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Conceptual model for the formation of bedforms along subglacial meltwater corridors (SMCs) by variable ice-water-bed interactions

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Abstract

Subglacial meltwater landforms found on palaeo-ice sheet beds allow the properties of meltwater drainage to be reconstructed, informing our understanding of modern-day subglacial hydrological processes. In northern Canada and Fennoscandia, subglacial meltwater landforms are largely organized into continental-scale networks of subglacial meltwater corridors (SMCs), interpreted as the relics of subglacial drainage systems undergoing variations in meltwater input, effective pressure and drainage efficiency. We review the current state of knowledge of bedforms (hummocks, ridges, murtoos, ribbed bedforms) and associated landforms (channels, eskers) described along SMCs and use selected high-resolution DEMs in Canada and Fennoscandia to complete the bedform catalogue and categorize their characteristics, patterning and spatial distributions. We synthesize the diversity of bedform and formation processes occurring along subglacial drainage routes in a conceptual model invoking spatiotemporal changes in hydraulic connectivity, basal meltwater pressure and ice-bed coupling, which influences the evolution of subglacial processes (bed deformation, erosion, deposition) along subglacial drainage systems. When the hydraulic capacity of the subglacial drainage system is overwhelmed glaciofluvial erosion and deposition will dominate in the SMC, resulting in tracts of hummocks and ridges arising from both fragmentation of underlying pre-existing bedforms and downstream deposition of sediments in basal cavities and crevasses. Re-coupling of ice with the bed, when meltwater supply decreases, facilitates deformation, transforming existing and producing new bedforms concomitant with the wider subglacial bedform imprint. We finally establish a range of future research perspectives to improve understanding of subglacial hydrology, geomorphic processes and bedform diversity along SMCs. These perspectives include the new acquisition of remote-sensing and field-based sedimentological and geomorphological data, a better connection between the interpreted subglacial drainage configurations down corridors and the mathematical treatments studying their stability, and the quantification of the scaling, distribution and evolution of the hydraulically connected drainage system beneath present-day ice masses to test our bedform-related conceptual model.

KEYWORDS
eskers, hummocks, meltwater bedforms, meltwater channels, murtoos, subglacial hydrology, subglacial meltwater corridor

1 | INTRODUCTION

The configuration and evolution of meltwater drainage under ice sheets is a key control on ice flow (Anandakrishnan & Alley, 1997; Andrews et al., 2014; Bartholomew et al., 2010; Smith et al., 2021), erosion (Alley et al., 2019; Cook et al., 2020; Cowton et al., 2012; Overeem et al., 2017), sedimentation (Bendixen et al., 2017; Simkins et al., 2017) and frontal ablation at water-terminating margins (Bunce et al., 2021; Fried et al., 2015; Jenkins, 2011; Slater et al., 2015). Understanding how subglacial drainage systems evolve under changing climate conditions is therefore paramount to studies trying to model the future of present-day ice sheets. However, a paucity of direct observations of the subglacial drainage system under present-day ice sheets limits the reconstruction of subglacial drainage system evolution on sub-decadal to decadal timescales (e.g. Fricker et al., 2016; Schroeder et al., 2013).

Meltwater landforms preserved in glaciated landscapes allow the properties of subglacial meltwater drainage to be reconstructed, typically over decadal to millennial time-scales and spatially over hundreds of kilometres (Burke et al., 2012a; Jennings et al., 2006; Ravier et al., 2022; Storrar et al., 2014). Such landforms therefore have enormous potential for informing our understanding of present-day subglacial hydrological configurations and processes (Davison et al., 2019; Greenwood et al., 2016; Simkins et al., 2023). With the advent of high-resolution digital elevation models (DEMs), one of the most obvious geomorphological expressions of former subglacial drainage systems is subglacial meltwater corridors (SMCs). SMCs are 100 s to 1000s m wide and up to 100 s km long tracts, whose formation has been attributed to subglacial drainage routes (Ahokangas et al., 2021; Burke et al., 2012a, 2012b; Campbell et al., 2020; Dredge et al., 1985; Kerr et al., 2014a, 2014b; Lewington et al., 2019, 2020; McMartin et al., 2021; McMartin, Campbell, Dredge, LeCheminant, et al., 2015; Ojala et al., 2019; Peterson et al., 2017, 2018; Peterson & Johnson, 2018; Rampton, 2000; Sharpe et al., 2017, 2021; St-Onge, 1984; Storrar & Livingstone, 2017; Utting et al., 2009; Vérité et al., 2022; Ward et al., 1997). SMCs can cut down into the bed forming negative expressions or can form positive-relief features comprising tracts of erosional landforms and glaciofluvial sediments (e.g. Lewington et al., 2020; Peterson et al., 2017; Peterson & Johnson, 2018). Mapping of meltwater traces from high-resolution (1–2 m) digital elevation models has revealed SMCs to be widespread beneath the former Laurentide (LIS) and Fennoscandian (FIS) ice sheets (Figure 1) (Ahokangas et al., 2021; Dewald et al., 2022; Lewington et al., 2020; McMartin et al., 2021; Öhrling et al., 2020; Peterson et al., 2017). The large-scale distribution of SMCs largely mirrors and extends that of eskers forming networks roughly parallel to ice flow that radiate out from former ice divides (Figure 1).

Challenging the historical binary categorization of a subglacial drainage system as either channelized or distributed, SMCs are inferred to be the imprint of hydraulically connected distributed subglacial drainage systems (Lewington et al., 2020). The style of meltwater drainage along these time-transgressive subglacial drainage systems is believed to be influenced by spatial and temporal variations in basal water pressures, hydraulic gradients, meltwater inputs and/or bed properties (Davison et al., 2019; Ojala et al., 2021; Vérité et al., 2022). An alternative hypothesis suggests that SMCs could result from focused synchronous drainage following a sheet flood from a subglacial water body (Sharpe et al., 2021; Shaw, 2002). Whatever the hydrological scenario envisaged, the various styles and magnitudes of drainage and resulting sediment remobilization processes (e.g. erosion, deposition and deformation) have been invoked to explain the geomorphological and sedimentological signature of SMCs.

SMCs have historically been identified via (i) their rough texture distinguishing them from the surrounding smoother till sheets (Rampton, 2000; Utting et al., 2009; Ward et al., 1997), (ii) sorted and poorly-sorted glaciofluvial sediments (Punkari, 1997; Rampton, 2000; St-Onge, 1984) and (iii) channelized drainage features such as eskers, meltwater channels, tunnel valleys and scoured beds (Aylsworth & Shilts, 1989; Brennand, 1994, 2000; Clark & Walder, 1994; Shreve, 1985). The identification of SMCs also encompasses a wide range of bedforms, meters to 10s m in amplitude and 10s to 1000s m in length, which correspond to undulating sedimentary mounds and ridges resulting from the remobilization of a sedimentary bed by ice and/or meltwater flow at the base of ice sheets (Aario, 1977; Allen, 1982). These include hummocks and ridges (e.g. Burke et al., 2012b; Campbell et al., 2020; Haiblen, 2017; Peterson et al., 2018; Rampton, 2000; St-Onge, 1984; Utting et al., 2009), murtoos and related bedforms (e.g. Ahokangas et al., 2021; Becher & Johnson, 2021; Mäkinen et al., 2017, 2023; Ojala et al., 2019, 2021; Peterson et al., 2017; Vérité et al., 2022) and ribbed bedforms (e.g. Campbell et al., 2020; Lewington, 2020; McMartin, Campbell, Dredge, LeCheminant, et al., 2015; Peterson et al., 2017). Beyond this apparent diversity in bedform types and hydrological conditions along SMCs, recent studies have revealed a morphological continuum between ribbed bedforms, murtoo-related bedforms and murtoos suggesting a continuity between bedform sizes and shapes and subglacial remobilization processes under alternating hydrological conditions (Becher & Johnson, 2021; Ojala et al., 2021; Vérité et al., 2022).

In this paper, we review the current state of knowledge of bedforms (and associated channelized landforms) that populate SMCs, focusing on their morphological characteristics, internal compositions and spatial distributions. Using selected high-resolution DEMs in northern Canada and Fennoscandia, we demonstrate the existence of distinct bedform tracts characterizing SMCs, whose morphometric diversity, patterns and spatial gradations unravel genetic relationships between a range of bedforms. Based on the review of existing literature and additional mapping, we discuss the formation processes of bedforms found in and around SMCs and build a conceptual model

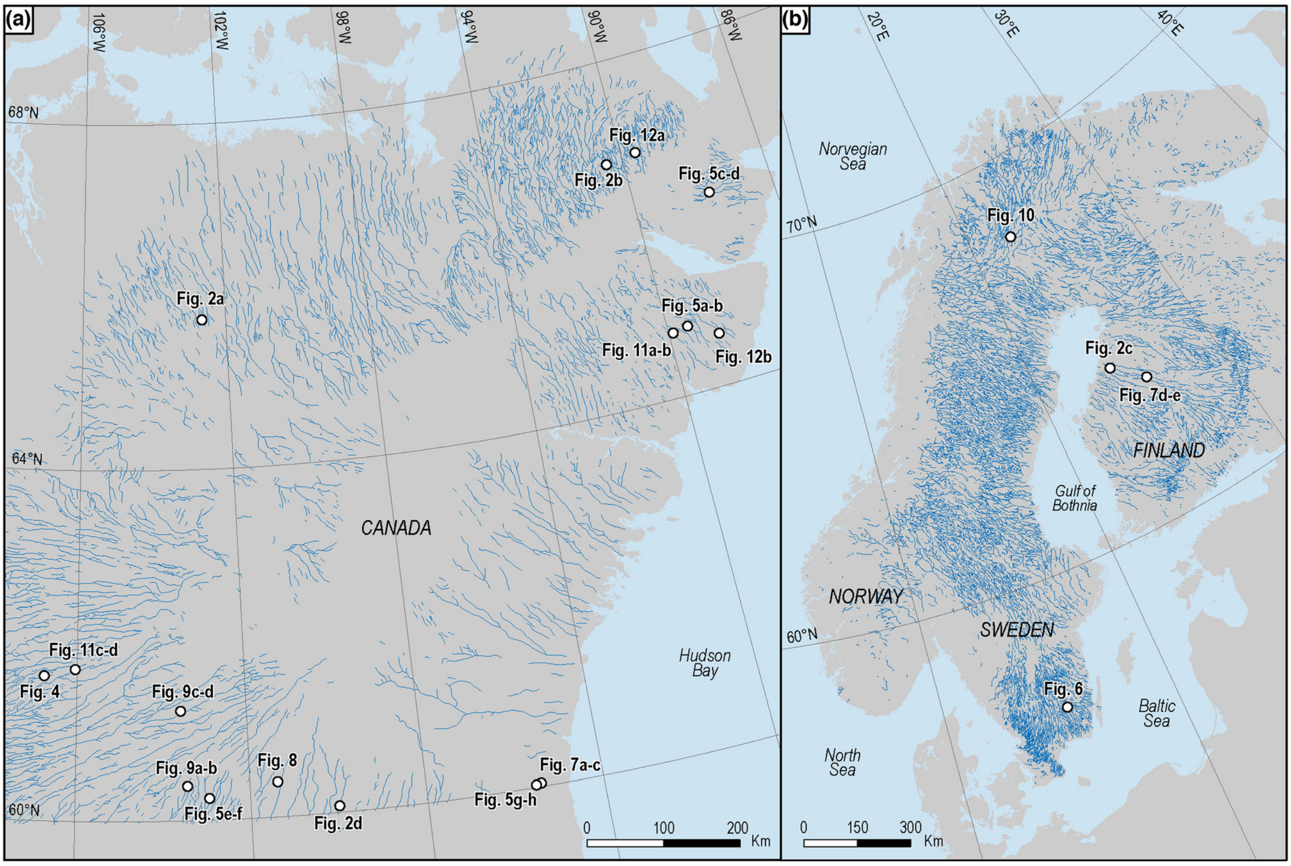

FIGURE 1 Mapped subglacial meltwater traces (blue lines) and locations of Figures 2-12 in (a) Keewatin, Canada (Lewington et al., 2020) and (b) Fennoscandia (Dewald et al., 2022). See detailed locations of Figures 2-12 in Table S1.

of SMC's formation depending on spatiotemporal changes in ice-water-bed interactions. In doing so we propose hypotheses to unify seemingly contradictory interpretations of bedform genesis spanning glacial, glaciofluvial and deformational processes. Finally, we identify perspectives for future research on SMCs to extend the understanding of SMCs in the frame of past and present subglacial hydrological systems.

2 | REVIEW OF BEDFORMS AND LANDFORMS IDENTIFIED WITHIN SMCS

A variety of bedforms has been reported within SMCs. In this section, we review their morphological characteristics, internal compositions and spatial distributions.

2.1 | Subglacial bedforms

2.1.1 | Hummocks

Hummocks are commonly identified within both Canadian and Fennoscandian SMCs and generally form tracts of irregular topography contrasting with the surrounding smoother and streamlined till sheets (Figure 2a) (e.g. hummock corridors – Peterson et al., 2017). Hummocks are 10s to 100 s m in length and width and 1 to 10s m in amplitude (e.g. Dahlgren, 2013; Haiblen, 2017; Lewington et al., 2019; Peterson & Johnson, 2018; Utting et al., 2009). Hummock composition varies considerably and consists of glaciofluvial sandy-to-gravelly material, sandy diamicton and older glacially reworked or eroded sediments (Campbell et al., 2020; Dahlgren, 2013; DesRosiers, 2021; Haiblen, 2017; McMartin, Campbell, Dredge, LeCheminant, et al., 2015; Öhrling et al., 2020; Peterson et al., 2018; Utting et al., 2009). Hummocks are commonly gathered along corridors – 10s to 100 km in length and 1 to 5 km in width – roughly parallel to former ice flow directions. Hummock corridors radiate out from palaeo-ice domes in the FIS and LIS and are mostly perpendicular to morainic complexes demarcating ice lobe positions during deglaciation phases (Dewald et al., 2022; Lewington et al., 2020; Peterson et al., 2017).

2.1.2 | Small-scale ridges

Linear to undulating ridges with transverse (and sometimes oblique) orientations relative to ice flow direction in northern Canada and Fennoscandia are spatially associated with hummocks and eskers within SMCs and variously termed bars, dunes or transverse ridges (Figure 2b) (Burke et al., 2012b; Campbell et al., 2020; McMartin et al., 2015, 2015; Peterson et al., 2018; Rampton, 2000; Sharpe et al., 2017; St-Onge, 1984; Utting et al., 2009). These ridges are 1–8 m in amplitude, 10–100 m in width and 10s to 100 s m in length. Based on their shape and small dimensions, they are referred to as

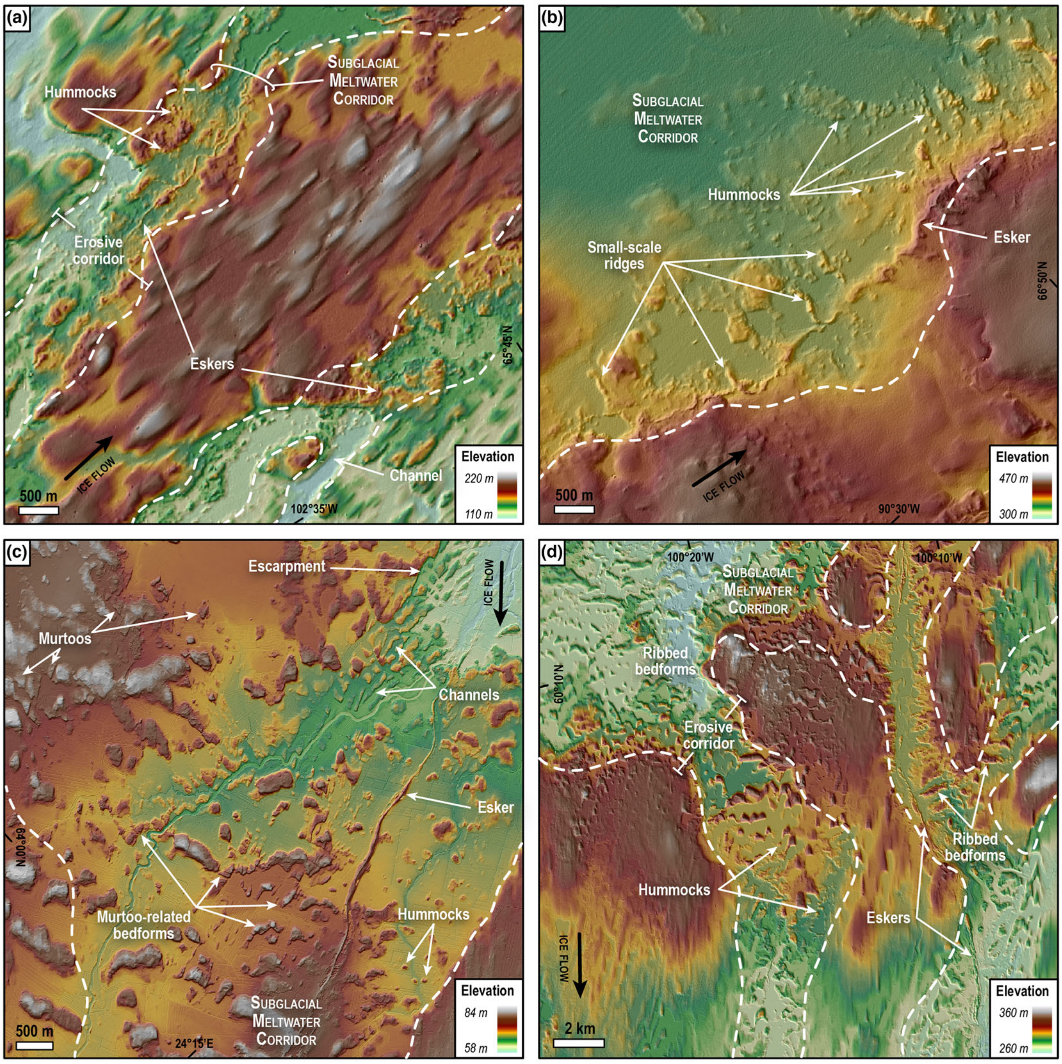

FIGURE 2 Inventory of bedforms described along subglacial meltwater corridors in the literature. (a) Hummock corridors surrounded by smoother streamlined till sheets in Canada (Lewington et al., 2019). (b) Small-scale ridges associated with hummocks and eskers in Canada (Utting et al., 2009). (c) Murtoos associated with eskers, channels, murtoo-related bedforms and escarpments in Finland (Ojala et al., 2019). (d) Corridor of ribbed bedforms associated with hummocks and eskers in Canada (Lewington, 2020). Dashed white lines indicate the interpreted position of SMCs lateral margins.

small-scale ridges to distinguish them from other transverse-to-oblique subglacial ridges such as ribbed bedforms. The internal composition of small-scale ridges varies from gravelly glaciofluvial material to sandy diamicton (Burke et al., 2012a; Campbell et al., 2020; McMartin, Campbell, Dredge, LeCheminant, et al., 2015; Rampton, 2000; St-Onge, 1984).

2.1.3 | Murtoos and murtoo-related bedforms

With the advent of the enhanced resolution of remote sensing data (e.g. Lidar data), murtoos have recently been discovered in Fennoscandia and often appear along SMCs (Figure 2c) (Ahokangas et al., 2021; Mäkinen et al., 2017; Ojala et al., 2019, 2021; Peterson et al., 2017; Vérité et al., 2022). Murtoos are triangular-shaped bedforms that are typically 30–200 m in length and width and with an amplitude of less than 5 m (Karpin et al., 2023; Ojala et al., 2019, 2021). Their tip points in the direction of ice flow and they have an asymmetric long-profile characterized by a shorter and steeper down-ice slope (Ojala et al., 2021). Murtoos are composed of sandy diamicton and sorted sediment (Becher & Johnson, 2021; Mäkinen et al., 2023; Ojala et al., 2022).

Along SMCs, murtoos are spatially associated with murtoo-related bedforms, oblique-parallel ridges and escarpments (Figure 2c). Murtoo-related bedforms – variously termed chevron-type, lobate-type and sub-triangular murtoos – share overlapping morphological characteristics with murtoos and contain similar sediments (Ojala et al., 2021, 2022; Vérité et al., 2022). Murtoos and murtoo-related bedforms cluster in fields and corridors that are elongated parallel to the local ice flow direction (Peterson et al., 2017). Oblique-parallel ridges and escarpments are 100 s m to a few km in length, 10–100 m in width and less than 5 m in amplitude, and also display an asymmetrical cross-profile. Escarpments refer to single features while oblique-parallel ridges refer to several oblique (relative to the local ice flow direction) bedforms that are parallel to each other. Oblique-parallel ridges tend to be orientated along the direction of meltwater drainage (Ojala et al., 2021).

Murtoo fields are frequently spatially associated with hummock fields and channelized features (i.e. eskers and channels) along SMCs (Ahokangas et al., 2021; Vérité et al., 2022). Spatial gradations have been described from the core to the margins of SMCs between murtoos and murtoo-related bedforms (Vérité et al., 2022) and escarpments have been typically described as delineating the lateral margins of SMCs (Ojala et al., 2022).

2.1.4 | Ribbed bedforms

Ribbed bedforms, typically 100 s m in length and 1–10 m in amplitude, are widespread in Fennoscandia and Canada and typically form broad fields (often greater than several hundred km^2). Ribbed bedforms are mostly composed of deformed subglacial tills although lenses of sorted sandy-to-gravelly sediments can also be observed (e.g. Hättestrand & Kleman, 1999; Lindén et al., 2008; Möller, 2010; Möller & Dowling, 2018; Trommelen et al., 2014). While most ribbed bedforms are not associated with SMCs, some ribbed bedforms are organized into ice-flow aligned corridors (or ribbon/narrow tracks) that are 100 s to 1000s m in width and 10s km in length (Aylsworth & Shilts, 1989; Dunlop & Clark, 2006; Trommelen et al., 2014). This includes at least 40 ice-flow parallel ribbed bedform tracts intercalated with streamlined terrains in SW Keewatin forming a typical 'barcode' landscape (Lewington, 2020; Vérité, 2022; Wagner, 2014).

In both Fennoscandia (Peterson et al., 2017) and northern Canada (Lewington, 2020; Vérité et al., 2023), some of these narrow corridors of ribbed bedforms have been associated with SMCs (Figure 2d). Furthermore, some of these ribbed bedform corridors are spatially associated with hummocks and murtoos along or in the vicinity of SMCs (Peterson et al., 2017; Remmert & Kristiansson, 2018; Ojala et al., 2019; Ahokangas et al., 2021; Vérité et al., 2022).

2.2 | Associated channelized landforms

2.2.1 | Eskers

Eskers and other associated glaciofluvial deposits, such as outwash fans that typically delineate former edges of retreating ice sheets, occur along SMCs or in-between corridor segments (e.g. Ahokangas et al., 2021; Campbell et al., 2020; Lewington et al., 2020; Sharpe et al., 2017; Storrar et al., 2014) without preferential location. Eskers form (sub-)continuous systems that commonly occur on bedrock or till surfaces. They are often observed superimposed on other subglacial meltwater corridor landforms/bedforms (Figures 2a-d) (Lewington et al., 2020; Peterson et al., 2017, 2018).

2.2.2 | Erosional channelized landforms

Meltwater flow within SMCs scours and exposes the bed producing apparent incised channelized features (Figure 2). Erosive corridors – 1 to 10 km in width – are relics of SMCs, incised in a subglacial sedimentary bed and frequently surrounded by streamlined bedforms (e.g. Campbell et al., 2020; Rampton, 2000; Sharpe et al., 2021) (Figures 2a, d). While the bottoms of these erosive corridors are commonly populated by hummocks, many of them are devoid of SMC-related bedforms (Lewington et al., 2020; Peterson et al., 2018; Utting et al., 2009). Meltwater channels – up to 10s m in width and less than 10 m deep – are frequently observed within SMCs and the sides of murtoos and murtoo-related bedforms (Mäkinen et al., 2017; Ojala et al., 2019; Vérité et al., 2022) (Figures 2a, c).

3 | IDENTIFICATION AND CHARACTERISTICS OF BEDFORM TRACTS ALONG SMCS

In the following section, we describe the morphological and patterning characteristics of a range of bedform assemblages, each associated with a predominant bedform type and defined as a bedform tract, which contributes to the reconstruction of SMCs (Dewald et al., 2022; Lewington et al., 2020). Although it is convenient to distinguish the different bedform tracts observed along the SMCs based on predominant bedform types, lateral and longitudinal transitions exist between these tracts and surrounding bedforms, sometimes making clear boundaries difficult to define. These transitions are also described in the following section.

3.1 | Data and methods

Guided by previous large-scale mapping of SMCs beneath the FIS and LIS (Dewald et al., 2022; Lewington et al., 2020; McMartin et al., 2021; Vérité et al., 2022), our approach is to study the distribution and assemblages of subglacial bedforms found within and in between SMCs, with a focus on the spatial transitions between the different types of bedforms. This involves mapping, morphometric description and interpretation of bedforms within portions of SMCs across northern Canada and Fennoscandia selected to capture the most exhaustive range of SMCs features (Figure 1).

High-resolution DEMs (2-m in spatial resolution), including national LiDAR datasets in Sweden (https://www.lantmateriet.se) and Finland (https://www.maanmittauslaitos.fi/en) and the ArcticDEM mosaic v7 (Porter et al., 2018; https://www.pgc.umn.edu/data/arcticdem) in Canada, are used to identify and describe subglacial bedforms and meltwater landforms. Visualization and mapping are carried out using a multidirectional hillshaded DEM in QGIS, to alleviate the issue of azimuth bias (e.g. Smith & Clark, 2005). Based on a selection of SMCs, length (i.e. longest axis), width (i.e. shortest axis) and amplitude (i.e. maximal height) are automatically computed from manually-contoured bedforms and compiled in Figure 3 and Supplementary Table S2. This selection is intended to be representative of the different types of SMC tracts and bedforms that constitute them but certainly does not provide an exhaustive list.

3.2 | Hummock tracts

3.2.1 | Morphological characteristics of hummock tracts

Hummock tracts are typically 1–2 km (but up to ~5 km) in width and either cut down into the bed forming negative SMCs or – although this is qualitatively rarer – occur on top of till sheets or other

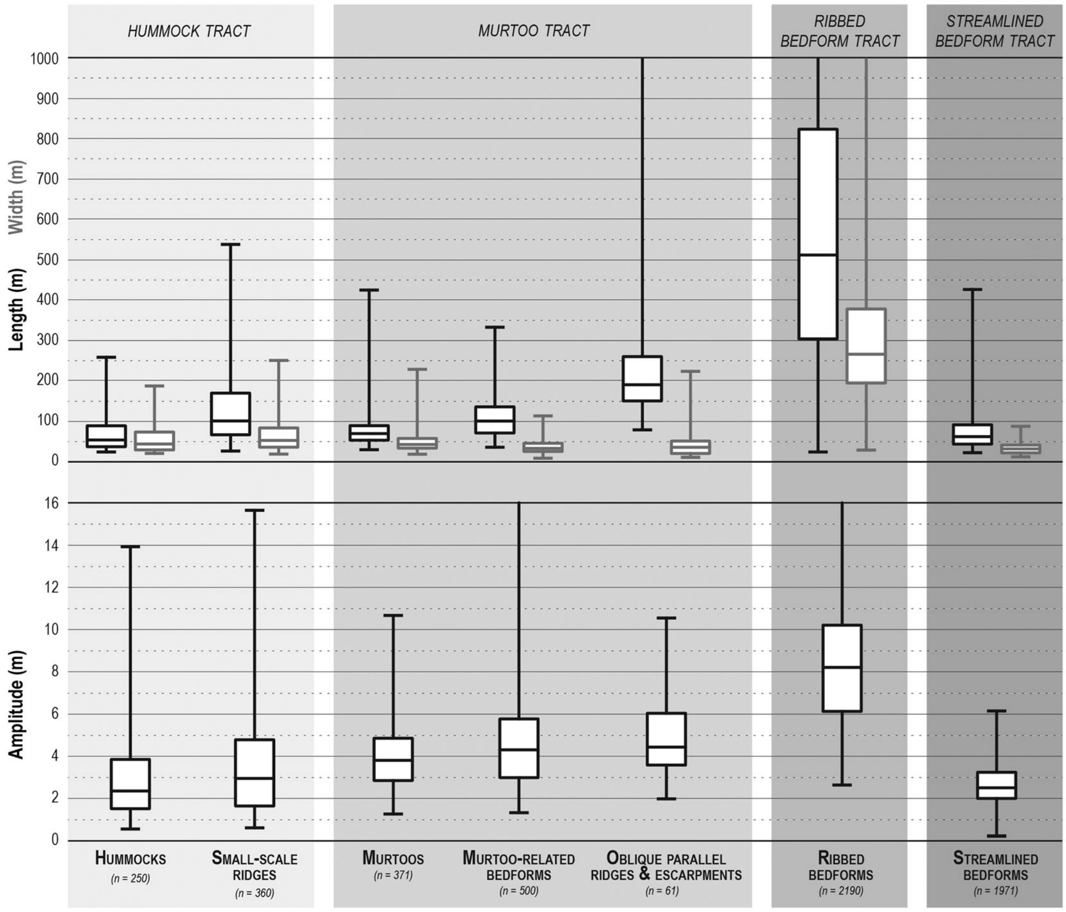

FIGURE 3 Length, width and amplitude of subglacial bedforms mapped along selected subglacial meltwater corridors and from a range of bedform tracts: hummock tracts [i.e. hummocks (n = 250) and small-scale ridges (n = 360) from Figure 4], murtoo tracts [i.e. murtoos (n = 371), murtoo-related bedforms (n = 500), oblique-parallel ridges and escarpments (n = 61) from Figure 6], ribbed bedform tracts [i.e. ribbed bedforms (n = 2,190) from Figure 8] and streamlined bedform tracts [i.e. stubby streamlined bedforms (n = 1971) from Figure 10]. Morphometric statistics are presented as box plots materializing minimal, 1st quartile, median, 3rd quartile and maximal values. Note that some maximal values have been truncated for graphical reasons, see Table S2 for exact values.

meltwater landforms producing positive SMCs (Figure 4). Hummock tracts are typically composed of irregular hummock and ridge topographies and often connect or contain eskers and meltwater channels. Hummocks – typically 30–90 m in length and width and less than 4 m in amplitude – commonly co-occur with small-scale ridges, 60–170 m in length, 30–80 m in width and 2–5 m in amplitude (Figure 3). Small-scale ridges are straight to sinuous and are more elongated perpendicular to local ice flow direction than hummocks but with a similar width and amplitude. These ridges are generally asymmetrical with steeper lee-side slopes.

Based on morphology, some ridges appear to be amalgamations of multiple hummocks while others appear as singular ridges. Small-scale ridges and hummocks often appear to form a size and shape continuum. While hummocks and ridges commonly show irregular patterns/alignments (Figure 5a-b), others can be more geometrically arranged in sets with different orientations in respect to assumed meltwater flow. Some are transverse (Figures 5c-d), some longitudinal (Figures 5e-f), some oblique and others arranged in a cross-hatched pattern (Figures 5g-h). When jointly associated, hummocks and ridges with irregular patterns tend to focus along the core of the corridor, while those geometrically arranged tend to be larger and focused along corridor margins (Figure 4).

3.2.2 | Spatial relationships of hummock tracts with other bedforms

Hummock tracts are commonly associated with a variety of bedforms. When ribbed bedforms are observed in the vicinity of hummock tracts, small-scale ridges - although much smaller and thinner (Figure 3) - are commonly aligned with a similar transverse orientation, forming horn-like features connected to ribbed bedforms, and are associated with channels winding in between (Figures 5c-d). Lateral transitions between flow-parallel alignments of hummocks, streamlined hummocks and short to large streamlined bedforms are also observed from the core of hummock tracts to the outside of SMCs (Figures 5e-f). Lateral and longitudinal transitions are observed between fields of murtoos (and related bedforms; see Section 3.3 for more details) and hummock tracts, both forming remarkable cross-hatched patterns. When observed jointly, small-scale ridges with oblique orientations are elongated parallel to the edges of murtoos, separated by channels (Figures 5g-h).

These spatial associations with larger bedforms (Figure 5) combined with observed morphometric gradations between bedforms constituting hummock tracts (Figure 3) could suggest common formation processes for hummocks and small-scale ridges as well as genetic

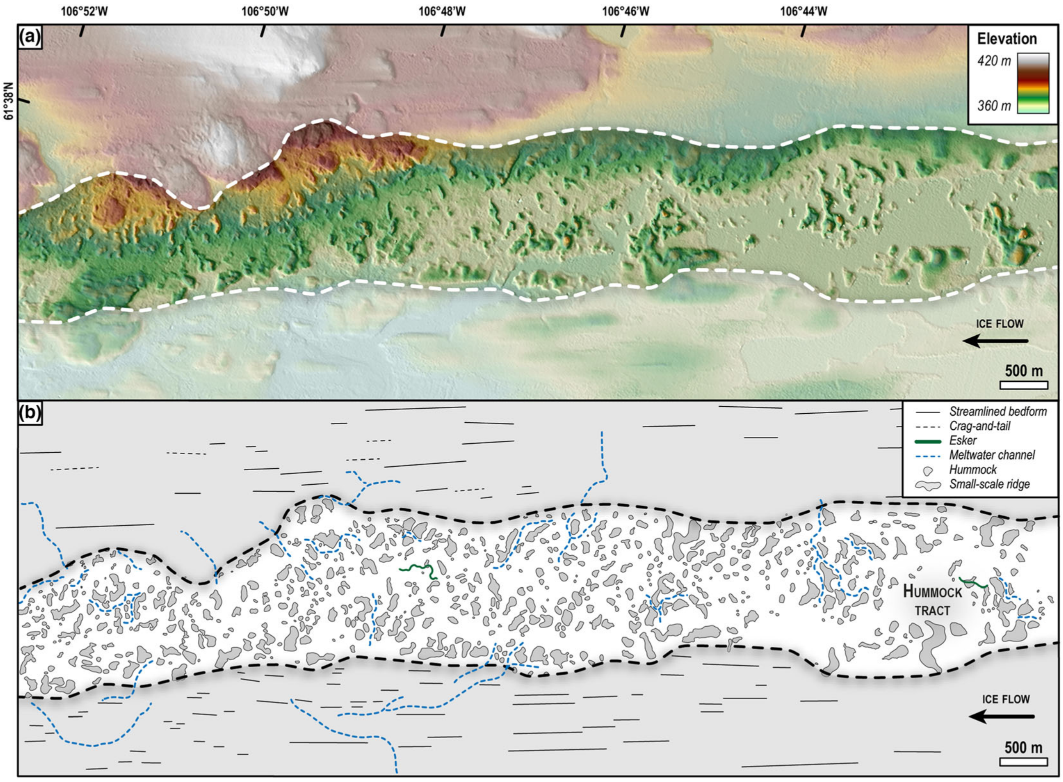

FIGURE 4 Assemblage of hummocks and small-scale ridges along a SMC, forming a typical hummock tract: (a) hillshaded DEM and (b) digitised bedforms. Along this portion of the SMC, there are only small minor esker ridges and channels associated with hummocks and small-scale ridges. Importantly, hummocks and ridges tend to have smaller dimensions and more chaotic patterns along the core of the corridor, while they are larger, more geometrically arranged along the margins and form flow-parallel alignments consistent with surrounding streamlined bedforms.

relationships with other larger bedforms found outside but also within SMCs, just as Vérité et al. (2022) have shown for murtoos (and their related bedforms) and ribbed bedforms observed outside SMCs.

3.3 | Murtoo tracts

3.3.1 | Morphological characteristics of murtoo tracts

Murtoos, murtoo-related bedforms, oblique-parallel ridges and escarpments tend to concentrate along flat to low-relief areas in corridors, referred to as murtoo tracts, which are roughly flow-parallel and typically 0.5–5 km (and up to 10 km) in width (Figure 6). Although murtoos and related landforms have been identified in landscapes formerly below the FIS, we establish that murtoos also occur along the LIS bed in association with SMCs (Figure 7a). Murtoos are typically 30–100 m in length and width and 3–5 m in amplitude (Figure 3). Murtoos commonly co-occur with (i) murtoo-related bedforms – 30-100 m in length, 20–50 m in width and 3–6 m in amplitude – that share overlapping morphologies with both murtoos and small-scale ridges, and (ii) landforms referred to as oblique-parallel ridges and escarpments that are more elongated (70–200 m long) and less periodic but similar in width and amplitude (Figure 3).

Escarpments are primarily elongated in the same direction as the downstream pointing sides of murtoos and sometimes trend into a murtoo at their downstream end (Figure 7e). Together, murtoos and murtoo-related bedforms can form a chevron-like pattern, similar to cross-hatched patterns observed in hummock tracts (Figures 7a-b).

3.3.2 | Spatial relationships of murtoo tracts with other bedforms

Murtoos and related landforms sometimes show lateral and longitudinal transitions with ribbed bedforms, though this is not the case for most murtoo tracts. Bedforms displaying an intermediate shape between ribbed bedforms and murtoos, referred to as remobilized ribbed bedforms by Vérité et al. (2022), suggest a partial reshaping of ribbed bedforms into murtoos along SMCs (Figure 7c).

Moreover, murtoos, murtoo-related bedforms, oblique-parallel ridges and escarpments populating murtoo tracts are commonly associated with hummocks and small-scale ridges, striking parallel to their edges and bordered by channels (Figures 5g-h).

3.4 | Ribbed bedform tracts

3.4.1 | Morphological characteristics of ribbed bedform tracts

In Keewatin and Fennoscandia, some corridors of ribbed bedforms, typically 2–5 km in width (Figure 8) but up to 20 km in width (in central Finland), are associated with SMCs and are therefore interpreted as ribbed bedform tracts. Ribbed bedforms observed within SMCs are typically wider than the small-scale ridges but have similar transverse to oblique orientations relative to the local ice flow direction. Ribbed bedforms mapped along SMCs are 300–800 m in length, 200–400 m in width and 4–9 m in amplitude (Figure 3), and tend to be typically less long and high than classical ribbed bedforms that are

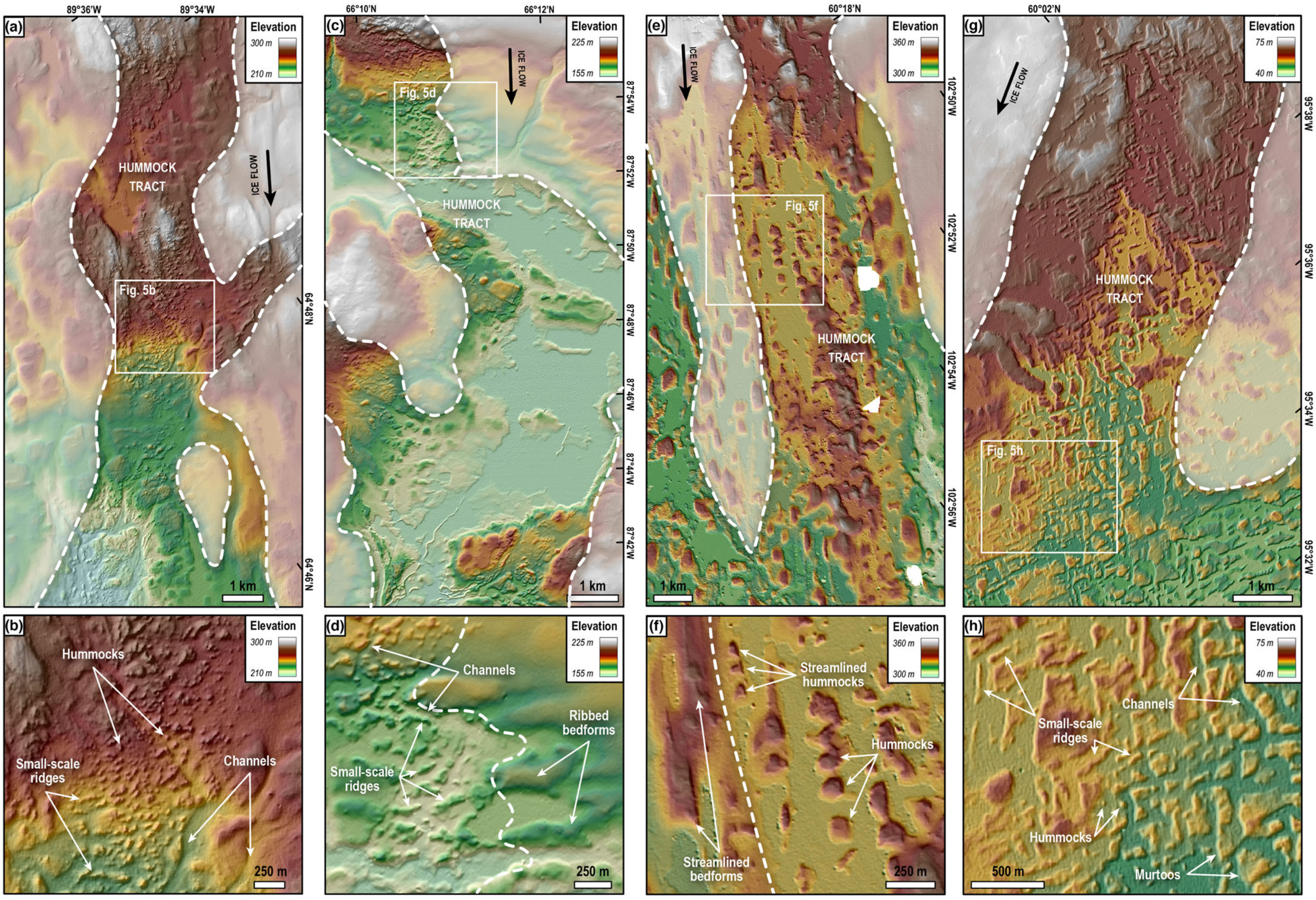

FIGURE 5 Examples of spatial patterns of hummocks and small-scale ridges found within SMCs. (a-b) Irregular (even chaotic), without geometric patterns. (c-d) Flow-transverse alignments of hummocks and small-scale ridges that are surrounded by ribbed bedforms located out of the SMC. (e-f) Flow-parallel alignments of hummocks that are associated with streamlined hummocks and surrounded by streamlined bedforms located out of the SMC. In (d) and (f), lateral gradations in size are observable - from large scale bedforms outside of SMCs to small-scale bedforms toward the core of SMCs. (g-h) Cross-hatched patterns of hummocks and small-scale ridges (with common oblique orientations) that are surrounded by murtoos and murtoo-related bedforms located within the SMC.

300–1900 m in length and 10 m in amplitude (see Ely et al., 2016 and Vérité, 2022 for data compilations).

Ribbed bedform tracts are often organized into a network that can be delineated using the abrupt transition with interspersed areas of smooth beds (Figures 9a-b) or streamlined bedforms (Figures 9c-d). Ribbed bedform tracts are commonly bordered by erosive margins and associated with channelized features (i.e. meltwater channels and eskers) (Figure 9). The orientation of ribbed bedforms located along SMCs is commonly consistent with the ice flow direction suggested by ribbed bedforms, streamlined ribbed bedforms or streamlined bedforms located outside the SMCs (Figure 8). Sometimes, ribbed bedforms strike obliquely to the SMCs they are contained within while some ribbed bedform tracts are not associated with any regional ribbed bedforms (Figures 9a-b).

3.4.2 | Spatial relationships of ribbed bedform tracts with other bedforms

Streamlined bedforms and streamlined ribbed bedforms commonly coexist in the vicinity of ribbed bedforms and SMCs. In some cases, streamlined ribbed bedforms – referred to as transitional bedforms by Vérité et al. (2023) – form lateral transitions between ribbed (inside the SMC) and streamlined bedforms (outside the SMC) and typically delineate SMC margins (Figure 9d).

Ribbed bedform tracts are commonly associated with murtoo tracts along SMCs. Ribbed bedforms within SMCs sometimes seem to have been breached/fragmented and have a more prominent/rugged appearance than ribbed bedforms found outside SMCs, which have a smoother appearance (Figure 7c).

3.5 | Streamlined bedform tracts

3.5.1 | Morphological characteristics of streamlined bedform tracts

SMCs are typically devoid of streamlined bedforms (i.e. drumlins and MSGLs) facilitating their identification within the smooth streamlined terrain that commonly surrounds them (Figures 4, 7d, 8). However, we identified several examples in northern Canada and Sweden where streamlined bedforms occur in kilometre-wide corridors, referred to as streamlined bedform tracts. These tracts contain landforms typical of SMCs, including eskers, channels, hummocks and scoured bedrock (Figures 10-11). Streamlined bedforms found along SMCs are typically 40–90 m in length, 15–30 m in width and less than 3 m in amplitude

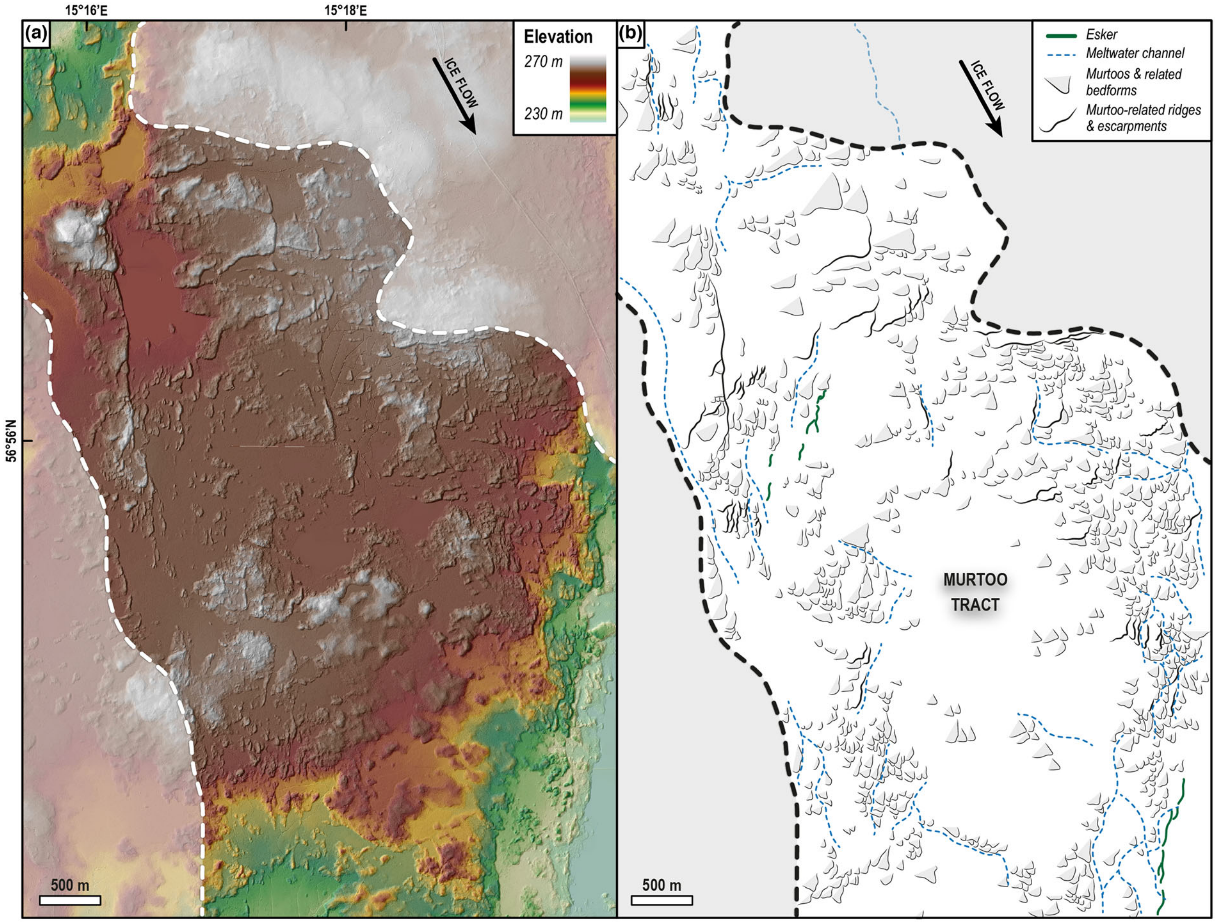

FIGURE 6 Assemblage of murtoos, murtoo-related bedforms, oblique-parallel ridges and escarpments along a SMC, forming a typical murtoo tract: (a) hillshaded DEM and (b) digitised bedforms. All these bedforms are associated with eskers and channels.

(Figure 3), and tend to be less long, wide and higher than typical streamlined bedforms that are 300–4,000 m in length, 100–500 m in width and 5–7 m in amplitude (see Ely et al., 2016 and Vérité, 2022 for data compilations).

Along streamlined bedform tracts, streamlined bedforms exhibit variations in morphology over short distances across flow: those located within the corridor are shorter (typically 10s to 100 s m long) and better defined than those outside the corridor (Figure 10). Considering their aspect and dimensions and to distinguish them from typical streamlined bedforms found outside SMCs, streamlined bedforms found along SMCs are hereafter referred to as "stubby" streamlined bedforms. Streamlined bedform tracts are negative-relief features, commonly associated with erosional channelized features (Figures 11b, d).

3.5.2 | Spatial relationships of streamlined bedform tracts with other bedforms

Stubby streamlined bedforms found along SMCs are commonly associated with wider and longer streamlined bedforms of similar orientation, found outside SMCs, which correlate with the wider geomorphic signature of palaeo-ice flow (Figures 11a-b). Some stubby streamlined bedforms also strike obliquely to the edges of SMCs, notably where the corridors change direction (Figures 11c-d). Within streamlined bedform tracts, stubby streamlined bedforms can occur with flow-aligned chains of hummocks (Figures 11c-d).

3.6 | Channelized drainage landforms associated with bedform tracts

Large esker systems – kms to 10s of kms long – are often either contained or partially contained within SMCs and misaligned with the central axis of the corridor (Figure 12a). Although not all SMCs contain an esker, esker-channel networks can also cross-cut corridors at oblique orientations and connect several SMCs (Figure 12b). Along networks of esker ridges, fan-shaped glaciofluvial deposits referred to as outwash fans are commonly observed (Figures 9d, 11d). Eskers are frequently superimposed on landforms or exposed bedrock found in SMCs (e.g. Figures 8, 11c-d). When associated with hummock tracts, large and continuous esker systems tend to be associated with poorly-developed (or poorly-preserved) tracts (Figure 12a), while small and disconnected esker ridges tend to be associated with well-developed hummock tracts (Figure 4).

Within SMCs, erosional channels – 10s to 100 s m wide and 100 s m long – are often found breaching ribbed bedforms (Figures 9a-b), meandering between hummocks and small-scale transverse to oblique ridges resulting in common cross-hatched patterns (Figures 5h, 7b, e) and delineating streamlined bedforms (Figures 11a-b). They also develop along the flanks of murtoos, murtoo-related bedforms, oblique-parallel ridges and escarpments (Figures 7d-e). These channels are not always parallel to the main SMC axis (Figure 12b). Larger channels – up to ~1 km in width and several kilometres in length – that follow the main drainage

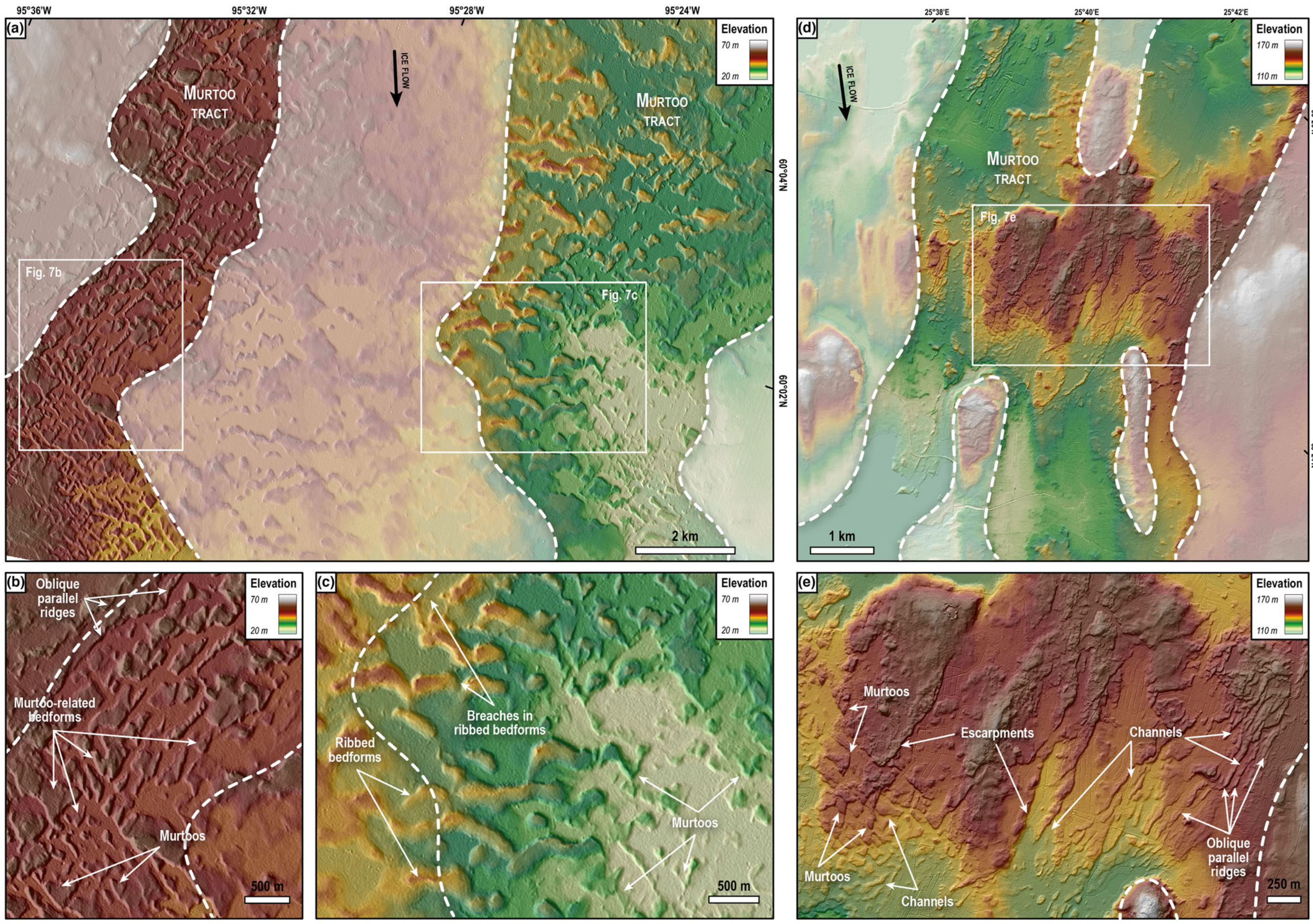

FIGURE 7 Examples of patterns and spatial distributions of murtoos, murtoo-related bedforms, oblique-parallel ridges and escarpments along murtoo tracts, which have been found in SMCs at the base of LIS (a-c) and FIS (d-e). (b) Murtoo-related bedforms and oblique-parallel ridges closely associated with murtoos and forming a chevron-like pattern. (c) Murtoo tract associated with prominent ribbed bedforms within the SMC (some seem to have been fragmented/breached), which are concordant with smoother ribbed bedforms located outside the SMC. (e) Oblique-parallel ridges and escarpments oriented/elongated in the same direction as murtoos.

axis are occasionally observed to cut through the original SMCs (Figure 9a), connect esker segments (Figure 8b), or form overflows from one corridor to the next (Figure 12b).

4 | PROCESSES OF BEDFORM FORMATION WITHIN SMCS

In this section, we review the formation processes of bedforms found in and around SMC based on our review of the existing literature and new geomorphological observations (i.e. morphometric characteristics of SMC bedform types, bedform patterns, spatial relationships and transitions between bedform tracts).

4.1 | Hummock tracts

Consisting of glaciofluvial sand and gravel materials, subglacial tills and/or glacially reworked sediments (Burke et al., 2012a; Campbell et al., 2020; Dahlgren, 2013; Haiblen, 2017; McMartin, Campbell, Dredge, LeCheminant, et al., 2015; Peterson et al., 2018; Rampton, 2000; St-Onge, 1984; Utting et al., 2009), both hummocks and small-scale ridges have been interpreted in the literature as resulting from depositional and/or erosional processes. The formation of hummocks within SMCs has been associated with: (i) deposition of glaciofluvial sediments within subglacial cavities during periods of high meltwater discharge (Utting et al., 2009), (ii) rapid deposition of sandy diamicton by hyper-concentrated flows in subglacial cavities following meltwater erosion of till (DesRosiers, 2021; Haiblen, 2017) and (iii) erosion of existing sediments (e.g. till plain) during SMC formation (Campbell et al., 2020; Peterson et al., 2018; Sjogren et al., 2002). Similarly, small-scale ridges have been described as gravel dunes deposited during large flood events (Burke et al., 2012a; Rampton, 2000), or as diamictic and gravelly infills of basal crevasses (St-Onge, 1984).

Our observations made along Canadian and Fennoscandian SMCs demonstrate that hummocks and small-scale ridges are intimately associated along hummock tracts (Figures 4, 5) and have size ranges that partly overlap each other (Figure 3), suggesting a morphometric continuum and a potential unifying formational process dominated by meltwater erosion and/or deposition.

4.1.1 | Erosional hummock tracts

Meltwater erosion is a significant process in producing the largely negative topography of SMCs, which are commonly characterized by a variety of erosional landforms such as exposed and scoured beds, boulder lags, plunge pools and erosional corridors with abrupt edges

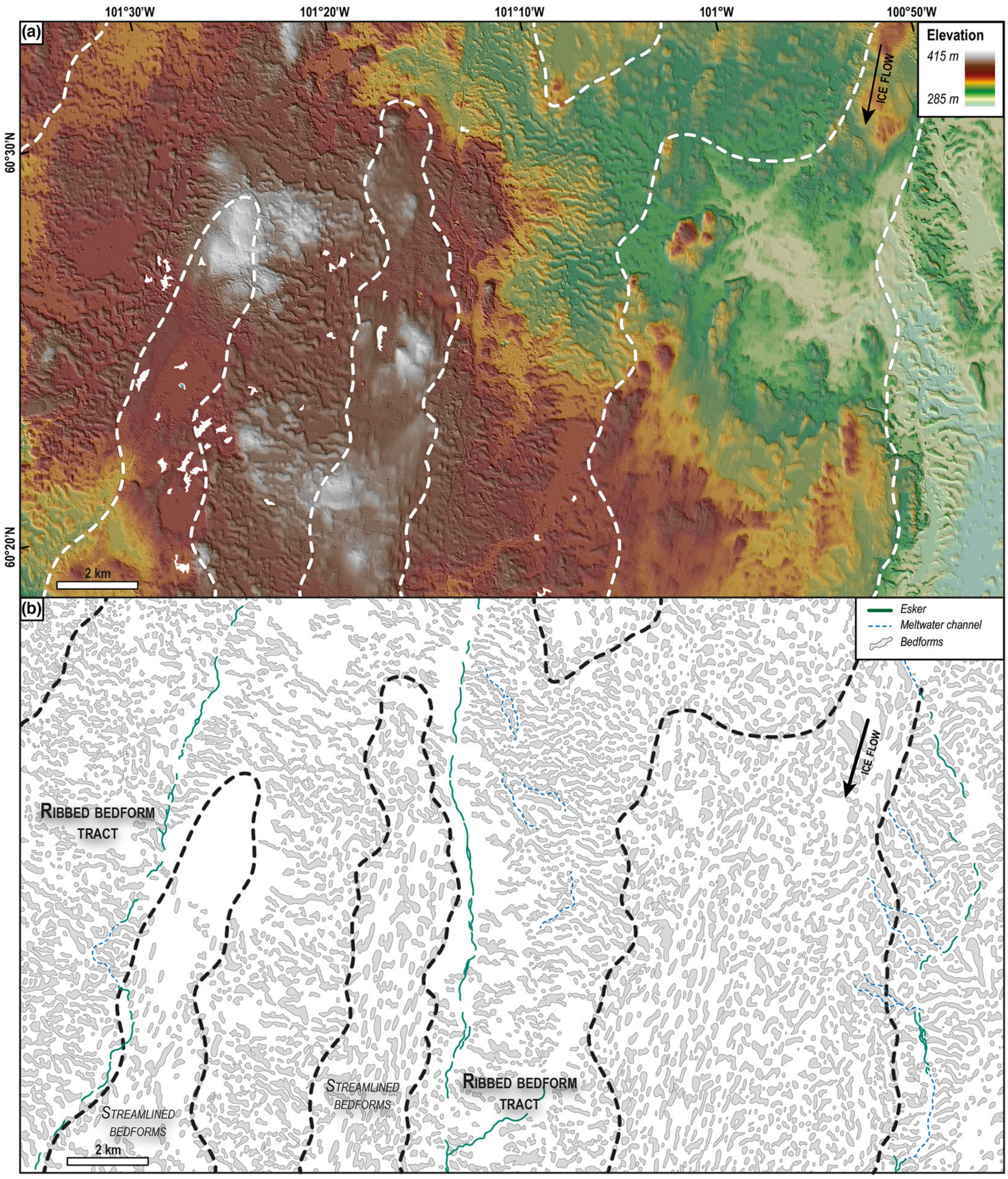

FIGURE 8 Flow-parallel fields of ribbed bedforms associated with eskers and channels that delineate ribbed bedform tracts and SMCs: (a) hillshaded DEM and (b) digitised bedforms. Ribbed bedform tracts, a few kilometres in width and up to 10s of kilometres in length, are surrounded by fields of streamlined bedforms indicating the palaeo-ice flow direction.

(e.g. Campbell et al., 2020; Rampton, 2000; Sharpe et al., 2021; van Boeckel et al., 2022). For these reasons, meltwater erosion is a potential key factor in producing the geometric arrangements of hummocks and small-scale ridges observed along Canadian and Fennoscandian SMCs (Figures 5c-h, 11d). The spatial relationship with ribbed and streamlined bedforms and murtoos – which are known to exhibit regularity in spacing and spatial organization (Clark et al., 2018; Ojala et al., 2019) – suggests hummocks and small-scale ridges arranged geometrically along hummock tracts could represent eroded roots of pre-existing subglacial bedforms (Delaney et al., 2023; Ojala et al., 2021; Peterson & Johnson, 2018), even though they might basically result from the erosion of till sheets. Following this hypothesis, the internal sedimentary composition of hummocks and small-scale ridges would be similar to those of surrounding bedforms or till sheets (Campbell et al., 2020; Haiblen, 2017; Peterson et al., 2018; Sjogren et al., 2002). Minor channels incised along the edges of murtoos (Figures 7d-e), breaching small-scale ridges and ribbed bedforms (Figures 5, 9a-b), and delineating stubby streamlined bedforms (Figures 11a-b) support this inference. Consequently, the glaciofluvial erosion of ribbed and streamlined bedforms could respectively explain flow-transverse and flow-parallel arrangements of hummocks and small-scale ridges, while the erosion of murtoos and related bedforms could result in more complex and cross-hatched patterns. More generally, geometric patterns and multiple channels separated by residual erosional topography are analogous to small (cm) and large-scale (m) patterns seen on beaches and river beds (e.g., Allen, 1982; Morton, 1978; Schuurman et al., 2016). Simple laboratory experiments also suggest these natural bedform patterns can be generated by erosion of sediment in a shallow, draining water layer (Daerr et al., 2003). Fragmentation of underlying subglacial bedforms into ridges and hummocks therefore suggests erosional processes related to meltwater drainage occurred after their formation.

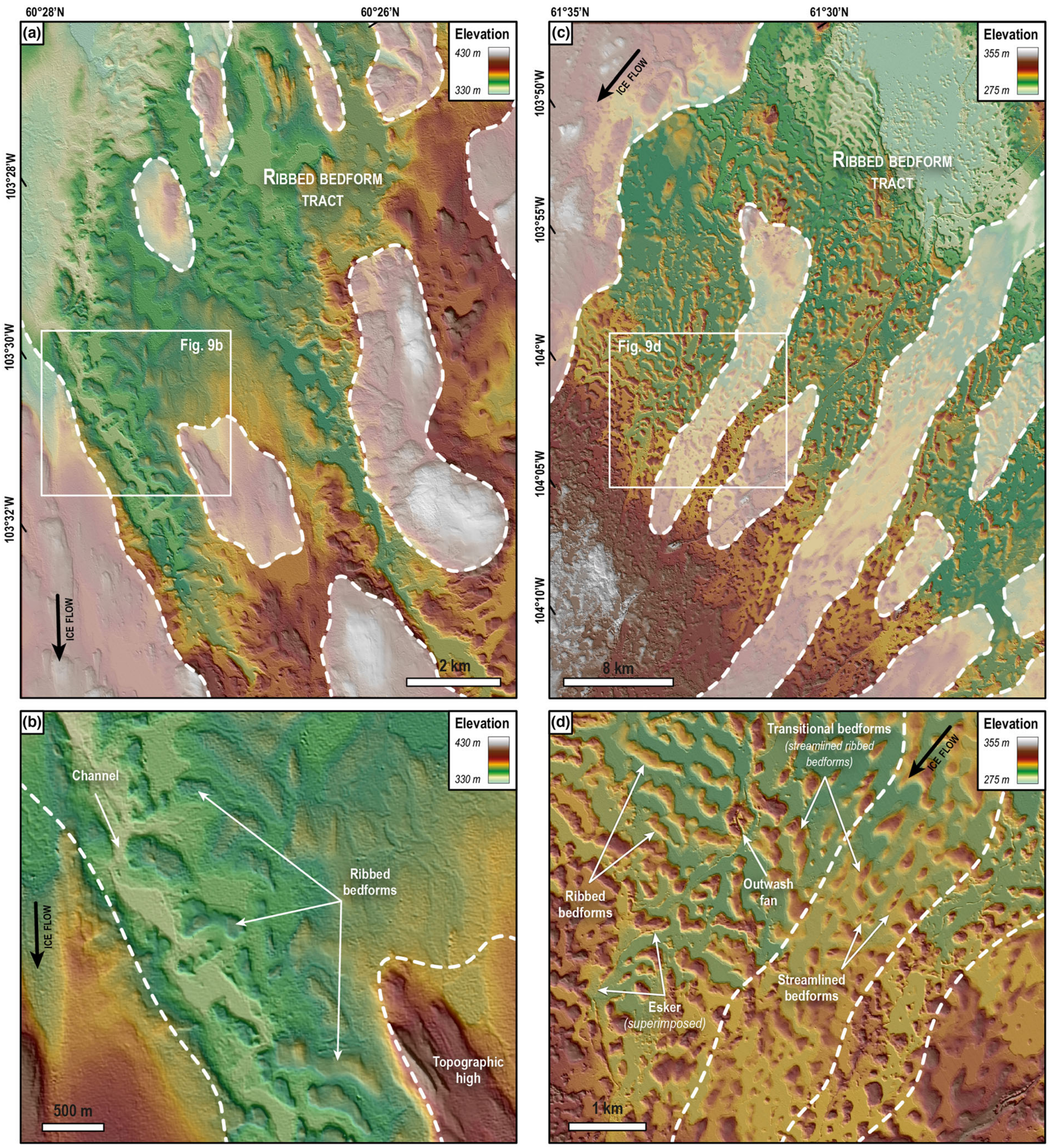

FIGURE 9 (a-b) Ribbed bedform tract showing oblique bedform orientations relative to the SMC orientation. The ribbed bedform tract is surrounded by till sheet and topographic highs. (c-d) Alternations between streamlined bedform fields/smooth till sheets and rougher ribbed bedform fields delineating the SMCs. Ribbed bedforms can often be traced outside SMCs where they are often streamlined, forming transitional bedforms between ribbed in the corridor and streamlined bedforms outside the corridor.

4.1.2 | Depositional hummock tracts

Some hummocks and small-scale ridges are superimposed on eroded/scoured bed surfaces along positive-relief SMCs (Figures 4, 5a), without any geometric arrangement. This association between hummocks and small-scale ridges along hummock tracts suggests they are formed synchronously (Peterson & Johnson, 2018) and not eroded from the surrounding bedforms or till sheets. Chaotic patterns of hummocks and small-scale ridges are therefore interpreted as resulting from depositional processes within SMCs. In these cases, hummocks and small-scale ridges could predominantly reflect conditions associated with large-magnitude drainage events capable of eroding, incorporating and then – during late waning phases – rapidly depositing reworked sediments in subglacial cavities (e.g. hyper-concentrated flows) (DesRosiers, 2021; Haiblen, 2017; Rampton, 2000; Utting et al., 2009). This is consistent with Utting et al. (2009), Haiblen (2017) and DesRosiers (2021) who suggested that depositional small-scale ridges and hummocks formed where meltwater flow eroded cavities at irregularities in subglacial conduits, providing accommodation space for rapid sedimentation. For the small-scale depositional ridges, the accommodation space could be controlled by basal crevasses (St-Onge, 1984) formed by hydro-fracturing during large subglacial meltwater drainage events, which is consistent with the interpretation of transverse ridges of similar

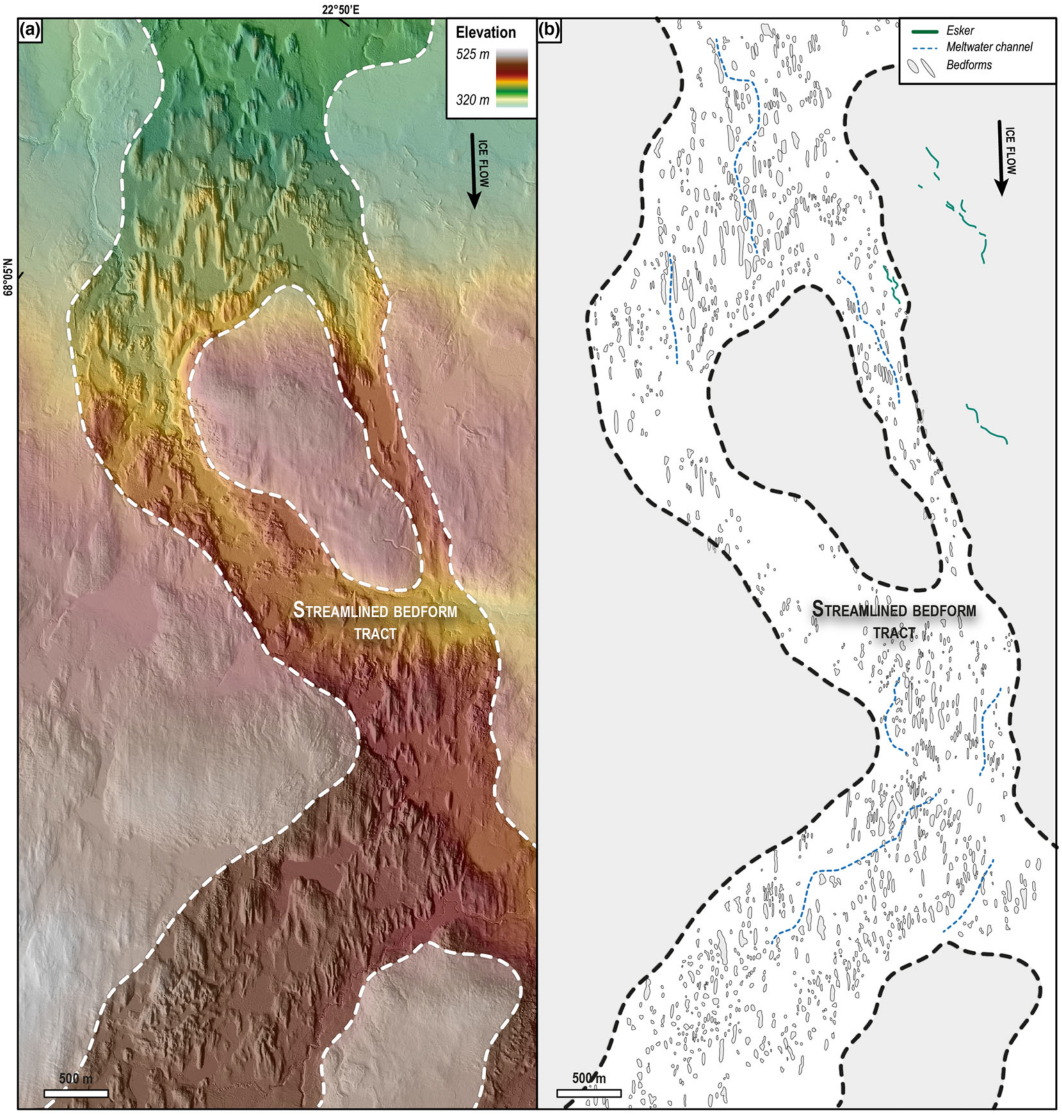

FIGURE 10 Fields of streamlined bedforms characterised by a rough texture and associated with eskers and channels delineate streamlined bedform tracts interpreted as SMCs: (a) hillshaded DEM and (b) digitised bedforms. Streamlined bedform tracts, 100 s m to a few kilometres in width and up to 10s of kilometres in length, are surrounded by smoother streamlined bedforms, till sheets or streamlined bedrock indicating the palaeo-ice flow direction. Streamlined bedforms along SMCs tend to be stubbier, smaller and more clearly defined than those located outside the SMC.

dimensions in Svalbard as crevasse-fill ridges (Evans et al., 2022). In some places (Figure 4), lateral transitions observed between hummocks and small-scale ridges with chaotic then geometric arrangement from the core towards the margins of SMCs could suggest that depositional hummock tracts form in a narrower subglacial drainage route than erosional ones, potentially within an efficient central conduit (Campbell et al., 2020). This hypothesis could be supported by the observation of chaotic hummock tracts associated with narrow esker-channel networks along the core of SMCs, suggesting drainage becomes concentrated in efficient networks of cavities and conduits – which generally develop toward the ice margin (Chandler et al., 2013, 2021; Dow et al., 2014; Nanni et al., 2021). However, with limited observations of the internal composition of hummocks and small-scale ridges and the link to surrounding landforms, it is challenging to determine their erosional or depositional nature based solely on geomorphology (see **Section 7** for future perspectives of work).

4.2 | Murtoo tracts

First documented in 2017 in Fennoscandia (Mäkinen et al., 2017; Peterson et al., 2017), fields of murtoos and related landforms (i.e. murtoo-related bedforms, oblique-parallel ridges and escarpments) are suggested to form under transitory high-pressure conditions when a significant amount of meltwater is episodically delivered to the ice sheet bed along subglacial meltwater routes. Two main processes of murtoo formation in corridors, not fully contradictory, have been proposed so far: the first one suggests that murtoos form mainly by deposition (and erosion to a lesser degree) of sediment in enlarging cavities at the transition between the distributed and semi-distributed drainage systems (e.g. Peterson Becher & Johnson, 2021; Hovikoski et al., 2023) and the second one suggests that murtoos form by remobilization (through erosion, deposition and deformation) of pre-existing subglacial bedforms along meltwater routes (Vérité et al., 2022).

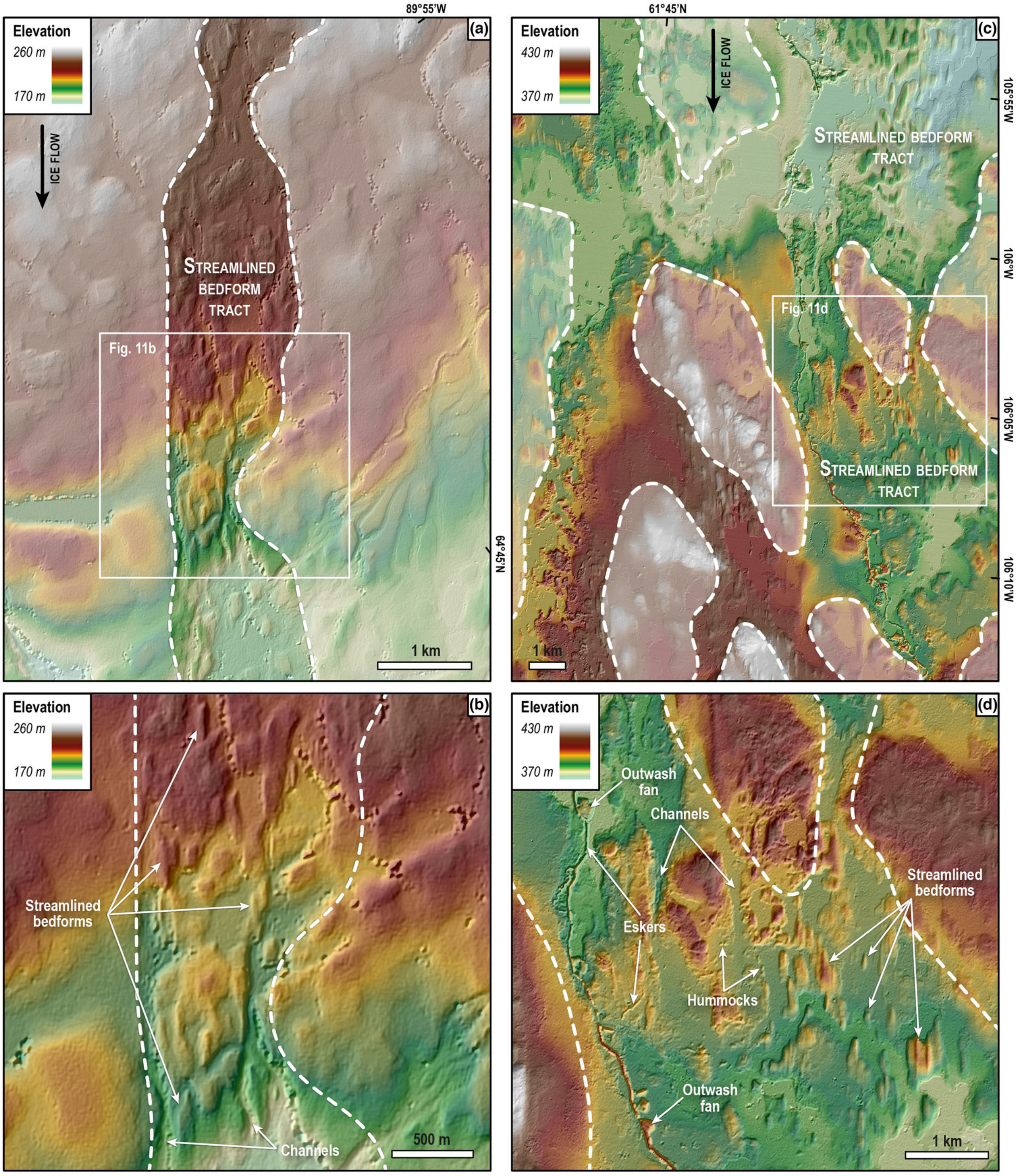

FIGURE 11 Streamlined bedform tracts in SMCs are associated with meltwater landforms (e.g. scoured bedrocks, channels and eskers). (a-b) Streamlined bedforms are intimately associated with channels along a negative-relief corridor. (c-d) the orientation of streamlined bedforms correlates with the local ice flow direction, interpreted via streamlined features outside SMC, but is oblique to the edges of SMC indicating a palaeo-drainage route. Streamlined bedforms are here organised in a tract populated by other landforms typical of SMCs, including flow-aligned chains of hummocks, eskers, outwash fans and channels.

4.2.1 | Depositional murtoos

Based on sediment sections, the formation of murtoos and related landforms has been interpreted as resulting primarily from the deposition of sediments by meltwater flow in a changing style of subglacial drainage system (from inefficient to efficient) due to the common occurrence of sorted sediments (silt to gravel) interbedded with diamicton in murtoo cores (Mäkinen et al., 2017, 2023; Peterson Becher & Johnson, 2021; Ojala et al., 2021, 2022;Hovikoski et al., 2023; Mäkinen et al., 2023). Moreover, longitudinal and/or vertical sequences of grain-size coarsening in murtoos (from silt/sand to gravel) suggest episodes of enhanced meltwater delivery and increases in flow velocity and water depth in relation to the enlargement of water conduits or subglacial cavities/ponds (Hovikoski et al., 2023; Mäkinen et al., 2023). The development of upper-flow-regime bedforms, including sigmoidal cross-stratification, humpback dunes, chutes-and-pools and cyclic steps in some murtoos indicate powerful flow and sediment deposition by density flows (Hovikoski et al., 2023). Late-stage channelization implies erosion on the murtoo sides (i.e. development of erosional triangular heads) and

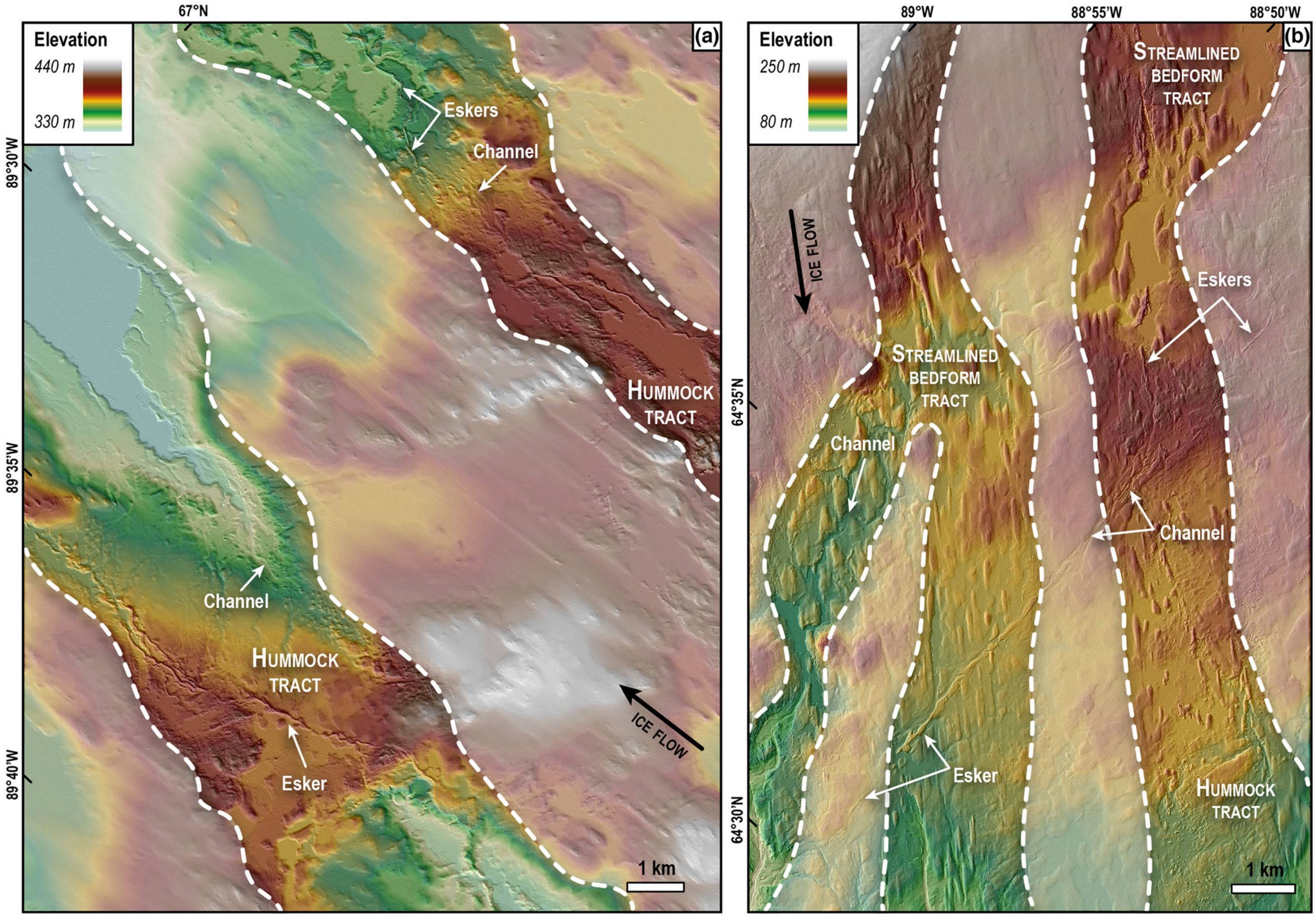

FIGURE 12 (a) A network of eskers and channels located within SMCs and hummock tracts that are misaligned with the central axis of the corridors. (b) a network of S-trending eskers and subglacial meltwater channels cross-cutting the SE-trending ice flow and SMCs, indicated via streamlined bedform tracts and hummock tracts.

possibly bouldery fills that are both thought to contribute to the final shaping of murtoos (Peterson Becher & Johnson, 2021; Hovikoski et al., 2023). Glaciofluvial erosion is particularly well recorded morphologically with the steep down-ice slopes of murtoos and related bedforms shaped by minor channels (Figure 7e) o Syn-sedimentary deformation of sediments (i.e. ductile deformation, hydrofracturing, liquefaction structures and strong fabrics) in murtoos have sometimes been reported and interpreted to record episodes of ice-bed recoupling when the water pressure drops in the subglacial cavity/conduit (Peterson Becher & Johnson, 2021).

4.2.2 | Remobilization of pre-existing bedforms

Using physical modelling and supported by spatial relationships (Figures 7a, c), Vérité et al. (2022) interpreted the high concentration of murtoos and related bedforms along well-defined tracts as the morphological expression of SMCs, where pre-existing ribbed bedforms have been flooded and reshaped along subglacial drainage routes. Correlating previous works from Peterson et al. (2017) and Ojala et al. (2019, 2021), Vérité et al. (2022) revealed a morphological and genetic continuum between ribbed bedforms, ribbed bedforms partially reshaped into murtoos, proto-murtoos (i.e. murtoo-related bedforms) and murtoos resulting from transient hydrological conditions and variable ice-water-bed interactions along subglacial drainage routes. More broadly, murtoo tracts described in Fennoscandia and – for the first time in this study (Figure 7a) – in northern Canada are associated with the reshaping of pre-existing sediments by a combination of glaciofluvial erosion and glacial deformation during periods of ice-bed recoupling (Becher & Johnson, 2021; van Boeckel et al., 2022). This dynamic concept invokes alternating phases of (i) significant meltwater discharge, high hydraulic connectivity and ice-bed decoupling (leading to bedform erosion and sediment re-deposition) and (ii) limited meltwater flow, low hydraulic connectivity and ice-bed recoupling (leading to bedform stretching/deformation).

4.3 | Ribbed and streamlined bedform tracts

Ribbed bedforms and streamlined bedforms are commonly observed along palaeo-ice sheet beds of the FIS and LIS and have mostly been interpreted as relics of former ice domes (Aylsworth & Shilts, 1989; Dyke et al., 1992; Greenwood & Kleman, 2010; Hättestrand & Kleman, 1999; Van Landeghem & Chiverrell, 2020) and ice streams (King et al., 2007; Stokes et al., 2013; Stokes & Clark, 1999, 2001), respectively. Numerous hypotheses of bedform formation have consequently been proposed, primarily associated with ice-bed coupling and bed deformation (e.g. Bouchard, 1989; Fannon et al., 2017; Fowler & Chapwanya, 2014; Hättestrand & Kleman, 1999; Hindmarsh, 1998; Lindén et al., 2008; Lundqvist, 1989, 1997;

Möller, 2006; Stokes et al., 2008), although Shaw (2002) and Möller (2010) also proposed that ribbed and streamlined bedforms could correspond to the sedimentary infill of basal cavities respectively resulting from ice erosion by subglacial sheet floods and basal melt of stagnant ice. Their formation along subglacial drainage routes, however, remains poorly constrained.

In this paper, the identification of 'barcode' landscapes comprising ribbed and streamlined bedform tracts, occurring down-ice or up-ice of typical SMC bedform tracts (i.e. hummock and murtoo tracts), suggests a potential genetic relationship with SMCs. Ice-flow aligned corridors of ribbed bedforms are identified below the Keewatin and Labrador Ice Domes, typically 10s km in length and 100 s m to 5 km in width, and organized into a network of alternating patchy and linear tracts that can be delineated using the transition with interspersed smoothed/streamlined terrains (Aylsworth & Shilts, 1989; Dunlop & Clark, 2006; Lewington, 2020; Trommelen et al., 2014; Wagner, 2014). To date, such 'tract' patterns of ribbed and streamlined bedforms have been interpreted to reflect variations in spatio-temporal ice dynamics (Trommelen et al., 2014), bed rheology/lithology (Aylsworth & Shilts, 1989) or thermal regime (Hättestrand & Kleman, 1999). For some of them, when forming narrow tracts, an apparent spatial relationship with SMCs could result from the preferential development of subglacial drainage routes – later during the glaciation – along existing bedform tracts.

Ribbed and streamlined bedforms are primarily thought to result from ice-water-bed interactions and bed deformation (e.g. Boulton, 1987; Ely et al., 2023; Fannon et al., 2017), modulated by factors such as grain size, bed thickness, topography, ice thickness, ice surface slope and/or ice velocity. Significantly, the spatiotemporal evolution of subglacial drainage systems, notably of hydraulic connectivity and water pressure, acts as an important controlling factor responsible for variations in ice-bed coupling and subglacial bed deformation (Boulton et al., 2001; Lewington et al., 2020). After the rapid increase in meltwater flow and pressure leading to the onset of a subglacial drainage route, the development of high hydraulic connectivity (associated with high drainage efficiency) reduces water pressure within SMCs, generating a pressure gradient from the outside (high water pressure) to the inside (low water pressure) of SMCs. Greater bed deformation is thought to occur outside the corridor because of increased areas of ice-bed coupling (weakly connected part of the subglacial drainage system). Conversely, along the hydraulically connected part of subglacial drainage systems that undergo repeated and more widespread ice-bed decoupling, bed deformation is reduced(e.g. Iverson et al., 2007; Piotrowski & Kraus, 1997). Therefore, it seems reasonable to explore the potential formation of narrow and flow-parallel tracts of ribbed and streamlined bedforms (Dunlop & Clark, 2006; Wagner, 2014) in the context of subglacial drainage routes (Lewington, 2020; Peterson et al., 2017; Vérité et al., 2023).

4.3.1 | Ribbed bedform tracts

Ribbed bedforms form before the onset of subglacial drainage routes

As ribbed bedform tracts are often bounded by streamlined ribbed bedforms and streamlined bedforms (Figures 8, 9c-d), one hypothesis is that ribbed bedforms are formed by subglacial bed deformation over an area wider than the SMCs before the formation of subglacial drainage routes. Later, ribbed bedform fields undergo a phase of streamlining spatially outside but contemporaneous with the development of subglacial drainage routes. Reduced bed deformation and inhibited streamlining processes along the hydraulically-connected part of subglacial drainage routes favour the partial preservation of ribbed bedforms along the SMC axis. Moreover, meltwater flows along SMCs would favour the erosion and thinning of the sedimentary bed around inherited bedforms, thus contributing to the development of the prominent appearance (i.e. rugged) of the ribbed bedforms and even their fragmentation/breaching (Figures 7c, 9d) (Alley et al., 1997, 2019; Lewington et al., 2020; Rampton, 2000; Swift et al., 2005; Vérité et al., 2022). Such a hypothesis could be supported by ribbed bedforms with orientations oblique to the main SMC axis but transverse to regional ice flow indicators, potentially suggesting distinct ice sheet configurations during bedform formation and subglacial drainage route activity (Figures 9a-b). However, ribbed bedforms could form prior to the onset of subglacial drainage routes without any changes in ice sheet configuration, therefore striking perpendicular to the SMC axis.

Ribbed bedforms form contemporaneously with the onset of subglacial drainage routes

An alternative hypothesis is that ribbed bedform tracts – as well as streamlined bedforms found outside SMCs – are formed contemporaneously with the development of SMCs. In this case, a lateral gradient in cumulative bed deformation, modulated by meltwater pressure gradients from inside to outside the SMC, is proposed to explain the lateral transition from ribbed to streamlined bedforms. Tracts of ribbed bedforms within SMCs are interpreted to record a lower degree of cumulative bed deformation (i.e. high hydraulic connectivity and limited ice-bed coupling), whereas streamlined bedform tracts represent a higher degree of cumulative bed deformation (i.e. low hydraulic connectivity and enhanced ice bed-coupling). Such an explanation would be compatible with the model of bedform continuum between ribbed, transitional and streamlined bedforms primarily controlled by a gradient of bed deformation (Aario, 1977; Ely et al., 2016; Vérité et al., 2023). This hypothesis is also supported by ribbed bedforms within SMCs that are consistently transverse to the orientation of both SMC axis and surrounding streamlined bedforms (Figures 9c-d). Such a scenario could also be envisaged when ribbed bedforms are restricted to SMCs or where the ribbed bedform tracts are morphologically different – potentially smaller and more closely spaced because of a lower degree of cumulative bed deformation – to surrounding ribbed bedform fields (see Dunlop & Clark, 2006).

4.3.2 | Streamlined bedform tracts

Streamlined bedforms form before the onset of subglacial drainage routes

Where swarms of streamlined bedforms constrained in SMCs exhibit oblique orientations compared with the orientation of the SMC axis (Figures 11c-d), a hypothesis would be that streamlined bedforms have formed prior to the development of the SMC, which subsequently develops as a sinuous route. Superimposition of depositional meltwater landforms or truncations caused by meltwater erosion after the formation of streamlined bedforms would be consistent with this hypothesis, although streamlined bedforms may also have formed contemporaneously with SMC activity during a phase earlier than that associated with glaciofluvial deposition.

Streamlined bedforms form contemporaneously with the onset of subglacial drainage routes

Lateral gradations from stubby (<100 m) streamlined bedforms within SMCs to streamlined bedforms – typically longer and wider – outside SMCs support the idea that streamlining processes and SMCs formation could be contemporaneous. Swarms of stubby streamlined bedforms organized in narrow tracts are consistent with reduced growth and bed deformation along SMCs. Their stubby appearance could reflect differences in till rheology (influencing bed stiffness and deformability) or the influence of increased erosion in-between bedforms through the development of meltwater channels in response to high effective pressures in the till and more efficient drainage (Figures 11a-b) (Rattas & Piotrowski, 2003). The combination of these hypotheses would indicate that ice-bed coupling and deformation on top of bedforms could co-exist with meltwater flow in-between bedforms, suggesting incomplete ice-bed coupling (Ely et al., 2023; Fannon et al., 2017).

Streamlined bedforms form later in the period of subglacial drainage route activity

Alternatively, some bedforms associated with earlier phases of drainage route activity could have formed first, such as hummock tracts, resulting in reduced sediment volume available to deform. Following this hypothesis, later phases of subglacial drainage route activity (or even after) associated with bed deformation during ice-bed coupling could re-activate streamlining processes, resulting in stubby streamlined bedforms, potentially corresponding to streamlined hummocks (Figure 5e). This kind of landform could also result from subglacial meltwater channelization along SMCs, producing parallel erosive channels and residual streamlined hills resembling stubby streamlined bedforms (Fowler, 2010; Shaw et al., 2008).

5 | A CONCEPTUAL MODEL FOR THE FORMATION AND EVOLUTION OF BEDFORMS ALONG SMCS BASED ON VARIABLE ICE-WATER-BED INTERACTIONS

Based on the above literature review (**Section 2**), new geomorphological observations (**Section 3**) and a synthesis of bedform formation processes along SMCs (**Section 4**), any potential unifying model to explain the diversity of SMC landforms must account for subglacial deposition, erosion and deformation processes. Below, we propose a spatiotemporal conceptual model for the formation and evolution of bedforms along SMCs that outlines how they could respond to the interplay between these subglacial processes, the evolution of subglacial drainage routes and pre-existing bedforms. To do so, we build our model on the significant legacy of field and remote observations (e.g., Ahokangas et al., 2021; Campbell et al., 2016, 2020; DesRosiers, 2021; Dredge et al., 1985; Haiblen, 2017; Lewington et al., 2019, 2020; McMartin et al., 2019, 2021; McMartin, Campbell, Dredge, LeCheminant, et al., 2015; Ojala et al., 2019, 2021, 2022; Peterson et al., 2017, 2018; Peterson & Johnson, 2018; Rampton, 2000; St-Onge, 1984; Utting et al., 2009; Ward et al., 1997), recent physical modelling (e.g. Vérité et al., 2022) and modern observations of ice sheet hydrological processes at land-terminating margins (see Davison et al., 2019 for a review).

The general premise of our conceptual model is that away from ice-divide zones meltwater tends to organize down 100 s m to kms wide SMCs characterized by high hydraulic connectivity (Figure 13a) (Andrews et al., 2014; Davison et al., 2019; Hoffman et al., 2016; Tedstone et al., 2014). Close to the ice margin, the hydraulically-connected drainage system likely contains a central conduit (Chandler et al., 2021; Nanni et al., 2021) while further upstream, thicker ice, fewer surface melt inputs and lower hydraulic gradients are more likely to maintain multiple smaller conduits (Vore et al., 2019). Surface meltwater inputs that overwhelm the hydraulic capacity of the subglacial drainage system produce rapid spikes in water pressure (Bougamont et al., 2014; Das et al., 2008; Hubbard et al., 1995; Iken & Bindschadler, 1986). Over the course of a melt season, increased hydraulic efficiency leads to higher effective pressures concentrated along narrower SMCs (Nanni et al., 2021; Rada & Schoof, 2018). It is these corridors of high hydraulic connectivity that are envisaged to produce SMCs (Lewington et al., 2020; Ojala et al., 2021).

5.1 | Water erosion and deposition-dominated SMCs (Figure 13b)

The bedform assemblages in SMCs are interpreted to record variations in ice-water-bed interactions caused by fluctuations in meltwater supply and pressure. Large inputs of meltwater to the bed during rapid lake – most likely supraglacial – drainage events (Das et al., 2008) and from diurnal and seasonal fluctuations in melt and rainfall events (Andrews et al., 2014; Doyle et al., 2015; Hubbard et al., 1995; Smith et al., 2021) can overwhelm the subglacial drainage system. These configurations are thought to facilitate cavity expansion (Cowton et al., 2016), ice-bed decoupling (Lai et al., 2021) and active drainage through the hydraulically connected drainage system (Figure 11b) (Nanni et al., 2021).

During periods of high-hydraulic connectivity, subglacial processes will be dominated by meltwater erosion and deposition along subglacial drainage routes under a range of drainage configurations resulting in a diversity of bedforms along SMCs (Lewington et al., 2020).

On the one hand, periods of high-hydraulic connectivity may favour the development of laterally restricted floods leading to scoured till and bedrock surfaces, over which hummocks, small-scale ridges, murtoos and related bedforms – forming hummock and murtoo tracts – would be deposited in cavities (Brennand, 1994; Burke et al., 2012b; DesRosiers, 2021; Evans et al., 2022; Haiblen, 2017; St-Onge, 1984; Utting et al., 2009). These cavities could correspond to subglacially-formed ice hollows or basal crevasses resulting from hydrofracturing. Rare examples of gravel mega-dunes described in the literature are thought to record laterally-restricted overflow down corridors (Burke et al., 2012b; Shaw & Gorrell, 1991), while the hummocks and till ridges are assumed to arise from water flow through a broad network of variably active conduits and cavities where ice is partially coupled with the bed (Vore et al., 2019). In the latter case, the deposition of hyper-concentrated flows of sediments is probably controlled by variations in accommodation space due to cavity expansion, sediment choking and hydrofracturing, likely during the waning of high-velocity flow conditions.

On the other hand, water flow may be less laterally constrained within the SMC resulting in geometric patterns of hummocks and small-scale ridges that are believed to result from the erosion of the adjacent till plain and pre-existing bedforms. The erosion of ribbed bedforms and streamlined bedforms is thought to result in flow-transverse alignments of small-scale ridges and hummocks (i.e. eroded ribbed bedforms) and flow-parallel alignments of hummocks (i.e. eroded streamlined bedforms) respectively. More complex, naturally arising cross-hatched patterns associated with meltwater erosion are possibly linked to the drainage of a shallow water layer (Daerr et al., 2003) and/or erosion of murtoo fields.

Although depositional and erosional hummocks and small-scale ridges are produced by different processes, with patterning thought to be more evident for erosional bedforms, they exhibit overlapping morphological ranges (Figure 3), implying some equifinality of form. In addition, both are associated with the formation of small-scale braided/anastomosing channel networks (Kirkham et al., 2021; Peterson et al., 2018).

As the lateral extent of the hydraulically connected region varies in space and time, we also expect the extent of geomorphic work to vary laterally and temporally. This hypothesis is supported by the preferential formation of channels towards the centre of corridors with the apparent greater erosion causing thinning/fragmentation of subglacial bedforms such as ribbed and streamlined bedforms into hummocks and small-scale ridges (Figure 5). Moreover, the superimposition of hummocks and ridges on top of eroded till or bedrock (Figure 4) indicates that the depositional phase typically post-dates the erosional phase with depositional processes likely occurring closer to or right at the ice margin. These observations are consistent with increased drainage efficiency (i.e. channelization) near ice margins leading to a concentration of meltwater flow along a narrower path (e.g. Nanni et al., 2021; Rada & Schoof, 2018). The relatively thinner ice near the margins would also have reduced the rate of conduit closure, facilitating prolonged waning stage flow (Roberts, 2005) and thus deposition (Burke et al., 2012a). An alternative scenario is that deposition could have occurred in a narrower zone during waning water flows as drainage efficiency reduced and the ice began to recouple to the bed. In any case, the rare occurrence of erosional and depositional bedforms beyond corridor margins likely indicates formation during high-magnitude events when the rate of meltwater supply occasionally vastly exceeds the drainage capacity of the hydrological system. As a consequence of the spatiotemporal dynamics of meltwater flow along drainage routes, discrete swarms of hummocks and small-scale ridges could have formed roughly synchronously and represent a single extensive subglacial meltwater drainage event, while repeated sequences of hummock tracts along a SMC could have formed time-transgressively as the margin receded.

Based on geomorphological observations, the dominant overall bedform type in SMCs appears to be erosional; this suggests that sediment from the subglacial drainage route is transported downstream and probably evacuated from under the ice toward the margin. However, at a regional scale, depositional bedforms are frequent, indicating local variability in erosion and deposition along individual drainage routes and potential variations in subglacial hydraulic gradients. Outside of corridors, the poor hydraulic connectivity of the weakly connected distributed drainage system limits sediment mobilization and restricts transport by meltwater (Alley et al., 1997).

5.2 | Deformation-dominated SMCs (Figure 13c)

Bed deformation is strongly controlled by water pressure and ice-bed coupling (Bougamont et al., 2014; Boulton et al., 2001; Damsgaard et al., 2016, 2020; Iverson et al., 2003, 2007; Kavanaugh & Clarke, 2006; Truffer & Harrison, 2006). It, therefore, follows that fluctuating subglacial water pressure within the hydraulically connected drainage system (Figure 13a) will generate complex configurations of meltwater drainage, where ice bed decoupling is predominant and limits the cumulative deformation accommodated by the bed through time. It differs from the surrounding weakly connected regions where low hydraulic connectivity and widespread ice-bed coupling are maintained (i.e. lower cumulative bed deformation).

Our review of the existing literature and new geomorphological observations suggest that the formation and growth of deformational bedforms – such as ribbed and streamlined bedforms – are generally reduced within SMCs. Repeated ice-bed decoupling phases, when the drainage system becomes overwhelmed, favour the preservation of ribbed and streamlined tracts within SMCs while greater ice-related deformation outside the corridors is able to keep reshaping bedforms.

Although we suggest there is reduced bed deformation within hydraulically-connected parts of distributed drainage systems compared to their surrounding weakly-connected parts (Vérité, 2022), repeated phases of ice-bed recoupling in response to fluctuating meltwater inputs (Becher & Johnson, 2021; Bougamont et al., 2014; Damsgaard et al., 2020; Lesemann et al., 2010; Truffer & Harrison, 2006) could result in the deformation of existing bedforms. Ice-bed coupling and bed deformation within SMCs manifests by streamlined and ribbed bedforms, which are both less smooth and with reduced dimensions compared with their counterparts observed outside corridors (see Vérité, 2022 for a compilation of bedform metrics). The well-delineated texture and reduced dimensions of streamlined and ribbed bedforms along SMCs could be explained by the combined effect of meltwater erosion – supported by relationships with minor channels – and limited bed deformation. Within SMCs where the transitory behaviour of hydraulic activity generates alternating phases of ice-bed coupling and decoupling, progressive bed deformation also manifests by a continuum of bedforms spanning over murtoos, murtoo-related bedforms, oblique-parallel ridges and escarpments (Vérité et al., 2022).

5.3 | SMCs evolution in response to changing ice-water-bed interactions

SMCs are a composite imprint of spatiotemporal variations in ice-water-bed interactions, forming typical landform systems such as those proposed by Sharpe et al. (2021) and Vérité et al. (2022), but which did not include all the diversity of SMC bedforms. The time-transgressive nature of landform assemblages found in SMCs is best illustrated by the occurrence of eskers corresponding to the

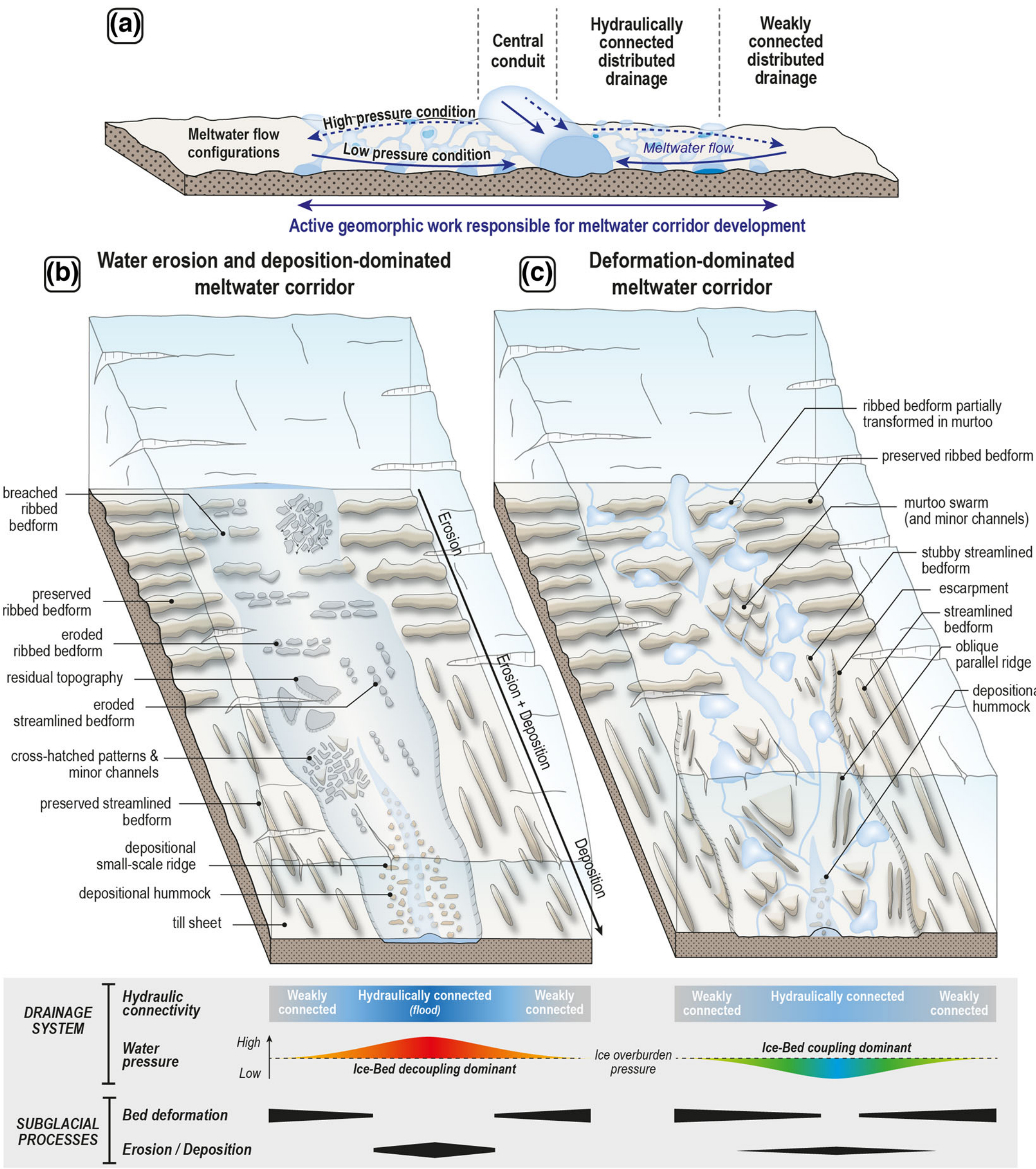

FIGURE 13 A general theory for SMCs formation. (a) SMCs are the morphological expression of the hydraulically well-connected parts of the subglacial drainage system, which undergo large variations in meltwater input, effective pressure and drainage efficiency. Based on the width of corridors the hydraulically well-connected drainage system is inferred to be hundreds of metres to several kilometres wide. (b) Snapshot of SMC processes and bedforms produced when a large and rapid meltwater input overwhelms the drainage capacity resulting in ice-bed decoupling, active water flow, erosion and deposition over a large lateral extent within the corridor. This is conceptualised as laterally-restricted overflow of the drainage system (i.e. laterally-restricted floods) but could also comprise other or additional drainage configurations (see Section 5 for more details). (c) Snapshot of SMC processes and bedforms produced when effective pressure increases and the ice recouples with the bed resulting in ice-bed recoupling, deformation of till sheets and existing bedforms. The black bars in the legend indicate extent (length) and magnitude (width) of bed deformation and erosion/deposition at the bed. Note, (b) and (c) could be 10s km in length. The size of example landforms is not to scale.

sedimentary infill of subglacial conduits that commonly overlay other SMC bedforms or even cross-cut SMCs.

Eskers and associated outwash fans could therefore be interpreted as recording the final phase of deposition in a subglacial conduit located within the subglacial drainage route, either close to or at the ice margin (e.g. Hewitt & Creyts, 2019; Lewington et al., 2020; Livingstone et al., 2020; Mäkinen, 2003; Peterson et al., 2018). Within the SMCs, longitudinal and lateral transitions between different bedform tracts (see **Section 3.6**) also suggest that the complex geomorphic record observed along SMCs results from multiple episodes of modification linked to spatiotemporal variations in ice-water-bed interactions.

Overall, where and when ice-bed decoupling dominates, meltwater scours till and bedrock-producing channels, progressively fragmenting the adjacent till sheet and existing bedforms (e.g. ribbed and streamlined bedforms) and potentially forming erosional hummock tracts and geometric arrangement of hummocks and small-scale ridges. The eroded sediments are ultimately either transported beyond the ice margin (e.g. as outwash fans) or re-deposited down-ice in cavities and crevasses, which could result in depositional hummock tracts and the chaotic arrangement of hummocks and small-scale ridges. Conversely, where and when ice-bed coupling predominates, bedforms related to bed deformation – such as ribbed and streamlined bedforms, murtoos and related landforms – are either formed, preserved when bed deformation is sufficiently low, or transformed/streamlined when bed deformation is high.

A simple explanation for variations in coupling could be that water pressure fluctuates hourly-to-seasonally, as seen in present-day glaciers and ice sheets (Andrews et al., 2014; Rada & Schoof, 2018). Hence, these fluctuations provoke alternations between meltwater erosion-deposition processes and glacially-induced deformation processes, which in turn leads to the formation, transformation and then fragmentation of bedforms. For example, the transformation of existing bedforms – such as ribbed bedforms associated with glacial stages older than subglacial drainage route development – into murtoos and related landforms appears to be the combined result of fluctuations in ice-bed coupling and decoupling related to repetitive overflow conditions along SMCs (Becher & Johnson, 2021; Mäkinen et al., 2017; Ojala et al., 2019, 2021; Vérité et al., 2022). Similarly, stubby streamlined bedforms – potentially corresponding to streamlined hummocks – could be interpreted to record deposition or erosion during ice-bed decoupling followed by deformation during ice-bed recoupling (Haiblen, 2017); the increase in elongation and frequency of streamlining towards the edge of corridors being concomitant with greater ice-bed coupling away from the main drainage axis.

The evolution and final landform signature of SMCs is therefore conditioned by (i) the landform assemblage that existed prior to subglacial drainage route development and (ii) the evolution of the drainage route itself, which we have tried to summarize in a potential spatiotemporal evolution model (Figure 14).

A first scenario, identified in SW Keewatin and Finland, could involve a regional-scale field of ribbed bedforms (Figure 14a) that are locally preserved along SMCs, forming ribbed bedforms tracts (Figure 14b), while outside the SMCs the ribbed bedforms are

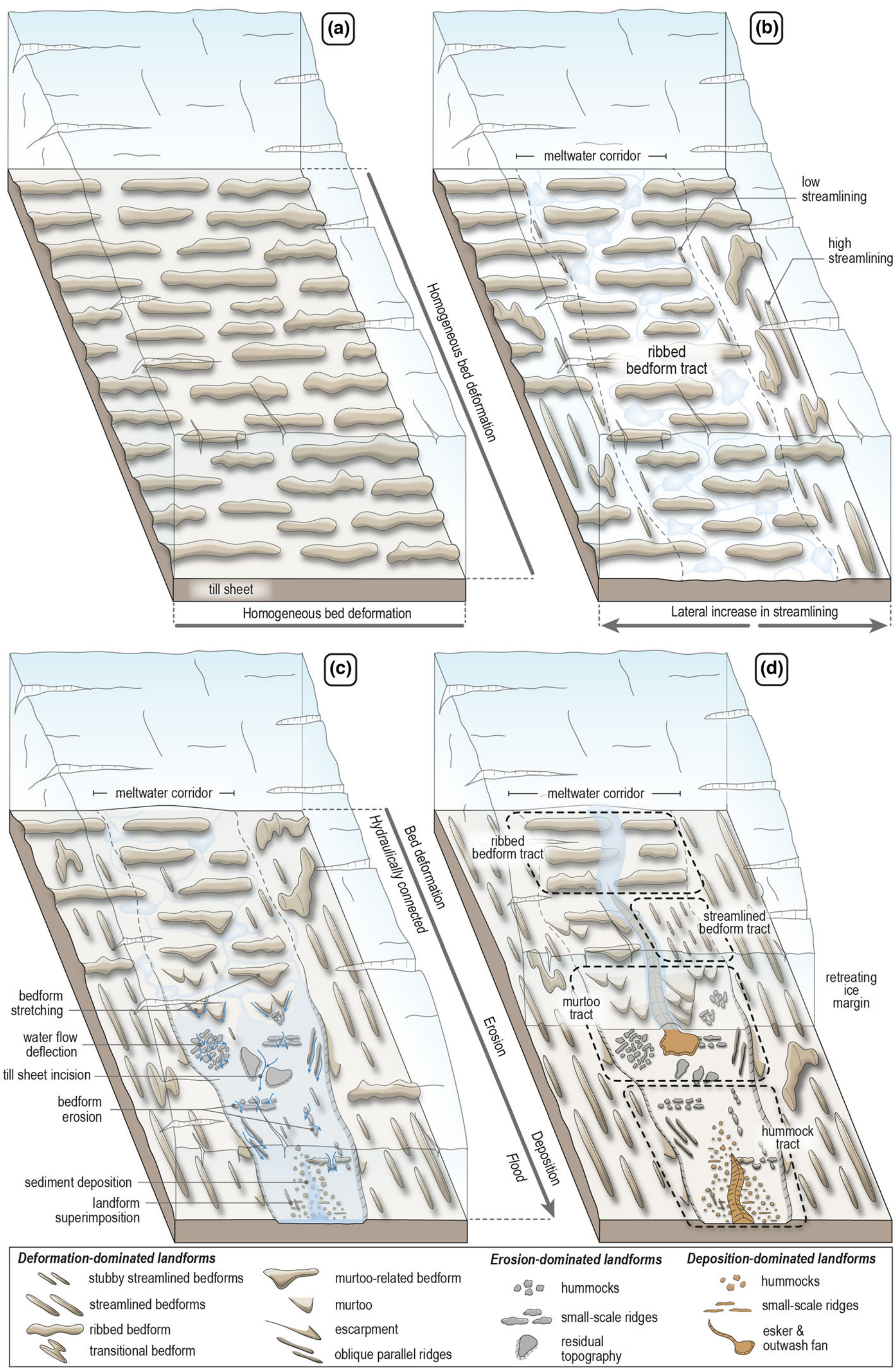

FIGURE 14 Potential spatiotemporal evolutionary model of a SMC in response to ice-water-bed interactions. (a) Ribbed bedforms form widely across the bed. (b) Meltwater flow becomes organised down a corridor inhibiting streamlining due to evacuation of sediment and ice-bed decoupling (greater hydraulic connectivity). The ribbed bedforms are largely preserved in the corridor apart from minor streamlining. (c) Continued variations in ice-water-bed interactions result in reshaping (i.e. due to sediment deformation) and fragmentation/breaching (i.e. due to dissection by water flow) of bedforms, and also deposition of new bedforms in the downstream part of the SMC. Erosion by minor channels results in the emergence of hummock and ridge networks forming geometric patterns: flow-transverse and flow-parallel alignments and cross-hatched-patterns. (d) Deposition in the conduit close to the margin produces an esker as ice recedes back across the region. See the main text for other possible landform signature evolutions.

transformed into transitional bedforms (i.e. streamlined ribbed bedforms) and streamlined bedforms – even if untransformed ribbed bedforms may also be observed outside SMCs preserving the signature of regional-scale field of ribbed bedforms. The degree to which the ribbed bedform tracts are subsequently modified (Figures 14c-d) and evolve into other tracts depends on the dominant processes of sediment remobilization along the subglacial drainage route: (i) erosion and/or deposition (hummock and murtoo tracts) or (ii) deformation (murtoo and streamlined bedform tracts). The spatio-temporal variations of these processes are controlled by changing water pressure and drainage conditions along the SMC.

Since the final landform signature of SMCs is conditioned by the inherited landform assemblage, formed prior to the subglacial drainage route, a second scenario could involve a regional-scale field of streamlined bedforms reworked during subglacial drainage route development. Erosion of existing streamlined bedforms could favour the formation of stubby lineations (i.e. streamlined bedform tract) and flow-aligned hummocks (i.e. erosional hummock tract), while the subsequent re-deposition of sediments would favour the formation of depositional hummocks and small-scale-ridges (i.e. depositional hummock tract).

Finally, as a third scenario, the formation of streamlined and ribbed bedform tracts (bothsurrounded by streamlined bedforms outside of SMCs) could also occur contemporaneously with the development of subglacial drainage routes considering an initial flat or completely overprinted (without relics of older bedforms) sedimentary bed. Such bedform assemblages, forming typical barcode patterns, may be explained by lateral gradations in cumulative bed deformation (Section 5.2). This scenario would be respectively evidenced by lateral gradations (i) between stubby streamlined bedforms and typical streamlined bedforms (i.e. drumlins) or (ii) between ribbed, transitional and streamlined bedforms from the core to the margins of SMCs. Thus, the timing of streamlining proposed in Figures 14b-c may either predate or occur contemporaneously with subglacial meltwater corridor formation.

6 | IMPLICATIONS FOR UNDERSTANDING SUBGLACIAL MELTWATER DRAINAGE AND ITS BROADER IMPACT

Our conceptual model for the formation of subglacial bedform tracts found along SMCs, and their widespread occurrence in northern Canada and Fennoscandia (Ahokangas et al., 2021; Dewald et al., 2022; Lewington et al., 2020; McMartin et al., 2021; Peterson et al., 2017) suggests that subglacial meltwater is often organized into a laterally-restricted and hydraulically-connected drainage system, with the surrounding bed likely characterized by high water pressures in a less efficient and weakly-connected drainage system. This concept of spatially varying water content, pressure and bed properties is consistent with the idea of a transient mosaic of bed conditions (Lee & Phillips, 2008; Murray et al., 2008; Piotrowski et al., 2004). It also suggests that water is a key control on the production of subglacial bedforms and ice-dynamic processes across significant regions of palaeo-ice sheet beds, with the SMCs below the Keewatin Ice Dome (LIS) estimated to comprise 5–36% of the bed (Lewington et al., 2020) except under large ice divide zones or relict cold-based landscapes where they are rare or absent (McMartin et al., 2021).

Spatial gradations of bedform types have been described in this paper between the central axis and the boundaries of SMCs, such as between (i) stubby streamlined bedforms and typical streamlined bedforms (e.g. drumlins), (ii) murtoos (and related landforms) and ribbed bedforms, and (iii) ribbed, transitional and streamlined bedforms. These spatial and morphological gradations could be interpreted as reflecting contemporaneous variations in ice-water-bed interactions. Thus, SMCs and their surrounding areas are likely to comprise a relic imprint of the distribution of subglacial processes at the ice-sheet scale, especially during late deglaciation.

As SMCs are interpreted to record variations in ice-water-bed interactions, our model requires pulsed delivery of meltwater to the bed, which could be caused by surface meltwater inputs and/or subglacial lake drainage. Given the limited evidence for subglacial lakes in Keewatin (Livingstone et al., 2013), and the ice-sheet scale organization and occurrence of SMCs (Dewald et al., 2022; Lewington et al., 2020) we favour a surface meltwater source associated with enhanced surface ablation during deglaciation (e.g. Carlson et al., 2008, 2009). This is consistent with modern observations of ice sheet hydrological processes, specifically, the formation of broad hydraulically connected ‘corridors’ during the melt season (Davison et al., 2019). Indeed, in the absence of surface-melt contributions to the bed, SMCs on the deglaciated Antarctic continental shelf can form but are rare (Simkins et al., 2021).

The palimpsest morphological signature of SMCs and bedform formation can also allow the relative timing and style of subglacial drainage activity to be unravelled. The time-transgressive nature of SMC formation is notably highlighted by (i) alternating phases of bed deformation during and maybe even after their active period, (ii) eskers formed during the final stage of deglaciating meltwater drainage at or near the ice-margin, (iii) the repetition of diverse bedform signatures both between and within individual SMCs, and (iv) evidence that SMC bedforms are transformed, deformed and eroded by repeated ice-bed decoupling and recoupling. The apparent time-transgressive nature of SMCs probably signifies that a broad continuum of preserved to reworked (to buried) SMCs is apparent across the landscape, that subglacial drainage routes were not all active at the same time and thus that whole networks were not formed synchronously by large sheet floods (e.g., see Rampton, 2000; Sharpe et al., 2017, 2021). Provided that future work demonstrates the time-transgressive nature of studied SMCs, it could therefore be possible to use their palimpsest record, and the width and repetition of discrete bedform tracts to infer the style and rates of ice retreat.

7 | CONCLUSION & FUTURE PERSPECTIVES

SMCs provide an important record for understanding subglacial hydrological processes, including the relative importance of the hydraulically-connected and weakly-connected drainage components, their spatiotemporal evolution with warming and their impact on ice dynamics. This paper reviews the current state of knowledge and uses high-resolution (2 m) DEMs in selected areas of northern Canada (LIS) and Fennoscandia (FIS) to catalogue the characteristics of bedform assemblages (hummock, murtoo, ribbed and streamlined bedform tracts) observed in SMCs. These data are used to discuss formational mechanisms, which are combined into an overarching conceptual model for the formation of SMCs caused by variations in ice-water-bed interactions in response to meltwater forcing.

Based on our model, during periods of enhanced meltwater supply, water overflows from the drainage system forming hydraulically-connected SMCs hundreds of metres to several kilometres wide. These laterally-restricted overflowing events modify till sheets, pre-existing streamlined bedforms, ribbed bedforms and murtoos by meltwater erosion, yielding geometric ridge and hummock patterns. Eroded sediments are partially redeposited downstream in cavities and basal crevasses. During periods of reduced water supply, the ice recouples with the bed resulting in the deformation of existing bedforms or the formation of new ones. Repeated cycles of ice-bed decoupling (i.e. overflow of the drainage system) and ice-bed recoupling (i.e. reduced water supply in the drainage system) produce a continuum of morphologies associated with the formation, transformation and fragmentation of bedforms. The evolution and final morphological signature of SMCs is conditioned by the pre-existing bedform assemblage and represents a time-integrated pattern of changing conditions during ice retreat and fluctuating melt forcing. The impact of the drainage configuration on cumulative deformation (ice-water-bed interactions) and sediment availability is suggested to play a key role in controlling bedform formation and morphology.

To facilitate validation or falsification of our conceptual model, we propose a number of future research priorities. The release of freely available, high-resolution DEMs has enabled new geomorphological insights into SMCs and their distribution (e.g. Lewington et al., 2020), but investigations into the internal composition of SMC bedforms and associated meltwater landforms is scarce due to the challenge of acquiring field data. A key prediction of the model, supported by limited sediment investigations, is the formation of both depositional and erosional hummocks and small-scale ridges, which might be distinguished based on their patterning (chaotic vs geometric respectively). Future work should expand on previous field investigations (e.g. Burke et al., 2012b; Campbell et al., 2020; Dahlgren, 2013; DesRosiers, 2021; Haiblen, 2017; McMartin et al., 2015, 2015; Peterson et al., 2018; Rampton, 2000; Sharpe et al., 2017; St-Onge, 1984; Utting et al., 2009), by targeting SMC hummocks and ridges to test the model and provide new understanding of bedform-sediment relationships and the processes controlling sediment remobilization and deposition (e.g. accommodation space). This will allow the overall spatial distribution of depositional vs erosional hummocks and ridges in SMCs to be better evaluated, including the extent to which different formational processes can be identified from their patterning (i.e. issues of equifinality). It might also help inform a wider-scale assessment of the ratio and distribution of erosion-dominated vs deposition-dominated SMCs. We suggest that erosional SMCs are dominant based on the predominance of incised corridors, but the extent to which these corridors contain reworked sediments eroded from further up ice is poorly constrained. A sediment-budget approach to investigating SMCs might help to identify the efficiency with which meltwater-driven sediment transport and re-deposition occurs under ice sheets or onto the foreland.

Subglacial bedforms found in SMCs display probably the most varied (i.e. shapes, metrics, arrangement, lateral/longitudinal transitions) landform assemblages encountered in subglacial environments. To better constrain the processes responsible for the formation of this wide range of bedforms, a more extensive morphological database (elongation, sinuosity, area, volume, amplitude) over a wider range of localities will help (1) compiling the accurate diversity of bedforms within SMCs and (2) identifying possible continuum between some bedforms but also break between some groups of bedforms indicating changes in the dominant processes of formation (erosion, deformation, deposition).

Although the full range of SMCs and associated morphological signatures are found in both northern Canada and Fennoscandia, murtoo tracts are noticeably more common in the latter (e.g., Ahokangas et al., 2021; Mäkinen et al., 2017; Ojala et al., 2019, 2021, 2022; Peterson et al., 2017; Vérité et al., 2022). These murtoos tend to be associated with former ice lobes and occur in locations corresponding to periods of rapid ice-margin retreat and delivery of large volumes of supraglacial meltwater to the bed (Ojala et al., 2019; Peterson Becher & Johnson, 2021). A systematic search for murtoos beneath the former LIS from high-resolution DEMs, focusing on the terrestrial ice lobe margins and in regions corresponding to periods of climatic warming would determine whether this pattern is real and what might control any differences. Finally, although external (climatic) controls on the large-scale distribution of murtoos have been studied (Ojala et al., 2019), internal factors influencing their formation such as bed lithology and bed topography remain under-explored (Mäkinen et al., 2023).

Although there has been progress in using SMCs and their landforms to improve our understanding of the distributed drainage system and its connectivity (Lewington et al., 2020; Ojala et al., 2022), the morphological record of distributed drainage configurations is poorly preserved compared to the channelized drainage system due to differences in scale and magnitude of meltwater flow. We therefore expect that the variability of drainage configurations down SMCs is biased towards the latter. This requires further work to better connect our interpretation of subglacial meltwater drainage down the corridors to mathematical treatments of the stability of various types of water drainage configurations. For example, Walder & Fowler (1994) and Ng (2000) showed theoretically that a water film over deformable sediment is unstable and would either collapse to R-channels (i.e. forming esker ridges) or wider sediment-floored 'canals', according to controls of effective pressure and water discharge. Interestingly, a prediction that arose is that highly efficient R-channels are favoured under steeper ice surface slopes and low-efficient canals under flatter slopes. This is exactly the circumstance we deduce from the evolution of meltwater corridors to eskers over time, whereupon wider canal-type flow is replaced by R-channel flow as the ice margin withdrew, noting that surface slopes are typically steeper close to the ice margin. It is also worth noting that Carter et al. (2017) found that drainage through sediment-floored canals rather than R-channels allowed them to better match some Antarctic subglacial lake drainage and refilling events. We suggest that our observations and data especially on the size and spacing of meltwater corridors and transitions between corridors to R-channel configurations may be useful in building or testing this model.

Finally, quantifying the scaling, distribution and evolution of the hydraulically connected drainage system beneath modern-day ice masses (e.g., Hubbard et al., 1995) offers an avenue to test our conceptual model and build an integrated theory linking meltwater fluctuations over short-term scales to the long-term geomorphic record.

Future studies might also conduct geophysical surveys focusing on geomorphic evidence of relict or actively forming SMCs beneath the ice and the foreland of glaciers and ice sheets.

AUTHOR CONTRIBUTIONS

EL and ND carried out the initial large-sale mapping of subglacial meltwater corridors. JV, SJL, ER, IM, JC, CDC identified and described individual landforms and landform tracts. JV, SJL, ER, ND produced the figures. The model was conceptualized by JV, ER, SJL, CDC, with contributions from all authors. JV and SJL wrote the paper with contributions from all authors.

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DATA AVAILABILITY STATEMENT

Publicly available high-resolution DEMs were used to identify and describe subglacial bedforms and meltwater landforms, including national 2-m LiDAR datasets in Sweden (https://www.lantmateriet.se) and Finland (https://www.maanmittauslaitos.fi/en) and the 2-m ArcticDEM mosaic v7 (https://www.pgc.umn.edu/data/arcticdem) in northern Canada. All datasets used in this paper are available from the corresponding author on request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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