Sound of Jura shows not only that hard-bed megalineations, if structurally controlled, can develop at a small angle to overall cumulative ice flow but also that subsequent switches in ice-flow direction may have little or no effect on the overall erosional geomorphology of the palaeo-ice stream bed.

9.3. Streamlining of sedimentary strata, Tyne Gap Ice Stream, northern England

Well-developed bedrock megagrooves and ridges occur in the Tyne Gap in northern England, which forms a low, broad breach between the Northumbrian Hills (Kielder Forest) to the north and the Northern Pennines to the south (Fig. 17). The megagrooves were described by Krabbendam and Bradwell (2011) and the general geomorphology, MSGLs and palaeo-ice stream reconstruction by Livingstone et al. (2008, 2010). Ice flow through the Tyne Gap was predominantly from west to east, indicated by both hard-bed megalineations and by numerous till-dominated drumlins and crag-and-tails, together forming a well-developed 'mixed-bed' assemblage of streamlined bedforms (Fig. 17(A)).

The bedrock in the Tyne Gap consists of a varied sequence of Carboniferous sedimentary strata (e.g., Taylor et al., 1971), including limestones, sandstones and mudstones, as well as a near-bedding-parallel dolerite sill (Whin Sill), outlined on Fig. 17(B). The bedrock properties are thus strongly varied, with different hardness (dolerite vs. mudstone) and different joint patterns: the limestone shows conjugate jointing, whereas the dolerite shows typical columnar jointing (Krabbendam and Bradwell, 2011). Bed thicknesses also vary widely, from <0.4 m to many metres.

Megagrooves in the Tyne Gap occur over an area of c. 5 by 20 km. The megagrooves are generally straight, with megaridges following the bedrock strike, and are 1–3 km long. The grooves are highly asymmetric, with steep north-facing escarpments and gently south-dipping dipslopes. Patchy till cover occurs in the grooves and on the dipslopes. The situation is thus similar to the Ullapool megagrooves, except that in the Tyne Gap strata show much more lithological diversity. This is exemplified by the dolerite Whin Sill which forms the most pronounced

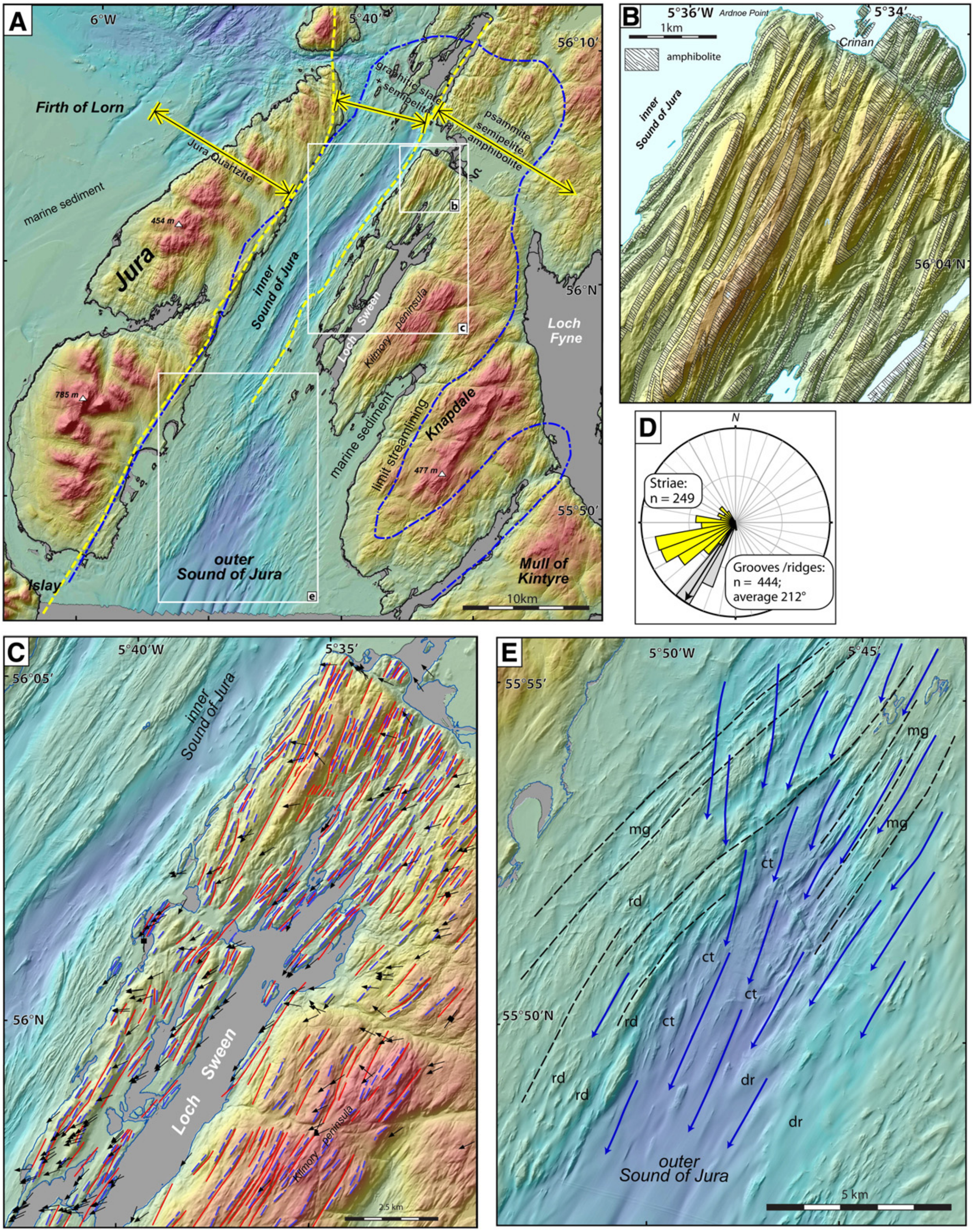

Fig. 16. (A) Overview of Sound of Jura groove–ridge field, outlined in blue; location *SJ* on Fig. 2. DTM and hillshade are a combination of onshore DTM and offshore side-swath bathymetry. Broad geological divisions indicated with yellow dashed lines. Very smooth seabed is post-glacial marine sediment cover. Boxes indicate position of figure (B), (C) and (E). (B) Outcrops of amphibolite overlain upon DTM. Ridges are dominated by amphibolite; grooves are dominated by other lithologies (psammite, quartzite, semipelite, limestone and graphitic pelite). After British Geological Survey (2003). (C) Glacial striae, taken from BGS 1:10 560 geological maps, plotted onto DTM. Grooves and ridges onshore are digitised. (D) Rose diagram with orientations of glacial striae, megaridges and megagrooves. (E) Offshore bathymetry of the outer Sound of Jura. Ice flow lines schematically indicated by blue arrows, based largely on crag-and-tails, long axes of till-covered drumlins and till lineations. Bedrock strike indicated by black dashed lines. dr = drumlin, rd = rock drumlin, mg = megagroove, ct = crag-and-tail. Onshore DTM from NEXTMap Britain Intermap Technologies; bathymetry courtesy of UK Maritime and Coastguard Agency and BGS.

megaridge in the Tyne Gap areas, with the deepest grooves on either side (Fig. 17(B)), a feature exploited by the Romans for the construction of the defensive Hadrian's Wall on the crest of that ridge. The angle between bedrock strike and ice flow strongly controls the development of megagrooves in this area. Due to gentle warping, the Carboniferous bedrock strike swings from east–west in the Tyne Gap itself to almost north–south in the Hallington area (top-right in Fig. 17(A)), where the ice flow is transverse to bedrock strike. In the Hallington area,

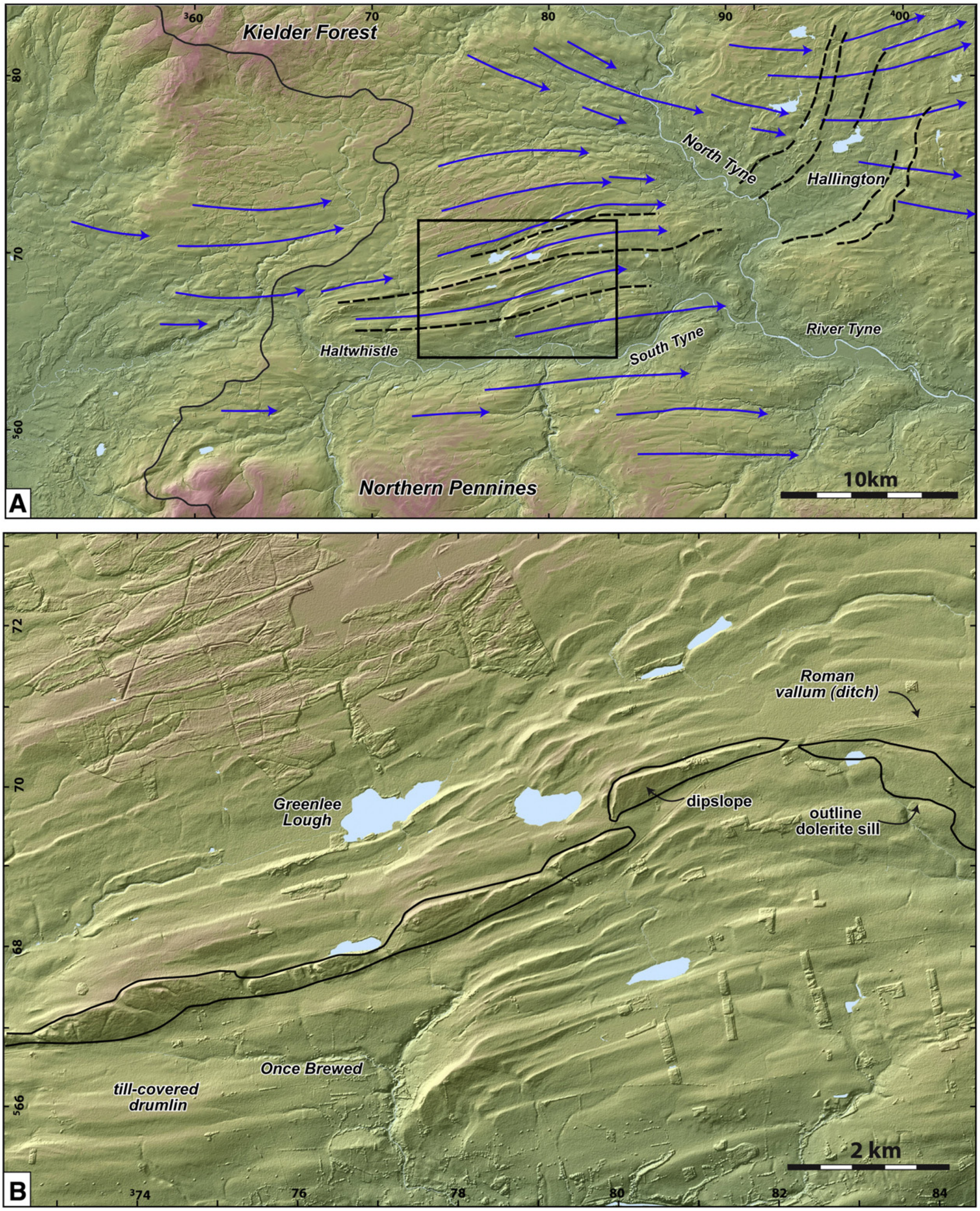

Fig. 17. (A) Setting of Tyne Gap megagroove field, northern England, location *TG* on Fig. 2. General ice flow lines shown in blue arrows—see also Livingstone et al. (2008, 2012); bedrock strike (black dashed lines) swings from east–west near Haltwhistle to north–south near Hallington. Till-covered drumlins occur north and south of the megagrooves. (B) Tyne Gap megagrooves, outcrop of Whin Sill dolerite is outlined in black. Dipslopes are partially exposed and dip gently to the south; escarpments face north. Hadrian's Wall is built on top of the highest crest of the Whin Sill. DTM from NEXTMap Britain Intermap Technologies.

megagrooves are absent; instead a till-dominated area occurs with numerous soft-sediment drumlins and crag-and-tails. Thus, the Tyne Gap provides a good example of how megagrooves can develop where ice flow is sub-parallel to bedrock strike, but do not develop where ice flow is transverse to strike. In this case, the grooves are strike-controlled, similar to those described by Zumberge (1954) in areas of gently dipping alternating lithologies.

10. Discussion

This paper highlights prominent areas of bedrock drumlins, megagrooves and megaridges based upon our own fieldwork, remote sensing imagery and previous literature. We show that such bedrock megalineations are common, and occur in a variety of glaciological settings, not only ranging from strongly topographically constrained palaeo-ice streams (e.g., Nass River, British Columbia); to palaeo-ice streams that are moderately topographically constrained, commonly in broad breaches (e.g., Tyne Gap, Ullapool; UK); but also including palaeo-ice streams in areas where topographic control is much more subtle (e.g., Ontario, Alberta, Saskatchewan). Rock-cut megalineations have recently been reported from the beds of retreating Antarctic ice streams (e.g., Graham et al., 2009) and inferred below the Greenland Iced Sheet (Jezek et al., 2011), supporting our primary finding that megalineations can equally form on soft-sediment and hard (rock) beds. Hard-bed megalineations are thus an important component of palaeo-ice stream footprints: if only soft-sediment features are mapped, the reconstructed footprints of palaeo-ice streams, and hence the dynamic configuration of former ice sheets, is incomplete (cf., Margold et al., 2015; Stokes et al., 2015). It is likely that uncertainty of recognising ice stream imprints on hard beds (see Margold et al., 2015) has underestimated the number and size of palaeo-ice streams.

10.1. Relation to bedrock structure

In all examples presented here, the presence and character of elongate rock bedforms is strongly influenced by bedrock properties and structure (Table 2). This bedrock control, which should be well understood to correctly interpret each example of glacial streamlining, can be summarised as follows.

Highly elongate rock bedforms occur broadly in three bedrock situations (Table 2 and Fig. 18):

- On homogeneous, isotropic bedrock surfaces, both on gneisses and on dipslopes of sedimentary rocks (Fig. 18(A)–(C)). Examples include Georgian Bay and the St. Lawrence Platform; possibly Cree Lake; Southampton Island, and Elphin, northwest Scotland (Bradwell, 2005).
- In stratified bedrock and parallel to bedrock strike, in both gently dipping and folded strata (Fig. 18(D), (E)). Examples include Ullapool, Tyne Gap, Sound of Jura in the UK; Isle Royale, Michigan (Zumberge, 1954); Mackenzie River, Frobisher Bay, Nass River, and Kaladar in Canada.
- In stratified bedrock transverse to bedrock strike, typically forming zig-zag escarpments with bullet-shaped mega rock drumlins (Fig. 18(F)). Examples are: Franklin Mountains; St. Lawrence Platform; Hazelton, Skeena River; Niagara escarpment (Eyles, 2012), and Anticosti Island (Eyles and Putkinen, 2014).

In a number of areas (Tyne Gap, Ullapool, Frobisher Bay) megagrooves and megaridges are well developed where ice flow was parallel to bedrock strike, but poorly developed or absent where ice-flow was transverse to bedrock strike. This indicates that elongate forms are easier to generate where ice flow was parallel to bedrock strike rather than transverse to strike, all other factors being equal. Thus strongly stratified bedrock with strike parallel to ice flow is particularly susceptible to the formation of elongate rock bedforms, probably because lateral plucking processes (Section 10.3) are particularly effective. The ease with which megagrooves form on homogeneous, isotropic bedrock surfaces (Georgian Bay, St. Lawrence platform) is difficult to judge, as such bedrock surfaces are relatively rare. Shield surfaces of ancient gneiss with dense and complex dense multi-directional fracture patterns, however, are very widespread (e.g., Krabbendam and Bradwell, 2014), but host elongate bedrock forms only rarely. These hard-bed substrates are thus particularly resistant to the formation of elongate bedforms, even if overridden by streaming ice. Bradwell (2013) used detailed geomorphological mapping to delineate a palaeo-ice stream tributary on the Lewisian Gneiss 'cnoc-and-lochan' terrain in Scotland; but tellingly, this particular ice stream footprint cannot be distinguished on satellite imagery or DTM data from adjacent Lewisian Gneiss terrain where ice streaming was absent.

We conclude that lithological and structural controls make some bedrock-dominated terrains much more susceptible to the formation of elongate rock bedforms than others. From this, it follows that the absence of elongate rock bedforms does not necessarily imply an absence

Table 2
Overview of characteristics, lithology, relation between ice flow and bedrock strike and measure of topographic steering of ice flow for sites described.

Site	Characteristics	Lithology	Relation ice flow and bedrock structure	Topographic steering
Georgian Bay, Lake Huron	Straight, symmetric, rounded megagrooves, 10s–100s m long.	Granulite gneiss	Not controlled by structure	Poor
St. Lawrence Platform, East Ontario	Large valley megagrooves with smaller rounded megagrooves	Limestone	Transverse to bedrock strike; parallel to faults; dipslopes	Poor
Kaladar, Ontario	Megagroove-ridge; 10s km long	Metasedimentary gneiss and schist	Parallel to bedrock strike	Poor
Lake Amadjuak, Baffin Island	Megagroove-ridges, narrow, 3–10 km long	Limestone	Not obvious, limestone probably low-angle dips, possible dipslope	Poor
Frobisher Bay, Baffin Island	Megagrooves and rock drumlins at two scales	Foliated granite gneiss	Parallel to bedrock strike	Moderate
Southampton Island, Hudson bay	Shallow megagrooves, 6–8 km long	Limestone	Transverse to bedrock strike; bedding low-angle dips?	Poor
Salisbury and Nottingham Island, Hudson bay	Megagrooves and ridges, 2–10 km long	Gneiss, abundant fractures, layering unknown	Not obvious; fracture controlled	Poor
Charles Island, Hudson Strait	Megagrooves and ridges, 2–10 km long	Gneiss, strong layering	Parallel to strike (inferred)	Moderate
Franklin Mountains, NW Territories	Megagrooves, originating on crest, 5–10 km long	Limestones, dolostone	Transverse to bedrock strike	Poor
Mackenzie River, NW Territories	Megagrooves at two scales	Limestones, dolostone	Parallel to subparallel to bedrock strike	Poor
Cree Lake, Saskatchewan	Rock drumlins and grooves, ≤1 km long	Sandstone	Transverse to bedrock strike, but no clear influence	Poor
Cameron Hills, Alberta	Straight grooves, 2–10 km long	Shale, sandstone, poorly consolidated	Not obvious	Poor
Nass and Skeena river, British Columbia	Megagrooves and ridges, crag-and-tails, rock drumlins, various scales	shale, limestone, sandstone—varied	Parallel to strike; oblique to strike; on dipslopes	Strong
Ullapool, NW Scotland	Asymmetric, angular megagrooves, 2–5 km long	Psammite, foliated, uniform	Parallel to bedrock strike	Moderate
Sound of Jura, West Scotland	Megagrooves and ridges, crag-and-tails, rock drumlins, 1–10 km long	Psammite, semipelite, amphibolite, quartzite—varied	Parallel and oblique to bedrock strike	Moderate to strong
Tyne Gap, England	Megagrooves and ridges, crag-and-tails, rock drumlins, 1–3 km long.	Limestone, sandstone, mudstone	Parallel to bedrock strike	Moderate

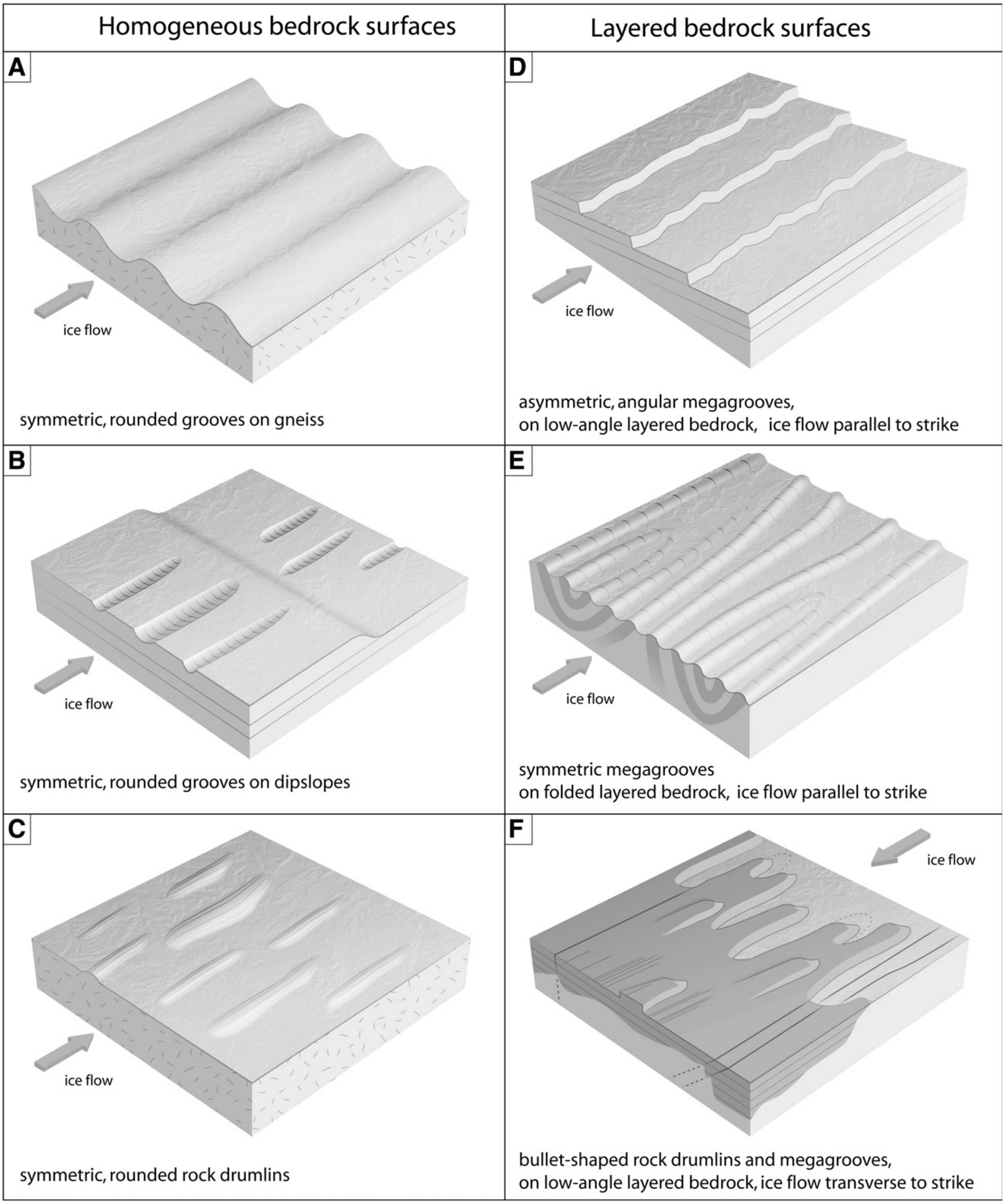

Fig. 18. Overview of different types of streamlined bedrock forms on different bedrock substrates. (A) Symmetric, rounded grooves on homogeneous rock. Example: Lake Huron, Ontario. (B) Symmetric, rounded grooves on dipslopes. Example: St. Lawrence Platform, Ontario. (C) Spindle shaped, rounded rock drumlins, independent of bedrock structure. Example: Cree Lake, NW Saskatchewan. (D) Angular, asymmetric megagrooves on stratified bedrock, gently dipping layering, with bedrock strike sub-parallel to ice flow. Examples: Ullapool, Scotland; Tyne Gap, England. (E) Symmetric grooves-ridges on stratified bedrock with steeply dipping, folded strata. Examples: Sound of Jura, Scotland; Kaladar, Ontario. (F) Bullet-shaped rock drumlins and fracture-controlled megagrooves on gently dipping strata with bedrock strike transverse to ice flow. Example: St. Lawrence Platform, Ontario.

of fast former ice flow. Thus, large areas of the deglaciated shield ares may have been exposed to fast ice-sheet flow but because of unfavourable bedrock conditions did not develop a clear geomorphic signature (e.g., Margold et al., 2015). Conversely, where large-scale elongate rock bedforms do occur on hard, resistant, unfavourable gneiss terrains (such as on Nottingham and Salisbury Island in the Hudson Strait, see Section 6), this probably implies very significant and sustained ice streaming.

10.2. Hard-bed, soft-bed and mixed-bed streamlining

On many palaeo-ice stream beds, both hard-bed and soft-bed streamlined bedforms occur. The hard-bed megagrooves at Kaladar and on the St. Lawrence Platform in Eastern Ontario are associated and aligned with soft-sediment drumlins and MSGLs of the Peterborough drumlin field in Ontario and farther down-ice in upper New York State (Boyce and Eyles, 1991; Kerr and Eyles, 2007). In Scotland, the hard-bed megalineated landscapes of the Sound of Jura and Ullapool are succeeded down-ice by 'mixed-bed' crag-and-tails and finally till-covered drumlins (Fig. 16; see also Dove et al., 2015; Bradwell and Stoker, 2015). Swath bathymetry has revealed similar 'mixed-bed' landform assemblages within submarine palaeo-ice streams tracks off West Antarctica and Norway (Ottesen et al., 2008; Graham et al., 2009; Livingstone et al., 2012; Rydningen et al., 2013). In most cases, hard-bed streamlining is followed sequentially down-ice by mixed-bed and soft-bed streamlining, logically suggesting a broad subglacial sediment flux down-ice. In coastal settings this means that, after post-glacial sea level rise, the present-day onshore record of a palaeo-ice stream may largely consist of hard-bed streamlining, with the soft-bed record occurring offshore (e.g., Sound of Jura, possibly Hudson Strait and west Norway).

The differences between hard-bed and soft-bed glacial streamlining are important for their interpretation. Hard-bed streamlining probably takes much longer to form than soft-bed streamlining: more 'geomorphic work' is needed, if only because the substrate is harder and requires more energy to erode. It is also likely that megagrooves and rock drumlins may record long-term, cumulative glacial erosion. This erosion may well involve multiple glaciations, specifically if ice streaming was strongly topographically controlled: the same topography is likely to be reoccupied repeatedly during successive glaciations. Once formed, a megalineated hard bed may be more robust and resistant to geomorphic change, so that a short-lived change in ice-flow direction leaves little or no geomorphic imprint (e.g., Sound of Jura). On soft beds, by contrast, short-lived changes in ice-flow direction may well leave a clear record of overprinting flow sets, or 'flow switching' (e.g., Jansson et al., 2003; Dowdeswell et al., 2006; Livingstone et al., 2010; Ó Cofaigh et al., 2010; Finlayson et al., 2014). In a temporal sense, hard-bed and soft-bed streamlined forms may thus record ice-flow episodes of different duration, and have different preservation potentials.

10.3. Formation mechanisms

No single erosion mechanism can explain the variety of elongate bedrock forms described in the case studies, but we regard some form of subglacial erosion paramount. A primary origin by subglacial meltwater (cf., Munro-Stasiuk et al., 2005; Lesemann and Brennand, 2009; McClenagan, 2013) is rejected here for the following reasons: (i) erosional forms generally regarded as subglacial meltwater features are typically short, localised and highly sinuous on the metre scale (e.g., Gray, 1981; Sawagaki and Hirakawa, 1997; Benn and Evans, 2010), which are very different to the long, large, distributed and straight forms described herein; (ii) flowing water is turbulent on a 0.1–10 m scale, compatible with metre-sized curvatures, whereas ice flow on this scale is essentially laminar, compatible with large-scale linear erosional features; (iii) englacial and subglacial meltwater channels in ice ('Röthlisberger Channels') are, owing to the continuous creep closure by ice, localised and ephemeral, often seasonal (Chandler et al., 2013), so that long-lived water flow in one locality is unlikely; and (iv) the linear bedrock forms described here are commonly associated with soft-sediment drumlin fields or MSGLs, collectively forming coherent flow sets covering many thousands of square kilometres, indicating formation below palaeo-ice streams, and incompatible with (i), (ii) and (iii) above. Nevertheless, curved and sinuous meltwater forms may locally occur as 'second-order' features (cf., Goldthwait, 1979) at the floors of megagrooves, as these are logical places for subglacial meltwater to concentrate. As an example, the sinuous s-forms described by Shaw (1988) and Kor et al. (1991) at Wilton Creek, Ontario, occupy a small part of the floor of a megagroove that is orders of magnitude larger and elsewhere devoid of s-forms (Section 5.2; Fig. 4(C)); similar nested meltwater forms occur at Kelley's Island, Ohio (Goldthwait, 1979).

For elongate bedforms to be formed by direct subglacial erosion, stoss-side and lee-side erosion must be suppressed, and vertical or lateral erosion enhanced. Furthermore, erosion must be sustained, aided by a positive feedback loop that enhances streamlining, whilst reducing bed asperities. We propose two 'end-member' mechanisms (Fig. 19). If some form of elongate initiation is formed (either a large striation or an s-form) or another pre-existing irregularity is present, narrow 'streams' of subglacial debris may focus abrasion, forming shallow grooves (Fig. 19(A)). The deeper and longer the groove, the stronger the tendency for large debris particles to concentrate in these grooves; this leads to increasing focussing of subglacial abrasion, enlarging and deepening the grooves, creating a positive feedback mechanism. This feedback loop will keep operating as long as large hard boulders occur at the base of the ice, and as long as ice keeps moving sub-parallel to the grooves. We suggest this abrasion-dominated mechanism is primarily responsible for the formation of the rounded, symmetric, medium-scale grooves found on the uniform granulite gneiss in the Georgian Bay area, central Ontario (Fig. 3), as well as on the limestone dipslopes on the St. Lawrence Platform in eastern Ontario (Fig. 4(C)). Thus, this mechanism is seen to be dominant on homogeneous, rock surfaces, with low initial surface roughness and relatively few bedrock irregularities.

The second 'end-member' megagroove formation mechanism relies on plucking of bedrock beneath mobile ice. Plucking as a general subglacial erosion mechanism is most effective in well-bedded and jointed rock (Krabbendam and Glasser, 2011; Hooyer et al., 2012). A special form of this process, lateral plucking (Krabbendam and Bradwell, 2011), works by plucking of rock steps oriented sub-parallel to ice flow (Fig. 19(B)). Joint-bounded blocks of the rock step, exposed to lateral ice flow, can translate or rotate out of position, depending on the joint orientation. As plucking proceeds, more joint-bounded blocks become exposed and susceptible to further plucking. Thus, strongly differential erosion occurs: slow vertical abrasion on the flat dipslopes and more rapid, sustained plucking on the lateral flanks of the bedforms (Krabbendam and Bradwell, 2011). This mechanism is likely dominant where the bedrock streamlining is sub-parallel to strike (e.g., Ullapool, Tyne Gap, Kaladar, Frobisher Bay, Nass and Skeena rivers), but we suggest it can also be effective in widening grooves initiated purely by abrasion, such as the wide megagrooves of the St. Lawrence Platform.

10.4. Ice streaming on a hard bed?

We have shown that hard-bed streamlining is common and occurred in a variety of palaeo-ice stream settings, and demonstrated that ice streaming on hard beds is certainly possible and likely to have been widespread. This is counterintuitive to the widely held notion that 'hard' beds create more basal drag and result in slower ice flow than soft beds, and that a 'deformable bed' of soft sediment may be required for ice streaming to occur (e.g., Alley et al., 1986; Peters et al., 2006; but see discussions in Piotrowski et al., 2001; Stokes and Clark, 2003; Winsborrow et al., 2010; Livingstone et al., 2012). The solution to this apparent conundrum is the realisation that a megalineated hard bed is often very smooth along the direction of ice flow. Few if any obstacles occur: melting-relegation or ice deformation around bedrock obstacles is not required for basal sliding to occur (cf., Weertman, 1957; Schoof, 2005). Instead, basal ice motion on a smooth hard bed occurs by simple frictional sliding lubricated by water, which is largely governed by the amount of basal debris in the ice. Recent in-situ and laboratory studies constrained the friction coefficient of wet-based ice, sliding over a rock surface, as $\mu = 0.02–0.05$, even at relatively high debris contents (Iverson et al., 2003; Cohen et al., 2005; Zoet et al., 2013), a

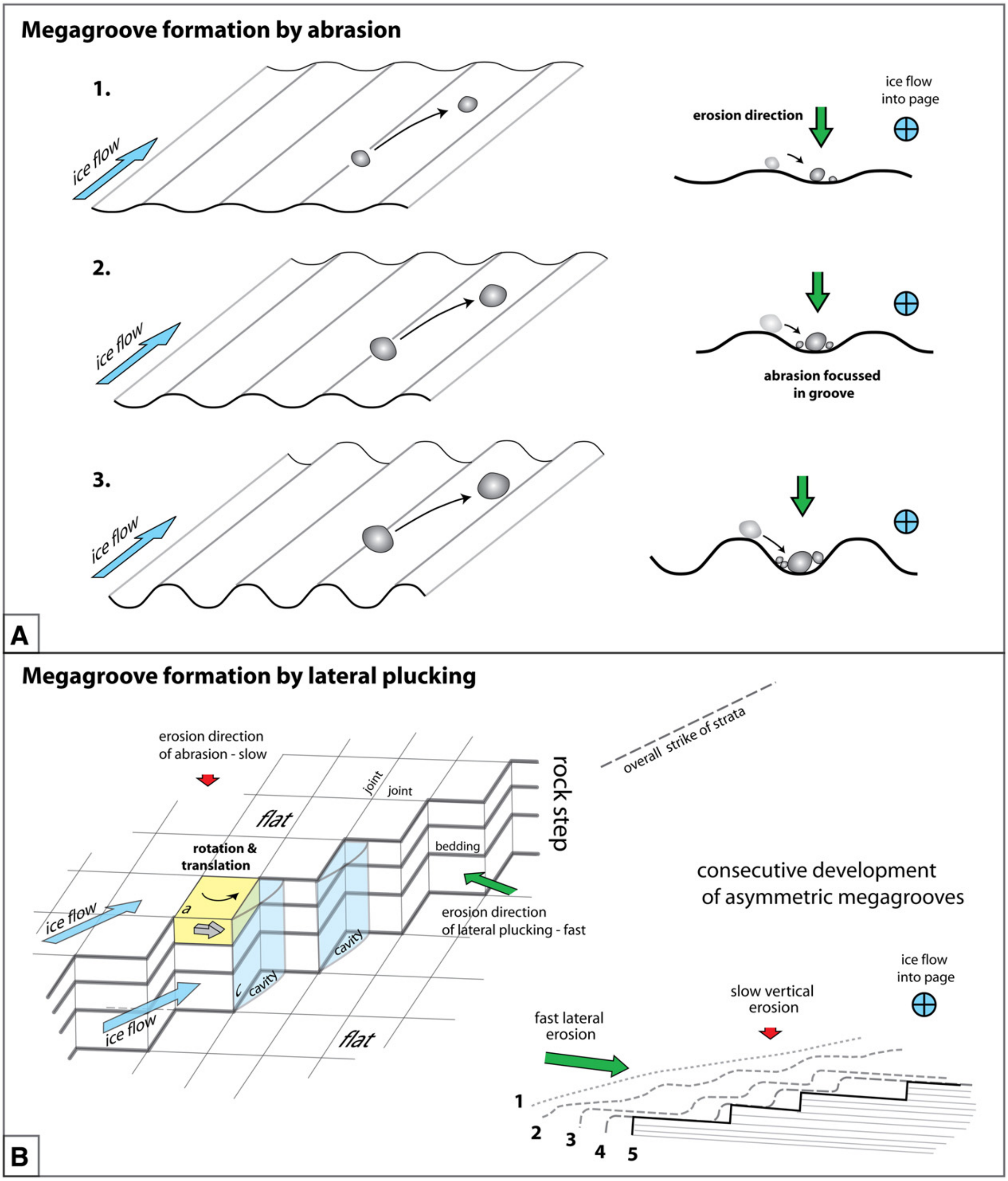

Fig. 19. (A) Proposed mechanism of megagroove formation by abrasion, focussed by debris concentration in grooves. This mechanism would be favourable for rocks that are more easily abraded than plucked. (B) Mechanism of lateral plucking, whereby lateral rock steps are subjected to fast lateral plucking, whilst the flats or dipslopes are subjected to slow abrasion only (Krabbendam and Bradwell, 2011).

figure lower than for 'Teflon' (polytetrafluoroethylene; Sawyer et al., 2003). Despite the low friction coefficient, frictional heating at high ice velocities will cause significant basal ice melting (Patterson, 1994), producing water which further lubricates the bed, but also enhances high contact forces between the basal clasts and the bed (Cohen et al., 2005), which further focusses abrasion. We suggest that the drag forces of basal ice motion over very smooth bedrock surfaces may be similarly low as for deformable sediment. Thus, because of their inherently low roughness, smooth hard beds can facilitate ice streaming, and need to be distinguished from rough hard beds.

11. Conclusions and implications

In this work we have identified and analysed a number of hard-bed glacial terrains, dominated by a range of large-scale elongate rock bedforms. We have found that these streamlined 'hard-bed' landsystems occur in variety of palaeo-glaciological settings, both on crystalline shield rock surfaces as well as on weaker sedimentary rocks. The often unstated assumption behind many assessments of former ice streams is that the geomorphic record has been primarily imprinted in sediment. Instead, we conclude that a substantial component of streamlined flow sets within the former mid-latitude ice sheets occur in bedrock. As more high-resolution digital terrain models and offshore bathymetry data become available, we expect that more glacial bedform fields will be discovered. Nevertheless, with currently available data it is clear that the significance of glacially streamlined bedrock for geomorphology and glaciology are manifold. Below we highlight six aspects:

- Regarding palaeo-glaciological reconstructions, more fast-flow corridors and palaeo-ice streams can be identified by mapping streamlined hard-bed landforms; in many cases, previously identified palaeo-ice stream footprints can be traced farther up-ice, into their bedrock-dominated onset zones.
- Elongate rock bedforms are formed by direct subglacial erosion. We propose that the main end-member formation mechanisms are focussed abrasion and lateral plucking. As many soft-bed and hard-bed landforms are morphologically similar, we suggest that this has broader implications for the formation mechanisms of some soft-bed landforms.
- A number of ice sheets (Pleistocene and modern) formed on Precambrian shield rocks, surrounded by younger sedimentary strata. Our work shows that different types of elongate rock bedforms form on different substrates.
- Bedrock streamlining provides evidence for long-term, cumulative fast ice flow, whereas soft-sediment streamlining provides evidence for more 'short-term' fast ice flow, such as transient ice streaming, flow switching and surge events.
- The widely held view that soft-sediment beds are required for ice streaming is not supported by the geological evidence. Ice streaming on hard beds was widespread, and almost certainly still occurs within modern ice sheets. It follows that a deformable bed is not a necessity for ice streaming to occur, rather the lack of roughness on streamlined hard beds, aided by frictional melting and associated lubrication, can facilitate fast basal sliding on such smooth substrates.

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