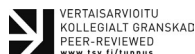# High-resolution LiDAR mapping of glacial landforms and ice stream lobes in Finland

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Abstract

Newly available high resolution airborne LiDAR (Light Detection And Ranging) technology is generating unprecedented next-generation imagery of Earth surface features. LiDAR datasets are being employed by the Geological Survey of Finland (GTK) as part of a new national geological initiative (Glacier Dynamic database: GDdatabase) to rapidly and cost-effectively map glacial landforms and sediments left by the last (Late Weichselian) Fennoscandian Ice Sheet (FIS). There is a high demand for such data in hydrogeological, geoengineering and mineral exploration projects and also for the identification of glacial landforms that provide key information regarding ice sheet rheology, growth and decay. An important step forward with this new technique is the recognition of paleo-ice stream corridors with fast flowing ice (> 3 km yr^{-1} based on modern ice sheets), surrounded by stagnant or sluggish-flowing ice. Precise geomorphic criteria are now available for recognition of paleo-ice streams, based on the elongation of subglacial streamlined bedforms and the presence of megascale glacial lineations. Flow sets of drumlins and megascale glacial lineations can now be mapped in high resolution using LiDAR and are now seen as genetically related forms in a continuum that records increasing ice flow velocity and the creation of a low friction bed. This paper briefly outlines the nature of the GDdatabase and the methodology behind its construction and provides examples of principal bedform types that record the dynamic interplay of paleo-ice stream lobes in the Finnish sector of the last FIS.

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1. Introduction

The use of high-resolution airborne Light Detection And Ranging (LiDAR) technology has revolutionized geological and geomorphological mapping (e.g., Johnson et al., 2015). Recent studies have shown that mega-scale landforms, such as drumlins, eskers and end moraine complexes, are revealed on LiDAR-based digital elevation models (DEM) in much greater detail than from traditional mapping and air photographic interpretation, and in addition, landforms that are smaller than hitherto resolved from conventional topographic maps and 10 m grid DEMs (e.g., small annual moraine ridges) can now be detected and mapped using LiDAR-based DEMs (e.g., Greenwood et al., 2015; Eyles et al., 2016; Dowling et al., 2016; Ojala, 2016).

Concurrent with advances in imaging technology, significant new understanding of paleo ice sheets has come about as a result of the recognition of corridors ('arteries') of fast flowing ice surrounded by sluggish flowing or stagnant ice. This is based on analysis of subglacial streamlined bedforms such as drumlins and their more elongate companions referred to as Mega-Scale Glacial Lineations (MSGLs). The last North American ice sheet (Laurentide) had at least 100 such ice streams and it is now apparent that the many 'lobes' hitherto recognized in Scandinavia are the expression of fast-flowing ice streams within the FIS (e.g., Boulton et al. 2001; Rydningen et al., 2013; Greenwood et al., 2015).

In Scandinavia, high-resolution DEM and LiDAR imagery has been employed to study a wide range of geomorphological features such as De Geer recessional moraines (Bouvier et al., 2015; Ojala et al., 2015; Dowling et al., 2016; Ojala 2016), ribbed and hummocky moraine areas (Möller & Dowling, 2015), subglacial meltwater systems (Sarala et al., 2015), beach ridges, cliffs and shore terraces (Ojala et al., 2013), fluvial terraces, floods plains, lateral meltwater channels (Eilertsen et al., 2015), post-glacial fault scarps and landslides, and surface features related to paleoseismic events (e.g. Sutinen et al., 2014; Mikko et al., 2015; Palmu et al., 2015), together with bedrock lineaments, fracture sets and fissures (Scheiber et al., 2015; Skyttä et al., 2015).

The technology has not only allowed significant advances in understanding the spatial occurrences and patterns of glacial and accompanying landforms – and possibly also their origin(s), but the development of LiDAR-based mathematical solutions and models to underpin field-based observations (Yu et al., 2015; Sookhan et al., 2016).

The availability of LiDAR DEMs has fundamentally changed the process of mapping Quaternary deposits (Putkinen et al., 2016). It has greatly reduced the duration of expensive field work and mapping time in general, proving an indispensable and convenient tool that is highly cost-effective. In Finland, this possibility has initiated the development of a new national geologic database in order to combine and store pre-existing data of superficial Quaternary deposits and landforms (Glacier Dynamic database or GDdatabase). The purpose is to produce completely new LiDAR imagery-based coverage of the country, focusing on the record of ice sheet dynamics during the last ice age. In addition to producing LiDAR DEMs collected by the National Land Survey of Finland (http://www.maanmittauslaitos.fi/en/professionals/topographic-data/remote-sensing/laser-scanning), the project aims at producing a wide selection of Quaternary geological map databases by the Geological Survey of Finland, and also specific themes which cover Finland partly or completely at scales varying between 1 : 10 000 and 1 : 1 000 000.

1.1. Purpose of this paper

The purpose of this paper is to briefly outline the Glacier Dynamic database (GDdatabase), the fundamental principles behind it, and to give representative examples of different geological features belonging to the GDdatabase. We also briefly provide examples of site-specific mapping and on how the stored information can be applied in understanding the dynamics of ice stream lobes during glaciation. It must be emphasized that mapping of paleo-ice stream beds in the FIS is still in its infancy and that there are subglacial landforms whose precise origins and glaciological significance are far from clear.

2. Glacial terrain mapping

Glacially derived sediments and landforms are inherently complex to classify and map and glacial geologists often simplify this process by employing a 'land system approach'; the terms 'depositional system' or 'facies model' are essentially synonymous. The fundamental assumption employed here is that surface landforms are genetically related – if depositional to their formation – with their internal sediments since they accumulated coevally during the same depositional event, e.g. during the closing stages of a single glacial cycle such as the Late Weichselian deglaciation at which the FIS formed and retreated over Finland approximately between 24 000–10.500 cal yr. BP (Johansson et al., 2011). The land system concept has proved very useful as an organizing framework for fundamental mapping projects and geo-engineering, mineral exploration and hydrogeological assessments.

A number of glacial land systems are now recognized, the most recent being the 'ice stream land system', emphasizing the presence of highly elongate ridges (MSGLs) and lateral shear margin moraines (see Benn & Evans, 2010; Ross et al., 2009, 2011; Evans et al., 2008, 2014; Ottesen et al., 2016; Eyles & Doughty, 2016). This and the closely related drumlinized 'subglacial land system' consists of drumlinized terrain underlain by subglacially deposited till reflecting the assumption that drumlins are *depositional* bedforms that grow upwards by localized bed deformation and till deposition (Eyles, 1983; Eyles & Eyles, 2010; Stokes et al., 2013; Spagnolo et al., 2016, Möller & Dowling, 2016) such that surface landforms and internal sediments, are genetically related. Similarly, areas of hummocky moraine topography (the 'supraglacial land system'), which might rest on a subglacial land system, are viewed as the expression of underlying, often complexly-structured ice-contact deposits resulting from the complex downwasting of an ice margin buried under supraglacial debris.

A land system approach has proven very useful in glacial geological studies for simplifying and integrating complex glacial systems (see Benn & Evans (2010) for a comprehensive review, Evans et al. (2008, 2014) for examples from western North America or Alexanderson et al. (2001) for examples from arctic Siberia). However, despite its great utility, the fundamental assumptions underpinning the method are not always appropriate, especially in those areas of multiple glaciations or multiple events during a single glacial cycle, such as where older glacial deposits and/or landforms are preserved or have been partially reworked (cf. Lunkka et al., 2016). It is not employed here to map subglacial landscapes and sediments given recent arguments that drumlins and megaflutings (are here synonymous with MSGLs) are primarily *erosional* in origin cut across underlying materials that can include both sediment and rock (see Möller & Dowling, 2015; Eyles et al., 2016; Krabbendam et al., 2016 and refs therein). In this sense many glacial landforms are palimpsest features resulting from reshaping of older materials (Benn & Evans, 1998; see page 535). In cases such as this, the subglacial bed and the bedforms on its surface (e.g. drumlins, megaflutings) represent a major glacially-streamlined unconformity cut across genetically-unrelated sediments (and/or rock). In view of this we simply employ the term 'terrain' and recognize 'paleo-ice stream terrains' left by fast-flowing corridors within the last ice sheet to have covered Finland. In this way sediments and landforms are integrated together and linked to the history of ice sheet dynamics.

3. Methodology and GD database

For mapping glacial deposits, a LiDAR based DEM with primarily Multi-Directional Oblique Weighted (MDOW) hill-shade was used, which allows exceptional visual perception of the surface form of entire landscapes and individual landforms.

Most of the Kuusamo Ice stream Lobe and about 70 % from the Finnish Lake District Ice stream Lobe (FLDL) area were interpreted with different kinds of hillshade and DEM enhancement options, on which were used ArcGIS 10.4.1 for Desktop Image Analysis gradient filters (see ArcGIS 10.4.1; Help documentation; Gonzalez & Wintz, 1987).

Convolution filters were applied to LiDAR and DEM 10 m data by 3 x 3 raster cell kernel, which calculates on different directional gradient to DEM data in 45 degree increments. Gradient filters are types of convolution filters, which are used in image analysis to edge detection (http://desktop.arcgis.com/en/arcmap/10.4/manage-data/raster-and-images/convolution-function.htm). These filtered layers are in use during the mapping process in some areas to help interpretation. On ArcGIS Image analysis, using those gradient filters in grayscale, the result raster will be hillshaded from calculated convolution direction. DEM data was also calculated by Laplacian 5 by 5 convolution kernel function to emphasize landforms. Combination of piled filter rasters emphasizes landforms from LiDAR DEMs regardless of orientation from different directions.

In this project individual landforms are commonly digitized by hand from LiDAR DEMs using ArcGIS editing tools. During the project some automatic or semi-automatic customized algorithms of ArcGIS and eCognition software for MGSL mapping were also tested. However, the result of the latter showed to be uncertain and too inaccurate for the intended use of the GDdatabase. It was noted that digitizing by hand was necessary for detailed mapping results. Landforms are preferably digitized in-line and closed areas are then labelled with points. In the end these are processed to polygons representing each class of deposit or bedform. However, some of the classes remain in line shape, for example glacial lineations including drumlins and flutings.

The new GDdatabase is created as a file geodatabase in Esri's ArcGIS platform and it consists of multiple datasets, feature classes and domain lists. The GDdatabase structure and classification of the deposits and landforms have been and are still subject to change during the ongoing development process. The up to date comprehensive classification chart of the GDdatabase is available as a supplementary data (Electronic Appendix B). The classification is thematic but also represents a simple technical composition (http://desktop.arcgis.com/en/arcmap/10.4/manage-data/geodatabases/types-of-geodatabases.htm).

In revising pre-existing data pertaining to previously mapped Quaternary deposits and aggregate deposits, we have also applied a grid and raster painting editor developed by Aris B.V. (http://www.aris.nl/gridrastereditor_arcmap). In this method polygons are transferred to raster in order to rapidly paint new borders and correct possible inaccuracies of different classes to pre-existing map shapes. This process is somewhat quicker than digitizing vertex by vertex in vectorised features. Both methods are in use but most of the new data is processed as vectorised data, polygons, lines and points.

3.1. Landform and deposit classes

The GDdatabase contains a large set of landforms and various sub classes as well as deposit types, all of which are identified on LiDAR MDOW DEM maps, together with explanations (see Electronic Appendices). This approach provides a powerful analytical tool for studying and recognizing different geological and geomorphological landform types across Finland indexed to the Preliminary Ice stream lobes Map of Finland (PIMF) (Fig. 1 and Electronic Appendix A). These classes of the GDdatabase are shown in Electronic Appendices B–E. They range from meltwater-deposited landforms (eskers, sandur plains, deltas, kames) and till-dominated complexes with secondary information as to the location of where they accumulated, e.g. as interlobate eskers or as ice marginal moraines (e.g., Fig. 2).
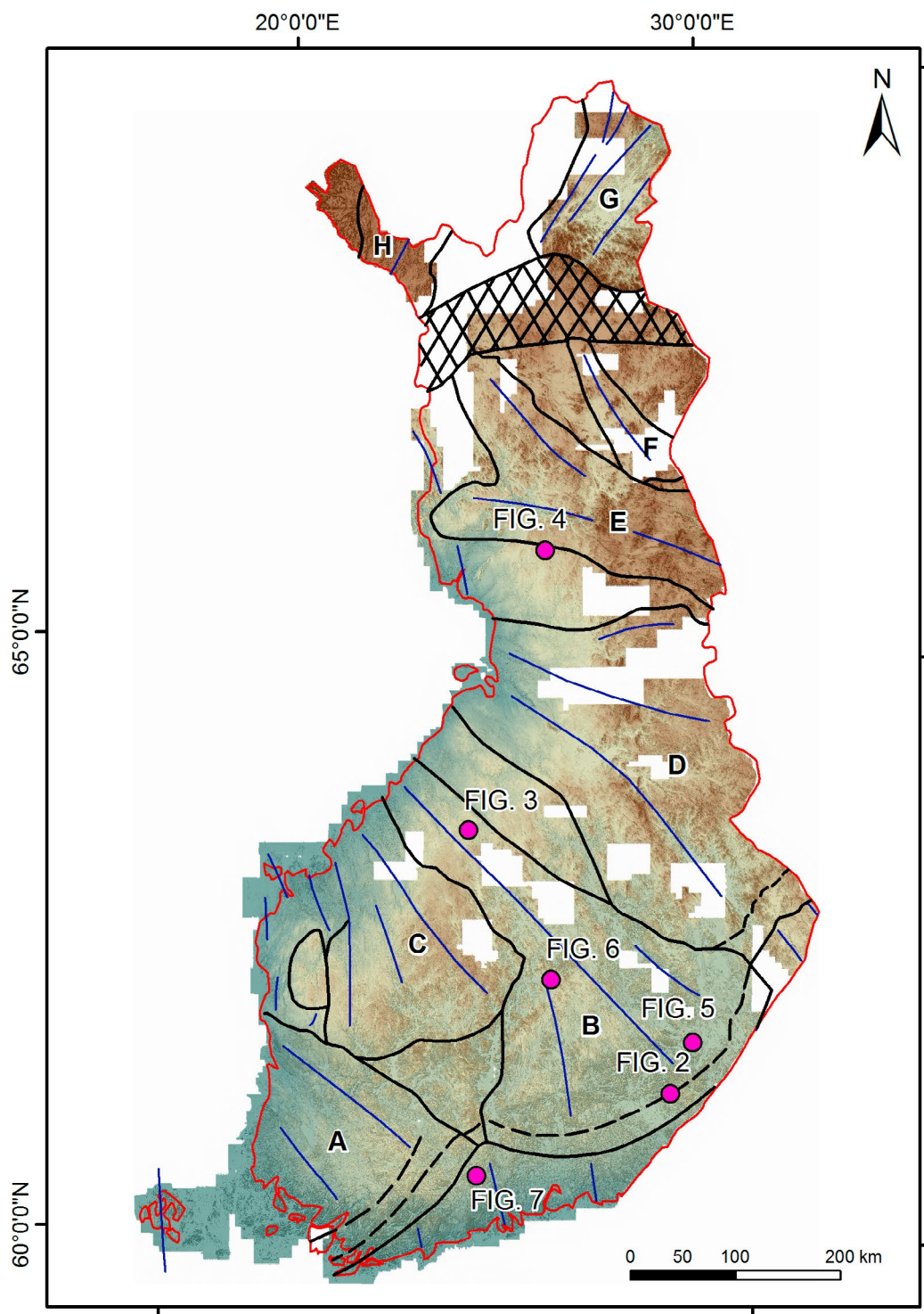
Figure 1. LiDAR-based Preliminary Ice stream lobes Map of Finland (PIMF). Main ice stream lobes (A. Baltic, B. Lake district, C. West, D. North Karelian/Oulu, E. Kuusamo, F. Salla, G. Inari and H. Enontekiö) of Finland resting on LiDAR DEM (6/2017 coverage). Ice lobe margins (black), ice divide zone at North (raster), main flow lines (blue) and figure locations are indicated.
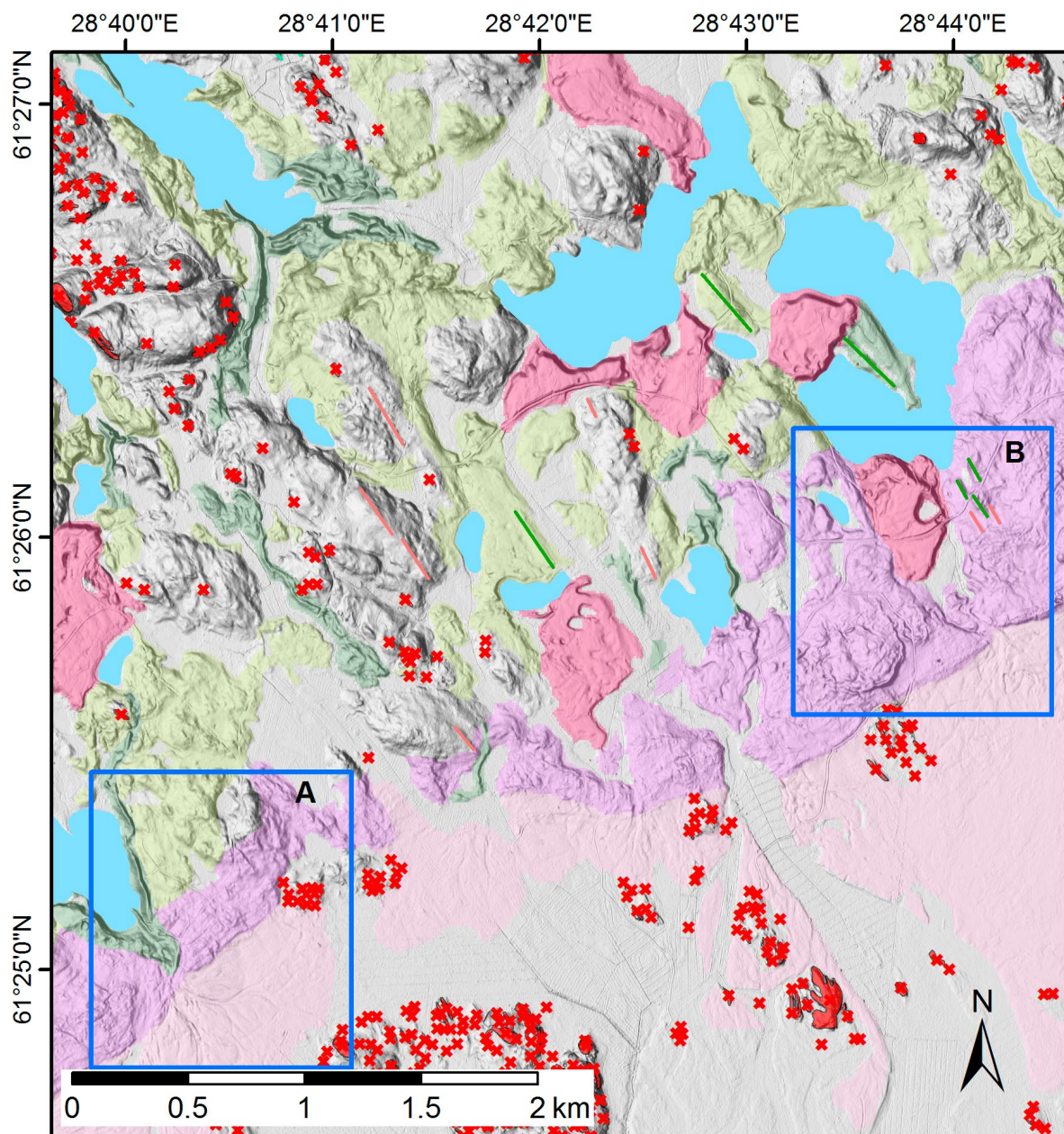
Figure 2. LiDAR DEM and landform interpretation and classification of a complex ice marginal deposit near the village of Reinikkala in southeastern Finland north of the Salpausselkä II moraine. Two inset rectangles (2A and 2B) show detailed landforms within the complex. Eskers (green), deltas (red) and an outwash plain (light pink) with braided channels, proximal ice-contact glaciofluvial sand and gravels (yellow) and a large ice marginal moraine (purple) are genetically-related and formed along the retreating ice margin. Ice flow directions are recorded by drumlins (green lines) and flutings (pink lines).
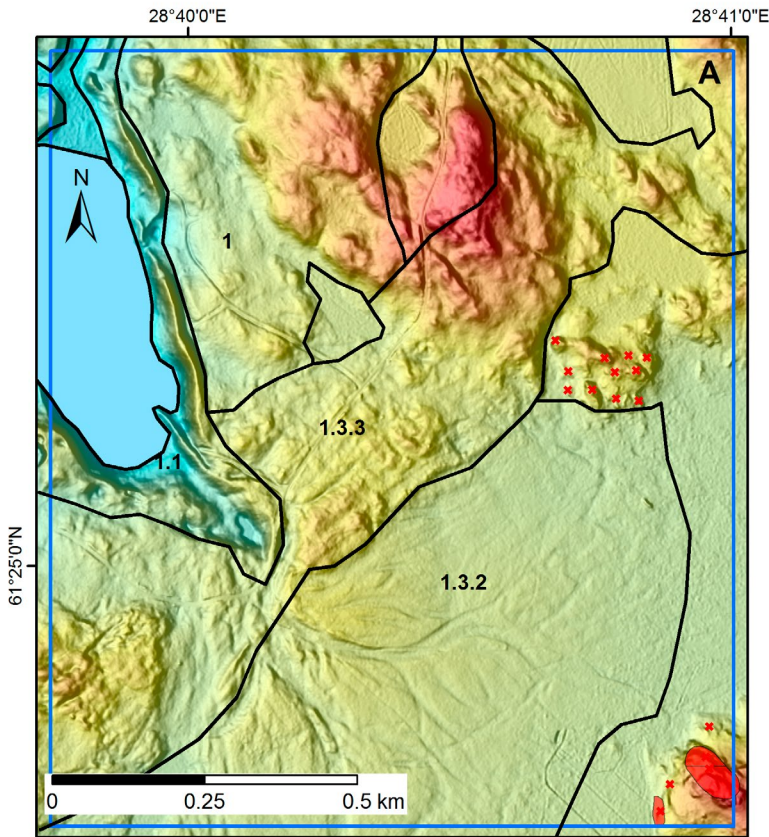
Figure 2, inset A. A glaciofluvial complex (1), an esker system (1.1), an outwash plain (1.3.2) with braided channels, and proximal ice-contact glaciofluvial sand and gravel (1.3.3) are formed at the Salpausselkä II.

Figure 2, inset B. A glaciofluvial delta (1.3.1), an outwash plain (1.3.2) with braided channels, an ice-contact glaciofluvial deposit (1.3.3), and a large ice marginal dump moraine complex (4.1.1) represent the position of the ice margin during the Salpausselkä II stage. Drumlins (green) and flutings (pink) indicate the ice flow direction toward the ice stream terminus.
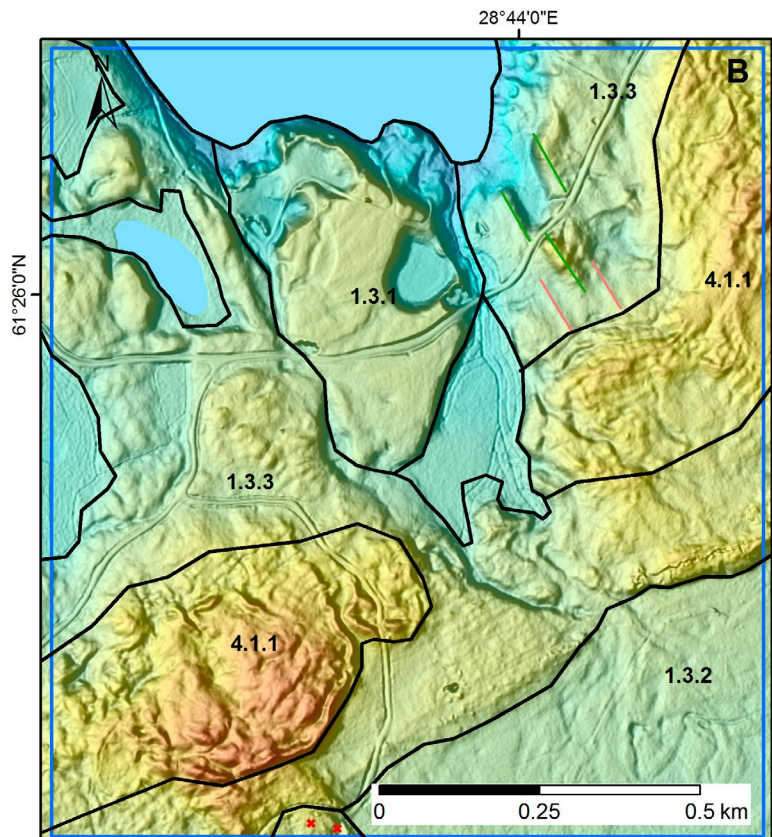
A wide variety of moraine ridge types are incorporated into the GDdatabase, ranging from recessional moraine ridges and De Geer moraines (Figs. 2 and 7; see also Electronic Appendices D:27, E:33, E:36, E:37, E:38 and E:39) to large push moraine complexes recording significant still stands of an ice margin (Fig. 2) see also Electronic Appendices C:15, D:23 and D:28), to areas of ribbed moraine forms typical of ice centres with sluggish or stagnant ice flows. Ribbed moraines are divided into three main morphological sub-types: hummocky ribbed moraine, Rogen moraine and minor ribbed moraine following the classifications of Hättestrand (1997) and Sarala (2003, 2006) (Figs. 3 and 4; see also ribbed moraine in the Electronic Appendices C:4, C:5, C:6, C:7 and

C:9). Furthermore, occasionally it is possible to recognize a fourth type of the ribbed moraines, "arcuate-shaped" forms composed of diamicton which are more closely related to subglacial hummocky moraines and meltstreams features (Fig. 3; see also Electronic Appendices C:8, C:9, E:32 and E:34). Understanding of these transverse moraine forms is not yet complete and awaits further subsurface data as to their composition; existing data identifies coarse-grained often bouldery cores indicative of limited distances of glacial transport (e.g., Mäkinen et al., 2017). Large areas of hummocky moraine record supraglacial deposition of diamicts as well as sorted glaciofluvial or glaciolacustrine sediment over stagnant ice. These sediments are ultimately redeposited during
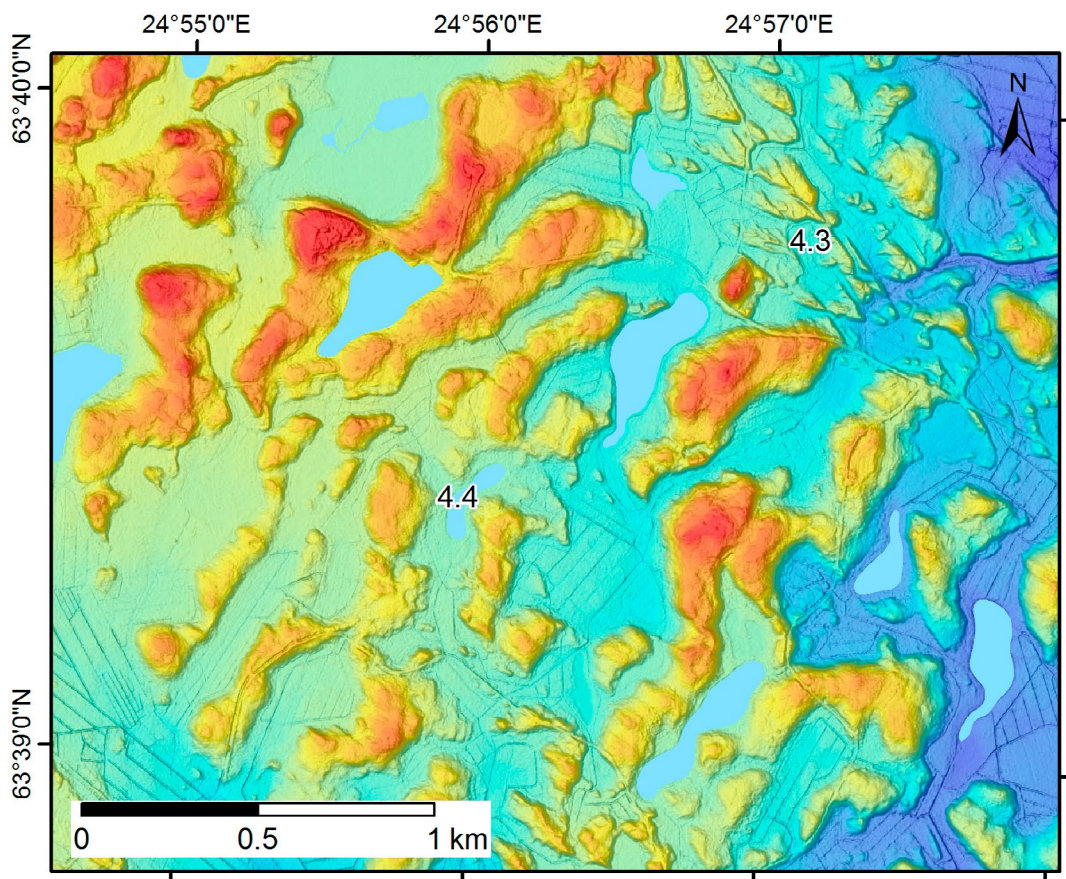

Figure 3. Ribbed moraine (code 4.4) deposited under sluggish ice flow velocities in Nivala-Haapajärvi in central Finland typical of inter ice stream areas and onset zones. Poorly understand arcuate-shaped hummocky ribbed moraines (code 4.3) may record some type of mass flow deposit. Fast ice flow and ice streaming is recorded by MSGLs (Fig. 5).
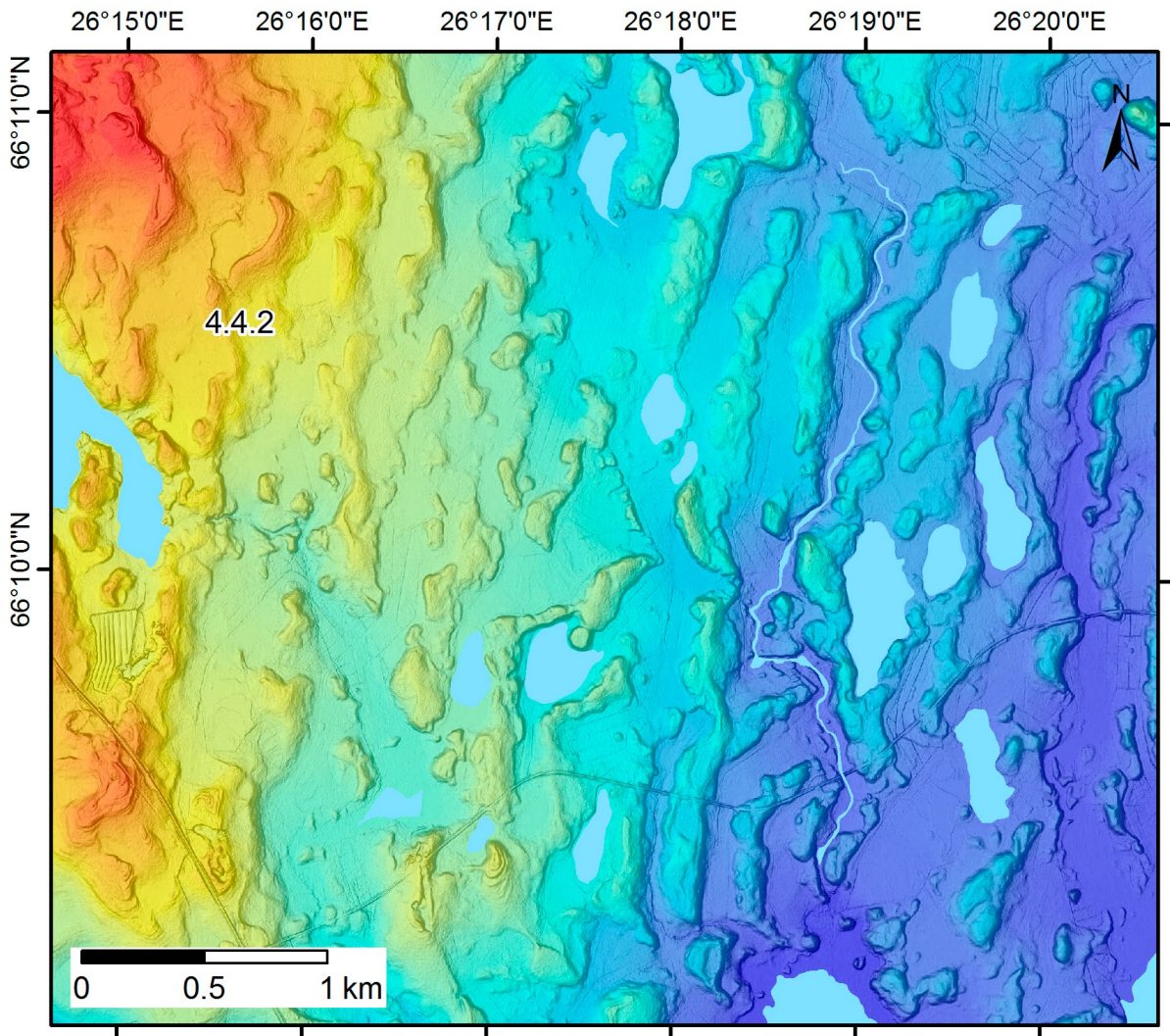
Figure 4. Well-developed ribbed (Rogen) moraine (code 4.4.2) typical of cold-based ice and sluggish ice flow velocities, in the Portimojärvi region about 20 km NW from the town of Ranua.

ice down-wasting, forming a hummocky or 'kettled' surface.

Other identified features are littoral deposits formed along former coasts. In addition, the database also relates to databases with drilling, ground penetrating radar, reflection seismic and downhole seismic and other geophysical data identifying the presence of buried pre-Late Weichselian deposits. Of special significance are glacially streamlined terrain composed of drumlins and megaflutings (Figs. 5 and 6), crag and tails and pre-crags (Fig. 5; see also Electronic Appendices C:1–3, C:8–13, D:16–D:22, D:24, D:26, D:29, E:31–32 and E:38). These not only identify flow direction at formation but also identify the trunks of ice streams and their lateral margins with slower-flowing or stagnant ice (Fig. 1 and Electronic Appendix A). Many of these sets suggest abrupt changes in ice flow direction, often expressed a superposed crossing striations and streamlined bedforms. This is consistent with 'ice flow switching' during deglaciation (see Electronic Appendices C:2, C:13 and D:29).
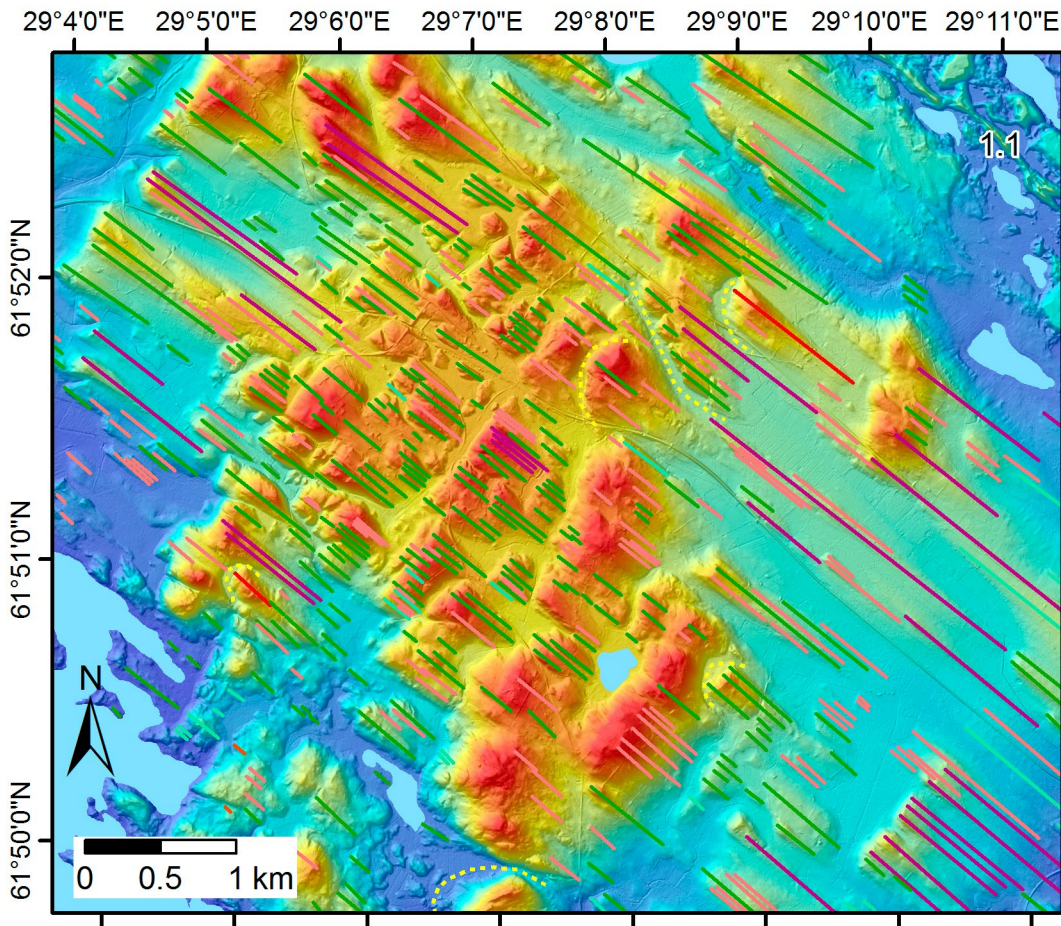
Figure 5. Large numbers of crag and tail glacier lineations suggest fast flowing ice masses crossing relatively thin sediment cover resting on the Fennoscandian shield at Kuuttilanmäki, Savonlinna. This type of prevalent topography occurs in large areas across the middle and southern Finland. Flutings are indicated in pink lines, drumlins (green), megaflutings (purple), through valleys and crescent troughs (yellow).

So-called 'pre-crag' deposits are common features in southwestern Finland. A typical pre-crag forms at divergent ice flow around an emergent bedrock high; subglacially deforming debris flow around bedrock preserves pre-existing sediment (such as till) on the upstream (stoss) side of the obstruction (e.g., Haavisto-Hyvärinen et al., 1989). Morphologically they are the mirror-image of crag and tails features where pre-existing sediment is left in lee of a bedrock knob or where sediment was deposited in subglacial lee-side cavities (see Electronic Appendix E:38).

Much drumlinized terrain in Finland is cut across thick antecedent older deposits leaving as large drumlinized 'uplands' (Gluckert, 1973; Möller & Dowling, 2015; Möller & Murray, 2015) (see Electronic Appendices D:19–21 and D:26) and what have been termed 'megadrumlins' (Eyles et al., 2016). These have conjoined drumlins on their surface reflecting limited subglacial erosion and dissection of pre-existing sediment. Drumlins are differentiated from megaflutings by conventional analysis of their elongation ratios (ER), i.e., length divided by width; megaflutings usually have ERs
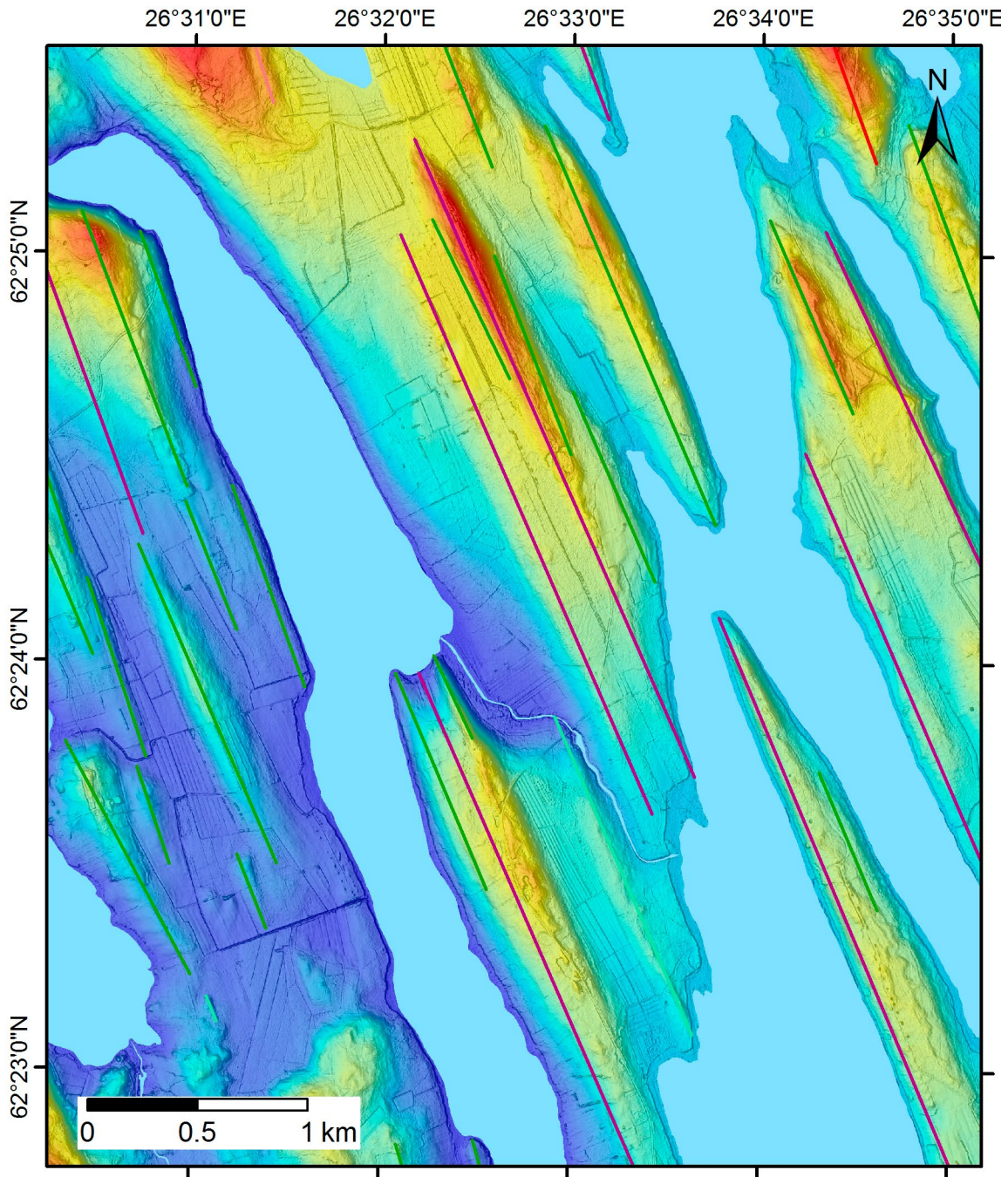
Figure 6. Megascale glacial lineations in the vicinity of Hankasalmi in the Suolivesi region typical of the subglacially-streamlined bed of the Finnish Lake District Ice stream Lobe that crossed central Finland (Fig. 8). For symbols see Fig. 5 and Electronic Appendices C–E.

larger than 7:1 and sometimes as much as 40:1 (Figs. 5 and 6). Typically, these bedforms consist of a thin (>1 m) carapace of till resting erosively on older sediment, which suggests an erosional origin at which the ice-bed interface has been smoothed by erosional streamlining of larger irregularities (i.e. drumlins), enabling faster ice flow over a lower friction surface (e.g., Eyles et al., 2016; Möller and Dowling, 2016). Some glacially streamlined bedforms are cut into rock of various types, in their dimensions ranging from roche moutonnées to drumlins and megaflutings scale (rock drumlins) (Krabbendam et al., 2016).

An ice stream terrain model is a very useful integrator of a diverse range of landforms and sediments associated with fast (and sluggish) flowing ice. As such it provides a very useful regional mapping framework and this is one of the prime objectives underlying development of the GDdatabase. A comprehensive inventory of landforms and deposits recording paleo-ice streams is now possible for the Finnish sector of the last FIS. While this is beyond the scope of the present study we give some provisional comments and illustrations below.

4. Ice stream lobes in Finland and deglaciation dynamics

Currently, the GDdatabase includes more than 280 000 individual glacial geomorphological features from four different ice stream lobes across Finland with a focus on the Inari, Kuusamo, Northern Karelia/Oulu and Finnish Lake District ice stream lobes for which there has been a systematic mapping effort (see Electronic Appendix A). Some of these landforms are illustrated elsewhere in this volume with examples of glacially streamlined terrain from the Kuusamo Ice stream Lobe (Sarala & Räisänen, this volume; also Putkinen & Lunkka, 2008) and the North Karelian/Oulu Ice stream Lobe (Nikarmaa et al., this volume; also Putkinen & Lunkka, 2008). What follows below is focussed on examples drawn from

the Finnish Lake District Ice Lobe (FLDL); however it must be emphasized that other ice stream lobes across the Fennoscandian Shield left similar terrain systems. Such typically consist of corridors with a distinct downflow 'morphosequences' composed of upstream ribbed moraine of Rogen type formed beneath slowly moving to close to stagnant ice near ice divides (Fig. 4), transforming downflow into streamlined terrain (drumlins) (e.g. Sarala, 2006; 2015), representing enhanced ice flow velocities ($\sim$100 m yr^{-1}), that in turn transforms into highly elongate megaflutings recording even faster ice flow (velocities above 400 m yr^{-1} and larger (3 km yr^{-1}) based on the behaviour of modern ice streams. Such morphosequence were first noted by Lundqvist (1969) and Aario (1977) but it is now possible to relate such bedform transitions to likely ice flow velocities as part of a glaciodynamic bedform hierarchy similar to that developed by fluvial sedimentologists for bedforms produced by unidirectional currents (e.g. Bridge, 2006). Downstream reductions in ice flow velocities are also expressed as transitions from megaflutings back to drumlins; former ice margin positions are recorded by large morainal complexes (Fig. 2), reflecting the delivery of much subglacial debris to the margin by advection of 'soft' deforming till (e.g. Eyles et al., 2011). Such debris is partially reworked subglacially by canalized meltwater streams and left as esker-fan complexes or much larger sandur plains during ice retreat (Fig. 2) (see Boulton et al., 2001; Putkinen & Lunkka, 2008; Eyles et al., 2015; Ojala et al., 2016). Significant areas of dissected meltwater-deposited sediment terrain underlain by glaciotectonically-deformed and partially collapsed outwash interbedded with diamict facies deposited by mass flow at subaqueous-terminating ice margins at water depths of 50 m or more. These relatively high standing landforms cross Southern Finland and contain significant groundwater resources that also recharge underlying and immediately surrounding areas of fractured crystalline rock.

The bed of the former FLDL is depicted by many examples in the Electronic Appendix D figures 17–22 with megaflutings and other
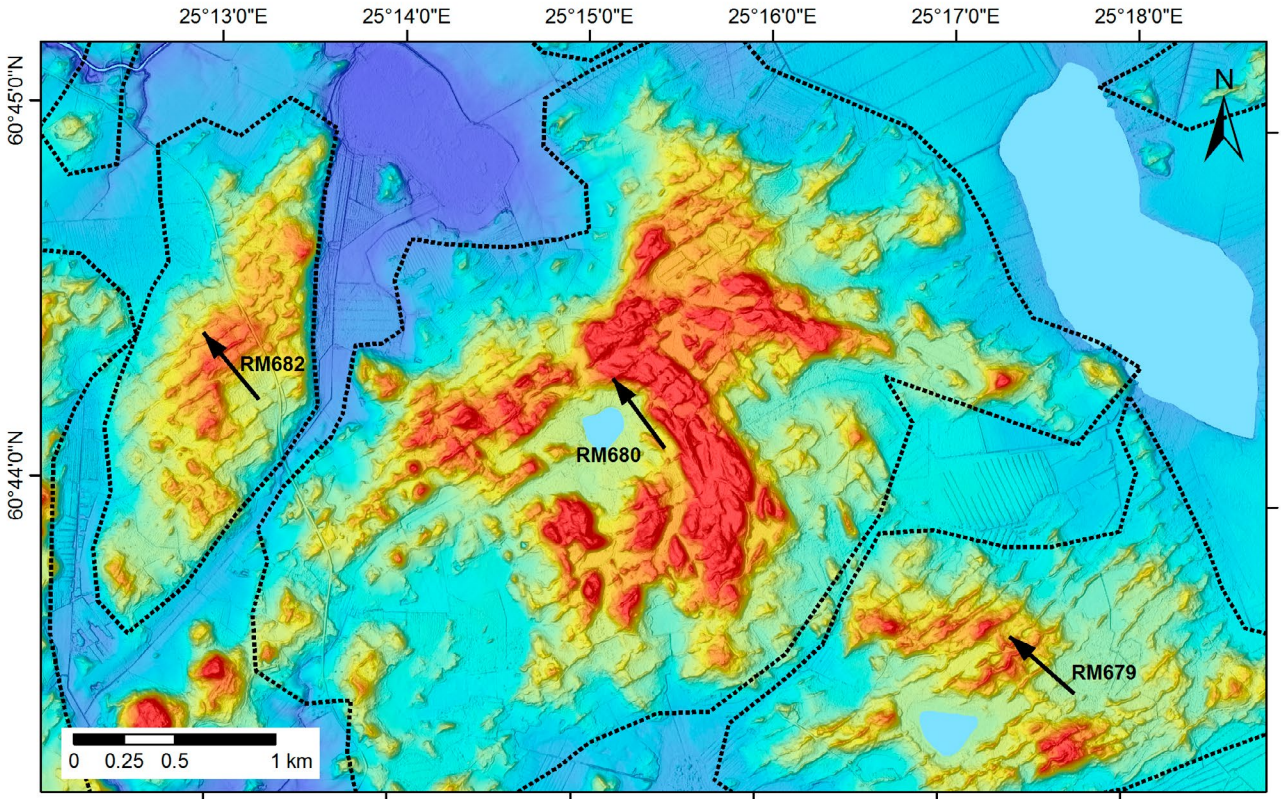
Figure 7. De Geer moraine fields (DGM #RM679, RM680, RM682) of the Sälinkää-Suojärvi-Sulkava areas of Mäntsälä in south-central Finland. Direction of deglaciation is shown by black arrows.

genetically-related subglacial bedforms such as pre-crags, drumlins (both rock drumlins and sediment-cored such) together with ribbed moraine when approaching adjacent to the ice flow corridors. An excellent example of the higher resolving power of LiDAR is provided by analysis of De Geer moraines (DGMs) formed during ice retreat (Fig. 7) at subaqueous margins.

LiDAR data are also generating new information regarding subglacial landforms whose origin is not yet fully understood. For example, topographically-irregular bodies of sediment that have been dissected by numerous poorly-integrated channels appear to have accumulated at the lateral margins of under fast flowing ice (Electronic Appendix E:34 and Mäkinen et al., 2017). These may represent poorly integrated subglacial drainage systems. Some have a distinctly beaded form likely recording successive retreat positions of the ice margin in water akin to the formation of beaded eskers. In this regard, large esker networks formed across the central southern Finland during the last deglaciation. These are largely parallel to glacier (FLDL) flow lines indicated by drumlins and megaflutings, suggesting there was no major ice stream re-organization in the FLDL during retreat from the Salpausselkä end moraine zone (Fig. 8).
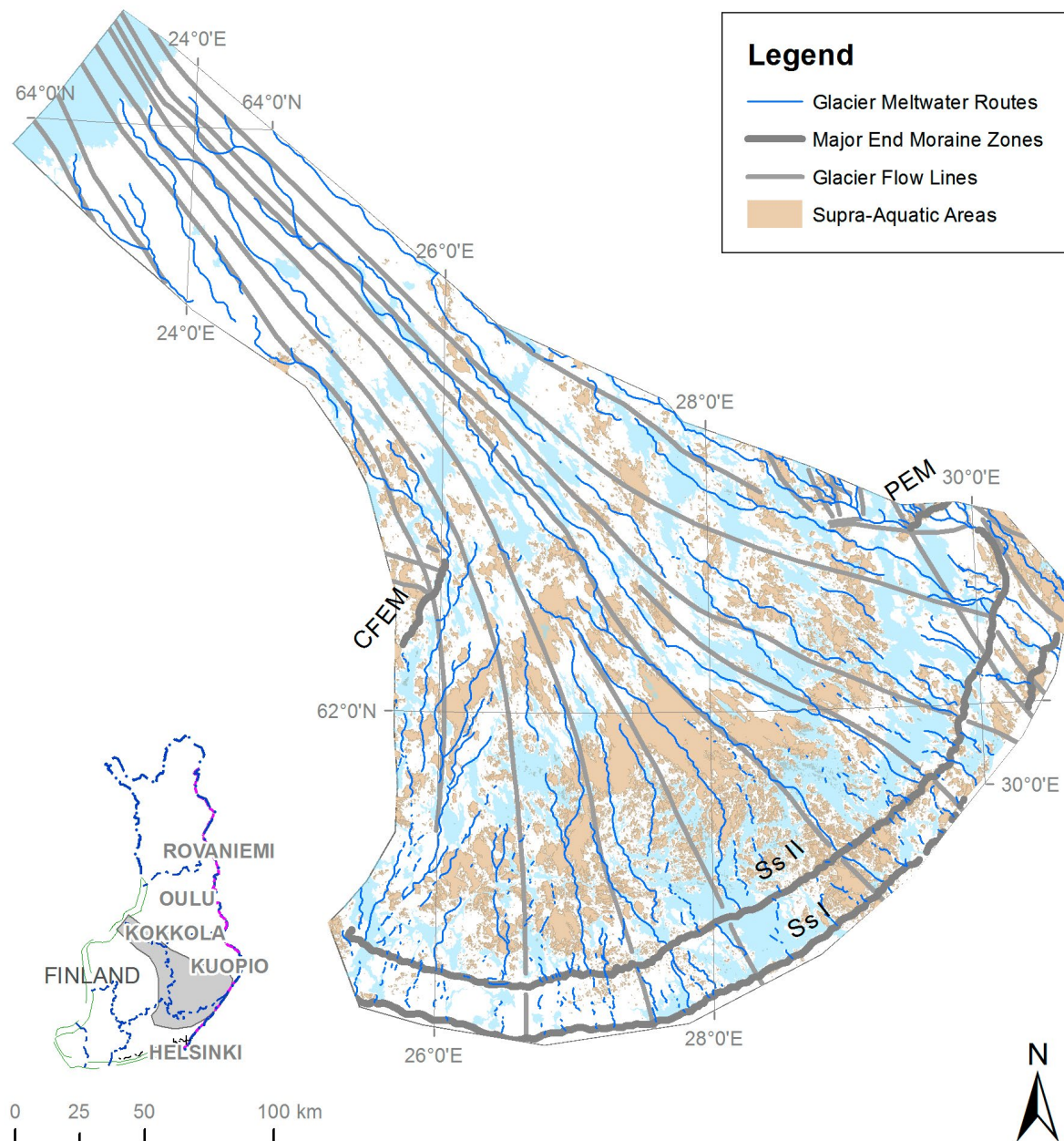
Figure 8. Preliminary map of the former extent of the 500 km long Finnish Lake District Ice stream Lobe in central Finland showing main glacier flow lines, principal routes of meltwaters and relatively high standing 'supra aquatic' areas. Margins of the ice stream are defined by the Central Finland End Moraine (CFEM), the Salpausselkä End Moraines (SS I, SS II) and the Pielisjärvi End Moraine (PEM). Fast ice flow may have been sustained by extensive marginal and submarginal bodies. Regional LiDAR mapping by GTK allows integration of diverse, widespread but genetically related landforms and sediments within distinct mappable 'ice stream terrains.'

5. Discussion

As related above, clearest advantage of the GDdatabase, and the glacial terrain mapping approach on which it is based, is that it integrates a wide variety of landforms and sediments that hitherto were mapped and treated quite separately. With the new approach genetically-related elements can be linked within a simple 'paleo-ice stream' terrain model. Their distribution of mapped glacial landform across Finland fundamentally reflects the flow and subsequent demise of ice streams and their associated lobate margins across the Fennoscandian Shield (Electronic Appendix A). This conceptual framework integrates data across large areas that have been treated separately on formerly produced individual Quaternary map areas at the 1:20 000, 1:50 000 or even 1:100 000 scale. Traditional mapping technique is also relatively expensive and time consuming, compared to LiDAR-based mapping. Broad scale LiDAR-based terrain mapping is rapid and inexpensive and data can be used to recreate regional-scale glacier dynamics reconstructions for the entire Finnish sector of the FIS and by that give the 'bigger picture' of ice-lobe dynamics. Another benefit of the LiDAR mapping is that it reveals cross-cutting relations between terrain elements as ribbed moraine, drumlins and megaflutings and older sediments/landforms from previous ice flow phases. This is critically important to mineral exploration projects where; much prior work has simply assumed that underlying sediments (and any mineralized 'float' present in the sediment) records the same phase (and direction) of ice flow as expressed by surface landforms. Detailed examination of these older deposits is now required, together with re-evaluation of their glaciological setting for new second-generation mineral exploration initiatives. In a glaciodynamic perspective such antecedent sediment bodies acted as a 'soft bed' and greatly reduced overall bed roughness at the ice-bed interface; they were also a source for producing till.

In conclusion, the GDdatabase being developed by Geological Survey of Finland represents a highly cost effective methodology not only for understanding the glacial history and dynamics of the Finnish sector of the last FIS, but also for rapidly conveying critical applied information with respect to glacial landscapes, topography and sediments. This knowledge is needed for a variety of projects involving geo-engineering, urban planning, water resource protection and management, together with mineral exploration projects and prospecting for aggregate supplies.

Acknowledgements

Supplementary data

Electronic Appendices A–E for this article are available via Bulletin of the Geological Society of Finland web page.

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