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# Crevasse-squeeze ridge corridors: Diagnostic features of late-stage palaeo-ice stream activity

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ABSTRACT

A 200-km-long and 10-km-wide linear assemblage of till-filled geometrical ridges on the bed of the Maskwa palaeo-ice stream of the late Wisconsinan southwest Laurentide Ice Sheet are interpreted as crevasse-squeeze ridges (CSR) developed during internal flow unit reorganization, immediately prior to ice stream shutdown. Ridge orientations are predominantly orientated WNW–ESE, with a subordinate WSW–ENE alignment, both indicative of ice fracture development transverse to former ice stream flow, as indicated by NNE–SSW aligned MSGL. Subglacial till injection into basal and/or full depth, mode I and II crevasses occurred at the approximate centreline of the ice stream, in response to extension and fracturing. Landform preservation indicates that this took place during the final stages of ice streaming, immediately prior to ice stream shutdown. This linear zone of ice fracturing therefore likely represents the narrowing of the fast-flowing trunk, similar to the plug flow identified in some surging valley glaciers. Lateral drag between the final active flow unit and the slower moving ice on either side is likely recorded by the up-ice bending of the CSR limbs. The resulting CSR corridor, here related to an individual ice stream flow unit, constitutes a previously unreported style of crevasse infilling and contrasts with two existing CSR patterns: (1) wide arcuate zones of CSRs related to widespread fracturing within glacier surge lobes; and (2) narrow concentric arcs of CSRs and recessional push moraines related to submarginal till deformation at active temperate glacier lobes.



## 1. Introduction

Crevasse squeeze ridges (CSRs) have been unequivocally linked to surging glaciers based upon modern process-form regimes (Sharp, 1985a, 1985b; Bennett et al., 1996; Evans and Rea, 1999, 2003; Evans et al., 2007), which have in turn been employed to identify glacier and ice stream surging in the palaeoglaciological record (Evans et al., 1999, 2008). In these contemporary and ancient case studies, the pattern of CSR development is distinctive in that they occur as cross-cutting, geometrical ridge networks composed of diamicton (basal till) and extend across large parts, if not all, of the glacier bed and form arcuate, ice flow-transverse, subparallel sets of conjugate paired ridges that cross-cut each other at a range of angles up to 90° (Sharp, 1985a; Evans and Rea, 1999, 2003). The requirements for the preservation of CSRs in the landform record are that they form by subglacial sediment injection into crevasses and following the switch from surge to quiescence phases no further, or minimal, internal creep deformation occurs; and hence the CSRs form the prominent part of the *death mask* (Wellner et al., 2006) of the glacier bed.

The process responsible for the development of CSRs has been linked to full depth crevassing by Rea and Evans (2011) in a reconciliation of CSR forms, the structural glaciology of modern surging glaciers, and linear elastic fracture mechanics (cf. van der Veen, 1998a, 1998b) for mode 1 tensional crevasses. They conclude that, although complex surface crevassing is a typical characteristic of surging glaciers because of the high extensional strain rates, they are unlikely to extend to the glacier bed and hence allow the vertical squeezing of subglacial till. More likely they develop by hydrofracturing as basal water pressures approach overburden, leading to the formation of full-depth, bottom-up, mode 1 tensional crevasses behind the surge front.

Despite an unequivocal association with surging glacier snouts, not all CSRs are diagnostic of surging, as some ridges have been reported from modern active temperate glacier margins, where they form in response to submarginal till extrusion into splaying crevasses or pecten (ice marginal reentrants) and are closely associated spatially and genetically to arcuate, inset sequences of recessional push moraines (Okko, 1955; Price, 1970; Evans et al., 2015). Surge-derived CSRs, on the other hand, are largely defined by their occurrence in expansive, submarginal to subglacial assemblages, typically juxtaposed with other elements of the surging glacial land system. Clearly, therefore, CSR patterns are critical to assessing surging versus nonsurging dynamics of former glaciers. Although large areas of CSRs have been associated

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with palaeo-surging in the SW Laurentide Ice Sheet, these occur as glacier-wide networks with arcuate, downflow-convex limbs (Evans et al., 1999, 2008, 2014). In contrast, we here report on a linear assemblage of diamicton-cored CSRs from the bed of a palaeo-ice stream that formerly operated within the southwest margin of the Laurentide Ice Sheet (Ross et al., 2009; Ó Cofaigh et al., 2010) and propose that the pattern and distribution of the ridge network is related to ice stream dynamics, specifically internal flow unit reorganization, immediately prior to its shutdown.

## 2. Methods

Glacial landform mapping in the field area was previously undertaken by Ó Cofaigh et al., 2010 using hillshade digital elevation models constructed from 3-arc sec (90-m resolution) Shuttle Radar Topography Mission (SRTM) imagery (Fig. 1). This facilitated mapping of the distribution of diagnostic palaeo-ice stream landforms such as flutings and megascale glacial lineations (MSGLs), zones of smoothed topography (ice stream trunk zones), and ice flow-transverse features such as moraines and CSRs. This mapping identified a number of cross-cutting palaeo-ice stream imprints, the most prominent of which was the early flow (phase 1) "Maskwa ice stream" (Ross et al., 2009; Ó Cofaigh et al., 2010). A prominent linear zone of transverse, cross-cutting ridges (CSRs) overprinting MSGL was identified within the southern part of the Maskwa ice stream trunk zone by Ó Cofaigh et al. (2010), who interpreted them as indicators of ice stream stagnation. In order to further understand the genesis of the CSRs in this area and more specifically their implications for interpreting ice stream dynamics, we mapped the geomorphology of the southern trunk zone of the Maskwa ice stream at large scale (1:10,000), using a combination of higher resolution (1-arc sec; 30-m) SRTM imagery, the Canadian Digital Elevation Database (CDED), and Google Earth images based on CNES SPOT imagery taken in 2003. This facilitated not only the accurate mapping of all components of the CSR network, but also their relationships to other palaeo-ice stream landforms.

## 3. Characteristics of crevasse-squeeze ridge (CSR) corridors

Geometrical ridge networks have long been recognized as important components of the glacial landform record in the Plains region of western Canada and the USA (Fig. 2A). Gravenor and Kupsch (1959) summarized the characteristics of these features, including the forms reported in this paper, based upon initial mapping and ground-based studies (cf. Flint, 1928; Sproule, 1939; Deane, 1950; Colton, 1955), describing them as till-cored, straight or slightly arcuate, and intersecting at acute or right angles to form waffle, diamond, or box patterns, with some intersections displaying a resemblance to hairpins or wishbones. These characteristics were used by Gravenor and Kupsch (1959) to link them to

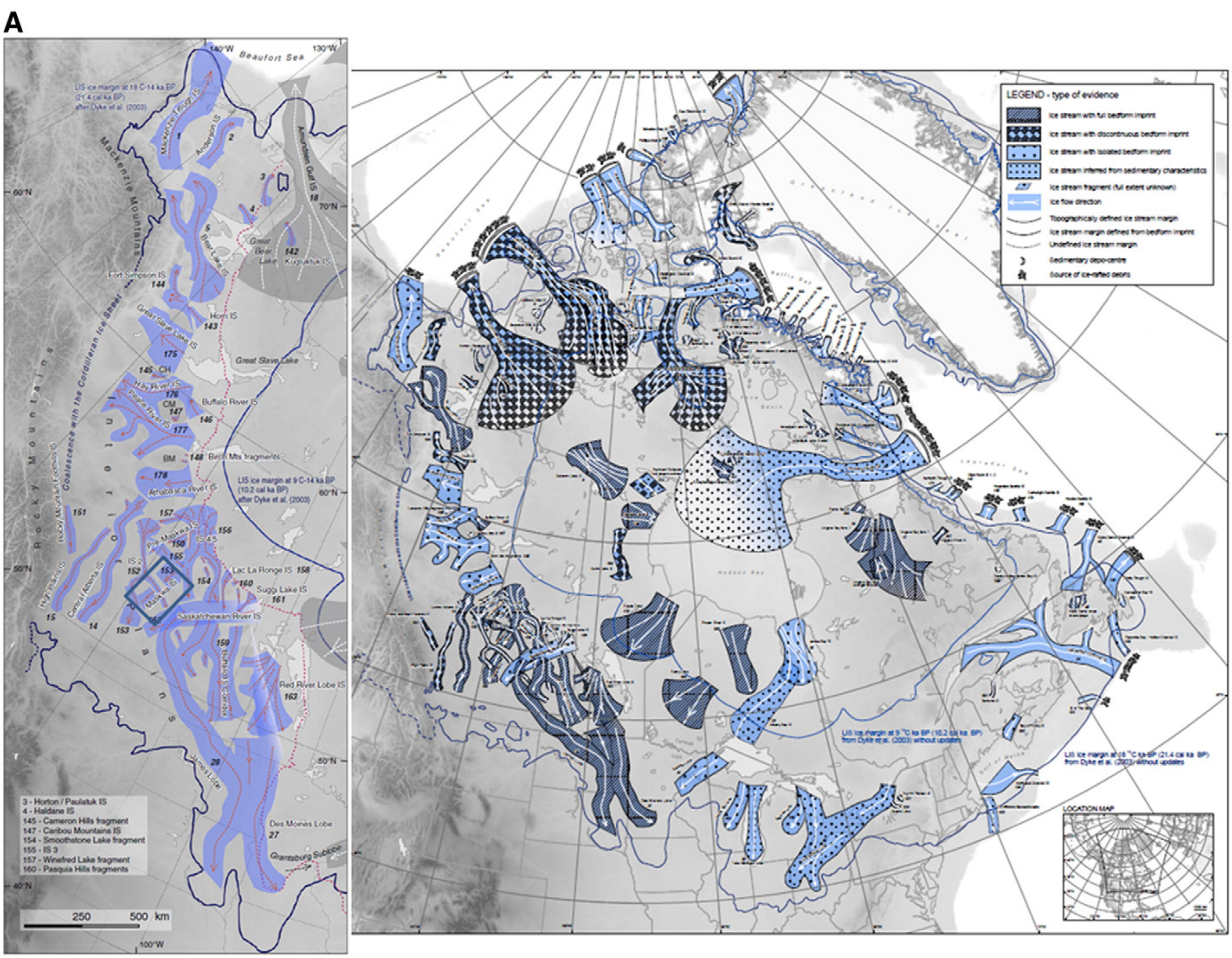


**Fig. 1.** Location maps (A) from Margold et al. (2015) and annotated SRTM imagery (B) from Ó Cofaigh et al. (2010) showing the locations of major palaeo-ice streams on the western plains of North America. The area of the Maskwa palaeo-ice stream bed used in this study is identified by a blue box on the large-scale map and SRTM image.