The glacial geomorphology of Kola Peninsula and adjacent areas in the Murmansk Region, Russia.

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Abstract: A map of the glacial geomorphology of Kola Peninsula and adjacent areas in the Murmansk region, northwestern Russia, is presented. The primary data source for identification and classification of landforms has been Landsat 7 Enhanced Thematic Mapper Plus (ETM+) satellite images, and aerial photograph interpretation and field work in selected areas. The map, at the scale 1:900,000, consists of over 20,000 landforms pertaining to the Quaternary glacial activity, considerably improving existing knowledge of this area. The landform types that have been mapped are glacial lineations, ribbed moraine, end moraines, end moraine complexes, hummocky moraine, eskers, glaciofluvial accumulations, lateral meltwater channels, large meltwater channels, very large meltwater channels, and relict shorelines. The distribution of landforms shows large variations. The central part of the peninsula lacks signs of glacial activity, apart from abundant lateral meltwater channels. In the rest of the area glacial lineations (drumlins, flutes, crag-and-tails) are the dominant landform type. The largest glacial landform system in the area is an ice marginal system running parallel to the southern and eastern coast of Kola Peninsula. This ice marginal system, the Keiva moraine complex, has in part been overrun and drumlinised by ice flow from the southwest. This indicates that this ice marginal belt was deposited before the last major ice expansion. The map presented will be used as the main source of data for a new reconstruction of glacial events in the eastern part of the Fennoscandian ice sheet area.

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1. Introduction

The Kola Peninsula region, NW Russia, is of particular interest because its' position lies between three dynamically different ice masses; the Fennoscandian Ice Sheet in the west, with White Sea ice lobes from the south, and the Barents Sea Ice Sheet in the north. Reconstruction of ice cover in the area is of particular interest because it is close to the maximum eastward extent of the Fennoscandian Ice Sheet and the White Sea likely acted as a major conduit for the export of ice (probably by ice streaming) from Fennoscandia (Boulton et al., 2001). Hence, ice centred on the Kola Peninsula may have played an important role in nourishing the Barents Sea Ice Sheet and later in influencing Arctic Ocean circulation during deglaciation. The glacial history of the region, however, remains elusive, which is the motivation for our mapping. Debate currently exists as to whether the Kola Peninsula was glaciated by eastwards-flowing Fennoscandian ice or whether an independent ice cap existed. Three models of ice cover and the pattern of deglaciation have been proposed: marginal retreat inwards from the coast, towards the central part of the peninsula (Hättestrand et al., in press); or deglaciation of the higher central part whilst ice lobes still occupied depressions and straits surrounding the peninsula (Yevzerov, 2001); or the existence of a dynamically independent ice cap, the Ponoy Ice Cap, centred on eastern Kola Peninsula in late-glacial time (Ekman et al., 1991), possibly in combination with ice lobes in the White Sea basin. These discrepancies result largely from an incomplete coverage of detailed geomorphological maps over the area.

The area has attracted interest from Quaternary geologists and geomorphologists for over 100 years and the mapping of glacial landforms started with Ramsey's (1898) exploration of western Kola Peninsula. During the 20th century, and especially in the 1960's, various mapping projects and general reconstructions of the glaciation history were conducted (e.g., Lavrova, 1960; Apukhtin et al., 1967). However, it was not until 1993 that the first comprehensive map of the Quaternary geology of the area was published (Niemelä et al., 1993), with the part covering Murmansk Region on that map largely based on existing unpublished data from Vladimir Yevzerov (unpublished manuscript maps) at the Kola Science Centre. The Niemelä et al. (1993) map, published jointly by Russian and Finnish authorities, primarily contains information on sediment type. The geomorphological data it contains is limited to end moraines, hummocky moraine, interlobate complexes and drumlins. Data on, for example, ribbed moraine and meltwater channels has hitherto been lacking.

In this map, we present geomorphological data pertaining to glacial activity, as mapped during 2000-2005, from satellite images, aerial photographs, and field work.

2. Methods

The glacial geomorphology was mapped using various data sources. For the whole area satellite images were scrutinised and landforms mapped by digitising directly into a GIS. In total, 16 Landsat 7 ETM+ images (Table 1) were used in various false colour composites of bands 2, 3, 4, 5 (with 30 m ground resolution), and the panchromatic band 8 (15 m ground resolution). In a few key areas panchromatic aerial photographs at the scale 1:40,000 were interpreted (Figure 1), using a Zeiss Jena Interpretoscope with 2-16 x magnification. Additional observations and field-checking of our image interpretations were conducted during field work in 2001, 2002, and 2004 (Figure 1). The elevation data, used as the background in the map, was extracted from the GTOPO30 database (http://edcdaac.usgs.gov/gtopo30/gtopo30.asp) and has an approximate spatial resolution of 1 km. Other background data (i.e. lakes, rivers and coastlines) were mapped from the satellite images.

2.1 Definitions and description of landforms on the map

Morainic landforms

Glacial lineations are glacially streamlined landforms, primarily made up of sediments (e.g., till, sorted sediments, regolith) (Figure 2a/b). Such landforms include, for example, drumlins, flutes, crag-and-tails and mega-scale glacial lineations (Clark, 1993). Regular symmetrical drumlins are the most common glacial lineation type in the mapped area. Lineations vary in size between 300-10,000 m in length, and 100-1000 m in width, and have elongation ratios between 3 and 10. The lineations in the south are generally more flute-like, with elongation ratios up to 20. Streamlined bedrock ridges are not included in the mapping. This is because the orientation of linear bedrock features is mostly related to the structural

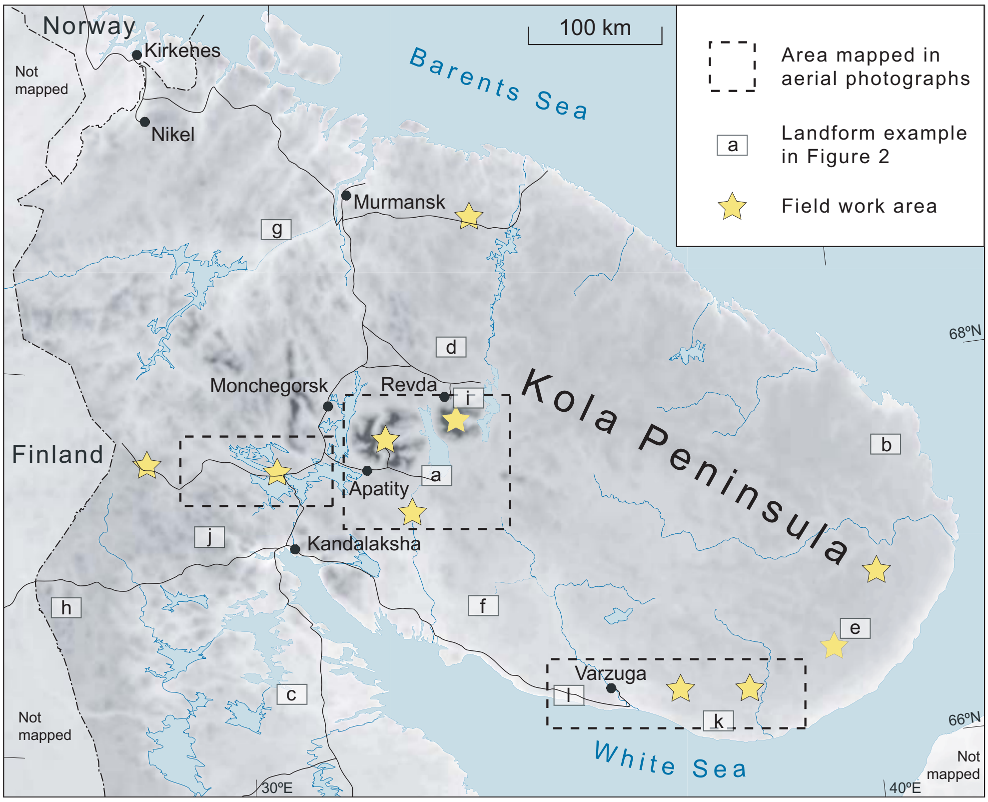

Figure 1. Location map, including areas that were mapped using aerial photographs (scale 1:40,000), areas visited during field work, and the locations of satellite image examples in Figure 2 (boxes a-l).

Path	**Row**	**Date of acquisition (y-m-d)**
182	013	2002-07-06
182	014	2000-06-30
183	013	2001-06-08
183	013	2002-06-11
184	012	2000-09-16
185	013	2001-06-22
186	012	2000-07-28
186	014	2000-07-28
187	011	2001-06-20
187	012	1999-07-17
187	013	1999-07-17
188	014	2000-07-26
189	012	2001-08-21
189	013	2001-08-21
190	011	1999-09-08
190	012	2002-05-27

Table 1. List of all Landsat ETM+ images used in the mapping.

geology rather than to ice flow directions.

Ribbed moraine is defined here as an area with large, regularly and closely spaced, moraine ridges consisting of glacial drift, usually till (Figure 2c). The ridges are mostly curved or anastomosing (with spurs pointing down-ice), but their general orientation is transverse to the ice flow that formed them (Hättestrand et al., 1999). Typical size values are: length - 300-1200 m; width - 150-300 m; and height - 10-30 m.

End moraines (distinct ridge) are individual moraine ridges with a defined crest (Figure 2d). Typically these end moraine ridges are less than 20 m high.

End moraine complexes are large ice marginal deposits, commonly including both till and glaciofluvial material (Figure 2e). These complexes often display a steep ice contact slope along one side, and can be flat, hummocky, or multi-crested on the top surface. Some of these moraine complexes are very large, particularly the Keiva moraine complex on southeastern Kola Peninsula, where continuous single end moraine segments can be up to 100 km long, 3 km wide, and 60 m high.

Hummocky moraine is here defined as irregular morainic topography, with numerous small lake depressions and hills (Figure 2f). Sometimes the depressions may be larger, giving the moraine an impression of a moraine ridge network, but in contrast to other moraine areas, such as ribbed moraines, the ridges have no preferred orientation. These moraine can cover large areas, up to 700 km^2, particularly in a zone across the central part of the peninsula and along the northern White Sea coast.

Glaciofluvial landforms

Eskers are single ridges composed of glaciofluvial material, running continuously over several kilometres (Figure 2g). Chains of esker segments can form long esker systems up to 200 km in length. They often display a winding anastomosing course and commonly have feeding eskers joining the main ridge at low angles.

Glaciofluvial accumulations include discrete and large accumulations of glaciofluvial material with a distinct outline, contrasting with surrounding terrain (Figure 2h). Most of these accumulations have planar surfaces, and include deltas, sandurs, and outwash plains. In a few cases, they display more irregular glaciofluvial accumulations, such as kame terrain. Because of the mapping technique used only large glaciofluvial accumulations, over a few square kilometres, have been mapped (see §2.2).

Lateral meltwater channels are dry channels running on slopes at an oblique angle to contours (Figure 2i). The direction of the channels follows the lateral margin of the former glacier or ice sheet that guided the water course along the slope. They almost invariably occur in series, with 2-50 parallel channels on a slope. The dimensions of these channels are usually up to one kilometre in length, <30 m in width and, <5 m in depth. Because meltwater channels are small features that often occur close to each other, some generalisation has been made in order to avoid cluttering on the map. We estimate that on average, 20% of the mapped channels have been deleted from the final map for cartographic reasons.

Large meltwater channels are dry channels that normally run perpendicular to contours on slopes or across cols (Figure 2j). Only those that are interpreted to be directly related to the meltwater drainage during deglaciation of glaciers and ice sheets have been mapped. Therefore, only large (>30 m wide/5 m deep) dry channels have been included.

Very large meltwater channels are similar to the previous class but have dimensions an order of magnitude larger, indicating discharge of large volumes of meltwater, such as during drainage of glacial lakes (Figure 2k). They are very large, often >500 m wide, >20 m deep, and >50 km long, and have distinct channel walls.

Shorelines

Relict shorelines are erosional or depositional benches running along contours (Figure 2l). The shorelines can be *marine*, which is likely in areas where they occur close to the present day marine shore (such as along the southern coast of the peninsula), or *glaciolacustrine*, particularly in higher areas where postglacial marine incursion is implausible. The *glaciolacustrine* shorelines indicate the presence of glacial lakes.

2.2 Accuracy and comprehensiveness

We regard the differences in landform distribution to reflect the true distribution pattern, rather than being related to variable source materials or land surface masking due to human activity. A single type of satellite image was used, and the mapping was performed using the same on-screen scale (1:50,000) throughout the area (although other mapping scales were

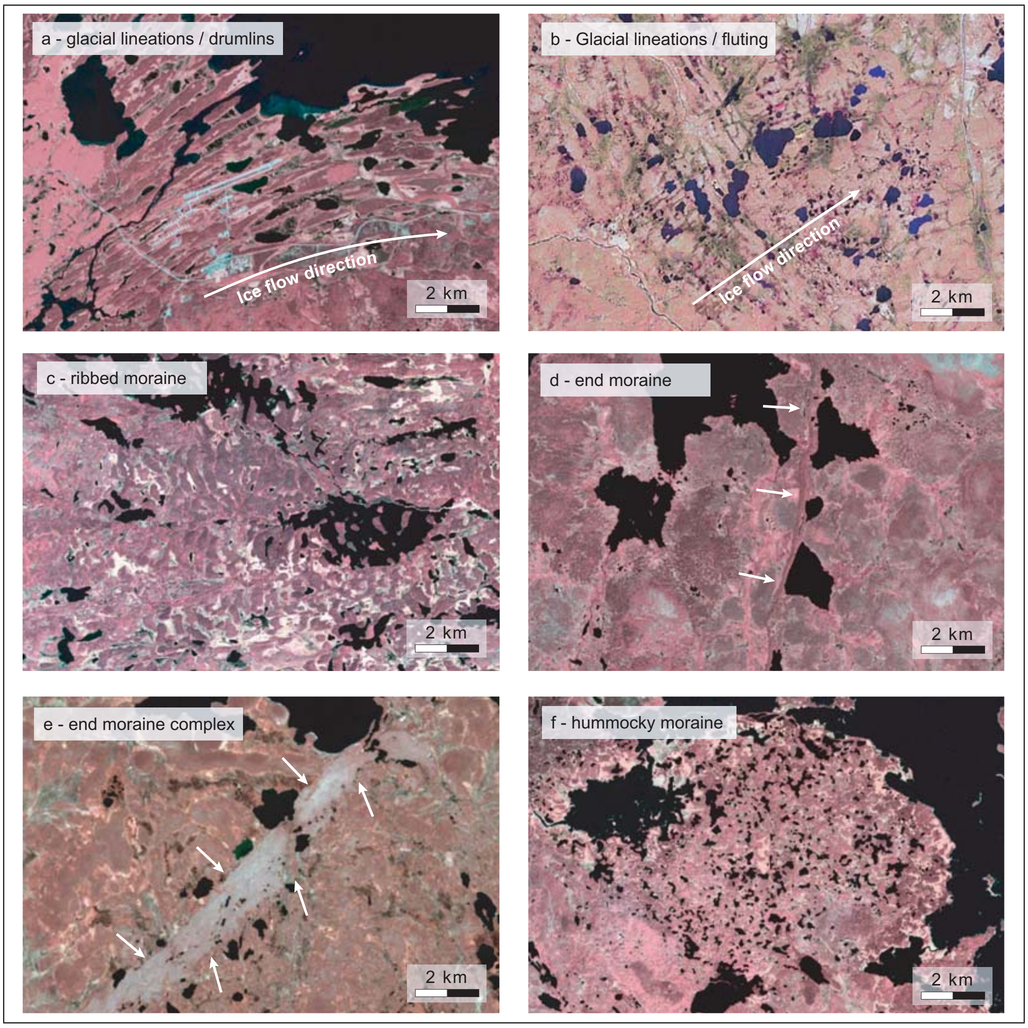

Figure 2. Examples of landforms as expressed on Landsat 7 ETM+ satellite images. The images are constructed by merging false colour composites of 30 m-resolution bands 4, 3, 2 (RGB) with the panchromatic band 8 (15 m resolution). For location of images, see Figure 1. North is at the top in all images. a) Glacial lineations (drumlins) south of the lake Umbozero. These lineations are of the regular symmetrical type. b) Glacial lineations (flutings) on northeastern Kola Peninsula. Here, the northern part of the Keiva moraine (parallel NW-SE oriented ridges) is drumlinised by ice flow from the southwest. c) Ribbed moraine south of Kovdozero. Ice flow was towards the west (right). There are also abundant glacial lineations and an esker (on the northern shore of the central lake) in this image. d) End moraine north of Lovozero Mountains. Arrows point towards the moraine ridge in the direction of inferred ice flow direction. e) End moraine complex within the Keiva moraine complex on eastern Kola Peninsula. Arrows point towards the moraine ridge in the direction of inferred flow direction of ice, which was probably on both sides of the moraine during formation. f) Hummocky moraine west of Varzuga River. An esker is running along the northern edge of the hummocky moraine area.

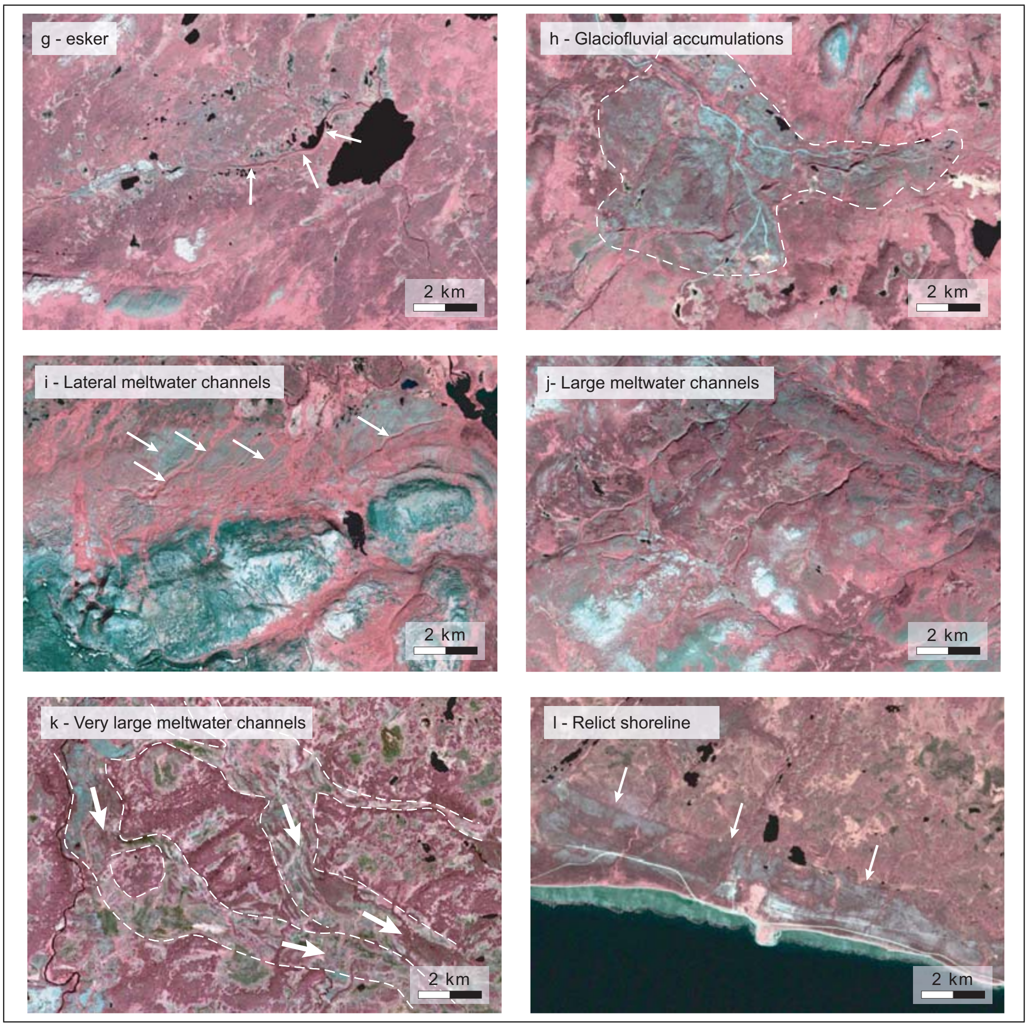

Figure 2 cont. g) Esker (marked by arrows) north of Tuloma River. h) Glaciofluvial accumulation (encircled by white dashed line) close to the Finnish border in the southwestern part of the map area. An esker is running east-west in the right part of the accumulation. i) Lateral meltwater channels (the major ones marked by arrows) formed during meltwater drainage towards east-northeast on the northern flank of Lovozero mountain. These channels indicate an ice sheet slope, and hence, ice flow direction, towards the east during deglaciation. j) Large meltwater channels formed during meltwater drainage towards east-northeast west of Kandalakša. The channels are cut partly in drift and partly as canyons in bedrock. k) Very large meltwater channels west of Strelna River. Dashed lines show channel walls and arrows mark palaeo-flow direction. The section shown on the image is just a part of a large system of these channels indicating massive discharge of meltwater towards the east-southeast on the southeastern Kola Peninsula. The channels have cut southwest-northeast oriented flutings preserved on the areas between the channels. l) Relict shoreline (marine) on the northern White Sea shore east of Varzuga River.

used additionally, where appropriate). Generally, there is very little large-scale, ground-covering, human activity (forestry, farming, urbanisation) in the area, which could potentially obscure the glacial geomorphological record. Farming is virtually non-existent, and urban land use (here as settlements and mining activity) is restricted to the major towns. In the southern part of the map area, forestry with clear cuts presents some complexity to the imagery, but not to the extent that mapping is precluded.

Glacial lineations, ribbed moraine, end moraine complexes, hummocky moraine, large meltwater channels, and very large meltwater channels, are all distinct landforms, that are much larger than the resolution limit of the imagery (15 m), and therefore present no size constraint to their mapping. They are easily recognised in the satellite images, and the distribution of these landforms on the map is therefore regarded as close to complete as shown.

Eskers and end moraines are often small to medium sized features that can be near the image resolution limit in relation to their width. However, they are linear features that are mostly continuous over several kilometres, which make them well-marked elements in the imagery. Secondary "control mapping" from aerial photographs (where eskers and end moraines can be mapped in detail) over selected areas added little to the mapping from the satellite images. We therefore believe that most eskers and end moraine ridges in the area are included in the map, but some smaller features may have been missed. There is also a slight chance of misinterpretation between these landforms, because they are both of similar dimensions and morphology. However, eskers commonly branch in a dendritic pattern, as a result of the subglacial drainage pattern, while end moraines usually form coherent single ridges. In addition, the glacial geomorphological context usually gives information on whether a particular ridge was formed parallel or transverse to ice flow. Nevertheless, isolated single unbranching segments can sometimes be difficult to classify, particularly where other ice flow directional information is complex or lacking altogether. For example, the ridges in the large areas of hummocky moraine west of Varzuga River have presented some problems.

Larger areas of glaciofluvial accumulations are straight forward to identify in the satellite imagery, forming large uniformly coloured areas with dry vegetation types contrasting to surrounding (usually till) terrain (Figure 2h). However, smaller areas with glaciofluvial material are much more difficult to identify because a patchy variability in vegetation type is always present in natural boreal ecosystems lacking (more or less) impact by human activity. Because of this, only large glaciofluvial accumulations more than a few kilometres across have been mapped.

Lateral meltwater channels and shorelines can often be smaller in width than the resolution limit of the imagery. It is therefore likely that the true number of these features is larger than shown on the map. Control mapping in aerial photographs added more channels, but because lateral meltwater channels are such a common landform, the major directions of meltwater drainage can be adequately reconstructed from channel systems mapped in the satellite images. Furthermore, because meltwater channels are generalised on the map, additional channels would not have been included on the map for cartographic reasons. Shorelines are likely to be greatly underestimated in our mapping. This is unfortunate because they are useful features for reconstruction of ice dammed lakes, and therefore deglaciation direction and pattern, and even small single shorelines can be important pieces of evidence when tracing the ice marginal retreat (Jansson, 2003). We have chosen to present those ice dammed lake shorelines that have been mapped, albeit incomplete, because such data is hitherto lacking for the area in question, and it can act as a base for future amendments to the distribution of these features.

3. Conclusions

The distribution of landforms shows large variations, indicating different glacial regimes in different areas. For example, the central part of the peninsula lacks signs of subglacial activity, and only exhibits lateral meltwater channels, which occur in great numbers. This indicates cold-based conditions of the ice sheet throughout the last glaciation(s), and deglaciation through ice surface melting and runoff alone (Dyke, 1993). In the western part of the area glacial lineations are the dominant landform type, and they indicate the presence of areas with fast, warm-based ice flow. For example, in the area south of Khibiny Mountains and in the southernmost part of the map area, densely spaced drumlins with high elongation ratios possibly indicate the presence of a palaeo-ice stream (Stokes et al., 2001). The largest coherent glacial landform system in the area is an ice marginal system running parallel to the southern and eastern coast of Kola Peninsula. This ice marginal system, the Keiva moraine complex, consists of end moraines, end moraine complexes, hummocky moraines, meltwater channels and outwash sediments. This moraine system has been known for over a hundred years, but no conclusive formation theory has been accepted (e.g., Ekman et al., 1991). In this map, we show that parts of the moraine system have been overrun and drumlinised by ice flow from the southwest, particularly in its western and northeastern parts. This relative age relationship indicates that the moraine complex was formed before the ice sheet reached the thickness and extent that it could overrun the whole Kola Peninsula, which probably was during a time near the Last Glacial Maximum (LGM). Hence, it appears that the Keiva moraine is a pre-LGM feature.

The map presented will be used in further studies as the main source of data for a new reconstruction of glacial events. We aim to reconstruct the ice retreat pattern, assess evidence for ice streaming, resolve the formation processes and context of the Keiva moraine complex and by using cosmogenic dating, provide some important constraints on the timing of ice sheet activity.

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Software

The satellite imagery was processed in ENVI 3.4, where false colour composites were made. These were then imported into ArcGIS 9.0 and used as background data during on-screen mapping of landforms. The GTOPO 30 data was processed in GMT and Adobe Photoshop CS, to form the background to the map. Coastal and lake contours were automatically digitised from the satellite imagery in Photoshop and Adobe Streamline 4.0, followed by manual corrections in Adobe Illustrator 10. Rivers were manually drawn from the satellite images in Illustrator. All data were imported into Illustrator, where final layout work was done.

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