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MORPHOLOGICAL STRUCTURE OF CRYOGENIC LANDSCAPES OF THE BOLSHEZEMELSKAYA TUNDRA

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Morphological structure of cryogenic landscapes of the Bolshezemelskaya tundra has been analyzed at the level of groups of natural boundaries according to the origin, age, ground composition and absolute elevations. Quantitative characteristics (in % of landscape type area) of areal distribution of groups of natural boundaries (forest, tundra, bog, peat) and permafrost have been determined for each geological-genetic type of landscapes. In addition, the area of closed taliks has also been estimated for each type of landscape and for the entire area of the tundra zone underlined by continuous permafrost. The relationship between various groups of natural boundaries and the areas of permafrost-affected and non-permafrost soils are estimated on the basis of quantitative analysis of landscape morphology. The variability in the landscape structure of the Bolshezemelskaya tundra both in latitudinal direction and depending on absolute altitudes of the interfluves has been shown.

Cryogenic landscapes, morphological structure, natural boundary, zonality

INTRODUCTION

Landscape studies generally underlie almost any other study of natural objects, both within the permafrost zone, and outside it. As is known, zonal and regional environmental factors largely control the landscapes of various scales, involving specific combinations of botanical, geomorphological, geotechnical and permafrost characteristics, soil properties, etc.

Qualitative and quantitative values of these characteristics related to a particular territory can be determined on the basis of the landscape-indicator method and further used for solving strategic, scientific and applied problems through the landscape morphology analysis [*Annenskaya et al., 1962; Golubev et al., 1996*]. The morphological structure is represented by the ratio of areas of different groups/types of natural boundaries within the genetic landscape of a particular natural zone/subzone. When taken into account (depending on availability of data on the properties of indicators of its constituent natural boundaries), the data on morphological landscape structure of the permafrost zone allows to optimize land- and natural resources management in the region. In particular, such valuable information also greatly contributes to the principles of validity and reliability of scientific research into various types of natural zonality (including geocryological), and to allocation of specially protected natural reservation (SPNR), monitoring stations, etc. In strategic terms, these will permit to realistically assess the ultimate involvement of the biosphere-significant areas in the industrial and settlement use without losing their existing biosphere status, to build a development strategy with due consideration of not only economic, but also social aspects (e.g. conflicts between traditional and focal/linear types of exploitation of natural resources). In practical terms (given the applicable law and the mechanisms of management control), the research results and findings would contribute to the quality requirements for design and survey works, to conducting more profound research into assessment and reduction of natural and technology-related risks in the permafrost area.

The purpose of the study is to reveal the aspects of landscape morphology of the Bolshezemelskaya tundra confined to varied natural zones/subzones, and to determine the "landscape morphology – permafrost subzone" relationship.

SPECIFIC FEATURES OF PERMAFROST-LANDSCAPE DIFFERENTIATION OF THE REGION

The Bolshezemelskaya Tundra is located in the Nenets Autonomous District and the northern part of the Komi Republic (Fig. 1).

Permafrost-landscape differentiation of the region is characterized at three spatial scales: zonal, regional and local.

Zonal scale

Zonal landscapes of the Bolshezemelskaya tundra are represented by the tundra subzones, which include predominantly southern shrubby, and to a lesser extent typical, southern and northern forest-tundra and northern part of the northernmost taiga [*Landscapes..., 2011*]. They progressively succeed one another from north to south, stretching in the latitudinal direction. For better convenience of the material presentation the authors assigned a numerical index to each of the zonal landscapes.

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Totally, the *tundra zone* (I) occupies slightly over 40 % of the study region. Subzones of the typical (I-a) and southern shrubby (I-b) tundra differ in size, with the southern shrubby tundra accounting for more than 75 %, while typical – for less than 25 % of the entire tundra area. In the north, the tundra is represented by azonal coastal landscape (I-c), which grades into to the northern forest-tundra in the south.

The *forest-tundra* zone is divided into *northern* (II) and *southern* (III) subzones. Their areas are commensurable in size, with northern tundra occupying ca. 15 %, and southern – 17 % of the total area of the Bolshezemelskaya tundra.

The southern Bolshezemelskaya tundra confined to the *northernmost taiga* subzone in its northern part (IV) occupies ca. 26 % of the territory, which is comparable with the area of the southern shrub tundra subzone (ca. 30 %).

The subzones boundaries are commonly of irregular shapes.

Almost the entire area is subsumed into the zone with varied permafrost distribution patterns. In terms of zonal division, all the area underlain by permafrost is classified into the northern and southern zones [*Tumel and Koroleva, 2008*]. The northern permafrost zone occupies 58 % of the Bolshezemelskaya tundra permafrost area and is represented by continuous and discontinuous permafrost subzones, which provisionally coincide with the tundra zone and the northern forest-tundra subzone, respectively. The southern permafrost zone is represented by massive-island and island permafrost subzones, which provisionally correspond to the southern forest-tundra and northernmost taiga subzones [*Maslov et al., 2005; Osadchaya, 2009*].

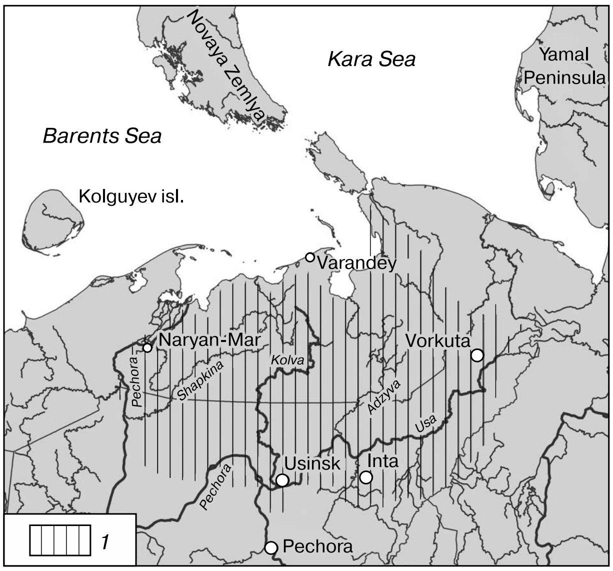

Fig. 1. The Bolshezemelskaya tundra (*1*) on the map of European North of Russia.

Regional scale (genetic landscapes)

There has been thus far no common approach to distinguishing *genetic landscapes*. Our study relies on the interpretation of geological and geomorphological features of the area from the perspective of depositional processes in a sedimentary basin.

Genetic landscapes of the permafrost zone were established on the basis of the State geological map of the Russian Federation at scale 1:200 000 [*Legend..., 1999*]. The age of genetic surfaces was assigned in accordance with the 2012 International Commission on Stratigraphy Resolution on lowering the level of the Neogene – Quaternary systems boundary [*Decision on lowering..., 2012*].

Depending on their age and genetic type, the surfaces have been divided into landscape types, with a letter index assigned to each, for more convenient use (Table 1) [*Legend..., 1999; Ivanov, 2011*]. The abrasion-accumulation surfaces of watersheds (A, B, C, D, E, F) represent a predominant type, while erosion-accumulation surfaces are rarer (G).

Moreover, the Late Pleistocene river terraces landscapes are developed in fragments (and are commonly considered in the studies at a local/regional scale). The intrazonal erosional accumulational-alluvial Holocene landscape (I) formed along the rivers and streams valleys, whereas azonal landscapes of the coastal plains (K, L, M) developed along the Barents Sea coast. The available materials allowed characterization of the morphological structure of the A–G landscape group.

Local scale (natural boundaries)

The analysis of morphological structure was carried out for genetic landscapes at a level of natural boundaries (stows). The permafrost-landscape differentiation of the area at this level appears most complicated. The existing approaches for delimiting natural boundaries and the scheme selected by the authors are shown on the diagram below.

Table 1. **Genetic landscapes of the permafrost zone of the Bolshezemelskaya tundra**

Landscape age and origin	Absolute elevations of terrain, m	Notation index of genetic landscape
amN_2^3	220–330	A
mE_1	180–220	B
mE_2	160–180	C
$m(gm)\ I_{1-2}$	115(120)–160	D
mI_{3-4}	90(100)–115(120)	E
laI_{5-6}	70–90(100)	F
laII	55(60)–70	G
$amIII_{1-2}$	22–55(60)	K
$a,laIII_{3-4}$	6(12)–22	L
mH	≤6	N
aI–III	River terraces	H
aH	Flood plains	I

SCHEMES FOR REGIONAL LANDSCAPE DIFFERENTIATION: LOCAL SCALE

In some measure, geocryological investigations have always been part of landscape and landscape-indicators studies of the permafrost zone. However, their practical application is a challenge in the Bolshezemelskaya tundra due to the lack of a common approach for landscape differentiation of the territory, including the landscape zoning schemes. In the works on separate sites (large-scale research), the designation of representative natural boundaries of the region in most cases was based on the landscape scheme typical for Western Siberia [*Melnikov et al., 1983*], however essential differences between the regions were largely neglected, in particular, almost ubiquitous development of block mesorelief in the northern Bolshezemelskaya tundra, which is not characteristic for Western Siberia [*Popov, 2013*]. The permafrost-landscape differentiation is best organized in the national inventory of representative natural boundaries of the Bolshezemelskaya tundra, proposed in the early 1990s by N.N. Dolgova (PechorNIPIneft, Ukhta) [*Dolgova et al., 1997; Osadchaya and Dolgova, 2004; Maslov et al., 2005*]. The inventory is supplemented with the updated information and was used by the authors as the basis for the landscapes morphology analysis.

Genetic landscapes of the northern permafrost zone of the Bolshezemelskaya tundra were successfully mapped by *Lavrinenko* [*2012*]. Their generalized characterization included natural-territorial complexes (NTC) that served as their constituent elements providing thereby qualitative characteristic of the morphological structure. Unfortunately, this scenario proved impractical due to the lack of georeferencing to absolute elevations on the map of the genetic landscapes, which will impede the use of the information in case of changing approaches to landscape discrimination [*Decision on lowering..., 2012*]. The zoning ordinance was issued almost simultaneously with the publication of the results by I.A. Lavrinenko, which, therefore, could not have been taken into consideration. The papers on the cartographic GIS-models also provided regional landscape zoning schemes without specifying area size for different types of natural boundaries within a certain landscape group (% in relation to the total area of this landscape) [*Drozdov, 2004*].

Qualitative characteristics of cryogenic landscapes morphology of the Bolshezemelskaya tundra are depicted by M.I. Mas'kov [*Yudakhin,* 2001]. The works by F.M. Rivkin and A.A. Popova provide a range of natural boundaries, sometimes facies, supplemented with calculations of area size (%) within the landscape type, but in some cases, the concept of "natural boundaries" (stows) and "facies" converge, for example, inter-block depressions within the natural boundaries of the tundra (facies) are equated with the natural boundaries of "small-stream valleys" [*Rivkin, 2005; Popova, 2012*]. There are numerous regional studies (including those GIS-based) in the field of pedology, geobotanics, etc., which can serve as an information basis for the landscape genetic structure analysis [*Atlas..., 1964; Atlas..., 2001; Atlas..., 2011; Soil Map..., 2011*].

METHODS FOR CALCULATIONS OF QUANTITY INDICATORS FOR LANDSCAPE MORPHOLOGY

In determinations of the quantity (areal) parameters of the morphological structure of landscapes, we used primarily our own actual data and materials obtained for key sites. The large-scale geocryological-geotechnical engineering and landscape maps generated at different times for all the key areas were underpinned by the materials from field studies (at the pre-field stage, remote sensing data were used to identify landscape indicators of geocryological characteristics). The analyzed data covered altogether 27 sites located in different natural subzones [*Osadchaya et al., 2015*]. The key sites area, cumulatively, ranged from 100 to 1,000 km^2. The landscape-indicative information was thus applied to a wide range of natural boundaries linked to a particular landscape.

The accumulated extensive factual material allowed to depict the local types of region-specific NTCs, or natural boundaries, which were classified into 30 major types. For the convenience of systematization at a local scale, the natural boundaries of zonal series were organized into four main groups according to the type of vegetation: forest (1), bog (2), peatlands (3), tundra (4). Each group included representative and baseline natural conditions for certain natural boundaries; a notional index was assigned to the groups, for convenience of their classification.

Previously, morphological structure of the constituent landscapes was calculated for each key site [*Koroleva and Osadchaya, 2013; Osadchaya and Khokhlova, 2013*]. In this paper, the obtained quantitative parameters are summarized for the entire subzone, and to this end the following research algorithm was developed:

– key sites are divided into groups according to the specific natural area/subzone they belong to; further study of the quantitative parameters of landscapes morphology deals with each zone/subzone, individually;

– landscapes are discriminated in all key site, with morphological structure calculated for each of them;

– information on the key site landscape morphology is summarized in each case, which includes: determination of the weighted average (%) of natural boundaries distribution (for a stow, or as they are arranged in larger groups), taking into account the "weight" (fraction) of landscape area of key sites in the cumulative (total) landscape area;

Table 2. **Representative natural boundaries of the Permafrost zone of the Bolshezemelskaya tundra (sample set from data massif after [*Osadchaya et al., 2015*])**

Natural boundaries index	Brief characterization of natural boundaries (composition of the upper part of soil section)	Relatedness to natural/ geocryological subzone	Distribution of permafrost
1	2	3	4
1a	Forest: spruce and birch; spruce and shrub-subshrub-moss-lichen (clayey silt)	II, III	Permafrost ≤5 %, linearly elongated patches of permafrost of both merging and sporadic types, more often on the slopes between genetic landscapes
1c	Thin forest: spruce-birch; moss-lichen (clayey silt)	II, III	Permafrost ≤5 %, merging type
2a	Bog: fenny, grass-mossy (peat)	II, III, IV	New formations of permafrost
2b	Bog: hummocky, shrub-subshrub- grass-moss with sparse trees (peat)	II, III, IV	New formations of permafrost
2c	Bog: ridge-hollow (lakelet), subshrub- grass-moss (peat)	III (rarely), IV	Permafrost – less than 30 %, merging type; thin (not more than 4–5 m) Permafrost confined to peat “ridges”
2d	Flat extensive thermokarst lows; cotton grass-sedge-moss with swamp ledum (peat)	I-a, I-b, I-c	Permafrost – 100 %, predominantly (over 90 %) of merging type
		II	Permafrost predominantly of merging type; complicated alternation of non-permafrost and frozen patches
3a	Peatlands with flat-topped hummocks; ledum-cloudberry moss-lichen on the hummocks and cotton grass-sedge-sphagnum in interhummocks depressions (peat)	I-a, I-b, I-c	Permafrost – 100 %, merging type
		II	Permafrost – 80–90 %, including 10 % for non-merging type. Permafrost confined to hummocks, partially to interhummock depressions; beneath interhummock depressions occur predominantly through taliks
		III	Permafrost – 70–80 %, merging type. Permafrost confined to hummocks, through taliks beneath interhummock depressions
3b	Peatlands: polygonal ledum-cloudberry-lichen on the blocks and cotton grass-sedge-sphagnum with birch in polygonal depressions (peat)	I-a, I-b	Permafrost – 100 %, of merging type
3c	Peatlands: polygonal lake-dominated with ledum-lichen associations on ridges and cotton grass-sedge-sphagnum in the inter-ridge depressions (peat)	I-a	Permafrost – 100 %, merging type
3d	Peatlands: raised-himmocky with lichen-ledum associations on the hummocks and ledum-cloudberry-sphagnum with dwarf birch thicket in interhummocks depressions (peat)	II	Permafrost – 50–70 %, merging type; permafrost confined to hummocks, beneath interhummock depressions – through taliks
		III	Permafrost – 60–70 %, merging type; permafrost confined to hummocks, through taliks beneath interhummock depressions
		IV	Permafrost – 50–60 %, merging type; permafrost confined to hummocks, through taliks beneath interhummock depressions
3e	Khasyreys with dwarf birch-ledum-lichen associations on the blocks and sedge- mixed herbs with willow stand on the bottom (peat, sand)	I-a, I-b, I-c	Permafrost – 100 %; merging permafrost – до 90 % (depending on the khasyrey development stage); closed taliks 20 m and more, confined to most moistened areas; layered permafrost development is likely (beneath peat hummocks – permafrost with thickness less than closed talik)
		II	Permafrost – 5–60 % (depending on the khasyrey development stage), confined to peat hummocks; through taliks on flat and exceedingly moistened areas

Continued tabl. 2

1	2	3	4
4a	Tundra: flat and undulating flatlands, dwarf birch thicket-willow stand-subshrub-moss, locally lichen-ledum with dwarf birch thicket, with sparse trees (clayey silt; peat, clayey silt)	II	Permafrost – 10–20 %; complicated combination of thawed and frozen patches; мощность permafrost from 1–2 to 50 m, predominantly of merging type; permafrost is developed mostly on flat peatland areas with ledum-lichen associations, beneath large coalesced tussocks and other remarkable positive microrelief foms
		III	Permafrost – 10–20 %; complicated combination of thawed and frozen patches; permafrost thickness from 1–2 to 30 m; non-merging permafr: ocks are not typical; permafrost is developed mostly on flat areas with thick moss cover (up to 30–35 cm) or peatified areas with ledum-lichen associations, and also beneath large coalesced tussocks
		IV	–
4b	Tundra of slightly concave gentle slopes with tree-like willow stands mixed herbs-herbs -moss with some convex blocks of dwarf birch-willow stands-moss-lichen (sand)	I-a, Ib, I-c	Permafrost – 100 %, of merging type ≤5 %. Permafrost of merging type confined to sparse hummocks
		II	Permafrost ≤5 %; through taliks ≥95 %. Permafrost confined to sparse hummocks
		III	–
4c	Tundra of slightly concave interfluves and valleys with tree-like willow stands, mixed herbs-herbs –moss with raised blocks of dwarf birch thicket- willow stands-moss-lichen (sand)	I-a, I-b, I-c	Permafrost – 100 %, non-merging type
		II, III	–
4i	Tundra hilly lichen-crowberry- amprocks with grass and subshrubs (sand)	I-a, I-b	Permafrost – 100 %, merging type
		II	Permafrost ≤10 %, predominantly non-merging type; exceedingly rarely – merging type; through taliks ≥90 %

– with the use of information on the extent of permafrost strata in various natural boundaries, its fraction within the natural boundaries area is calculated for each landscape.

Table 2 shows a sample set from the entire range of natural boundaries, providing also characteristics of those further used for substantiation of the permafrost subzone boundaries. A complete list of natural boundaries and their permafrost parameters are given in [*Osadchaya and Tumel, 2012; Osadchaya et al., 2015*].

The data on the permafrost areal extent for each natural boundaries (Table 2) are further used for refining the permafrost zones/subzones boundaries. As was already mentioned, weighted averages of the permafrost area within the entire landscape were derived from the landscape morphology parameters and the area of permafrost distribution in each constituent part of the landscape structure. The calculation results served as a basis for verification of the permafrost zones/subzones boundaries, while analysis of the causes of any substantial variation in the permafrost areal extent provides ground for delimiting natural boundaries to serve as regional indicators [*Osadchaya et al., 2013*].

In general terms, the number of representative natural boundaries allocated in each natural subzone/zone varies within the groups as shown below: I (I-a, I-b) – 12; II – 19; III – 14; IV – 10. The number of subzones "shared" with neighboring natural boundaries tends to be close: I, II – 10; II, III – 12; III, IV – 10.

MORPHOLOGICAL STRUCTURE OF LANDSCAPES

The values obtained for the areas of groups of natural boundaries (% of the total area of landscape type) are represented by Table 3, which also includes marking for the following cases: if landscape occurs rarely (less than 3 times) on the key sites, the lines for them are marked by a gray shaded fill; if the landscape was totally absent, a dash is used in the respective column.

Northernmost taiga (IV)

The subzone is dominated by forest natural boundaries, and bogs appear a subdominant element. The natural boundaries of peatlands and tundra are developed insignificantly. The general trend shows a decrease in the area covered by forest from landscapes with higher to lower absolute elevations; the area of all other groups of natural boundaries tends to increase in that same direction. The general "permafrost" background forms at the expense of peatlands (up to 50–60 % of permafrost); inasmuch as they occupy a subordinate position in the entire landscape structure, the permafrost distribution also appears insignificant. According to the general

Table 3. **Morphological structure of landscapes, %**

Notional index of genetic landscape	Distribution of groups of natural boundaries			
	Forest	Bog	Peatlands	Tundra
Northernmost taiga (IV)				
A (0)	100 (0)	0	0	0
B (1)	88 (0)	11 (1)	0	1 (0)
C(1.5)	87 (0)	10 (1)	1 (0.5)	2 (0)
D (4)	82 (0)	14 (3)	2 (1)	2 (0)
E (8)	60 (0)	30 (4)	8 (4)	3 (0)
F (10)	50 (0)	35 (5)	10 (5)	5 (0)
G (8)	54 (0)	35 (5)	6 (3)	5 (0)
Southern forest-tundra (III)				
A (50)	0	0	0	100 (50)
B (11)	83 (0)	1 (0)	0	16 (11)
C (20)	66 (0)	7 (≤0.5)	≤0.5 (≤0.1)	27 (20)
D (24.5)	45 (2)	16 (0.5)	3 (2)	36 (20)
E (22)	43 (2)	20 (0.5)	27 (19)	10 (0.5)
F (21.4)	40 (1)	32 (1)	26 (19)	2 (0.4)
G (11.6)	48 (3)	39 (1.5)	12 (10)	1 (0.1)
Northern forest-tundra (II)				
A (75)	0	0	≤0.5 (≤0.2)	≥99.5 (75)
B (65)	2 (0)	1 (0)	6 (5)	87 (60)
C (65)	2 (0)	2 (0)	6 (5)	88 (60)
D (60.5)	3 (0)	10 (0)	8 (5.5)	78 (55)
E (48)	8 (0.2)	16 (0)	41 (36)	33 (12)
F(60)	4 (0)	20 (0)	60 (51.5)	16 (8.5)
G (7)	72 (4)	24 (0)	4 (3)	–
Tundra (I)*				
A	–	–	–	–
B	0	1	8	91 (14)
C	0	2	30	64 (9)
D	0	0	31	63 (9)
E	0	0	22	71 (8)
F	0	0	6	74 (8)
G	0	2	21	55 (3)

Note. Distribution of permafrost relative to landscape area is given in parenthesis (%).

* Distribution of closed taliks relative to landscape area is given in parenthesis (%).

trend, the absolute area of permafrost distribution increases as the absolute elevations of the landscapes decrease. Landscape A shows a total absence of permafrost.

On the whole, the maximum extent of permafrost (10 %) is typical for landscape F, which distinctly evidences the coincidence of the northernmost taiga subzones (in its northern part) with the island permafrost subzone.

Southern forest-tundra (III)

The subzone is dominated by forest natural boundaries, and its subdominant types (depending on the landscape) are either peatlands (E), or bogs (F, G), or tundra (B, C, D) natural boundaries. Landscape A is represented solely by the tundra.

There is a general trend for a decrease in the forest cover extent from landscapes with higher to the lower absolute elevations (except for A); the area of natural boundaries of peatland and wetland progressively increases in the same direction. There is no distinctive trend for the "weight" (fraction) of natural boundaries of the tundra landscapes in the overall structure, but it generally decreases as absolute elevations become lower. The permafrost "background" is formed by the tundra landscapes types A, B, C, D, and at the expense of peatlands in landscapes E, F, G (in some sites, permafrost has formed in 80 % of the area). There is no clear trend showing permafrost area increase/decrease with changes in absolute elevations; except for landscape A (50 % of the area), where the "permafrost background" is sufficiently uniform, underlying from 11 to 24.5 % of the area, which is associated with the fact that areas with the occurrence of permafrost developed primarily within the tundra and peatland areas. The former are subdominant, as was discussed above, in landscapes with higher absolute elevations, the latter (at about the same area ratios) – in landscapes with lower elevations. On the whole, the permafrost fraction in the landscapes range from 11 to 50 %, which conclusively indicates congruence between the southern forest-tundra subzone and massive-island permafrost subzone.

Northern forest-tundra (II)

The dominant natural boundaries in this subzone vary depending on the landscape type: the tundra natural boundaries tend to dominate in landscapes types A, B, C, D, whereas peatland natural boundaries – in landscape types E, F. Only landscape type G is dominated by forests (the "warmest" landscape, developed along the narrow elongated fragments along large rivers).The "permafrost background" is formed primarily by the tundra presence in landscapes types A, B, C, D, and at the expense of peatlands in landscapes E, F, G (in some parts, permafrost underlies 90 % of the area). At the same time, in the forested and boggy areas, the permafrost fraction range from insignificant to non-existent. These sites may also occupy extensive areas, alternating with territories where areas underlain by permafrost tend to dominate.

The general trend shows a decrease in areas underlain by permafrost as the absolute elevations of the surface area become lower (except for E type landscape, where the tundra dominates among natural boundaries 4a). In total, across the landscapes (except for E type, and forested G type), the permafrost interval accounts for 60 to 75 %, which attests to the congruence of the northern forest-tundra subzone with the discontinuous permafrost subzone.

Tundra (I)

At the subzone level, all the landscapes tend to be dominated by the tundra natural boundaries, with peatlands being subdominant type. The permafrost distribution is ubiquitously continuous, with closed taliks confined mainly to the inter-block depressions and extensive areas overgrown by shrubs (willow trees). Closed taliks occur widely on landscape type B, with more developed mesoreliefis. In general, the permafrost zone of the Bolshezemelskaya tundra distinctly reflects both zonal and regional peculiarities of the formation of its morphological structure. The forest and tundra natural boundaries feature zonal characteristics. The forest natural boundaries dominate ubiquitously in the northernmost taiga subzone within the southern part of the permafrost zone. As the southern forest-tundra advances northwardly and grades into northern forest-tundra, their fraction reduces in the morphological structure, and only relict patches of forest vegetation are observed in the tundra zone. Accordingly, the occurrence of natural boundaries of the second type (tundra) increases from south to north in the tundra zone. Analysis of the distribution of natural boundaries developed on organogenic soils has provided evidence gradual replacement of natural boundaries of bogs with peatlands, in that same direction.

Regionally, landscapes in subzones II, III, IV are highlighted due to the highest absolute surface elevations (220–330 m). The mechanisms of zonal (climate) impact on the formation of the natural environment are remarkably realized in these landscapes, while influence of regional factors – moisture/soil cover conditions appear negligibly small in them. For example, in the taiga subzone, only northernmost landscape A is completely covered with forest, whereas other landscapes represent a combination of natural boundaries of forests (dominant type), bogs, peatlands, and tundras. The situation with landscape A changes drastically as it grades into the forest-tundra: it is represented only by the tundra natural boundaries; landscapes with lower absolute elevations are still the combination of natural boundaries of forests, bogs, peatlands and tundras, just in different percentage rating.

The results of analysis of qualitative and quantitative characteristics of the landscape morphology conducted for each natural sub-zone revealed some most common patterns, as given below.

1. In the northernmost taiga and southern forest-tundra subzones, forest extent tends to reduce beginning from landscape with high absolute surface elevations (A, B, respectively) to low (F, G). The area occupied by natural boundaries on the organogenic soils (bogs and peatlands) increases in the same direction. The tundra natural boundaries in the northernmost taiga are developed sparsely throughout the area, while in the southern forest-tundra, their areal extent decreases with the increasing degree of bogginess (with minimum development on landscapes F, G).

2. In the northern part of the region, confined to the northern permafrost zone, the most distinct patterns of morphological changes in the landscape structure (featured by increased waterlogged areas; reduced fractions of the tundra natural boundaries; slightly developed forest stands) can be traced in the northern forest-tundra, from landscapes A, B to landscape F. The forested landscape G “stands out” due to its development in fragments, mainly along large rivers.

3. Forest natural boundaries are localized in the “low”, “warm” landscapes near the northern border of their present tree line position, where influence of regional factors is the highest. Forest natural boundaries are almost totally absent from the high watershed areas, which is indicative of the lack of response of natural baseline complexes on modern climate change at regional scale.

4. The tundra zone shows a general, though fairly indistinct, increasing trend for the area occupied by peatlands, from landscape B to landscape G (the tundra natural boundaries tend to decrease in that same direction).

More detailed information on the structure of each group of natural boundaries is required for verification of quantitative indicators for the permafrost-affected areas. Table 4 provides data related to the tundra natural boundaries: the refined extent of natural boundaries for groups with particular permafrost-geotechnical and geobotanical characteristics.

Table 4. **Distributions of the tundra natural boundaries (% of the landscape area)**

Natural subzone	Additional characteristics of the tundra natural boundaries	Genetic landscapes						
		A	B	C	D	E	F	G
Tundras	Developed on clayey-silt soils	–	40	60	61	56	60	25
	Developed on sandy soils	–	51	4	2	15	14	30
	Natural boundaries of tree-like willow stands	–	0	4	6	7	20	20
	Total areas with merging permafrost	–	77	55	54	63	66	52
Northern forest-tundra	With predominance of non-permafrost soils	1	4	7	9	18	5	–
	With predominance of permafrost	98	83	81	69	15	11	–
	Natural boundaries of tree-like willow stands	1	3	2	1	2	0	–

Table 5. **Distribution of natural boundaries of peatlands (% of landscape area)**

Natural subzone	Natural boundaries type	Genetic landscapes						
		A	B	C	D	E	F	G
Tundras	3a	–	0	14	3	3	5	10
	3b	–	2	6	16	10	0	11
	3c	–	0	3	3	3	0	0
	3e	–	6	7	9	6	1	0
Northern forest-tundra	3a	0	5	6	2	7	49	1
	3d	0	1	0	6	34	11	3
Southern forest-tundra	3a	0	0	0	0	15	14	3
	3d	0	0	≤0.5	3	12	12	9

Thus, the data on the extent of growth of closed taliks can be considered valuable for the tundra zone, which are also inherent in natural boundaries type 4b, 4c (for sands, see Table 2), though appear unrepresentative for other natural boundaries, developed on the sands. At the same time, in the southern shrub tundra subzone closed taliks are commonly present in the tundra natural boundaries, developed on clayey silts. When investigating the tundra natural boundaries of the northern forest-tundra, it is necessary to refine the distribution of natural boundaries type 4b, 4c (with predominance of through taliks), as well as the areal extent of natural boundaries 4a (occur mainly on non-permafrost soils). Table 5 shows the distribution of indicators of natural boundaries of peatlands, which allows to calculate the fraction of through taliks or permafrost of non-merging type developed within their borders.

The landscape morphology data resulted from the studies can be used to refine the boundaries of the permafrost subzones. In the context of a particular sub-zone, it is possible to calculate actual area (%) underlain by permafrost, taking into account both the permafrost distribution in the natural boundaries (Tables 2, 4, 5), and the occurrence of this type natural boundaries within the genetic landscape, and morphological structure of the latter. Rounded calculation results are shown in Table 3 (for the tundra zone – the fraction of areas with non-merging permafrost in the tundra natural boundaries). These results, supplemented with the data on the morphological structure of the landscape and the extent of permafrost within them, corroborate the correctness of the allocated natural boundaries-indicators previously selected by the authors for delineation of the boundaries between the permafrost subzones [*Osadchaya and Tumel, 2012*].

It should be noted that the zonality of the natural conditions of the region is pointedly expressed within a relatively small areal extent. At this, genetic landscapes may be oriented in such a way that they cross several natural subzones. They feature the cumulative impact of the zonal and regional environmental factors on the permafrost conditions. As a result, the boundaries of permafrost subzones may not reflect taxonomic units of the geological systems which should be considered in geoinformational (including maps) modeling in geocryology.

CONCLUSIONS

1. All the considered genetic types of landscapes occur almost in each and every zonal landscapes of the Bolshezemelskaya tundra, except for the interfluves with the highest absolute elevations (220–330 m), and all groups of natural boundaries, except for the forest type (non-existent in the tundra).

2. Natural boundaries of forests and tundras are attributed to zonal level. However, the processes of replacement of typical peat bog landscapes with peatlands remarkably progress from south to north.

3. Zonality is most distinctly manifested in landscapes with the highest absolute elevations: A, B, C (marked by shrinking areas of forest and expansion of the tundra zone). In this context, the impact of regional factors (moistening, soils) appears insignificant, which is pointedly reflected in the distribution of bogs and peatlands: on such elevations, they show no clear trends within any of the zonal landscapes.

4. The absolute elevation level (storied relief) does affect the distribution of forest and tundra natural boundaries. As the surface elevation tapers from the maximum (220–330 m) to 90 m or less, the area size of forest and tundra natural boundaries tends to decrease. This is the so called “altitudinal zonality”. The exception is the northern forest-tundra, where forests are confined to the fore-valley landscape G (55–70 m). The forest coverage of this landscape accounts for 72 %, with exceedingly low distribution of permafrost (7 %).

5. In the same-name geological and geomorphological landscape types (genetic landscape) and their respective groups of natural boundaries, permafrost conditions are differentiated when one landscape subzone is succeeded by another, which should be taken into account when the landscape-indicator research method is employed. In this case, the data on landscape morphologies and permafrost distribution within them are used to identify natural boundaries-

indicators, the appearance/disappearance of which attests to the shift of geocryological subzone.

6. The following parallels between the natural and permafrost zonality have been established: tundra zone – continuous permafrost subzone, the northern forest-tundra subzone – discontinuous permafrost subzone, southern forest-tundra subzone – massive-island permafrost subzone, northernmost taiga subzone (northern part) – island permafrost subzone.

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