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GENESIS AND GEOGRAPHY OF SOILS

The Role of Frost Boils in the Development of Cryozems on Coastal Lowlands of Northern Yakutia

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Abstract—The influence of frost boils on the development of cryozems (Turbic Cryosols) in the tundra zone of northern Yakutia is discussed. Mechanisms of the input, redistribution, and transformation of raw organic matter with its accumulation in the deep part of the profile of cryozems are elucidated. As a result, specific organomineral or organic horizons are formed above the permafrost table. The development of cryozems has a cyclic pattern: from the stage of barren frost boil to the stage of mature soil profile. However, this cycle can be interrupted at any stage of overgrowing of the barren surface of frost boil. The rates of overgrowing and the formation of the profile of cryozem, and the ^{14}C age of organic matter accumulated in the organomineral suprapermafrost horizons are estimated.

Keywords: cryozem, Turbic Cryosol, permafrost, cryoturbation, suprapermafrost accumulative horizons, ^{14}C age

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INTRODUCTION

In the area of cryohydromorphic nongley soils (cryozems) forming on coastal lowlands of northern Yakutia, specific soil objects—frost boils with barren surface—can be found. The morphology of the soil profile forming in the mineral material extruded onto the surface by frost heave resembles the morphology of primitive clayey soils (pelozems). Another type of barren surfaces—barren circles—is formed under the impact of snow corrasion and is more or less stable in time. In contrast, the soils of frost boils are intermittent objects and characterize one of the stages of the evolutionary development of cryozems [2]. The set of processes ensuring the formation of frost boils and their gradual overgrowing with vegetation accompanied by the zonal pedogenesis is important for the development of cryozems. These processes specify a number of features in the profiles of cryozems making them different from the soils that are not subjected to the development of frost boils. This difference can be reflected at the high taxonomic level.

OBJECTS AND METHODS

In this paper, we consider materials on cryozems forming in the arctic, typical, and southern tundra subzones within the Kolyma Lowland in the north of Yakutia. We studied soils in the areas of active development of frost boils under different mesorelief and drainage conditions: on the interfluves and slopes of different aspects within elevations composed of the ice complex (yedoma) deposits, and on terraces of lacustrine–thermokarst (alas) depressions formed in different periods of the Holocene. Field works were performed on several key sites located in different landscapes of the Kolyma Lowland from the coast of the East Siberian Sea in the north to the northern taiga zone in the south (Fig. 1). Each of the sites was characterized by a number of soil transects.

These studies were conducted for 35 years (1980–2016); the key sites were revisited once in 3–5 years. A larger part of field studies was performed in the second half of August–the beginning of September, during the period of maximum thawing depth of the soils. The dependence of the morphology of soil profiles and their major properties on the particular local conditions and on the intensity of cryogenic processes was examined; the major attention was paid to the processes of cryogenic mass exchanges, including the development of frost boils.

The activity of the development of frost boils in dependence on the local environmental conditions and weather conditions during observation periods was estimated, and the influence of this activity on the formation, morphology, and properties of cryozems examined. In particular, we studied the rate of overgrowing of barren frost boils with vegetation with the formation of surface organic horizons. Temperature

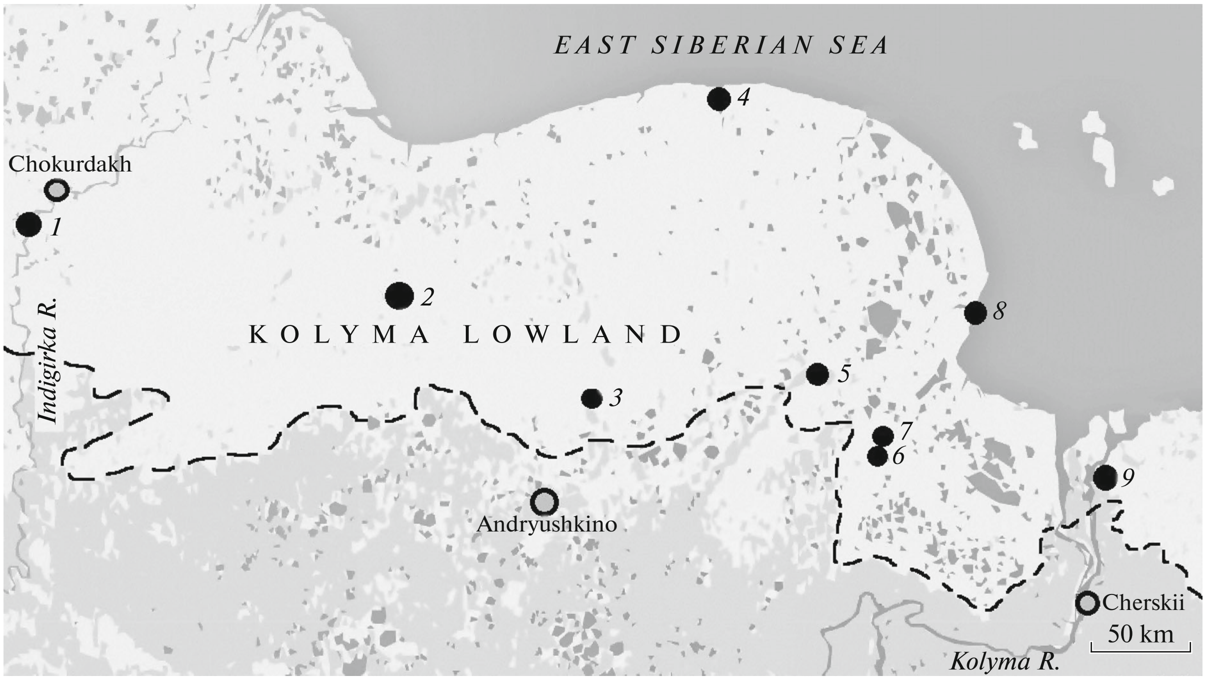

Fig. 1. Key sites studied in the Kolyma Lowland: (*1*) Allaikha, (*2*) Khomus-Yuryakh, (*3*) Alazeya, (*4*) Kuropatoch'ya, (*5*) Chukoch'ya, (*6*) Kon'kovaya-1, (*7*) Kon'kovaya-2, (*8*) Cape Chukochii, and (*9*) Sukharnaya. Dashed line shows the northern boundary of the taiga zone.

loggers Hobo U12 were used to obtain data on temperature regimes (with an accuracy of ±0.21°C) of the "mature" profiles of cryozems and the soil profiles of frost boils at different stages of their overgrowing. Drilling of the soil profiles in winter period (March–April) with extraction of core samples was applied to study the ice content and the particular forms of ground ice separations in different genetic horizons of the soils.

The major physical, chemical, and physicochemical soil properties were analyzed in the Chemical Laboratory of the Institute of Physicochemical and Biological Problems of Soil Science in Pushchino with the use of routine methods. Thin sections for examination of the soil microfabric were prepared from undisturbed soil samples of the main genetic horizons and specific soil zones enriched in the cryoturbated organic matter.

ENVIRONMENTAL CONDITIONS OF THE DEVELOPMENT OF CRYOZEMS

The type of cryozems is diagnosed by the presence of a peaty litter horizon (O), under which a cryoturbated horizon (CR) underlain by permafrost (C) are found. Mineral cryoturbated horizon with inclusions of fragments of organic material is the major is the major diagnostic horizon of cryozems [14]. According to its structural features, the CR horizon can often be subdivided into the upper (CR_1) part with thin (1–3 mm) platy structure and lower part (CR_2) with thick (up to 30–40 mm) platy aggregates.

In tundra landscapes of the Kolyma Lowland, the formation of cryozems takes place on the surface of yedomas—small hilly elevations representing the residues of the vast Late Pleistocene plain of ancient Beringia composed of silty loamy sediments with thick ice wedges (ice complex). Cryozems can also develop in the slopes of these elevations and on the high and medium-level terraces of thermokarst lakes, whose origin dates back to the Early or Middle Holocene [7]. Parent materials (the yedoma suite) contain significant amounts of relict organic matter (0.8–2.0% C_{org}) [4, 6]. This territory is characterized by a sharply continental climate and by the low-temperature permafrost (–7...–13°C); the active layer thickness varies from about 0.4 m in the arctic tundra to 0.7 m in the southern tundra near the boundary with the northern taiga zone. Soil thawing in the summer proceeds slowly, whereas soil freezing in the fall is relatively fast. The mean annual precipitation is about 150 mm with a maximum in the winter season and with drizzles in the summer time. The precipitation-to potential evaporation ratio (the humidity coefficient) is about 1.0 [1].

Cryozems are developed under conditions of a nanopolygonal microtopography of the surface creating specific cryogenic soil complexes [3]: regularly alternating low (30–45 cm) nanopolygons, on which the development of cryozems takes place, and cryogenic cracks with organic soils between these nanop-

Table 1. Characteristics of the cryogenic nanotopography and maximum thawing depth in different tundra subzones of the Kolyma Lowland (averaged data of measurements performed in 1980–2016), cm

Subzone	Nanopolygons			Interpolygonal microlows	
	diameter	height	thawing depth	width	thawing depth
Southern tundra boundary (n = 140)	84	45	67	24	23
Typical tundra (n = 160)	82	43	68	22	22
Arctic tundra (n = 80)	68	38	44	24	12

olygons [3, 7, 9, 12, 17]. Average characteristics of the linear size and height of nanopolygons, seasonal thawing depths, and widths of cryogenic cracks somewhat change in dependence on the particular tundra subzone (Table 1).

The surface of nanopolygons in the typical tundra subzone is occupied by the moss–sedge–grassy vegetation with participation of mountain avens and forbs. In the arctic tundra, the portion of sedges in the vegetation increases, and the portion of grasses and forbs decreases. Interpolygonal troughs (fissure zones) are covered by mosses. On the microslopes of nanopolygons, mountain cranberry, dwarf birch, and Arctic willow predominate in the tundra zone. In the area of cryozem formation, the nanopolygonal topography is unevenly covered by vegetation: barren frost boils with primitive clayey soils (pelozems) alternate with nanopolygons at different stages of overgrowing with vegetation up to continuous vegetation cover, under which typical cryozems are formed in good drainage conditions. At the same time, there are vast territories, where the features of modern formation of frost boils are poorly expressed, or where the overgrowing of former frost boils proceeds very quickly.

THE ORIGIN AND DEVELOPMENT OF NANOPOLYGONAL TOPOGRAPHY AND SOIL EVOLUTION

The formation of nanopolygons is usually attributed to the processes of frost cracking of the surface in the course of initial stages of the soil freezing [19, 26]. The surveyed bottoms of recently drained thermokarst lakes and low lake terraces indicate that the polygonal cracking of the surface can only be considered as one of the triggering mechanisms of the development of typical nanopolygonal topography. In such areas, the development of nanopolygons usually takes place after the overgrowing of former lake bottoms with mosses in the course of subsequent vegetation successions. This stage of the development of nanotopography is characterized by the predominant formation of gleyzems or thin organic (peat) soils underlain by permafrost at a very shallow (<15 cm) depth. Often, the underlying permafrost is represented by pure ice bodies.

In the course of subsequent development of thermokarst depressions and deepening of the level of thermokarst lakes, their terraces become better drained, and the character of their vegetation changes: sedges appear among the cover of green mosses. This is accompanied by the development of better-pronounced polygonal microtopography with the size of polygons varying from 10 to 15 m. The appearance of separate sedge tussocks and, then, microloci with grasses leads to a progressive accumulation of plant litter and changes in the thermophysical properties of the surface organic horizons; this is accompanied by the redistribution of moisture and activation of ice formation during the soil freezing and frost heave processes. Gradually, the surface becomes differentiated into nanopolygons with slightly elevated centers and depressed periphery subjected to cryogenic cracking. This is the initial stage of the development of the nanopolygonal microtopography proper. During this stage, the initial thin peat soils are transformed into peat gley soils (peat gleyzems).

On the terraces of a higher level that were shaped in the Middle Holocene period, nanopolygons become better manifested. Grasses, forbs, and shrubs (Arctic willow) appear on the surface of nanopolygons. Low shrubs tend to occupy their slopes toward interpolygonal depressions that are covered by mosses. At this stage of the development of the nanopolygonal topography, the size of nanopolygons, their relative height, and the width of nanodepressions (cracks, fissure zones) separating are highly variable.

The considered stage of the development of the nanopolygonal surface is specified by an increase in the diversity of soils forming on nanoelevations (nanopolygons), though peat gley soils continue to predominate on them. The morphological development of nanopolygons is favored by the further development of the soils in the interpolygonal cracks with active accumulation of weakly decomposed plant litter and growth of mosses; peat formation is clearly pronounced in these zones. Owing to their shadowed position, increased moisture supply, and the accumulation and slow melting of snow, the thickness of the active layer in these zones decreases; small ice wedges may exist even in the summer time. With time, the nanopolygonal topography acquires well-pronounced patterns.

The next stage in the development of cryogenic nanotopography is tightly associated with the formation of cryozems on nanopolygons. This is observed in terraces of the high level and on interfluves and their

Table 2. Long-term dynamics of the formation of fresh frost boils on the surface of nanopolygons at key sited in the typical tundra subzone (% of the total number of nanopolygons on plots 10 × 10 m)

Years of observation	Key sites				
	Kon'kovaya-1	Kon'kovaya-2	Cape Chukochii	Chukoch'ya	Sukharnaya
1984	Not det.		3	Not det.	7
1987	3	4	5	4	2
1991	6	15	3	6	8
1995	4	3	3	3	3
1998	3	4	2	4	5
2005	Not det.		3	4	Not det.
2013			Not det.		2

slopes. The degree of soil gleyzation decreases, and the cryogenic structuring of the middle-profile horizons becomes much more distinct. The development of a typical cryogenic (cryoturbated) CR horizon takes place. The organic part of the profile becomes differentiated with respect to the degree of decomposition of plant material. The upper peaty litter horizon (O) becomes underlain by thin (2–4 cm) horizons with raw-humus (O_{ao}) and mucky (O_h) materials. In comparison with peat gleyzems and gleyzems, the profiles of cryozems are characterized by a sharp reduction in the water content of mineral horizons in the period of maximum soil thawing; in the winter season, these horizons are characterized by abundant ice segregation in the form of thin and medium-thick ice schlieren, which predetermines the cryogenic structuring of the soil material. On the surface of some nanopolygons, frost boils are formed: barren circles of mineral material extruded onto the surface during the soil freezing are clearly seen. In the middle-profile horizons, dark mottles of cryoturbated organic material appear.

THE FORMATION OF FROST BOILS AND THEIR ROLE IN THE DEVELOPMENT OF THE PROFILES OF CRYOZEMS

The development of cryozems under conditions of the mature nanopolygonal topography and shallow (up to 70 cm) depth of permafrost is accompanied by periodical extrusion or squeezing of wet mineral material in the plastic state from the central parts of the profiles. This process is known as the formation of frost boils.

Observations performed in the period of fast soil freezing in the fall (in the middle and end of October) confirmed the fact that frost boils are mainly formed due to the cryostatic pressure in central parts of the nanopolygons during the soil freezing. This mechanism of the development of frost boils is widespread in the tundra zone, though other mechanisms of the formation of frost boils and barren circles are also known [8, 10–12, 18, 20, 23, 24, 26]. The material pressed out onto the surface buries fragments of organic horizons together with vegetation, so that surface organic matter appears at some depth within the soil profile (Fig. 2).

Long-term observations on key plots on the interfluves and slopes within the Kolyma–Indigirka tundra indicate that the formation of frost boils is an uneven process both in space and in time. On two neighboring yedoma surfaces, one of which was in a 1.2-m-deep microlow and the other one on the flat surface, under conditions of a sharp drop in the air temperature to −25°C in the middle of October and the absence of snow cover, fresh frost boils were found on 15% of nanopolygons at the flat site and on 6% of nanopolygons in the microlow. During two decades of periodical observations on five interfluvial sites in different parts of the typical tundra subzone, the number of newly formed frost boils averaged 3–5% in 3–5 years (Table 2). Calculations show that, theoretically, each of the nanopolygons may be subjected to the formation of frost boil once in a century.

In the course of overgrowing of barren frost boil surface with vegetation, the following succession of vegetation communities is observed: barren surface → algal–lichen film → moss–grassy cover → moss–sedge–grassy cover with participation of forbs and dwarf shrubs. Similar successions have been described in tundra of many other permafrost regions [1, 8, 10, 16, 19, 23, 25].

At the stage of barren surface, a thin (2–3 cm) crusty K horizon is formed in the upper part of the profile. It is underlain by a thin layer of silty loam with granular or fine crumb structure. The material of former surface organic horizons in the course of the expulsion of the mineral mass onto the surface is buried to the depth of 10–15 cm and acquires a funnel shape. Central parts of the soil profiles are less disturbed by cryoturbation.

Clearly pronounced overgrowing of the surface of nanopolygons with algae and lichens takes place on the third–fourth year. A dark vegetative film (2–3 mm) covers the surface of the crusty horizon and is partly subjected to cracking during summer desiccation. Gradually, it is overgrown with mosses, and grass

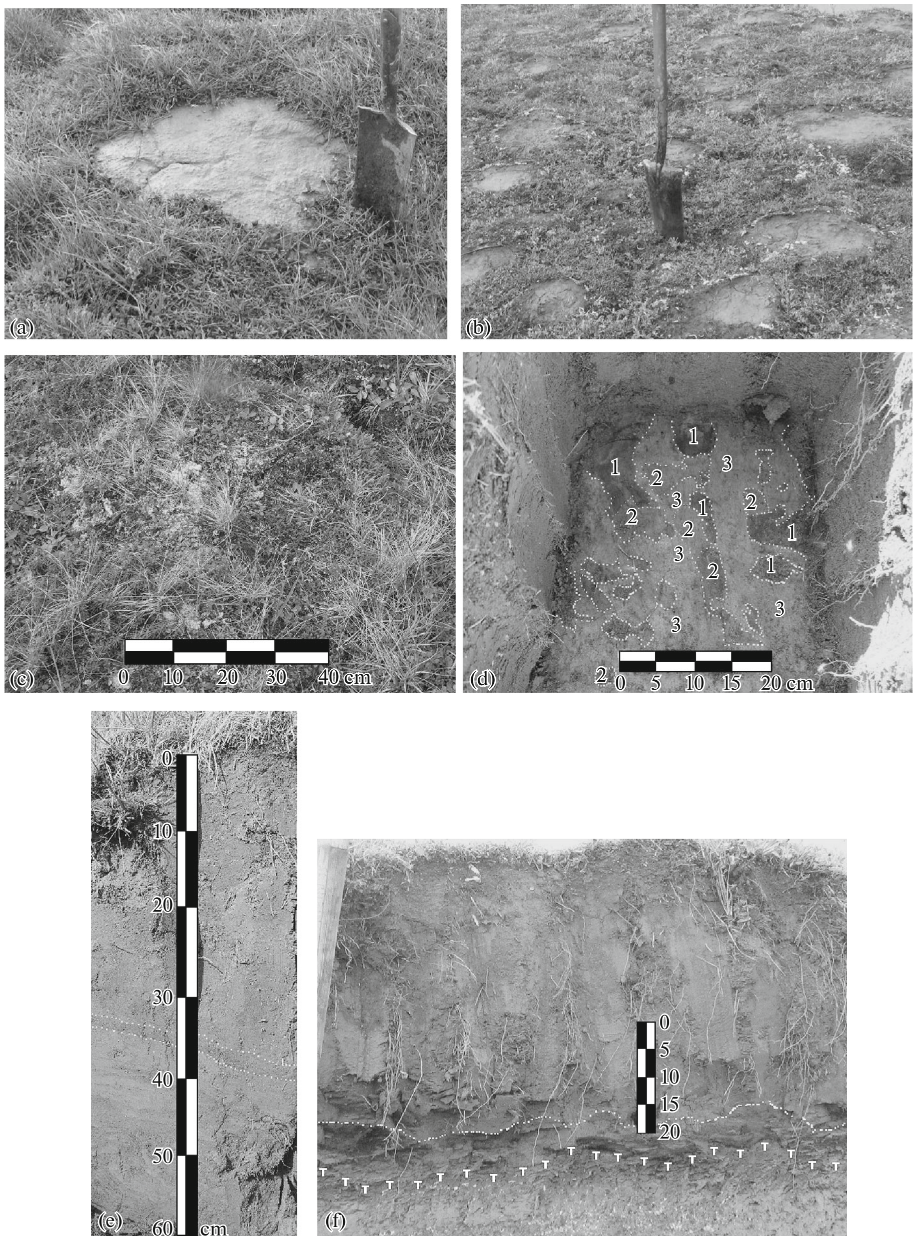

Fig. 2. Frost boils on nanopolygons and morphology of the CRO horizon. (a) Fresh barren frost boil on the surface of nanopolygon: (b) active formation of frost boils in some parts of tundra; (c) initial stage of the overgrowing of frost boil with grasses; (d) horizontal section of the CRO horizon (alternation of the zones with (*1*) weakly and (*2*) highly decomposed organic matter in the (*3*) enclosing mineral mass); (e) CRO horizon on the dry wall of the pit; and (f) CRO horizon on the wall of recently excavated pit. Dashed lines show the boundaries of the zones with cryoturbated organic material (Fig. 2d) and of the CRO horizon (Figs. 2e and 2f).

bunches appear along the periphery. This is a transitional stage from the initial pelozem to cryozem; it lasts for about 10–15 years. The end of this stage is marked by the appearance of continuous vegetation cover on the surface of nanopolygon with the appearance of grasses, sedges, and some forbs in its central part.

Separate crystals and druses of ice, fine roots, plant remains, and organic compounds produced during decomposition of plant litter favor aggregation of the soil mass. The former crusty horizon is transformed into the new mineral horizon with granular or fine crumb structure. An evolutionary sequence of surface mineral horizons includes the stages of the W (primitive), A_0, and A_h horizons above which the O horizon is gradually formed.

The lower mineral part of the soil profile retains the morphology inherited from the previous stages of the soil development. They are characterized by distinct

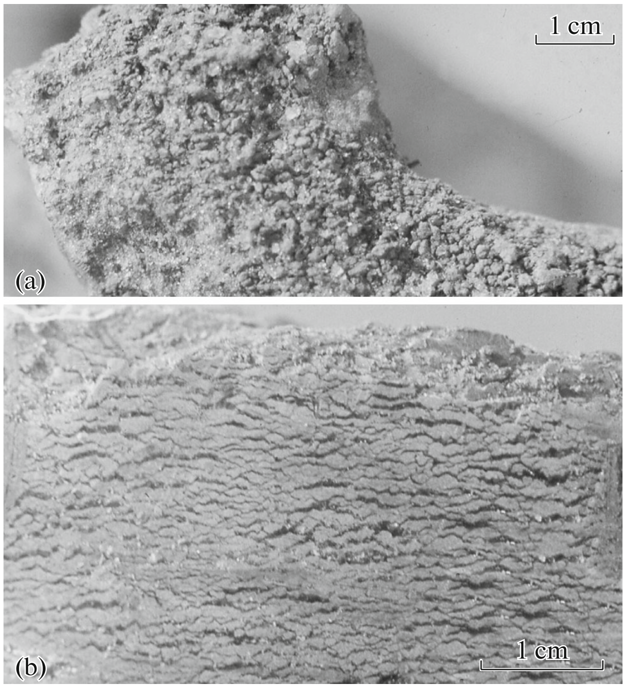

Fig. 3. Separations of ice crystals and ice druses in the crusty horizon (a) and ice schlieren in the CRO_1 horizon (b).

thin or thick platy structure. The progressive development of mosses and grasses on the soil surface is accompanied by the active destruction of the crusty horizon; fine roots of herbs and dwarf shrubs growing along the periphery of nanopolygons penetrate into it.

At the considered stage of pedogenesis (as well as at the previous stage), weak gleyzation processes manifest themselves at the depths of 5–20 cm in the central parts of nanopolygons. Large (20–30 cm) slightly gleyed mottles are seen in this zone. They disappear after 15–20 years of the former frost boil evolution. The presence of the gleyed zone during a relatively long time within the cryoturbated CR horizon makes it possible to designate this part of the soil profile as the CRg horizon. Vasil'evskaya [3] attributed the development of the gleyed zone to a quicker thawing of this part of the profile under a barren or slightly vegetated surface accompanied by the additional migration of water and temporary waterlogging of this zone. Winter observations indicate that this zone is characterized by the higher content of segregated ice. The freezing of this zone proceeds faster than the soil freezing under vegetated nanopolygons. The analysis of core samples of frozen soils taken at the end of March shows that in the uppermost part of the soil ice is segregated into separate crystals or small druses, whereas ice schlieren appear in the deeper horizons. The volume of ice in this part of the profile may reach 30–40% of the total volume of corresponding horizon (Fig. 3). A similar picture was noted for the soils of frost boils in tundra of the Taimyr Peninsula An increase in the soil water (ice) content under the surface of fresh frost boils by four–five times was also proved by the studied of cryolithologists [18].

During the final stage of overgrowing of frost boils, the thickness of litter horizon increases; the development of organic horizons takes place. At this stage, seasonal regimes of the soil moistening and ice segregation become stabilized, which favors the development of stable cryogenic structure of definite shapes and sized at the particular depths and differentiation of the CR horizon into the CR1 and CR_1 and CR_2 subhorizons differing in the size of platy aggregates. In general, the morphology of the soil profiles at this stage meets the criteria of cryozems.

Long-term observations over the particular stages of overgrowing of fresh frost boils at key sites in the typical tundra subzone and at several plots with well-dated artifacts on the surface indicate that the development of vegetation cover with the formation of the well-shaped organic horizon on the surface of barren frost boil takes place in about 50–60 years. During this period, the system of O–AO horizons of 4–6 cm in thickness takes place at the surface of nanopolygons. The organic horizon becomes differentiated into the peaty litter and the brown-colored raw-humus (AO) horizon.

The presence of frost boils devoid of vegetation for decades on some interfluves of coastal lowlands is a rare phenomenon. Mostly, it is observed near coastal or lake cliffs and on brows of windward slopes of yedoma elevations. The unvegetated state of barren circles at such sites is sustained by the removal of the snow cover and snow corrasion processes that prevent the development of vegetation on the surface of nanopolygons. Barren circles on the surface differ in their nature from the considered model of frost boil development.

A comparison of the amount of frost boils at different stages of overgrowing and data on the composition and size of the zones of cryoturbated organic material in the central parts of the profiles of cryozems indicates that these characteristics can be used to assess the activity of frost boil formation. Soil morphological zones consisting of the cryoturbated organic material within the mineral soil mass are generally small, because the development of frost boils mainly takes place of nanopolygons at the early stages of their overgrowing, when the protecting organic horizon remains relatively thin.

It was found that the formation of a new frost boil may take place at any stage of the overgrowing of nanopolygons. However, most often, this is observed, when the thickness of the surface organic horizon is no more than 2–3 cm. In this particular case, the extrusion of the mineral soil mass onto the surface leads to burying of relatively small volumes of the organic matter within the mineral soil horizons. The appearance of fresh mineral matter on the soil surface specifies the beginning of a new cycle of the soil development.

Table 3. Properties of cryozems at different stages of overgrowing of frost boils and properties of separate microzones of the cryoturbated organic material (*h*) and the enclosing mineral material (*m*) in the CRO horizon

Soil	Horizon	Depth, cm	Loss on ignition, %	Corg, %	C : N	pH H_2O	Sum of exchangeable bases, cmol (+)/kg	CO_2 carb., %
Soil (pelozem) of recent frost boil, pit P-15 (Turbic Cryosol (Novic))	K	0–3	6.0	1.0	3.2	6.6	12.2	0.2
	CRg	3–18	6.2	1.3	5.6	5.8	13.4	0.1
	CR_1	18–36	5.1	1.5	6.8	5.5	12.4	0.1
	CR_2	36–62	5.8	2.1	8.4	5.2	10.4	0.2
	CRO*	54–62	8.9	3.8	12.3	5.0	9.4	0.2
	h**	58	11.8	4.3	14.4	4.8	Not det.	
	m***	58	6.7	1.7	8.9	5.0	″	
Typical raw-humus cryozem of the overgrowing frost boil, pit P-28 (Turbic Cryosol)	W	0–3	12.4	3.2	Not det.	5.3	″	
	AO	3–6	8.4	2.4	9.1	5.4	11.4	0.2
	CR_1	6–33	5.5	1.4	8.6	5.8	12.8	0.2
	CR_2	33–64	6.1	1.2	9.6	5.6	11.6	0.1
	CRO*	57–64	12.1	3.6	14.2	5.2	11.4	0.1
Typical raw-humus cryozem of the overgrown frost boil, pit P-127 (Turbic Cryosol)	O	0–6	Not det.				Not det.	
	AO	6–9	7.2	1.8	9.1	5.2	10.3	0.2
	CR_1	9–36	6.2	1.4	8.3	5.6	10.4	0.2
	CR_2	36–65	5.8	1.9	11.1	5.7	11.5	0.2
	CRO*	58–65	11.5	2.4	11.8	5.3	10.2	0.2
	h**	60	12.8	4.8	15.9	5.0	Not det.	
	m***	60	6.2	1.7	10.0	5.0	10.9	Not det.

* Characteristics of averaged samples of the material of the CRO horizon separated in the lower part of the CR_2 horizon.
** Characteristics of the organic material in organic microzones of the CRO horizon.
*** Characteristics of the enclosing mineral material of the CRO horizon.

Data on the major chemical properties of cryozems at different stages of the overgrowing of fresh frost boils are presented in Table 3. Their analysis indicates that the most significant changes in the soil properties during vegetation succession are observed in the uppermost horizons. At the stage of fresh frost boil with barren surface (pit P-15), the material of the newly formed crusty (K) horizon is characterized by the lower loss on ignition and C_{org} content in comparison with the underlying CR_g and CR_1 horizons and higher (close to neutral) pH_{water} values. The composition and sum of exchangeable bases, the content of carbonates, and some other properties remain comparable with those in the underlying horizons, which served as the source of material extruded onto the surface.

In the course of overgrowing of the frost boil (pit P-28), the crusty horizon is transformed into the weakly developed and thin raw-humus (W) horizon within two–three decades [14]. This horizon is characterized by the accumulation of both partly mineralized and strongly comminuted plant residues and brown-colored humic substances. Data on the loss on ignition and on the C : N ratio confirm the raw-humus nature of the developing W horizon. The soil reaction in this horizon shifts towards slightly acid pH values.

The overgrown frost boil with a fully developed profile of cryozem is characterized by approximately the same thickness of the raw-humus (AO) horizon, in which the C_{org} content and the loss on ignition become somewhat lower. A narrower C : N ratio may be considered an indication of a higher degree of humification of the organic matter accumulated in this horizon. The C : N ratio in the underlying mineral horizons is lower than that in the AO horizon, except for the lower part of the profile above the permafrost table.

The buried material of the former organic horizon drastically differs in its properties from the enclosing mineral mass. In the course of regular freeze–thaw and wetting–drying cycles, a complicated redistribution of moisture, ice segregation, soil shrinkage, and microheaving takes place. In a decade, these processes lead to considerable disturbance of the initially buried organic material; it is separated into fragments; partial destruction of buried plant residues and their mixing with the enclosing mineral mass are observed.

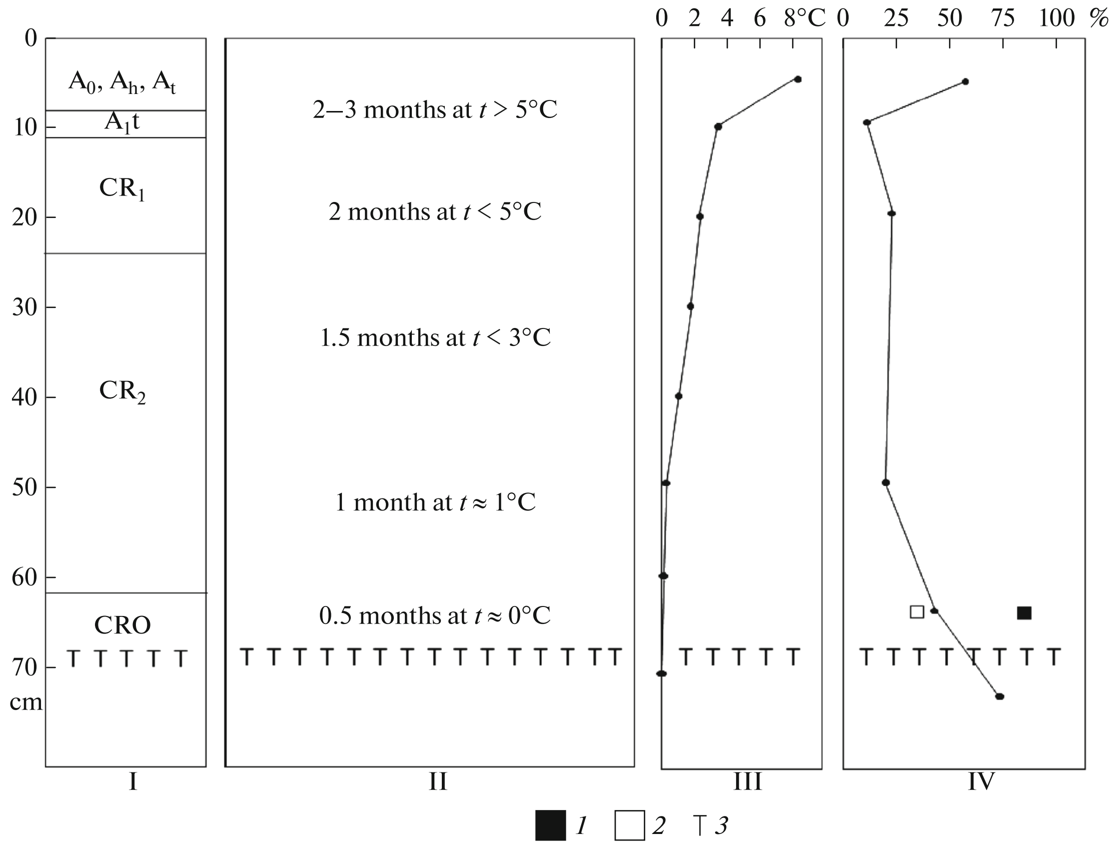

Fig. 4. Hydrothermic conditions of the development of cryozems: (I) horizonation of the profile, (II) duration of the period with above-zero temperatures, (III) mean summer temperature in the profile (data of 2008–2012); and (IV) soil water content in the period of maximum soil thawing (averaged data on separate horizons; *1*—water content in the organic material of the CRO horizon, and *2*—water content in the enclosing mineral material of the CRO horizon); *3*—permafrost table.

Turbation processes favor a gradual downward migration of the fragments with raw organic material. Field observations indicate that this migration is favored by the active ice segregation in the surface horizons. Small lenses, druses, and separate ice crystals forming upon the soil freezing from the surface are mainly formed in the upper parts of the fragments and zones composed of the raw organic matter. Rapid growth of the ice volumes presses down the organic material into the still unfrozen underlying mineral mass in the state of high plasticity.

Further ice segregation deforms the morphology of the zones (mottles) of organic material, mechanical comminution of plant remains, and changes in their disposition within the horizon.

With time, separate zones of the partly homogenized raw organic material reach the lower part of the profile above the permafrost table, where their accumulation takes place. As a result, in the profiles of cryozems, a layer enriched in the raw cryoturbated organic matter is formed immediately above the permafrost table. The pool of organic matter stored in this part of the profile is comparable with that in the surface organic horizons. It was suggested that such horizons should be distinguished as a separate type of suprapermafrost organoaccumulative horizons (CRO) [5, 15].

Table 3 contains data on characteristics of the CR_2 horizon as a single lower-profile horizon and its part distinguished as the CRO horizon. The latter horizon has a number of distinctive morphological features (color pattern, composition of the material, structure, character of boundaries, etc.); it also differs from the main mass of the CR_2 horizon in a higher content of C_{org}, higher loss on ignition, wider C : N ratio, more acid reaction, and a lower content of adsorbed bases. Considerable variations in the composition, properties, and frequency of occurrence of organic fragments that may constitute up to 60% of the horizon volume specify the high variability in the properties and major chemical characteristics of the CRO horizon.

Cryoturbated organic material in the middle-profile and lower (suprapermafrost) horizons contains both dark-colored zones of highly decomposed organic matter and brown zones of organic matter with well-preserved plant tissues. On one hand, this is dictated by the rapid transfer of some part of the initial organic material into the deep parts of the profile; at the same depth, fragments of organic material of different ages may be present. On the other hand, low

Table 4. Radiocarbon ages of raw organic material from the suprapermafrost CRO horizon of cryozems

Sample no.	Key site	Depth, cm	Laboratory code	^{14}C date	Calibrated age, 1σ, years ago
1	Sukharnaya	48–55	Ki-18332	720 ± 50	649–698
2	Sukharnaya	53–60	Ki-18334	1530 ± 50	1356–1420 1461–1513
3	Alazeya	46–58	IGAN-3953	2050 ± 90	1920–2125
4	Alazeya	53	IGAN-3954	1780 ± 100	1599–1820
5	Alazeya	68–71	IGAN-3955	2070 ± 50	1988–2117
6	Alazeya	62–74	IGAN-3956	1970 ± 100	1816–2060
7	Allaikha	44–51	Ki-18790	4530 ± 60	5055–5188
8	Allaikha	56–58	Ki-18792	2120 ± 50	2034–2151
9	Allaikha	40–45	Ki-18793	2280 ± 70	2158–2255 2299–2351
10	Allaikha	31–33	Ki-18794	3080 ± 90	3201–3396
11	Khomus-Yuryakh	41–48	IGAN-3951	1900 ± 40	1813–1897
12	Khomus-Yuryakh	60–65	IGAN-3952	1150 ± 80	977–1146

summer temperatures in the suprapermafrost horizon (no higher than 3–4°C) and short duration of the period of the thawed state of the soil (Fig. 4) hamper the decomposition of organic matter. Even in the thawed state, temperature in the lower part of cryozems is close to 0°C. Thus, during each cycle of frost boil development, middle-profile and lower horizons become enriched with raw organic matter. In these horizons, the buried organic matter is subjected to transformation and very slow decomposition. Gradually, it accumulates immediately above the permafrost table.

The radiocarbon age of organic material from the suprapermafrost horizons of cryozems on interfluves in different parts of the Kolyma Lowland ranges between 1 and 4 ka; most of the dates are within 2 ka (Table 4). It can be supposed that the date obtained for the averaged sample from each of the profiles characterizes some averaged age of organic material that got into the suprapermafrost layer in different times. In this context, the fact of relative similarity of the dates of organic matter in suprapermafrost horizons of cryozems spaced apart for more than 300 km and characterized by somewhat different mechanisms of the formation of these horizons [15] is noteworthy. This fact allows us to assume that the beginning of formation of the CRO horizon on the interfluves dates back to the Late Holocene and that the period and intensity of formation of this horizon have been approximately the same within the vast territory of the tundra zone of northern Yakutia.

Special study of the layer subjected to maximum thawing in the Holocene and now being in the frozen state [5] showed the absence of analogous horizons of the accumulation of raw organic matter in it. This fact also points to approximately the same time of the beginning of formation of these horizons and to the same activity of frost boiling and downward migration and transformation of raw organic matter in the profiles of cryozems. This may be specified by the particular evolutionary stage of the development of nanopolygonal topography with stabilization of the layer of seasonal thawing and the permafrost table at certain depths.

MAJOR CHARACTERISTICS OF THE CRYOTURBATED ORGANIC MATTER IN THE PROFILES OF CRYOZEMS

The analysis of morphology of the zones enriched in the cryoturbated organic matter shows that it may differ considerably within the same nanopolygon and at the same depth. These differences are explained by the initial differences in the character and volume of the initial organic material brought into the mineral horizons, the degree of its transformation, and the degree of its mixing with the enclosing mineral mass. In general, the degree of morphological distinctness of separate fragments (zones) of this material decreases down the soil profile. In the deep horizon, such zones look like mottles; their brown color is replaced by dark gray color. In parallel, the degrees of humification and mineralization of plant residues increase (Fig. 5).

The enrichment of the considered organic zones with mineral admixtures begins immediately after their burying. In the upper mineral part of the profile (the CR_1 horizon), cryoturbated organic material is relatively loose. Deeper, in the CR_2 horizon, it becomes more compacted and fragmented into relatively small (3–5 cm) separates that are partly mixed with the mineral soil material. Gradually, such fragments lose their identity and look like mottles enriched in the organic matter. In the CRO horizon immediately above the per-

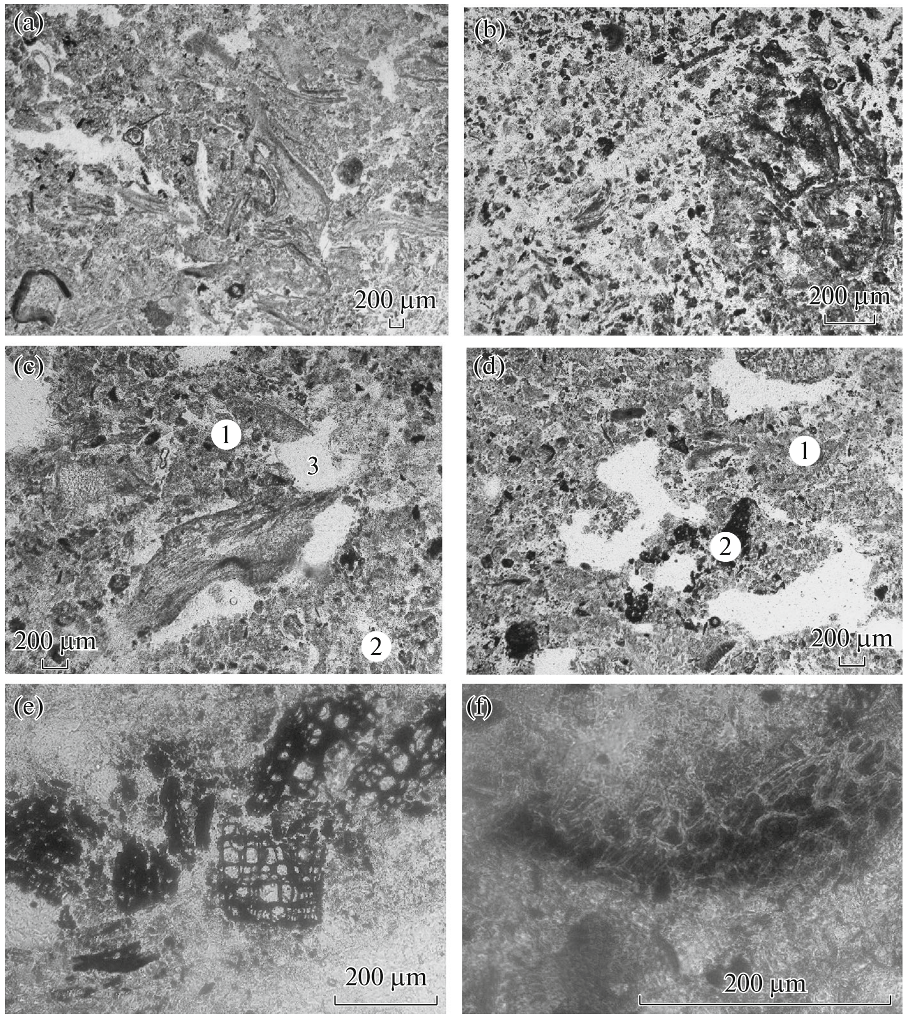

Fig. 5. Microfabrics of the zones of accumulation of organic materials in different genetic horizons of cryozems (a) CR1 horizon, plant remains in the brown (7.5YR 5/2) organic material, N II; (b) CR2 horizon, partly transformed plant remains in the brown (7.5YR 5/2) organic material, N II; (c) CRO horizon, coarse plant remains in the mass of dark-colored (7.5YR 3/0) organic material (*1*—zone of the organic material accumulation, *2*—enclosing mineral material, *3*—voids forming in place of melted ice), N II; (d) CRO horizon, dark-colored (7.5YR 3/2) organic material with different features of transformation of plant remains (*1*—accumulation of iron hydroxides in plant tissues, *2*—sulfate reduction), N II; (e) CRO horizon, plant remains with the features of sulfide segregation in the dark-colored (7.5YR 3/0) organic material, N II; and (f) CRO horizon, accumulation of iron hydroxides in the cells of mineralizng plant tissues in the dark-brown (7.5YR 3/2) organic material, N II.

mafrost table, the organic material enters the composition of mottles consisting of dark homogenized mass. The volume of such mottles is up to 70% of the volume of this horizon (average values are 40–60%). The thickness of the CRO horizon varies from 3–5 to 7 cm. Often, narrow (5–20 mm) zones of gleyed bluish material are formed along the margins of organic-rich mottles. Distinct brown-colored microzones containing weakly transformed plant remains are rarely present in the CRO horizon. However, some single mottles may be entirely composed of weakly transformed plant remains, which is related to their fast migration toward the permafrost table. In the dark-colored mottles, microzones with separations of an opaque material (sulfides?) in plant cells and tissues preserving their structure (fresh root remains?) can be seen (Figs. 5d and 5e). Upon treatment with hydrochloric acid, the smell of hydrogen sulfide appears, which confirms the processes of sulfate reduction in such microzones. Data on the chemical properties of separate mottles and other morphological elements in the suprapermafrost horizons are given in Table 3.

In the course of migration and transformation of organic material in the middle-profile horizons and in the zone of the organic matter accumulation above the permafrost table, these microzones partly retain their properties and acquire some new properties, e.g., they become acidified. These microzones specify the major properties of the CRO (suprapermafrost organoaccumulative) horizon. The morphology and properties of this horizon largely depend on the proportion between the organic matter input and the enclosing mineral mass. Along with organic suprapermafrost horizons, it is reasonable to distinguish organomineral suprapermafrost horizons, in which the portion of the mineral mass is higher, which dictates specificity of their properties.

DIVERSITY OF OTHER FORMS OF THE ORGANIC MATTER TURBATION IN THE PROFILES OF CRYOZEMS

The analysis of morphology of the profiles of cryozems and, in particular, the zones of their contact with organic soils of interpolygonal fissures indicates that the migration of raw organic matter into the soils of nanopolygons from the interpolygonal fissures is a relatively rare phenomenon. Just small volumes of the organic material in the form of thin wedges and the depths of 20–40 cm may penetrate from the fissure zone into the marginal parts of nanopolygons. Their contribution to the organic matter content in the mineral part of the profile of cryozems is relatively small.

At the same time, on some large yedoma elevations, cryozems have been found, in which the migration of raw organic matter along the permafrost table from the interpolygonal fissure zone into the suprapermafrost horizons of cryozems is considerable [15]. The considered mechanism of the lateral transfer of raw organic matter is realized in the period of maximum soil thawing under conditions of distinct microtopography of the permafrost table, when excessive moisture migrates atop this frozen aquiclude. Upon melting of ice schlieren in the ice-rich suprapermafrost horizon under nanopolygons, the organic material accumulated in the interpolygonal fissure zones slides aside along the slope of the permafrost under nanopolygons and fills the space formerly occupied by ice. This lateral transfer of raw organic matter also leads to the organic matter accumulation in the suprapermafrost horizons designated as CRO horizons [15]. There are certain differences in the properties of soils forming under the impact of the first (burying and cryoturbation of organic matter in the predominantly vertical direction) and second (lateral transfer of organic matter from the interpolygonal fissure zone) mechanisms. In the second case, the organic material in the suprapermafrost organoaccumulative horizon is less decomposed and has a peaty character. The study of cryozems within the Kolyma Lowland indicates than modern processes of the lateral transfer of raw organic matter and its downward migration in the course of frost boil development may take place simultaneously and complement one another.

In the mineral horizons of cryozems forming on slopes, interlayers of raw organic matter may appear due to typical slope processes, such as creep, solifluction, and suffosion.

Under conditions of the fast processes of reshaping the surface, permafrost table, drainage network, and thermokarst lakes in the studied area during the Holocene, active destruction of the Early Holocene peatlands takes place on the well-drained elevated positions and high lake terraces. Upon low thickness of the active layer and progressive enrichment of the upper part of degrading peat with silty material coming from unvegetated surfaces of former steep lake slopes (cliffs), cryozems are formed, the lower parts of which consist of differently decomposed peat, and the middle-profile and upper silty horizons are very rich in the raw organic matter.

CONCLUSIONS

(1) On drained surfaces in the tundra zone of northern Yakutia, the development of cryogenic nanopolygonal topography is accompanied by the formation of frost boils that exert great influence on the character of pedogenesis.

(2) Frost boil formation on nanopolygons has a cyclic pattern. The initial stage is the extrusion of the mineral material onto the surface of nanopolygon and the development of primitive soil of the barren circle; this soil has a crusty horizon and meets the criteria of pelozems (primitive clayey soils). The final stage of the cycle is marked by the development of a mature profile of cryozem.

(3) The new cycle of frost boil formation may begin at virtually any stage of overgrowing of the initial barren surface and the formation of cryozems. The frequency of the cycles is specified by the particular cryogenic (permafrost) and weather conditions (air temperature, degree of soil moistening, and depth of the snow cover thickness at the beginning of the soil freezing in the fall).

(3) In the course of each of the cycles of frost boiling, middle-profile horizons of the soils are subjected to the input of surface organic material buried under the extruded mineral mass. This organic material may include fragments of the W, O, and AO horizons. Gradually, the material of these horizons is transformed with its simultaneous downward movement toward the permafrost table. Atop the permafrost table, organomineral or even organic horizons are formed; they can be referred to as suprapermafrost horizons of the organic matter accumulation.

(4) Suprapermafrost horizons of the organic matter accumulation are in paragenetic association with the overlying pedogenetic horizons; they have their own specific properties and diagnostic features. We suggest that such horizons can be distinguished as a separate type of genetic horizons. Repeated cycles of frost boil formation favor progressive accumulation of organic materials in the lower part of the soil profiles, and the temperature regime in this part of the profile hampers their mineralization and transformation and favors their accumulation in this zone.

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