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GENESIS AND GEOGRAPHY OF SOILS

Suprapermafrost Horizons of the Accumulation of Raw Organic Matter in Tundra Cryozems of Northern Yakutia

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Abstract—In the profiles of cryozems (Oxyaquic Turbic Cryosols) developing in tundra of northern Yakutia under conditions of shallow active layer, suprapermafrost horizons of the accumulation of raw organic matter are formed. Taking into account their genesis, stable and regular position in the soil profile, paragenetic links with the overlying horizons and neighboring soil profiles, and a set of diagnostic features and properties, these horizons can be separated as a new type of genetic soil horizons—the organomineral accumulative suprapermafrost horizon (CRO). Its qualitative composition (the ratio of organic and mineral matter in the material) can be reflected at a lower level. In relation to the separation of the new genetic horizon within the framework of the new Russian soil classification system, a new genetic types of soils—cryozem with suprapermafrost accumulation of raw organic matter (suprapermafrost organo-accumulative cryozem)—can be established. Its diagnostic profile has the following horizonation: (O, AO, T)–CR–CRO–$_{\perp}$C.

Keywords: cryozem, Oxyaquic Turbic Cryosol, tundra, permafrost, cryoturbation, formation of frost boils, organic matter, suprapermafrost accumulation of organic matter, radiocarbon age

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INTRODUCTION

The soil cover of cold arid territories, including the tundra zone of the northeast of Russia, is characterized by the widespread distribution of cryohydromorphic soils (cryozems) with overmoistened soil profile, in which gley features are absent or weakly expressed [21]. It has been found that suprapermafrost horizons of cryozems (Oxyaquic Turbic Cryosols) in the tundra zone of northern Yakutia are characterized by distinct accumulation of raw organic matter [5, 6, 15]. The leading role in the formation of this layer is played by active processes of cryogenic mass exchange, including the development of frost boils, which lead to penetration of the raw organic matter into the upper mineral horizons followed by its downward movement in the soil profile and accumulation above the permafrost table. Knowledge of the particular mechanisms of the formation of this layer and its properties is important in the context of general concepts of the specificity of cryogenic pedogenesis and diversity of soils developing in the permafrost zone.

The aim of this study is to substantiate the separation of this layer as a specific genetic soil horizon of the suprapermafrost accumulation of organic matter in cryozems, to identify the processes of its formation, its diagnostic features and major properties, its genetic links with other soil horizons, and its position in the general system of genetic soil horizons, as well as the classification position of soils with this horizon.

OBJECTS AND METHODS

Soils and the soil cover of coastal lowlands composed of the ice complex deposits with pronounced cryogenic microtopography of the surface were studied in northern Yakutia [2, 6, 8, 11]. Special attention was paid to the suprapermafrost horizon of the accumulation of raw organic matter in the profiles of cryozems (Oxyaquic Turbic Cryosols).

Field trips were made within the tundra zone of the Kolyma Lowland. Regular observations (since 1979) over the dynamics of surface microtopography, frost boils, overgrowing of barren circles, and hydrothermic regime of soils were performed on five key plots on the Kolyma–Indigirka interfluve. Field studies on these plots were performed in the late summer–early fall, i.e., in the period of maximum soil thawing. This made it possible to obtain the most detailed data on the morphology and properties of suprapermafrost horizons and underlying permafrost and to assess their interrelationships. In parallel, the studies of permafrost-affected soils and their contact with permafrost were performed for the walls of natural exposures of the thermal erosion and thermokarst origins along the sea coast and along the valleys of large rivers and numerous thermokarst lakes. The total length of examined walls of natural soil exposures reached hundreds of meters, which made it possible to trace spatial changes in soil morphology and microfeatures of topography and to assess their spatial relationships. Overall, the morphology of more than 400 profiles of cryozems was studied. Analytical data were obtained on 180 soil profiles.

Special studies of soils in the frozen state with the aim to estimate the amount and location of ice segregations were performed in December and in March–April, when the soil temperature was –15 to –25°C. Core samples were taken to the depth of 1 m; additionally, soil pits were examined. The samples taken in the winter period were studied in laboratory at subzero temperatures.

Munsell color charts [32] were used to determine the color of soil horizons and separate morphological elements directly in the pits and in the ground air-dry samples sieved through a 1-mm screen.

The chemical analysis of soils was performed by routine methods in the Center of Collective Use at the Institute of Physicochemical and Biological Problems of Soil Science in Pushchino. Bulk elemental composition was determined by X-ray fluorometry on a Spectroscan MAX GV fluorescence spectrometer, and total nitrogen was determined on a C-N analyzer Vario EL III (Elementar, Germany). Soil microfabric was examined under an optical microscope Carl Zeiss Axioscope A1 equipped with Axiocam MR5 camera. Submicromorphological studies were performed on a scanning electron microscope Vega3 LSU with an Aztec Energy EDS microanalyzer.

MAJOR MORPHOLOGICAL FEATURES AND PROPERTIES OF CRYOZEMS

Cryozems in the tundra zone of the Kolyma Lowland are developed on the surface of the Late Pleistocene elevations (yedomas) and on high lake terraces and their slopes composed of the silty loams under good drainage conditions. The surface has a pronounced polygonal microtopography with elevated nanopolygons of up to 1 m in diameter and 0.2–0.4 m in height [6, 8]. The morphology of and major chemical properties of cryozems belonging to the order of cryoturbated soils are studied sufficiently well [3, 5, 6, 8, 10, 17, 23–25]. Their profiles consist of the following horizons: O, AO, T, CR, ┬C. At the level of soil types, cryozems are subdivided with respect to the relationships between the surface peat litter horizon and the cryoturbated (CR) horizon. At the subtype level, specific features of the organic horizon, gley features, and features of the cryogenic transformation (cryometamorphism) and pale (palevyi) pedogenesis are taken into account [13].

However, the morphological diversity of cryoturbation process, qualitative composition of the material of cryoturbated horizons, and its quantitative characteristics in the entire profile and in the particular horizons are not properly considered in the existing classification systems. The importance of this process seems to be underestimated, and its particular manifestations in the soil profiles have yet to be scrutinized. Many authors noted an increase in the degree of manifestation of cryoturbation, such as the mottled color pattern and the presence of raw organic materials (often, mixed with the mineral soil mass) in the deep soil horizons above the permafrost table [1, 8–10, 12, 14, 17, 18, 28, 31–34, 36, 37].

As follows from published works, most of field descriptions of soil pits in the tundra of northern Yakutia were obtained in July or at the beginning of August, i.e., in the period, when the lower parts of the soil profiles still remained in the frozen state and could not be examined in detail. Data on the maximum thickness of the active layer in different parts of the tundra of northern Yakutia obtained in the recent 15 years within the framework of the Circumpolar Active Layer Monitoring (CALM) program [29] indicate that the lowermost 15–30 cm of the soil profiles in that period remain in the frozen state and are not properly studied.

According to a number of morphological features and properties of cryozems related to the action of cryoturbation, the cryoturbated CR horizon may be different in different permafrost-affected soils [1, 3, 12, 18, 30, 33, 37]. Thus, in cryozems of coastal lowlands of northern Yakutia, this horizon is usually described as a horizon with a monotonous grayish brown color with mottles of gray or brown color consisting of comminuted and decomposed plant residues mixed with the loamy mineral material; the area of these mottles reaches 5–15% of the section of the horizon on the vertical wall. Long-term morphological study of cryozems in northern Yakutia indicate that the cryoturbated horizon is clearly differentiated according to its structure: thin platy (or scaly) structure is typical of its upper part, and thick platy structure is developed in the lower part of the cryoturbated horizon. This fact allows us to distinguish two cryoturbated subhorizons: CR_1 and CR_2. In most of the profiles of cryozems, these horizons are located at the depths of 5 to 35–40 cm (CR_1) and from 35–40 cm to the permafrost table or to the suprapermafrost horizon with the high content of raw organic material (CR_2).

The analysis of CR horizon in different types of cryozems attests to the fact that the morphological elements enriched in the organic matter (organic-containing zones, OCZ) in the form of separate mottles are also differentiated according to their specific morphological features, substantive composition, and properties. This differentiation is mainly related to the content of raw organic matter in the OCZ. Overall, four kinds of the OCZ have been identified. They differ in the character of organic material, the degree of its transformation, and the relationships between the

Table 1. Characterization of different groups of organic-containing zones in the profiles of cryozems

Group	Morphological description	Color in the pit	Munsell color	Qualitative composition	Source of organic material (horizons)	Bulk density, g/cm^3
OCZ_1	Rounded flattened mottles (4–6 cm) and concentrations; loose consistence; admixture of loamy material	Gray	10YR 5/1	Mucky material; smeary; fine detritus of herbs, remains of fine roots; gray loam	A, OA,W	0.7–1.2
OCZ_2	Flattened mottles and zones of rounded and irregular shape of 3–6cm in diameter; compact; with participation of plant residues and loamy admixture	Brownish gray	10YR 4/1	Residues of fine roots, semidecomposed residues of herbs; gray loam	A, W, OA	0.7–1.0
OCZ_3	Mottles of irregular shape; flattened; up to 4–8 cm in diameter; compact; with well-preserved plant residues and small admixture of loamy material	Brown	2.5Y 4/2	Weakly decomposed residues of mosses, semidecomposed residues of herbs; gray loam	T, OA	0.4–0.7
OCZ_4	Mottles and zones of rounded and flattened shape of 4–10 cm in diameter; strongly compact; mixture of the homogeneous dark gray organic material with dark-colored loam	Dark gray to black	2.5Y 3/0	Strongly comminuted plant remains without cell structure; inclusions of dark gray and bluish loam	Strongly transformed material from OCM_1, OCM_2, OCM_3	1.1–1.3

organic and mineral components (Table 1). Morphological characteristics of the OCZ material are most pronounced on pit walls under conditions of natural moistening in the period of maximum soil thawing. In the air-dry samples sieved through a 1-mm screen, Munsell color characteristics do not differ much. The chemical properties of the material of OCZ, its quantity, and the ratios of different forms of organic matter in it significantly affect the properties of the cryoturbated horizons and its particular parts (Table 2). In some profiles, the area of OCZ in the lower subhorizon (CR_2) may reach 15–30% of the horizon area in the section. This specifies the high content of C_{org} in the CR_2 horizon, high loss on ignition, C/N ratio, and several other properties.

In tundras of coastal lowlands on relatively drained sites with a pronounced nonopolygonal topography of the surface, shallow permafrost (up to 80 cm), moss–forb–grassy vegetation, and active development of frost boils, the profiles of cryozems usually contain a layer enriched in the raw organic matter immediately above the permafrost table (in the suprapermafrost horizon). In this horizon, the portion of OCZ reaches 30% and more [5, 6, 17]. The enclosing loamy material may have gley features. It was suggested that this layer could be considered a specific suprapermafrost organomineral horizon of the accumulation of raw organic matter and be distinguished as a separate type of genetic soil horizons designated by symbol CRO (cryoturbated horizon with the accumulation of raw organic matter) [15]. This designation is used in our paper. The analysis of materials of soil-geographic studies in coastal lowlands of northern Yakutia with special attention to suprapermafrost horizons indicates that this type of horizon can be found in the profiles of cryozems within all the studied regions, though it is most common of cryozems in typical tundra of the Kolyma Lowland [6, 15]. The morphology and properties of this horizon are rather diverse and depend on the particular conditions of soil formation and major pedogenic processes.

PROCESSES AND MECHANISMS OF FORMATION OF THE CRO HORIZON

One of the major mechanisms of the development of this horizon is the translocation of raw organic material from the upper organic horizon into the deep suprapermafrost soil layer combined with its transformation in the course of the downward migration and accumulation above the permafrost table. The middle-profile horizons of cryozems represent the zone of transit. These horizons remain in the thawed state with the low (<3°C) temperature about 2–2.5 months per year. The lower soil horizons remain in the thawed state with the temperature about 1°C for less than a month. This specifies the low intensity of biochemical

Table 2. Characteristics of organic-containing zones (OCZ), mineral material (MM), and averaged samples from the enclosing horizons

Object	Depth, cm	Munsell color	LOI	C_{org}	N_{tot}	C/N	pH		Particle-size data		*W*, %	*D*, g/cm^3
			%				H_2O	KCl	>0.01 mm	<0.01 mm		
Pit 153												
CR_2	35–55	2.5Y 5/4	6.38	1.10	0.16	6.9	6.5	5.1	71.5	28.5	25.0	1.64
OCZ_1		2.5Y 5/2	12.31	6.12	0.41	7.3	6.0	5.1	Not det.		36.7	–
OCZ_2		2.5Y 5/2	9.11	3.01	0.44	13.9	6.4	4.9	"		32.4	–
MM		10YR 6/2	6.12	1.12	0.20	5.6	6.3	5.0	"		24.8	–
CRO	55–63	2.5Y 6/4	10.76	3.67	0.26	14.1	6.2	5.0	73.4	26.6	46.6	1.25
OCZ_1		2.5Y 4/2	12.75	5.99	0.27	17.4	6.4	5.0	Not det.		–	0.82
OCZ_3		2.5Y 5/2	10.71	8.14	0.32	18.7	5.9	5.1	"		74.3	–
OCZ_4		2.5Y 5/2	19.21	4.71	0.42	19.3	6.1	4.9	"		56.8	1.12
MM		2.5Y 5/2	7.45	2.67	0.32	8.3	6.3	5.1	"		38.4	1.34
MM		2.5Y 5/0	6.14	1.82	0.21	8.6	6.2	5.2	"		40.4	–
Pit 149												
CR_2	47–64	2.5Y 6/2	6.71	1.06	0.15	7.0	6.7	5.2	66.9	33.1	21.8	1.45
OCZ_1		2.5Y 5/2	9.11	2.42	0.24	10.1	6.2	5.2	Not det.		28.6	1.14
OCZ_3		2.5Y 4/2	11.14	3.14	0.28	11.2	6.0	4.9	"		20.7	0.52
MM		2.5Y 6/2	5.81	1.51	0.13	11.6	6.1	5.7	"		19.5	–
MM		2.5Y 6/2	5.42	1.03	0.16	6.4	5.7	6.7	"		–	1.12
CRO	64–72	2.5Y 4/4	12.25	5.51	0.42	13.1	6.8	5.7	68.6	31.4	56.7	1.31
OCZ_2		2.5Y 5/4	11.14	6.12	0.43	14.2	6.2	5.5	"		72.3	–
OCZ_2		2.5Y 5/4	10.12	4.48	0.42	11.7	5.4	5.8	"		64.3	0.89
OCZ_3		2.5Y 4/4	16.51	7.12	0.48	14.8	6.8	5.7	"		–	0.76
MM		2.5Y 5/2	9.16	2.1	0.26	8.1	6.1	5.5	"		58.3	1.23
MM		2.5Y 5/2	10.25	3.01	0.38	7.9	6.2	5.3	"		49.9	–

W is the water content, and *D* is the soil bulk density.

transformation of the organic material in these horizons. Finally, the lowermost soil layer immediately above the permafrost table thaws out for less than 2 weeks, and its temperature does not exceed 0.1–0.2°C. The material of this layer is characterized by the high water content (>60%). These conditions favor long-term preservation and very slow transformation of the raw organic material in the suprapermafrost horizon, which favors its gradual accumulation in this part of the profile.

The input of raw organic material into the deep mineral horizons of cryozems is often associated with the development of frost boils. In the loamy soils, the development of frost boils takes place in the fall upon freezing of the soil under nanopolygons. Cryostatic pressure developing in central parts of nanopolygons squeezes that material of upper mineral horizons onto the soil surface, and the surface organic horizons become buried and are found as separate fragments at the depth of 15–30 cm. The activity of frost boil development is controlled by the water content of mineral horizons at the moment of freezing and the velocity of freezing depending on air temperature in that period and the presence and depth of the snow cover. Long-term observations at several key sites indicate that the barren circles of frost boils appear on about 2–5% of nanopolygons once in 3–5 years. This process has its own periodicity, which is confirmed by the presence of raw organic materials of different botanical compositions, different degrees of transformation, and different ages in the OCZ of the soil profile. Thus, a relatively regular repetition of phases—soil of barren circle (frost boil)—soil of overgrowing frost boil—mature cryozem—takes place attesting to the cyclic pattern of the development of cryozems. The formation of frost boils on the surface of nanopolygons may take place at virtually any phase of overgrowing of surface upon various vegetation successions. This, organic horizons of different thickness of different degree of development may become buried. This is an important factor affecting the diversity of the composition, amount, and properties of the organic material buried in the soil profile and included in the OCZ.

At the same time, this cyclic pattern of soil development complicates the reliable determination of the nature of organic layer forming on the soil surface and its belonging to one of the organic horizons (O, T, or AO), though this characteristics is taken into account at the type level in the classification of cryozems [13].

The organic material admixed to the upper part of the cryoturbated (CR) horizon may be involved in the new cycle of frost boiling and become exposed to the surface again. This circumstance coupled with a relatively high activity of decomposition processes in the upper soil horizons explains a relatively low portion of OCZ in the upper parts of mineral horizons of the considered cryozems.

The organic material moving deeper into the soil profile is subjected to transformed. Large-scale seasonal ice segregation and ice melting ensure mixing of the organic material with the mineral soil matrix, and the movement of water front upon the soil thawing toward the permafrost table ensures downward migration of the products of mineralization of this organic material. Cryogenic homogenization of the material leads to a gradual disappearance of some OCZ and changes in their morphology and properties; generally, the enclosing mineral loamy material becomes enriched in fine (0.2 mm) plant detritus, which favors more active biochemical transformation of this material.

Data of seasonal observations demonstrated that the water content of the OCZ is higher than that in the enclosing mineral material. During the soil freezing in the fall, small lenses, druses, and separate crystals of ice are formed in the upper overmoistened part of the OCZ. Under their impact, the material is gradually squeezed into the underlying wet and plastic mineral mass and, partly, towards the margins. This predetermined the dominant downward movement of the OCS material resulting in its accumulation in above the permafrost table.

Periodical cycles of frost boiling specify the presence of the organic materials of different ages in the profile and its accumulation in the suprapermafrost horizon. Data on the radiocarbon age of the raw organic material from the CRO horizon ($n = 9$) show that the major part of the dates lies within the interval of 1000–2300 years. The radiocarbon age of OCZ in the upper part of the CR horizon does not exceed 400–600 yrs ($n = 3$). Taking into account the mechanism of the development of CRO horizon, the radiocarbon age of the average sample from this horizon is an integral characteristic reflecting the ages of both older and younger masses of the OCZ included in the CRO horizon. At the same time, a relatively small range of radiocarbon ages of the CRO horizon from cryozems sampled in different parts of coastal lowlands indicates that there was a period, when certain landscape and climatic conditions favoring the development of the CRO horizon were established in the area. Among these conditions, the formation of mature nanopolygonal topography, regular frost boil cycles, and long-term stabilization of the lower boundary of seasonal soil thawing should be mentioned.

MORPHOLOGY OF THE CRO HORIZON

The CRO horizon lies immediately above the contact with the permafrost table in the period of maximum soil thawing. Its topography generally corresponds to the topography of permafrost table and is characterized by some lowering under the central parts of nanopolygons; towards the margins of the nanopolygons, in the contact zone with the organic soils of cryogenic troughs, the boundary of maximum thawing depth somewhat rises. In plan, it has a kettle-like pattern (Fig. 1).

The CRO horizon is a layer of 3–10 cm in thickness composed of the compacted organomineral material with a heterogeneous mottled color pattern; gray brown colors (7.5YR 4/1, 10YR 4/2) predominate. The OCZ (mottles) is of dark gray or dark brown color and consists of differently decomposed plant tissues, smeary mucky material, and the admixture of dark or dove-colored silty loam. The loam enclosing the OCS is of the gray-blue color (10Y 5/2, 5GY 5/3). The size of OCS is usually about 3–5 cm. Often, the mottles of OCZ are flattened. Their material may bear the features of thin layering with alternation of the layers of organic and loamy material of 3–15 mm in thickness. In some places, the OCZ material is concentrated in larger (15–20 cm) zones that occupy up to 30–70% of the area on the vertical section of the horizon. The average portion of the OCZ on the vertical section of the CRO horizon is 62% ($n = 28$). The morphology of this horizon can clearly observed on horizontal sections of soil pits near the boundary with the permafrost table. Because of the flattened shape of OCZ, its portion on the horizontal section increased by 10–15% and may reach 80%.

The enclosing loamy mineral mass of the horizon is virtually devoid of raw organic matter. The boundaries between the OCZ and the enclosing mass are different: they are sharp for the OCZ containing weakly decomposed plant tissues and diffuse for the OCZ with the high content of mineral admixtures. The zones of mineral material are characterized by indistinct medium-thick platy structure.

The material of the CRO horizon may contain separate small (up to 1–1.5 cm) black concentrations of sulfides. Their treatment with 10% HCl, as well as the treatment of peaty loci, results in the appearance of the smell of hydrogen sulfide.

In the frozen state, the zones with the high content of the mineral material display a lattice type of cryo-

Fig. 1. Morphology of the CRO horizon as seen on the (a) vertical section (pit wall) and (b) horizontal section at the depth of permafrost table.

texture with subhorizontal ice schlieren of up to 1–1.5 cm in thickness. In the thawed state, the horizon may be differently moistened (from the slightly dry to the satiated wet state); in the case of its high moistening, it may display thixotropic properties.

The upper boundary of the CRO horizon is uneven. The transition from the overlying CR_2 horizon is gradual and is displayed by changes in the color pattern, the content of OCZs, and the soil structure. The transitional zone has a thickness of 3–6 cm. The lower boundary of the CRO horizon is distinct and abrupt; it is also uneven, as fragments of the CRO horizon may penetrate the upper permafrost layer to a depth of 3–8 cm. The maximum seasonal thawing depth of the profiles of cryozems varies from 50 to 75 cm.

The CRO horizon is underlain by the frozen silty loam (C horizon) with different ice contents and with thin or medium-thick schlieren ice texture; in some cases, thick (5–10 cm) layers of transparent ice occur in this horizon. In the thawed state, this horizon displays bluish or olive colors; it is devoid of the OCZs, or contains their rare small fragments. The silty loamy material of the C horizon represents ice complex deposits that contain relict organic matter that was involved in the zone of seasonal thawing (active layer) in the warm periods of the Early and Middle Holocene; these layers are referred to as the transition zone with the transient layer in its upper part [4, 16, 27].

SPATIAL DISTRIBUTION OF THE CRO HORIZON

In relation to the complex nanotopography and cyclic combinations (complexes) of soils and vegetation, as well as cyclic pattern of the permafrost table, the CRO horizon is discrete in the horizontal direction. It is present within nanopolygons with cryozems and disappears in the interpolygonal troughs (microlows), where it is replaced by organic or gley horizons. This horizon may be absent or indistinctly manifested on neighboring nanopolygons and be clearly pronounced under nanopolygons within the area of dozens of square meters. The study of this horizon in long sections of thermokarst escarpments indicates that it is present in 40–80% of the profiles of cryozems, and its development depends on the particular geomorphic position and age of the surface.

MAJOR CHEMICAL PROPERTIES OF THE CRO HORIZON

The CRO horizon is developed in the course of the long-term accumulation of organic matter from the upper horizons and mobile products of pedogenesis (water-soluble humus, oxides, biogenic elements, etc.) included in the OCZs above the permafrost table. The composition of the OCZ may be different because of the different natures of the initial materials(fragments of the O, AO, W, or T horizons) and their transformation in the middle-profile horizons and in the suprapermafrost zone of their accumulation. The variable content of the mineral constituent of the CRO horizon specifies considerable ranges of the chemical properties of the CRO horizon even within neighboring nanopolygons.

Table 2 contains data on the properties of separate OCZs differing in their color, organic matter content and composition, and properties of the mineral material. Data on averaged samples from the CR and CRO horizons from two profiles of cryozems located in different parts of the Kolyma Lowland are also presented. The high variability in the contents and quality of organic matter in the OCZs within the same horizons and in different horizons should be noted. The analysis of the chemical properties of OCZs combined with their meso- and micromorphological study shows that many important properties of the OCZs, such as the loss on ignition, the C_{org} content, and the C/N ratio are mainly specified by the botanical composition of enclosed plant residues and the degree of their mineralization. The highest values of the loss on ignition and the wide C/N ratios are typical of the OCZs with a predominance of the residues of mosses. A relatively high content of C_{org}, narrower C/N ratio, and lower loss on ignition are typical of the OCZs with a predominance of comminuted and partly mineralized residues of grasses and forbs and fragments of root residues with the high admixture of the mineral material. The pH values of the OCZs do not depend on their morphology, botanical composition of plant tissues, and the degree of their transformation. Usually, they are within a relatively narrow range from the slightly acid to neutral reaction.

Micromorphological analysis of the OCZs from the CR_2 and CRO horizons attest to presence of separate loci of the accumulation of idiomorphic fine opaque mineral grains. Their more detailed study with the use of optical and electron microscopy showed that these are pyrite grains. In the CR_2 horizon, the loci of pyritization are only found in the OCZs containing transformed residues of herbs and characterized by the increased water content. In the CRO horizon, such loci may found in any kind of OCZs, though they tend to be more frequent in the OCZs containing relatively fresh plant residues. Microconcentrations of pyrite in the loamy material confirm the development of reducing conditions in the suprapermafrost horizons of cryozems.

In the mineral material of the CR_2 horizon, the loss on ignition, C_{org} content, and C/N ratio are close to those in the average sample from this horizon (Table 2). In the CRO horizon, where the loamy mineral material is often present in separate zones, the values of these characteristics are generally higher, which is specified by the downward migration and accumulation of the mobile products of pedogenesis, including water-soluble humus compounds, in this horizon [10] and by the in situ mineralization and humification processes. Micromorphological analysis of mineral zones from the CRO horizon does not indicate the presence of increased amounts of the raw organic matter and strongly comminuted (<0.2 mm) plant detritus in these zones.

The wide range of the properties of separate groups of OCZs, their amount and proportion between them, and their participation in the enclosing mineral material together with other substances migrating from the upper soil horizons dictate the wide range of variations in the major chemical properties of CRO horizons. In Table 3, data on the properties of cryozems with the CRO horizon from the same soil area (pits 281 and 252) and on the properties of cryozem without the CRO horizon (pit 274), but with the suprapermafrost CR_2 horizon with an increased content of OCZs (20% of the vertical section) are listed. Table 4 presents data on the lower parts of the profiles of cryozems studied in different regions of the Kolyma Lowland.

The CRO horizon of cryozems from the coastal lowlands of northern Yakutia is generally characterized by the high C_{org} content (often, 1.5–3 times higher than that in overlying horizons) ranging from 1.5 to 5.5% with the average value of 2.9% ($n = 22$) (Table 4). The loss on ignition varies from 8 to 15% with the average value of 10.5% ($n = 25$), and the C/N ratio is about 11 ($n = 22$). These data confirm the organomineral nature of the material of the CRO horizon and the presence of raw organic matter in it. These specific features of the suprapermafrost horizon are developed due to cryoturbation. The average C_{ha}/C_{fa} ratio in this horizon is 0.8 ($n = 12$), which corresponds to the humate–fulvate nature of humus; the fraction of fulvic acids bound with sesquioxides predominates in the composition of humus. The fractional composition of humus is generally close to that in the overlying mineral horizons, which has been proved by special studies of the organic matter of these soils [26]. The raw-humus nature of the organic matter in this horizon, the botanical composition of plant tissues included in it, and their relatively weak humification under conditions of the low microbiological activity specify the high percent of the fraction of nonhydrolyzable residue (the humin fraction) in the fractional composition of humus; the variation in the content of this fraction is considerable ($62 \pm 14\%$, $n = 12$). The horizon is characterized by a slightly acid or neutral reaction; often, it is the least acidic horizon in the soil profile with its pH values close to those in the underlying permafrost. Calcium predominates in the composition of exchangeable cations; the cation exchange capacity is relatively low and is comparable to or somewhat higher than that in the overlying mineral horizons. The degree of base saturation is high; it is comparable with that in the overlying CR horizon, though somewhat lower than base saturation of the material in the underlying permafrost.

One of the important features of CRO horizons in tundra soils is their enrichment in viable microorganisms in comparison with the overlying mineral horizons. These microorganisms migrate toward the permafrost table with downward water flows and gradually accumulate in the CRO horizon [19, 22]. Thus, this horizon contains ciliates, flagellates, and nematodes, which are usually found in the upper organic horizons of the studied cryozems. These protozoans are present in the OCZ material of the CR and CRO horizons and are absent in the enclosing mineral mass. It was found that most of them remain in the viable state in the course of cryoturbation. In the OCZ immediately above the permafrost table and in the upper permafrost horizons, they are present in the state of the long-term (thousands of years) cryobiosis; taken together, they can be considered the specific bank of the Holocene microfauna [7].

Table 3. Properties of cryozems with different rates of accumulation of cryoturbated raw organic material in the lower part of the profile

Horizon	Depth, cm	LOI	C_{org}	C/N	pH		Sum of exchangeable bases, cmol(+)/kg	Exchangeable bases, cmol(+)/kg		Base saturation, %	Tamm's extract, %		C_{ha}/C_{fa}
		%			H_2O	KCl		Ca	Mg		Fe_2O_3	Al_2O_3	
							Pit 343						
CR	42–58	5.7	1.2	5.3	5.7	5.0	16.2	12.6	3.1	67	1.1	0.7	nd
CRO	58–68	8.6	2.1	8.4	6.4	6.0	19.4	14.2	4.2	59	1.5	1.1	nd
⊤C	75	6.0	1.3	4.2	6.8	5.9	21.1	16.4	3.9	72	0.9	1.1	nd
							Pit 224						
CR	40–61	6.6	1.0	5.0	5.6	5.1	11.9	8.9	2.6	62	1.1	0.9	0.4
CRO	61–70	9.3	1.7	7.6	5.8	5.3	12.3	7.3	3.3	51	1.3	1.1	0.8
⊤C	80	5.4	1.1	5.1	6.4	6.0	21.6	12.6	6.4	70	1.0	1.2	0.6
							Pit 212						
CR	38–56	5.2	0.8	5.6	6.6	6.0	12.1	9.3	3.1	68	1.3	1.0	0.7
CRO	56–60	8.9	1.6	10.1	6.0	5.7	16.6	11.4	4.9	61	2.2	0.6	0.7
⊤C	72	5.7	0.9	6.2	7.1	6.8	18.2	12.3	4.6	74	1.1	0.9	0.6
							Pit 302						
CR	40–58	7.1	1.2	6.2	7.2	6.1	14.3	10.0	3.1	65	1.1	1.3	nd
CRO	58–64	10.2	2.3	9.8	7.4	6.3	18.3	12.6	4.9	59	1.6	1.1	nd
⊤C	75	6.1	1.1	5.6	7.6	6.3	20.2	14.8	5.0	72	1.0	0.7	nd
							Pit 337						
CR	42–53	5.0	1.3	7.1	6.2	5.9	14.8	9.3	4.1	60	0.6	1.1	0.5
CRO	53–62	12.3	3.6	12.1	6.8	6.0	15.9	10.0	4.0	55	1.1	0.7	0.7
⊤C	70	4.6	1.1	5.9	7.0	6.9	16.2	10.3	4.9	64	0.6	1.2	0.6
							Pit 175						
CR	36–56	6.1	2.4	6.9	5.8	5.4	14.4	9.0	4.2	58	1.4	0.6	0.6
CRO	56–64	14.1	4.1	14.5	6.0	5.5	12.1	8.1	3.3	51	1.7	0.9	0.8
⊤	73	7.1	1.2	6.2	6.2	5.9	15.8	11.4	3.0	76	1.2	1.1	0.6
							Pit 16						
CR_2	40–62	5.6	1.8	7.3	6.3	6.1	20.1	14.0	5.3	58	0.9	0.7	0.6
CRO	62–70	12.3	4.2	10.1	7.3	6.5	18.4	12.3	4.2	52	1.3	0.9	0.9

Table 4. Properties of the CR and CRO horizons and the upper part of the underlying permafrost ($_{\top}$C horizon)

Properties	CR		CRO		$_{\top}$C	
	$M \pm$	range	$M \pm$	range	$M \pm$	range
LOI, %	6.25 ± 0.61	5.0–7.1	10.55 ± 1.78	8.0–14.5	5.39 ± 1.03	4.1–7.1
C_{org}, %	1.38 ± 0.36	0.8–2.4	2.88 ± 1.31	1.3–5.5	1.17 ± 0.25	1.7–0.8
C/N	6.73 ± 0.81	5.0–7.3	11.15 ± 2.16	7.6–14.1	6.30 ± 1.46	4.5–8.1
pH_{H_2O}	6.15 ± 0.48	5.3–7.2	6.45 ± 0.56	5.8–7.3	7.12 ± 0.34	6.4–7.5
pH_{KCl}	5.46 ± 0.42	5.1–6.1	5.80 ± 0.46	5.3–6.4	6.42 ± 0.41	5.9–6.9
Sum of exchangeable bases, cmol(+)/kg	15.20 ± 2.52	11.9–20.4	15.07 ± 2.63	12.1–18.4	18.97 ± 1.74	16.2–21.6
Base saturation, %	65.50 ± 5.50	58.0–77.0	59.42 ± 8.15	51.0–78.0	72.50 ± 4.65	80.0–64.0
C_{ha}/C_{fa}	0.60 ± 0.07	0.5–0.7	0.7 ± 0.10	0.6–0.9	0.7 ± 0.07	0.6–0.8

M ± is the mean arithmetic value and standard deviation.

CLASSIFICATION POSITION OF THE CONSIDERED HORIZONS AND SOILS WITH THEM

Earlier, we have described the suprapermafrost horizon of the accumulation of raw organic matter forming in the course of its lateral migration above the permafrost table from the organic soils of cryogenic cracks toward the suprapermafrost layers of cryozems [15]. This horizon is found immediately above the permafrost table and has a thickness of 4–7 cm. Its OCZs are mainly composed of the weakly or moderately decomposed peat; the content of mineral admixtures in them is relatively low. This horizon is characterized by the considerable loss on ignition (up to 30%) and the high content of C_{org}, though these properties are highly variable in space. The ^{14}C age of the organic material from the OCZs reaches c 1780–2070 yrs ($n = 4$).

The material presented in this paper concerns the morphology of cryozems affected by frost boil formation, active cryogenic mass exchange, and lateral migration of raw organic matter above the permafrost table. Taken together, these processes lead to the accumulation of considerable volumes of raw organic matter immediately above the permafrost table in cryozems.

Such horizons may appear in the course of active cryoturbation leading to the accumulation of organic substances with a higher degree of physical destruction, decomposition, and mixing (homogenization) with the enclosing loamy material.

Taken into account the genesis of the suprapermafrost horizon of the accumulation of raw organic matter, its paragenetic links with the overlying horizons and neighboring soils of the cryogenic soil complex, and its specific diagnostic features making it different from other genetic horizons, we suggest that this horizon can be distinguished as a separate type of genetic soil horizons and designated as the CRO horizon. According to the new classification system of Russian soils [13], the presence of a new horizon in the profile assumes separation of a new genetic type of soils. We suggest that the order of cryoturbated soils with the existing types of cryozems should be supplemented with a new type of cryozems with the suprapermafrost accumulation of raw organic matter. The genetic profile of this type of cryozems consists of the following set of horizons: (O, AO, T)–CR–CRO–$_{\top}$C.

From our point of view, this approach reflects the specificity of cryogenic pedogenesis in soils with a shallow (<1 m) permafrost and does not contradict the principle of openness of the new Russian soil classification system allowing "introduction of new, previously unknown or poorly studied soils into the system without disturbing the inner integrity of this system" [13]. However, this approach requires certain revision of classification positions of permafrost-affected soils and their diagnostic properties as described in the *Classification and Diagnostic System of Russian Soils* [13] and in the field guide on soil correlation [20].

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