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

Maarten Krabbendam [a,*], Nick Eyles [b], Niko Putkinen [c], Tom Bradwell [a,d], Lina Arbelaez-Moreno [b]

[a] British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA Scotland, UK
[b] Physical and Environmental Sciences, University of Toronto, Scarborough, ON M1C 1A4, Canada
[c] Geological Survey of Finland, P.O Box 97, F1-67101 Kokkola, Finland
[d] Biological and Environmental Sciences, University of Stirling, Stirling, FK9 4LA Scotland, UK

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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

* Corresponding author.
E-mail address: mkrab@bgs.ac.uk (M. Krabbendam).

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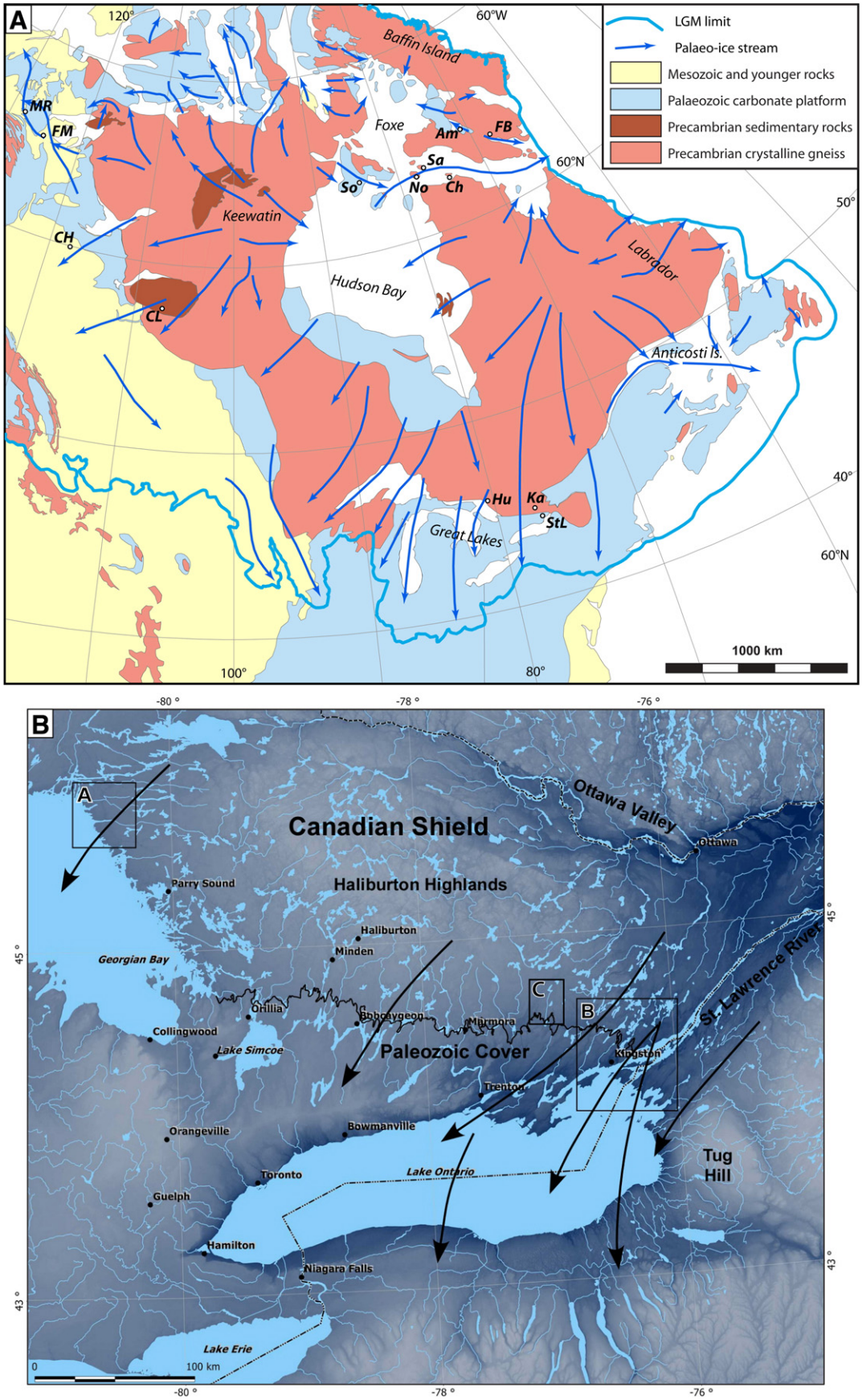

Fig. 1. (A) Laurentide Ice Sheet with reported palaeo-ice streams (schematic), simplified bedrock geology, extent at Last Glacial Maximum (LGM). Indicated study areas: Am = Lake Amadjuak; Ch = Charles Island; CH = Cameron Hills; CL = Cree Lake; FB = Frobisher Bay; FM = Franklin Mountains; Hu = Lake Huron; 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.