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GENESIS AND GEOGRAPHY OF SOILS

Soils of Loamy Watersheds of Coastal Tundra in the North of Yakutia: Pedogenetic Conditions and Processes

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Abstract—This paper considers regularities governing the formation of automorphic tundra soils on glacial loamy deposits containing relict organic matter mainly represented by very fine plant detritus. Drainage, microtopography, and cryoturbation activity are the major controls of the development of these soils. With an increase in drainage, the following pedogenetic trend is observed on the surface of yedoma (Ice Complex) areas: gleyzem–cryozem–cryometamorphic soil. The climate change in the Holocene induced quick transformation of topography and general landscape situation and promoted formation and development of cryogenic soil complexes in the considered territory. Upon the low intensity of pedogenesis, the features and properties of previous soil formation stages are often preserved in the soil profiles; these are: gleyzation, peat accumulation, and cryoturbation.

Keywords: cryozem, gleyzem, cryometamorphic soils, Cryosol, permafrost soils, thermokarst, glacial complex, yedoma, alas, cryogenic mass exchange, gleyzation, Late Pleistocene, Holocene

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INTRODUCTION

Soil formation under automorphic conditions is the starting point for learning the soil-formation potential of climate and biota, trends in soil formation, and their manifestation in different parent materials with time. The coastal lowlands of the Northern Yakutia stretching along the Arctic Ocean from the Lena to the Kolyma Rivers for more than 2.5 thousand km and encompassing the tundra and the northern taiga zones passed through a complex history in the Holocene. Almost the entire area is composed of frozen silty loam. The surface of the Late Pleistocene plain was radically changed during the last 10–11 thousand years by quick and large-scale thermokarst processes and developing river network. Many vast terraced alas basins have been formed, which are still intensely developing now. This resulted in setting apart some Late Pleistocene surfaces, hence, in the formation of residual hills or uplands (yedomas), and somewhat later in the formation of neoautomorphic surfaces (separated by the newly formed Early and Middle Holocene lakes) (Fig. 1). Automorphic cryogenic soil formation is proceeding there under good drainage conditions.

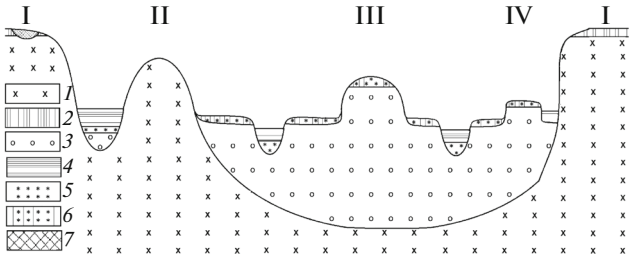

Fig. 1. Schematic surface structure and distribution of parent materials in the coastal lowlands in the northern Yakutia. Outliers of the Late Pleistocene plain (yedomas): I—high-level yedomas; II—medium- and low-level yedomas. Neoautomorphic surfaces: III—alases of high level; IV—alases of low level. Parent materials: (*1*) Ice Complex deposits, (*2*) intermediate layer, (*3*) taberal deposits, (*4*) lakes, (*5*) lacustrine deposits, (*6*) lacustrine-bog deposits, and (*7*) organic sediments of the Early and Late Holocene thermokarst basins and embryonic thermokarst lakes.

Localities showing the semihydromorphic and hydromorphic soil-formation conditions exist at watershed surfaces. A strongly continental climate, a short summer with low heat supply determining a short total period of soil formation, as well as the ice-rich frozen ground occurring close to the surface result in a wide spectrum of soils forming on watersheds.

OBJECTS AND METHODS

Soils and soil cover of automorphic and neoautomorphic surfaces were studied in the Indigirka and the Kolyma rivers interfluve in tundra [10]. The deposits

and soils are light loamy with coarse silt fraction predominating (60–70%) and a low content of clay (less than 10%) [6, 30]. The temperature in the upper permafrost layer ranges within −7...−13°C, and the average depth of the active layer ranges within 40 and 60 cm. The climatic conditions control the slow thawing of soils, so that most soil profiles exist in the regime of low positive temperatures (below 3–5°C) in summer. This is the reason of slow biochemical transformations there and a short total time of soil formation [27].

Along with the soil study by means of terrain routes crossing the area from the sea coast to the taiga zone, we have investigated soils and soil cover at the key sites, which we visited not less often than once in 5 years for 30 year. These were: Cape M. Chukochy (69.615889° N, 160.940463° E), Sukharnaya River mouth (69.390361° N, 161.627833° E), confluence of B. and M. Kon'kovaya rivers (69.488451° N, 160.669162° E), and the right bank of Panteleikha River (68.743843° N, 161.410328° E)). The observations were conducted on the dynamics of seasonal thawing, moisture, ice content, activity of cryoturbation processes and their distribution in time and by seasons, long-term dynamics of spot formation and overgrowing, as well as on the condition of soil and day surface in winter. An important methodological aspect was the study of soil structure and underlying frozen deposits in new thermoerosional escarpments of river banks, lake and sea coasts stretching for tens and hundreds meters. This permitted us to find out some time-spatial regularities in the arrangement and evolution of soils and soil cover, to reveal a number of specific features in the structure of soil-cryogenic complex, i.e., the recent soils and the upper (transient and intermediate) layers of permafrost that thawed in the warmest periods in the Holocene [11, 24], to assess the properties of this layer, as well as of other Holocene soil-forming deposits. It should be stressed that our field studies were performed in the period of the maximum profile thawing (late August-early September), which allowed us to scrutinize in detail the structural features of supra-permafrost horizons of tundra soils [11].

Samples for meso- and micromorphological analyses were also taken at that time. The chemical characteristics of studied soils were analyzed by the routine methods in the laboratory of IPCBPSS RAS. The soil microstructure was studied using the Carl Zeiss Axioscope A1 microscope equipped with Axiocam MR5 camera. The Classification and diagnostics of Russian soils published in 2004 was used in this work [22].

RESULTS AND DISCUSSION

Holocene history of lowlands and characteristics of parent rocks. We studied both neo-automorphic and automorphic surfaces, which represent low residual hills composed of silty loams (deposits of Late Pleistocene Ice Complex, IC) with thick wedge ice. In the Russian and foreign publications, the latter are commonly referred to as yedomas, and the deposits composing them, as yedoma deposits. Neo-automorphic uplands are the parts of thermokarst lake basins, which dried in Early and Middle Holocene to turn now into the isolated residual elevated plots – remnants due to the ongoing thermoerosional downcutting. The soil-forming materials consist there of lacustrine sediments and underlying taberal permafrost deposits with ice veins thawed out upon the formation of thermokarst lakes. These sediments existed for a long time in the under-lake talik with low positive temperatures (about 1°C). Later, after the disappearance of lakes or significant reducing of their areas and/or depths, these strata returned to the frozen state.

The yedoma surface is preserved due to drainage, which was improving along with the development of river network in the region. With time, many such remnants became separated from the river channels by valleys and from thermokarst lakes by terraced slopes, the deposits of which protect the underlying IC strata from further active destruction.

Thermal abrasion develops in case yedomas are located close to thermokarst lakes or banks of major rivers. The coastal line of East-Siberian Sea is found out to retreat at a rate of 2–4 m/year on average in the coasts composed of IC deposits, and somewhere, at a rate 6–8 m/year and more [1, 37]. According to calculations based on GIS-technologies, the yedoma surfaces cover 15% of the Kolyma Lowland [36].

As a result of coastal thermal abrasion and slope destruction, the poorly drained central parts of yedoma surfaces approach the slope edges within the time spans comparable to the soil-formation period (hundreds of years). The surface drainage drastically improves there, which alters the soil-formation. This important specific feature in the landscape development in the considered territory explains a great variety of transitional soils ranging from gleyzems to cryozems on the yedoma surfaces, the presence of paleopedogenic features in their profiles and the discrepancy between the soil structure and properties on one hand, and their position in the landscape on the other. This is manifested in the preservation of gley features, rather thick peat horizon, and cryoturbation input of organics to the middle and lower parts of soil profiles.

The presence of organic substances [10, 25, 32, 38, 40] and a high content of available forms of biophilic elements [5, 14] (preserved since the time of sediment accumulation due to permafrost) appear to be important features of IC deposits. The bulk of organic matter consists of fine (up to 0.02 mm in size) detritus of Late Pleistocene moss-grass vegetation and to a lesser extent of humus compounds [7]. The content of C_{org} ranges within 0.8–2.5%.

The present-day thickness of the active layer is equal to 40–60 cm. On the automorphic surfaces of the Late Pleistocene plain outliers, soils are formed on the permafrost intermediate layer, which was the active layer in

the period of maximal warming and now returned to the frozen state. Its thickness including the soil profile is equal to 1–1.5 m in the tundra zone. In the Early Holocene, this layer existed for a long time (tens of thousands years) under low positive temperature, which transformed partially the initial properties of IC deposits, i.e., resulted in their gleying and some changes in the content of the most labile components (table).

The fresh matter of IC deposits participates in soil formation as a parent material in automorphic positions only at watersheds adjoining the slope edges. During the permafrost thawing in summer, the already formed profiles or their individual horizons may creep down along the slightly sloping permafrost surface. As a result, the underlying fresh material of IC deposits, controlling the properties of the lower soil horizons and sometimes, of the entire mineral profile, is involved in soil formation. The deposits of IC are evenly colored (7.5YR 6/0, 7.5YR 5/0, 10Y 6/1), they contain plant detritus, and the seasonal thawing-freezing leads to quick cryogenic structuring [9]. All these factors complicate significantly identification of such newly formed soils or the soils with "rejuvenated" middle and lower profile parts. On the neoautomorphic surfaces, the parent material having passed aquatic phases in their development show diverse properties and mosaic distribution. The deposits of former bogged lake basins (alases) though being of the same texture as the IC material, manifest lower ice content and higher density. The content of C_{org} is comparable, however, the share of fulvic acids in humus is higher [7, 31], whereas the amounts of fine plant detritus as well as the mobile potassium and phosphorus are lower. The content of C_{org} in the stratified alas deposits may reach 6–12% in some layers with a high content plant detritus, with the loss on ignition reaching 25%.

The complicated Holocene history of Late Pleistocene residual surfaces, the formation and the subsequent disappearance of Early Holocene thermokarst lakes, development or degradation of various glacial landforms, destruction of peatbogs or peat soils favor the stable preservation of lithogenic or paleosol features in many soil profiles. This fact often controls the intricate character of soil profiles and the present-day soil cover arrangement.

The leading processes of soil formation on watershed surfaces. Two trends in the present-day pedogenesis are traced in tundra of coastal lowlands:

—Gleyic soil formation developing on the bottoms, low terraces, poorly drained medium and high terraces, nondrained watershed surfaces with hummocky microrelief;

—Cryozem formation going on nanopolygons and predominating under the good drainage conditions and well developed nanopolygonal cryogenic relief [6, 13, 18, 30]. The soil complex consisting of cryozems on nanopolygons and organic soils in fissures or sinks is formed there.

The following processes are considered to be predominant on coastal lowlands in watershed soils on loamy deposits upon close to the surface permafrost:

—Accumulation or slow decomposition of coarse organic matter in the upper parts of the profiles;

—Formation of water-soluble humus compounds in organic horizons and in the uppermost mineral part of profile, their slow downward migration, even distribution and fixation in the central and lower parts of soil profile ("impregnation humus");

—Cryogenic mass exchange, with cryoturbation processes being its leading constituent, which bring considerable amount of raw organic matter from the upper organic horizons to slowly transform it biochemically in central parts and to accumulate in the supra-permafrost parts of the profiles;

—Partial homogenization and cryodestruction of organic matter brought to the mineral horizons of the profile;

—Lateral transportation of coarse organic matter along the permafrost surface from the fractures of peat soils and internanopolygonal sinks to the supra-permafrost horizons of nanopolygonal soils and its accumulation there; cryogenic structuring;

—Gleying of supra-permafrost horizons.

Many of the above-mentioned processes of cryogenic soil formation are scrutinized in multiple publications on the soils of tundra and the northern taiga zones [3, 12, 13, 17, 18, 21, 23]. The analysis of physicochemical properties of coastal lowland tundra [6, 14, 29, 30] did not reveal any reliably identified features of transformation and redistribution of mineral products of soil formation in their profiles, which must be caused or may be concealed by active and large-scale cryological mass exchange processes. The features of redistribution of mobile components in the profile are identified, i.e., the organic substance, the related compounds of biophilic elements, ferric and ferrous compounds detectable in fresh soil samples [8, 13, 18, 29]. The existing profile differentiation by horizons is identified above all by the structure, i.e., by the size and shape of flattened textural blocks produced under the impact of ice schlierens formed in the soil profile (CR1 and CR2 horizons) and by the gleying intensity.

Cryoturbation and frost boiling. Cryoturbations and their most vivid manifestation—frost boiling is the main component of cryogenic mass exchange in the automorphic soils in the northern Yakutia. Boiling circles are formed on nanopolygons of 10—25 cm in height and 40—80 cm in diameter in nanopolygonal tundra with the cryozems dominating the soil cover. Nanopolygonal cryozems are associated with soils of interpolygonal cracks, i.e., peat gleyzems or peat soils. Circles are being formed most intensely at the sites

Chemical properties of the studied bodies

Object	Horizon	Depth, cm	Loss on ignition	C org	pH H_2O	Exchangeable bases, cmol(equiv.)kg					C/N	CO_2 carb, %	Mobile, mg/100 g soil		Tamm's extract, %	
			%			Ca	Mg	Na	K	Σ			P_2O_5	K_2O	Fe_2O_3	Al_2O_3
Cryozem	O	4–8	28.0	Not det.	5.1	Not det.										
	AO	8–13	6.1	1.1	7.4	10.2	6.4	0.2	0.3	17.1	1.6	0.3	10.2	3.6	0.4	0.3
	CR1	13–41	5.3	0.7	7.7	11.8	6.4	0.3	0.4	18.9	1.2	0.2	26.1	4.8	1.0	0.5
	⊥CR2	41–55	6.3	1.2	7.8	14.3	6.8	0.5	0.4	22.0	3.0	0.3	31.1	6.2	1.1	0.5
Intermediate layer	C	60–80	7.1	1.1	8.1	14.4	5.3	0.4	0.3	20.4	11.0	0.2	38.0	8.4	1.0	0.5
	C	80–120	7.2	1.3	8.0	16.2	5.0	0.5	0.4	22.1	13.0	0.2	36.4	12.1	1.1	0.5
Ice Complex	[AC]	160	7.6	1.4	8.4	14.8	5.2	0.7	0.3	21.0	14.0	0.3	40.1	14.7	1.0	0.6
	[AC]	260	8.0	1.2	8.2	13.7	4.2	0.5	0.3	18.2	12.0	0.4	32.0	8.8	1.2	0.8
Barren boiling circles	K*	0–2	4.0	1.0	6.6	9.1	4.4	0.3	0.4	14.5	3.4	0.2	16.0	5.6	1.1	0.5
	CR1	2–5	6.2	1.3	6.4	8.8	4.0	0.4	0.4	13.6	2.6	0.2	18.7	4.7	1.2	0.6
	CR2	5–17	5.7	1.0	6.6	7.0	5.5	0.3	0.3	13.1	2.5	0.2	20.1	10.1	1.7	0.6
	⊥CRg	17–47	6.9	1.3	5.9	5.1	4.8	0.3	0.3	10.5	5.0	0.2	28.4	8.9	1.1	0.5
	C	47–67	8.7	1.7	5.0	6.2	7.2	0.3	0.3	14.0	8.5	0.3	29.0	8.2	1.2	0.6
Cryometamorphic raw-humus soil	AO	0–6	18.6	Not det.	7.0	Not det.										
	CRM1	6–42	7.1	1.9	7.2	10.2	8.0	0.4	0.5	19.1	2.4	0.2	11.2	6.4	0.9	0.5
	⊥CRM2	42–58	6.3	1.2	6.8	14.4	5.5	0.3	0.4	20.6	1.7	0.3	16.2	7.8	0.9	0.5
	C	58–70	6.0	1.0	7.1	12.3	3.7	0.4	0.5	16.9	2.5	0.3	10.5	10.3	1.2	0.7
Gleyzem	O	0–10	28.4	Not det.	5.4	Not det.										
	A0A1	10–14	12.0	4.2	5.6	9.4	4.7	0.4	0.4	14.9	5.0	0.3	16.7	10.3	1.5	0.5
	BG	14–30	6.4	1.4	5.8	8.9	4.1	0.4	0.3	13.7	2.5	0.3	18.4	8.2	1.8	0.6
	⊥G	30–45	6.6	1.6	5.9	8.4	5.2	0.6	0.5	14.7	3.8	0.3	19.6	8.2	1.8	0.8

*Thin crust.

with the active layer of 40—70 cm thick. Just these processes of spot formation are believed to produce this nanotopography [2, 16, 28, 33, 34]. However, according to the observations over the surfaces of thermokarst lake terraces of different age and over the bottoms of recently disappeared lakes, this is not the only or most common mechanism of cryogenic nanopolygonal nanotopography formation in the considered tundra.

With the improvement of drainage of low-level terraces, the sedge hummocks are transformed with time to cereal hummocks putting the basis for the subsequent formation of nanopolygonal relief. The specifics in the fall freezing of grass hummocks, migration of additional moisture to their central parts, and intense ice formation result in heaving of these parts, segregation and further growing of nanopolygons on their basis. The next stage in their development is controlled by the outflowing of mineral matter of the nanopolygons' central parts on the surface, i.e., mottle formation. Cryogenic nanopolygonal relief widespread on the high-level terraces is one of the indicators of the formation age and duration of these landforms, and it determines the development of semihydromorphic soils there.

The studies carried out during the seasonal freezing of soils in the fall attested to the absolutely predominating soil outflow upon the growing cryostatic pressure in the central parts of nanopolygons on their freezing [33, 39]. Being covered by the outflowed mineral mass, the organic substance of the upper horizons submerges to a depth of 10—20 cm. Further, in the course of seasonal freezing-thawing cycles, the prominent difference in the mechanical and thermophysical properties between the coarse organic matter and the enclosing mineral substance produces an intricate distribution pattern of moisture, ice segregation, as well as rates of shrinkage and frost heaving. Already in 3—5 years, the initial occurrence of buried organic matter becomes noticeably disturbed; its separate parts become isolated, coarse plant residues are partially decomposed, and they are gradually being redistributed and partially mixed with the mineral material of the central and lower horizons [35]. With time, some fragments of poorly homogenized coarse material reach the supra-permafrost parts of the profile, where it is gradually accumulated. As a result, in a number of cryozem profiles at the permafrost boundary, a layer is being formed enriched in the cryoturbation organics, the reserves of which may exceed those in organic horizons of the upper parts of cryozem profiles. It is suggested that such horizons should be distinguished as a separate kind of diagnostic genetic horizons, i.e., organic supra-permafrost accumulative horizons (CRO) [24].

Another way of such horizon formation was described earlier [11, 24]. It is performed by the lateral transfer of coarse organic matter down the permafrost sloping surface from the peat soils of internanopolygonal cracks towards the more deeply thawing supra-permafrost parts of cryozem profiles on nanopolygons.

Structure and formation of organic profiles. The properties and thickness of organic surface horizons occurring under automorphic conditions on lowlands are controlled, above all, by the plant cover composition, meso-, micro-, and nanotopography of the surface, its age, duration of soil formation going there, activity of cryoturbation processes (spot formation), and slope processes including the widely spread solifluction developing even upon very insignificant slope gradient. Snow cover and wind regime play a special role in the accumulation and transformation of organics under automorphic conditions in the lowlands, as they control the cryogenic destruction of coarse organic residues and eolian removal of the by-forming plant detritus.

In tundra, the following obvious regularities are registered in the organic horizon formation on the surface of yedoma outliers and neoautomorphic surfaces. In sites, remote from slopes, hence, with impeded drainage, or in the areas of former thermokarst basins under the green moss cover with cotton-grass and sedge, the organic horizons develop (O, T, OT) characterized by a weak transformation in organic residues. The total thickness of litter-peat and peat horizons including the moss litter is equal to 12—15 cm, with the moss litter reaching half their thickness. Organic horizons is underlain by thin (up to 2 cm) dark brown raw-humus horizon (AO) consisting of fine plant detritus, mineral material (silt particles) covered by dark humus films. On poorly drained watersheds, thick peat horizons affect the water regime and maintain and preserve the initial gley soils there.

In the better drained parts of automorphic surfaces (close to slopes) with predominating cryogenic nanopolygonal landforms, cryological mass exchange and spot formation develop much more intensely. The litter-peat horizon (O) of 7—9 cm thickness is being formed in mature cryozem profiles on nanopolygons under the moss-sedge-grass cover. Its organic material is moderately decomposed, while the lower part of O horizon manifests features of deeper transformation.

In the underlying AO horizon, 3—7 cm thick, along with detritus, humus compounds play an active part, coloring the horizon in brownish-gray.

The thickness and development of organic horizons in cryozems depends directly on the duration of overgrowing of barren circles, passing certain development stages, which are determined by the plant cover composition and the degree of plant residues transformation [20]. Observations over the spot overgrowing based on the findings of some well-dated artefacts on their once fresh surfaces (household items of deer-breeders temporary settlements dated as 1950—1960s) proved that the O + AO horizons, up to 6-cm thick, have been formed there for the past 60 years, and their

differentiation by the degree of organic decomposition has started. The formation of organic horizons is accompanied by the stabilization of moistening, freezing-thawing and seasonal ice-formation regimes in the mineral parts of soil profile. The differences in the ice schlieren size formed at different depths cause or intensify their differentiation by horizons, which are distinguished above all by the size of flattened peds. Taking into account that the soils have been formed on the deposits initially containing organic carbon, and also with consideration of the ongoing cryogenic input of organic material and the downward migration of water-soluble compounds, we may estimate the C_{org} content in the mineral horizons of cryozem profiles at 0.8–1.2%; in dark mottles, it reaches 2–5%. The Cha/Cfa ratio ranges within 0.5–0.7 in the middle part of the profiles [31].

As proceeds from the analysis of a large database on the C_{org} distribution in the cryozem profiles of Kolyma-Indigirka interfluve tundra, its content in the lower supra-permafrost horizons is by 10–20% higher than that in the middle part of the profile for more than in 40% of these soils. This fact permitted Karavaeva and Targulian [19] to propose a hypothesis of supra-permafrost 'retinization' of humus in the bottom of cryogenic tundra soil profiles. The performed micromorphological analysis of supra-permafrost horizons in cryozems testified to a considerable amount of very fine organic residues (detritus) of 0.5–0.02 mm in size brought there in the course of cryoturbations and later significantly transformed in situ [4]. This fact does not rule out the possible downward migration and accumulation of water-soluble humus compounds in the zone of cryogenic aquiclude, but points to some more powerful mechanical ways of organic matter input to the lower parts of profile [8, 25].

Gleyzation. Severe climate in the region is a well-known factor suppressing development of gleying [26]. A wide range of manifested gley features in automorphic soil profiles in interfluvial areas is controlled by the drainage conditions of a particular site, ice content in the upper permafrost layer, modern and past meso- and microlandforms on the day surface and on the permafrost surface, plant cover composition, thickness and specifics of organic horizons, and the position of the seasonally thawed layer boundary.

The frequency of spot formation in the particular nanopolygon plays is important, though yet poorly studied in terms of gley manifestations in the cryozems. The spot formation process disturbs horizonation and soil consistence and partially mixes the upper mineral parts of profile. At the initial stages of soil development, the gley nucleus is formed under the bare spot. Easy penetration of snowmelt water in quickly thawing mass in spring, of rainwater in summer, and rich ice segregation upon freezing favor this process. The gley nucleus is gradually disappearing with the development of plant cover (moss, in particular) and its thickening, as well as organic horizon formation. This is caused by a sharp reduction in ice segregation and general moistening of the material there. At the tundra sites, where spot formation is most intense, the mineral horizons of cryozems are colored as 2.5Y 6/2; 5/2.

The analysis of cryozem profiles during the periods of maximal thawing and the study of permafrost transitional layer on the walls in the thermokarst outcrops showed that distinct signs of gley in the supra-permafrost horizons, such as even dove color, are of relic origin in many soils. The relic gleying results from the soil formation in the earlier Holocene periods, when hydromorphic conditions predominated, and thawing of the active layer was much deeper [6, 7, 30]. At present, on some well drained tundra sites, these relic gley horizons may be included in cryozem profiles only at the time of the maximal thawing, as well as in some years, or in prolonged warm periods, therefore, they cannot be always studied or identified.

In case of high moisture or high ice content in the lower parts of soil profiles, the above- permafrost gleying typical of tundra soils [23] is combined with the relic gleying, which is most vividly manifested at the sites with impeded drainage or lateral moisture inflow or seasonally snowmelt runoff downslope the cryogenic aquiclude surface [24]. This supra-permafrost gley horizon, 7–10 cm thick, is always present in the supra-permafrost profile part; and it is gradually merging into the overlying gleyic or nongley horizon. On better drainage, decreasing moisture, the morphological signs of gleying in the lower parts of the profile become weaker: the dove color disappears; the ocherous films appear to provide mottling, more rarely marble-like color to the horizon. Analytically, this is registered in a decreasing content of acid-soluble iron in 0.1 N H_2SO_4 extract as compared to the horizons of actual supra-permafrost gleying [29].

If rather well-preserved cryoturbated raw organic matter is present in central parts of the profiles, mineral zones adjacent to them may display chromatic gley features; such horizons may be referred to as gleyic horizons.

The surface gleying is weakly pronounced in the cryozem profiles in the contact zone between the mineral part of profile and well developed organic horizons. Its development is inhibited by a rather strong (granular) structure in this part of the profile, quick thawing in the uppermost mineral horizons, and the absence of water stagnation. As seen from the analysis of gley forms and the content of different compounds of mobile iron in tundra soils, the amount of reduced forms is directly proportional to the hydromorphism degree of profiles and individual horizons [29].

Upon the summer thawing of soils, excessive moisture accumulates at the top of descending permafrost surface. This moisture is spent for replenishing the moisture deficit in the central parts of profiles caused

by winter freezing (the winter desiccation layers). This seasonal redistribution of moisture often prevents overmoistening in the upper parts of soil profiles leading to a weaker gleying even up to its total disappearance. Perennial observations over the moisture in cryozem profiles in the north of Yakutia attested to its possible broad variation depending on weather conditions and mostly on the kind and time of summer precipitation. Upon heavy rain, which is a rare phenomenon in tundra in August, and which is capable to percolating the moss falloff layer and organic horizon, the moisture in the mineral horizons rises sharply. This influences the thixotropic properties of soil; it may drastically enhance formation of circles on nanopolygons upon sudden freezing in the fall; and it also influences the size of forming schlieren, i.e., the fabrics of individual horizons. Drizzly summer rains typical for tundra (50–70 mm, the mean annual precipitation being 150–200 mm) are largely spent for evaporation and soak into the upper organic part of profile keeping the stable regime of its moistening.

Fine (1–3 mm) organo-ferric concretions, the content of which reaches 3 g/dm^3, are found at a depth of 20–35 cm in automorphic cryozems without gley features. They are supposed to be of relic origin and to have been formed in the Early Holocene [6].

The soil cover pattern at automorphic surfaces. At the sites remote from the watershed edge, upon poor drainage, the Early Holocene deposits of thermokarst basins and minor shallow lakes are preserved in slightly transformed state (Fig. 2). Vegetation is presented by mosses with widespread sedge, cotton-grass, cereals (sporadically); and sedge-covered hummocks prevail among microlandforms. A wide range of gleyzems (O–G–CG), peat gleyzems (T–G–CG), oligotrophic (TO) and eutrophic (TE) peat soils sometimes with the signs of degrading organic horizons are formed there. Destructive hummocky peatbogs occur. The soil diversity and the soil cover pattern are complicated by cryogenic landforms at different stages of development or degradation (ridged-polygonal, fracture-polygonal).

In the central parts of yedomas, outside the zones of ancient depressions, the soils are being formed with weak gley features. The soil cover is complex there. The soil-cryogenic complex includes mineral soils, i.e., cryozems and spot soils of nanopolygons, as well as peat (T) or peat gleyzems (T–G–CG) being formed in internanopolygonal holes or in fissures.

Within nanopolygons, typical peat cryozems (T–CR–C), gleyic peat cryozems (T–CRg–Cg) including those with modern and relic supra-permafrost gleying, typical cryozems (O–CR–C) and supra-permafrost organo-accumulative cryozems, i.e., cryozems with the organic supra-permafrost accumulative horizons proposed by the authors (CRO) [24] to be identified, are under formation.

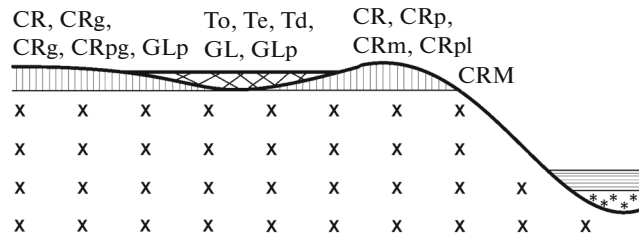

Fig. 2. Soils on automorphic surfaces of coastal lowlands in the northern Yakutia. Types and subtypes of soils (symbols in accordance with the Classification..., 2004 [22]): CR—typical cryozems; CRg—gleyic cryozems; CRm—mucky cryozems; CRpl—pale-metamorphized cryozems; CRp—typical peat cryozems, CRpg—gleyic peat cryozems; CRM—cryometamorphic soils, GL—typical gleyzems; GLp—peat gleyzems, To—oligotrophic peat soils, Te—eutrophic peat soils, and Td—dry-peat (folic) soils.

The transitional forms from peat cryozems to peat gleyzems are widespread under the conditions of weak drainage and less intense spot formation.

In addition to soil-formation conditions controlled by the specifics of a certain site, the individual development factors influence the properties and structure of soils at each nanopolygon, i.e., the stage of spot overgrowing, related thickness and differentiation of organic horizon, structure, ice content, summer moisture, the content of cryoturbated organic substance, the depths of seasonal thawing, etc. This results in substantial differences in the profiles and in the taxonomic position of neighboring pedons.

Typical cryozems (O–CR–C) and mucky cryozems (Oh–CR–C) are widely confined to the edges of yedoma remnants upon the better surface drainage, thinner snow cover, higher insulation and evaporation.

At the very edges of steep slopes the plant cover changes: the share of dryad, lousewort, and cereals rises, whereas the share of moss falls; and the polygons get flattened. The blowing off of snow, especially, on windward slopes, reduces the profile moisture and stops spot formation. At the same time, the plant litter destruction by snow corrasion drastically increases, and the fragmented plant residues are partially removed elsewhere. Substantial surface heating in summer leads to the active development of roots, intensification of root and grass falloff humification, formation of features typical for mucky and even humus horizons responsible for the formation of water-stable structure.

The mineral soil horizons do not display gley features, they acquire pale gray or gray color and contain a relatively high amount of fine roots. The cryogenic structure acquires some signs of transformation to weak crumb and even granular, and elevated water stability. These soils may be classified as cryometamorphic—organo-cryometamorphic (O–CRM–C) including

raw-humus cryometamorphic (Oao–CRM–C) subtype and raw-humus cryometamorphic (AO–CRM–C) type with a pale-metamorphic (AO–CRMpl–C) subtype.

In the course of yedoma relief development and the progressive decrease of watershed areas, the central parts of yedomas may relatively quickly (in respect to the soil time, i.e., hundreds of years) be found in their peripheral parts with strongly improved drainage [40]. Under these conditions, the main properties of already formed soils and often of vegetation are transformed more slowly than relief and soil-formation conditions depending on them [15]. Low intensity of biochemical processes in soils aggravates the inconsistence between the soils occurring there and the present-day landscape situation with the current soil formation conditions.

CONCLUSIONS

The analysis of soil formation conditions and properties of soils formed on the watershed surfaces of coastal lowlands composed of silty loams in the north of Yakutia revealed their close correlation with the developing automorphic surfaces of Late Pleistocene remnants (yedomas) in Holocene, their areas, deposits formed at that time, and the developing cryogenic meso- and microrelief.

The current development of soils in automorphic conditions is controlled above all by the drainage degree of the active layer. With progressively reducing yedoma areas and improving drainage, the following evolutionary soil sequence is being formed on their surface: gleyzems–cryozems–cryometamorphic soils, which reflects the trend in current soil formation on watersheds under the conditions of changing cryogenic nanopolygonal microrelief. Gleyic cryozems and typical cryozems appear to be the predominant soils on watersheds.

In the considered evolutionary sequence, the transition from gleyzems to cryozems is controlled by the formation of nanopolygonal relief, by drastic increase in cryoturbation activity manifested in spot formation. With frequently recurring cycles: spot formation–spot overgrowing–mature cryozem–spot formation, the mineral parts of cryozem profiles are enriched with raw organic matter, which is contained in some zones. Its further gradual downward migration and accumulation on the permafrost boundary lead to the formation of specific organic supra-permafrost accumulative horizons (CRO) there.

Upon quick changes in the shape and area of watershed surfaces with the development of meso- and microlandforms on them and low intensity of pedogenesis, the soil formation on the watershed edges may be slower than their transformation by other exogenous processes with corresponding changes in their regimes. This determines a wide range of soils being formed there, and often, the incompliance of the structure and properties of some of these soils to the current topographical position. The supra-permafrost gley horizon, as well as raw-humus morphons in some soil profiles may be considered relic features in cryozems developed on the surfaces of some yedoma outliers. A part of plant detritus in the profiles of cryozems and the high content of mobile phosphorus and potassium in them may also be considered Late Pleistocene pedorelics partly transformed by the Holocene pedogenesis. Cryometamorphic soils have inherited from the previous cryozemic stage of soil formation some strongly transformed mottles of dark organic matter in the lower parts of profiles, as well as the organoaccumulative suprapermafrost horizons.

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