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GENESIS AND EVOLUTION OF PEAT PLATEUAS IN THE SPORADIC PERMAFROST AREA IN THE EUROPEAN NORTH-EAST (MIDDLE BASIN OF THE KOSYU RIVER)

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This paper provides analysis of origin, evolution and modern state of permafrost peatlands in the southernmost parts of East European permafrost zone on the basis of the data on the botanical and palynological composition of peat. The surfaces of existing peat plateaus represent the remnants of past wetlands and bogs, which development had been caused by thermal erosion processes. The paleoreconstruction allowed to identify the onset of peat accumulation in the middle Holocene about 8 ka BP. The growth of peat seems first to have considerably slowed and almost ceased between 2,500–850 BP, which was followed by its gradual and slow accumulation at a later stage. The vegetative cover of peat mounds (palsas) prevents degradation of permafrost under modern climate warming. Thawing of permafrost peat plateaus from the surface occurs either due to their destruction or under the conditions of impeded surface runoff, which may result in the development of lakes and fens.

Genesis, evolution, permafrost, peat plateau, palynological and botanical composition

INTRODUCTION

In the NE of European part of Russia, permafrost peat plateaus are widely developed in the areas of tundra and forest-tundra, whereas they are fairly scarce in the northernmost taiga zone. Given a significant warming trend in the region, the permafrost, or perennially frozen deposits (PFD), will be subjected to long-term degradation [*Oberman, 2008*]. Inasmuch as peatlands hold a significant stock of preserved organic carbon, the peat pool plays an important role in the carbon biogeochemical cycle and the processes of climate change [*Borgmark, 2005*]. The peat monoliths in themselves are archives of information about the paleo-environments [*Yeloff and Mauquoy, 2006*].

Throughout the Holocene, the borders of permafrost zone and northernmost geographical progression of nemoral vegetation were repeatedly subjected to changes in the European North [*Khotinskii, 1982*]. In the Atlantic and in the middle Subboreal periods, the permafrost degraded and the tree line advanced as far as the coast, whereas at the end of the Subboreal, subsequent to the cold snap, the permafrost boundary was localized significantly more southward versus its modern limits [*Maksimova and Ospennikov, 2012*]. The permafrost has thus far survived only under peat plateaus in the circumpolar taiga, which serve as perfect estimation targets for climate change impacts in case of permafrost degradation.

The study area is situated on the high-level waterlogged terrace above the flood-plain with the relief formed by erosion-accumulative processes in the interfluve area of the Bolshaya Inta and Malaya Inta rivers (58–60 m a.s.l.). As an object of study it is organized into an extensive system of bogs "Intanyur" with its area exceeding 3,000 ha. The Intanyur is one of the southern most systems of peat plateau in the European part and is characterized by a braided hydrological network (lakes, lakelets, streams), great diversity of plant species, and by a complicated structure of vegetation and soil covers. Quaternary deposits are represented by a complex of lacustrine-boggy sediments, with their thickness up to 6 m. Peat deposits up to 3.0–3.5 m thick on the mound tops are underlain by a layer of frozen sands and (or) sand-loams, grading below into thick hard-frozen silty clay-loam. The interpretation of satellite imagery coupled with detailed land surveys resulted in generation of a large-scale map, which allowed delimiting a key site with its total area of 576.6 hectares.

The purpose of this work is to provide a detailed characterization of origin, evolution and modern state of the perennially frozen peat plateaus coincident with the southern border of the contemporary permafrost zone, in the middle reaches of the Kosyu river.

The field works included standard geo-botanical descriptions [*Shennikov, 1964; Ipatov and Kirikova,* *1997*], the initiation and description of soil profiles, and sampling of soil horizons. Latin names of the plant species are given in accordance with the report by [*Czerepanov, 1995*]. Determinations of soil types and indexing of genetic horizons were consistent with the World Reference Base for soil resources (International soil classification system for naming soils and creating legends for soil maps) [*IUSS..., 2014*]. Large-scale soil maps generated using the ArcGIS 9.1 software and manual digitized polygons as the basis, were supplemented with the *QuickBird* satellite imagery and with the descriptions of soil profiles and plant communities.

RESEARCH RESULTS

Study site characterization

The study site is located on the southernmost border of the permafrost zone in the interfluve area of the Bolshaya Inta and Malaya Inta rivers, both being the tributaries of the Usa river (the Pechora Rv. basin) (Fig. 1). Geographically, the area is situated in the circumpolar taiga subzone and is confined to the central part of Intin region of the Komi Republic and is subsumed into the subarctic climate zone characterized by long, cold winters and fairly short cool summers. The mean annual air temperature is about −4 °C, averaging −19.5 °C in January, and +13.5 °C in July; the mean annual amount of precipitation is about 700 mm. The prevailing wind direction is southernly for winters, and northernly for summers [*Atlas..., 1997*].

The site is positioned on the southern boundary of the permafrost zone, within the extent of sporadic distribution of PFD, up to 15 m thick [*Geocryological Map..., 1998*]. The widely spread boreal wetlands, including peat plateaus, are beneficial for the preservation of permafrost areas in the circumpolar taiga subzone. The mean annual temperature of permafrost ranges from 0 to −0.5 °C. The instrumental drilling in 2013 revealed that the permafrost table occurs on permafrost mounds at a depth of 0.5–0.7 m, lowering 10 m deeper on the periphery of fens adjacent to the peat plateaus. That is, within the extent of the study site, permafrost patches are preserved only under palsas on the peat plateaus, forming a system of through-taliks below the non-permafrost fens (swampy hollows).

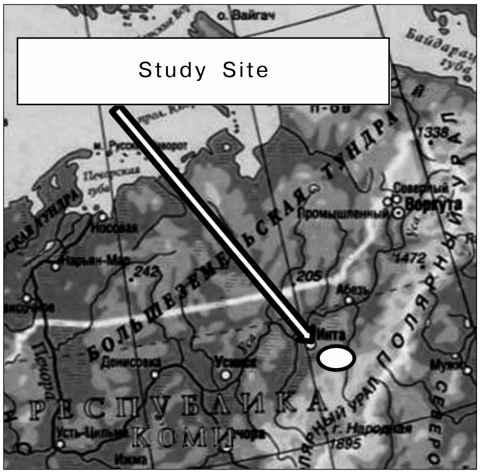

Fig. 1. Location of the study area.

Characterization of vegetation cover of the "Intanyur" bogs system

The study bog forms a complex system. It is a typical peat plateau occupying a vast flat watershed area. It comprises mound forms at different stages of their growth, which account for 40–70 % of the area occupied by the palsa peatland complexes. The well-defined frost mounds of round shape represent the predominant type of landforms (permafrost table depth: 45–70 cm in July–August), with their height varying from 2.0 to 3.5 m, and are over 20–30 meters in dia. In the marginal parts, frost mounds elongate to form ridges. Most of the plateau abounds with hummock-lakelets and hummock-fenny complexes.

At elevations, polydominant subshrub-lichen and subshrub-cloudberry-lichen plant communities are wide-spread. Herbaceous-low shrub level of the mounds tops is predominantly extenuated, depressed and formed by *Ledum palustre*, *Empetrum hermaphroditum*, *Rubus chamaemorus*, *Betula nana*, *Oxycoccus microcarpus*, *Vaccinium vitis-idaea* and *V. uliginosum*. The projective cover of each of these plant species ranges from 5 to 25 %. The topsoil cover is dominated by lichens (coverage: 70 % of the area). The most abundant and persistent are *Flavocetraria nivalis*, *F. islandica, Cladonia arbuscula*, *C. rangiferina*, *C. stellaris* (with total coverage up to 40 %).

The presence of other lichens appears essentially lower. Mosses in most of these communities are represented solely by *Polytrichum strictum*, *Pleurozium schreberi* and *Dicranum elongatum*, with total abundance of these species not exceeding 30 %. Sphagnum mosses (*Sphagnum fuscum*, *S. compactum* et al.) are rare. The vegetation cover on the mounds tops occasionally bears the evidence of the weathering-induced degradation.

The slopes of peat mounds and mounds from the marginal part slightly differ in composition and structure of plant communities, with trees growing on some of them – *Betula pubescens* and *Picea obovata* (up to 2 m in height). The vegetation cover is marked by the a substantially increased role of *Ledum palustre*, *Chamaedaphne calyculata* and *Andromeda polifolia*. The plants are higher and more stout. Plant communities with the dominance of *Betula nana* have formed a dense canopy (coverage: up to 90–100 %). Beneath them, *Rubus chamaemorus* and *Vaccinium* *myrtillus* tend to grow. Other species appear similar to those on the mounds summits. The soil cover is either missing or sparse, and is for the most part composed by lichens: *Polytrichum strictum*, *Pleurozium schreberi*, by the species the *Dicranum*, *Sphagnum fuscum*, *S. compactum*, *S. russowii* genus, etc.

The topographic lows are waterlogged and impassable in the central part. They are formed mainly by cotton-grass-sphagnum and sedge-sphagnum and rotation phytocenoses with predominance of *Eriophorum russeolum*, *Carex limosa* and *C. paupercula*, rarely *Carex chordorrhiza*, *C. rotundata* and *Menyanthes trifoliata*. The soil cover is dominated by *Sphagnum lindbergii*, *S. riparium*, *S. jensenii* and *S. majus*.

In general, the vegetation cover of hummock-fenny bog is represented by a complex consisting of low shrubs-lichen communities dwelling on the mounds, and sedge-sphagnum and cotton grass-sedge-sphagnum communities – in the topographic lows. Peat mounds covered with soils of peat plateaus (Cryic Histosols) occupy a considerable area (about 40 % of the bog surface) of the study site. The mounds shape vary from oval to predominantly elongated to form flat-topped peat ridges facing SE to NW. The height of the mounds ranges from 1 to 3 m, they are from 10 to 20–30 m in diameter across. The micro-relief of the day surface is dominated by hummocks 20–30 cm in height and 30–50 cm in diameter. The area occupied by thermokarst lakes accounts for about 8 % of the hummock-fenny bog.

Characterization of the “Intanyur system” soil cover

The compiled maps contain information on soil types of the polygons, their geo-referencing and the area size. The analysis of basic digital data, which served as a basis for soil maps generation, provided a good study of the soil cover structure of key sites (Fig. 2).

The spots of bare peat are formed primarily on the edges of peat mounds. The areas of bare peat circles account for about 1 % of the hummock-fenny bog complex. The area of individual bare circles ranging from 2 to 15–17 m in dia varies from 5 to 300–500 m^2, with the length of individual mounds exceeding 500 m (Fig. 2). According to World Reference Base [*IUSS..., 2014*] soils of bare circles are classified as Cryic Histosols Turbic. The signs of pedoturbations with the processes of exfoliation and peat-structuring marked in the upper peat horizon represent a distinguishing diagnostic feature of these soils.

Soils of non-permafrost peatlands (Fibric/Hemic Histosols) account for about 50 % of the bog surface. Non-permafrost soils develop immediately below the sedge- and cotton-grass, moss, grass-moss and moss communities of topographic lows in the micro-relief. About 4 % of the peatland bog is occupied by non-permafrost peat soils (Fibric Histosols Floatic) of the greatly waterlogged fens, which represent in themselves the initial stages of plant colonization of shallow thermokarst lakes and creeks. The bog rims with mineral-cored slopes and separate internal treed massifs are occupied by Albic Podzols developed on the sands (3 % of the area).

Morphology and botanical composition of frost mounds

The descriptions of Cryic Histosols – soil of permafrost peat mounds (palsas) (Table 1) and Histosols – non-permafrost soil of fens (Table 2) – are pro-

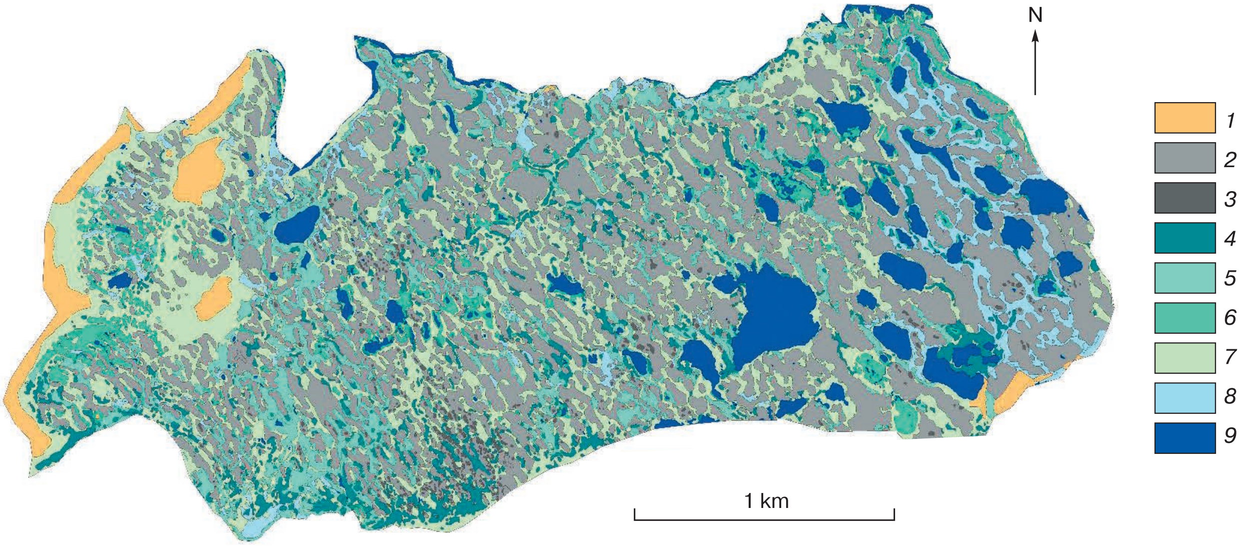

Fig. 2. Soil map of the study site.

Soils: *1* – Albic Podzols, *2* – Cryic Folic Histosols, *3* – Cryic Histosols Turbic, *4* – Fibric (Hemic) Histosols, *5* – Fibric Histisols, *6* – Fibric Histosols Floatic, *7* – soils complex of bog hollows (Histosols), *8* – Hemic Histosols. *9* – lakes.

Table 1. **Morphological description of dry-peat permafrost soil of peat mounds (Cryic Folic Histosol)**

Horizon	Depth, cm	Morphological description of horizons
O	0–5	Yellowish-dark-brownish-loose, dry subshrub-moss-lichen peaty mat, interwoven with roots; the grading of colors and textures is distinct
T_1	5–15	Brownish-brown low shrub sphagnum peat, R = 15–20 %
T_2	15–25	Dark-brown low shrub sphagnum peat, wet, layered, grassy turf, compacted, R = 25 %
T_3	25–87	From light- to dark-brown, sedgy-hypnaceous lowland peat, wet to a depth of 45 cm, with permafrost lying immediately below, massive cryogenic structure, layered, compacted, R = 20–25 %
T_4	87–94	Dark-brown subshrub-sedgy lowland peat, massive cryogenic structure, in the bottom part of core sample ice-rich interlayer 2 mm thick, ice-rich, R = 30–35 %
T_5	94–106	Dark-brown rotational-sedgy lowland peat, ataxitic cryogenic structure, ice soil, coarse-grained structure of ice (grain size 1–3 mm), pure and transparent ice, R = 30–35 %
T_6	106–150	Dark-brown sedgy lowland peat, ataxitic cryogenic structure, coarse-grained (grain size 2–3 mm) ice is pure and transparent, ice soil is encountered, R = 30–35 %, with 110 cm R = 45–50 %, with 130 cm R = 35 %
T_7	150–170	Brown-brownish arboreous-sedgy lowland peat, massive cryogenic structure, ice-rich, fragments of shrub stems, R = 30–35 %
T_8	170–190	Brown-brownish sphagnum lowland peat, ice-rich with elements of laminated cryogenic structure, R = 25 %
T_9	190–210	Dark-brown-brownish willow-sphagnum lowland peat, extremely ice-rich, massive cryogenic structure, R = 45 %
T_{10}	210–220	Dark-brownish brown, extremely ice-rich, willow-sphagnum lowland peat, R = 45 %
T_{11}	220–250	Brown-brownish sphagnum lowland peat, ice-rich, massive cryogenic structure, R = 20–25 %
T_{12}	260–280	Light-brown-brownish hypnaceous lowland peat, large interlayers of ice up to 3 mm thick, R = 20–25 %
T_{13}	280–300	Light-brownish sphagnum lowland peat, in the uppermost part admixed with brown hypnaceous lowland peat, massive cryogenic structure, R = 20–25 %
T_{14}	300–320	Light-brown hypnaceous lowland peat, massive-laminated cryogenic structure, layers of ice up to 2 mm, R = 20–25 %
T_{15}	330–360	Dark-brownish rotational-hypnaceous lowland peat, extremely ice-rich, massive cryogenic structure with elements of laminated structure, layers of ice with thickness 1–2 mm, R = 25 %
	360–590	Glaucous-gray sand-loam, massive and laminated cryogenic structure
	590–1000	Grayish-glaucous clay-loam, extremely ice-rich, large crystals of ice

Note. R – level of peat decomposition.

Table 2. **Morphological description of oligotrophic peat soils of fens (Fibric Histosols)**

Horizon	Depth, cm	Morphological description of horizon
O	0–5	Light-yellowish-green fresh sphagnous tirr, spongious, wet, distinct grading of shades color
T_1	5–10	Yellowish-brown sphagnous transition peat, layered, wet, weakly compacted, distinct grading of shades color, R = 5–10 %
T_2	10–20	Yellowish-brownish sphagnous transition peat, wet, spongious, roots of low shrubs, R = 10 %
T_3	20–40	Yellowish-brownish sphagnous transition peat, layered, saturated with water, R = 10–15 %

vided for the study area, along with botanical characteristic and palynological composition of soil horizons.

The Inta-1 section is located in the central part of hummock-fenny complex on the summit of a permafrost peat mound (Fig. 3). The height of flat-topped peat plateau averaging 2–3 m, they are partially covered with cryogenic spots. The vegetation cover is low shrub-lichen, with the latter dominated by *Ledum palustre, Vaccinium vitis-idaea*, *V. uliginosum*, *Betula nana* and *Cladonia arbuscula*, *C. rangiferina* lichens. Bare peat circles occupy up to 10 % of the peat mound. The depth of seasonal thaw on the mound is 35 cm.

The peat mound is composed primarily of peat herbaceous-hypnum, sedge-hypnum and herbaceous-sphagnum, admixed with dwarf birch in composition (Fig. 4), succeeding the preexisted herbaceous-hypnum eutrophic community largely dominated by hygrophilous species (*Warnstorfia* sp., *Meesia* sp., *Menyanthes trifoliata*, etc.) in present place of the peat mound. Then *Bryidae* superseded sphagnum mosses and reigned for a sufficiently long time-period. A greater abundance of mesotrophic shrubs and subshrubs (*Salix* sp., *Betula nana* and representatives of the Ericaceae family) became characteristic of the herbaceous-low shrub level. Peats with predominance of low shrubs concordant with the present-day

Fig. 3. General view of the vegetation cover of frost mound (*a*) and the profile of dry-peat permafrost soil forming below it (*b*).

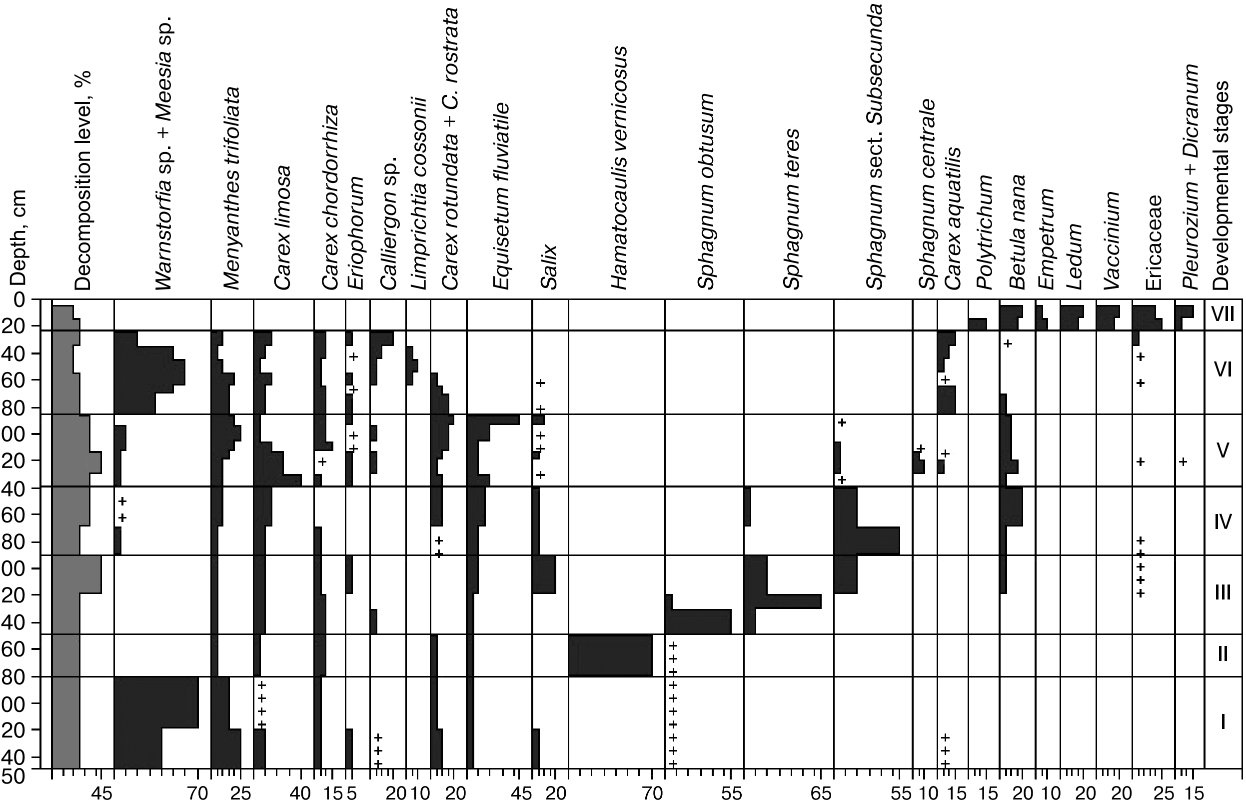

Fig. 4. Botanical composition of the Inta-1 section (mound).

vegetation are marked only in the topmost layer of peat deposits.

Palynological composition of permafrost peat mounds

Palynological analysis of the samples indicates to the presence of well-preserved pollen and spores. The analysis results revealed that permafrost peat mound consists of eight spore-pollen complexes (Fig. 5).

Spore-pollen complex I (depth interval (d.int.): 10.0–7.9 m, layer (L.) 1 – clay-loams). Shrub groups were dominated by dwarf birch-trees and shrubs, with rare presence of spruce and pine. The boggy-tundra formations were common.

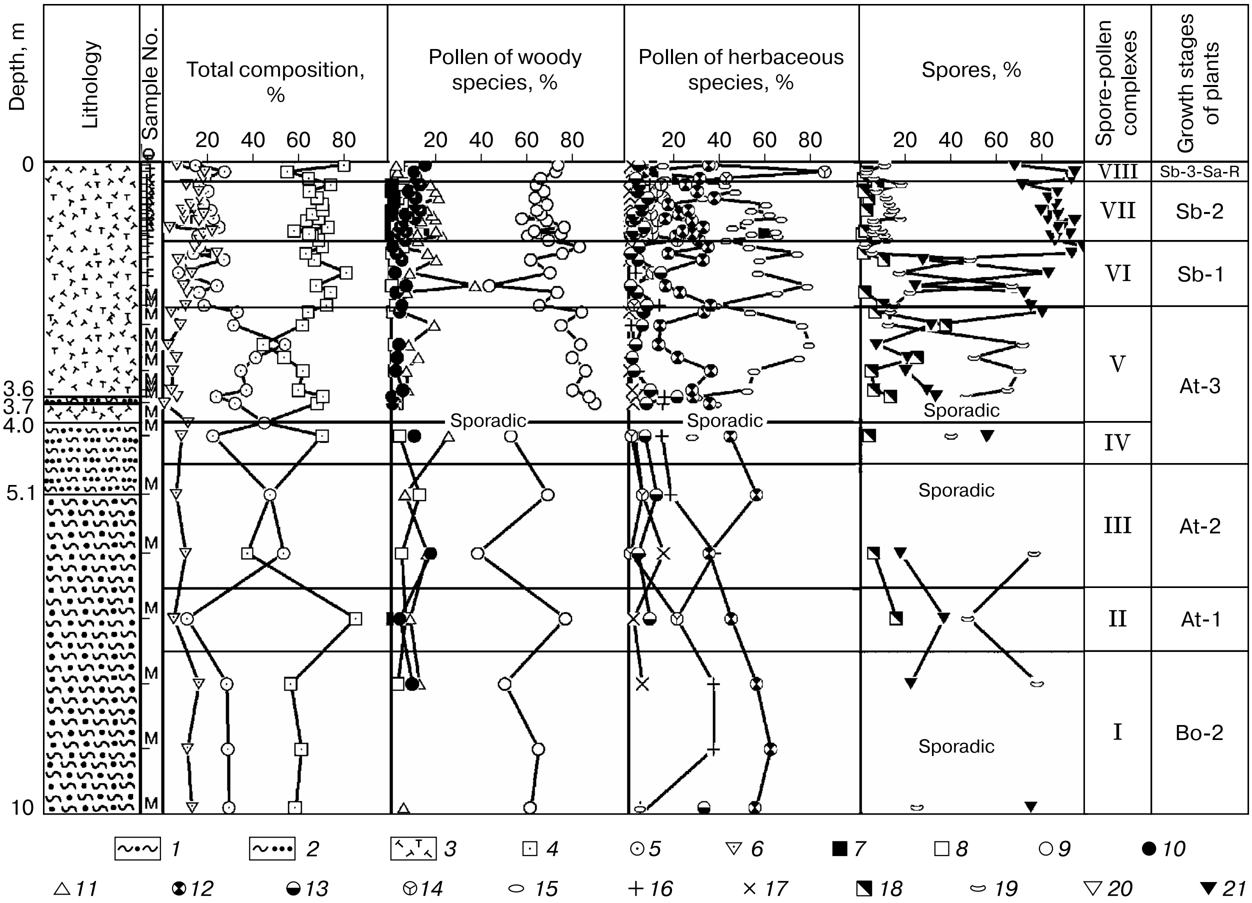

Fig. 5. Palynological composition of the Inta-1 section (mound).

1 – clay-loam; *2* – sand-loam; *3* – peat; *4* – cumulative pollen of woody plants; *5* – cumulative pollen of herbaceous plants; *6* – cumulative spores of ferns; *7* – cumulative pollen of broad-leaved species; *8* – alder; *9* – birch; *10* – pine; *11* – spruce; *12* – cumulative pollen of miscellaneous herbs; *13* – gramineous plants; *14* – heath family (Ericaceae); *15* – sedges; *16* – sages; *17* – goosefoot family (Chenopodiaceae); *18* – club mosses (Lycopodium); *19* – ferns; *20* – true mosses (Bryales); *21* – sphagnum mosses.

Spore-pollen complex II (d.int.: 7.9–6.9 m, L. 1 – clay-loams) with dominance of birchwoods admixed with spruce, pine and alder, and sporadic representatives of broad-leaved woods (ulmus, linden). Open areas were occupied by herbaceous communities and cowberry-ericaceous (Vacciniaceae–Ericaceae) dwarf shrubs.

Spore-pollen complex III (d.int.: 6.9–4.2 m, L. 1 – clay-loams, L. 2 – sand-loam) predominated by thin forests, composed of birch, incidentally by spruce and pine. Along with the boggy-tundra formations, xerophytic communities formed by wormwood and goosefoot families.

Spore-pollen complex IV (d.int.: 4.2–4.0 m, L. 2 – sand-loam), predominated by taiga forest groups, composed of spruce, pine and birch-trees, admixed with cedar. Open areas were occupied by herbaceous communities.

Spore-pollen complex V (d.int.: 4.0–2.3 m, L. 2 – sand-loam, L. 3 – peat), predominated by birch forests with presence of spruce, pine, and admixed with cedar, alder, and willow. Herbaceous associations, sedges communities and mesophilous grasslands were developed.

Spore-pollen complex VI (d.int.: 2.3–1.2 m, L. 3 – peat): shrub and subshrub groups developed from *Betula*, admixed with arborescent birch, spruce, pine and, sporadically, cedar. The boggy-tundra formations were extensively developed.

Spore-pollen complex VII (d.int.: 1.2–0.25 m, L. 1 – peat), with predominance of birch-spruce forests admixed with pine, cedar, alder, willow and even broad-leaved species (ulmus, oak, linden). Open areas were water-logged and occupied by herbaceous communities and sphagnum.

Spore-pollen complex VIII ((d.int.: 0.25–0.0 m; L. 3 – peat): was predominated by shrub groups of dwarf shrub- and shrub-birch trees, with low abundance of arborescent birch, spruce and pine. The boggy-tundra formations were existing.

Fig. 6. General view of the vegetation cover of fen (*a*) and the profile of peat oligotrophic soil forming beneath (*b*).

Morphology and botanical composition of non-permafrost fens

The Inta-1 section underlies the cottongrass-sphagnous communities of lowlands (Fig. 6). The dominant species are *Oxycoccus palustris*, *Eriophorum russeolum*, *Carex limosa* and *C. paupercula*, *Sphagnum lindbergii*, *S. riparium*, *S. jensenii* and *S. majus*.

Given that permafrost is absent from first 10 meters, ground waters systematically ingress into the section from a depth of 30 cm.

The sampling was not done at depths greater than 40 cm, since non-permafrost layers of peat tend to mix thereby, which is why the attempts to sample the peat either with a peat sampler, or by the machine drilling during winter-time indicated that it is all but impossible to determine the effective sampling depth.

Palynological composition of non-permafrost fens

On the basis of analysis conducted for oligotrophic peat soil of fens, one spore-pollen complex has been identified (Fig. 7).

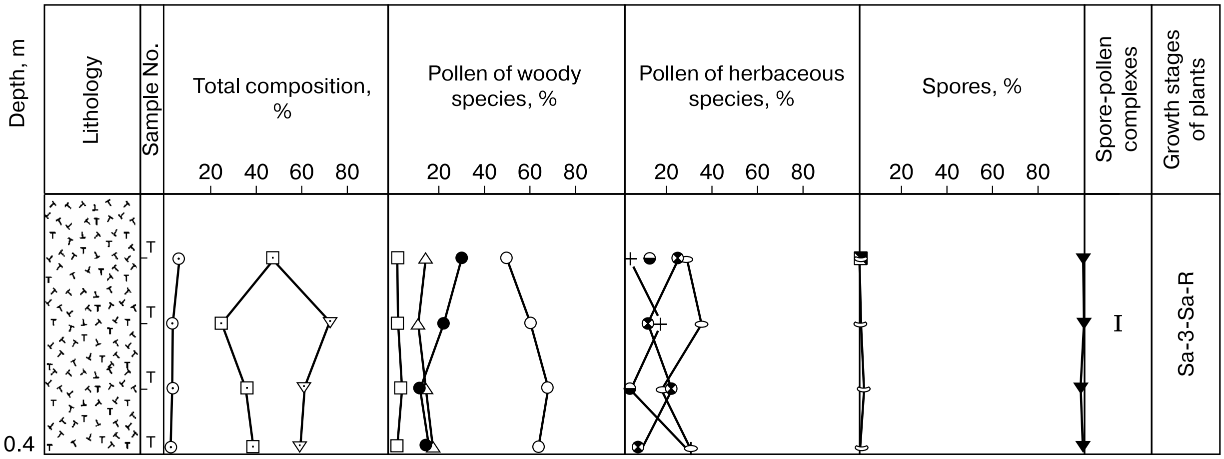

Fig. 7. Palynological composition of the Inta-1 section (fen).

Cf. legends of Fig. 5.

Spore-pollen complex I (samples: T_1–T_4; depth int.: 0.4–0.05 m, L. 1 – peat). Shrub groups of subshruby and shrubby birch trees predominated, with sparsely present arborescent birch, pine, spruce and alder.

Herbaceous plants are fairly diverse. Pollen of cowberry-ericaceous Vacciniaceae–Ericaceae (48 %) and Cyperaceae (ca 35 %) is the most abundant. Markedly present are *Artemisia* sp., Poaceae, Chenopodiaceae. Herbs are represented by Ranunculaceae, Brassicaceae, Saxifragaceae, Asteraceae, Droseraceae. Among sporophytes, *Sphagnum* sp. is prevailing, which accounts for 99.5 % of total spores. Ferns from Polypodiaceae family and *Lycopodium clavatum* clubmoss are sporadic.

Palynological spectrum indicates that in this area, birch and spruce-birch thin woods are abundant and alternate with bogs and extensive areas of shrub-tundra and dwarf and shrubby birches, willows, alder (Fig. 7). Open areas are occupied by herbaceous and cowberry-ericaceous (Vacciniaceae–Ericaceae) low shrub communities.

DISCUSSION OF RESULTS

Problem of origin of peat plateaus

Peat mounds with a core of mineral soil from a few tens of centimeters (small-hummock bogs) to several meters (large mounds bogs) in height typify geomorphology of peat plateau. The hummock's growth in height is equated with increased height of ice core, or lens (hydro laccolith), which tends to melt in case the surface is subject to fracturing, causing, ultimately, the destruction of the peat mound and providing for potential formation of water migration-induced hummocks of palza type [*Vasil'chuk et al., 2011*].

Flat-topped peat plateaus (ridge-hollow complexes) commonly develop either as a result of uneven growth of mosses, giving rise to individual local elevations (tussocks, ridges) above the sediments, or thermal erosion affecting ice wedges. There are two main viewpoints on the origin of flat-topped peat plateaus and large-palsa (ice-filled peat mounds) bogs: 1) shrinking wetlands areas due to thermoerosion, and 2) frost heaving. Despite numerous efforts to establish patterns of their formation and distribution, there has been thus far no common understanding among researchers [*Maksimova and Ospennikov, 2012*].

In reality, it's not rare that both large round-shaped and flatter mound forms, including ridge-hollow and ridge-hollow-lakelet complexes are equally found even within a separately taken palsa bog examined in this paper, and any explanation of the causes of peat plateaus formation is therefore primarily focused on flatter forms of meso-relief with impeded surface runoff that would contribute to paludification processes (formation of bogs with peat accumulation).

During the permafrost aggradation stages such strongly water-logged areas became centers of development of multiyear pingos, both isolated and in groups, however a key factor most likely to have consisted in the erosion- and thermokarst-induced shrinking of bogs' surface.

These mound forms represent for the most part outliers of the pre-existed bog surface, hitherto not destroyed by the erosion and thermokarst processes [*P'yavchenko, 1955; Prozorov, 1974; Boreal Peatland..., 2006*]. The presence of negligibly small, up to 50–60 cm high, hummocks in the middle of extensive water-logged hollows, can probably be corroborated by another group of hypotheses linking the formation of peat plateaus with the processes of permafrost heaving [*Dostovalov and Kudryavtsev, 1967; Vasil'chuk et al., 2011; Osadchaya and Tumel, 2012*].

Many researchers believe that rapid destruction of peatland complexes is set to be unfolding, along with thawing of permafrost, decomposition of organic matter and enhanced greenhouse gas emissions. However, the authors will argue that the permafrost peat plateaus have proven sufficiently stable even under past climatic changes. To demonstrate this, below is provided an insight into their development during the Holocene.

Evolution of the Intanyur peat plateau in the Holocene

The present-day mean air temperature in the study area is estimated to be –4 °C (Fig. 8). The mean annual temperature of deposits (with influence from lithology and modern landscapes taken into account) is by 3.5–4.5 °C warmer than the air temperature. In European NE, contemporary permafrost conditions began to form with the active deglaciation processes, running in parallel with melting of dead ice of ice-cored Late Pleistocene moraines (about 14 ka BP), with subsequent formation of first large thermokarst lakes. The radiocarbon dating performed for the base of lacustrine sediments determined their age to be 12.9–11.6 ka BP [*Henriksen et al., 2001*]. The initial stage of the thermokarst processes development was temporarily interrupted by the final climate cooling and aridity events ca. 11.0–10.3 ka BP (the late Dryas) [*Maksimova and Ospennikov, 2012*].

The climate changes pattern was analyzed on the basis of the Blitt-Sernander chart for the Holocene periods, modified by *N.A. Khotinskii* [*1977*].

Inasmuch as the formation of the most ancient and largest peat deposits began to accumulate back in the Preboreal (VPB, 10.3–9.3 ka BP) in East European forest-tundra and tundra [*Routh et al., 2014*], the study of the materials on the Inta-1 section on the basis of palynologic analysis allowed to establish with a high probability the onset time for sediments deposition as the late Boreal (Bo-2, 8.5–8 ka BP). The development of wetlands systems commenced with the plants and peat communities colonization of areas of lakes of various origin, primarily, thermokarst lakes with subbotom taliks.

At the end of the Boreal period, with the onset of the cooling (Bo-2, complex I), the study area was dominated by shrub groups composed of dwarf and shrubby birch, with sparsely present spruce and pine. The boggy tundra formations became widespread.

During the Atlantic period (At, 8–4.6 kya) the paludification processes occurred most intensively, with the mean air temperature being 3–4 °C warmer and the amount of precipitation greater by 50–75 mm versus those under contemporary climate [*Klimanov, 1986*]. Initially, peat accumulated within the non-permafrost bogs covered with woody plants, sedges and mosses. Given that regional climatic conditions were warmer, the tree line advanced as far as the coastline [*Andreicheva et al., 2007*]. The warming in the early Atlantic period (At-1, the complex II) gave rise to the growth of birch forests admixed with spruce, pine, alder.

The composition of forest communities was marked by the sporadic presence of broad-leaved elm, linden. In the middle Atlantic period (At-2, complex III), the cooling events favored the appearance of thin forests composed mostly of birch, sometimes admixed with spruce and pine. The bog-tundra formations and xerophytic communities were widely distributed. During the Late Atlantic warming (At-3, complexes IV–V) dominated forest vegetation with predominance of spruce, pine admixed with cedar, alder and willow. Herbaceous association of sedges and mesophilic grasses are also fairly well developed.

Early and late in the Subboreal period (Sb, 4.6–2.5 ka BP), the onset of cooling commanded the freeze-through of massive bog massifs. The upper horizon of PFD developed and hummocky terrain was formed thereby, resembling modern relief, with minimum temperature dated 2.5 ka, even though a significant warming by 1.5–2.5 °C took place in the middle of the Subboreal.

Early in middle Subboreal (Sb-1, complex VI), the cooling events the role of spruce-birch and birch woods diminished, which brought about changes in their composition. The role of shrub and subshrub groups of *Betula fruticose*, *Betula nana* was significantly growing, though. The boggy tundra formations and communities of ferns became widespread. During a significant warming in the middle Subboreal (Sb-2, complex VII, 4.3–3.2 ka) the birch-spruce woods admixed with pine, cedar, alder and willow experienced a resurgence in this area.

The plant communities compositions were represented to some extent by broad-leaved trees (elm, oak, linden). Open areas were occupied by herbaceous associations. The sphagnum and hydrophilous species known to be attracted by water-logged areas and largely present there, indicate that moisture content of the area is very high.

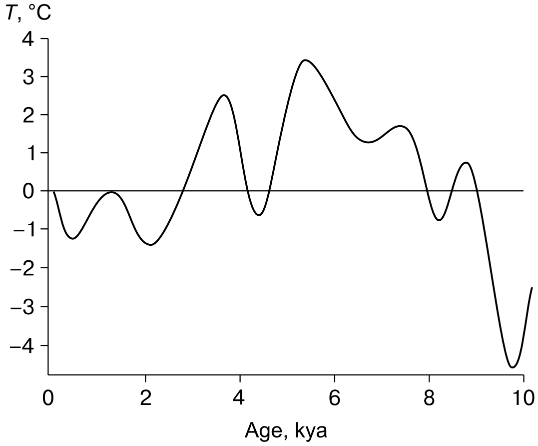

Fig. 8. Deflection curve for mean annual air temperatures (ΔT) in the Holocene versus present-day temperatures in the northern taiga 64–66° N (according to the data from Yu.V. Golubeva).

The next stage (Sb-3/Sa-1-Sa-R, complex VIII, 2500 ya – till present) evidences the subsequent cooling, which caused the dominance of shrub groupings of dwarf and shrubby birch sparsely admixed with spruce and pine. Palynological analysis of the peat plateau attests to a stratigraphic hiatus between 2,500 and 850 BP, i.e. the aggradation of permafrost was given start to ca. 2.5 ka BP, which is largely manifested in permafrost heaving and dramatic decrease in peat accumulation. Simultaneously, the erosion- and thermokarst-induced dissection of the surface of the perennially frozen bog massif was taking place.

These processes have shaped the modern permafrost peat plateaus. The processes of paludification and erosion degradation of hummocks are very likely to have been more active in the late Subatlantic-recent (Sa-3-Sa-R) periods of the Holocene, i.e. after the Little Ice Age and at the beginning of the small climatic optimum (ca. 850 BP). At that time, permafrost partly degraded and in most of the study area, non-permafrost sphagnum bogs formed thereby [*Zoltai, 1993; Oksanen et al., 2001*].

A similar break in peat accumulation, driven by climatic changes, is observed not only on the Pechora plain, but also in the West Siberian lowland (WSL). According to its age, peat can be divided into two layers on most mounds (the Nadym river basin, WSL). Peat of the topmost layer at depths of about 0.0–0.5 m is dated 750 (550) years. Peat in the lower layer is variously aged, but always greater than 3,000 years. Peat accumulation rate in the uppermost layer appears significantly lower than that of the underlying peat [*Ponomareva et al., 2012*].

In the context of recent climate warming, the vegetation cover of peat mounds prevents permafrost thawing. Upon draining and desiccating, the surface of peat mounds provokes the change of moss and lichen phytocenoses, as well as the formation of bare circles. Dry peat with its higher insulating properties arrests further thawing of permafrost. The leading role in further destruction of peat mounds belongs to wind and thermal erosion, which in practice does not lead to the development of thermokarst, though. Thawing of permafrost peat areas from the surface occurs only either in case they are destroyed, or with impeded runoff readily favorable for the formation of lakes and pools.

The paleoreconstruction thus indicates, that the accumulation of peat began about 8 ka BP. Then the peat accumulation significantly retarded and actually ceased between 2,500–850 BP, which progressively proceeded at a slower rate henceforth.

The present level of knowledge of history of peatlands deposition allows quality reconstructions of peatland carbon accumulation and sequestration. In upland forests, before the paludification began to proceed, a fairly rapid carbon cycle was realized, with soil mineralization and washing out processes taking place under aerobic conditions. The boggy peatlands would then accumulate in anaerobic non-permafrost environments during the period spanning 5,000 years characterized by incidentally ongoing rapid aerobic decomposition in the upper (aerated) horizons of akrotelm prior to their merging into the water saturated anaerobic katotelm environments, where their anaerobic decay proceeded, slowly. Affected by permafrost aggradation decomposition of peat carbon dramatically slowed down below the active layer 2.5 ka BP. The formation of peat mounds and good drainage, favored by frost heaving, resulted in dry aerobic conditions in the active layer during the warm season, whereas the lowland peat turned out to be preserved in the permafrost strata. During the followed degradation of permafrost and increased thermokarst phenomena, peat was repeatedly subjected to slow anaerobic decomposition under katotelm conditions. Recent reaggradation of permafrost re-suppressed peat decomposition in deeper layers, while the upper dry peat has undergone greater aerobic decomposition. However, insulating properties of dry peat have substantially impeded the deepening of the active layer.

At present, key large-scale differences in the structure of soil cover of hummock-fenny bogs of the northernmost taiga zone are dictated by the conditions of their formation and hydrological regime, whereas structural differences are determined by the ratio of the areas of permafrost peat mounds (or ridges) and non-permafrost swampy hollows, including inter-palsa lows. Fairly closed hydrological regime of the bog's area accounts for the widespread peat mounds overlain by permafrost soils (40 % of the area). Taking into account recent climate change trends and the ongoing processes of destruction of frost peat mounds, relative share of permafrost soils will be gradually and slowly decreasing in the future.

CONCLUSIONS

The permafrost peat plateaus analyzed in this paper are located on the southern border of the permafrost zone and appear to be water migration-driven palsas rather than frost mounds (pingos). Their origin was dictated by the influence of erosion and thermokarst processes i.e. peat plateaus are in themselves outliers of pre-existed bog surfaces complicated by uneven growth of mosses (local elevations in the form of hummocks and ridges) and the frost heaving that produced hummocks less than 50–60 cm in height (but not 3–4 m high frost mounds!).

The palynology analysis-derived paleoreconstruction indicates with reasonable probability that the onset of peat accumulation correlates with the middle Holocene, specifically the Atlantic period (At). The interval of 2,500–850 BP is characterized by decreased and almost stopped peat accumulation processes. In the late Subatlantic-recent (Sa-3–Sa-R) Holocene period, peat accumulation gradually proceeded at a markedly slower rate. After the Little Ice Age and the beginning of the Little Climatic Optimum (about 850 years ago) the surface of permafrost bog massif experienced active erosion processes and thermokarst dissection, which, ultimately, triggered the formation of permafrost peat plateaus of modern state.

The authors believe that, given the ongoing climate change and modern processes of frost mounds degradation, the projected relative share of permafrost soils tends to be progressively decreasing.

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