ISSN 1064-2293, Eurasian Soil Science, 2015, Vol. 48, No. 2, pp. 128–138. © Pleiades Publishing, Ltd., 2015.
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GENESIS AND GEOGRAPHY OF SOILS

Specific Features of the Genesis of Automorphic Soils of the Northern Forest-Tundra (Southeast of the Bol'shezemel'skaya Tundra)

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Received July 8, 2013

Abstract—Automorphic soils developed from sandy materials (podzolized podburs, (Entic Podzols) and iron-illuvial podzols (Haplic Podzols)) and loamy materials (organic cryometamorphic soils (Gelic Cambisols) and iron-illuvial svetlozems (Spodi-Stagnic Cambisols)) were studied in the northern forest-tundra zone. Podzolized podburs and podzols of tundra cenoses were less podzolized in comparison with the analogous soils developed under forest cenoses. This can be explained by a higher intensity of cryogenic processes favoring the fixation of iron–humus films on skeletal grains in the sandy soils of tundra cenoses. In the organic cryometamorphic soils, the illuviation of Al–Fe-humus compounds with the formation of bleached skeletans in the upper part of the mineral horizon was identified. The eluvial–illuvial differentiation of the soil mass diagnosed by the analyses of intraped mass was weakly pronounced. The features attributed to the activity of cryogenic processes were also described in these soils. Iron-illuvial svetlozems were characterized by the migration of iron compounds within the microprofile of podzol in the topsoil and by the specific well-structured cryometamorphic horizons in the lower part of the profile. The features inherited from the previous stages of soil development were identified in these soils.

Keywords: podburs, podzols, organic cryometamorphic soils, svetlozems, mesomorphology, micromorphology, inherited soil features

DOI: 10.1134/S1064229315020106

INTRODUCTION

The state of the soil cover is one of the factors controlling biodiversity of ecosystems. The conservation of biodiversity is among the key ecological problems of our time because of the continuing vanishing of species. In the ecotones between neighboring natural zones, including forest and tundra zones, natural ecosystems are distinguished by their specific and complex structure. The presence of biogeocenoses typical of the neighboring territories (forest and tundra) within relatively small transitional zones is reflected in the diverse pedogenetic features within these zones. The number of studies specially devoted to pedogenesis in the forest–tundra ecotone is insufficient [8, 18, 27, 32]. In recent years, interesting and significant results in this field have been obtained by Tonkonogov with coauthors [32, 34]. Various aspects of the genesis and classification of cryogenic soils forming under taiga and tundra cenoses have been studied by Russian and foreign researchers [4–6, 8, 13, 16, 24, 32, 40–42].

Podzols developed from sand under conditions of good drainage were described 280 km to the north of the northern tree line in Quebec, Canada [38]. The presence of podzolic soils and paleosols in the Arctic tundra was explained by the development of forest vegetation in this zone in the past [36]. This genetic concept was also confirmed by the studies of peatlands [2, 14] and wood remains found in the tundra zone [15, 35, 37]. The presence of typical taiga species, such as *Moneses uniflora* (L.) and *Ramischia secunda* (L.), in forest groves in the coastal zone of the Barents Sea (in the More-Yu River Basin) [31] points to the wider extent of forest vegetation in the warm climatic phases of the Holocene. According to [37], the maximum density of forest stands in the northwest of the Bol'shezemel'skaya tundra (68°02′ N, 54°08′ E) was observed about 5500–3000 yrs. ago. This conclusion was made on the basis of data on buried trunks of the trees and the analysis of pollen in the corresponding horizons of the peatland. The features inherited by the soils from the previous stages of their development attest to the polygenetic origin of these soils. The genetic interpretation of these features is often ambiguous. Thus, the eluvial–illuvial differentiation of the soil profiles according to the textural properties and bulk elemental compositions of the eluvial and illuvial horizons is often considered the result of former pedogenesis in the Holocene climatic optimum [8, 29]. At the same time, it cannot be excluded that this differentiation is due to the soil development from the initially heterogeneous (two-layered) substrates. In this case, the genesis of the specific two-layered covering loam in the northeast of the East European Plain is to be studied [32]. Some authors [26] argue that no considerable shifts in the boundaries of forest vegetation took place during the climatic optimum of the Holocene. To solve these complicated problems, new methods and approaches have to be applied.

In this paper, we consider pedogenetic features of automorphic soils developed under tundra cenoses and under isolated forest groves in the forest-tundra zone; recently formed cryogenic and pedogenic features are distinguished from the features inherited from the previous stages of the soil development.

OBJECTS AND METHODS

Field studies were performed in the basins of the Khoseda-Yu and Seida rivers. The studied territory belongs to the forest–tundra ecotone with predominant hummocky lichen–moss shrub tundra cenoses and with dwarf shrub–lichen spruce and spruce–birch forests allocated to the well-drained slopes of river valleys.

Permafrost is present in the form of large isolated "islands." The thickness of permafrost is up to 50 m, and its upper table is found at the depths of 0.5 to 8 m. Glaciofluvial and lacustrine–alluvial sands, moraine loams and loamy sands, two-layered deposits, and typical covering (mantle) loams are the main types of parent materials in this area. We studied podzolized podburs and iron-illuvial podzols developed from sands and cryometamorphic soils and iron-illuvial svetlozems developed from silt loams under both tundra and forest cenoses.

Soils Developed from Coarse-Textured Sediments in the Upper Reaches of the Khoseda-Yu River

Podzolized podbur (Entic Podzol) was studied on a flat top of a local hill (67.20° N, 59.52° E) with a hummocky microtopography under dwarf birch tundra with polytrichum mosses and lichens in the ground cover. The soil profile had the following horizonation.

O1, 0–4 cm. Brown semidecomposed litter; loose; slightly dry.

O2, 4–8 cm. Dark brown litter with an admixture of bleached sand grains; loose; slightly dry; densely penetrated by roots; clear wavy boundary.

BHFe, 8–12 cm. Light yellow, with dark brown interlayers and whitish mottles; sand with loose fine crumb structure; slightly compact; slightly dry; many roots; clear wavy boundary.

BHF1, 12–32 cm. Ocherous brown with large whitish and rusty mottles; sand with loose fine crumb structure; slightly compact; slightly dry; many roots; diffuse boundary.

BHF2, 32–47 cm. Ocherous sand with loose crumb structure; slightly compact; slightly dry; few roots; diffuse boundary.

BHF3, 47–68 cm. Ocherous to dark brown with rusty mottles; sand with crumb structure; slightly compact; moist; single roots; clear wavy boundary.

BC, 68–78 cm. Yellow-brown sand with small rusty mottles; structureless; relatively compact; moist.

No permafrost was present in the examined section down to 130 cm.

This soil profile had the following micromorphological features.

O2—light-colored sand grains with brown coatings; in some loci, sand grains are cemented by dark brown plasma; there are two types of aggregates composed of (a) fine plant detritus and (b) humic substances with coagulated microaggregates of the first order.

BHFe—rounded sand grains covered by thick dark brown coatings against the light brown background color; coagulated microaggregates are present in packing voids; humic plasma contains inclusions of silt grains; there are loci with brown color and with fragments of plant detritus.

BHF—light brown with brown fragments; thin clayey coatings on rounded and angular sand grains; dark gray and large brown fragments cemented by humus–iron and clayey plasma; brown plasma with scaly fabric in the lower part.

BC—dark gray mottles against the brown background color; subparallel lens-shaped layers of sand and silt particles cemented by plasma; few reddish brown clayey infillings between skeletal grains and humus–iron coatings on the skeletal grains.

Iron-illuvial gleyic cryoturbated podzol (Haplic Endogleyic Podzol) was described on the upper part of a gentle slope of a hill (67.21° N, 59.50° E) under dwarf birch tundra with lichens in the ground cover.

O1, 0–2 cm. Light reddish brown loose litter composed of the remains of lichens; slightly dry.

O2, 2–5 cm. Dark reddish brown with black mottles and tongues of the highly decomposed organic matter; loose; slightly dry; densely penetrated by roots; sharp wavy boundary.

E, 5–8(14) cm. Whitish sand with light yellow mottles; loose crumb structure; slightly compact; slightly dry; many roots; distinct irregular boundary.

BHFcr, 8(14)–19 cm. Yellowish ocherous sand with whitish and dark brown pockets, mottles, and interlayers in the entire horizon (the features of cryoturbation); crumb structure; relatively compact; slightly dry; moderate number of roots; distinct wavy (left side) to tonguing (right side) boundary.

BHF1, 19–32 cm. Ocherous-yellow with numerous black mottles of the highly decomposed organic matter; sand; loose crumb structure; moderately compact; moist; small amount or roots; diffuse boundary.

BHF2, 32–51 cm. Ocherous-yellow with few small and medium-size black mottles; sand; loose crumb structure; moderately compact; moist; single roots; distinct wavy boundary.

BCg, 51–76 cm. Bluish gray with black mottles; sand; crumb structure; compact; moist.

No permafrost was present in the examined section down to 130 cm.

This soil profile had the following micromorphological features.

E—whitish color; loose fabric; some light-colored sand grains are devoid of coatings; most of the grains are covered by yellow-brown coatings; corroded skeletal grains are arranged into ellipsoid clusters (cryogenic sorting); brown plant detritus.

BHFcr—light brown, more compact; iron–humus brown or yellow brown coatings on sand grains and iron–humus bridges between the grains; densely packed concentrations of sand and silt particles cemented by plasma are encircled by iron-rich microzones.

BHF1—brown; skeletal grains with thick dark brown coatings and bridges between them; some grains are covered by thin clayey coatings with inclusions of silt particles; many densely packed concentrations of sand and silt particles; few plant residues.

BC—brown, more compact; sand and silt particles with thin anisotropic clayey coatings on some of them; few iron concretions.

Iron-illuvial gleyic podzol (Haplic Endogleyic Podzol) was described on the terrace of the Khoseda-Yu River (67.17° N, 59.41° E) under spruce grove with dwarf birch and with lichens in the ground cover.

O1, 0–3 cm. Light yellow undecomposed loose lichen litter; slightly dry.

O2, 3–5 cm. Dark brown peaty mass with inclusions of bleached sand grains; loose; slightly dry; densely penetrated by roots; distinct uneven boundary.

Eg, 5–11 cm. Whitish gray sand with coffee-brown pockets; loose crumb structure; slightly dry; distinct wavy boundary.

E, 11–20 cm. Whitish structureless sand; slightly compact; moist; abundant roots; distinct irregular boundary.

BHF1, 20–29 cm. Coffee-brown structureless sand; compact; moist; moderate amount of roots; distinct wavy boundary.

BHF2, 29–46 cm. Light reddish brown sand with loose crumb structure; slightly compact; moist; few roots; distinct wavy boundary.

Bg, 46–63 cm. Light yellow with few rusty mottles; sand with loose crumb structure; slightly compact; moist; few roots in the upper part; diffuse boundary.

BC, 63–71 cm. Light yellow sand; loose crumb structure; moderately compact; wet.

No permafrost was present in the examined section down to 125 cm.

Soils on Silty Covering Loams in the Seida River Basin

Organo-cryometamorphic soil (Gelic Cambisol) was described on a convex part of a local ridge (67.02° N, 63.03° E) under the dwarf birch tundra with dwarf shrubs and hypnum mosses in the ground cover; polytrichum mosses were developed in the microdepressions.

O, 0–7 cm. Dark brown loose moist litter with a raw-humus 2-cm-thick interlayer at the contact zone with the mineral soil.

CRM1, 7–11 cm. Brow with reddish brown and whitish brown mottles in the upper part; silty loam with subangular blocky aggregates of 3–5 mm in size; thin whitish skeletans and brown films cover the surface of the aggregates; intraped pores of less than 1 mm in diameter are clearly seen; compact; slightly dry, with ocherous punctuations; abundant roots; diffuse boundary.

CRM2, 11–24 cm. Light brown with reddish brown and whitish brown mottles; silty loam with polyhedral angular structure; the size of aggregates is about 5–7 mm; they are covered by thick whitish skeletans (1–2 mm). Intraped mass of light brown, with black punctuations and small dark brown iron–humus mottles; fine rounded pores. Whitish mottles tend to have a subhorizontal orientation; they are composed of platy aggregates of 1–2 mm in thickness and 7 mm in length; skeletans on the upper sides of the aggregates are up to 1–2 mm in thickness; they are also present on the lower sides of the aggregates. Fine pores; black punctuations. Compact; slightly dry; the number of ocherous punctuations increases in the lower part of the horizon; many roots; diffuse boundary.

CRM3, 24–38 cm. Light brown silty loam with dark brown mottles; few roots; polyhedral aggregates of 5–8 mm in length and 5 mm in thickness; skeletans form relatively thick (1–3 mm) coatings on the upper sides of the aggregates and are also found in the intraped pores; some of the aggregates are covered by brown clayey coatings. The intraped mass is light brown with ocherous microzones. Tube-shaped pores are up to 1 mm in diameter; a tendency for layered arrangement of the soil mass with subhorizontal skeletans is seen. Compact; slightly dry; single roots; diffuse boundary.

CRM4, 38–70 cm. Light brown silty loam with dark brown mottles; more dense; moderate amount of roots; angular polyhedral aggregates; skeletans are light brown in color; they are thinner than those in the overlying horizon; fine intraped porosity. Dark brown fragments are characterized by granular structure. The size of peds is about 5 × 3 mm; their thickness is about 2 mm. The intraped mass is light brown, with black and rusty punctuations. In the upper part, there are abundant nodules of 3 × 4 mm in size; they are encircled by whitish 1-mm-thick coatings. Whitish skeletans are seen around large fissures and on the surface of aggregates. The lower part of the horizon has a massive fabric and is more compact. Whitish skeletans disappear. Dark brown films appear around the pores. Brown mottles are seen on ped faces. The size of aggregates is somewhat smaller. Tube-like intraped pores are up to 1 mm in diameter.

From the depth of 100 cm, the soil was in the frozen state.

Iron-illuvial svetlozem (Spodic Stagnic Cambisol) was studied in the upper part of the slope of a local ridge (67.02° N, 63.04° E) under a birch–spruce woodland. Birch trees were up to 4–5 m in height; spruce trees were up to 6 m in height. Dwarf birch and dwarf willow were in the shrub layer; dwarf shrubs included blueberry, cowberry, bilberry, and crowberry. Green and polytrichum mosses and lichens were present in the ground cover.

O, 0–4(5) cm. Dark brown loose litter; differently decomposed plant residues; a black organomineral layer is seen in the lower part at the contact with the mineral horizon; densely penetrated by roots, with black fragments of plant residues.

E, 4(5)–8(11) cm. Bluish–whitish coarse silty loam with a tendency for platy aggregation; slightly compact; moist. Platy and scaly aggregates are covered by whitish skeletans; fine tube-shaped pores are devoid of skeletans; small (1–2 mm) ocherous-brown concretions; indistinct wavy boundary.

BF, 8(11)–14(19) cm. Rusty ocherous coarse silty loam; fine granular structure; compact; moist; abundant roots; alternating whitish and brown interlayers are clearly seen; rounded aggregates (ooids) are less than 1 mm in size; narrow tube-shaped pores have bleached walls; compact; contains small (1–2 mm) concretions. Diffuse boundary.

CRMg, 14(19)–33 cm. Bluish to grayish brown; silty coarse loam with angular blocky and granular structure; the size of large aggregates is up to 2–3 cm. Skeletans are present in the pores and in the intraped spaces; concretions of 1–2 and <1 mm in sizes are clearly seen in the soil mass; compact, moist, with a moderate amount of roots; diffuse boundary.

CRMi. 33–58 cm. Light brown silty medium loam with fine crumb to angular blocky structure; the size of peds is up to 7–10 mm; brown coatings are seen on their faces; whitish skeletans are present in the interaggregate space; very compact; moist; few roots; diffuse boundary.

CRMC, 58–85 cm. Bluish brown coarse silty loam with crumb to fine angular blocky structure; compact; moist.

The upper horizons have an intermittent character; they are disturbed by slope processes. Within the upper 2 m, permafrost was absent.

These soils were studied with the use of macro- and micromorphological methods. Thin sections [9] were prepared from the samples of sandy soils. The set of standard soil analyses was supplemented with determination of the optical density of oxalate extracts from the soils to diagnose the eluvial–illuvial differentiation of the organic matter and iron and aluminum oxides in the soil profiles [39]. In the clayey tundra soils, the examination of their cutans was specially performed using the methods suggested by Targulian [28]. Undisturbed soil samples were taken to describe mesomorphological features of the soil mass under five-fold magnification. Skeletans were separated by hand with a razor. Intraped mass was separately studied after the removal of the surface layer. The results of the chemical analyses of the skeletans and intraped mass were reliably different. Their genetic interpretation is discussed below. The method of wet sifting was used to separate concretions, which were also separately analyzed. Thus, we obtained chemical data on the major components of the soil fabric: intraped mass, skeletans, and concretions. Physicochemical properties of the soils were determined by routine methods [1, 30]. The criterion of oxidogenesis was calculated according to Vodyanitskii [3]. The names and symbols of soil horizons are given according to the new classification system of Russian soils [10, 17].

RESULTS AND DISCUSSION

Soils developed from coarse-textured deposits. The eluvial–illuvial differentiation of sesquioxides in the podzolized podbur (Table 1) proves the podzolized character of the described soil profile. However, the distribution of optical density values in the oxalate extracts from the soil horizons has an accumulative character with a maximum in the uppermost layer. The development of podburs on the tops of local interfluves is favored by the accumulation of humus in the form of humus films and cryogenic coagulated aggregates with inclusions of silty grains in the BHe horizon. The coagulated nature of humus decreases the development of podzolization. The latter is displayed in the form of separate mottles of bleached material. According to Goryachkin [4], podzolized podburs in the tundra zone of European Russia are developed under mesomorphic conditions; in the extreme conditions of the tops of local hills and ridges, the features of podzolization are virtually absent. Podburs are developed in association with the soils of cryogenic barren circles.

The whitish yellow E horizon of podzols in the tundra landscapes was characterized by the presence of bleached sand grains together with sand grains covered by brown coatings. The presence of these coatings attests to the weak aggressive impact of the soil solution of the material of this horizon, i.e., to the retardation of podzolization processes. It is probable that cryogenic processes favoring coagulation and condensation of humic compounds impede the development of podzolization; the podzolized horizon (E) has a brown color (10YR 6/4). IN the BF horizon, iron–humus films are formed on the surface of sand grains and fill bridges between them. In some loci, more compact

Table 1. Physicochemical properties of the soils developed from sandy substrates

Horizon	Depth, cm	pH		C	N	Exchangeable acidity, cmol (+)/kg			Ca	Mg	Tamm's extract, %		Optical density of the oxalate extract
		water	salt	%		total	H^+	Al^{3+}	cmol (+)/kg		Fe_2O_3	Al_2O_3	
Podzolized podbur (tundra)													
O1	0–4	4.18	3.32	28.2	0.88	–	–	7.80	2.86	0.83	0.30	0.35	–
O2	4–8	4.09	3.33	7.99	0.24	7.95	0.15	3.92	0.47	0.14	0.30	0.36	–
BHFe	8–12	4.53	3.67	2.37	0.13	4.02	0.10	2.10	0.06	0.02	0.27	0.37	0.225
BHF1	17–32	5.02	4.23	0.43	0.03	2.14	0.04	1.56	0.04	0.00	0.34	0.44	0.132
BHF2	32–47	5.15	4.33	0.72	0.04	1.60	–	–	0.19	0.05	0.51	0.47	0.098
BHF3	47–68	5.48	4.26	0.25	0.02	1.72	–	1.68	0.67	0.24	0.54	0.39	–
BC	68–78	5.53	4.12	0.17	0.01	1.18	–	1.14	1.21	0.43	0.17	0.16	–
Iron-illuvial gleyed cryoturbated podzol (tundra)													
O1	0–2	3.93	3.06	40.9	1.39	9.80	1.10	8.70	5.36	1.34	0.11	0.29	–
O2	2–5	4.22	3.39	31.4	0.99	9.56	0.40	9.16	0.81	0.55	0.42	0.49	–
E	5–8(14)	4.38	3.70	1.67	0.08	4.78	0.06	4.72	0.11	0.32	0.11	0.20	0.109
BHFcr	14–19	4.88	4.28	1.05	0.04	2.82	0.06	2.76	0.17	0.04	0.50	0.60	0.167
BHF1	19–32	4.96	4.03	0.47	0.06	3.92	0.08	3.84	0.20	0.08	0.32	0.29	0.041
BHF2	32–51	4.67	4.23	0.34	0.03	1.76	0.04	1.72	0.29	0.10	0.24	0.44	–
BCg	51–76	5.27	4.13	0.13	0.01	1.12	0.06	1.06	1.00	0.28	0.11	0.30	–
Iron-illuvial gleyed podzol (forest)													
O1	0–3	4.14	3.12	39.5	1.34	7.04	1.20	5.84	2.30	1.34	0.15	0.21	–
O2	3–5	3.98	3.09	5.48	0.31	4.12	0.42	3.70	0.48	0.33	0.12	0.13	–
Eg	5–11	4.10	3.21	1.91	0.12	2.68	0.20	2.66	0.28	0.18	0.08	0.07	0.076
E	11–20	4.84	3.91	0.14	0.11	0.86	0.08	0.78	0.21	0.09	0.01	0.00	0.320
BHF1	20–29	5.03	4.40	1.18	0.05	1.90	0.04	1.86	0.26	0.10	0.28	0.76	0.418
BHF2	30–40	4.73	4.59	0.61	0.03	1.12	0.04	1.08	0.24	0.13	0.15	0.52	0.202
Bg	50–60	5.14	4.70	0.17	0.01	0.74	0.06	0.68	0.24	0.09	0.06	0.27	–
BC	63–71	5.26	4.63	0.12	0.01	0.72	0.04	0.68	0.23	0.10	0.08	0.18	–

Hereinafter, dashes denote the absence of data.

fragments of cemented sand are seen. It is probable that they represent the residues of the former ortstein destroyed by cryogenic processes. The soils transitional between podburs and podzols have also been described. Their morphology corresponds to the morphology of podburs (without a bleached eluvial horizon), and their chemical properties with a clearly pronounced eluvial–illuvial redistribution of sesquioxides and optical density values correspond to podzols.

In the tundra cenoses that occupy more "severe" niches (in comparison with forest groves), the cryogenic processes in the soils are enhanced. This leads to the fixation of humus and sesquioxides in the form of coagulated aggregates and films on the surface of sand grains. As a result, the whitish color of the eluvial horizon disappears. As noted in [32], bleached podzolic horizon tends to disappear under tundra cenoses. In the podzols under forest groves, the E horizon has a whitish color (7.5 YR 7/1); the intensity of the eluvial–illuvial redistribution of substances in these soils is higher, which is also proved by the higher optical density values of oxalate extracts from the soil horizons. Under tundra cenoses, podburs are developed at present. Podzols under forest cenoses in the forest-tundra zone display clear eluvial–illuvial redistribution of sesquioxides [19]. These soils are similar to podzols developed under northern taiga cenoses. These soils are shaped by the same elementary pedogenetic processes, though their intensity becomes weaker in the northward direction [4].

Soils developed from silty loamy deposits under well-drained conditions in the tundra are characterized by the absence of the gley horizon. They are specified by the high degree of cryogenic aggregation in the upper mineral horizons and by the presence of a raw-humus material above the mineral layer. Such soils are referred to as the organo-cryometamorphic soils. The good development of the cryogenic structure favors soil aeration and iron oxidation (Table 2). Cryoturbation processes are slowed down because of the absence of the soil overmoistening. The downward migration of the soil solutions is active; this can be judged from

Table 2. The contents of mobile sesquioxides, Ñ, and N in the structural components (skeletans/intraped mass) of soils developed from covering loams, %

Horizon	Depth, cm	Tamm's extract		Fe_2O_3 by Mehra–Jackson's method	C	N	C/N	Degree of oxidogenesis, bulk soil mass
		Fe_2O_3	Al_2O_3					
Organo-cryometamorphic soil								
CRM1	5–12	0.30/0.32	0.16/0.18	0.85/0.75	0.17/0.20	0.02/0.03	8/7	0.3
CRM2	12–27	0.22/0.45	0.10/0.20	0.43/0.50	0.22/0.27	0.02/0.03	11/9	0.4
CRM3	27–45	0.25/0.42	0.11/0.18	0.45/0.79	0.21/0.21	0.03/0.03	7/7	0.4
CRM4	45–70	0.23/0.22	0.11/0.22	0.33/0.72	0.18/0.24	0.02/0.03	9/8	0.4
Iron-illuvial svetlozem								
E	2.5–10	0.20/0.34	0.09/0.15	0.42/0.58	0.29/0.51	0.04/0.05	7/10	–
BF	10–17	0.33/0.46	0.15/0.21	0.61/0.60	0.60/1.14	0.06/0.12	10/9	–
CRMg	16–34	0.24/0.36	0.12/0.17	0.38/0.37	0.26/0.38	0.04/0.05	6/8	–
CRMi	34–67	0.26/0.25	0.11/0.11	0.30/0.64	0.12/0.20	0.02/0.04	6/5	–
CRMC	67–93	0.42/0.65	0.06/0.11	0.42/0.65	0.13/0.19	0.02/0.03	6/6	–

an increase in the carbon content of the skeletans in the deeper soil layers.

Whitish mottles with layered fabric were described in the upper part of the mineral layer, in the CRM1 horizon. It is probable that they represent the fragments of the former podzolic horizon. Whitish mottles are also seen in the intraped mass. The soil profile is well aggregated. The size of aggregates increases down the soil profile from the upper part of the cryometamorphic horizon CRM1 (3 × 5 mm) to its lower part (5 × 8 mm). The lower part of the profile (60–70 cm) has a massive fabric; it is less aggregated because of the shallow occurrence of permafrost and water stagnation above it. Thin whitish skeletans are present in the CRM1 horizon; in the lower horizons, their amount increases, and their thickness reaches 1–3 mm. The skeletans fill interaggregate spaces and intraped pores. In the lower part of the profile, they are concentrated around large fissures, and their thickness increases to 1–3 mm. The skeletans are seen inside intraped pores and in the interaggregate space. In the lower part of the profile, they are only present in fissure zones and on the surface of some aggregates.

The sand and coarse silt fractions of the soils are subjected to the cryohydration weathering with the formation of fissures and caverns on their surface [11]. The roughness of the surface of sand and silt grains favors the accumulation of the products of pedogenesis leached off from the topsoil horizons. The chemical analysis of the material of the skeletans proved the accumulation of both dithionite- and oxalate-extractable iron and aluminum oxides in the CRM1 horizon. It can be supposed that Al–Fe-humus compounds accumulated in the CRM horizon are partly illuviated from the litter (without the formation of the illuvial BHF horizon); their ascending migration to the freezing front is also possible. The soil freezing with ice segregation is accompanied by the release of oxygen [11], so that iron oxides precipitate on the surface of skeletans. Thus, cryogenic process play an important role in the genesis of tundra soils. Under the peaty litter horizon, there are dark brown and brown organomineral coatings enriched in the oxides of Fe and Al on the surface of sand grains. A similar distribution pattern of sesquioxides was described in the organo-cryometamorphic soil underlain by the buried soddy-podzolic soil (at the depth of 37–80 cm). Mobile organic substances produced in the litter and not bound to sesquioxides migrate into deeper horizons. They precipitate on the sand grains of the skeletans and in the intraped

Table 3. The content and size distribution of concretions

Horizon	Depth, cm	Concretions, % of the soil mass	Fractional composition of concretions, % of their total mass			
			<1 mm	1–2 mm	2–3 mm	>3 mm
Organo-cryometamorphic soil						
CRMe	7–24	1.67	26	57	10	6
CRM1	24–38(45)	0.12	10	30	17	43
CRM2	38(45)–63(69)	0.29	32	31	13	24
CG	100–110	0.63	20	31	11	38
Iron-illuvial svetlozem						
AO	2.5–4(5)	1.61	58	38	3	1
E–BF	4(5)–16(17)	3.20	76	22	2	0
CRMg	16(17)–34	0.10	44	45	11	0
CRMi	34–67	0.04	13	67	20	0
CRMC	67–93	0.08	24	50	15	11
C	93–112(113)	0.05	7	29	12	52

mass of the CRM2 horizon. This horizons is also specified by some accumulation of oxalate-extractable sesquioxides in the intraped mass. Dark brown mottles in the intraped mass of this horizon attest to the active precipitation of Al–Fe-humic compounds that could take place in the earlier stages of the soil development. At present, the precipitation of substances leached off from the upper horizons mainly takes place in the intraped space (on the surface of skeletans).

Bleached microzones in the upper part of the CRM1 horizon are depleted of sesquioxides; their accumulation is observed in the CRM2 horizon. According to [32], the bleached microzones of the CRM1 horizon are enriched in the SiO_2; in the CRM2 horizon, the bulk content of silica somewhat decreases (profile 8-PA of the organo-cryometamorphic soil). In the soil studied by us, the eluvial–illuvial redistribution of the oxalate-extractable sesquioxides and carbon in the intraped mass was diagnosed. Thus, the weakly pronounced Al–Fe-humus podzolization of the organo-cryometamorphic soil can be judged from the accumulation of sesquioxides in the bulk soil mass; the intraped mass of the CRM horizon is weakly transformed by this process. The eluvial horizon is only preserved in the form of small fragments under the litter. It can be supposed that it was destroyed by the cryogenic processes. The material of this horizon could be incorporated into the material of the cryometamorphic horizons in their middle and lower parts. The activity of Al–Fe-humus illuviation can be judged from the analysis of skeletans sampled from different depths. At present, the zones of skeletans serve as the main pathways for the migration of substances in the soil profile.

Table 4. Bulk chemical composition of concretions from the organo-cryometamorphic soil, %

Horizon	Depth, cm	SiO_2	Fe_2O_3	MnO
Concretions of 1–2 mm in size				
CRMe	7–24	54.70	27.16	1.00
CRM2	38(45)–63(69)	62.65	17.74	0.59
CG	100–110	71.10	10.11	0.15
Concretions of >3 mm in size				
CRMe	7–24	51.62	31.40	0.71
CRM2	38(45)–63(69)	60.72	18.72	0.88
CG	100–110	64.97	15.56	0.31

Soil concretions represent another important source of information about modern processes. In the organo-cryometamorphic soils, the maximum content of concretions is typical of the upper (CRMe) mineral horizon. These are hard reddish brown rounded pedofeatures with a predominant size of 1–2 mm. In the lower horizons, rounded concretions are larger (>3 mm); there are also rusty brown tube-shaped iron concentrations of 1 to 12 mm in length. Data on the size distribution of concretions are given in Table 3.

In the large concretions, the concentrations of iron and manganese exceed those in the enclosing mass by 4–7 and 14–34 times, respectively (Table 4). The maximum concentration of Fe is observed in the large concretions of the cryometamorphic soil. In the upper part of the profile, the concentration of Mn in the concretions increases with a decrease in their size. In the lower part of the profile, the reverse phenomenon is observed: small concretions are impoverished in Mn. Data on the size distribution of concretions in the soil profile (Table 3) and on the concentrations of major oxides in the concretions of different sizes (Table 4) attest to different redox conditions in the upper (0–40 cm) and lower (40–100 cm) parts of the soil profile. The maximum accumulation of Fe and Mn in the concretions formed in the CRMe horizon points to frequent changes in the redox potential of this horizon.

Table 5. Bulk chemical composition of the iron-illuvial svetlozem, % of ignited sample

Horizon	Depth, cm	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O	P_2O_5	Sum
Bulk soil mass (pit 5-PA) [34]											
E	5–10	77.21	1.89	11.95	0.97	0.20	6.91	2.20	0.89	0.29	99.57
BF	10–20	76.18	3.68	12.46	0.67	0.23	5.39	1.81	0.62	0.01	101.07
CRMg	20–40	74.62	3.60	12.63	0.74	0.22	6.14	1.91	0.46	0.01	100.35
CRMi	40–50	73.43	3.38	12.13	0.73	0.28	7.43	1.95	0.74	0.02	100.11
CRMC	60–70	70.34	4.18	13.42	0.78	0.39	7.78	2.00	0.71	0.04	99.66
Intraped mass											
E	2.5–10	75.3	4.40	12.36	0.91	0.99	0.89	2.11	Not det.	0.13	Not det.
BF	10–17	72.9	5.11	12.85	0.97	0.87	0.89	2.15	"	0.11	"
CRMg	16–34	75.3	4.62	12.09	0.90	0.91	0.87	2.10	"	0.12	"
CRMi	34–67	72.9	5.38	13.19	0.97	1.24	0.98	2.22	"	0.15	"
CRMC	67–93	72.6	5.35	13.56	0.90	1.20	1.10	2.17	"	0.18	"

Table 6. Particle-size distribution data on the iron-illuvial svetlozem, % (pit 5-PA) [34]

Horizon	Depth, cm	Fraction content, %; particle size, mm					
		0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	<0.01
E	5–10	31	40	8	6	16	30
BF	10–20	18	51	6	8	17	31
CRMg	20–40	13	54	5	7	20	33
CRMi	40–50	13	55	6	7	19	32
CRMC	60–70	24	36	7	7	26	40

Fraction 1–0.25 mm was absent in the soil samples.

Among other pedogenetic processes shaping these soils, the accumulation and migration of mobile organic acids and relatively weak Al–Fe-humus illuviation should be mentioned. The eluvial–illuvial differentiation of the profile is inherited from the previous stages of pedogenesis. Inherited pedogenetic features have been described in some other soils of the region [21, 22]. At present, the corresponding processes do not lead to significant transformation of the soil properties.

In the iron-illuvial svetlozems developing under forest cenoses on the slopes protected from strong winds, a specific profile with distinct podzolized (E) and iron-illuvial horizons in the upper light loamy part is formed; it is underlain by the medium loamy well-structured cryometamorphic horizon. Particle-size distribution data (Table 6) do not attest to the initial lithological heterogeneity of the deposits: the sum of the fractions of fine sand and coarse silt in the upper and lower horizons is approximately the same in the upper and lower horizons. At the same time, the clay fraction is clearly differentiated: at the depth of 60–70 cm, its content is 1.3 times higher than that at the depth 20–50 cm. The illuviation of the clay fraction is seen in the development of clayey coatings in the CRMi horizon. The described soil belongs to the clay-illuvial subtype of svetlozems. In its upper part with a coarse texture, a microprofile of Al–Fe-humus podzol is developed. Texture-differentiated podzolic soils with a microprofile of podzols in the upper coarse-textured layer are known in the northern taiga zone. In the studied soils of the forest-tundra zone, the pedogenic differentiation of the soil profiles is less pronounced.

It is supposed that taiga soils in the Late Atlantic period of the Holocene extended far to the north of their modern northern boundary, up to the Barents Sea coast [7]. This is confirmed by the presence of a buried soddy-podzolic soil (6030 ± 170 BP, IGRAN-2271) 5.5 km to the north of Vorkuta [20].

According to published data [32], svetlozems are not differentiated by the clay content and by the bulk content of aluminum oxides. Our data on the bulk chemical composition of the intraped mass attest to the eluvial character of the upper part of the profile (down to 34 cm) relative to its lower part with respect to content of CaO and MgO; a less distinct differentiation is observed for R_2O_3, P_2O_5, and K_2O (Table 5).

Table 7. The values of lithochemical indices in the soil profiles

Soil	Horizon	Depth, cm	CIA*	ICV**
Basin of the Seida River				
Iron-illuvial svetlozem, 67°02′50″ [34]	E	4(5)–8(11)	91	0.91
	BF	8(11)–14(19)	93	0.84
	CRM	14(19)–33(40)	95	0.87
Cryometamorphic gleyzem, 67°02′50″ [21]	Gox-Bf	5–12	79	–
	G	15–18	78	–
	CRMg1	20–30	80	–
	CRMg2	40–50	82	–
	CRMG	60–70	83	–
Basin of the Vorkuta River				
Cryometamorphic gleyzem (virgin), 67°31′79″ [22]	B	14–46	71	0.78
	Bt	46–89	72	–
	Btc	89–137	76	0.64
	D1	137–158	79	0.55
	D2	158–170	76	0.60
Cryometamorphic gleyzem (sown meadow), 67°31′79″ [22]	B1	20–38	71	0.75
	B2	38–60	71	0.81
	B3	60–100	75	0.62
	BC1	100–140	75	0.70

* CIA is the chemical index of alteration of the parent material.
** ICV is the index of compositional variability of aluminosilicates in the parent material.

As the intraped mass is less sensitive to the aggressive impact of the soil solutions in comparison with the coatings, the differentiation of its chemical composition is probably inherited from the previous stages of pedogenesis. In the macroprofile of podzol developed in the upper layer, the E horizon is enriched in the SiO_2 and depleted of R_2O_3. In this macroprofile, the eluvial–illuvial redistribution of sesquioxides is distinctly pronounced both in the bulk soil mass and in the intraped mass. The differentiation of dithionite- and oxalate-extractable sesquioxides in the intraped mass and in the skeletans is distinct in the microprofile of podzol. This differentiation is due to the Al–Fe-humus migration; redox processes accompanied by the mobilization of iron in the E horizon and its accumulation in the BF horizon (in particular, in iron concretions) also contributes to the differentiation of sesquioxides. Oxalate-extractable aluminum is also differentiated in the soil profile (both in the intraped mass and in the skeletans) with a maximum in the BF horizon.

The inherited character of the lower heavy-textured part of the profile is illustrated by data on the lithochemical indices [25] of mineral alteration in the upper and lower parts of the profile (Table 7). In the lower horizons, the degree of mineral alteration is higher, which may be attributed to the previous stage of taiga pedogenesis. Later, the texture-differentiated soil developed under taiga vegetation was transformed by the processes of cryogenic metamorphism with the formation of a specific structure of the CRM horizon. The upper part of the soil profile is indicative of the modern redox–Al–Fe-humus podzolization described by Tonkonogov [32] in the similar soils.

In the iron-illuvial svetlozem, the maximum content of small (1.0–1.5 mm) iron concretions is observed in the BF horizon. In the deeper horizons, the content of iron concretions decreases (Table 3). The distribution of concretions in the soils depends on the regime of the soil moistening with alternation of reducing and oxidizing conditions. It also reflects the history of pedogenetic processes.

In general, our study of the structural organization of the described soils with the use of mesomorphological methods and with differentiated chemical analyses of the intraped mass and skeletans (sandy and silty coatings) made it possible to differentiate between the effects of the proper pedogenic and cryogenic processes. The eluvial–illuvial differentiation of the profiles of loamy soils in the forest-tundra zone is considered to be inherited from the previous stage of taiga pedogenesis; its results were then transformed by the active cryogenic processes.

CONCLUSIONS

(1) Podzolized podburs developing from sandy deposits in the landscapes of spotty tundra are characterized by a distinct eluvial–illuvial differentiation of sesquioxides in the soil profile. At the same time, optical density values in the oxalate extracts from the soil profile have an accumulative distribution pattern with a maximum in the uppermost horizons. A higher intensity of cryogenic processes under tundra cenoses in comparison with that under forest groves in the forest-tundra zone leads to a retardation of podzolization processes at the modern stage of the development of these soils.

(3) In the iron-illuvial podzols of tundra landscapes, the physicochemical characteristics of podzols are preserved, whereas their typical morphological features are somewhat altered under the impact of cryogenic processes. The bleached eluvial horizon has a fragmentary character, and the morphology of the soil profiles is closer to the morphology of podburs. Under forest groves, the features of podzolization are more pronounced, and the soil morphology resembles that of the podzols in the taiga zone.

(3) Organo-cryometamorphic soils developing from loamy sediments in the well-drained positions of tundra landscapes are characterized by the accumulation of mobile organic compounds and their migration in the soil profile. The Al–Fe-humus illuviation is diagnosed by the analysis of skeletans filling the main pathways of the water migration in the soil profile. The eluvial–illuvial differentiation of the profile can be judged from the analysis of intraped mass protected by

coatings from the modern leaching processes. This differentiation is inherited from the previous stages of pedogenesis. The inherited features do not change the genetic type of the soils. Their presence attests to a polygenetic origin of the cryometamorphic soils.

(4) A specific feature of iron-illuvial clay-differentiated svetlozems developing from loamy substrates under forest cenoses of the forest-tundra zone is the presence of well-structured cryometamorphic horizons in the lower part of the profile; a subprofile (microprofile) of podzol is developed in the upper part of the profile of these soils. The microprofile of podzol displays clear features of podzolization with the accumulation of SiO_2 in the intraped mass of the eluvial (E) horizon and the eluvial–illuvial redistribution of sesquioxides in the E–BF horizons. At the same time, the features attesting to the activity of redox processes with iron segregation in concretions are clearly pronounced in these soils. The middle-profile and lower horizons bear the features inherited from the previous stages of pedogenesis; the presence of clayey illuviation coatings on ped faces in these horizons attests to activity of clay illuviation processes in the past. However, the morphology of these horizons differs from the morphology of typical BT horizons because of their active cryogenic transformation with the development of a specific polyhedral structure.

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Translated by D. Konyushkov