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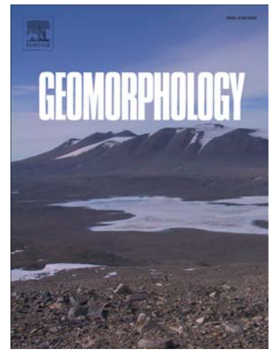

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Crevasse-squeeze ridge corridors: diagnostic features of late-stage palaeo-ice stream activity

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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.

Keywords: crevasse-squeeze ridge; palaeo-ice stream; full depth crevassing; Laurentide Ice Sheet

1. Introduction

Crevasse squeeze ridges (CSRs) have been unequivocally linked to surging glaciers based upon modern process-form regimes (Sharp, 1985a, b; 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, b) 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 with palaeo-surging in the SW Laurentide Ice Sheet, these occur as glacier-wide networks with arcuate, downflow-concave 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 second (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 second; 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 controlled disintegration, whereby ice structures dictated the accumulation of diamictic sediment; hence they became known as *linear disintegration ridges*. The spatial patterns and regional distributions of these ridge networks have more recently been employed by Evans et al. (1999, 2008, 2014) to propose that they originate by the squeezing of subglacial till into basal crevasses formed during glacier surging, as identified on modern surging glaciers (Fig. 2A; Sharp, 1985a, b; Evans and Rea, 1999, 2003; Evans et al., 2007; Schomacker and Kjaer, 2007).

The CSRs overprinting MSGL in the trunk zone of the Maskwa palaeo-ice stream (Ó Cofaigh et al., 2010) are 1–4.5 m high based on field observations. These features had previously been mapped by Campbell (1987a, b) on the surficial geology maps for North Battleford (National Topographic System [NTS] 73C) and St Walburg (NTS 73F) and variously classified as *crevasse fillings* and *minor ridged moraine*. As a network, these CSRs occur within a corridor up to 11.3 km across (mean 6.4 km) bordered by predominantly abrupt margins (Figs. 4, 6). This corridor extends for approximately 200 km and comprises two segments that span the North Saskatchewan River valley (Fig. 5) on either side of the ESE-flowing phase 2 palaeo-ice stream of Ó Cofaigh et al. (2010) that we refer to as the North Saskatchewan River Valley Ice Stream. The CSRs are absent in the area that has been cross-cut by this later ice stream flow. The margins of the former Maskwa ice stream are clearly demarcated by ice stream shear margin moraines (*sensu* Stokes & Clark, 2002). Measurements of the orientations of individual CSR ridges taken from the Google Earth imagery (Fig. 6) reveal a prominent WNW-ESE alignment with a subordinate direction to the WSW-ENE. This likely reflects fracture development transverse to former ice stream flow, which was predominantly NNE-SSW based upon the majority of MSGL alignments (Fig. 6). The lengths of individual CSRs derived from the Google Earth imagery (Fig. 6) tend to cluster around 400-1000 m, although a few individual ridges are between 3000-5000 m long.

The southernmost limit of the CSR corridor is demarcated by a conspicuous multiridge moraine (Figs. 4, 7), hereby called the Handel moraine after a nearby village. The moraine does not represent an ice stream shear margin feature of the southern phase 2 ice stream because it displays a distinct lobate shape (with the most prominent lobe coinciding with the southern end of the CSR corridor) and because the cross-cutting phase 2 ice stream bed lies farther to the south.

North-south orientated eskers that could be associated with drainage from the Maskwa ice stream are sparsely distributed over the bed and only a few, straight-limbed eskers occur in the CSR corridor. Other potential subglacial drainage features are north-south orientated, water-filled depressions, an excellent example being Tramping Lake reservoir at the south end of the CSR corridor (Figs. 3, 4). In contrast, meltwater features at the northern end of the south CSR corridor form a continuous chain of aligned channel and esker segments running across (i.e., ice flow-transverse) the bed of the Maskwa ice stream and parallel with the margin of the younger North Saskatchewan River Valley Ice Stream ~ 8 km to the north (Figs. 3B, 4).

A later stage assemblage of features clearly cross-cuts the subglacial bedforms of the Maskwa ice stream at the southernmost limit of the mapped area (Fig. 4) and comprises a fluted hill-hole pair and esker network produced by the incursion of a glacier lobe flowing from NNW-SSE. This assemblage is identified here merely to differentiate it from the Maskwa ice stream features.

4. Interpretation of the Saskatchewan CSR corridor

Simple landform relationships facilitate an interpretation of the sequence of events that led to the development of the Maskwa palaeo-ice stream land system. The earliest phase of ice streaming (Ó Cofaigh et al., 2010) is evident through the association with MSGL and shear margin moraines (Fig. 4). Based upon its excellent preservation and superimposition on all other bedforms, the CSR corridor represents the final stages of this early phase of ice streaming; whereby a linear zone of ice fracturing developed along the approximate centreline of the Maskwa ice stream. Regardless of the sediment infilling mechanism (i.e., top down vs. bottom up), the CSR pattern is unlike any reported from other settings, such as surging glaciers and radially crevassed active temperate lobes (Fig. 8). Modern ice streams, particularly examples of pure ice streams along the Antarctic Siple Coast, have been observed to develop such linear zones of crevasses along shear margins at the junction between relatively fast- and slow-moving ice flow units. These crevassed zones are several kilometres wide and have been observed to comprise arcuate and intersecting crevasses (Vornberger and Whillans, 1990; Bindschadler and Scambos, 1991; Whillans and van der Veen, 1997; Harrison et al., 1998; Raymond et al., 2001). Kamb et al. (1985) reported the development of wrench faults along the lateral margins of Variegated Glacier, Alaska, between the fast-moving plug flow of the surging ice and the slow-moving ice along the valley sides.

Raymond et al. (2001) and Whillans et al. (2001) reported a distinct crevasse pattern produced at modern ice stream shear margins, which displays an outer zone of arcuate crevasses several hundred metres wide, inboard of which occurs a chaotically crevassed zone several kilometres wide and then an inner zone of arcuate crevasses bending down flow. This is in contrast to the pattern of CSRs on the Maskwa palaeo-ice stream bed, which form cross-cutting linear, flow transverse to concave, down ice-bending ridges along the centreline of the ice stream.

Other modern analogues from the Antarctic Ice Sheet include fast-flowing outlet glaciers comprising heavily crevassed multiple flow units separated by apparent incipient shear zones, an excellent example being the Mulock Glacier in the Transantarctic Mountains (Fig. 9). The image clearly illustrates that separate flow units are operating within one glacier trunk, but the lack of full depth crevasse penetration is problematic in using this as an appropriate analogue. The modern Antarctic linear crevasse zones do not penetrate to the bed and hence could not be filled with till and cannot generate a landform. Basal or full depth crevassing is necessary for the Maskwa CSRs to form by till injection, so we likely have to entertain the notion that the ice was relatively thin and full depth crevassing was initiated in a similar fashion to the full depth crevassing created during surging of terrestrially-based ice lobes (cf. Rea and Evans, 2011). This is not unreasonable considering that the ice stream was close to final shutdown and that the CSRs are well preserved; hence a lot of ice-contact melting and late-stage motion did not disrupt their forms. We therefore propose that the CSR corridor represents extension and fracturing of the last active flow unit within the Maskwa ice stream, potentially representing the narrowing of its fast-flowing centreline and akin to Kamb et al.'s (1985) plug flow in surging glaciers; the lateral drag between this final active flow unit and the slower, possibly stagnant ice on either side is evident in the apparent up-ice bending of the CSR limbs (actually the down-ice deflection of the central part of the flow), especially in the southernmost part of the CSR corridor. The Handel moraine demarcates the location of the ice stream margin at this time, and its lobate extension at the southern end of the CSR corridor clearly records the more extensive limit of the active plug within the ice stream.

There are a number of ways to interpret the formation of the Maskwa CSRs. Drawing on the surging glacier model (Evans and Rea, 1999, 2003; Evans et al., 1999), they formed by injection of till into basal crevasses immediately prior to ice stream shutdown. Subsequent to formation, little internal deformation occurred, as testified by the preservation of the CSRs. The restricted extent of the CSRs within the middle of the palaeo-ice stream bed is unusual and could be interpreted in a number of ways. The CSRs represent a mix between mode 1 purely tensile fractures and mode 2 strike-slip fractures. The mode 2 fractures indicate lateral shear (van der Veen, 1999) presumably between the west and east sides of the ice stream, suggesting that the centre and eastern side of the ice stream displayed a relative velocity difference; they were either moving as two individual flow units or the ice stream margin migrated westward. Following the analyses by van der Veen (1999), the relatively small angular difference between the principal tensile stress and the mode 2 crevasses suggests that the ratio of shear to tensile stress, during crevasse propagation, was in the order of 0.1-0.5. The asymmetrically concave down-flow pattern displayed by the CSRs in the southern half of the Maskwa ice stream suggests that the western side was the fastest/latest flowing unit, creating a sinistral shear zone. The lack of CSRs outside of this zone is intriguing and suggests that it was only in this zone between the two flow units that stresses were sufficient to promote full-depth or basal crevassing. Tentatively this could indicate that basal water pressures were not sufficiently high to form hydrofractures across the entire bed. Alternatively, water pressures may have been similar across the bed and lateral shear initiated the crevasses, because mode 2 fracture is independent of the lithostatic stress and so can be full depth and hence water pressure is not critical (either from filling in the case of top-down or at the bed in the case of bottom-up) (Hambrey, 1976; van der Veen, 1999).

The relative paucity of glacifluvial deposits and sparsity of obvious straight-limbed esker ridges within the CSR corridor indicates that glacifluvial infilling, akin to either the zig-zag esker development in heavily crevassed surging glaciers (Evans and Rea, 1999, 2003) or the pressurized ice tunnels and hydrofracture fill eskers of subpolar glaciers (Evans et al., 2012), was subordinate to subglacial till squeezing in terms of landform generation. However, preservation potential might be significant here. In explaining their *linear disintegration ridges*, Gravenor and Kupsch (1959) proposed a combination of top down infill (stratified sediment ridges; Flint, 1928) and bottom up infill (till squeezing; Hoppe, 1952). As the pattern of crevasse opening at an ice stream shear margin would be similar in basal and surface locations, the pattern of geometrical ridge networks would also be similar once let down onto the glacier bed, albeit with supraglacial ridges superimposed on subglacial ridges unless full depth crevassing had prevailed. However, two processes specific to the accumulation of top down infills would make their preservation less likely after deglaciation: (i) the large amount of supraglacial reworking of the surface infills during ice meltout would result in them being less pronounced in the final landscape record, thereby leaving discontinuous, linear chains of glacifluvial hummocks; (ii) the likely relative sparsity of supraglacial debris on a continental ice sheet presumably resulted in only a restricted number of crevasses being infilled, specifically those that were used as meltwater drainage pathways, thereby creating infills that resemble the zig-zag eskers of surging glacier land systems (i.e., eskers ridges with linear segments aligned subparallel to former ice flow). More significantly, subglacial meltwater drainage pathways within an ice stream system are likely to have been well developed, as indicated by the ice flow parallel esker ridges and tunnel channels on the geomorphology map (Fig. 4), and hence glacifluvial deposition was less disrupted by crevassing than in surging systems. However, an interesting association of meltwater features at the northern end of the south CSR corridor, in the form of aligned channel and esker segments running across the former ice stream bed (i.e., transverse to ice flow directional indicators), documents meltwater drainage that must post-date Maskwa ice stream shutdown. We suggest that this was subglacial drainage that developed in the stagnant Maskwa ice stream along the southern edge of the phase 2 (North Saskatchewan River valley) ice stream when it was operating.

5. Discussion

The interpretation of narrow corridors of CSRs on the bed of the Maskwa palaeo-ice stream as the product of fracture during the final stages of ice stream shut down further demonstrates that these landforms individually are not diagnostic of either surging on the one hand or glacier submarginal till extrusion into splaying crevasses on the other. However, patterns of CSR distribution can be employed to infer palaeoglacier dynamics. Common to all genetic origins, and essential for landform preservation, is the squeezing of subglacial till into crevasses. Three CSR patterns can therefore be reconciled with specific glacier dynamics and depositional settings (Fig. 8): (i) wide arcuate zones of CSRs related to widespread fracturing within glacier surge lobes (Evans and Rea, 1999, 2003; Rea and Evans, 2011); (ii) narrow concentric arcs of CSRs and recessional push moraines related to submarginal till deformation at active temperate glacier lobes, which are marginal features related to active ice recession and hence not applicable to the present case study (Okko, 1955; Price, 1970; Evans et al., 2015); and (iii) CSR corridors related to the fracturing of individual flow units between the lateral shear zones formed within ice streams.

Within the more extensive assemblages of surge lobe CSRs, zig-zag eskers are also likely to develop in association with the ridges because meltwater drains away from the bed via full depth crevasse networks, creating depositional features that are recognizable in a landscape record that is intimately linked with surge termination (Evans and Rea, 2003). Apparently, the eskers associated with the CSR corridor reported here, whilst displaying linear or straight segments, do not develop strong zig-zag morphologies. This is likely related to either the maintenance of subglacial meltwater drainage pathways in ice streams, which do not get disrupted or blocked in the same ways as those in surging systems, or more likely there was insufficient meltwater to drain upward through fractures as occurs in surging glaciers.

In contrast to CSRs created by surging and ice streaming, those produced in pecten along the narrow zones of active temperate glacier snouts are unlikely to be associated with zig-zag eskers because meltwater drainage pathways are operating as well-established arborescent subglacial drainage basins in such settings (Boulton et al., 2007a, b; Storrar et al., 2015). This allows us to further refine the diagnostic criteria for CSRs produced in push moraine assemblages of active temperate glacier lobes (Fig. 8), whereby they are never juxtaposed with zig-zag eskers in a single process-form regime.

6. Conclusions

A 200-km-long and 10-km-wide linear assemblage or corridor of geometrical ridges has been identified within the geomorphic signature of the bed of the Maskwa palaeo-ice stream of the southwest Laurentide Ice Sheet. The diamictic composition of the ridges indicates that they were created by subglacial till injection into basal and/or full depth crevasses and are therefore crevasse squeeze ridges (CSR). Their preservation implies that they are the product of the final stages of ice streaming prior to ice stream shutdown, whereby a linear zone of ice fracturing developed in response to extension and fracturing of the last active flow unit. This likely represents the narrowing of the fast-flowing trunk, with lateral drag between the final active flow unit and the slower moving ice on the eastern margin recorded by the up-ice bending of the CSR limbs.

With respect to structural glaciology, the CSRs represent a mix between purely tensile, mode 1, fractures and strike-slip, mode 2, fractures, with the mode 2 fractures representing lateral shear either between two individual ice stream flow units or due to lateral margin migration and narrowing of a single flow unit. The concave down-flow pattern displayed by the CSRs in the southern half of the Maskwa ice stream trunk signature is thought to reflect the development of a sinistral shear zone created by the relatively faster flow of the ice stream's western edge. The concentration of CSRs in a corridor associated with the development of lateral shear indicates that it was the only area where stresses were sufficient to promote full-depth or basal crevassing.

The identification of narrow corridors of CSRs on the beds of palaeo-ice streams, where evolution is linked to the final stages of ice stream shutdown, reveals that these landforms individually are not diagnostic of surging or glacier submarginal till extrusion into splaying crevasses. This is despite having common process origins that are essential for landform preservation, *vis a vis* the squeezing of subglacial till into basal crevasses. Nevertheless, patterns of CSR distribution and their relationships with other landforms can be employed in a glacial land systems methodology to infer palaeoglacier dynamics. Hence three CSR patterns can be identified in this context, including (i) wide arcuate zones of CSRs related to widespread fracturing within glacier surge lobes; (ii) narrow concentric arcs of CSRs and recessional push moraines related to sub-marginal till deformation at active temperate glacier lobes; and (iii) CSR corridors related to the fracturing of individual flow units along the lateral shear zones formed within ice streams.

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Figure captions

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.

Fig. 2. Aerial photograph images of CSRs from: (A) near Lloydminster, Alberta, Canada, on the bed of the former SW Laurentide Ice Sheet; and (B) on the recently deglaciated foreland of the Icelandic surging glacier Bruarjökull (ice margin demarcated by broken white line).

Fig. 3. Relief-shaded SRTM images (azimuth is 315° and sun angle is 45°) of the Laurendtide Ice Sheet bed in the vicinity of the Maskwa palaeo-ice stream showing the landforms depicted in Fig. 4: (A) location, topography, and subglacial bedforms; (B) detailed view of the southern part of the ice stream bed showing various glacial landforms.

Fig. 4. Glacial geomorphology map of the central Maskwa ice stream bed in the vicinity of the CSR corridor.

Fig. 5. Google Earth extracts of parts of the CSR corridor located to the (A) north and (B) south of the North Saskatchewan River Valley Ice Stream footprint. Locations are given in Fig. 3A.

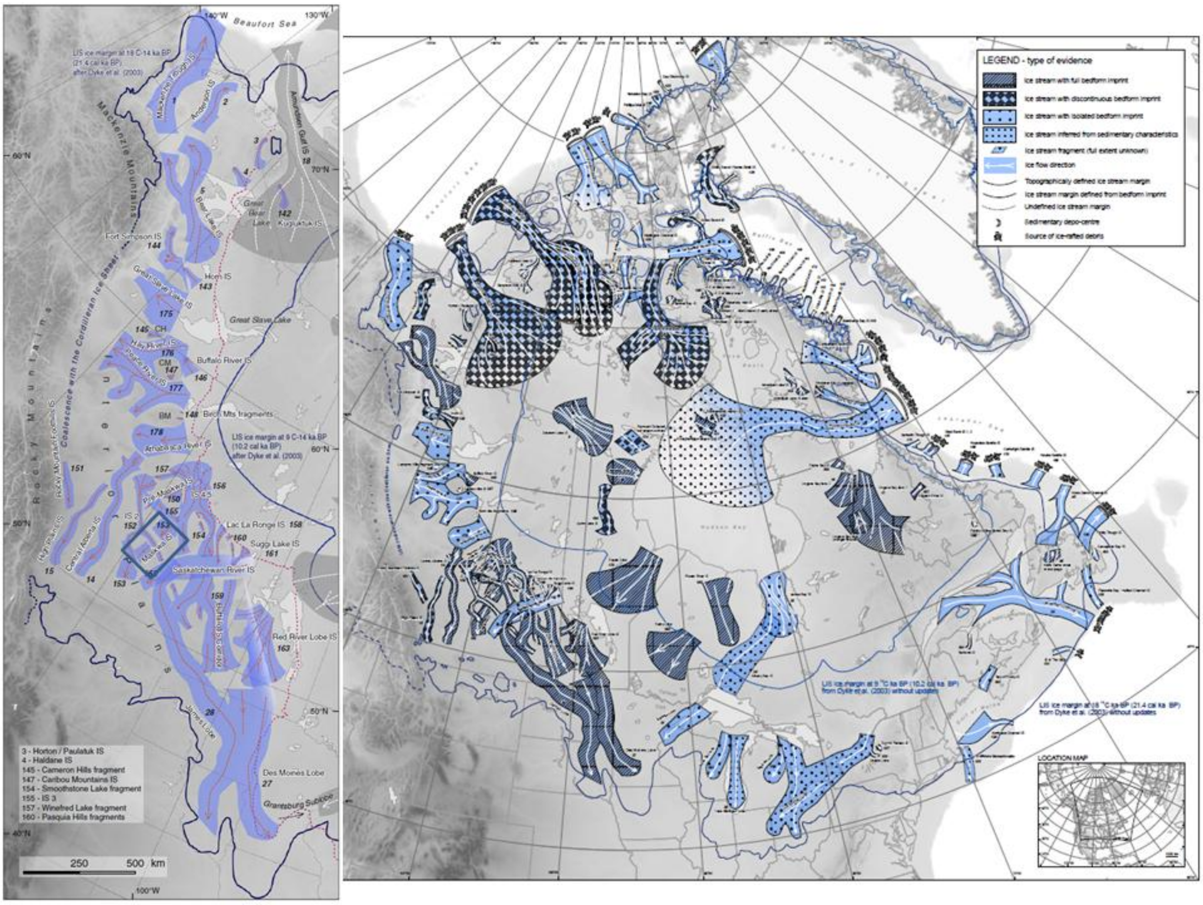
Fig. 6. Map showing the CSRs and CSR corridor extent (heavy lines), alongside morphometric data collected from Google Earth imagery. Separate measurements of CSR and MSGL orientation were collected from the northern and southern sectors of the Maskwa Ice Stream bed. Line graphs show the CSR corridor width and the histogram shows the distribution of individual CSR length for all CSRs. n = sample size and r = radius size.

Fig. 7. The Handel moraine near Tramping Lake, shown in (A) SRTM and (B) Google Earth imagery (showing the area indicated by the box in A).

Fig. 8. Schematic representation of the different CSR patterns produced by glaciers with particular flow characteristics and dynamics. Blue lines are CSRs in surge lobes and ice streams but push moraines, minor CSRs, and till eskers around active temperate lobes. Arrow heads

represent esker ridges, which for CSR corridors are hypothetical and require further testing. Ice flow in each case is from top right to bottom left.

Fig. 9. Google Earth image from 1999 showing the surface of the Mulock Glacier, Antarctica, and its heavily crevassed, multiple flow units separated by apparent incipient shear zones.


Beaufort Sea
Mackenzie Mountains
Amundsen Gulf IS
Great Bear Lake
Kugluktuk IS
Fort Simpson IS
Great Slave Lake
Buffalo River IS
Birch Mts fragments
Athabasca River IS
Lac La Ronge IS
Saskatchewan River IS
Red River Lobe IS
James Lobe
Des Moines Lobe
3 - Horton / Paulatuk IS
4 - Haldane IS
145 - Cameron Hills fragment
147 - Caribou Mountains IS
154 - Smoothstone Lake fragment
155 - IS 3
157 - Winefred Lake fragment
160 - Pasquia Hills fragments
250 500 km
LEGEND - type of evidence
Ice stream with full bedform imprint
Ice stream with discontinuous bedform imprint
Ice stream with isolated bedform imprint
Ice stream inferred from sedimentary characteristics
Ice stream fragment (full extent unknown)
Ice flow direction
Topographically defined ice stream margin
Ice stream margin defined from bedform imprint
Undefined ice stream margin
Sedimentary depo-centre
Source of ice-rafted debris
LOCATION MAP

(B)
110°
55°
53°
49°
Pre 1
Pre 1
Pre 1
3
1
1
1/
Pre 1
Pre
1
2/3
2
3/4
1
Pre
1
2
1
3
2/3
2
2-4?
1/
Pre 1
2/3
1
1
Pre 1
1
Pre
1/1
2
1
1
Pre 1
Pre 1
Pre 1
Ice Stream
Track
Overridden
Moraines
End Moraines
Late Wisconsinan
Ice Limit

Fig. 1

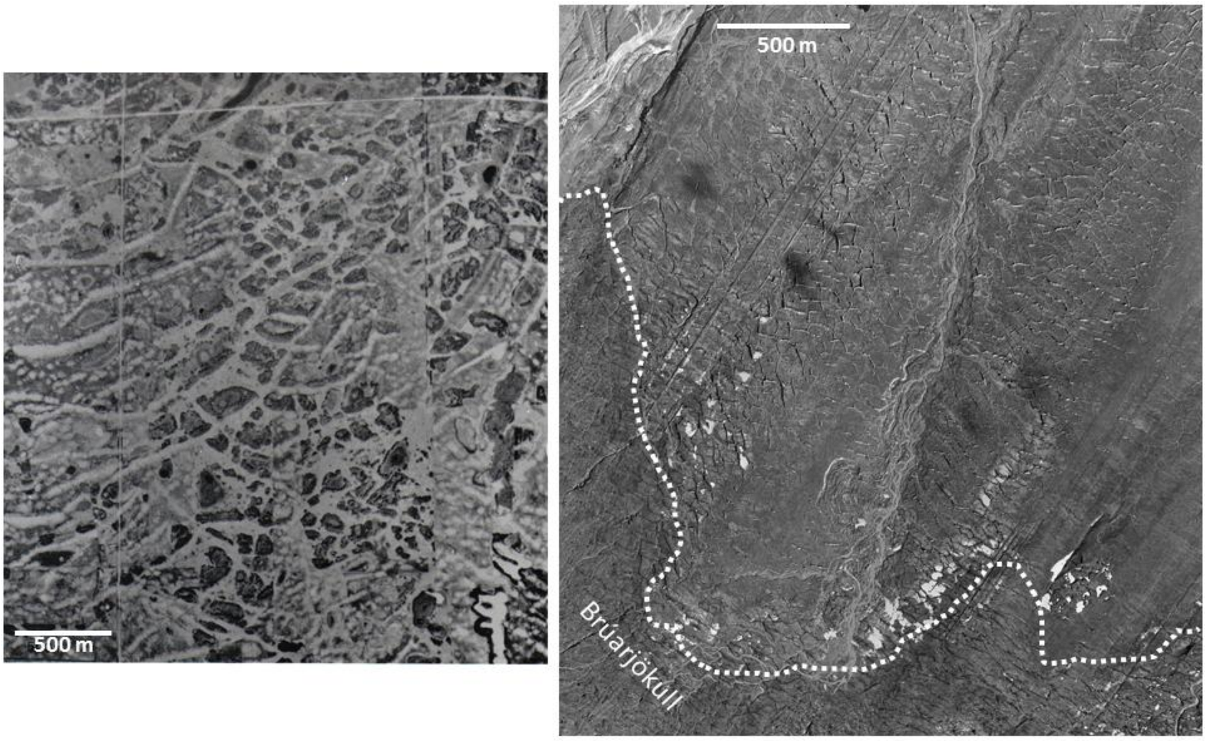
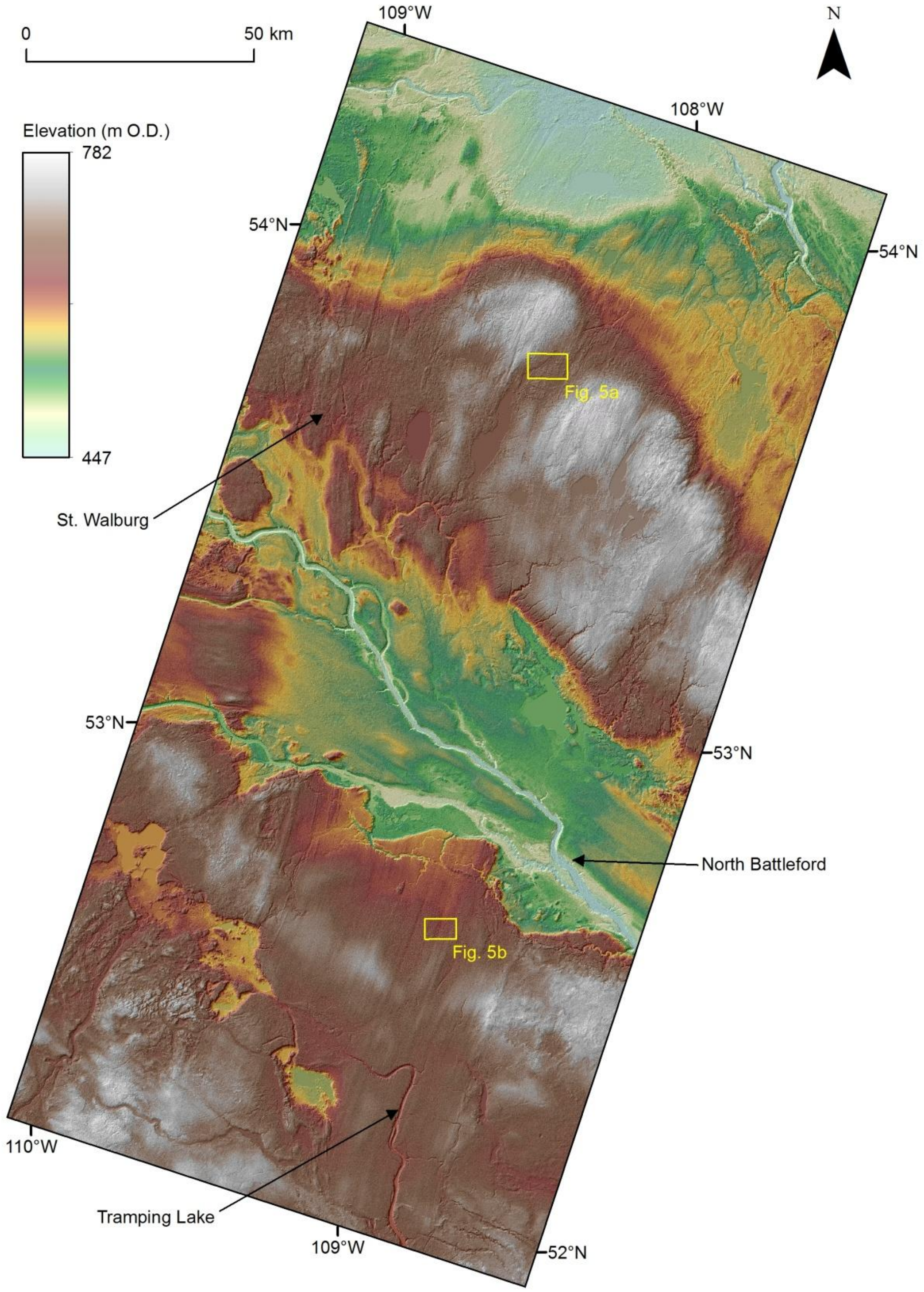


Fig. 2



0
50 km
Elevation (m O.D.)
782
447
109°W
108°W
N
54°N
54°N
53°N
53°N
52°N
110°W
109°W
Fig. 5a
Fig. 5b
St. Walburg
North Battleford
Tramping Lake

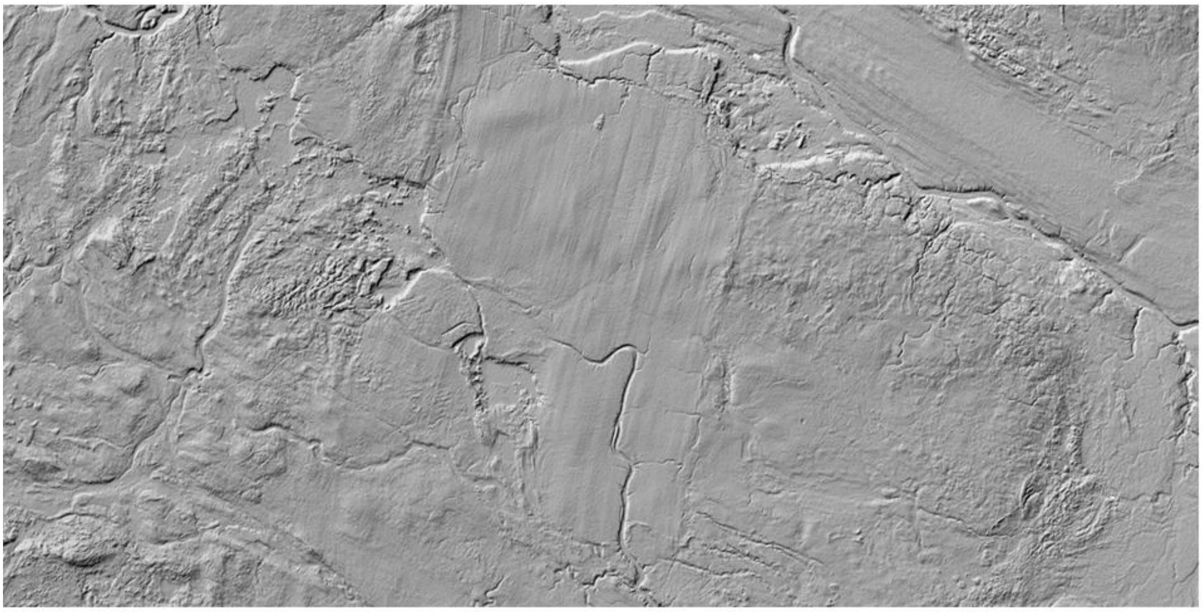


Fig. 3

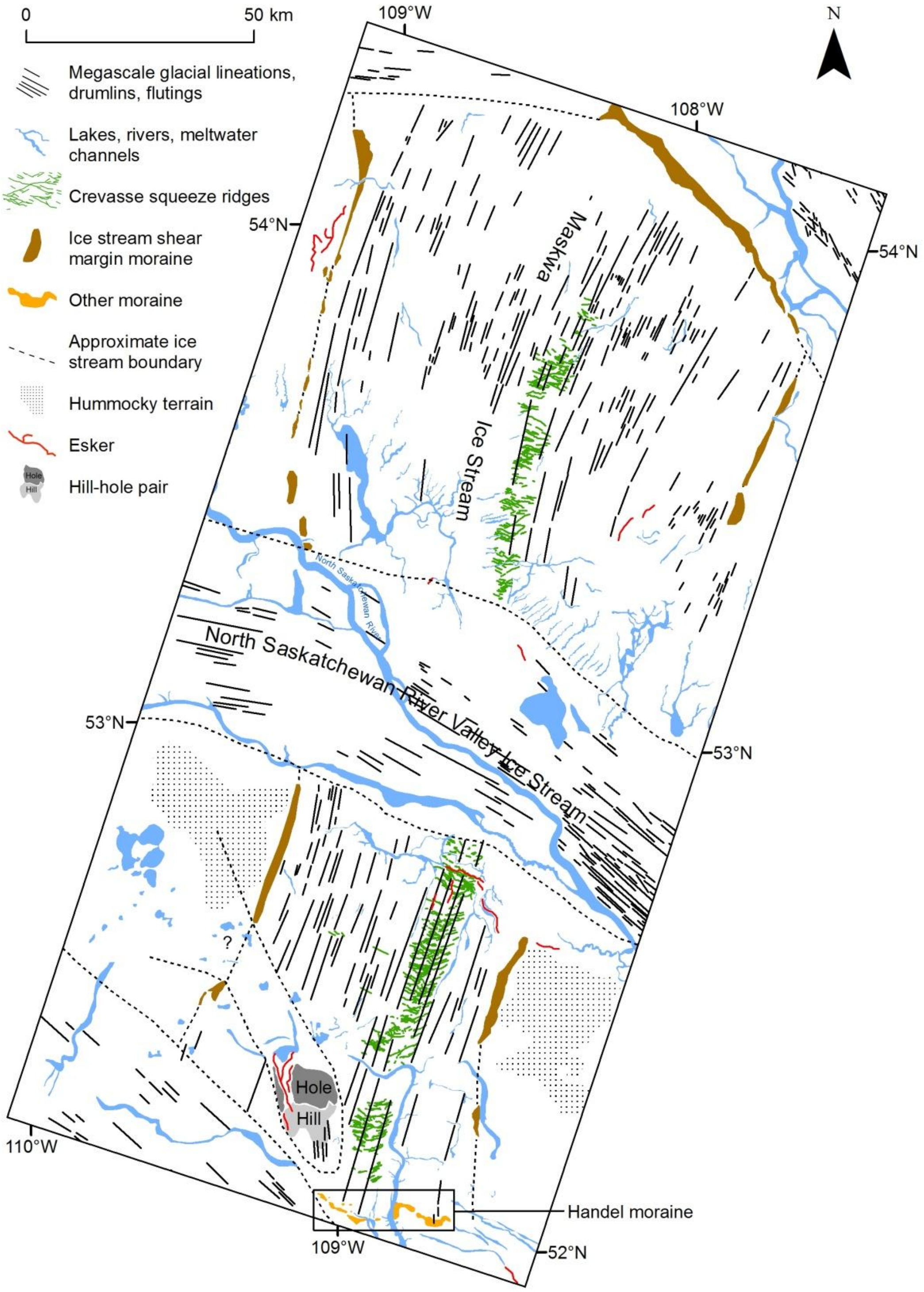

0
50 km
Megascale glacial lineations, drumlins, flutings
Lakes, rivers, meltwater channels
Crevasse squeeze ridges
Ice stream shear margin moraine
Other moraine
Approximate ice stream boundary
Hummocky terrain
Esker
Hill-hole pair
109°W
108°W
54°N
53°N
52°N
110°W
N
Maskwa
Ice Stream
North Saskatchewan River
North Saskatchewan River Valley Ice Stream
Hole
Hill
?
Handel moraine

Fig. 4


Google earth
2 km
N

Fig. 5

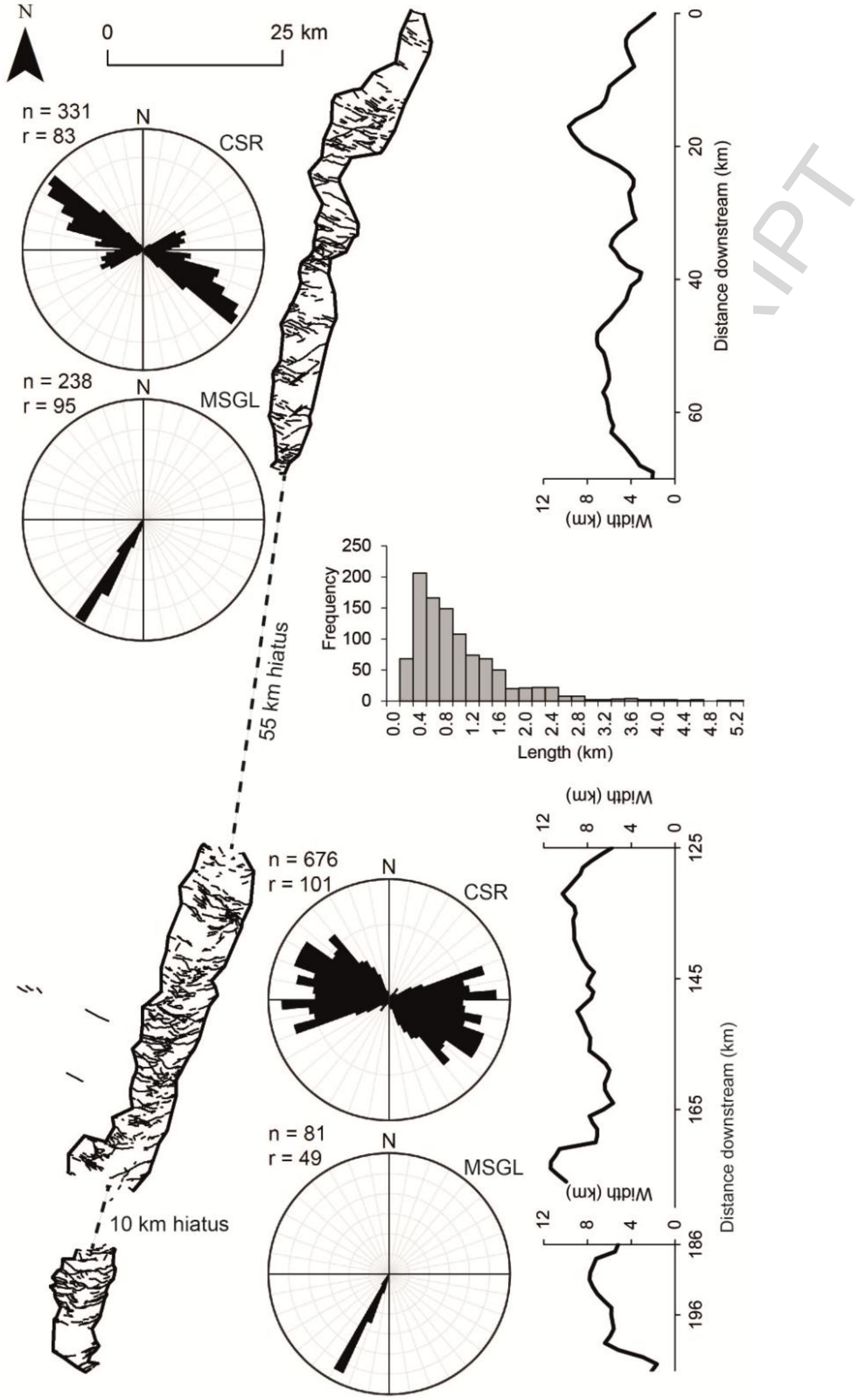

N
0
25 km
n = 331
r = 83
CSR
n = 238
r = 95
MSGL
55 km hiatus
n = 676
r = 101
CSR
n = 81
r = 49
MSGL
10 km hiatus
Distance downstream (km)
Width (km)
Frequency
Length (km)

Fig. 6

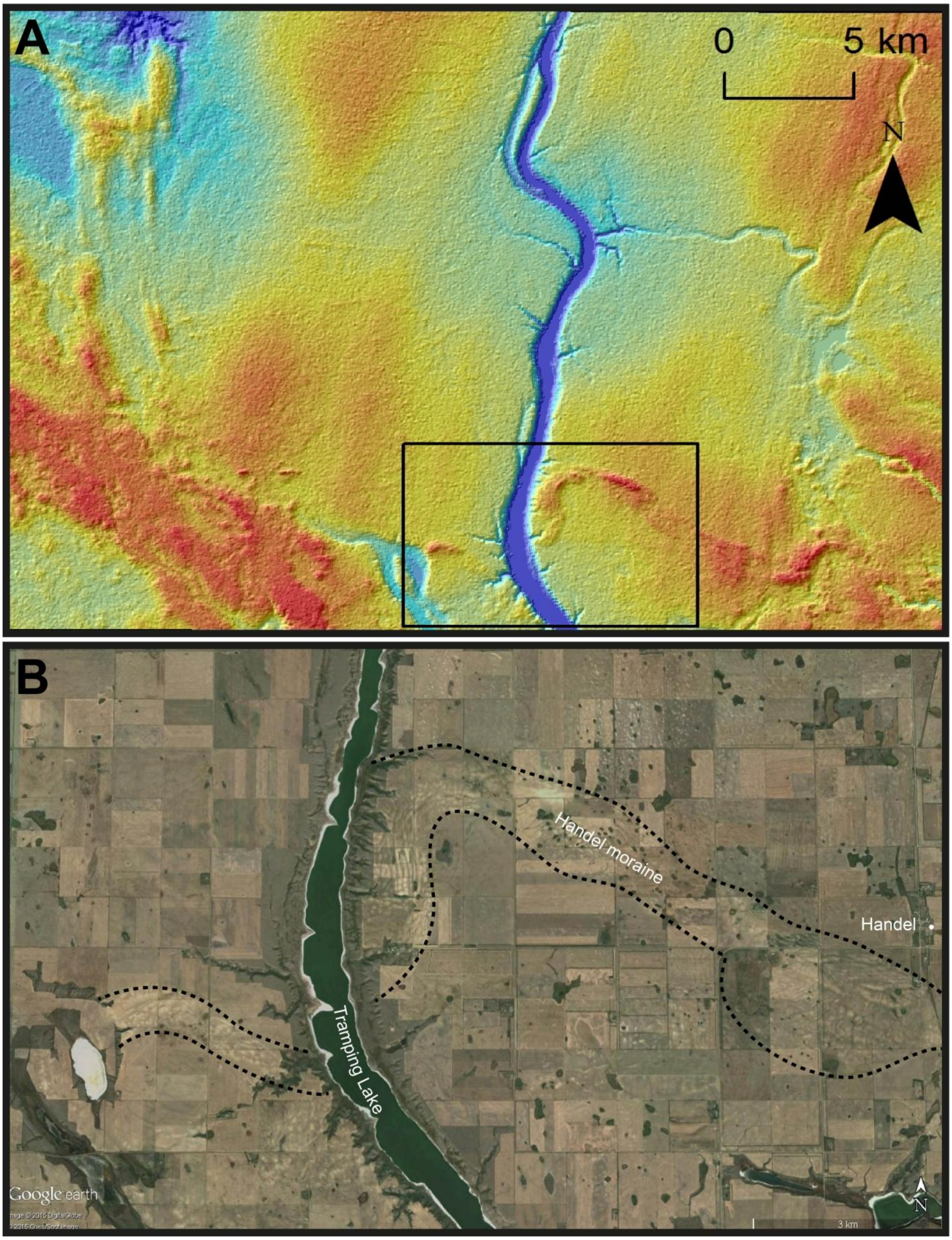

A
0
5 km
N
B
Handel moraine
Handel
Tramping Lake
Google earth
3 km
N

Fig. 7

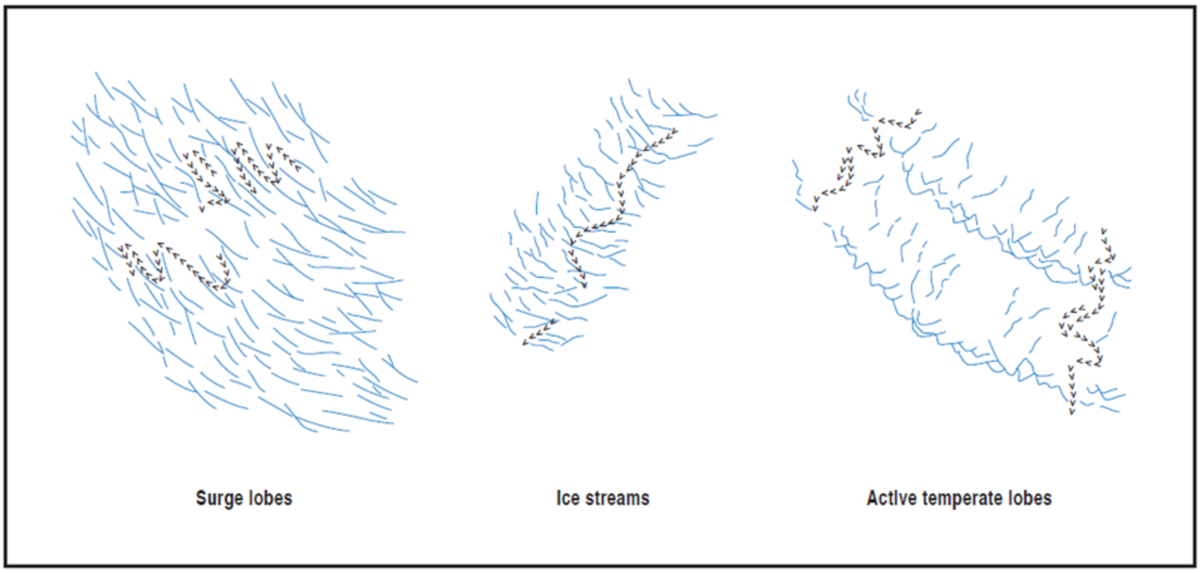


Fig. 8

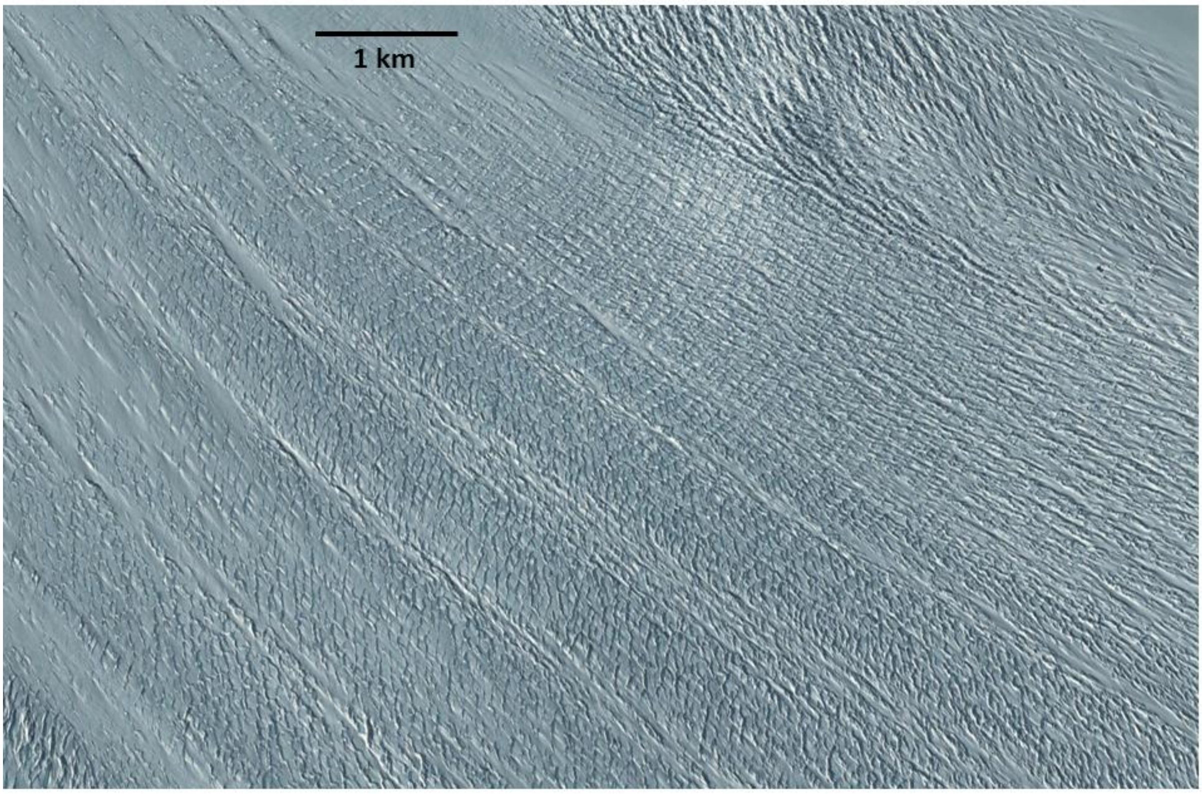


Fig. 9

Highlights

- Crevasse squeeze ridge corridors record late stage ice stream shutdown
- Ice stream shutdown was characterized by flow unit narrowing as plug flow
- CSR corridors contrast with those produced by surging and active temperate glaciers