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Ice-marginal ridge relief complex in northern Kola Peninsula (NW Russia): morphology, structure, and genetic interpretation

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Abstract

A widely spread ridge relief complex was formed by the last ice cover in the north-eastern part of the Kola Peninsula. The complex belongs to the ice-marginal formations of the ice streams of the north-eastern Fennoscandian Ice Sheet. The applied morphometric research technique (including the analysis of the digital elevation model) has allowed identifying the ridge relief complex to make a sub-longitudinal belt. The belt comprises frontal and radial ridges, ridges and hills of the distal part of the belt, and complex-shaped ridges. These landforms were studied in eight outcrops and trenches. The frontal and some complex-shaped ridges consist of basal and ablation tills and glaciofluvial deposits deformed by the east- and north-eastward advancing glacier. The radial ridges composed of glaciofluvial sediments are the eskers. Glaciofluvial deposits with a thin cover of ablation and flow tills form the ridges on the distal part of the belt. They mark the limits of glacier expansion at an individual glacial stage. Some complex-shaped ridges are composed only of the ablation melt-out till and formed in crevasses of dead ice massifs. The ridge relief complex shows morphological similarities with the Veiki moraine in North Sweden, Pulju moraine in Finland, and ridges of the "ice-walled-lake plains" in North America.

The location of the moraine ridge landforms is controlled by the topography of crystalline bedrock. During the last glaciation, the glacier retreated in several stages marked by belts of the ridge landforms. Each stage was followed by a series of oscillations corresponding to chains of frontal moraine ridges. The correlation of the ice-marginal forms in other parts of the Kola and Karelia regions allows the authors to refer them to the Neva Stage (other names are Keiva I, Syamozero), which took place in the Older Dryas Stadial.

Keywords: Fennoscandian Ice Sheet, deglaciation moraine, ridge relief complex, glaciotectonic deformations, till, glaciofluvial deposits, Kola Peninsula, Russia

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1. Introduction

Specific glacial ridge relief complex of the Kola Peninsula is represented by sinuous, S-shaped, U-shaped, or ring ridges with inter-ridge hollows occupied by lakes or peatlands (Armand 1964; Dedkov et al. 1989; Kolka 1998; Semenova 2004; Boyes et al. 2021b). These glacial landscapes occupy different-shaped areas (up to 250 km^2) or form belts (up to 70 × 10 km) (Figs. 1 and 2). Extensive areas of the ridge relief complex are situated on plateaux and slopes of uplands at elevations of approximately 180–320 m above sea level (a.s.l.). Moreover, the belts of the ridge landforms are traced on plains with a thin cover of the Quaternary sediments (up to 5–10 m thick) at elevations ranging from 80–100 to 260 m a.s.l. (Petrov & Lopatin 2000a, b; Semenova 2004).

The internal structure and origin of the ridge landscapes present a controversial issue. Previously, the genesis of these landforms was explained by the deposition of ablation melt-out till from melting dead ice blocks during the deglaciation in the Late Pleistocene (Armand 1964; Strelkov et al. 1976, Kolka 1998). Later, thrust glaciotectonic deformations were found in some ridges (Yevzerov & Koshechkin 1980; Yevzerov et al. 1993), and their formation was associated with a contact of the active ice margin and dead ice massifs during a short-term re-advance in the Older Dryas Stadial (Yevzerov 2015). A number of reviews concerning the deglaciation of north-eastern Fennoscandia correlate the ridge landforms of the Kola Region with the boundaries of degradation stages of the last ice sheet (Ekman & Iljin 1991; Petrov & Lopatin 2000a; Svendsen et al. 2004; Demidov et al. 2006; Bogdanov 2012a; Stroeven et al. 2016; Astakhov et al. 2016). Geological and geomorphological maps of the Kola Region mostly refer to these landforms as hummocky moraine (Niemelä et al. 1993; Hättestrand & Clark 2006b; Boyes et al. 2021b).

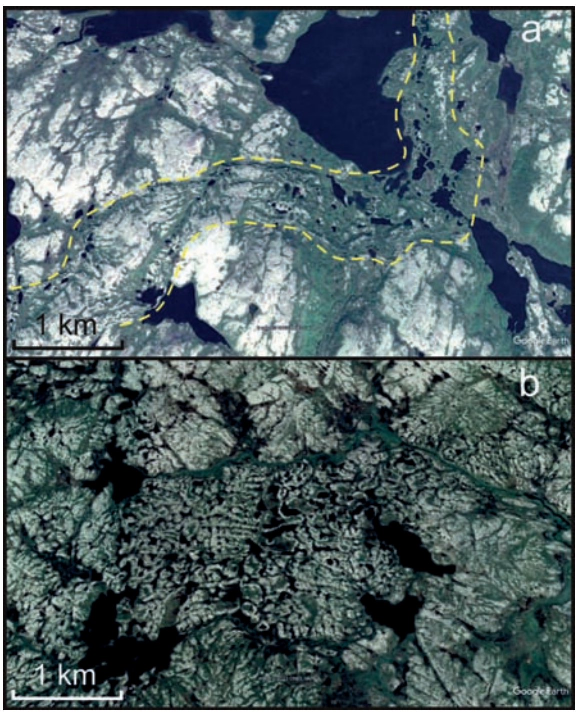

Figure 1. Satellite images of the ridge relief complex in form of a belt (a) and an area (b) (images are taken from Google Earth). Locations of the images are shown in Fig. 2.

Morphologically similar glacial landscapes represented by sinuous and ring ridges are known in north-western Finland as the Pulju moraine (Kujansuu 1967; Johansson & Nenonen 1991) and in northern Sweden as the Veiki moraine (Lagerbäck 1988; Lagerbäck & Robertsson, 1988; Hättestrand 1997). Analogous forms called ice-walled-lake plains are also found in North America (Boone & Eyles 2001; Johnson & Clayton 2003; Clayton et al. 2008). Their genesis has been associated to supraglacial lakes with ice shorelines and the subsequent accumulation of ablation till on the walls of these depressions. A complex of ring ridges and dividing depressions ultimately formed due to the melting of dead ice (Lagerbäck 1988; Clayton et al. 2008). Some studies also note that the core of the ridges may contain basal melt-out till formed due to squeezing of water-saturated till into crevasses in dead ice blocks during the deglaciation stage (Johansson & Nenonen 1991).

Glacial landscape of the study area differs from the above mentioned settings. The complex-shaped ridges here are accompanied by regularly

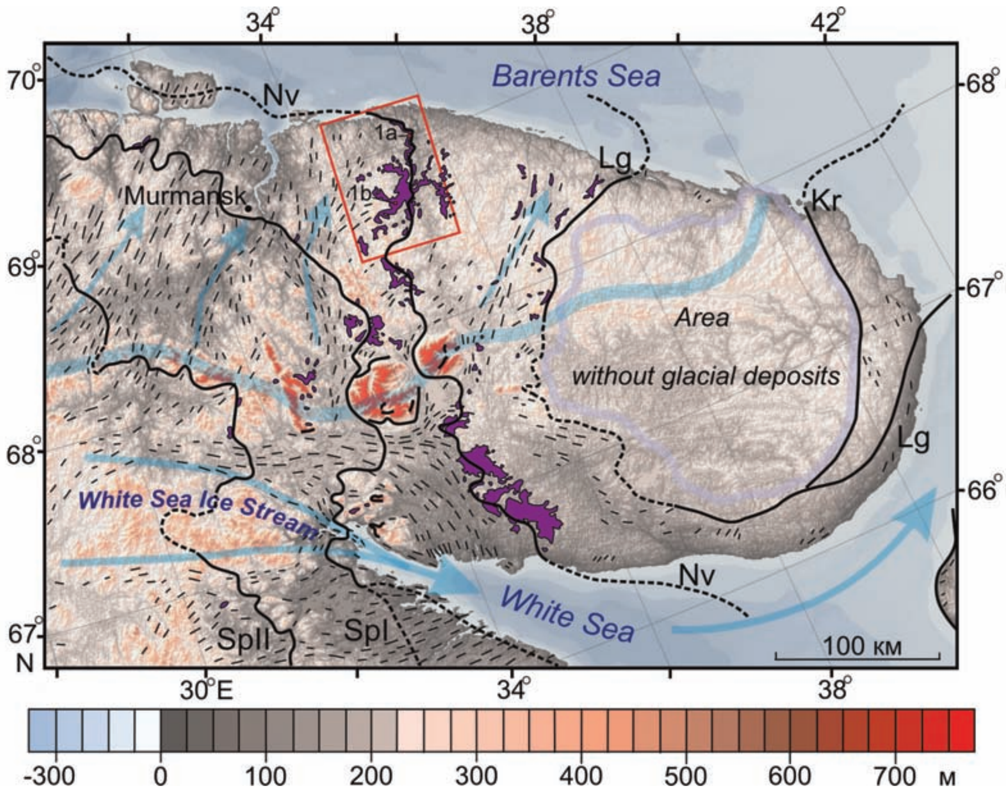

Figure 2. Distribution of the ridge relief complex in the Kola Region and location of the study area. The black lines show the boundaries of the last ice sheet during the stages: Kr – Krestsy, Lg – Luga (Keiva I, Karelia), Nv – Neva (Keiva II, Syamozero), SpI, SpII – Salpausselkä I and II, compiled using (Astakhov et al. 2016; Korsakova et al. 2023a, c); dotted lines – proposed boundaries. Transparent blue line – the north margin of the White Sea Ice Stream of the Fennoscandian Ice Sheet; transparent blue arrows – flow directions of the Fennoscandian Ice Sheet (by Yevzerov 2015; Boyes et al. 2023 a, b); black short lines – subglacial lineations (by Petrov & Lopatin 2000a; Boyes et al. 2021b), transparent violet outline – the area without glacial deposits in the central part of the Kola Peninsula (by Niemelä et al. 1993; Bogdanov 2012a, b); violet areas – ridge relief complex (hummocks Type 2a and 3 according to Boyes et al. 2021b).1a, 1b – locations of the satellite images from Fig. 1.

situated frontal, radial, and distal slope ridges located in accordance with the ice-marginal zone configuration. It should be noted that the Veiki moraine in northern Sweden is associated with terminal moraines (similar to the frontal ridges mentioned in this article) too, indicating the margins of the pre-Late Weichselian glaciation (Hättestrand 2007).

The age of the Veiki moraine in northern Sweden was initially related to MIS 5a–d (Lagerbäck 1988). Later, it was interpreted as a possible local glaciation during MIS 3 (Hättestrand 2007; Lindqvist 2020). The age of the ice-walled-lake plains in North America was determined to be MIS 2 (Boone & Eyles 2001; Johnson & Clayton 2003; Clayton et al. 2008).

The objectives of this study are (1) to describe geomorphological and geological features of complicated ridge landforms in the northern part of the Kola Region, and (2) to discuss their depositional settings and origin.

2. Study area

The ridge landforms were studied at key sites near the Martimyavr and Perkhyavr lakes (Voronya River basin) and Tumanny Settlement (Figs. 2

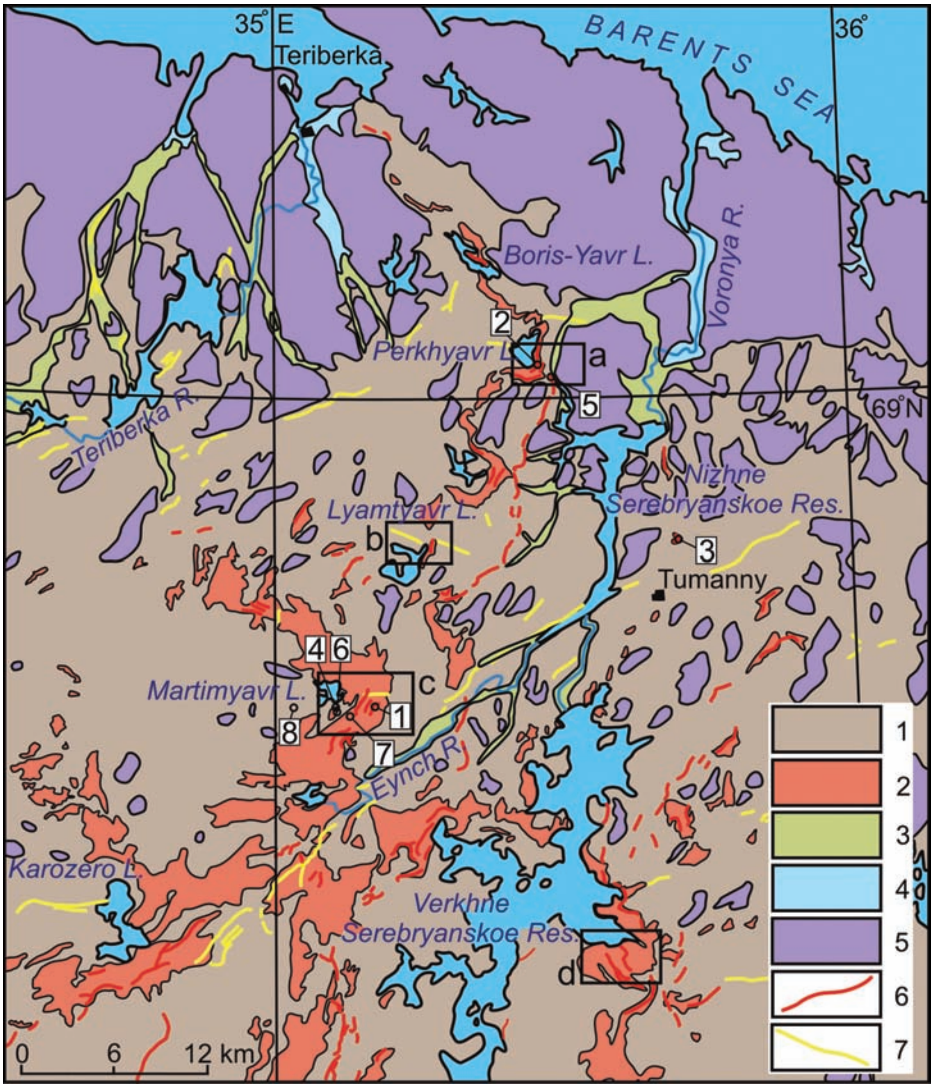

Figure 3. Morphological scheme of the study area (using Dedkov et al. 1989; Niemelä et al. 1993; Yevzerov et al. 1993; Petrov & Lopatin 2000a; Boyes et al. 2021b). 1 – areas covered by basal till; 2 – areas of the ridge relief complex; 3 – glaciofluvial deposits; 4 – marine deposits; 5 – bedrock outcrops; 6 – large moraine ridges; 7 – eskers. Numbers 1–8 indicate the outcrops considered in the article. Letters a – d indicate the areas shown in Fig. 4.

and 3). The study area is located within a dissected plateau-like plain with predominating altitudes of 100–260 m a.s.l. Some large hills of crystalline basement reach elevations of up to 375 m a.s.l. The bedrock is mostly composed of granitoids of the Murmansk Domain and exposes over large areas (Petrov & Lopatin 2000a, b). In the study area, narrow (up to 1–5 km) and deep (up to 50–150 m) depressions occupied by lake basins and river valleys are widespread. They are usually elongated and controlled by disjunctive dislocations of the bedrock (Strelkov et al. 1976; Petrov & Lopatin 2000a).

The bedrock is overlain by the Quaternary marine, glacial, glaciofluvial, and alluvial sediments up to 80 m thick (in large depressions with river valleys) (Petrov & Lopatin 2000a, b). On the plateau-like surface of the plain, the average thickness of the Quaternary sediments is

0.5–5.0 m. The basal and ablation tills, glaciofluvial and glaciolacustrine sediments are frequently overlain by peatland and lacustrine deposits (Yevzerov et al. 1993; Semenova 2004; Petrov & Lopatin 2000a). Within the areas with ridge landforms, the thickness of the Quaternary sediments increases to 5.0–25.0 m due to the greater thickness of tills and glaciofluvial deposits.

Near Lake Martimyavr and Tumanny Settlement, the ridge relief complex is situated at an elevation of 150–240 m a.s.l., while near Lake Perkhyavr and Teriberka Settlement its altitude descends to 60–110 m a.s.l.

3. Methods

Geological features of glacial and glaciofluvial landforms were studied in open pits, trenches, and at the natural ridge slopes. Grain-size analysis was conducted during the fieldwork by means of a set of standard sieves with a mesh diameter of 1–10 mm. The colour of the deposits was determined using the Munsell Soil Color Charts. The fabric of glacial sediments and direction of glacier pressure were studied by means of the mass measurements of dip azimuth and dip angle of planar (foliation and lamination surfaces) and linear (long axes of pebbles and boulders) elements (Aboltinš 1989; Benn 2013). There were 25 to 100 measurements in a layer. In the sections of deformed deposits the planar and linear elements were measured in several parts. When an individual glacial form was observed in the section over an area of ≥2 m^2, the measurements were executed evenly along the whole excavated area at 2–5 points. If an outcropped fragment of a glacial structure had an area of <2 m^2, the measurements were performed at one point. The obtained data were processed using the OpenStereo 0.1.2 software, and the structural diagrams were plotted on the lower hemisphere of the Schmidt equal area net.

The most useful data for reconstruction of the direction of glacier pressure were received from measurements of dip azimuth and dip angle of foliation and lamination surfaces. They show one peak opposite to glacier flow direction (on the lower hemisphere) on the diagrams (Aboltinš 1989; Komarovsky 2008). The data obtained from measurements of dip azimuth and dip angle of long axes of pebbles and boulders are usually scattered and therefore inappropriate. The data can be used only if there are one or two distinct peaks on the diagrams, provided that there are more than 50 measurements. An additional peak of orientation of long axis of clasts may appear on the diagrams due to compression of the material during the formation of individual ridges. The peak appearance is caused by the turn of elongated clasts according to the compression surface of debris-rich ice. In the absence of data on foliation orientation, the additional measurements of dip azimuth and angles of individual lenses and interlayers in till were made to distinguish the main direction of glacier pressure and compression surface of the material; the ridge orientation and morphology were also taken into account.

The fieldwork included determination of length, height, slope gradient, orientation, width of the apex part, and crests of the ridges in the ridge relief complex. The observed landforms were compared with their images in the ArcticDEM digital elevation model (Porter et al. 2018). The method allowed visual identification and classification of the ridge relief complex on the key site and whole study area. Also, based on ArcticDEM, subglacial bedforms (lineations and streamlined bedrock), eskers and glaciofluvial deposits outside the ridge relief complex were visually identified (using the method of Boyes et al. 2021b). The results of the DEM interpretation were verified using the available geological information (Dedkov et al. 1989; Niemelä et al. 1993; Yevzerov et al. 1993; Petrov & Lopatin 2000a) and our own geological observations. A morphological scheme of the study area was constructed in the result of compilation of morphometric data and geological information (Fig. 3).

Composition of boulder fraction (>100 mm size) was determined at an area of 5 × 5 m on the surface of the ridge crest. The boulders were visually divided into rock groups, from which the most representative samples were chosen to prepare thin sections. Pebbles (10–100 mm size) and coarse gravels (5–10 mm size) were sieved from samples of the diamictons and further studied using a stereoscopic (binocular) microscope. The identified rock groups were compared with the bedrock of the study area and the whole Kola Peninsula in order to determine the sources of clastic material.

4. Results and interpretation

4.1 Glacial landscapes

In the northern part of the study area, near Teriberka Settlement and Lake Perkhyavr, glacial landscapes form a sinuous band with a width of 0.4–0.7 km and a length of over 40 km (Figs. 1a and 4a). This band has a lobate form. The ridge relief band shifts to the east and northeast in depressions of the pre-Quaternary surface. Here, glacial landscape is usually associated with either a single large lake basin or with a number of small ones. In contrast to this, the ridge relief band located within bedrock heights shifts to the west, with ridges reproducing the morphology of the upland slope.

To the southwest, near Lake Lyamtyavr, the band consists of several subparallel fragments (Fig. 4b). It becomes wider (up to 2–4 km) near Lake Martimyavr due to adjoining of isometric areas of the ridge relief complex (Fig. 4c). In the north-eastern part of the Verkhne-Serebryanskoe Reservoir, the band changes direction to sublatitudinal and has a width of up to 3 km (Figs. 3 and 4d). Three subparallel arcs of the ridge relief complex can be traced in the southern part of the study area (Fig. 3).

In some cases, the frontal ridges occur singly or form small areas with complex-shaped ridges. In the study area, such ridges were found north of Tumanny Settlement (Fig. 5c).

As noted above, the cover of the Kola Region Quaternary deposits is relatively thin. The bedrock exposes in many places, forming a rather complex relief. Therefore, a visual interpretation of digital elevation model data, satellite images, or topographic maps needs to be verified by means of morphometric analysis of determined landforms and by studying of their geological structure.

The morphometric analysis was applied to separate glacial accumulative forms from the topography of the bedrock surface. The forms differ in major morphometric indicators, especially in number of peaks per 1 km^2 and slope gradient-to-height ratio (Table 1). Large ledges of the pre-Quaternary surface distinctly differ from glacial relief in length (over 300 m) and height of slopes (up to 50 m), minimum number of individual peaks (up to 2 units per 1 km^2), and minimum slope gradient-to-height ratio (up to 0.15). Also, the morphometric analysis made it possible to divide the glacial landforms into the following groups: frontal and radial ridges, ridges and hills of the distal part of the belt, and complex-shaped ridges.

The *frontal ridges*, which are sinuous and crescent-shaped or straightened, form chains. One chain may include 2–7 ridges and more. The ridge chains are parallel and spaced at a distance of 0.25–0.8 km (Figs. 4a–d and 5a). They stretch according to the orientation of the band which they belong to. For example, there are at least six parallel chains of frontal ridges near Lake Martimyavr; three chains are situated near Lake Perkhyavr; and only one chain lies near Tumanny Settlement. Frontal ridges have narrow (2–8 m) crests and asymmetric slopes with a distinct edge and inner margin. The western slopes are straight or concave with a gradient of 14–28°. The eastern slopes have a gradient of 20–32°. The slopes of the highest ridges are stepped and have a gradient of up to 35–38°.

The *radial ridges* are predominantly perpendicular to the extension both of the frontal ridges and ridges of the distal part of the belt. The most expressed and extensive radial ridges tend to the lake depressions or are associated with river valleys (Figs. 4a–d). They may compose complexes of three to six straightened, slightly sinuous ridges with a total length of over 3 km. Such complexes are usually

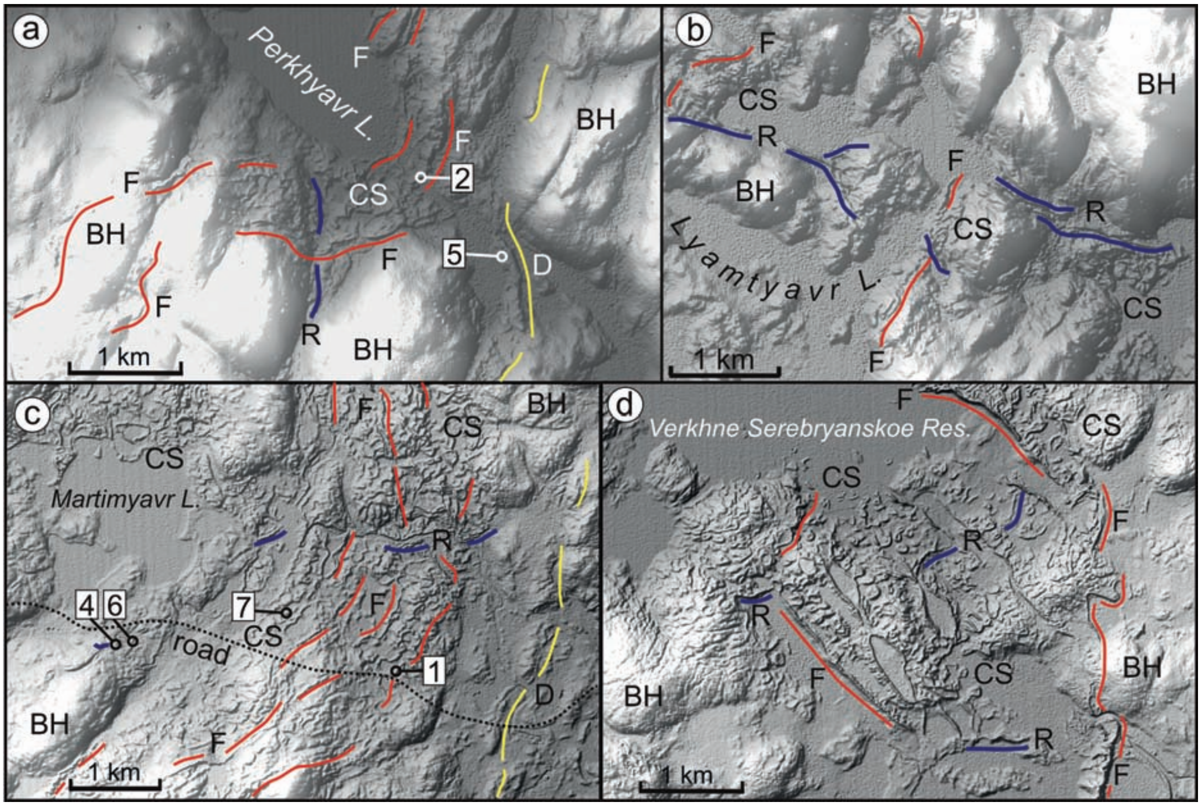

Figure 4. The most typical glacial landscapes in the north of the Kola Region. Images are based on the ArcticDEM 2 m (Porther et al. 2018). The locations of areas a, b, c, d are shown in Fig. 3. Letters indicate: F – frontal (red line); R – radial (dark-blue line); CS – complex-shaped ridges; D -- ridges of the distal part of the belt (yellow line), BH – bedrock heights. Numbers show the location of the studied outcrops, see Fig. 3.

located beyond the bands with ridge moraine relief. The radial ridges have narrow crests with a width of up to 10 m and symmetric straight slopes.

The ridges of the distal part of the belt are 0.5–1.3 km away from the proximal (eastern) margin of the bands with ridge relief complex. They are usually represented by one chain of straightened, slightly sinuous ridges with a wide crest (up to 200 m) (Figs. 4a, c). The ridges of the distal part of the belt differ significantly from the frontal and radial ones in their greater width, gentler slopes, and the plateau-like shape of the crest, which may be complicated by small crests and dividing kettles of a1.5–3 m depth (Fig. 5b). The ridge slopes are asymmetric, while the eastern slope is usually flatter (by 5–10°) than the western one.

The *complex-shaped ridges* occupy the areas between the frontal and radial ridges (Figs. 4a–d). Usually, these ridges are lower and shorter than the frontal or radial ones (Table 1), but they have steep and frequently asymmetric slopes with a difference in a gradient of about 10–15°. No common orientation of these U-shaped, S-shaped, and ring ridges has been determined. These landforms outline isometric depressions occupied by small lakes or peatlands (Fig. 5d). Near Tumanny Settlement, low (up to 2–3 m height) ring ridges are immediately adjacent to the well-expressed frontal ridge.

4.2 Geology of glacial landscapes

The geological structure of the glacial landscapes was studied in two key areas near the Martimyavr (Fig. 3, Outcrops 1, 4, 6–8) and Perkhyavr lakes (Fig. 3, Outcrops 2, 5) and in a small area near Tumanny Settlement (Fig. 3, Outcrop 3).

Table 1. The major morphometric indicators of the glacial landscapes in the study area

Landforms	Mean length of ridges, m	Mean length of slopes, m	Mean height of slopes, m	Mean slope gradient	Number of peaks per 1 km^2	Slope gradient-to-height ratio
Ridge relief complex						
Frontal ridges	740	32.5	8.5	14.7°	28–40	1.73
Radial ridges	450	37.5	6.25	9.5°		1.52
Ridges of the distal part of the belt	650	82	6.75	4.7°		0.70
Complex-shaped ridges	230	18.5	3.75	11.5°		3.07
Accumulative landforms of the moraine plain						
Hills	-	175	12.5	4.1°	2–4	0.33
Landforms associated with bedrock ledges						
Hills and plateaux	-	375	57	8.6°	1–2	0.15

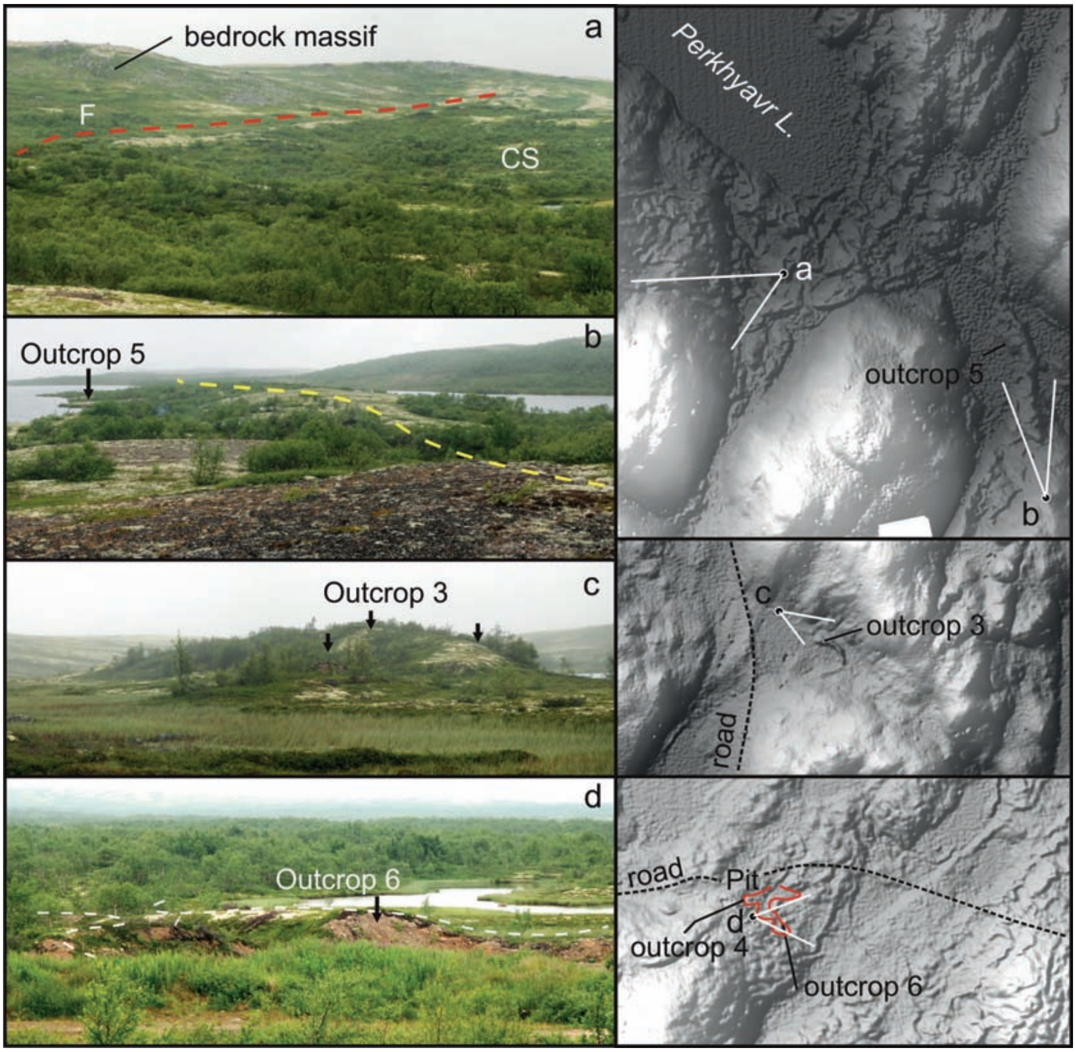

Figure 5. The most typical forms of the glacial relief (using DEM-images (Porther et al. 2018): a – frontal ridge (F) and complex-shaped ridges (CS) southeast of Lake Perkhyavr; b – ridge of the distal part of the belt east of Lake Perkhyayr; c – a separate frontal moraine ridge north of Tumanny Settlement; d – complex-shaped ridges south of Lake Martimyavr.

4.2.1 Frontal ridges

The longest and relatively high frontal ridges, which form pronounced chains, usually consist of one or several layers of diamicton pushed over each other.

The structure of the frontal ridges was studied in Outcrop 1 near Lake Martimyavr (N 68º 49' 08", E 35º 13' 16", Fig. 6a). There is a ridge with a length of approximately 0.48 km, width of 35–42 m, and a 5–9 m wide horizontal crest and asymmetric slopes. The western slope has a gradient of 20–28º and a height of 4.5–5 m. The eastern one has a gradient 22–32º and a height of 4–4.5 m. The ridge is oriented at an azimuth of 35–215º and is slightly sinuous in a plan. A peatland depression is located to the west of it. Another ridge with a similar shape, size, and orientation is situated behind the depression.

From the surface, the ridge is composed of yellowish-brown (10YR, 5/4) fine-to-coarse-grained sand with gravel, pebbles, and boulders with a diameter of up to 0.6 m. The thickness of these sediments is 0.75–0.8 m, 0.35–0.4 m, and 0.25–0.3 m in the western, central, and eastern parts of the cross-section, respectively (Fig. 6a). Down the cross-section, a greenish-grey (Gley 1, 5/10Y) compact diamicton with gravel, pebbles, and boulders with a diameter of up to 1.5 m was observed. The visible thickness of the diamicton is over 2.5 m. The diamicton has a distinct foliated structure and contains numerous thin lenses of light-grey (2.5Y 7/2) fine-to-coarse-grained sand, predominantly fine-grained with rare gravel. The thickness of the lenses varies from 1–2 mm to 2–3.5 cm. The similar sand occurs immediately under the boulders. Also, there are lenses of olive-brown (2.5Y, 4/3) diamicton (clayey compacted fine-to-medium-grained sand with gravel, pebbles, and boulders) with a thickness of up to 25–28 cm. The lenses occur as folds, which limbs are oriented parallel to the foliation in the diamicton (Fig. 7a).

In the western part of Outcrop 1, the foliation of the greenish-grey diamicton dips 15–30º at 255–275º. The dip angle increases up to 35–40º towards the center of the cross-section. Here, the diamicton contains an interlayer of light-grey sand, which top and bottom dip 44º at 258º. Below this interlayer, the foliation in the diamicton forms an asymmetric fold in which the western limb is steeper than the eastern one. On the eastern limb of the fold, foliation dips approximately 20º at 75–90º. This limb corresponds to the eastern slope of the ridge.

At the study area near Lake Perkhyavr (Fig. 4a), a frontal ridge at an altitude of 86–88 m a.s.l. was investigated in the Outcrop 2 (N 69º01'14", E 35º31'00"; Fig. 6b). On the surface of the ridge, there is brown (7.5YR, 5/2) predominantly fine-grained sand with gravel, pebbles, and boulders, of up to 0.55 m thick. At the crest of this ridge, there is the diamicton, i.e., dark yellowish-brown (10YR, 4/6) clayey sand with gravel, pebbles, and boulders, cemented to conglomerates by iron hydroxides. On the surface of the ridge, at the edge of the eastern slope, a dark reddish-brown (2.5YR, 2.5/3) compacted peat (up to 0.6 m thick) was found. These sediments are underlain by olive-grey (5Y, 5/2) diamicton (clayey fine-grained sand with a lot of gravel, pebbles, and boulders) with a total thickness of over 2.2 m (Fig. 6b). The diamicton has a foliated structure expressed by 1–2 mm thick individual plates (Fig. 7b). Fine-grained light-grey sand occurs at the contact of the plates. The foliation evenly dips about 25° at 210. In addition, the diamicton has thin interlayers of light-grey (5Y 7/1) medium- to-fine-grained sand with rare gravel. The interlayers dip concordantly with the diamicton foliation.

Near Tumanny Settlement, a U-shaped frontal ridge was studied in Outcrop 3 (N 68º55'04", E 35º43'42"; Fig. 5c). From the east, it outlines a lake basin. Predominantly fine-grained dark reddish-brown (5YR, 2.5/2) sand full of gravel and pebbles lies on the surface of the ridge; no lamination is observed. In lenses, the sand with a total thickness of up to 1 cm is cemented by iron hydroxides. In some areas at the ridge crest, sands are overlain by compacted very dusky red (2.5YR, 2.5/2) peat up to 0.5 m thick. The peat and sand overlie the light olive-grey (5Y, 6/2) and light olive-brown (2.5Y, 5/3) diamicton with predominating fine-grained clayey sand. The diamicton has lenses

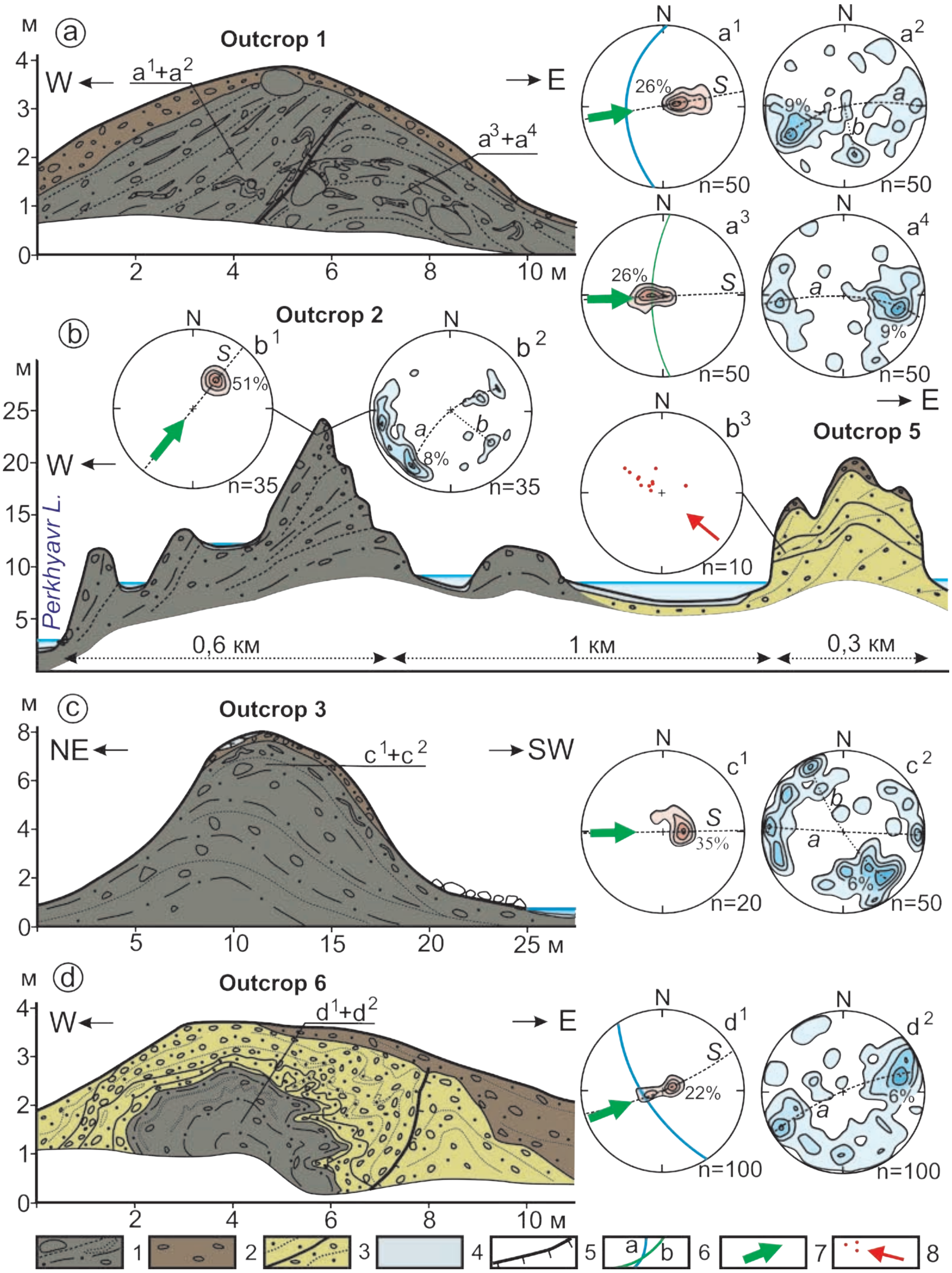

Figure 6. Geological structure of the frontal ridge east of Lake Martimyavr (a), frontal ridges and ridges of the distal part of the belt southeast and east of Lake Perkhyavr (b), frontal moraine ridge north of Tumanny Settlement (c), complex-shaped ridge south of Lake Martimyavr (d). 1 – foliated diamicton; 2 – boulders and pebbles with gravel and sand, unsorted; 3 – glaciofluvial sands with gravel and pebbles, sorted; 4 – lacustrine sediments; 5 – planes of glacial thrusts; 6 – lines of a large circle in structural diagrams; 7 – direction of glacier pressure (reconstruction); 8 – dip direction of lamination in glaciofluvial deposits. The structural diagrams are plotted on the lower hemisphere of the equal area net. On the diagrams: S – reconstruction of the glacier pressure plane on diagrams of the orientation of foliation; a, b – reconstruction of stress planes during the formation of tills, on diagrams of the dip orientation of the long axes of pebbles and boulders. Locations of the outcrops are shown in Fig. 3.

and interlayers of olive-grey (5Y, 5/2) sandy silt with a thickness of up to 10 cm. Under pebbles and boulders, there are thin interlayers of light-grey (5Y, 7/1) fine-grained sand. On the ridge crest, the foliation in the diamicton predominantly dips approximately 20° at 270°. In the lower part of the eastern ridge slope, some lenses dip in the opposite direction, i.e., 10–15° at 100–120° (Fig. 6c).

4.2.2 Radial ridges

The radial ridges, oriented perpendicular to the frontal ones, are studied less than the other groups. Unsorted boulder-pebble deposits with gravel and sand were found in several small outcrops without the layers of diamicton. Such structure is more typical for radial eskers.

A radial ridge was studied in Outcrop 4 (N 68º49'20", E 35º08'51"; Fig. 7c). The ridge is located near Lake Martimyavr and has a length of over 80 m, width of 20–30 m, and height of up to 4 m (Fig. 4c). On the surface, there are predominantly well-rounded pebbles and boulders with unsorted sand and gravel, without visible lamination, up to 1.5 m thick. This layer is underlain by light brownish-grey (2.5Y, 6/2) sand with gravel, pebbles, and boulders (Fig. 7c). The sand is bedded due to lenses of well-rounded pebbles and boulders. The lenses dip 7º at 92º.

4.2.3 Ridges of the distal part of the belt

The ridges of the distal part of the belt are composed of sorted fine-to-coarse-grained sands and are, apparently, prefrontal marginal eskers.

The ridge of the distal part of the belt was investigated in Outcrop 5 (Fig. 4a). The western and north-eastern ridge slopes with a plateau-like surface were studied in two trenches on the shore scarps of the Nizhne-Serebryanskoe Reservoir. Glacial deposits in both trenches have a similar geological structure. On the western slope of the ridge (N 69º00'37", E 35º32'07'), the following lithology is observed in a 5.4 m high outcrop from the top downward (Fig. 6b and Fig. 7d):

(1) fine-to-coarse-grained olive-brown (2.5Y, 4/3) sand with light-grey sand patches, with a thickness of 0.25 m;
(2) greyish-brown (2.5Y, 5/2) sand with gravel, pebbles, and rare boulders, 0.15 m thick, without visible lamination;
(3) interlayered medium- to-fine-grained light yellowish-brown (2.5Y, 6/3) and fine-grained light olive-grey (5Y, 6/2) sand with individual interlayers and lenses of coarse-grained sand with gravel and pebbles; the lamination dips 14–23º at 294–326°; the layer bottom is generally uneven with erosion features of the underlying sediment; the thickness of the layer is 2.35 m;
(4) fine-to-coarse-grained light yellowish-brown (2.5Y, 6/3) sand, predominantly medium-grained, with rare gravel. Lamination is subparallel and dips 6º at 238–310°. There are interlayers of brownish-grey (2.5Y, 6/2) clayey sand, 2.5 cm thick. The thickness of the layer is up to 0.4 m;
(5) gravel with pebbles and coarse-grained greyish-brown (10YR, 5/2) sand, bedded due to interlayers with predominating pebbles. The thickness is up to 0.25 m;
(6) medium-grained light yellowish-brown (2.5Y, 6/4) sand with rare gravel and interlayers of coarse-grained sand. Lamination is near-horizontal and dips 6 º at 293°. The thickness of the layer is 0.4 m;
(7) fine-to-coarse-grained, predominantly coarse-grained, cross-bedded light yellowish-brown (2.5Y, 6/4) sand with gravel; lamination dips 22° at 291°; visible layer thickness is over 1.6 m.

4.2.4 Complex-shaped ridges

Complex-shaped ridges are almost always composed of massive diamicton, but in some cases, the diamicton may be deformed together with glaciofluvial deposits into complex folds.

There are two types of cross-sections of complex-shaped ridges. The first type is represented in Outcrop 6 0.6 km southeast of Lake Martimyavr

(N 68°49’20”, E 35°09’04”). An open pit is situated on a crescent-shaped ridge with a length of 0.14 km, width of 15–24 m, and height of 2–4 m (Fig. 5d). The ridge has a flattened crest and straight slopes. The eastern (distal) slope has a gradient of 20–29° and the western (proximal) one has a gradient of 25–31°. An area with small lake basins adjoins the ridge from the distal side.

The ridge comprises two non-conformably occurring sets of beds. The first set consists of two beds. The lower bed is composed of fine-to-coarse-grained yellowish-brown (10YR, 5/4) sand with gravel, pebbles, and boulders with sand patches enriched with iron hydroxides. The upper bed is composed of light brownish-grey (10YR, 6/2) sand with gravel, pebbles, and boulders (Fig. 6d). Pebbles and boulders are well- and moderately rounded. Both beds of this set have no visible lamination, but there are interlayers of fine-to-coarse-grained (predominantly medium-grained) brownish-yellow (10YR, 6/8) sand on the eastern slope of the ridge, which dip 14–17° at 105–118°. The sand is enriched with iron hydroxides. The set with a total thickness of over 2.5 m occurs only at the eastern slope of the ridge.

The sediments of the second set overthrust the first one along the contact dipping 68° at 237°. The deposits near the contact are cemented with iron hydroxides. The coarse-grained clastic material of the first set is oriented along this contact. The sediments of the second set form an asymmetric fold (Fig. 6d). On the limbs of the fold and in its hinge part, there are alternating 1) brownish-yellow (10YR, 6/8) sand with gravels, pebbles, and boulders, 2) predominantly fine-grained yellowish-brown (10YR, 5/4) sand, and 3) coarse-grained brownish-yellow (10YR, 6/8) sand with gravels. Pebbles and boulders are mainly moderate and well-rounded. Greenish-grey (Glay 1, 5/10Y) diamicton is found in these sediments in the form of thin lenses. The lamination of sand layers on the western fold limb dips southwestwards at an azimuth of 236–246° and angles of 38° to 68°. In the hinge part of the fold, the sands occur near-horizontally, enveloping the core of the fold. The total thickness of the sands on the western limb and hinge of the fold is 1–1.4 m. On the eastern limb, the sediments form numerous V-shaped recumbent folds with limbs up to 0.7 m high. Also, these sands occur near-vertically, dipping predominantly westwards at angles of 65–85°. The total thickness of the sands increases up to 1.6–2 m there.

A greenish-grey foliated diamicton mainly composed of clayey sand is present in the core of the fold. It contains 1–2 mm thin lenses and interlayers of fine-grained light-grey (2.5Y, 7/1) sand at the foliation boundaries and in the lower parts of cells occupied by large pebbles and boulders. These sand interlayers are well seen in the hinge part of the fold. On the fold limbs, the interlayers fall into individual lenses and patches up to 1 cm thick. The thickness of the diamicton in the core of the fold is over 1.8 m. The structural analysis of the diamicton foliation and lamination demonstrates a distribution of the orientation peaks in the form of a curved belt (Fig. 6d). Such pattern is typical of conic glacial fold; the western and eastern limbs dip at an azimuth of 239° and 78°, respectively. The fold hinge submerges at an azimuth of 162° (southeastwards) and an angle of 5°.

The second cross-section type of complex-shaped ridges was observed in Outcrop 7 (N 68°49’20”, E 35°09’04”) and several trenches on the crests of the adjacent ridges. The ridge studied in the outcrop has a crescent shape, a length of approximately 95 m, width of up to 18 m, and height of up to 2.5 m. It is composed of grey and greenish-grey (Glay 1, 5/10Y) diamicton with predominating clayey sand and an admixture of light-grey (2.5Y, 7/1) fine-grained massive sand (Fig. 7e). The diamicton has no foliation; there are no complex glacial structures. The total thickness of the diamicton is up to 1.5 m. On the surface of the ridge, the massive diamicton is overlain by light yellowish-brown (10YR, 5/6) fine-to-coarse-grained unstratified sand with gravel and pebbles up to 0.6 m thick.

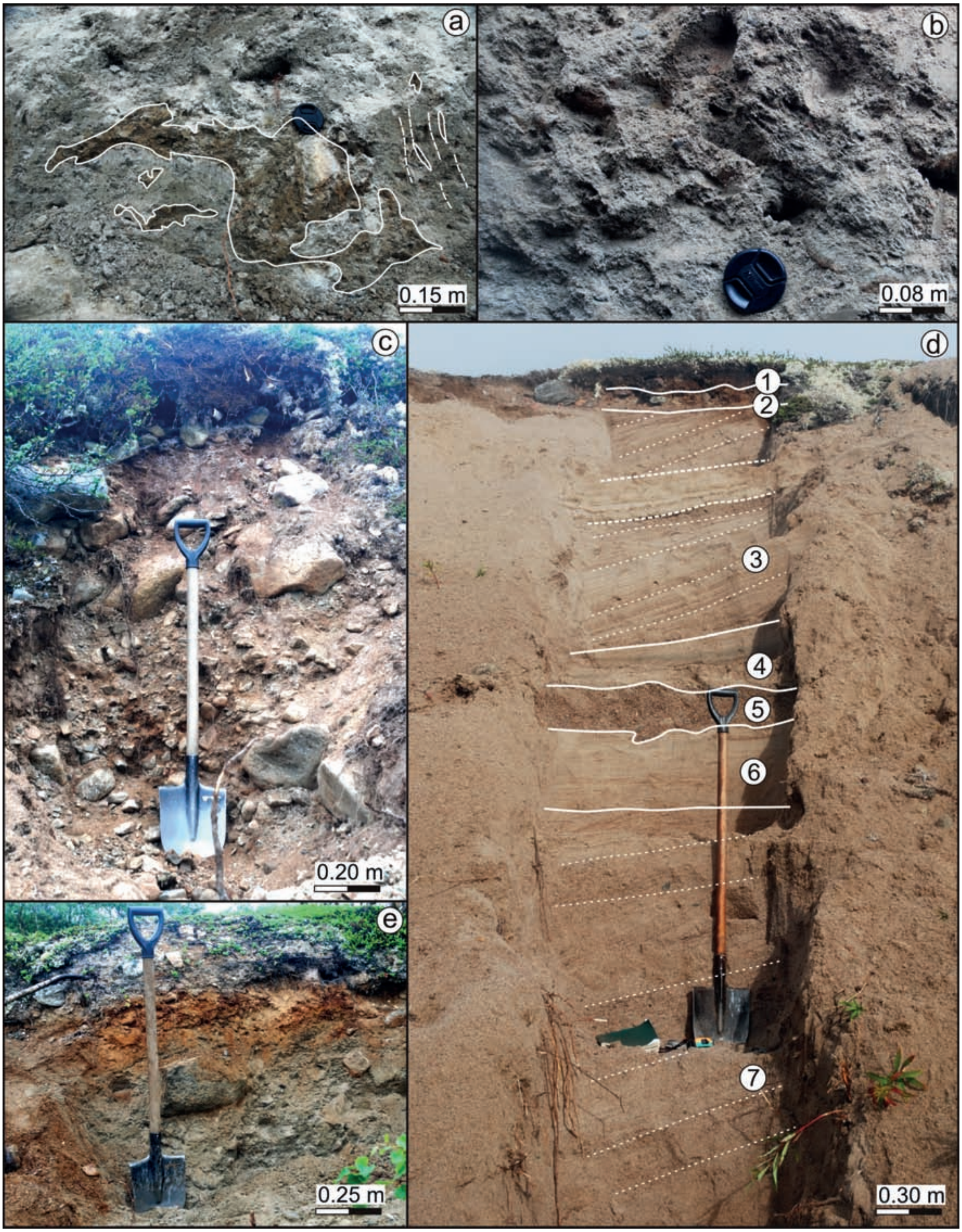

Figure 7. Structural features of the glacial relief: a – lens of olive-brown diamicton in the deformed greenish-grey diamicton in the frontal ridge east of Lake Martimyavr (Outcrop 1); b – foliated diamicton in the frontal ridge near Lake Perkhyavr (Outcrop 2); c – glaciofluvial material in the radial ridge southeast of Lake Martimyavr (Outcrop 4); d – glaciofluvial deposits in the ridge of the distal part of the belt, southeast of Lake Perkhyavr (layers 1–7, Outcrop 5); e – diamicton without an ordered structure in the complex-shaped ridge near Lake Martimyavr (Outcrop 7).

Table 2. Petrographic composition of boulders, pebbles, and coarse gravel in the NE Kola Peninsula, in %

Fraction	Boulders	Pebbles					Gravels				
Outcrop №*	**1**	**2**	**3**	**6**	**1**	**8**	**2**	**3**	**6**	**1**	**8**
Plagiogranites, diorites and gneisses after them**	58.0	54.5	38.3	83.7	80.4	86.1	68.2	49.0	76.6	72.4	77.1
Pink granites	36.6	38.8	58.7	7.3	12.0	6.0	24.5	47.9	16.4	17.7	15.1
Biotite gneisses, plagiogranites with garnet	-	0.6	0.2	3.7	0.6	3.7	0.6	0.1	2.0	0.8	1.4
Biotite gneisses, plagiogranites with sillimanite	-	0.3	-	0.5	0.6	0.2	0.1	-	0.3	0.3	0.2
Amphibolites	2.4	1.0	-	0.8	1.2	-	1.6	0.5	0.4	1.1	0.1
Gabbroids	2.1	0.6	2.0	2.9	4.3	2.8	1.2	1.2	2.1	1.9	2.2
Metaperidotite,olivinite	-	-	-	0.3	-	0.2	-	-	-	-	-
Nepheline syenites	0.9	2.6	0.2	0.3	-	0.5	1.0	0.1	0.2	1.3	0.5
Foidolites	-	0.3	-	-	0.3	-	0.3	-	-	-	-
Quartz	-	1.0	0.6	0.5	0.6	0.5	2.0	0.7	1.9	2.9	2.3
Feldspar	-	0.3	-	-	-	-	0.5	0.5	0.2	1.6	0.9

* Outcrop № is shown in Figure 3

** Group of plagiogranites, diorites, and gneisses after them includes transitional and altered granite varieties, enderbites etc.

4.2.5 Glacial plain

In the west, near Lake Martimyavr, a glacial plain adjoins the area of the ridge relief complex. It was studied in Outcrop 8 (N 68°49'20", E 35°09'04") (Fig. 3). On the surface, the plain is composed of brownish-yellow (10YR, 6/8) ferruginous fine-to-coarse-grained unstratified sand with gravel, pebbles, and boulders, up to 0.4 m thick. The layer is underlain by greenish-grey (Glay 1, 5/10Y) well-foliated diamicton, represented mainly by fine-to-coarse-grained (predominantly fine-grained) clayey sand. Its foliation consists of plates (up to 0.5 cm thick) dipping at angles of 10–15° mainly west-, southwest-, and southwards. The diamicton contains many thin lenses of greenish-grey (Glay 1, 5/10GY) silt and light brownish-grey (2.5Y, 6/2) fine-grained homogenous and clayey sand. The thickness of the diamicton is 1.5 m and more.

4.3 Petrographic composition of the coarse-grained fraction of diamicton

The coarse-grained fraction of diamicton is mainly represented by local rocks, which compose the crystalline basement in the study area (Table 2). Near Lake Martimyavr, the diamicton contains more plagiogranites, diorites, and associated gneisses and intermediate varieties ascribed to the intrusions of the Murmansk Complex (Figs. 8a, b) (Mitrofanov 2001). The diamicton near Lake Perkhyavr and Tumanny Settlement is rich in pink granites of the Voronya Complex (Fig. 8c) at a reducing share of the plagiogranites of the Murmansk Complex. In addition, the diamicton contains fragments of orthopyroxene-bearing diorites (enderbites), amphibole diorites, and granodiorites with typical grey plagioclase possibly displaced from the Chudzyavr Complex (Fig. 8d), which occur further south and southwest. Fragments of garnet- and sillimanite-bearing biotite gneisses sourced from the Volshpakhk Formation have been transported from the west and southwest

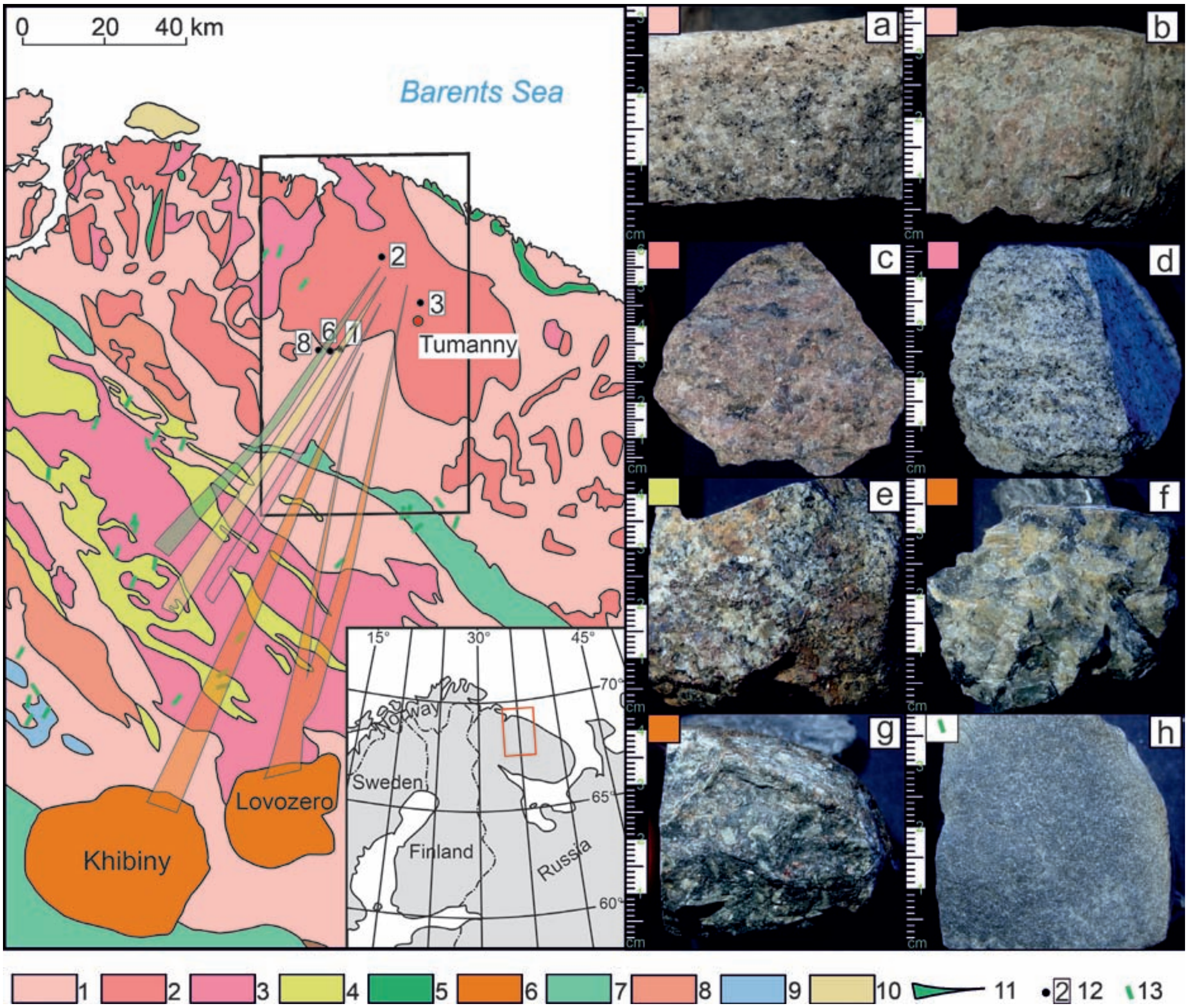

Figure 8. Map of the sources and displacement directions of diamicton coarse clastic material (based on (Mitrofanov 2001) and rock fragments found in diamicton on the surface of the frontal ridge to the east of Lake Martimyavr (Fig. 3, Outcrop 1). 1 – plagiogranites, granodiorites (Murmansk Complex), 2 – leucogranites, granodiorites (Voronya Complex), 3 – enderbites, granodiorites (Chudzyavr Complex), 4 – mica, garnet-mica gneisses with kyanite and (or) sillimanite (Volshpakhk Formation), 5 – dolerites (sills, dykes) (Barents-Sea Complex), 6 – nepheline syenites of Khibiny and Lovozero massifs, 7 – rocks of volcanogenic-sedimentary belts, 8 – enderbites (Canentyavr Complex), 9 – gneisses, amphibolites, ferruginous quartzites (Olenegorsk Formation), 10 – sandstones, siltstones, carbonate rocks of the Kildin Island, 11 – displacement directions of diamicton clastic material, 12 – sampling points (outcrops, see Fig. 3), 13 – dolerite dykes (Barents Sea Complex). Rock fragments on the photos: a, b – plagiogranites (Murmansk Complex), c – pink granite (Voronya Complex); d – granodiorite with grey plagioclase (Chudzyavr Complex), e – biotite gneiss with garnet (Volshpakhk Formation); f – nepheline syenite (Khibiny Massif); g – nepheline syenite (eudialytic luyavrite) (Lovozero Massif); h – fine-grained dolerite (Barents Sea Complex).

too (Fig. 8e). The diamicton also contains the gabbroid group rocks including monotonous fine-grained dolerites, which form dykes of the Barents Sea Complex cutting the Murmansk and Chudzyavr complexes and the Volshpakhk Formation south-west of the study area (Fig. 8h).

The fragments of nepheline syenites from the Khibiny and Lovozero massifs occupying the central part of the Kola Peninsula are found in minor amounts almost in all samples and fractions (Figs. 8f, g). A few revealed foidolite fragments are transported from the same massifs.

5. Discussion

5.1. Frontal ridges

The lithological features of the foliated diamictons of frontal ridges, some complex-shaped ridges, and adjoining moraine plain (Outcrops 1, 2, 3, 6, and 8) are mostly similar to the basal till of the Kola Region (Yevzerov et al. 1993; Semenova 2004; Yevzerov 2015). These features include granulometric composition, foliated (platy) structure, and presence of thin interlayers of sorted fine-grained sand (Lavrushin 1976; Aboltinš 1989; Kaplyanskaya & Tarnogradsky 1993; Yevzerov 2017). However, the diamictons form slabs up to 3 m thick and folds within some frontal ridges. It is therefore possible to attribute these ridges to pushed moraine formed in the ice-marginal zone.

For example, basal tills are deformed to thrusts and folds combined in some cross-sections (Fig. 6a). In Outcrop 1, the overthrust unit overlies a glacial fold; this is evidenced by an angular unconformity of foliation and lamination. The frontal ridge near Lake Perkhyavr is interpreted as a series of glacial thrusts (Fig. 6b). It is indicated by the similar orientation of foliation in basal tills in several parts of Outcrop 2 and asymmetric slopes of the ridge, with a flat proximal and stepped distal slope. The landforms composed of till near Tumanny Settlement may be assigned to the frontal ridges built up only by glacial folds (Fig. 6c).

The thrust and folded glaciotectonic deformations in the frontal ridges are related to the squeezing of the debris-oversaturated ice into the crevasses and cavities of the glacier in the ice-marginal zone. Such settings could exist either in the areas where crystalline bedrock didn't occur deep or when an active glacier came into contact with dead ice (Lavrushin 1976; Aboltinš 1989; Benn & Evans 1998; Yevzerov 2015). The strain areas could predominantly be oriented across the ice front and predetermined by the Pre-Quaternary surface topography. The movement of the material was accompanied by the deformation of the earlier deposited basal tills and glaciofluvial sediments (Fig. 9a). For example, greenish-grey and olive-grey basal tills mainly preserved their structure and were divided into large blocks. But the yellowish-brown tills underwent a substantial deformation, now occurring only as small isometric erratic masses (Fig. 7a). These tills are probably more ancient than the greenish-grey and olive-grey varieties. Tills in the form of the same inclusions were known in sections of the Kola Region; they were earlier attributed by some researchers to the moraine of the previous glaciation in MIS4 (Yevzerov et al. 1993; Semenova 2004).

The dip of the thrust surface, limbs of the glacial fold, foliation in basal till, and long axes of pebbles and boulders in glaciotectonic deformations shows that the active ice predominantly moved from the west and southwest (Fig. 6, diagrams a^1, a^3, b^1, c^1). On the diagrams of the dip of the long axes of pebbles and boulders, one or two peaks are often registered. If a frontal ridge has a sinuous shape, diagrams may show many local peaks, one pair of which is always related to the dip direction of the foliation and lamination (Fig. 6, diagrams a^2, a^4, b^2, c^2). The flow direction of the active glacier is corroborated by petrographic analysis of the clastic material from the deformed basal tills. Analysis of probable sources indicates the general trend of material migration from southwest to northeast. The ice cover gradually eroded the rocks of the Volshpakhk Formation, Chudzyavr, Murmansk, and Voronya Complexes (Fig. 8). The predominance of local bedrock in the till indicates an active impact of the glacier on the substratum. The possible reasons may be either an uneven surface of the basement and glacial erosion of uplifted rocks of the Murmansk and Voronya Complexes, or a frozen glacial bed near the marginal zone of the glacier. Rare fragments of nepheline syenites from the Khibiny and Lovozero massifs may account for a transfer of this material by a glacier from south to north along the depressions of modern lakes of Umbozero and Bolshaya Imandra (Yevzerov & Koshechkin 1980; Boyes et al. 2023a).

5.2. Radial ridges

The radial ridges are mainly composed of glaciofluvial deposits, represented by sands, gravel, pebbles, and boulders, in various proportions. The formation of these sediments in a fast-stream setting is evidenced by well-rounded clasts. Poorly sorted material lying on the surface of some ridges may possibly be a flow-till washed by meltwater streams. Such structure is typical of eskers of closed subglacial streams, which could terminate both in standing waters and subaerially (Kaplyanskaya & Tarnogradsky 1993; Brennand 2000). The highest and longest radial ridges cut across the whole band of the ridge relief complex and may go beyond them. Such ridges represent part of the long dendritic esker systems that are widespread in the northern part of the Kola Region (Petrov & Lopatin 2000a). They began to arise at the early stages of deglaciation and could continue forming simultaneously with the frontal ridges (Fig. 9a). The debris-saturated meltwater streams were often divided near the marginal zone within the glacier; therefore some radial ridges have several parallel crests (Fig. 4b).The relatively short radial ridges (Outcrop 4) cut across only some frontal or complex-shaped ridges. Such landforms were formed during the final degradation of the glacier within the belt of ridge relief complex; essentially, they are short meltwater channels among dead ice blocks (Fig. 9b).

5.3. Ridges of the distal part of the belt

The ridges of the distal part of the belt (Outcrop 5) are also glaciofluvial formations. Their material is well sorted and cross-bedded and has not any shear deformations. This indicates a sedimentation on the substratum, which had already been free of dead ice. The cross-bedding dipping northwestward indicates the direction of the glacial meltwater flow that is mainly parallel to the orientation of the ridge relief complex band and frontal ridges. Near Lake Perkhyavr, such flow direction was possible in case dead ice having blocked a valley opened southeastwards to the Voronya River. The presence of dead ice there was previously noticed in (Yevzerov 2015). Thus, these ridges may be marginal supraglacial eskers formed in open channels (Kaplyanskaya & Tarnogradsky 1993) or H-channels (Gorrel & Shaw 1991; Brennand 2000). These supraglacial marginal formations may mark an actual ice margin during the generation of a ridge relief complex band (Kaplyanskaya & Tarnogradsky 1993). Near Lake Martimyavr, east of the chain of ridges of the distal part of the belt, there are areas of outwash valleys traced along depressions and modern river valleys (Yevzerov et al. 1993).

The formation of the ridges of the distal part of the belt may have occurred simultaneously with the formation of the frontal ridges or continued for some time after the degradation of the glacier (Figs. 9a, b). The absence of deformations in glaciofluvial sediments indicates that the proximal ice margin did not affect previous deposits. Only flow tills and ablation moraine could get here (Kaplyanskaya & Tarnogradsky 1993). The presence of sandurs on the distal side of the ridges indicates that the area to the east of them may already have been free of dead ice.

5.4. Complex-shaped ridges

Complex-shaped ridges have a very diverse structure. It indicates that they had been formed during various processes near the ice-marginal zone. The most typical ones were formations analogous to the ridge studied in Outcrop 6. It represents a folded deformation including till (similar in composition and structure to basal till) in the core of the fold and glaciofluvial sediments on the limbs. The abundant glaciofluvial material there may be deformed deposits of the meltwater channels.

The glaciotectonic deformations that caused the complex-shaped ridges to be expressed in the modern relief may have been formed in the ice sheet zone, where many faults occurred. Their number and dimensions may increase near the areas with uneven glacier bed. Here, disorderly-oriented crevasses and open subglacial cavities were infused with debris-oversaturated ice and earlier

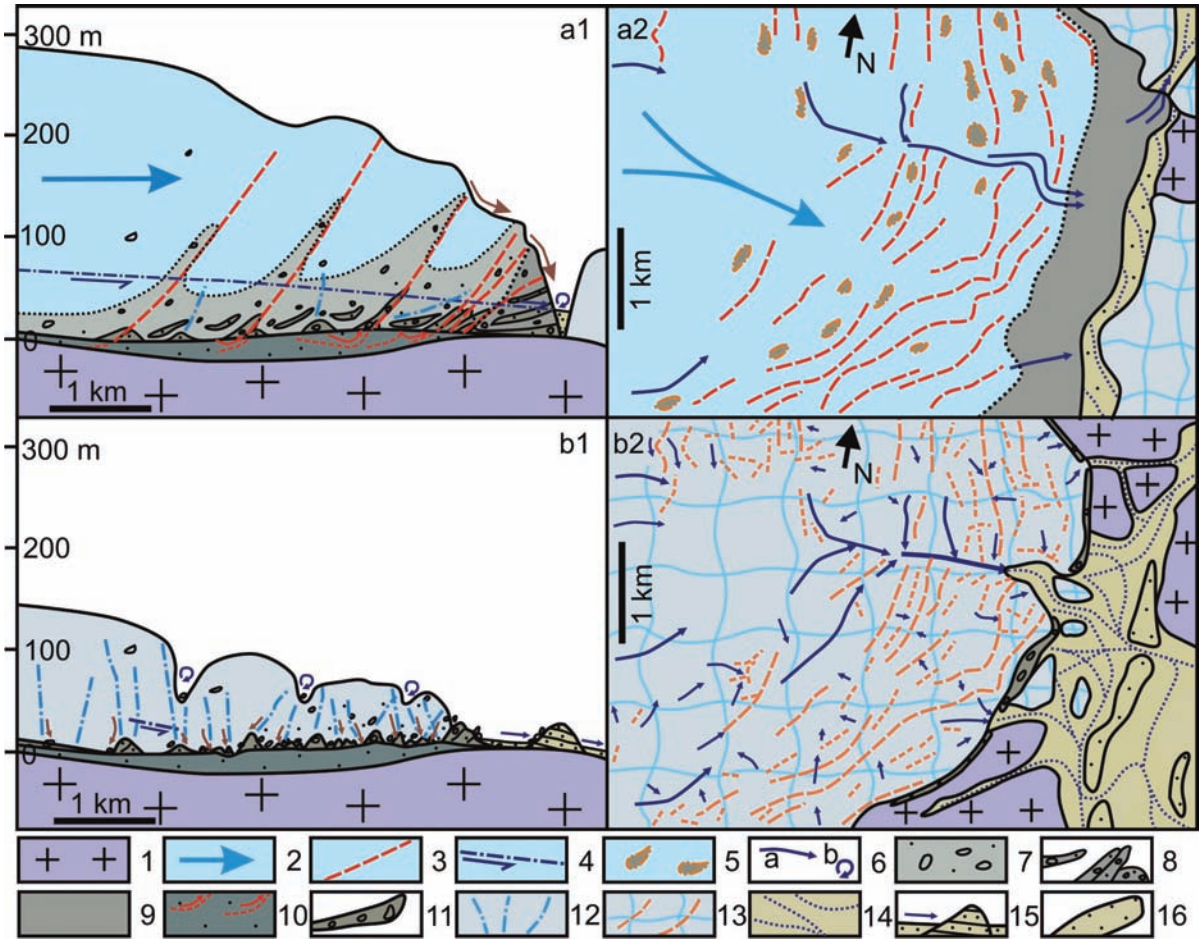

Figure 9. Scheme of the formation of the ridge relief complex near Lake Martymyavr (Fig. 4c). a1 – scheme of the formation of the frontal ridges and the ridge of the distal part of the belt, and the beginning of the formation of the radial and complex-shaped ridges during the active movement of the glacier; a2 – the same, on a plan; b1 – the scheme of the end of the formation of radial and complex-shaped ridges; b2 – the same, on a plan. 1 – bedrock; 2 – active glacier; 3 – thrust zones in the marginal zone of the active glacier; 4 – subglacial meltwater channels; 5 – areas of formation of glacial folds in the cores of complex-shaped ridges; 6 – subglacial meltwater streams on the plan (a) and supraglacial streams on the scheme (b); 7 – active glacier saturated with debris; 8 – glacial folds and thrusts; 9 – marginal zone of an active glacier on the plan a2; 10 – loose deposits of the ice bed and deformations in them; 11 – formed frontal ridges on the plan b2; 12 – crevasses in dead ice; 13 – dead ice and crevasses in it on the plan; 14 – proglacial streams on the plan; 15 – deposits of proglacial streams on the scheme; 16 – ridges of the distal part of the belt on the plan b2.

deposited basal till. As a result, asymmetric conic infusion glacial folds were formed with greenish-grey basal till in the core and glaciofluvial sediments on the limbs. The analysis of the fold elements demonstrates that the glacial structure occurred due to the northeastward pressure (Fig. 6d and diagram d1). The small length (up to 140 m) and crescent shape of the ridge may indicate the formation of a glacial fold at the contact of active ice and dead ice massif. This contact was significantly water-saturated, which is indicated by the sediments cemented with iron hydroxides. As the ice sheet degraded, crevasses between the dead-ice massifs were filled either with glaciofluvial sediments or ablation tills.

The ablation till was found in Outcrop 7 and some trenches, where the deposits are 1 to 4 meters thick. The diamictons in these complex-shaped ridges have no clear foliation and ordering of the coarse-grained material. Similar sediments in the ring and sinuous ridges were previously described in the Kola Region (Armand 1964), as well as in Finnish Lapland (Johansson & Nenonen 1991). As in earlier publications (Armand 1964; Kolka 1998), we have ascribed these deposits to the ablation melt-out tills (Kaplyanskaya & Tarnogradsky 1993). Such sediments could fill up open crevasses and flanks of large hollows in a melting glacier (Fig. 9b). Nevertheless, the content of clayey particles and coarse-grained material and the color of the ablation tills are quite close to the basal till characteristics. These features may be explained by re-deposition of the material from the debris-oversaturated ice in the marginal parts of the glaciers (Lavrushin 1976; Benn & Evans 2010).

5.5. Dynamics of the last ice sheet in the northern part of the Kola region

The authors consider the distinguished belts of the ridge relief complex to be ice-marginal deposits of the last glaciation on account of the geological and morphological features. These belts may be compared with the retreat stages of numerous ice lobes in the north-east of the Kola Region in the Late Pleistocene (Stroeven et al. 2016; Astakhov et al. 2016; Boyes et al. 2023a). The age of these stages is correlated with either the Older Dryas (Yevzerov 2015) or Younger Dryas Stadial (Rainio et al. 1995; Svendsen et al. 2004; Stroeven et al. 2016; Boyes et al, 2023b).

It is currently difficult to determine the age of ridge landforms in the study area. There are no OSL and ^{10}Be data from this area, and there are very few ^{14}C data for the onset of the organic accumulation in lakes on the proximal side of the landforms. They imply a ^{14}C age of organogenic sediments to be ca. 11.5 – 13.7 ka BP (Yevzerov 2015; Boeys et al. 2021a, 2023a). The correlation of the ridge relief complex belts with the marginal formations of European Russia demonstrates the correspondence of the studied landforms with the period lasting from the end of the Luga Stage (Karelian in Karelia and Keiva I in the southern part of the Kola Region) to the Neva Stage (Syamozero in Karelia and Keiva II in the south part of the Kola Region) (Astakhov et al. 2016; Korsakova et al. 2023a, b). The end of the Luga Stage in northeastern Russia is determined at ca. 15.1–14.7 ka BP, and the Neva Stage is correlated with cooling of the Older Dryas Stadial ca. 14.1–13.9 ka BP (Fig. 10) (Velichko et al. 2017; Korsakova et al. 2023a, b). Thus, according to our data in the Younger Dryas Stadial (Tromsø – Lyngen in North Norway), the glacial lobe did not advance into the study area. The evidence for this was that periglacial and periglacial-marine basins appeared in northeastern Fennoscandia already in the Allerød Interstadial and were not covered by glacier later (Snyder et al. 1997; Kolka et al. 2013; Korsakova et al. 2016; Tolstobrov et al. 2018; Lenz et al. 2020; Korsakova et al. 2021). In addition, during the Younger Dryas Stadial a glacier with low ice thickness would have to overcome an area with high bedrock massifs in a short time interval (Fig. 10).

The active glacier that had formed the ridge landforms had a relatively small thickness (200–300 m) near the ice-marginal zone; the thickness depended on the topography of the glacier bed and reached its maximum value in depressions. This information is based on the position of lateral moraines and lateral meltwater channels on the slopes of the Khibiny and Lovozero massifs (Hättestrand & Clark 2006a; Yevzerov & Nikolaeva 2010; Boyes et al. 2021b). At the same time, there are no lateral moraines or lateral meltwater channels on the bedrock ledges with a relative height of up to 150 m located to the west and southwest. These ledges are entirely covered by basal till (Niemelä et al. 1993; Petrov & Lopatin 2000a). However, the dissected topography of the glacier bed has predetermined the lobate appearance of the ice margin. This explains the localization of ridge relief complex in bedrock depressions.

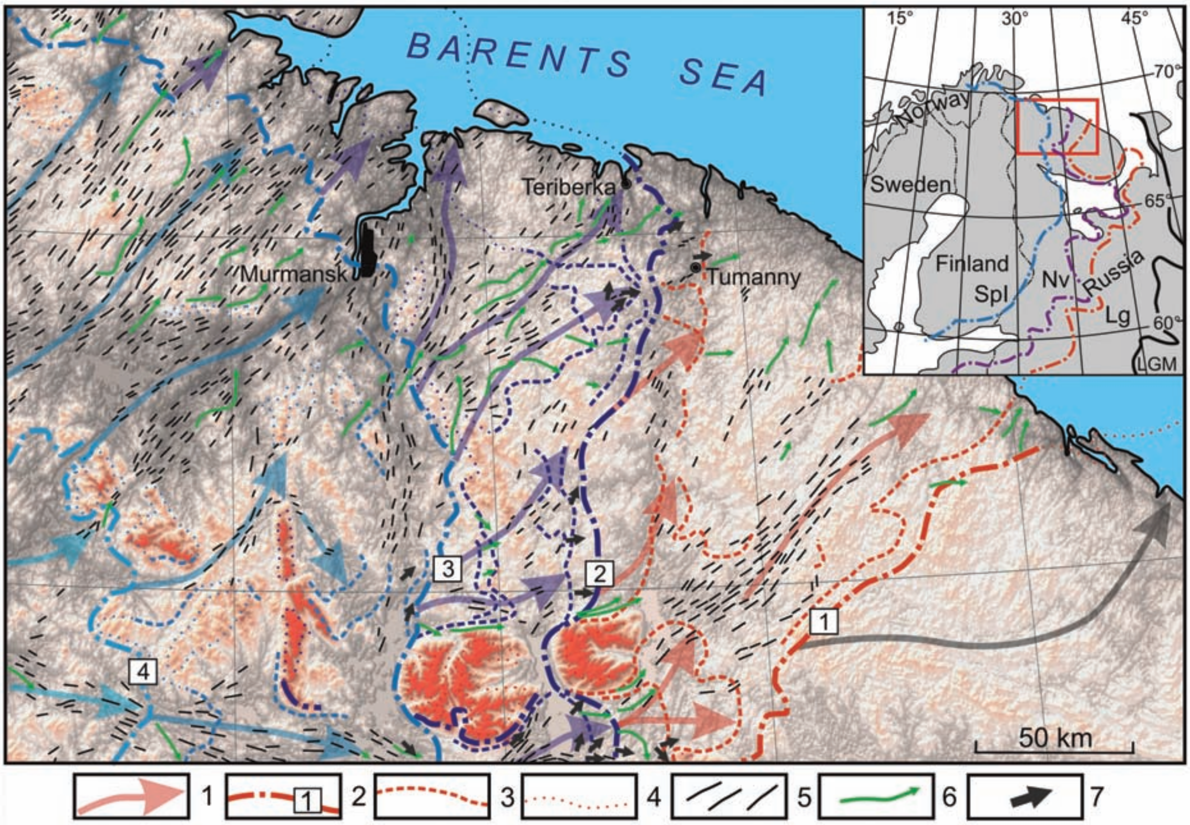

Figure 10. Scheme of deglaciation of the northern part of the Kola Region (using Astakhov et al. 2016; Boyes et al. 2023a, b; Korsakova et al. 2023a, b, c). 1 – flow direction of the glacier during the retreat stages; 2 – boundaries of the retreat stages of the last ice sheet and their numbers; 3 – intermediate position of the glacier margin between the retreat stages; 4 – assumed intermediate boundaries of the ice sheet within sea and on bedrock heights; 5 – linearly oriented relief forms (glacial lineations); 6 – meltwater channels (eskers); 7 – pressure direction of the glacier, reconstructed from the analysis of the structure of glaciotectonic deformations. The retreat stages of the ice sheet are marked by numbers: 1 – Luga Stage, 2 – Neva Stage (Older Dryas Stadial), 3 – Salpausselkä I (Younger Dryas Stadial), 4 – Salpausselkä II.

The retreat of the glacier was accompanied by several oscillations of the ice margin. The longest retreat stages correspond to the belts of the ice-marginal formations and unite several oscillations that formed a number of subparallel chains of frontal ridges. At least four of such chains were formed during the Luga Stage and up to five chains were formed at the Neva Stage (Fig. 10). The combination of folded and thrust deformations shows a possible change in the velocity of the active glacier in the ice-marginal zone during the oscillations. At the maximum stages the outer edge of the glacier may have been marked by marginal eskers or small outwash plains. The presence of several episodes of activation and re-advance of an active glacier during the Luga and Neva Stages was previously determined at the territory of Latvia, Estonia, the Pskov Region of Russia (Kalm 2012; Karpukhina 2013), and in the south of the Kola Peninsula (Vashkov & Nosova 2022). Also, this information is consistent with the glaciodynamic model built by B. Boyes (Boyes et al. 2023b).

Further work should be directed to the absolute dating of glaciofluvial sediments of marginal eskers and sandurs with the aim of more accurate determination of age of the ridge complexes.

6. Conclusions

1. Ridge relief complex in the north of the Kola Region is the most expressive element of the glacial landscape. According to the morphometric indicators, this landscape differs distinctly from the large bedrock massifs. This relief forms pronounced belts, within which the frontal and radial ridges, ridges of the distal part of the belt, and complex-shaped ridges are well distinguished. The framework of each belt leans on the frontal ridges forming chains parallel to each other and usually built by folded and thrust deposits. The radial ridges vary in length. Some of them cross the whole belt, and the others are up to 100 m long. Glaciofluvial sediments compose these ridges, making it possible to compare them with eskers. The ridges on the distal part of the belt are characterized by a large width and relatively low height. They consist of sorted glaciofluvial deposits and, apparently, are marginal eskers. Complex-shaped ridges have a variety of shapes and can be composed both of folded glacial deposits and massive ablation moraines. They were formed in the result of melting of dead ice blocks in the ice-marginal zone.

2. The ridge relief complex in the north of the Kola Peninsula (Russia) near the Martimyavr and Perkhyavr lakes is correlated with the ice-marginal formations of the Last Glaciation. Each of the moraine ridge belts corresponds to one retreat stage of the ice sheet. The narrowness of the relief bands indicates the stabilization of the glacial margin for a relatively short period. There are at least two main belts of the ridge relief complex with oscillation ridges in the study area (the north of the Kola Region).

The correlation of the ridge relief complex belts with the ice-marginal formations of European Russia demonstrates the correspondence of the studied landforms with the ending of the Luga Stage ca. 15.0–14.7 ka BP and the Neva Stage (14.1-13.9 ka BP). Presently, the age determination of the moraine ridge landforms in the study area is complicated since there are only very few ^{14}C data for the onset of the accumulation of the organic in lake basins located on the proximal side of the ridge relief.

3. Each belt of the ice-marginal ridge landscape was formed during a single cycle (stage) consisting of two episodes. The first episode is associated with an active ice sheet. Each frontal ridge chain inside the belt corresponds to a short-term oscillation of the active glacier. Ridges of the distal part of the belt were formed at the free edge of the glacier or at its contact with fields of dead ice. Also, the largest radial ridges appeared in the deepest depressions. Some complex-shaped ridges with folded deformations were formed simultaneously with the frontal ones.

The second episode relates to the reduction of the ice cover and its disintegration into the dead ice blocks in the marginal zone. During the second episode, the sediments of the glacial meltwater channels continued forming the system of radial ridges or eskers. The final depositional phase of the ridge system followed the regression of the glacier; it is related to the filling of numerous crevasses on the glacier surface and the occurrence of swells on the shores of small glacial water basins. Kettle holes with small lake basins and peatlands were formed in the areas where the largest dead ice blocks melted.

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