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# The distribution of glacial meltwater routes and associated murtoo fields in Finland

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ABSTRACT

High-resolution LiDAR (Light detection and Ranging) -based digital elevation models (DEM) have greatly improved the mapping of glacial landforms and revealed new ones such as murtoos. Murtoos have extensive diversity in form, relief and size, and they often appear along meltwater routes. However, not all meltwater routes in the recently glaciated terrains include murtoos. We mapped different types of subglacial meltwater routes and the related distribution of murtoos in the Finnish part of Fennoscandian Ice Sheet (FIS). Subglacial meltwater routes represent a previously unknown extension of the subglacial hydrological system that supplements esker networks. Murtoo deposition along the routes is dictated by the marked concentration and routing of subglacial meltwater in a high-pressure environment outside the subglacial tunnel flow and channelized drainage zone. The main environments of murtoo route genesis include the margins of glacial lineation fields, lateral shear margins of ice streams or in between ice-flow sectors or corridors, confluence zones of ice stream onset areas, lee-sides of bedrock protrusions or thresholds, bedrock fracture valleys and potential subglacial lake inputs and outputs. This study adds to the knowledge of the development of subglacial drainage and emphasizes the role of murtoos as the potential missing link between the channelized and distributed subglacial drainage.

## 1. Introduction

Subglacial hydrology plays a crucial role in understanding of the melting of ice sheets, as well as ice dynamics. The main components of subglacial hydrological networks are distributed inefficient and channelized efficient drainage systems (including R- and N-channels), which differ in their hydraulic properties and water flow capacity (Hooke, 2020). These systems form separate entities but also interact. When water pressure decreases and discharge increases (Röthlisberger, 1972), water flows from smaller conduits towards larger ones and an arborescent drainage network develops (Shreve, 1972; Hooke, 2020). If both water pressure and discharge increase, a braided or distributed conduit system develops. The roof of a conduit on deforming till tends to close when $P_w < P_i$, but this tendency is balanced by melting in the steady state. Additionally, the creep of till into the conduit constricts it, and in the steady state, any such flow must be balanced by erosion of the till by flowing water (Hooke, 2020).

Subglacial channelized (efficient) networks form within 50 km from the ice margin (Bartholomew et al., 2011; Chandler et al., 2013) and leave identifiable traces such as eskers and tunnel valleys. Eskers are the most recognizable landform, representing the sedimentary infill of R-channels (Clark and Walder, 1994). Their formation is mostly attributed to pressurized subglacial tunnels (Shreve, 1972, 1985; Syverson et al., 1994; Brennand and Shaw, 1996), tunnel mouths (Brodzikowski and van Loon, 1991), the grounding line environment (Gorrell and Shaw, 1991) or, at the ice margin, to the deposition of subaqueous fans, deltas or esker beads (Powell, 1990; Warren and Ashley, 1994; Mäkinen, 2003). Both time-transgressive and synchronous formation have been discussed. Instead, the traces of distributed drainage systems are difficult to identify. Likewise, formation of subglacial drainage networks between distributed and channelized components are also mostly unknown.

Traces of subglacial meltwater flow have also been recognized in the form of various corridors, e.g., glaciofluvial corridors or subglacial meltwater corridors (GFC), glaciofluvial corridor hummocks (Utting et al., 2009) and hummocky corridors (St-Onge, 1984; Brennand and Sharpe, 1993; Rampton, 2000; Dredge et al., 2013; Sharpe et al., 2013, 2017; Peterson and Johnson, 2018). These corridors can range from a few hundreds of metres to several kilometres in width and from a few kilometres to tens of kilometres in length. Abrupt boundaries for glaciofluvial and hummocky corridors (Utting et al., 2009; Peterson and Johnson, 2018) and erosion of till within the corridors have been recognized. Peterson and Johnson (2018) refer to individual positive

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landforms with an irregular topography as ‘hummocks’. Large areas of these landforms compose a ‘hummock tract’, and when restricted to elongated zones with clear boundaries between them and the surrounding landscape, they refer to a hummock tract as a ‘hummock corridor’. Positive and negative features are distinguished, the latter referring to corridors incised into the substrate. The corridors are considered as subglacial features, although their detailed characteristics and genesis are poorly understood.

Recently discovered landforms called murtoos potentially represent the missing link between the two subglacial hydrological network components (Mäkinen et al., 2017; Ojala et al., 2019b; Mäkinen et al., 2019; Ojala et al., 2021; Peterson Becher and Johnson, 2021). Murtoos are distinct triangular-shaped landforms that have a triangular tip oriented parallel to the ice-flow direction (Fig. 1). They are typically 30–200 m in length and width and commonly <5 m in relief. Their edges are sharp and steep and the asymmetrical longitudinal profile has a short and steeper down-ice slope (Ojala et al., 2019b). When compared with glaciodynamic (GD) areas (Palmu et al., 2021) (Fig. 2A), murtoo fields mostly concentrate to ice lobe provinces and interlobate regions in southern and central Finland (Fig. 2B). In recent mapping and classification in Finland, Ojala et al. (2021) noticed that the triangular-shaped appearance is only one diagnostic characteristic of murtoos, and they actually show extensive diversity and variability in shape, relief and size. Based on their morphometric analysis, murtoos and murtoo-related landforms can be divided into five main types: (i) triangle-type murtoos (TTM), (ii) chevron-type murtoos (CTM), (iii) lobate-type murtoos (LTM), (iv) murtoo-related ridges and escarpments (MRE) (cf. Fig. 2B) and (v) other murtoo-related polymorphous landforms (PMR) that appear as small mounds and ridges.

Murtoos occur in fields that are connected to hummocky corridors with a variety of different hummocks, both positive and negative relief and sharp to indistinct margins, and are also associated with eskers, river valleys, and lake basins (Mäkinen et al., 2017; Peterson et al., 2017; Ojala et al., 2019b; Ahokangas et al., 2020a). Their distribution and morphometry are known in both Finland and Sweden (Peterson et al., 2017; Ojala et al., 2019b, 2021) and sedimentology for southern Sweden (Peterson Becher and Johnson, 2021). Based on the preliminary sedimentological data from Finland (Mäkinen et al., 2017, 2019), murtoos are stratified and composed of sandy and gravelly diamictons with low mud content, and partly preserved sorted sediments. In addition, high concentration of surface boulders is a typical feature of murtoos. Murtoos are interpreted as depositional landforms with erosional triangular heads. Morphological and sedimentological investigations indicate that they form subglacially with fluctuations in the meltwater flow and pressure (Mäkinen et al., 2019; Peterson Becher and Johnson, 2021).

Large parts of the Fennoscandian Ice Sheet (FIS) area have nationwide LiDAR coverage (Finland, Sweden, Norway). In Finland, the Geological Survey of Finland has mapped glaciofluvial landforms (including eskers) from a LiDAR DEM as part of the nationwide mapping of glaciodynamic (GD) areas and the construction of a GD database (Putkinen et al., 2017; Geological Survey of Finland, 2021). Some extensive areas, such as northern Canada, have been mapped for eskers using aerial photographs and field observations (Aylsworth and Shilts, 1989; Aylsworth et al., 2012). Recently, a map of glacigenic features and glacial land systems has been produced from ArcticDEM data and Landsat 9 imagery from Nunavut, Canada (McMartin et al., 2021), and traces of subglacial meltwater drainage have been mapped from the Arctic

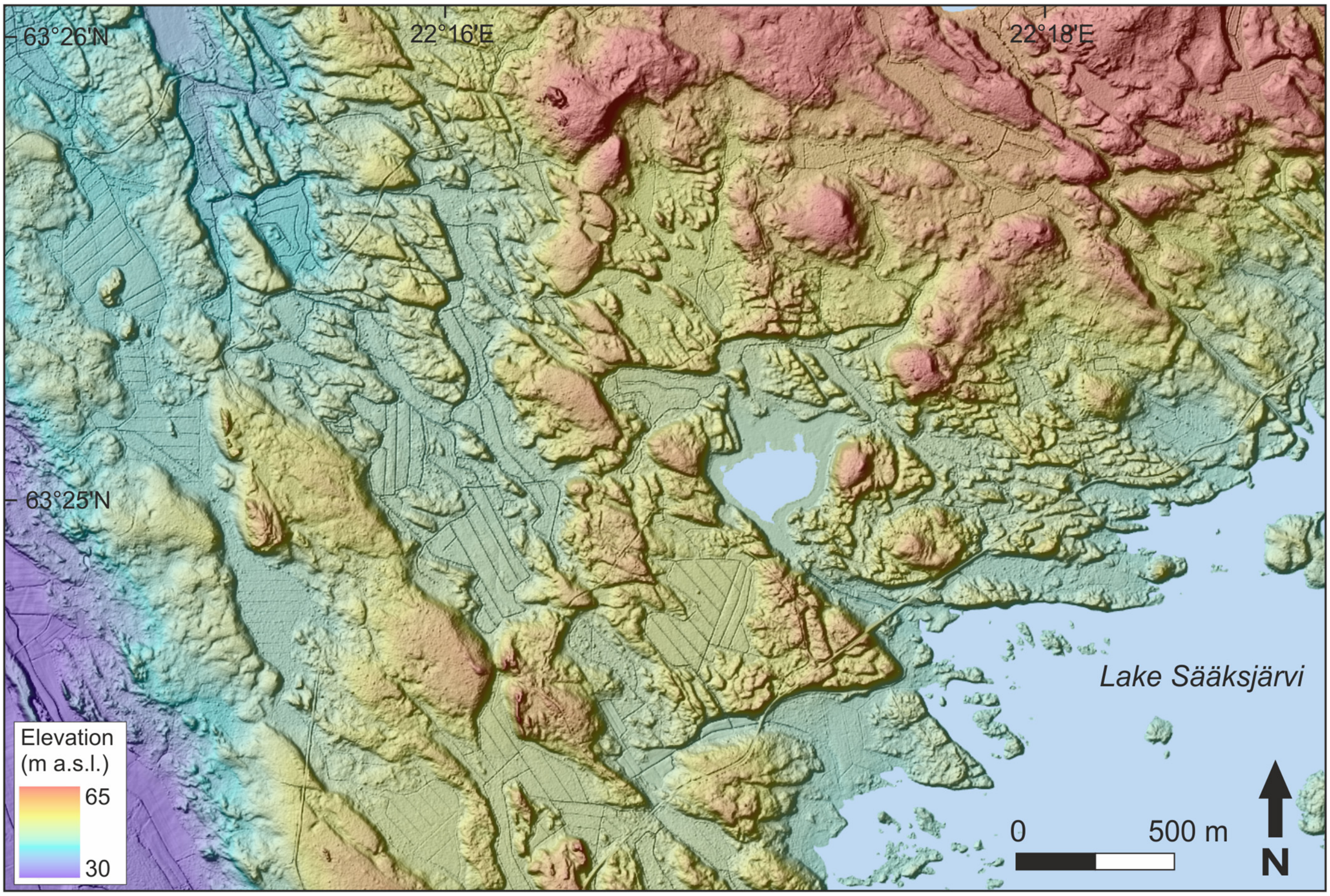
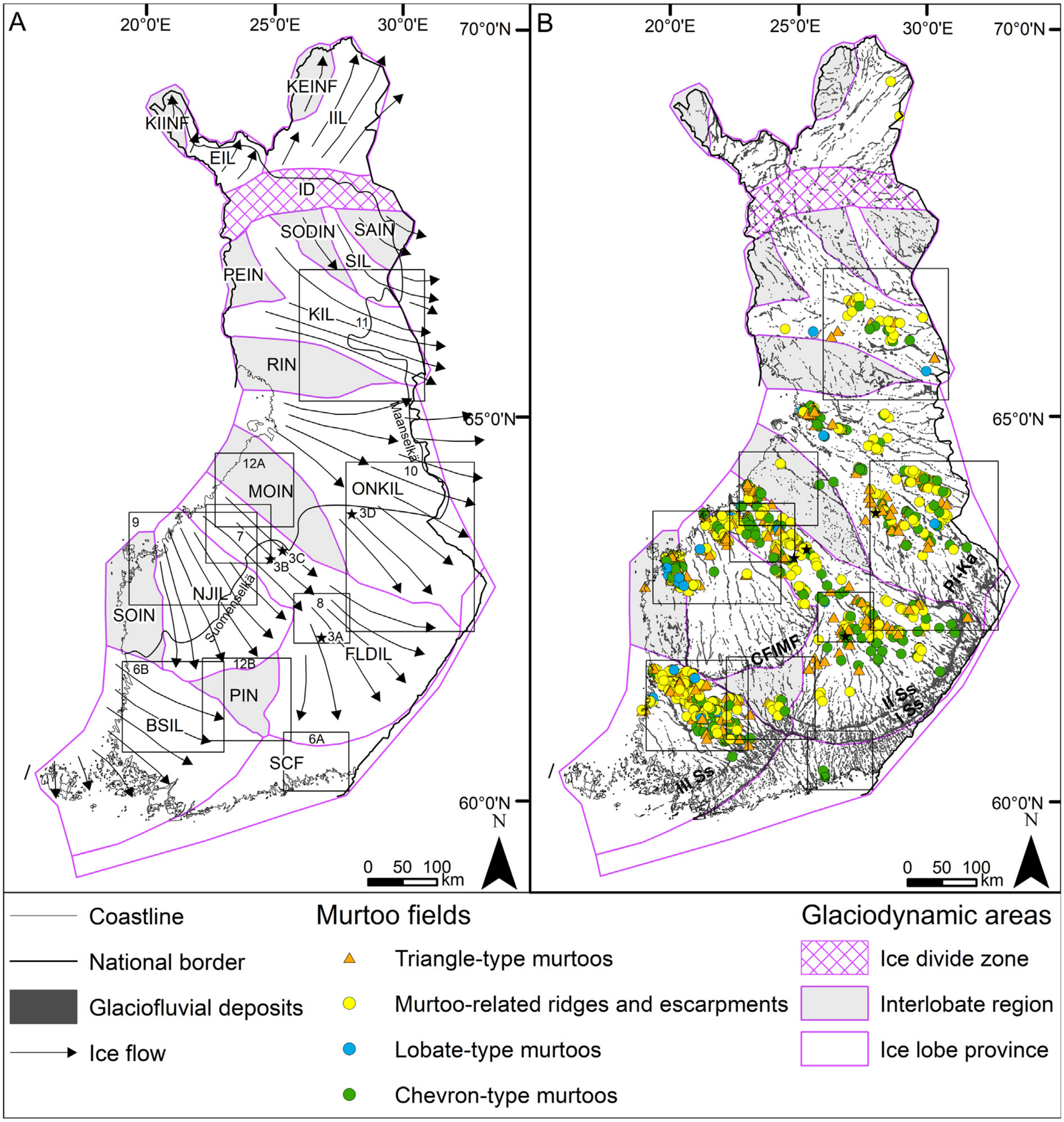


**Fig. 1.** Triangle-type murtoos and murtoo-related diagonal ridges and escarpments (Modified from Mäkinen et al., 2017). The field is located northwest of Lake Sääksjärvi, SW Finland.



**Ice lobe provinces**
SCF: Southern coastal Finland province
BSIL: Baltic Sea Ice lobe province
FLDIL: Finnish Lake District Ice lobe province
NJIL: Näsijärvi-Jyväskylä Ice lobe province
ONKIL: Oulu-North-Karelian Ice lobe province
KIL: Kuusamo Ice lobe province
SIL: Salla Ice lobe province
IIL: Inari Ice lobe province
EIL: Enontekiö Ice lobe province

**Interlobate regions**
PIN: Päijänne interlobate region
SOIN: Southern Ostrobothnian interlobate region
MOIN: Middle Ostrobothnian interlobate region
RIN: Ranua interlobate region
PEIN: Pello interlobate region
SODIN: Sodankylä interlobate region
SAIN: Savukoski interlobate region
KEINF: Kevo interlobate Fjell province
KIINF: Kilpisjärvi interlobate Fjell province

**ID: Ice divide zone**

**Fig. 2.** A) The glaciodynamic areas of Finland based on the Glacier Dynamic geodatabase (GD database) (Palmu et al., 2021), the main ice-flow directions, water divide (solid black line) and the figure locations. B) The glaciodynamic areas, glaciofluvial deposits, end moraines (CFIMF: Central Finland ice marginal formation; I, II and III Ss: I, II and III Salpausselkä, and Pi-Ka: Pielinen-Kalevala end moraine), and location of different types of murtoo fields (Ojala et al., 2021).

DEM dataset in the Keewatin ice-divide area of Canada (Lewington et al., 2020). In addition, hummocky corridors have been mapped with automated methods in northern Canada and Scandinavia (Lewington et al., 2019). In southern Sweden, glacial landforms south of the Swedish uplands (Peterson et al., 2017) and glacial geomorphology between Lakes Vänern and Vättern (Öhrling et al., 2020) have been mapped from LiDAR-based DEMs. In addition, the genesis of hummocks in tunnel valleys has been investigated based on sedimentology and optically stimulated luminescence (OSL) dating (Peterson et al., 2018).

Recently, Lewington et al. (2020) mapped all sub-glacial meltwater drainage traces (including meltwater corridors, eskers with lateral splay and esker ridges) into meltwater routes in the Keewatin area of Canada. The meltwater corridors also include meltwater channels, tunnel channels and valleys. Mäkinen et al. (2017) refer to distributed drainage routes when discussing segments of murtoos (triangular landforms) present along distinguishable routes in SW Finland.

The main scope of this study is to understand how murtoos and murtoo-related landforms (see Ojala et al., 2019b, 2021) are associated with different type of subglacial meltwater routes in the Finnish area of the Fennoscandian Ice Sheet. The observations are connected to the regional geomorphology and ice dynamics during the deglaciation. The distribution and characteristics of glacial meltwater routes were mapped and classified utilizing LiDAR DEM data. Our study aims to improve understanding of subglacial hydrology and the related transition between ineffective (distributed) and effective (channelized) drainage within areas influenced by the ice-flow activity. The present study also provides new data for the future modelling of subglacial hydrology and the related ice-stream dynamics under the warming climate of the Earth.

## 2. Description of the study area in Finland

Prior to the Younger Dryas period, the margin of the Fennoscandian Ice Sheet located on the southern coast of Finland and displayed a non-lobate structure (ca. 13–12.7 cal. Kyr BP) (Stroeven et al., 2016). Based on large ice-marginal complexes, esker systems, interlobate eskers and glacial lineations, the ice sheet divided into several ice-lobe provinces and interlobate regions (Punkari, 1980; Salonen, 1986; Punkari, 1997; Boulton et al., 2001; Lunkka et al., 2004; Johansson and Kujansuu, 2005; Putkinen et al., 2017; Palmu et al., 2021) (Fig. 2A). Ice-lobe provinces correspond to an area of intense motion (flow) of a continental ice sheet. They are often bordered on both sides by large interlobate deposits (interlobate eskers and moraines). The provinces often end distally in ice-marginal complexes composed of glaciofluvial sandurs and deltas, as well as moraine (both glaciofluvial and diamictic material) ridges (Palmu et al., 2021). The interlobate regions represent passive ice areas surrounding the ice-lobe provinces with fast ice flow. They are characterized by varied and complex landform surfaces but lack dominating late-stage streamlined ice-flow forms and ice-marginal deposits. The fell regions are higher-altitude areas located above and between significant ice-flow areas (ice-flow provinces). Cold-based conditions occurred for some of the interlobate regions, as well as the ice-divide zone in Lapland. The Suupohja area in the southern part of the Southern Ostrobothnian interlobate region as well as the Middle Ostrobothnian interlobate region have been described as areas with low glacial erosion and several preserved pre-late Weichselian deposits (cf. Pitkäranta, 2013; Räsänen et al., 2021).

The ice lobes (Fig. 2A) mainly existed during the latest deglaciation in the Younger Dryas stage to early Holocene about 12.7 to ca. 11 cal. kyr BP ago (cf. Stroeven et al., 2016). The southern coastal Finland province is considered as a pre-Younger Dryas glaciodynamic province. The Salpausselkä I-III ice-marginal complexes formed in front of the Baltic Sea ice-lobe province (BSIL) in southwestern Finland and Salpausselkäs I-II in front of the Finnish Lake District ice-lobe province (FLDIL) in central Finland. The Pielinen–Kalevala end moraine northeast of Salpausselkä II formed in front of the Oulu–North Karelian ice-lobe province (ONKIL). The Oulu–North Karelian ice-lobe province mainly retreated in two parts (Putkinen, 2011). The Ranua interlobate region existed between ONKIL and KIL. The Kuusamo ice-lobe province and the smaller Salla ice-lobe province (SIL) with smaller interlobate regions (Pello, Sodankylä and Savukoski) occupied the area south of the ice-divide zone. The Enontekiö ice-lobe province (EIL) and Inari ice-lobe province (IIL) existed in northernmost Lapland. The Näsijärvi–Jyväskylä ice-lobe province (NJIL) existed during the early Holocene between BSIL and FLDIL and Central Finland ice-marginal formation (CFIMF) formed in front of it (Fig. 2).

The subaquatic areas are concentrated in the coastal areas of southern and western–central Finland and the supra-aquatic areas in eastern and northern Finland (cf. Fig. 4) (Ojala et al., 2013). The Suomenselkä watershed (Fig. 2A) has the largest supra-aquatic areas in western Finland, while the Finnish Lake District in central Finland is composed of separate supra-aquatic islands (cf. Fig. 4).

## 3. Materials and methods

High-resolution LiDAR DEMs (2-m grid/0.3 m vertical resolution) with multidirectional oblique-weighted hillshade (MDOW) (Jenness, 2013) and slope derivatives (see, e.g., Palmu et al., 2015; Putkinen et al., 2017) provided the primary data for mapping. Interpretation of the structural geology and its influence on the landforms utilized spatial data on bedrock observations (Geological Survey of Finland, 2013) and bedrock maps (scale 1: 1000 000) (Geological Survey of Finland, 2016). Quaternary deposit maps (scale 1:20000 to 1: 1000 000) allowed assessment of the sediment types of the deposits. The maps were supplemented with stratum data for superficial deposits, which were based on an observation database of superficial deposits (Geological Survey of Finland, 2015, 2018a). Ancient shoreline data (Ojala et al., 2013) were utilized in estimating the proglacial water depths and the extent of supraglacial areas.

The glacial dynamic provinces and regions, as well as the glacial features, were obtained from the Glacier Dynamic database (GD database) of the Geological Survey of Finland (Putkinen et al., 2017; Palmu et al., 2021). The glacial features dataset showing Finland's glacial features was used in assessment of the mapping results. This dataset contains a wide variety of features, from glaciofluvial sand and gravel deposits to moraine deposits and landforms. The dataset of postglacial faults and landslides (Ojala et al., 2019a) was used for Lapland as a reference for sediments related to seismic activity.

The meltwater routes and eskers were manually mapped by using ArcMap 10.6.1 software of the Environmental Systems Research Institute (ESRI). The routes were digitized as polylines along the central line of the interpreted meltwater route, as this was more efficient than the use of polygons in nationwide mapping. The route margins were not delineated due to their highly varying character. Eskers were digitized by utilizing the existing glaciofluvial landforms data collected as part of the mapping of glaciodynamic (GD) areas (Putkinen et al., 2017; Palmu et al., 2021). The routes were divided into four categories: 1) meltwater routes with murtoos or murtoo-related landforms (in short: murtoo routes), such as diagonal ridges and escarpments (see Ojala et al., 2021) 2) distinct (hummock) routes without murtoos or murtoo-related landforms, 3) other meltwater routes and 4) proglacial or marginal meltwater routes.

Abrupt corridor boundaries were not found in most parts of the present study area in Finland, since the boundaries of the hummocky tracts, including murtoos and low escarpments, were highly variable. Therefore, we use the term ‘route’ in our classification, as it does not suggest the presence of abrupt or clearly defined margins for the zone of (hummocky) landforms. We use the term ‘meltwater route’ to describe the meltwater traces in Finland and further divide it into distributed and channelized meltwater routes.

## 4. Results

### 4.1. Description of meltwater route types

Meltwater routes, including murtoo fields and/or murtoo-related escarpments (category 1, Fig. 3A, B), were identified based on the landforms recognized earlier (cf. Mäkinen et al., 2017; Ojala et al., 2021). Murtoos form distinct identifiable fields that vary in size and shape along or adjacent to the meltwater routes. The size of murtoo fields

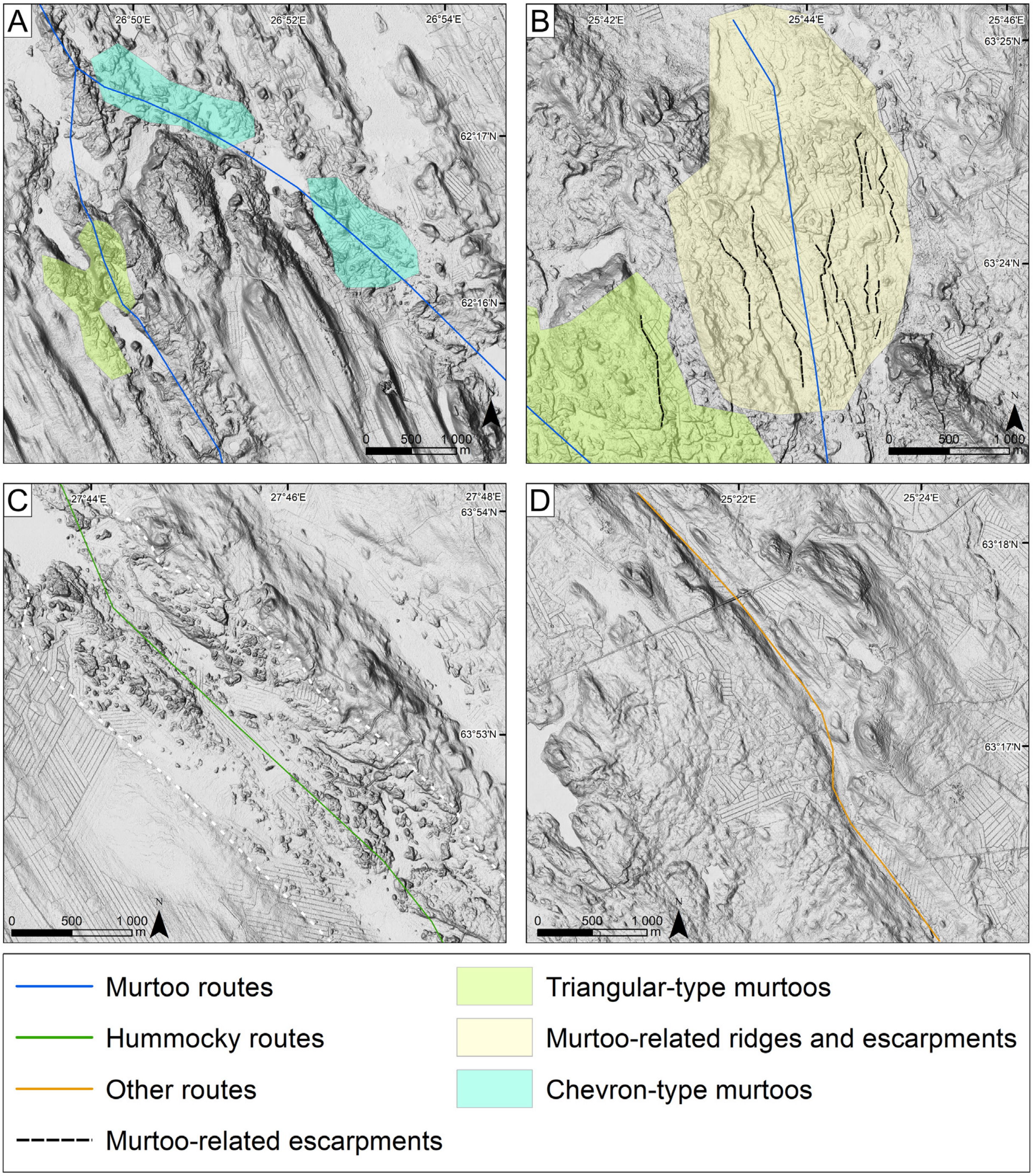


**Fig. 3.** A) Two routes (blue lines) with murtoo fields within them in the drumlinized terrain of the lobate part of FLDIL in central Finland. B) A field of low escarpments (black dashed lines) within a meltwater route. C) A hummocky route (green line) with irregular hummocks and relatively clear margins (white dashed lines). D) Other meltwater routes (orange line) with a connection to bedrock fractures and mostly lacking (hummocky) landforms. Cf. Fig. 2A for site locations.

can vary within a route, typically in the range between 0.3 and 8 km$^2$ (see Ojala et al., 2019b, 2021), and the fields are occasionally minor (<5%) compared to the dimensions of the meltwater routes. Murtoo fields can occur completely within or alongside these routes or only partially within a route. Importantly, only in few cases they exist without any major route.

The hummocky routes (category 2) contain irregularly spaced polygenetic hummocks but lack any fields with murtoos or murtoo-related landforms (Fig. 3C). Other meltwater routes (category 3) mostly lack hummocks but show signs of erosion of the underlying sediment (till), or often have a connection to the bedrock fractures or structures with a well-defined and deeply scarred appearance (Fig. 3D). Less extensive proglacial/marginal routes (category 4) consist of subglacial meltwater channels, including subglacial gorges, proglacial overflow channels, marginal channels and extramarginal channels (cf. Johansson et al., 2007). Eskers from the earlier mapping are considered as their own group and referred to as channelized meltwater routes. In places, eskers cross or follow the meltwater routes, indicating that they are later features. Murtoo routes and hummocky routes are also referred to as distributed meltwater routes and are common in both sub- and supra-aquatic areas (Fig. 4A). Proglacial/marginal routes (channels) are mostly found in supra-aquatic areas (Fig. 4B). They

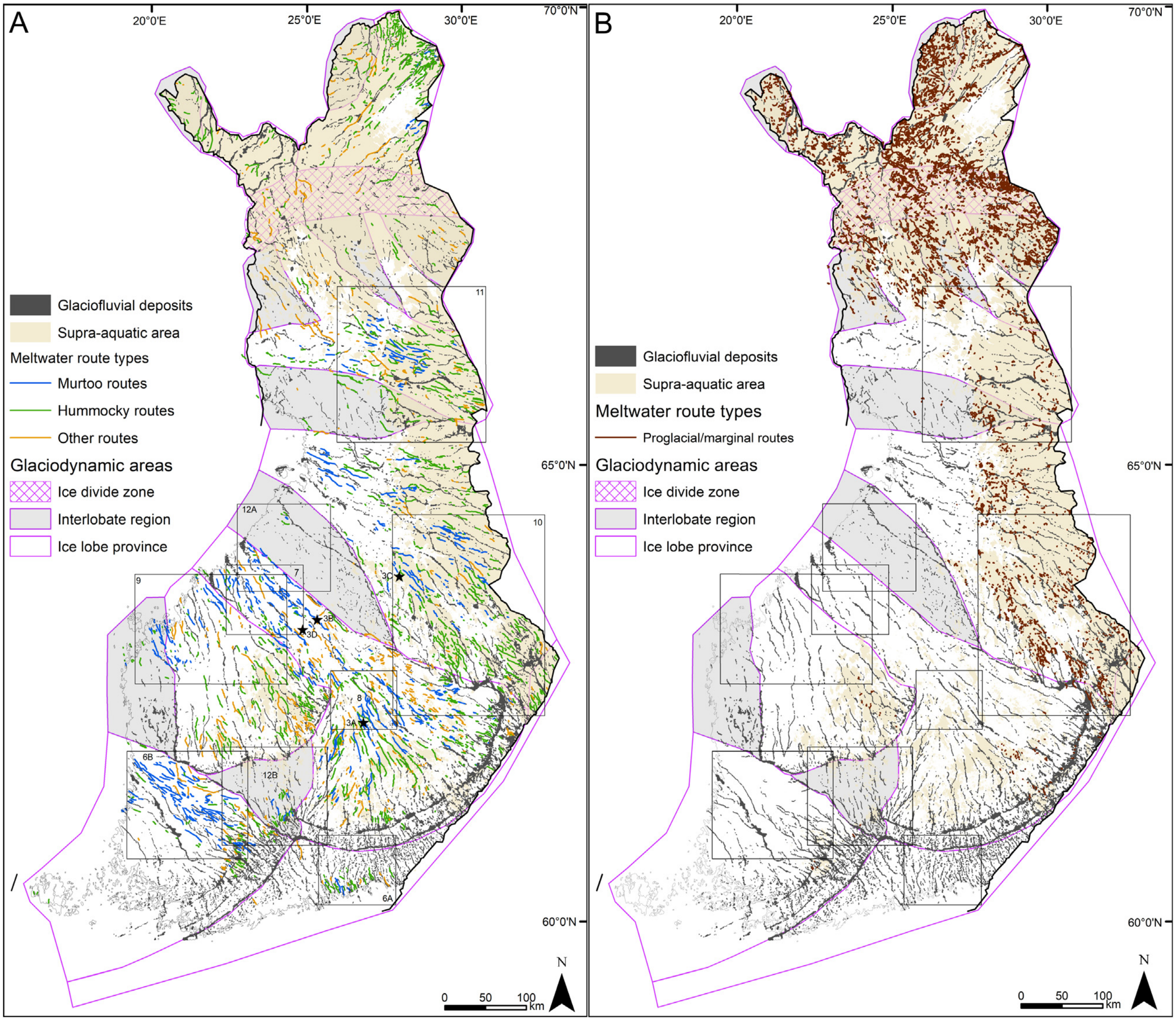


**Fig. 4.** The distribution of A) murtoo and murtoo-related landform routes, hummocky routes and other routes, and B) proglacial/marginal routes, shown with glaciofluvial deposits, supra-aquatic areas and glaciodynamic (GD) areas in Finland.

typically have sharp margins, flat or V-shaped bottoms and they often form branching networks with several tributaries. They also seem to appear out of nowhere without any marked origin. Proglacial/marginal routes may or may not connect to other meltwater routes and their directions may differ from both ice flow and meltwater route directions. Overall, the widths of the meltwater routes usually vary between (0.2–) 0.5–3 km, in places 3–5 km. The width can vary along a meltwater route, and the widest routes often contain multiple parts (e.g., indications of flow division). Murtoo and hummocky routes are wider than other and proglacial/marginal routes.

Altogether, the presently collected mapping dataset consists of 15,240 meltwater routes, of which 8373 are new and previously unmapped meltwater routes. Of these, 573 are murtoo and murtoo-related escarpment routes, 1461 are hummocky routes, 655 are other routes, and 5681 are proglacial/marginal routes (Table 1). In addition, we listed 6870 eskers, mostly based on previous data of GTK. The average length of all routes is 3.35 km, with a minimum of 0.04 km and a maximum of 175.33 km. The mean lengths of meltwater routes vary from 1.71 to 7.19 km. Murtoo routes have the highest mean and median values and pro-glacial/marginal routes and eskers the lowest. The

**Table 1**
Statistics on the length (km) of all and different types of meltwater routes.

| | Murtoo routes | Hummocky routes | Other routes | Proglacial/marginal routes | Eskers | All routes |
|---|---|---|---|---|---|---|
| N | 573 | 1461 | 655 | 5681 | 6870 | 15,240 |
| Min | 0.19 | 0.12 | 0.11 | 0.07 | 0.04 | 0.04 |
| Max | 47.56 | 87.86 | 48.38 | 50.99 | 175.33 | 175.33 |
| Mean | 7.19 | 4.75 | 4.94 | 1.71 | 3.94 | 3.35 |
| Median | 5.22 | 3.04 | 3.28 | 1.00 | 1.28 | 1.35 |
| 1st quartile | 2.64 | 1.37 | 1.81 | 0.53 | 0.53 | 0.61 |
| 3rd quartile | 9.60 | 5.97 | 6.17 | 1.97 | 3.51 | 3.35 |

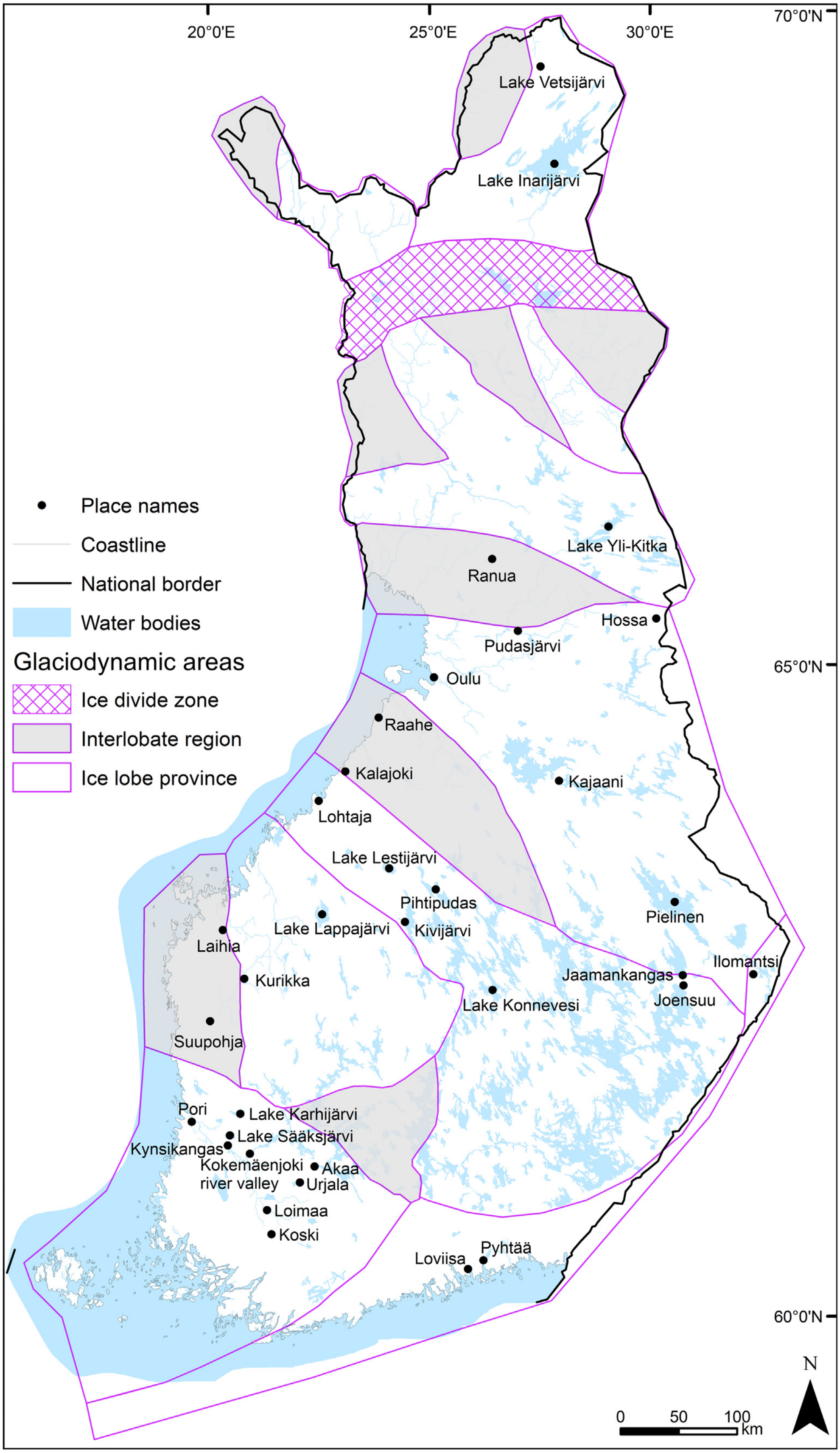


**Fig. 5.** Place name index map with glaciodynamic areas (Palmu et al., 2021).

maximum lengths of murtoos routes (47.56 km), other routes (48.38 km) and proglacial/marginal routes (50.99 km) are very similar, but shorter than the maximum lengths of hummocky routes (87.86 km) and eskers (175.33 km). However, it is noteworthy that only 49 eskers are over 50 km long. The locations of various places mentioned in the text are presented in Fig. 5.

### *4.2. Southern coastal Finland province (SCF)*

The meltwater routes occur within 25–30 km from the coastline of the Gulf of Finland, but also terminate about 25–30 km up-ice from the Younger Dryas Salpausselkä I lobate ice-marginal complex (Fig. 6A). Moreover, the termination of the routes is accompanied by a more fragmented pattern of the eskers (Fig. 6A). The routes mostly occur in the area with thicker sediments (up to 30 m) in the centre of the province (Geological Survey of Finland, 2018b) within the Kymi rapakivi granite area. Bedrock areas (<1 m sediment) and clay plains dominate in other parts of the province. In general, the province lacks apparent glacial lineation fields. The few murtoo routes are associated with a more extensive field of subglacial hummocky moraines (Geological Survey of Finland, 2021) between the Loviisa and the Pyhtää eskers; they are the most continuous eskers within the rapakivi bedrock area along the southern coast. In this approximately 20-km-wide area, the orientation of De Geer moraines slightly deviates from those located to east of the Pyhtää esker, whereas to the west of the Loviisa esker, De Geer moraines are lacking. This indicates that the area with murtoo routes had a slightly different behaviour during deglaciation within the Pre-Younger Dryas glaciodynamic province.

### *4.3. The Baltic Sea ice-lobe province (BSIL)*

A large cluster of murtoo routes strongly dominates the northeastern margin of BSIL, which forms the Loimaa sub-province delineated in the west by the interlobate Pori–Koski esker (Fig. 6B). The bedrock-dominated coastal area southwest of the interlobate esker almost completely lacks meltwater routes and is characterized by rather uniformly distributed glacial lineations and a scarcity of eskers. A few murtoo and hummocky routes occur on the coast of the Bothnian Bay close to the margin of the Satakunta sandstone depression and adjacent to the tributary eskers of the interlobate esker (Fig. 6B). The confining role of the bedrock topography is apparent east of the interlobate esker. Here lies the bedrock contact between the Jothnian sandstone depression and the Svecofennian basement rocks, as well as the major Kynsikangas shear zone northeast of the contact (Pietikäinen, 1994; Pajunen et al., 2001). Importantly, the Kynsikangas shear zone is followed by the longest continuous esker inside the Loimaa sub-province, and associated with several murtoo routes.

Immediately to the east of this zone are wide areas of subglacial hummocky moraines with a major concentration of ribbed moraines near the SE part of the bedrock shear zone. The margins of the hummocky and ribbed moraine area are outlined by long and well-developed murtoo routes that show signs of spreading and escaping of meltwaters outside the route areas. Furthermore, this area completely lacks eskers. Ribbed moraines near the larger lake basins show clearly lineated surfaces. Murtoos cut ribbed moraines and also exhibit lineated surfaces in places.

The topography of the bedrock-dominated terrain has mainly influenced the position and direction of the meltwater routes in the most northeastern part of BSIL. Interestingly, Lake Karhijärvi (Fig. 6B: LK) has multiple murtoo routes both entering and exiting its basin. The Kokemäenjoki river valley (cf. Fig. 5), which runs across the Loimaa sub-province transverse to the ice-flow direction, appears to cut the murtoo routes into two main areas. Southeast of the river valley, murtoo routes are concentrated adjacent to the eskers in the centre and in the northeastern part of the Loimaa sub-province (cf. Punkari, 1980; Salonen, 1991; Mäkinen, 2003), as well as marginal to the main glacial lineation fields. In addition, two murtoo routes terminate proximally to the proposed Urjala–Akaa subglacial lake position (cf. Mäkinen et al., 2017). The majority of the murtoo routes are located over 30 km from the Salpausselkä III ice-marginal complex (Fig. 6B). However,

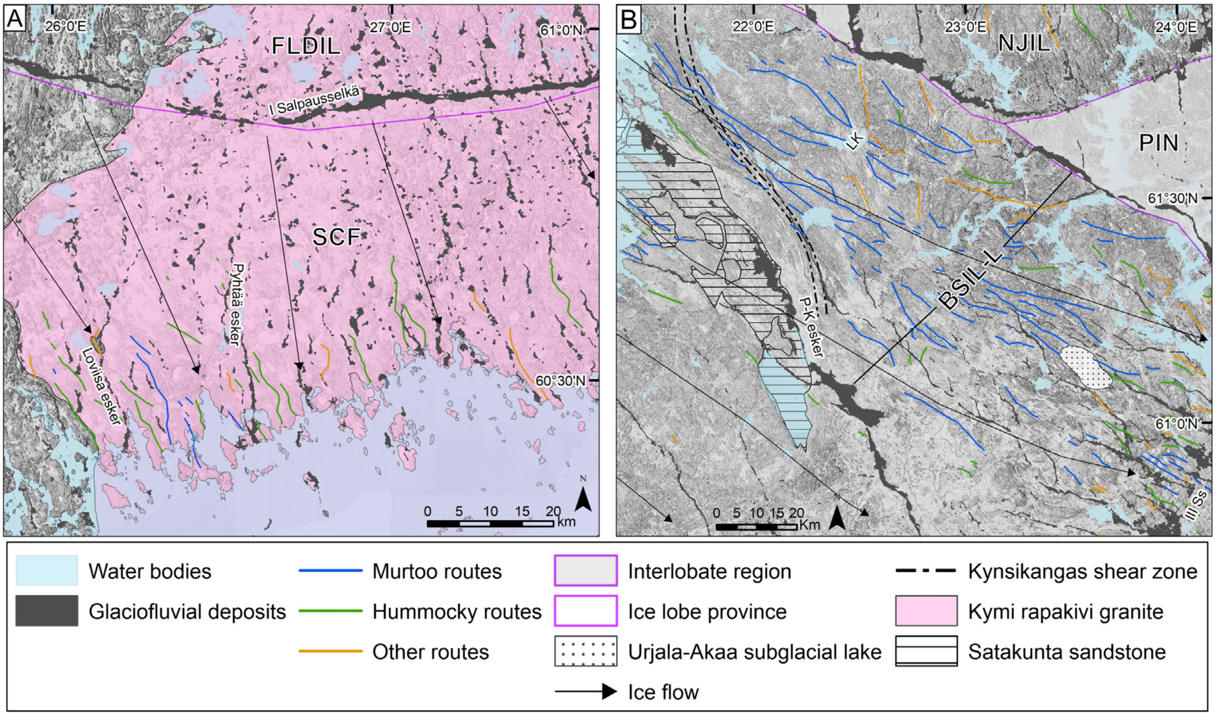


**Fig. 6.** A) The distribution of meltwater routes south of Salpausselkä I in SCF. The routes are concentrated in the Kymi rapakivi granite area on the coast of the Gulf of Finland. B) Meltwater route distribution within the Loimaa sub-province (BSIL-L,) (cf. Palmu et al., 2021) southeast of the interlobate Pori–Koski esker (P-K esker). The Satakunta sandstone area and Kynsikangas shear zone influenced the murtoo route distribution in the southwest. The position of the Urjala–Akaa subglacial lake (U–A) is indicated with a white dotted polygon. Lake Karhijärvi (LK).

some murtoo routes occur closer to it, but again these routes are over 35 km from the Salpausselkä I ice-marginal complex.

Some hummocky routes lie in the coastal area and central part of the Loimaa sub-province and become more common near Salpausselkä III. A few hummocky routes exist between Salpausselkä I and III. The Loimaa lowlands with clay plains adjacent to the SE part of the interlobate esker are almost completely without meltwater routes. The influence of topography on subglacial drainage and the distribution of routes within BSIL is larger than, for instance, in FLDIL.

### *4.4. The Finnish Lake District ice-lobe province (FLDIL)*

#### *4.4.1. The trunk area of the FLDIL lobe*

Both the murtoo and hummocky routes are focused on the flanks of the FLDIL trunk central axis, which exhibits some of the longest glacial lineations within the Lake Lestijärvi area (Fig. 7). Murtoo routes are common and mainly located within the subglacial hummocky moraines and ribbed moraines, which form longitudinal bands on the sides of the three main glacial lineation fields of the trunk. The NE margin of the central main lineation field exhibits a few hummocky and ribbed moraines that have lineated surfaces NW of a weak ice-flow zone adjacent to the Kalajoki–Pihtipudas (Ka-Pi) esker (Fig. 7). The connection between murtoo routes and eskers is clearer in the northeastern part of the trunk. Furthermore, the interlobate esker in the northeastern margin disappears, and has several murtoo meltwater routes as its continuation (Figs. 7, 12A). Some murtoo routes and other routes are connected to esker tributaries on the coast of the Bothnian Bay, excluding the Lohtaja–Kivijärvi esker. The Lohtaja-Kivijärvi ice lobe margin esker has a few murtoo routes directly connected to it, while some murtoo routes run parallel to it on the eastern side. Murtoo routes also follow the margins of weakening ice-flow areas (cf. Ahokangas and Mäkinen, 2014) (Fig. 7). Fewer murtoo routes exist on the southeastern end of the trunk, where it joins the lobate part of FLDIL (Fig. 4A). However, hummocky routes instead appear.

#### *4.4.2. The lobate part of the FLDIL lobe*

In general, the murtoo and hummocky routes are concentrated in the central part of the FLDIL lobe (Fig. 4A). They occur immediately southeast of the end of the FLDIL trunk. Importantly, no murtoo routes are found within 30–50 km up-ice from the arcuate Salpausselkä ice-marginal complexes, but instead, these routes are hummocky. Particularly in the eastern half of the ice lobe, numerous water bodies mask

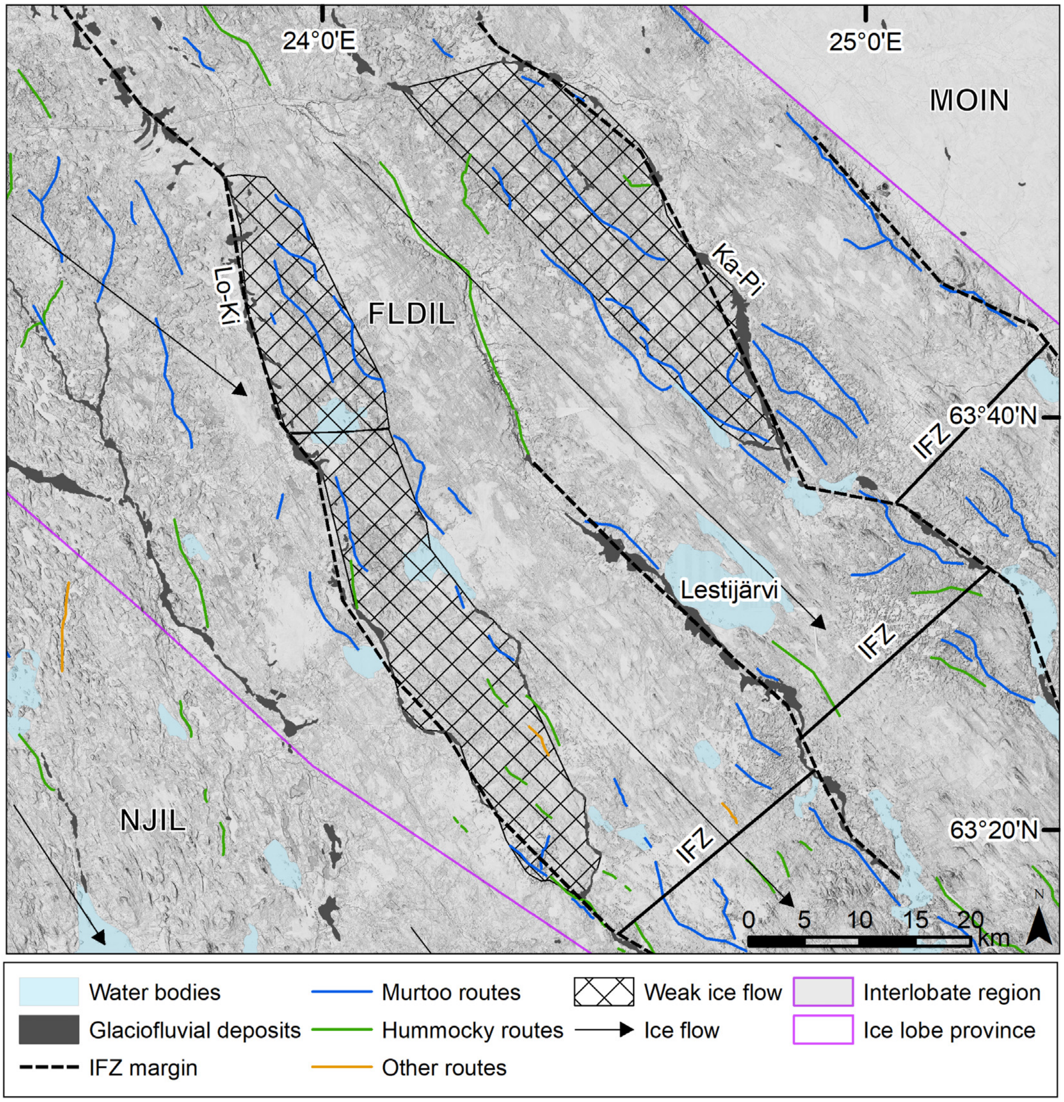


**Fig. 7.** The location of the meltwater route in the trunk area of FLDIL with shear zones, ice-flow zones (IFZ) and weak ice-flow areas modified from Ahokangas and Mäkinen (2014). Lo–Ki: Lohtaja–Kivijärvi ice-lobe margin esker and Ka–Pi: Kalajoki–Pihtipudas esker.

the area, causing routes to appear more fragmented than in the west. The terrain in the central part of the lobe is heavily drumlinized (Glückert, 1973), and the hummocky moraine bands occur adjacent to the esker chains. Abundant bedrock outcrops dominate in the area up-ice from the Salpausselkäs.

Some murtoo and hummocky routes are clustered distal to a larger, mostly supra-aquatic bedrock areas, such as southeast of Lake Konnevesi (Fig. 8). A few murtoo routes are aligned towards the interlobate area in the southeastern margin of the lobe. The route directions correspond well with the general direction of the eskers in the lobate part of FLDIL. However, near the southeastern margin of the lobe, a few murtoo routes are aligned towards the large Jaamankangas interlobate complex belonging to the Jaamankangas-Pielinen end moraine (Fig. 10). Numerous eskers join the Salpausselkä I and II ice-marginal complexes. The eskers become more tightly spaced and fragmented towards Salpausselkä II. Only eskers are present between Salpausselkä I and II. The distribution and pattern of the murtoo routes also reflect the major division of the streamlined terrain into three main subareas delineated by two major esker chains. The central subarea has the strongest glacial lineations associated with lineation sets bordered by the most frequent murtoo and hummocky routes. Murtoo routes are scarcest within the more rugged terrain along the NE margin of the ice lobe, which is characterized by large lake basins and the main lineation field across their southern parts.

### 4.5. The Näsijärvi–Jyväskylä ice-lobe province (NJIL)

The esker networks are densest in the mostly supra-aquatic eastern part of NJIL and become sparser towards the western and central part of the province (cf. Fig. 4A). Some till-covered eskers occur ca. 30–40 km inland from the Central Finland Ice-Marginal Formation (CFIMF), indicating readvance. Murtoo routes are scarce within this province, except in the west near the lobe margin and along the coastal zone within the narrowest part of the lobe (Fig. 9). Murtoo routes are associated with the subglacial hummocky moraine bands between the glacial lineation fields and with the western interlobate Laihia–Kurikka esker proximal to the Suupohja cold-based ice area (Fig. 9). Interestingly, most of the hummocky routes lie on supra-aquatic areas in the SE part of the area and only some in the subaquatic areas of NJIL (cf. Fig. 4A). The central part of the lobe around Lake Lappajärvi (LJ) only contains sparse hummocky routes (Fig. 9). Scattered proglacial/marginal routes are found within the supra-aquatic area (cf. Fig. 4B).

### 4.6. The Oulu–North Karelia ice-lobe province (ONKIL)

The Oulu–North Karelia ice lobe province is divided into two sublobes separated by the continuous Oulu–Kajaani esker running across the lobe from the coast of the Bothnian Bay to the Jaamankangas-Pielinen end moraine. Murtoo routes are mostly concentrated in the supra-aquatic eastern parts of ONKIL, where they are sometimes confined to the floors of small bedrock valleys. Both murtoo and hummocky routes noticeably increase in the higher-lying areas, where crystalline bedrock dominates the topography down-ice from the major bedrock threshold of the Maanselkä watershed (cf. Fig. 2A). Murtoo routes by the coast occur in the narrowest part of the province before the widening of the ice lobe. Murtoo routes exist within subglacial hummocky moraine and ribbed moraine tracts aligned in the ice-flow direction between glacial lineation fields. Murtoo routes are concentrated adjacent to a few continuous esker systems. All these murtoo routes consist of well-developed murtoo fields, murtoo-related landforms and hummocky tracks. Till-covered eskers and till-covered ice marginal glaciofluvial deposits are common in the northern parts of the ice lobe. These landforms are most likely pre-Late Weichselian (Nordkalottproject, 1986; Sutinen, 1992). A few murtoo or hummocky routes are found adjacent to these till-covered eskers or ice-marginal deposits.

Murtoo routes are mainly lacking from the interlobate margins of ONKIL, where only continuous eskers are found. Hummocky routes are densest close to the southern margin of the lobe and the

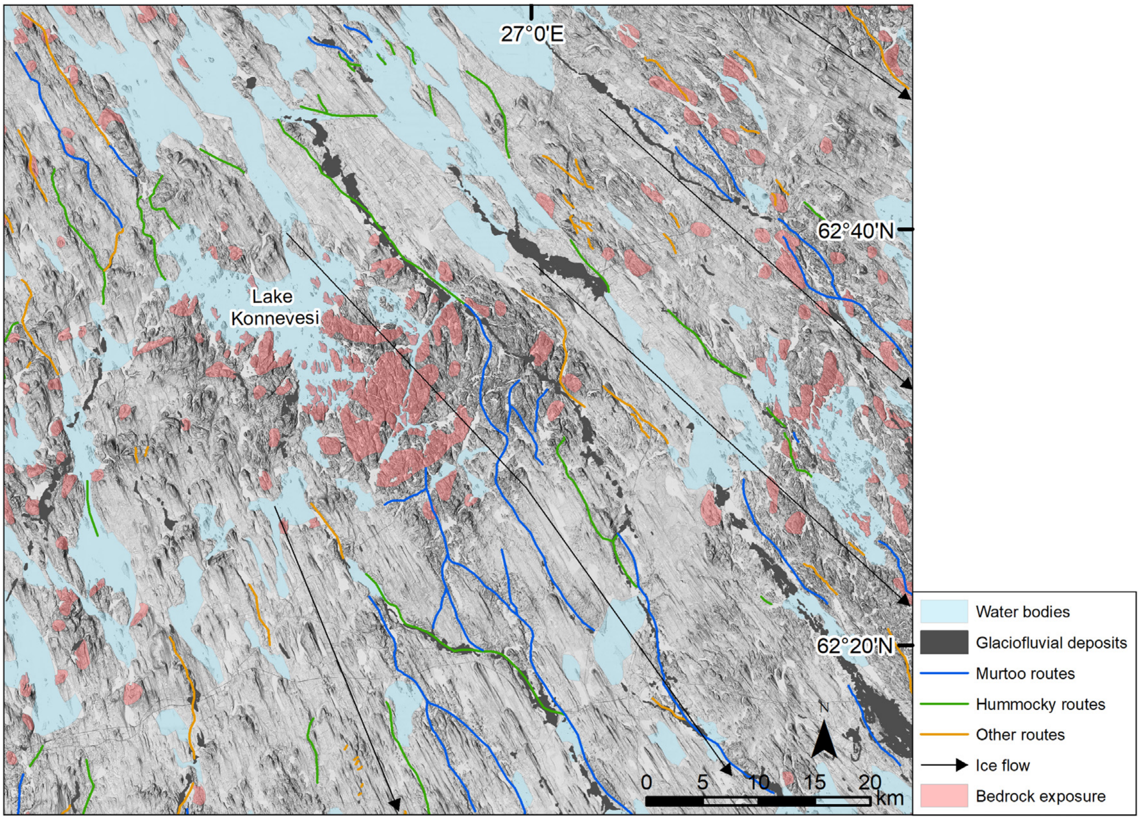


**Fig. 8.** The Lake Konnevesi bedrock outcrop area and its influence on the distribution of murtoo and hummocky routes in the FLDIL lobe.

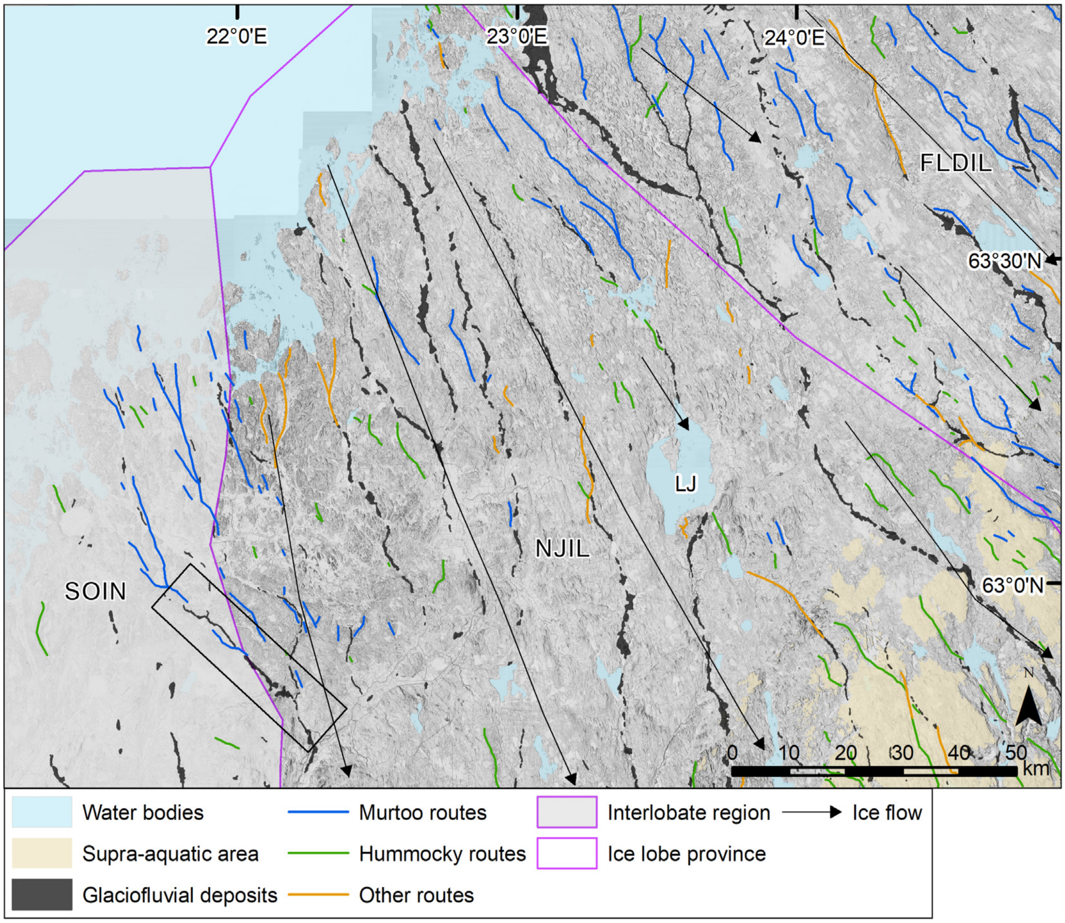


**Fig. 9.** Murtoo routes in the northwestern part of NJIL and northeastern part of SOIN. Note the concentration of routes adjacent to the interlobate Laihia–Kurikka esker in the west (black rectangle). LJ: Lake Lappajärvi.

Jaamankangas-Pielinen end moraine. They are mainly aligned parallel to the esker networks, but some exceptions occur near the major interlobate Raahe–Joensuu esker in the southeastern margin of ONKIL. Here, the hummocky routes are crossed by eskers and are in places aligned parallel to the interlobate esker (Fig. 10). Murtoo routes appear about 65 km from the major Joensuu–Ilomantsi end moraine. Numerous proglacial and marginal meltwater channels are common in the supra-aquatic higher-lying areas of ONKIL.

### 4.7. The Kuusamo ice-lobe province (KIL)

The Kuusamo ice lobe province consists of two western branches that combine into one in the central part of the lobe associated with the majority of the murtoo routes (Fig. 2A). The northwestern branch has abundant till-covered eskers, some hummocky routes, and scattered eskers that become continuous in the central part of KIL. The western branch has sparse but continuous eskers associated with scattered hummocky routes and some till-covered eskers. The murtoo routes and fields with murtoos and murtoo-related landforms are mainly situated in the supra-aquatic topographic high-lying areas in the central-eastern part of the lobe (Fig. 11). They mainly occur between the two largest and continuous eskers and are associated with the ribbed type of moraines, including the Sihtuuna moraines (Aario et al., 1997). Interestingly, several murtoo routes terminate up-ice from Lake Yli-Kitka and a few connect to it (Fig. 11), which might indicate the presence of a subglacial lake. Numerous pro-glacial and extra marginal channels characterize the northwestern branch and eastern part of KIL. The pro-glacial and extramarginal channels are mainly related to the evolution of local and short-lived proglacial ice lakes (Johansson and Kujansuu, 2005).

### 4.8. Salla ice-lobe province (SIL)

The province is collated with the northern margin of the Kuusamo ice lobe (KIL) (Fig. 11). The main glacial lineation field dominates in the northwestern part of the province, which shows scattered eskers and till-covered eskers. The somewhat streamlined higher-lying terrain to the west of SIL terminates abruptly against KIL and eskers become more continuous towards the southeast. No murtoo fields or routes are found in this province. The impact of topography is apparent in the distribution of hummocky routes and pro-glacial channels, as they all are found in the supra-aquatic areas. The hummocky routes all appear to connect to eskers, with the exception of the northwestern part of SIL.

### 4.9. Inari ice-lobe province (IIL)

The Inari ice-lobe province (cf. Fig. 2A) is dominated by a large field of glacial lineations along the lower-lying terrain to the NW of the Lake Inarinjärvi and by continuous esker systems running in a SW–NE direction. The hummocky routes are common and mostly associated with the esker systems in the low-lying and higher-lying areas on both sides of the main lineation field. A few murtoo routes, mostly associated with valleys, occur close to the easternmost part of the province. The routes include hummocky tracts and a few murtoo fields on the lee side of topographical obstacles, e.g., small-sized fells. The channelized meltwater network is denser in the higher elevation areas than in the lower relief basin of the Inari ice lobe province. There are a few potential subglacial lakes in the northernmost fell region, with Lake Vetsijärvi already having been interpreted by Sutinen et al. (2009). Proglacial/marginal meltwater routes and morphologies indicating proglacial outburst floods

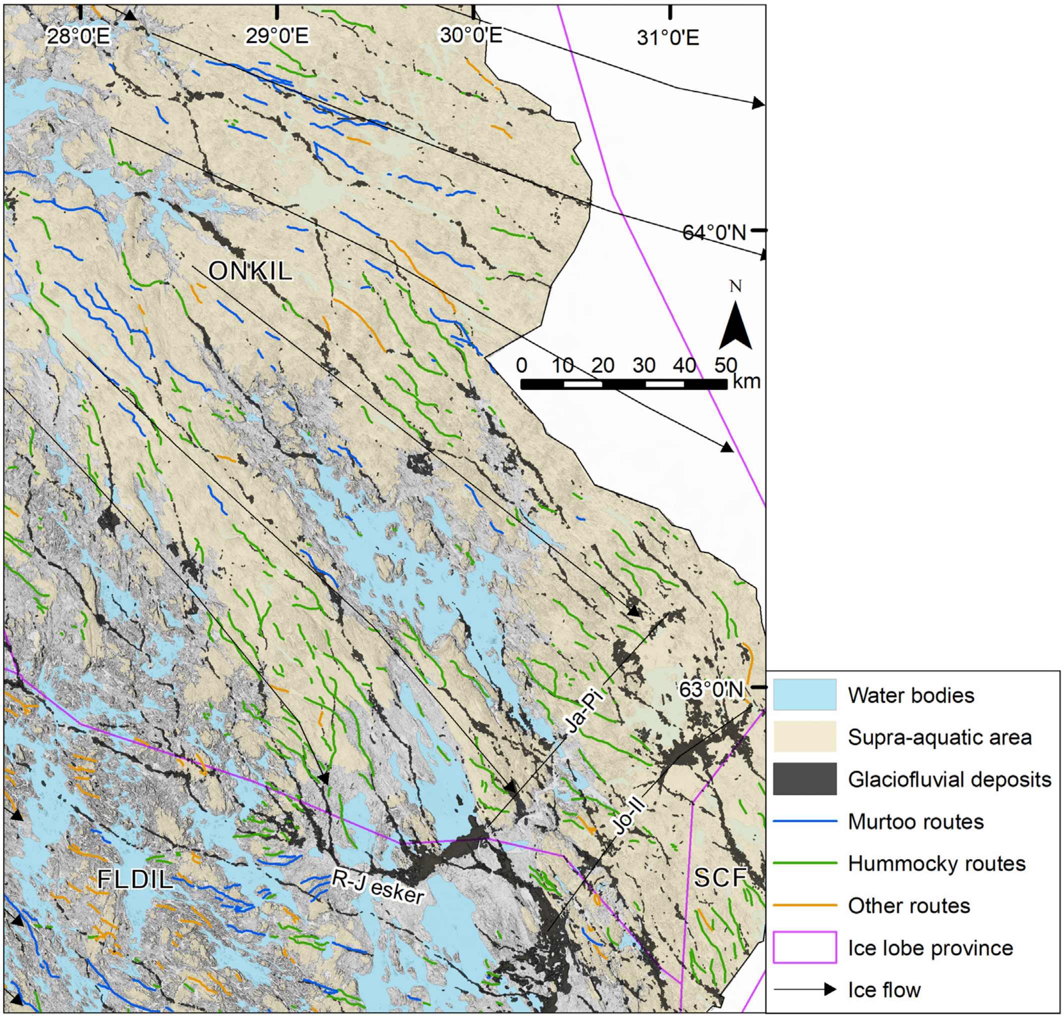


**Fig. 10.** Concentration of esker and meltwater routes in the southeastern part of ONKIL, adjacent to the Raahe–Joensuu interlobate esker (R-J esker). Ja-Pi: Jaamankangas–Pielinen end moraine, Jo-Il: Joensuu–Ilomantsi end moraine. Note the difference in the orientation of hummocky and esker routes. Some murtoo routes turn towards the interlobate esker from the south in the FLDIL area.

characterize the highlands. Another distinctive feature in the area is numerous marginal erosional channels and sorted crevasse infills that show the spatial progression of the former ice margin front during the last deglaciation.

### *4.10. Enontekiö ice-lobe province (EIL)*

The Enontekiö ice-lobe province (Fig. 2A) is without glacial lineation fields but includes several continuous esker systems running SW–SE or S–E. Murtoo routes are lacking from the province, while some hummocky routes occur mostly in association with eskers. Proglacial/marginal routes are most common in the western and central parts. The direction of these routes (mainly NW–SE) clearly deviates from eskers and hummocky routes.

### *4.11. The interlobate regions*

Till-covered pre-Late Weichselian eskers are common in most interlobate regions, such as the Southern Ostrobothnia interlobate region in the west and interlobate regions in northern Finland. Till-covered eskers are sparse in the Middle Ostrobothnian interlobate region and are lacking from the Päijänne interlobate region. Overall, murtoo routes are scarce within the interlobate regions compared to the ice-lobe provinces. The scattered murtoo and hummocky routes in the interlobate regions are mostly connected to continuous eskers within and in the margins of the interlobate regions in the Southern Ostrobothnia interlobate region (SOIN) (cf. Fig. 9), the Middle Ostrobothnian interlobate region (MOIN) (Fig. 12A), and on the southern margin of the Ranua interlobate region (RIN) (cf. Fig. 11). Murtoo routes within MOIN are also associated with ribbed moraines. Murtoo and hummocky routes connecting to eskers are concentrated in the southern half of PIN, about 30–60 km from the Salpausselkä I ice-marginal complex. The murtoo routes occur on the sides of the main glacial lineation field. Murtoo routes end and eskers become discontinuous and smaller towards the bedrock outcrop-dominated northern area (Fig. 12B). Murtoo and hummocky routes are scarce or almost completely absent in the interlobate areas surrounding the Oulu–North Karelia and Kuusamo ice-lobe provinces, as well as interlobate regions adjacent to the ice-divide zone and Kilpisjärvi and Kevo fell provinces in the north (Fig. 4A). Hummocky routes are mostly connected to eskers in these areas. Proglacial/marginal routes are the most common features in the easternmost parts of the Ranua and other interlobate regions in northern Finland (cf. Fig. 4B). These features are lacking in the SOIN, PIN and MOIN interlobate regions.

### *4.12. Ice-divide zone*

The ice-divide zone between the ice-lobe provinces and interlobate regions has some eskers that run outside the zone, especially in the north and east. Some till-covered eskers run outside the zone in the

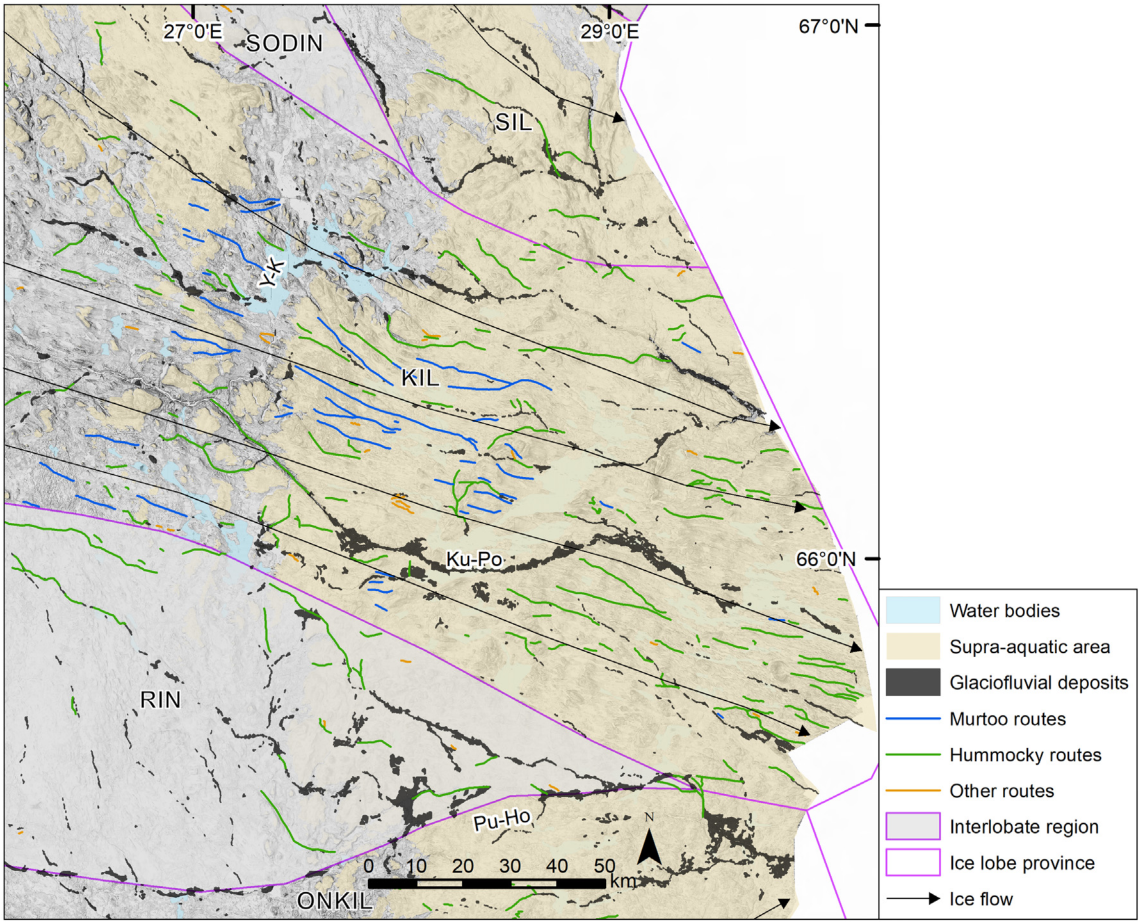


**Fig. 11.** The distribution of meltwater routes in the Kuusamo ice-lobe province (KIL) with murtoo routes in the central-eastern part, and the Ranua interlobate region (RIN) with some hummocky routes connected to the branched Pudasjärvi–Hossa interlobate esker (Pu-Ho) (Sutinen, 1992) in the southern margin. Lake Yli-Kitka (Y-K).

south and few in the north. Till-covered eskers are scattered throughout the area and some of them are continuous and quite long. Some hummocky routes occur throughout the zone, except in the central part of the southern margin. Hummocky routes mostly join eskers and till-covered eskers. Proglacial/marginal routes are abundant, especially closer to the Inari ice-lobe province in the north, as well as the Sodankylä and Savukoski interlobate regions in the south (cf. Fig. 4B). These routes are sparser in the central part of the zone, as well as in the west, where they are most common closer to the Pello interlobate region and Kuusamo ice-lobe province. Proglacial/marginal routes in the west are in places quite long and lie adjacent to the largest esker in the west.

## 5. Discussion

### *5.1. Extensive meltwater drainage network in Finland*

The results of our LiDAR mapping reveal a previously unmapped distribution of various meltwater routes, substantially extending the well-known and mapped esker network in the Finnish area of the FIS. The connection of murtoo and hummocky routes to eskers is very apparent throughout Finland, and they often create a continuation for eskers by joining or running parallel to them. In places, eskers appear in areas of murtoo or hummocky routes, suggesting the utilization of the same meltwater route in the latest stages of the last deglaciation. This indicates that the routes developed prior to esker formation further away from the ice margin, while eskers formed time-transgressively closer to the ice margin (cf. Mäkinen, 2003).

Many meltwater routes containing murtoos are interpreted to have been formed in the transition zone of the channelized and distributed subglacial hydrological networks (Mäkinen et al., 2017, 2019). Murtoos formed between approximately 35–40 km from the ice margin, as inferred from their spatial distribution in comparison to major ice-marginal formations (Mäkinen et al., 2017, Ojala et al., 2019b). Geomorphologically distinguishable routes with murtoos and associated fan-shaped hollows are a part of the comprehensive subglacial drainage systems (cf. Mäkinen et al., 2017), but their distribution is more limited compared to the hummocky routes. The number of meltwater routes with murtoos and murtoo-related landforms (category 1), as well as other routes (category 3), is clearly smaller than the number of hummocky routes (category 2), eskers and proglacial/marginal routes (category 4), which supports an increasing flux of meltwater towards the ice margin. Moreover, the meltwater routes with murtoos or murtoo-related landforms show the highest mean length of all routes, which could be explained by a time-transgressive origin associated with their continuation up-ice from the channelized drainage system.

Hummocky routes in Finland have features of both positive and negative forms similar to those described by Peterson and Johnson (2018). They suggest that the positive forms have a similar genesis to glaciofluvial corridors (GCF), while the negative forms are classified as tunnel valleys. The surficial deposit thicknesses in Finland are usually only 1–10 m, with thicker sediments on eskers and ice-marginal features, as well as large sandstone depressions and buried river valleys (30–50 m or more) (Geological Survey of Finland, 2018b). Some hummocky routes are related to slightly thicker sediments (10–30 m), which supports the potential connection to tunnel valleys. Narrower

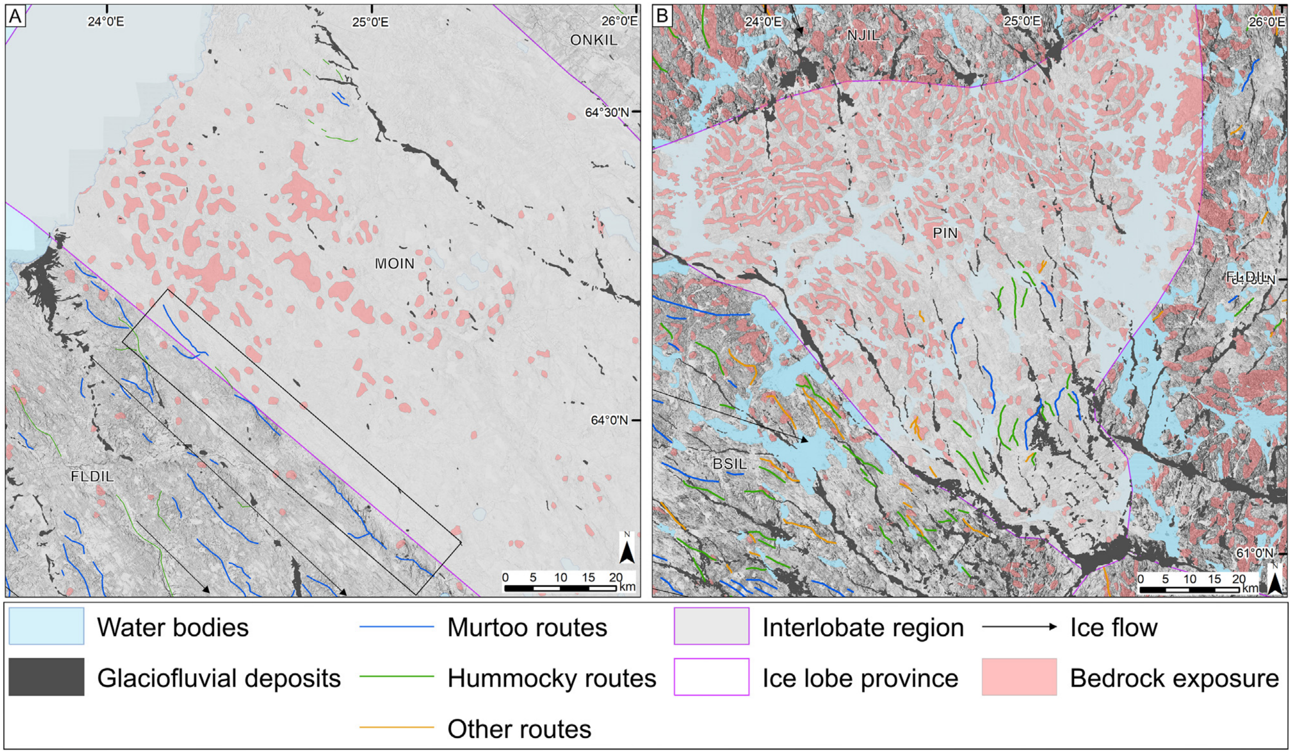


**Fig. 12.** A) The sparse murtoo routes of MOIN. Murtoo routes form the continuation of a disappearing interlobate esker in the northeastern margin (diagonal rectangle). B) The location of murtoo routes within the southern part of PIN, where the northern part is dominated by bedrock outcrops.

corridors are related to greater sediment thicknesses in Canada (cf. Sjogren et al., 2002), but further research is required to address this relationship. Other routes clearly relate to bedrock fractures and features reflecting the channelling of meltwaters through them, especially the routes with marked erosion of underlying till.

Hummocky routes are the major distributed drainage system, and together with eskers, they cover all the GD provinces and the interlobate regions, as well as the cold-based areas and the ice-divide zone. They represent later thinning of the ice sheet during deglaciation and the transition towards a channelized drainage and tunnel environment that acted as a locus for esker deposition closer to the ice margin. In addition to eskers, hummocky routes and other routes commonly also exist near the ice-marginal complexes and interlobate joints (cf. Fig. 4A), indicating that when not associated with eskers, they probably relate to short-lived routing of abundant ice-marginal meltwater flow during the rapid melting and evacuation of increased supraglacial meltwater flux into the ice sheet bed.

In addition to the discovered meltwater routes, we found areas influenced by more widespread meltwater activity away from the routes, some up to tens of square kilometres in size. These are indicated, for instance, by erosion of the underlying till deposits, small channels and washed bare bedrock areas. One of the largest of such areas is up to 20 km long and 7–10 km wide and occurs in the northeastern corner of NJIL, with several hummocky routes running through the area. Otherwise, widespread meltwater-influenced areas are common in the BSIL and FLDIL areas. Apparently, the routes could not accommodate all the meltwater, resulting in their escape out of the routes into the surroundings. Furthermore, the large Satakunta ribbed and subglacial hummocky moraine field with more widespread murtoos and without eskers in the up-ice part of the Loimaa sub-province within BSIL could represent a slush bottom or "swampy area" (cf. Kyrke-Smith and Fowler, 2014) beneath the ice sheet that was drained by the murtoo routes.

The earlier proposed Urjala–Akaa subglacial lake in the Loimaa sub-province (cf. Kajuutti et al., 2016) was fed and partly drained by murtoo routes. Similarly, the Kokemäenjoki river valley and the Karhijärvi lake basin form intersecting areas of murtoo routes, where the murtoo routes entering the areas originate from the extensive Satakunta ribbed and hummocky moraine field. Both areas probably hosted subglacial lakes that drained and filled. However, the murtoo route pattern also suggests that during the later ice-flow phase of the Salpausselkä III stage, these lakes were connected. Furthermore, Tuunainen (2018) has proposed that some of the clay-covered lowlands within the Loimaa sub-province were also occupied by interconnected subglacial lakes.

### *5.2. The significance of murtoos and murtoo genesis to ice-stream dynamics*

The distribution of murtoo routes in the Finnish area of the FIS mimics the general pattern of eskers and is spatially related to the ice-stream tracts, such as drumlins, flutings and mega-scale lineations, which are the dominant characteristics of the glaciated terrain in the area. The overall distribution of murtoo routes is highest in the central parts of the glaciodynamic (GD) areas (ice lobes). In terms of ice dynamics, the ice flow is fastest along the central axis of an ice lobe trunk, as well as in the centre of the lobate part (cf. Clark and Stokes, 2003). Faster ice flow promotes more melting and erosion/deposition of subglacial sediment, both of which are prerequisites for murtoo and murtoo route formation.

Murtoo routes in Finland typically occur along the margins of major drumlin fields or glacial lineation sets and often cut across ribbed moraine fields. Moreover, murtoo routes are substantially concentrated within the FLDIL ice-stream tract, which also has the densest occurrence of drumlin fields throughout the paleo ice-stream bed. These relationships imply that murtoo route genesis and the development of the semi-efficient drainage system is related to the speed of the ice flow, so that murtoos represent slow to moderate flow speeds associated with locally concentrated meltwater drainage and effective pressure close to zero (cf. Mäkinen et al., 2017). It is evident that murtoo genesis takes place within warm-based ice and appears to be related to increased melting during the last deglaciation, especially after the Younger Dryas period when ice-flow rates were controlled by ice-stream activity. Conversely, the simultaneously up-iceterminating murtoo and hummocky routes and declining esker network indicate a temporarily cooling climate with diminished meltwater production. This is suggested by the southern coastal Finland province (change towards the Younger Dryas cooling) and the Päijänne interlobate region possibly related to a preboreal cooling event. Moreover, murtoos mapped in southern Sweden distal to the Middle Swedish end-moraine zone are related to the Bølling–Allerød interstadial, 14.6–12.9 ka BP (Rasmussen et al., 2014) before the onset of the Younger Dryas period, and show abundant deformation (Peterson et al., 2019; Peterson Becher and Johnson, 2021).

The distribution of murtoo routes in relation to glaciodynamic provinces indicates that murtoo formation is absent within cold-based ice regions and ice-divide zones, as well as the Enontekiö and Salla ice-lobe provinces. The abundant proglacial/marginal routes are lateral/submarginal channels (cf. Greenwood et al., 2016) that drained supraglacial meltwaters along the glacier margin and were pinned against the fell slopes, especially in the ice-divide zone in Lapland (e.g., Johansson and Kujansuu, 2005). Lateral channels form where the ice margin was cold-based and meltwater could not infiltrate downward. These landforms dominate the ice-divide zone, which implies that cold-based or polythermal ice was present during deglaciation (Kleman et al., 1992; Dyke, 1993). The Suupohja region in western Finland was close to the ice-divide zone in the central area of the SIS during the latest and probably also during earlier glaciations (Pitkäranta, 2009), as well as the ice-divide zone in northern Finland. The areas of stagnant and cold-based ice are more common in central than in more distal areas of the ice sheets (Boulton and Clark, 1990; Kleman et al., 1997; Hättestrand and Stroeven, 2002). Furthermore, murtoos did not develop in ice-flow sectors with a thin ice cover, such as in the late deglaciation Early Holocene provinces of NJIL (the lobate sector) and those around the ice-divide zone in Lapland (e.g., IIL and SIL). The ice pressure needs to be high enough to result in a suitable effective pressure required for murtoo formation. In addition, it appears that murtoo route development might be inhibited up-ice from the ice margin that ended in a deeper proglacial water body. These conditions are suggested by the central area of BSIL, which retreated along the current Bothnian Sea basin. Based on the relatively sharp boundary of murtoo route distribution within BSIL in SW Finland, the critical depth might have been around 100 m.

The Satakunta murtoo fields and routes are confined to the Loimaa sub-province of BSIL. They are related to the changes in ice dynamics in the Gulf of Bothnia. Lundqvist (2007) proposed an idea concerning a surging lobe and ice-dome breakdown for the whole Gulf of Bothnia. However, Greenwood et al. (2017), based on their high-resolution multibeam bathymetry data, stated that the Bothnian Sea did not host a basin-wide stream or surge event (Kleman and Applegate, 2014), at least during its final deglaciation. Instead, any large ice lobe that may have existed in the Bothnian Sea was dissected by spatially and temporally variable flow behaviour (cf. ice flow corridors by Ahokangas and Mäkinen, 2014). The ice-stream event in flowset A recorded by Greenwood et al. (2016) post-dates the Baltic Sea lobe configuration and mobilized only a local corridor within the Bothnian Sea. Moreover, abundant meltwater channels occur on the bottom of the Bothnian Sea. The interlobate Säkylänharju–Virttaankangas esker within BSIL in SW Finland continues on the Gulf of Bothnia floor to Härnosand, on the east coast of Sweden (Lindroos and Niemelä, 1986). The esker is associated with a major meltwater system cutting through lineations where up to 500-m-wide channels feed a 4-km-wide meltwater corridor floored with glaciofluvial sediments (Greenwood et al., 2016). This implies that a major meltwater corridor existed prior to the deposition of the interlobate esker and fed abundant meltwaters across the Bothnian Sea floor. The deposition of the interlobate esker in the 1-km-wide Satakunta sandstone depression might have been preceded by subglacial meltwater erosion in SW Finland, ca. 50 km from the Bothnian Sea coast (cf. Ahokangas et al., 2020b). The coastal area of SW Finland within BSIL, associated with deeper proglacial water, is devoid of murtoos and murtoo routes. This might be explained by more uniform ice-flow conditions in the Bothnian Sea basin, whereas the topographically different marginal eastern side of the lobe was more subjected to local variations in ice flow and related bed shear stresses, probably affected by the presence of subglacial lakes.

Our results indicate that murtoo deposition is dictated by the marked concentration and routing of subglacial meltwater in a high-pressure environment (related to critical ice thickness and semi-efficient drainage) outside the zone of subglacial tunnel flow and channelized drainage. According to Wingham et al. (2006), Sergienko and Hindmarsh (2013), and Andrews et al. (2018), among others, the following factors are responsible for the distribution of increased subglacial meltwater delivery: 1) increased basal melting due to a localized increase in basal shear stress, 2) drainage from subglacial water storages (subglacial lakes), and 3) drainage from supraglacial water sources. As murtoos are depositional landforms related to saturated till and subglacial highly sediment-concentrated flows, their occurrence also necessitates sufficient subglacial material to be mobilized. The spatial distribution of murtoos and murtoo routes in areas of easily erodible rock types, predominantly biotite paragneisses, suggests that the erodibility of the bedrock strongly assists in murtoo formation. Furthermore, this could explain the high number of surficial boulders associated with murtoo fields.

Importantly, the relationship between glacial dynamics, glacial geomorphology and murtoo route distribution outside but adjacent to the fastest ice-flow sectors implies that the concentration of subglacial meltwaters and origin of routes are dominated by increased bed shear stress conditions or shear-induced melting of temperate ice in certain environments, as exemplified by the relationship between murtoos and the distribution of ribbed-type moraines. The environments with elevated shear stresses and a related increase in meltwater flux include the lateral shear margins of ice streams (cf. Meyer et al., 2018) or between neighbouring ice-flow sectors or corridors (cf. FLDIL), confluence zones of ice stream onset areas (cf. KIL), valley floors (cf. ONKIL), flow proximal areas of cold-based ice (pressure melting), stoss sides of bedrock highs (cf. Konnevesi massif within FLDIL), and the ice flow along and/or over topographically distinct bedrock thresholds (cf. the bedrock contact zone in BSIL and the Maanselkä watershed in ONKIL) (Fig. 13). A subglacial water system of broad distributed channels transitioning into fewer concentrated channels on and over a bedrock ridge has been documented in Antarctica (Schroeder et al., 2013). This transition occurs at a location with an ascending ice-surface slope, increasing basal water flux and an increase in basal shear stress (Joughin et al., 1999), all predicted by a theoretical model of subglacial drainage (Walder and Fowler, 1994).

Interestingly, for the Antarctic Bindschadler ice stream, Meyer et al. (2018) described the evolution of a temperate ice zone along an ice stream shear margin that is coupled to the evolution of the subglacial hydrological system about 15–70 km from the grounding line. Their results suggest a narrow shear margin composed of warm ice that significantly softens downstream. The water draining from the temperate ice adds to subglacial meltwater flow, which includes a rapid transition from distributed to channelized drainage within a few ice thicknesses downstream of the onset of the temperate zone. Furthermore, the water supplied by the temperate ice to the bed affects the strength of basal sediments and saturation of till. The environment described by Meyer et al. (2018) for the Bindschadler ice stream corresponds well with the environment and conditions proposed for murtoo genesis between distributed and channelized drainage during the rapidly decaying ice streams of the FIS during deglaciation (Mäkinen et al., 2017; Ojala et al., 2019b). Moreover, the decaying FIS was probably associated with higher ice surface temperatures than present-day Antarctica, thus promoting a larger extent of the temperate ice zone (cf. Hunter et al., 2021).

The few murtoo routes within interlobate regions support the idea that ice streams with sufficiently high flow rates explain the distribution

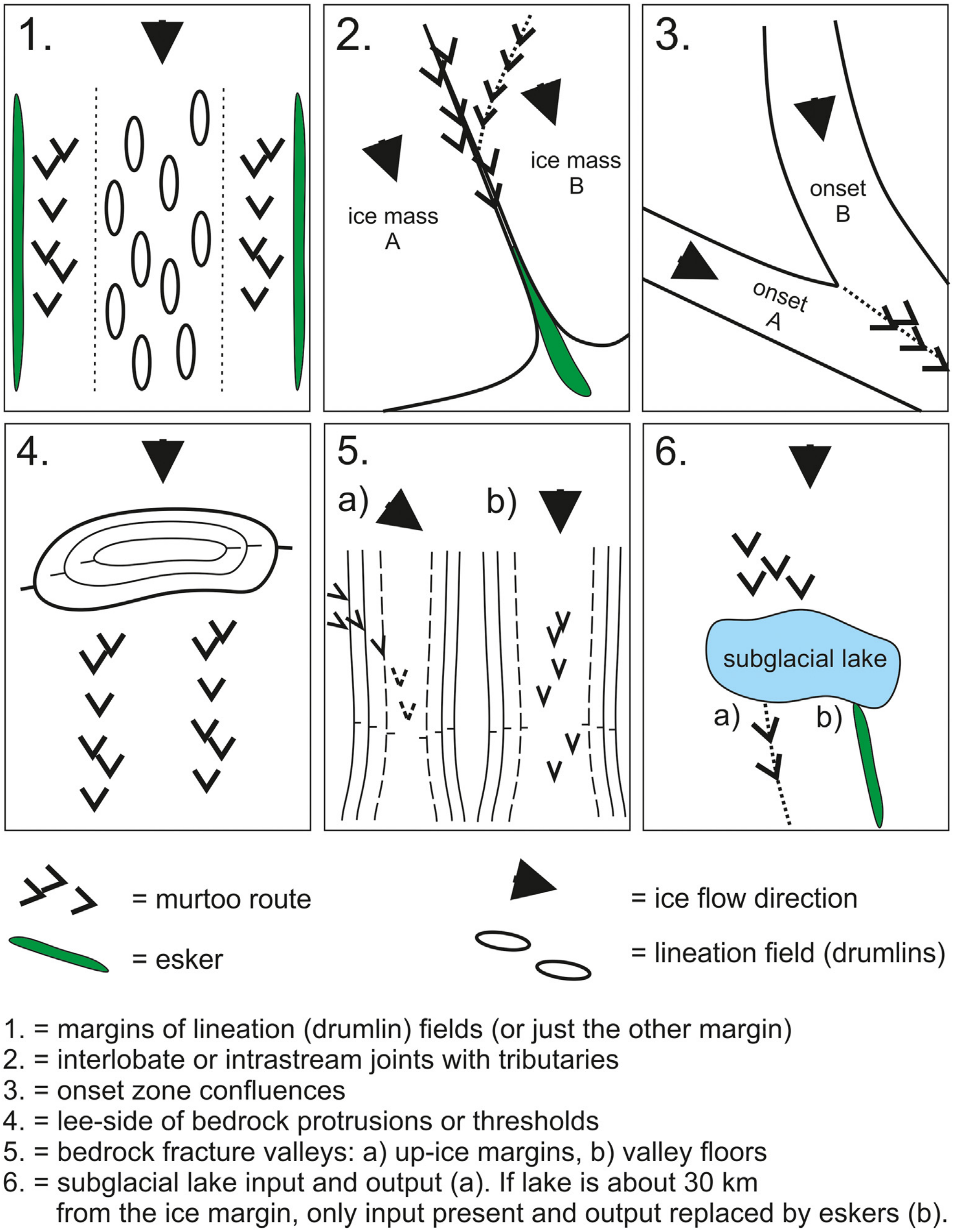


**Fig. 13.** The main environments of murtoo route genesis within the ice streams of the Fennoscandian Ice Sheet in Finland. In all cases, murtoo routes occur as semi-distributed drainage systems with the mobilization of saturated till 30–40 km from the ice margin and with efficient pressure close to zero (as also commonly described for subglacial lakes). Murtoo routes are related to the formation of a shear-induced (frictional heating/melting) temperate ice zone, as well as areas with intermediate bed shear stress and ice-flow rates between ribbed moraine formation and drumlinization. It is also possible that increased meltwater fluxes are influenced by the penetration of supraglacial waters in places.

of murtoo routes and related occurrence of higher bed shear stresses (Fig. 13). The routes of the Finnish Lake District ice-lobe trunk area are confined to the shear margins of the ice-flow corridors (cf. Ahokangas and Mäkinen, 2014) and the flanks of the FLDIL trunk central axis. This implies that meltwater production was pronounced in places where ice flow was faster and induced more melting along the axis of the trunk (Clark and Stokes, 2003). The northeastern interlobate margin of the trunk bordering the Middle Ostrobothnian interlobate region was more favourable for the formation of murtoo routes compared to the southwestern flank of the FLDIL trunk, which was associated with a narrow interstream margin after the readvance of NJIL.

It is also possible that some murtoo routes or parts of more extensive routes were associated with periodic flooding of subglacial lakes during deglaciation (Fig. 6B) (see also Mäkinen et al., 2017). Occasional flooding episodes might also explain the typical discontinuous occurrence of murtoo fields along many of the meltwater routes. In general, murtoos are proposed to form within higher pressure areas over 40 km from the ice margin, whereas most of the delivery of supraglacial meltwater to the ice–bed interface probably concentrated closer to the marginal zone, where hummocky meltwater routes and eskers prevail. However, some of the supraglacial meltwaters in areas with thinner and weaker crevassed ice (cf. Colgan et al., 2011) were likely to penetrate the ice at higher ice-sheet altitudes, which might also explain the occurrence of murtoo fields. In Greenland, lakes of 250–800 m in diameter contain enough water to drive hydro-fractures to the bed through 1 km of subfreezing ice (Krawczynski et al., 2009), and recently, supraglacial lakes draining through hydro-fractures were discovered at high altitudes up to 60–80 km up-glacier (Yang et al., 2021). Lewington et al. (2020) describe meltwater corridors associated with lateral shift due to a variable pressure axis (VPA) between distributed and channelized drainage, but without murtoo landforms. These routes might be comparable to our hummocky routes. They also suggest that the scarcity of meltwater routes beneath palaeo-ice streams is due to lower ice-surface slopes and hydraulic gradients favouring distributed rather than channelized drainage, and that channelized drainage network patterns are typically more dendritic, as shown here.

## 6. Conclusions

LiDAR-based nationwide mapping revealed an extensive subglacial meltwater route network with 2689 new subglacial routes and 5681 ice-marginal or proglacial routes that supplement the known esker network. The mapped meltwater routes indicate that the distribution of murtoo routes is dominated by ice-stream tracts, including interlobate joints and onset zone confluence areas. Murtoo routes are lacking in interlobate regions and the ice-divide zone, with cold-based ice, and from areas with a thin ice cover. Murtoo routes often occur adjacent to drumlin fields or lineation sets and within ribbed moraines cross-cutting them. The topographical control for the origin of murtoo routes is related to lake basins (in places possibly indicating the position of a subglacial lake), bedrock depressions and thresholds, as well as with the lee sides of some of the major bedrock protrusions. Murtoo routes exist between approximately 35–40 km from the ice margin, whereas hummocky routes without murtoos or murtoo-related landforms occur closer to the ice margin. Hummocky routes are the most common and represent a major subglacial drainage system linking the semi-distributed murtoo-forming environment to channelized drainage with esker deposition.

The following factors have been considered to promote the genesis of murtoo fields and murtoo routes: A) warm-bedded ice, B) thick enough ice with semi-distributed drainage, C) a high subglacial meltwater concentration with a localized effective pressure close to zero, D) intermediate ice-flow rates and bed shear stress between ribbed moraine formation and the conditions for drumlinization, E) shear-induced temperate ice zone development, and F) the availability of subglacial saturated sediment (till). In addition, bedrock topography and easily erodible bedrock are assisting factors.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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