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GENESIS
AND GEOGRAPHY OF SOILS

Soil Formation and the Underlying Permafrost

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Abstract—The composition and fabric of the upper permafrost layer and its relationships with the permafrost-affected soils developing from the loamy substrates on the interfluves within coastal lowlands of northern Yakutia are considered. The studied area is characterized by the maximum activity of cryogenic processes and a shallow depth of seasonal thawing. The permafrost layer affected by the maximum thawing during the Holocene has a specific morphology attesting to the impact of soil processes on it. In general, the modern soil profile and the underlying permafrost layer can be distinguished as the soil–permafrost complex. It is subdivided into the soil profile, the transient layer, and the intermediate layer. The morphology and properties of the transient layer depend on the character of the soil horizons above the permafrost table. The lateral migration of raw organic substances takes place above the permafrost surface between the particular elements of the cryogenic soil complexes; this material tends to accumulate within the transient layer.

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INTRODUCTION

Permafrost with a shallow (about 1 m and less) depth of the upper boundary affects the character of pedogenesis and dictates the development of a number of specific features and properties in soils. First of all, it serves as a physical and geochemical barrier, which restricts the vertical migration of substances and favors their redistribution in the lateral direction. The dynamic character of the upper permafrost boundary is one of the reasons for the development of the specific morphology of the upper permafrost layers reflecting complicated temporal and spatial relationships between the surface soil and the underlying permafrost.

Permafrost-affected soils and the underlying permafrost. The most active interaction between soil-forming processes and permafrost takes place at the interface between the layer of seasonal thawing (the active layer) and the underlying permafrost. Taking into account the climatic fluctuations, the weather conditions of the particular years, the dynamics of the soil processes, and the dynamics of the surface vegetation, this zone is very unstable. In the years of maximum thawing, it may be in the thawed state; in the years with insufficient heat supply, it remains frozen. In the latter case, it becomes the uppermost layer of the permafrost proper. Shur [18] distinguished the transient layer, i.e., the uppermost permafrost layer, which could be in the thawed state in the years of maximum thawing. The thickness and diagnostic features of this layer are of great importance for correct interpretation of soil data; it is also important to know the annual and interannual dynamics of this layer. Unfortunately, soil studies in permafrost-affected regions are mostly performed at the time when the soil thawing is still less than the maximum thawing depth, i.e., when the lowermost part of the soil profile remains in the frozen state. The real thickness of such profiles and their morphology should be studied during the maximum thawing period. Within the coastal lowlands of northern Yakutia, this is the period from the middle of September to the beginning of October. In fact, the maximum thawing depth is achieved after the beginning of the soil freezing from the top and the establishment of the snow cover.

A detailed and informative picture of the contact zone between the active layer and the permafrost can be obtained from the analysis of long walls exposing the upper permafrost layers. In particular, these are exposures created by river erosion and thermal erosion processes. Their length can reach tens and hundreds of meters. The analysis of the contact zone between the modern soil profiles and the underlying transient layer in such exposures shows that it has an extremely complicated cryogenic fabric both in the vertical and lateral directions. Within the coastal lowlands of northern Yakutia, permafrost under the transient layer is composed of frozen silty loams. Normally, they have a layered structure with different ice contents and cryogenic fabrics in separate layers. The layers of 20–80 cm in thickness may also differ in the contents of the inclusions of raw (weakly decomposed) organic materials and root remains. On leveled interfluves, landslides and solifluction may lead to the partial translocation of the material of the active layer; after this, its partial renewal owing to the thawing of the underlying permafrost takes place. In such cases, it is hardly possible to distinguish the transient layer. On the plots studied by us, landslides and solifluction were inactive, and the transient layer, together with the intermediate layer, could be clearly seen on the walls. Our measurements of the total thickness of these layers show that it reaches 2.5 m in the northern part of the taiga zone (2.3 ± 0.9 m, $n = 16$) and about 1.5 m (1.4 ± 0.4 m, $n = 28$) in the tundra zone. These layers are clearly diagnosed on the walls of long exposures, as they are underlain by the monotonous gray-colored Late Pleistocene ice-rich silty loams and thick ice wedges of the edoma (the ice complex) deposits. Shur [18] considered the upper permafrost layer subjected to maximum thawing during the Holocene climatic optimum as the intermediate layer. He analyzed data on the thickness and cryogenic fabric of this layer in different parts of the Arctic and Subarctic zones in Russia. In general, the results were similar to those obtained by us for coastal lowlands of northern Yakutia. Available radiocarbon dates of the raw organic material accumulated at the foot of this layer due to cryoturbation are within 8–9 ka BP. Thus, the permafrost table at the beginning of the Holocene was at this depth. This finding confirms the hypothesis about radical environmental changes at the very beginning of the Holocene: the Late Pleistocene tundra-steppe landscapes [6, 16] were transformed into the modern zonal landscapes, and the synlithogenic type of soil formation during the Late Pleistocene gave way to the epigenic (postlithogenic) type of soil formation during the Holocene [3, 4]. It should be stressed that the currently determined thickness of the intermediate layers does not necessarily reflects the real thickness of the active layer during the period of maximum thawing in the Holocene. In fact, this thickness could be increased due to progressive ice accumulation in the transient layer; the latter may contain thick (up to 15 cm) lenses of pure ice or 60- to 80-cm-thick frozen sediments with an ataxic cryogenic fabric and an ice content of more than 80%.

Within the leveled interfluves, the following distribution of sediment layers with different cryogenic fabrics can be seen within the intermediate layer above the Late Pleistocene sediments with clear features of the synlithogenic soil formation. At the foot of the intermediate layer (near its contact with the edoma deposits), an ice content of very high, banded ice fabric is formed. Above this lowermost horizon, a horizon with an ataxic cryogenic fabric is formed. Above the horizon with the ataxic fabric, the latticed cryogenic fabric is seen in the profile (Fig. 1). It can be supposed that each of these horizons is indicative of the history of permafrost thawing in the Holocene. In other words, each of them was formed under the particular environmental conditions, including climatic features, soils, vegetation, surface topography, etc. However, this assumption is only true if the development of the intermediate layer was characterized by a progressive decrease in the thawing depth. In this case, the cryolithological indices of each of the horizons within the intermediate layer should contain information about the moisture status of the lower part of the former active layer in the period of its transition into the permanently frozen state. Thus, they are important for judging the character of pedogenesis during the particular stages of the Holocene.

A number of chemical and morphological characteristics of the soil profiles that developed within the former active layers were then preserved in the frozen state in the form of separate horizons composing the intermediate layer. Certainly, the cryodiagenetic changes in the properties of these horizons should be taken into account for correct interpretation of these data.

It is important that separate horizons (interlayers) within the transient layer contain inclusions that could only be formed on the soil surface. Their presence in the intermediate layer is explained by the development of cryoturbation within the former deep active layer. These are fragments of peat or mucky horizons, the remains of the aboveground parts of plants, pollen, phytoliths, remains of insects, bones of small animals, etc. The roots of grasses that penetrated from the soil surface down to the former permafrost table can also be found in the intermediate layer. Often, the remains of these roots in their lowermost parts are well preserved (as they remain in the permanently frozen state) and can be used for the species identification of the former vegetation. Radiocarbon dating makes it possible to determine the age of their transition into the frozen state. Note that the upper parts of these roots (even within the intermediate layer) are absent, as they were subjected to humification and mineralization. The intermediate layer may contain the remains of several generations of root systems reflecting a progressive rise of the permafrost table and a decrease in the active layer thickness during the Holocene. Radiocarbon dates obtained for root remains and inclusions of peat and muck materials in different horizons of the intermediate layer indicate that their absolute ages generally increase with the depth, which confirms the tendency for a staged rise of the upper permafrost boundary [2]. The results of radiocarbon dating of the cryoturbated organic materials buried within the intermediate layer (grass roots and fragments of surface organic horizons) from the Zelenyi Mys site (Fig. 1) (the Kolyma Lowland in the northern part of the taiga zone), coupled with data on the cryogenic fabrics within the intermediate layer, allow us to suppose that the active layer thickness in this region progressively decreased from the period of the Holocene optimum up to the present time. This conclusion is in agreement with the paleoclimatic scheme for this region suggested by Khotinskii [17].

As each of the horizons (interlayers) within the intermediate layer may be considered the upper permafrost boundary (permafrost table) of a particular period in the Holocene, their properties and morphology (including their cryogenic fabric) may be indicative of the past soil-forming conditions. Our data suggest that

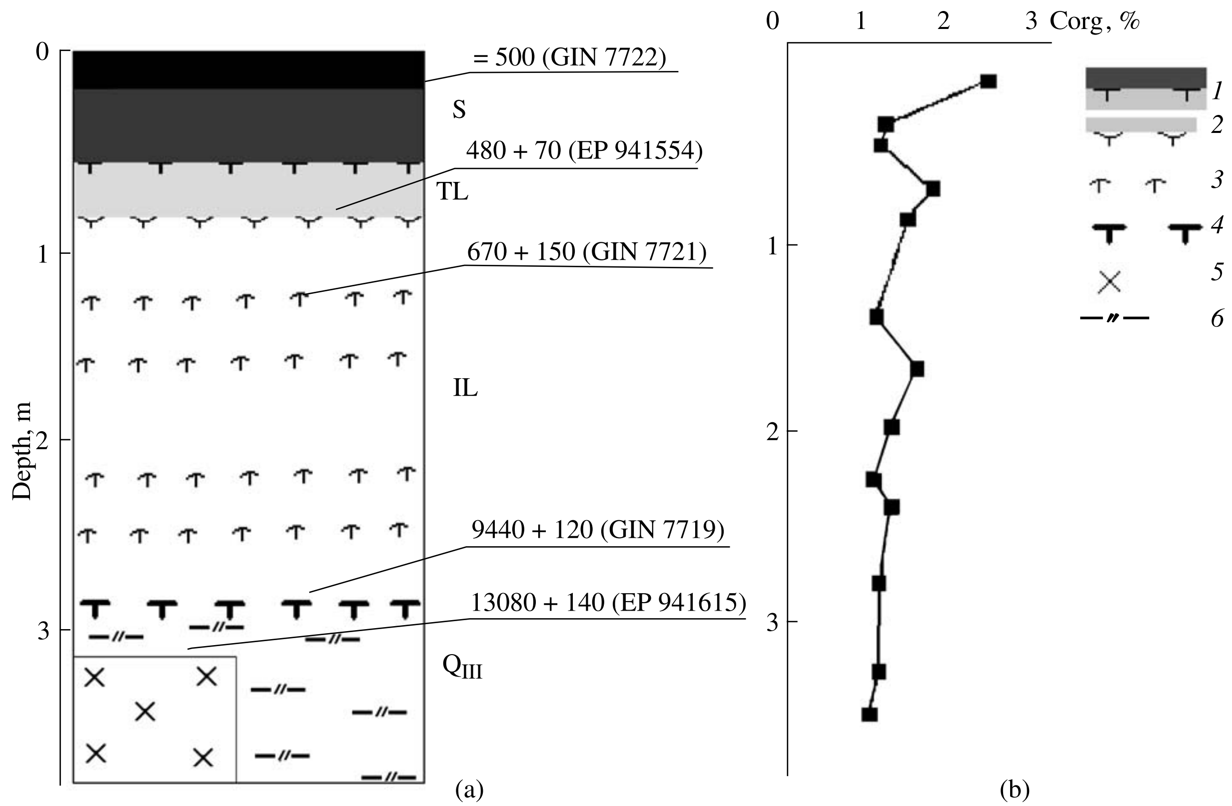

Fig. 1. A schematic horizonation of the Holocene soil–permafrost complex (a) and the organic carbon distribution in it (b). The scheme is derived from the study of the Zelenyi Mys permafrost escarpment. Designations: S—modern soil, TL—transient layer, IL—intermediate layer, and Q_{III}—Late Pleistocene edoma deposits (the ice complex); (*1*) the modern boundary of the active layer, (*2*) the lower boundary of the transient layer, (*3*) boundaries between the layers differing in their cryogenic fabrics, (*4*) the lowermost boundary of the maximum soil thawing in the Holocene, and (*5*) the Late Pleistocene ice wedge.

reliable changes in the diagnostic indices (the content and composition of organic matter, the morphochromatic indices of gleyzation, the contents of oxalate-extractable sesquioxides, etc.) of separate horizons within the intermediate layer can only be traced in its deep part (at least 20 to 60 cm deeper than the modern permafrost table). The diagnostics of the former Holocene pedogenesis recorded in the intermediate layer are a difficult challenge, because this layer also preserved the features of the synlithogenic pedogenesis in the Late Pleistocene, when its material was deposited, partly transformed by pedogenic processes, and fixed in the frozen state. However, we can tentatively estimate the lowermost boundary of the active Holocene pedogenesis. If we exclude ice volumes contained in the intermediate layer, we can say that the maximum thickness of the soil profiles during the climatic optimum of the Holocene within the Kolyma–Indigirka Lowland exceeded its modern thickness by 10–20 cm in the tundra zone and by 30–60 cm in the north of the taiga zone. The lower-lying horizons within the intermediate layer are only slightly affected by the pedogenesis (except for rare admixtures of the cryoturbated material); they represent the lowermost horizons of the former soil profiles (the BCg and Cg horizons) immediately above the former permafrost table. To diagnose them properly, more detailed studies are necessary.

It is known that the disturbance of the thermophysical properties of the upper horizons of permafrost-affected soils (cryozems and gleyzems) under the impact of fires, overgrazing, vehicles, snow redistribution, surface water flows, and other factors results in a rapid and considerable increase in the thawing depth. This means that the modern soil profile, after its deep thawing, includes the horizons that were actually formed during previous periods of the Holocene. Often, these relict horizons have very distinct morphological features and chemical properties that are taken into account in soil diagnostics (e.g., gley features). Thus, their inclusion into the modern soil profiles may change the classification position of the latter. In this context, it is important to distinguish between the relict soil features and the modern soil features created by the recent pedogenic processes.

Under conditions of a shallow depth of permafrost and the activity of various slope processes (first of all, solifluction and landslides) that often take place even on gentle (about 3°) slopes, the profiles of permafrost-affected soils are subjected to regular and strong disturbances. Often, they are completely destroyed by the cryogenic processes. The removal of the surface soil horizons involves thawing of the underlying permafrost, including the transient and intermediate layers. The latter are included in the zone of active modern pedogenesis. At the same time, the removed material accumulates on the lower parts of the slopes and at the footslopes. There, it is subjected to freezing, and its lower horizons become permanently frozen. A new soil profile is formed in the upper part of the redeposited material. Thus, on slopes, the upper part of the permafrost underlying the soil profile does not reflect the history of the bioclimatic changes, thawing depth, and soil formation during the Holocene, as it is strongly disturbed by the slope processes. However, permafrost-affected soils on slopes may characterize separate stages of the Holocene pedogenesis proceeding against the background of the activity of powerful cryogenic and slope processes.

Makeev [14] pointed to a close relationship between the development of permafrost-affected soils and the underlying permafrost. He suggested the notion of the soil–frozen ground complex as a layer encompassing the soil profile and the entire zone of annual temperature fluctuations. The thickness of this zone in the areas with a sharply continental climate and low-temperature permafrost may reach 20–30 m [1]. A separation of this complex is quite logical from the viewpoint of the study of its temperature and moisture regimes and the heat and mass exchange processes taking place within the zone of annual temperature fluctuations. However, it is difficult to judge the evolution of this deep layer and the history of the interactions between the soils proper and the underlying strata subjected to annual heat exchange processes. In this context, we suggest that a separate notion of the soil–permafrost complex should be introduced. The composition and properties of this complex reflect the history of interactions between the permafrost surface and the soil profile. This complex represents a natural formation with quite definite boundaries, definite morphology and structure, and definite age. As it consists of two separate natural bodies (the soil proper and the underlying permafrost layer, whose development is intimately associated with the history of the soil formation), the notion of the complex (system) seems to be appropriate. The soil–permafrost complex (SPC) consists of the following elements: the modern soil (S), the transient layer (TL), and the intermediate layer (IL):

$$SPC = S + TL + IL.$$

The analysis of paleopedological and cryolithological data on the edoma deposits composing costal lowlands in the north of Yakutia shows that the SPC notion is also applicable to the buried Late-Pleistocene paleosols formed under conditions of a shallow permafrost [7]. The presence of the SPC in the syngenetic sediments transformed by the pedogenesis makes it possible to distinguish buried paleosols from the interlayers enriched with the allochthonous organic material and to study the particular stages of the soil formation in the Pleistocene. Moreover, there are good reasons to suppose that analogous soil–permafrost complexes were formed during the cold Pleistocene epochs in the areas that are currently found beyond the permafrost zone. In such areas, the remains of the former transient and intermediate layers should be present.

C r y o g e n i c p e d o g e n e s i s a n d t h e t r a n s i e n t p e r m a f r o s t l a y e r. Soil studies on the coastal lowlands of northern Yakutia during the period of maximum soil thawing and the analysis of the soil morphology, together with the transient layer morphology on the walls of permafrost exposures, made it possible to distinguish between the two types of the SPC morphology; these types also differ in their structural arrangement and spatial distribution. A characteristic feature of the first type is the presence of an interlayer of raw organic matter with some admixture of the mineral material in the lowermost part of the soil profile and the upper part of the transient layer. The thickness of this layer is up to 15 cm. In the second type, this organic-rich layer is absent; it is replaced by the gleyed material with some participation of differently decomposed organic materials. Special studies were performed in order to determine the properties of these two characteristic interlayers (horizons) and their relationships with the modern soil formation and the character of permafrost.

STUDY OBJECTS

We studied permafrost-affected soils of the nanopolygonal soil complex composed of cryozemic soils of the nanopolygons and peat soils of the cryogenic cracks separating the nanopolygons. The transient layer under the soil profiles was also studied. These investigations were performed in the tundra zone on large leveled interfluves in the upper reaches of the Khomus-Yuryakh River (the Indigirka Lowland; 70°00′N, 153°36′E) and in the lower reaches of the Kolyma River (in the basin of the Sukharnaya River). In both cases, the soil-forming material is represented by the Late-Pleistocene silty loams with some features of the synlithogenic pedogenesis and with thick ice wedges. Such deposits are referred to as Ice Complex deposits, or the edoma deposits. The thickness of the SPC within the studied plots varies from 1.2 to 1.5 m. The slope of the surface does not exceed 2–3°. The soil surface has a pronounced patchy moundy microtopography. Mosses, sedges, and cotton grass predominate on the plots studied in the Indigirka tundra; and mosses, grasses, and dwarf shrubs (*Dryas*) predominate in the lower Kolyma reaches. The more xerophytic (steppe-like) character of the vegetation in the Kolyma tundra (within the studied plots) is specified by the lower thickness of the snow cover owing to stronger winds and better drainage of the territory.

An important difference between these two sites is the higher percentage of poorly vegetated or barren nanopolygons within the Indigirka tundra. The thickness of the organic horizons under vegetated nanopolygons within the Indigirka tundra is generally lower than that within the Kolyma tundra. The mineral profiles of cryozems in the Indigirka tundra contain relatively small fragments of organic matter admixed into the deep soil horizons from the soil surface due to cryoturbation. Our analysis of the morphology of soil profiles under 60 relatively large (about 80 cm in diameter) and high (30 cm in relative height) nanopolygons showed that the organic horizons formed on the polygons and in the crack zones between them are relatively thin. Therefore, large fragments of these horizons cannot be admixed into the mineral parts of the soil profiles under the impact of cryoturbation. At the same time, the poor development of the surface organic horizons is explained by the more frequent cryoturbation events with expulsion of the mineral soil mass onto the soil surface.

In the Lower Kolyma tundra, the mineral horizons of soils under barren and vegetated nanopolygons usually contain large fragments of the buried (cryoturbated) organic horizons. The same material with a somewhat higher degree of humification and mineralization can be found immediately above the underlying permafrost and in the upper permafrost horizons (in the transient layer). We suppose that the formation of barren spots at both sites is driven by similar mechanisms. Our field observations in the Kolyma tundra in the fall and winter seasons indicate that the beginning of soil freezing is accompanied by the development of considerable cryostatic pressures. Under their impact, well-moistened mineral material from the middle horizons is squeezed upwards and covers the surface organic horizons. Under conditions of the low air temperatures, it is subjected to freezing and forms small (5–10 cm in height) ridges on the top of the soil. Upon the soil thawing in the spring, the overwetted loam from these ridges flows across the polygons and forms the surface of barren mineral circles. The former surface organic horizons are disrupted and, after being covered with the mineral material, participate in the cryoturbation processes within the soil solum. They are admixed into the mineral soil mass within the entire soil profile. Often, they are accumulated immediately above the permafrost table. Upon the horizontal cutting of the soil at a depth of 10–25 cm, the ringlike or funnellike patterns of the buried organic material are seen. The cryoturbation mechanism of the redistribution of organic material in the soil profiles is quite evident in this case.

Another mechanism of the admixture of raw organic materials into deep mineral soil horizons under the nanopolygons is less frequent. It is related to the development of peat soils in the cryogenic cracks encircling the polygons. The lower parts of the peat material in the cracks penetrate under the polygons along the bowl-shaped permafrost surface. Upon the soil freezing, these parts may be torn off from the main peat mass. Then, such parts exist in the mineral soil profiles as separate bodies (inclusions) and can participate in cryoturbation movements.

At both sites, the soils of vegetated nanopolygons are classified as cryozemic soils with slightly pronounced gley features above the permafrost table in the Kolyma tundra and with more pronounced gley features in the Indigirka tundra. In both cases, the mineral part of the soil profiles is poorly differentiated into the B1 and B2 horizons differing in their structure. In turn, the latter is dictated by the character of the ice segregation upon the soil freezing. In all the soils, gley features are better pronounced in the lowermost horizons and within the transient layer. Upon the squeezing of the material from the deep soil horizons onto the soil surface (the formation of barren cryogenic circles), weak gley features may also be present in the upper parts of the profiles under barren circles. However, in the course of their overgrowing with vegetation, the development of the upper organic horizons, and the formation of a stable cryogenic structure in this material, the gley features disappear from it.

The depth of the seasonal thawing under nanopolygons of average sizes in the Lower Kolyma tundra is about 48 ± 3 cm ($n = 40$); in the Indigirka tundra, the thawing depth is somewhat greater 65 ± 4, ($n = 90$). Under the high nanopolygons, the thawing depth may reach 80 cm.

The studied sites also differ in the thickness of the peat soils developing in cryogenic cracks between the nanopolygons. In the Kolyma tundra, the average thickness of the peat soils in the cracks reaches 32 ± 3 cm ($n = 20$), whereas the soil thawing depth in the cracks is 40 ± 2 cm. In other words, the lowermost parts of the peat soils (peat wedges) in the cracks do not reach the permafrost table.

In the Indigirka tundra, the thickness of the peat soils in the cracks is greater, so that their lower parts of 15–20 cm thickness occur in the permanently frozen state. The total thickness of the moss and pear cover in the cracks reaches 50–55 cm. The thawing depth of the peat is about 38 ± 4 cm ($n = 22$). The peat material in the cracks is differentiated into several horizons differing in their bulk densities and the degree of decomposition of the plant residues. Often, the peat contains thin (1–2 cm) interlayers enriched in the mineral material. The origin of these interlayers is related to the erosion of the surface of barren nanopolygons.

STUDY METHODS

Our studies of the morphology and properties of permafrost-affected soils and the underlying transient layer at the key sites were performed at the end of August and the beginning of September, in a period close to the dates of the maximum soil thawing determined on the experimental plots. At the Lower Kolyma site, two 60-cm-wide trenches 2 and 5 m in length were dug through the entire thickness of the SPC. The morphology of the soil profiles was studied on the walls of these trenches; the horizontal sections at the bottom of the trenches during their excavation made it possible to study the morphology of the transient layer under the particular elements of the surface nanotopography. To study the spatial variability of the soil and transient layer properties, additional soil pits ($n = 15$) penetrating to a depth of 20 cm into the underlying permafrost (its transient layer) were dug under nanopolygons of similar sizes but differing in the character of their overgrowing with vegetation (from barren circles to densely vegetated nanopolygons).

Taking into account the more complicated morphology of the lower parts of cryozems and the underlying transient layer at the Indigirka site, the latter was studied in detail on two experimental plots. The first plot (250 × 250 cm in size) was established on a wide leveled interfluve. The second (additional) plot (80 × 200 cm in size) was established at a distance of 150 m from the first plot on the upper part of a gentle (3°) slope. These plots were chosen so as to encompass all the characteristic elements of the surface microtopography: nanopolygons of different sizes and different degrees of overgrowing with vegetation, the cryogenic cracks between them, and specific elevated organic tussocks composed of sedges and cotton grass. Such tussocks were more frequent in the area of plot 2. Other elements of the cryogenic microtopography at both of the plots were relatively similar.

An instrumental leveling survey of the topography of the soil surface and the permafrost table was performed on plot 1 with an accuracy of 1 cm using a 5-cm grid pattern. The measurements were made from a local reference point (the surface of the most elevated nanopolygon). Overall, the soil surface and the permafrost surface topographies were characterized by 2500 measurements each. The thickness of the soil horizons and the transient layer was also thoroughly measured; the cryogenic fabric of the transient layer was investigated on the walls of 10 successively dug 25-cm-wide trenches.

In the course of the excavation works, the horizontal sections of the bottom were thoroughly described and the boundaries of the main components composing the transient layer—ice, ice-cemented mineral material, and frozen organic material—were determined. On this basis, schematic maps depicting the surface morphology of the transient layer were compiled. The thickness of this layer was determined under each of its major morphological elements; the ice content and the character of the cryogenic fabric were visually determined.

The walls of the most representative trenches were also thoroughly described and sampled. The computer-based treatment of the obtained data made it possible to develop schematic maps of the soil surface topography and the permafrost surface topography; 3-D models of the SPC were developed, and schematic maps depicting the composition of the transient layer and the pattern of the surface vegetation were compiled (Figs. 2 and 3).

Additional soil pits ($n = 15$) were studied around the key plots; the pits were dug into the upper part (20 cm) of the transient layer. The soil thawing depths were measured under the nanopolygons of different morphologies and at different stages of vegetation succession and under the cryogenic cracks of different widths and with different plant communities (with different thicknesses of the moss layer and with different percentages of dwarf shrubs and sedges shadowing the moss surface). Overall, 130 measurements of thawing depths were made.

An analogous study was performed on the second key plot using a 10-cm grid pattern.

RESULTS AND DISCUSSION

The results of our study in the Lower Kolyma tundra generally confirmed the known regularities of pedogenesis on the loamy substrates in the nanopolygonal tundra, including the organization of the soil profiles under the nanopolygons and in the cryogenic cracks between them, the character of the changes in the thawing depth, and the major features of the transient layer [2, 5, 11]. In general, all these parameters depend on the size of the particular nanopolygons, the character of the surface vegetation, and the character and thickness of the soil organic horizons (Fig. 4a).

During the period of maximum thawing, the soil horizons above the permafrost table have a relatively low water content, which agrees with the absence or very weak manifestation of gley features in them. The permafrost table is uneven; microdepressions are found in the zones of maximum thawing depths (under the nanopolygons), and microelevations of the permafrost table are found under peat soils in the zones of cryogenic cracks. The soil moisture within the microdepressions is increased; often, the soil material in them contains morphochromatic indices of gleyzation. The ice content in the underlying frozen material is very high.

The micromorphological study of the material from dark-colored zones in the mineral horizons of cryozems shows that they are enriched in differently decomposed organic remains with a predominance of weakly decomposed plant tissues typical of the surface organic horizons of these soils.

The transient layer under all the elements of the soil complex (the nanopolygon, the transitional zone, and the cryogenic crack) has approximately the same morphology; fine ice schlieren are present in it, and the ice content is not very high. Moderately developed morphochromatic gley features can be seen in the transient layer. The ice content and the thickness of the ice schlieren somewhat increase under the nanopolygons.

The zones enriched in the buried (cryoturbated) raw organic material are more frequently found in the

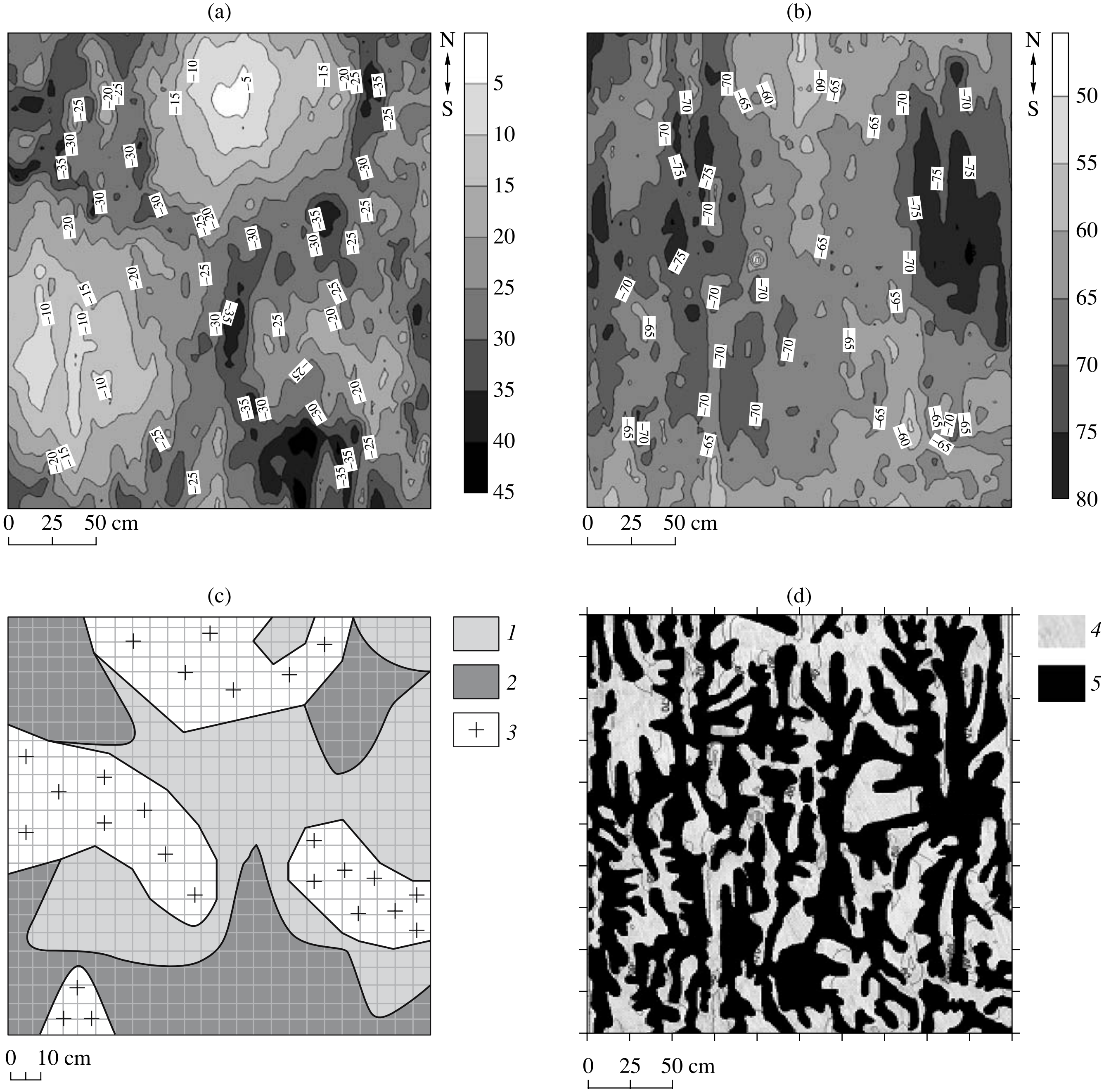

Fig. 2. Schematic maps of plot 1: (a) relative heights of the soil surface microtopography, (b) relative heights of the permafrost surface microtopography, (c) cryolithological structure of the transient layer (*1*—ice-rich mineral material, *2*—organic material with inclusions of mineral material, and *3*—ice bodies), and (d) distribution of matter fluxes over the transient layer surface (*4*—zones of matter removal; *5*—zones of matter migration and accumulation). Maps (a) and (b) are derived from measurements in the nodes of the 5-cm grid; the contour interval is 5 cm.

uppermost (5–7 cm) part of the transient layer and immediately above it under the nanopolygons. In the deeper parts of the transient layer, the content of buried organic matter decreases. In the transient layer under the crack zones with peat soils, the organic matter content is lower than that under the polygon. Moreover, the organic carbon content in the slightly gleyed loam without the admixture of raw organic material in the transient layer under the cracks is lower than the average organic carbon content in the transient layer (0.8 and 1.3%, respectively; $n = 15$). The same organic carbon content is typical of the middle part of the mineral soil profiles (under the nanopolygons) and of the deeper parts of the transient layer. The analysis of thin sections prepared from the material of the transient layer and the above-lying horizons without evident features of the

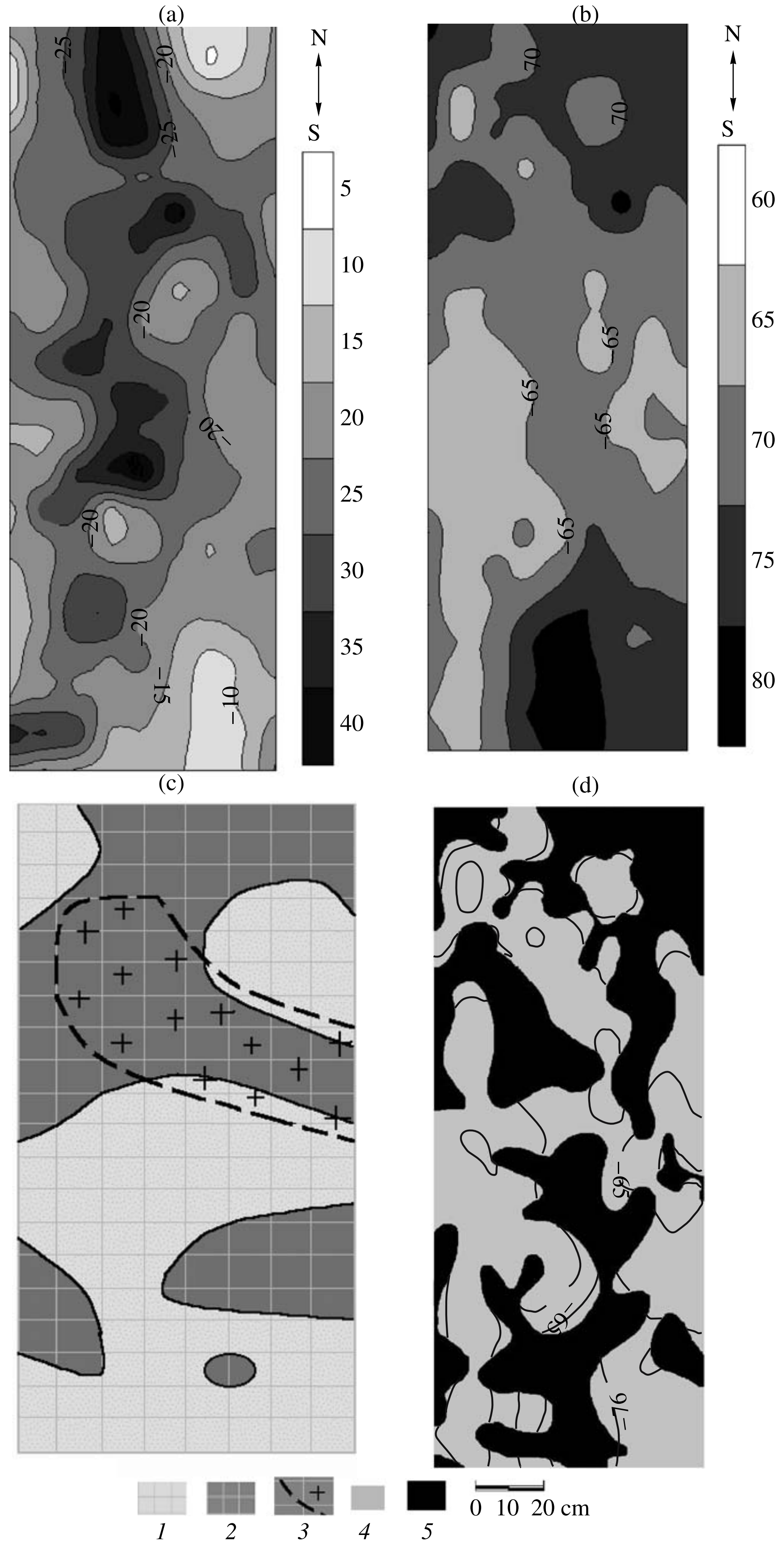

Fig. 3. Schematic maps of plot 2. The designations are the same as in Fig. 2. Maps (a–d) are derived from measurements in the nodes of the 10-cm grid; the contour interval is 5 cm.

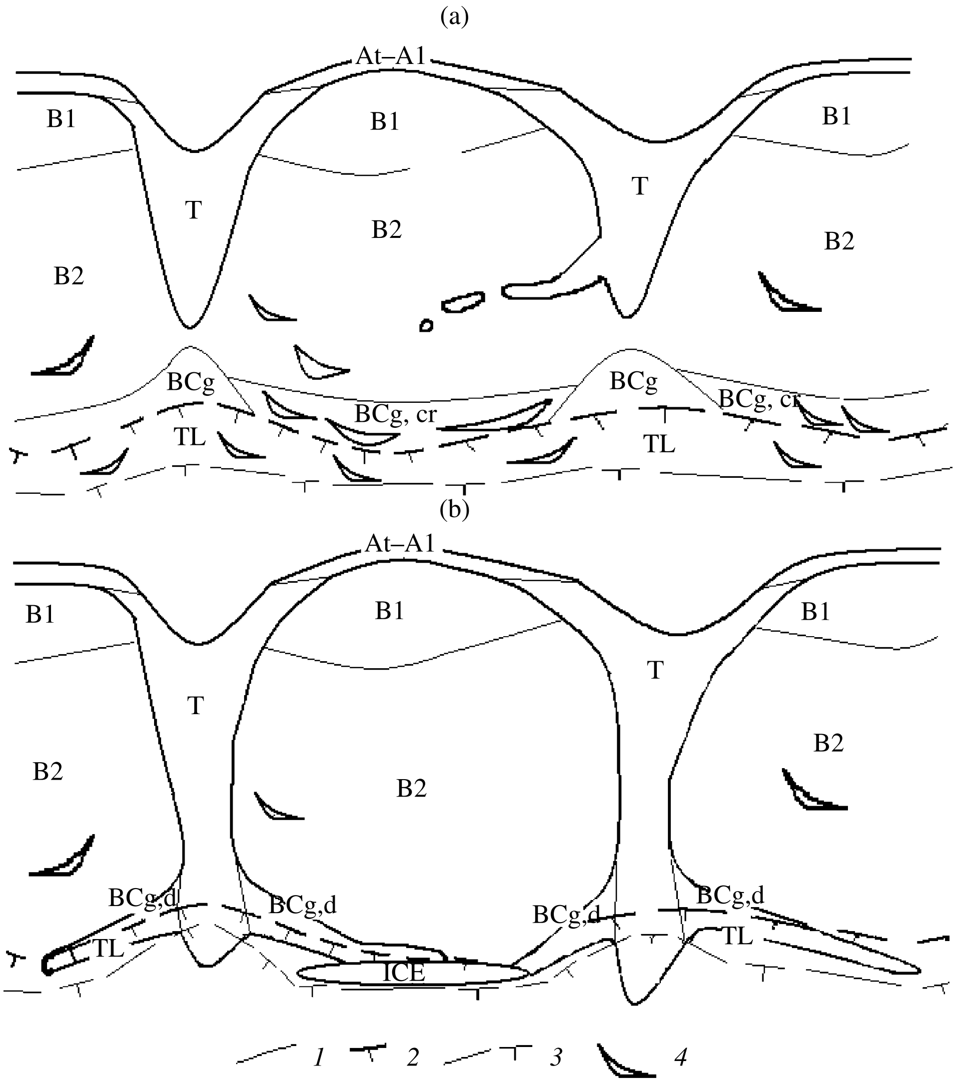

Fig. 4. Morphology of cryogenic pedocomplexes upon the (a) accumulation of the cryoturbated organic material above the permafrost surface (the Lower Kolyma tundra) and (b) lateral redistribution and accumulation of the organic material in the superpermafrost horizon (the Indigirka tundra). Designations: (*1*) boundaries of genetic soil horizons, (*2*) lower boundary of the active layer, (*3*) lower boundary of the transient layer, and (*4*) fragments of the cryoturbated organic material.

accumulation of buried organic horizons shows that this material also contains very fine (0.2–1 mm) fragments of partly transformed remains of mosses, sedges, grasses, and dwarf shrubs. Thus, raw organic materials from the surface horizons are involved in cryoturbation and enrich the soil mass in the deep soil horizons and in the upper part of the transient layer. The presence of these mechanically admixed raw organic materials in the deep soil horizons contradicts the hypothesis about the cheluvial (through migration in solutions) accumulation of humic substances above the permafrost table in tundra soils of the eastern sector of the Russian Arctic and Subarctic regions advanced by Karavaeva and Targulian [10].

Cryozems forming under the overgrown nanopolygons have the following horizonation: AtA1–B1–B2–BCg,d(BCg), where At (turf) denotes the raw-humus or peat matter; in addition to the indices used in [12], we denoted the gleyed horizon with an increased content of the buried organic material by the letter d (cryoturbated dynamic horizon). The presence of this horizon above the permafrost table is an important feature of the studied soils. In the new system of soil horizons suggested in [13], there are no special indices for the horizons of that type. The cryoturbated horizons CR, Bcr, and Gcr do not always meet the diagnostic criteria of the cryoturbated and slightly gleyed horizon immediately above the permafrost table.

The increased content of cryoturbated organic material immediately above the permafrost table and in the uppermost part of the transient layer and the absence (or very low amount) of such inclusions in the deeper parts of the transient layer allow us to suppose that the periods of active cryoturbation (resulting in the admixture of surface organic materials into the deep soil layers) corresponded to the periods with a relatively high position of the boundary of seasonal soil thawing (i.e., to the periods with the active layer thickness close to or somewhat exceeding the modern values).

In the Indigirka tundra, the morphology of the transient layer proved to be more complicated and spatially heterogeneous. Some parts of this layer consist of virtually pure ice with a thickness of 15–20 cm; other parts represent gleyed silty loam with a high ice content and a latticed cryogenic fabric; there are also fragments consisting of frozen organic material with a low admixture of mineral particles (Figs. 2 and 3). In the contact zones between the thick ice lenses and the organic material, the latter may be covered by the ice-rich interlayer, under which it gradually thins out to disappear at a distance of 10–15 cm. The presence of ice interlayers under the profiles of permafrost-affected soils of Yakutia was earlier noted in the literature [8].

The leveling survey of the key plots demonstrated that the amplitude of the heights of the permafrost surface microtopography reaches 30 cm; the amplitude of the heights of the soil surface microtopography (from the top of the elevated nanopolygons to the upper boundary of the peat layer in the crack zones) reaches 50 cm (key plot 1).

Superposition of schematic maps of the soil surface and the permafrost surface topographies for this plot shows that the most elevated elements of the permafrost table occur under the nanopolygons. The ice content in the transient layer within such elements reaches its maximum. Such an unusual pattern of the permafrost surface may be explained by the previous history of the development of the cryogenic microtopography on the studied plot. Earlier, during the stage of a barren circle on the nanopolygon surface, the thawing depth under it gained its maximum. Upon the soil thawing, water accumulated in the microdepression of the permafrost surface under the nanopolygon. Then, upon the soil freezing, this water was segregated into relatively thick ice bodies. The gradual settling of vegetation on the barren circle and the development of the surface organic horizon gradually decreased the heat flux into the soil. The differences in the thermophysical properties of the ice bodies under the nanopolygons and of the surrounding mineral and organic materials predetermined the complicated pattern of the modern seasonal thawing.

On plot 2, the relationship between the soil surface and the permafrost surface topographies is somewhat different (Fig. 3a, b). The lowermost parts of the permafrost surface tend to occur under the central parts of the nanopolygons; the transient layer under them consists of the ice-rich fine-grained material with inclusions of frozen organic matter. Elevated parts of the permafrost table are found under the cracks with peat soils. Thick ice lenses are found within the transient layer at a depth of 5–10 cm from its surface in the zones under peripheral parts of the nanopolygons. Such patterns of the permafrost surface microtopography have been traced in a number of pits and can be considered typical of the studied plot. Under ice bodies near the cracks, the material of the transient layer is enriched in the weakly decomposed organic matter with some admixture of the loamy material; this organic matter represents the lowermost parts of the peat soils in the cracks. It composes 5- to 7-cm-thick interlayers stretching from the crack zones to the central parts of the nanopolygons (Fig. 4b).

The distinct microtopography of the permafrost surface and spatial differentiation of the composition of the transient layer are conditioned by the processes taking place in the deep soil horizons. The admixture of peat matter under the central parts of nanopolygons is very considerable: the average loss on ignition reaches 20.2%, and the organic carbon content is 4.7% ($n = 6$). This organic material accumulates immediately above the permafrost table and, especially, in the uppermost part of the transient layer. Deeper, its content decreases. The composition of the lowermost part of the soil profile and the transient layer is spatially heterogeneous. In some zones, the loss on ignition is up to 62.5%, and the organic carbon content is 23.4%. In the predominantly mineral zones, the loss on ignition is 6.0%, and the organic carbon content is 3.2%. In the mixed samples taken from the zones enriched in organic matter, the loss on ignition reaches 32.0% and the C org content, 10.1% ($n = 10$, plot 1). On plot 2, the corresponding values are 30.1 and 8.9%, respectively ($n = 6$). The thickness of the organic-rich horizon above the permafrost table varies from 7 to 12 cm; together with the organic-rich material in the upper part of the transient layer, it varies from 25 to 32 cm.

The thickness of surface organic (raw-humus or mucky–peat) horizons formed within the overgrown nanopolygons does not exceed 7–13 cm; the loss on ignition in them averages 46.5%, and the organic carbon content is 8.9%. Taking into account the areas occupied by the organic-rich material in the deep parts of the soil profiles and in the transient layer, we can say that the total reserves of organic matter in these deep horizons are comparable with or even exceed the reserves of organic matter in the surface soil horizons (except for the peat soils in the cracks).

Thus, the lowermost soil horizon in the Indigirka tundra is enriched in the peat-like organic matter; it differs considerably from the cryoturbated superpermafrost horizons in the lower reaches of the Kolyma and Indigirka rivers [11], other parts of the tundra zone in northern Yakutia [5], and in the East European tundra [9]. Cryozems with organic-rich horizons in the lowermost parts of the soil profile and in the transient layer were described by us in the 1980s and 1990s during surveys in the typical tundra zone on the Kolyma–Alazeya interfluve. The areas of such soils are relatively small. An obligatory condition for their formation is the presence of crack zones with peat soils, whose lowermost parts reach the surface of the transient layer and penetrate into it. Thus, their development is conditioned by the processes in the upper part of the SPC (the formation of peat and muck horizons), as well as by the intensity of cryoturbation and the depth of seasonal thawing. It is probable that the enrichment of the lowermost soil horizon in the peat organic matter could have taken place during previous stages of the SPC development in the Holocene.

A thorough analysis of the morphology of pit walls in a period close to the period of maximum soil thawing made it possible to judge the mechanism responsible for the involvement of organic matter into the lowermost soil horizons and the transient layer. When the seasonal thawing reaches its maximum depths, the lowermost soil horizons become water-saturated due to the melting ice lenses. Active water flows are formed in the hollows of the permafrost surface. Schematic maps of the distribution of water flows over the permafrost surface have been obtained from the analysis of the microtopography of the latter [15] (Figs. 2d and 3d). The water flows take place under pressure; they involve peat-like organic material, which is also redistributed between separate elements of the soil nanocomplex. The general direction of these flows is from the elevated parts of the permafrost surface under the cracks toward the depressed parts under the nanopolygons. Our data suggests that the slopes of the permafrost surface in the soil nanocomplexes are about 2–5°; in some cases, much steeper slopes (up to 20°) are formed. The well-pronounced microtopography of the permafrost surface facilitates the migration. Another factor enhancing it is the presence of ice-rich material with latticed cryogenic fabric in the deep soil horizons and in the transient layer. The melting of ice lattices and the discharge of superpermafrost water along the general slope of the surface are essential factors. The melting of ice lattices makes the material cemented by them very loose. Thus, some portions of peat may be torn off from the main peat bodies and involved into the flows directed toward the depressed parts of the permafrost surface microtopography.

The general discharge of superpermafrost water into the local drainage network is clearly pronounced in the north of Yakutia from the end of August to the middle of September. During this period, the thawing of deep ice-saturated soil horizons results in their oversaturation with water. The superpermafrost water becomes enriched in the dissolved organic matter and, after filling all the microdepressions in the permafrost table, migrates along the general slope of the surface toward the local rivers. Often, it forms temporal surface water flows. This water is dark-colored owing to the high concentration of dissolved organic substances; this phenomenon is referred to as the black water period by local people. Active water flows during the period of maximum thawing result in some rise in the water level of small rivers; they also fill local thermokarst depressions.

It is probable that the migration of raw organic matter above the permafrost surface is enhanced by the cryostatic pressure appearing in the system during the beginning of soil freezing from the top and from the side zones filled with water-saturated peat. The accumulation of peat in the deep soil layers changes their thermophysical properties; the thawing depth decreases, and the lowermost parts of the layer enriched in organic matter become permanently frozen.

The presence of the organic horizon in the deep parts of the SPC (including the transient layer) allows us to distinguish this horizon separately. Its continuous character differs from the local accumulations of organic matter within the mineral soil mass attributed to cryoturbation (the BCg,cr horizon, Fig. 4a). We suggest that a continuous horizon enriched in the raw organic material directly above the permafrost table can be referred to as the superpermafrost lateral raw-humus horizon (the BCg,l horizon, Fig. 4b).

The specific genesis, morphology, and properties of this horizon, as well as its specific location in the soil profile, make it different from the humus and organic horizons distinguished in the *Classification and Diagnostic System of Russian Soils* [13]; it also differs from the buried humus and organic horizons. As the genesis of this horizon is related to the lateral migration of substances above the permafrost surface, it can be referred to as a specific lateral raw-humus horizon, because the accumulation of organic matter in it is mainly due to lateral migration processes. From our point of view, this horizon should be included in the general system of soil horizons distinguished in [13].

CONCLUSIONS

The analysis of the morphology and properties of the frozen Late Pleistocene loamy deposits composing coastal lowlands in the north of Yakutia suggests that their upper part under the modern soil profile is characterized by a number of specific features. The properties of the upper permafrost layer beneath the modern soils are conditioned by the complicated history of the bioclimatic conditions in the region during the Holocene. This part of the permafrost was subjected to thawing during the Holocene climatic optimum. Its properties are tightly associated with the processes that took place in the former active layer. It is suggested that the soil profile, together with the underlying permafrost subjected to thawing during the Holocene climatic optimum, can be distinguished as a soil–permafrost complex. This complex consists of three parts: the soil solum, the transient layer that may be subjected to thawing during the warmest years, and the underlying intermediate layer that was subjected to thawing during the Holocene optimum. The interface between the transient layer and the lowermost (superpermafrost) soil horizon is the zone of active cryogenic pedogenesis, the specific features of which are recorded in the morphology and properties of the superpermafrost soil horizon and the frozen transient layer. These parts of the soil–permafrost complex are closely associated with one another, and their properties and spatial variability are indicative of the processes shaping the complicated patterns of permafrost-affected soils.

The development of a distinct microtopography of the permafrost surface, the high ice content in the uppermost permafrost layers, and the water saturation of the superpermafrost horizon during the period of maximum soil thawing (owing to ice melting) are responsible for the large-scale lateral migration of water and raw (peat-like) organic material above the permafrost surface; the organic material tends to accumulate in the microdepressions of the permafrost table, where it forms specific raw-humus horizons of the lateral accumulation of organic matter.

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