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MINERALOGY AND MICROMORPHOLOGY OF SOILS

Mineralogical and Micromorphological Diagnostics of Pedogenesis on Intermediate and Mafic Rocks in the Northern Taiga of the Timan Range

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Abstract—Mineralogical, micromorphological, and physicochemical characteristics of soils developed on the outcrops of intermediate and mafic rocks in the central part of the Timan Range under northern taiga vegetation are discussed. These soils have been classified within the order or iron-metamorphic soils of the new Russian soil classification system and as Hyperskeletic Leptosols (Humic) in the WRB system. The in situ accumulation of nonsilicate iron compounds (ferrugination) controlled by the specific features of iron-rich parent rocks is the major process in these soils. In dependence on the composition of parent material, the direction of its modern weathering, the character of plant litter, the degree of its biological transformation, and the presence of features attesting to the mobility of silicate plasmic material, these soils are subdivided into two types: rzhavozems on colluvium of mafic rocks with some admixture of siliceous morainic fine earth and organic rzhavozems on the eluvium of mafic rocks with a predominance of specific polycrystalline aggregates of iddingsite and bowlingite (saponite) representing supergene postmagmatic pseudomorphs after pyroxenes and olivine with the initially different iron contents.

Keywords: soils on mafic rocks, Central Timan, micromorphological analysis, iron-metamorphic horizon, soil mineral weathering, soil classification

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INTRODUCTION

Specific features of pedogenesis and weathering on the eluvium (or colluvium) of intermediate and mafic magmatic rocks in the continental and moderately continental humid climate have been described for different regions of Russia [2, 10, 13, 25, 26, 28]. Russian and foreign researchers argue that the morphology and properties of these soils differ from those of the soils developed on felsic magmatic and acidic rocks [3–5, 9, 10, 13, 16, 20, 23, 24, 28, 32]. Under conditions of cold humid climate, humus- and iron-illuvial (Al–Fe-humus) soils—podburs—are formed; they are characterized by the accumulative distribution of the finely dispersed products of pedogenesis. The soils developing from mafic rocks in the mountainous taiga of East Siberia and the Far East are usually classified as different types and subtypes of burozems (brown taiga soils).

The works devoted to weathering of different magmatic rocks in the soil profile indicate that the geochemical type of weathering is largely controlled by the chemical and mineralogical composition of these rocks; in particular, the presence or absence of volcanic glass is important [2, 13, 24]. The color of upper and middle-profile soil horizons varies from yellowish brown to ocherous and reddish brown hues due to the accumulation of iron hydroxides in the course of weathering of iron-rich primary minerals. The absence of initially light-colored or capable of bleaching in the course of weathering minerals (quartz and K–Na feldspars) in the mafic rocks and the abundance of iron and aluminum hydroxides released from the primary minerals retard the development of bleached (podzolized) horizons in the upper part of the soil profile [24–26].

The analysis of relatively scarce data on northern taiga soils developed on local outcrops of mafic rocks [21, 22] indicates elementary pedogenic processes in the soils forming on paleotypal (altered by postmagmatic processes) effusive mafic rocks differ from those in the soils formic on cenotypal effusive mafic rocks. Thus, Sedov et al. [22] studied the soils on mafic rocks of the Valaam Island and demonstrated that the prepedogenic alteration of crystalline rocks results in the formation of considerable amounts of phyllosilicates changing the initial mineralogical composition of the rock. As a result, the Al–Fe-humus pedogenesis is often replaced by the metamorphic pedogenesis with the development of different types and subtypes of burozems. According to Sedov [21], the processes of argillization and ferrugination (accumulation of nonsilicate iron in the course of alteration of phyllosilicates) play the major role in the development of mineral horizons of soils on the paleotypal mafic rocks of the Valaam Island, whereas the processes of Al–Fe-humus migration are less pronounced.

In the European part of Russia, analogous soils have also been described in the northern taiga landscapes on bedrock outcrops denuded by glacier (selga landscapes) of Karelia [14–16].

The Timan Range is another place in European Russia with the outcrops of mafic rocks in the taiga zone. The morphology of soils developing from the eluvium and colluvium of these rocks has been described in a few works [9, 11]. The Timan Range represents a system of several strongly denuded and partially leveled ridges extending from the northwest to the southeast for more than 800 km. It is subdivided into the southern, central, and northern parts. We studied soils in the central part of the Timan Range, where small areas of intermediate and mafic magmatic rocks outcrop to the surface against the background of siliceous metamorphic rocks. Thus, the soils on mafic rocks have relatively small areas separated in space [1]. The morphological and physicochemical characteristics of these soils were only published in the work by Goryachkin and Makeev [9]. Data on the mineralogical composition of sand fractions and micromorphological features of these soils were not presented. In our study, we attempted to specify the genesis of these soils and characterize elementary pedogenetic processes acting in them taking into account new mineralogical and micromorphological data. Detailed macro- and micromorphological analysis of these soils is particularly important in the context of the environmental protection and monitoring of the state of soil and land resources in the area of the adjacent central Timan deposit of bauxite. Its open-pit mining is (more than 35 million tons of bauxite have been extracted since 2002) is accompanied by the destruction of soils and vegetation on considerable areas, so that the proper environmental and soil monitoring is necessary.

We studied the mineralogical and micromorphological specificities of automorphic taiga soils developing from intermediate and mafic magmatic rocks and their derivatives, including those with some admixture of the silicic morainic material.

OBJECTS AND METHODS

Three key profiles characterizing soils of autonomous positions in the northern taiga subzone were examined (Fig. 1). According to a geobotanic zoning, the studied area belongs to the Central Timan district of the Vychegda–Pechora subprovince of the European taiga province [8]. Spruce and spruce–birch forests with a considerable admixture of larch (*Larix sibirica*) trees predominate. The height of mature stands reaches 20–25 m, and the diameter of tree trunks is up to 30–40 (60) cm. Ridged hilly and slightly ridged topography is typical of the interfluves and upper parts of valley south of the studied area), the climate is characterized by the mean annual temperature of −1.5°C, mean January temperature of −18°C, and mean July temperature of +15°C. Annual precipitation is about 600 mm; the period with stable snow cover lasts for 198 days [1].

Designations of soil horizons and soil names in this study are made according to the *Field Guide for Identification of Russian Soils* [19]. The color of soil horizons (for the samples in the air-dry state) was determined using the Munsell color charts [33]. Field descriptions of soil profiles and soil sampling for the micromorphological analysis were performed under the supervision of V.D. Tonkonogov. Physicochemical analyses of the samples were performed according to standard procedures [7]. The bulk elemental composition of the soils was determined by the X-ray fluorescence method. Particle-size distribution analysis was performed according to Kachinskii with the soil pretreatment via boiling with NaOH.

Optical identification of minerals was performed in thin sections from the undisturbed soil and rock samples from the major genetic horizons. We also studied the coarse sand fraction using the immersion method. Thin sections were prepared by M.A. Lebedev. Their micromorphological description under an Olympus BX51 microscope with a digital camera Olympus DP26 was made in agreement with the international guidelines [34] in the Laboratory of Mineralogy and Micromorphology of Soils of the V.V. Dokuchaev Soil Science Institute. In addition, separate grains were analyzed under a scanning electron microscope JEOL 6610 LV with an energy-dispersing microanalyzer INCA Xact (Oxford Instruments) in the Laboratory of Radiocarbon Dating and Electron Microscope of the Institute of Geography of the Russian Academy of Sciences.

RESULTS AND DISCUSSION

Macro- and micromorphological features of the major genetic horizons of the studied pits are briefly described below (Fig. 2).

Pit 1-Zh (64°50′ N, 51°26′ E) was excavated on the top of local rocky cliff on the right bank of the Pechorskaya Pizhma River at 141 m a.s.l. under the larch–pine forest with lingonberry–green moss ground cover. Pine trees (*Pinus sylvestris*) predominate in the young growth; the shrub layer is composed by juniper (*Juniperus communis*). Dwarf shrubs are represented

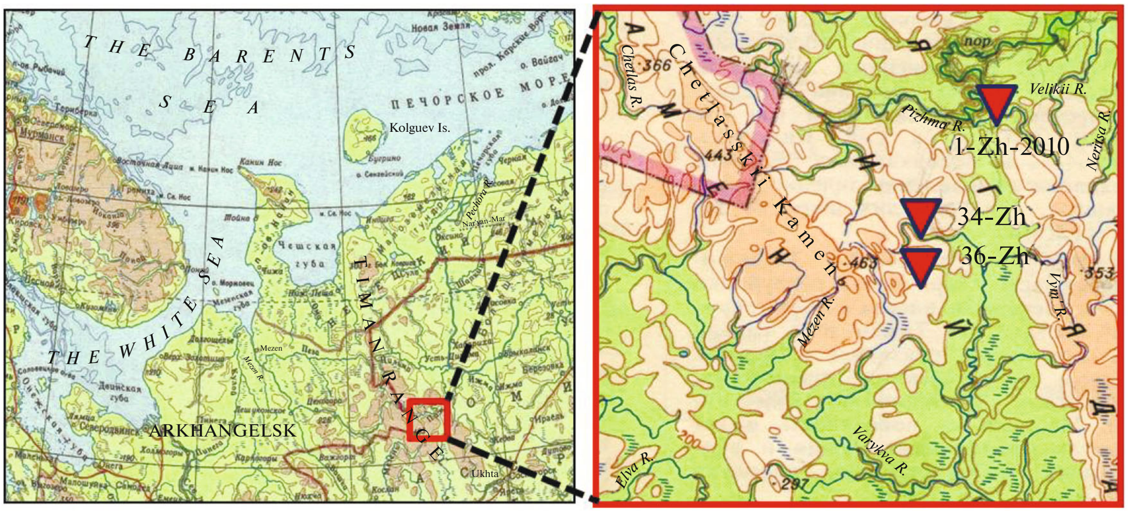


Fig. 1. Schematic map of the location of studied area and soil pits.

by lingonberry (*Vaccinium vitis-idaea*) and blueberry; green mosses are represented by red-stemmed feather-moss (*Pleurozium schreberi*).

Oao, 0–5(6) cm. Dark brown-gray weakly decomposed peaty litter with needles, twigs, and cones on the surface. In the lower part, the litter of dark gray color is densely penetrated by the roots of shrubs and contains an admixture of mineral grains.

BFM1, 5(6)–15 cm. Reddish brown (5YR 5/4 to 2.5 YR 4/6) loamy sand; slightly dry, relatively loose, structureless or with slightly developed fine crumb (powdery) structure; abundant tree roots of 3–10 mm in diameter; contains the inclusions of small pebbles (1–2 cm) of hard rock; diffuse boundary.

In the thin section from this horizon, specific angular spherical fragments of 0.5–1.0 (2.0) mm in diameter are present. Most of them have bright yellow or yellow-red color and distinct microzonality (Figs. 2a and 2b), which is typical of iddingsite minerals (according to [30]). There are also rock debris of yellowish green color (Figs. 2c and 2d) that were preliminarily identified as debris of bowlingite (according to [30]). Roots remains of different degrees of decomposition are present in the horizon. Some pores are filled with bleached silty material (silty infillings [34]).

BFM2, 15–25 cm. This horizon is somewhat lighter in color (5YR 5/6); it is composed of loamy sandy fine earth and contains abundant (up to 30–40%) inclusions of fine and medium-size gravels (up to 2–3 cm). Small gravels are strongly weathered and can be crushed by hand into fine earth mass of the yellow–ocherous color. The transition to the underlying horizon is seen from a sharp increase in the pebble content.

In thin sections, the abundance of yellowish red rock debris of irregular shape with the modal size of 1–2 mm is clearly seen. Larger debris (1–2 mm) consist of smaller (0.1–1 mm) fragments. Some of them look like crystalline “roses.” The amount of silty infillings increases in comparison with that in the overlying horizon, which attests to the development of illuviation of silt particles (partluvation) in the upper part of the profile. At the same time, these infillings are often fragmented to the size of fine sand particles (Fig. 2b).

BC, 25–30 cm. Dull brown (7.5YR 5/4) structureless loamy sand with the high (>50%) content of pebbles of different sizes (5–10 mm to 4–5 cm); fine earth materials fills spaces between the pebbles. The surface of pebbles is not covered by films. Few fine roots of trees. Small gravels (2–5 mm) are weathered and can by crushed by hand. The transition is seen from the increase in the content and size of pebbles.

In thin sections, the specific debris (1–2 mm) consisting of smaller “rose-shaped” crystals described above predominate. Silty infillings are absent in this horizon.

C, 30–40 cm. Dull brown (7.5YR 5/4); pebbles and rock fragments predominate over fine earth; the modal size of pebbles is 3–5 cm; these pebbles can be cut by knife. At the depth of more than 40 cm, strongly fissured bedrock is found; the content of fine earth is no more than 5–10%. Large monolithic (without fissures) rock fragments represent olivine dolerite with features of postmagmatic alteration: plagioclase grains were subjected to intense sericitic and saussuritic alteration.

This soil was classified as a raw-humus organic rzhavozem [19] or as a Hyperskeletic Leptosol [31].

Pit 34-Zh (64°19′ N, 51°08′ E) was studied in the southeastern part of the Chetlasskii Kamen massif in the central Timan, on the upper part of a gentle (3°–5°) slope of western aspect at 290m a.s.l. under spruce forest with an admixture of larch and single birch trees. Blueberry (*Vaccinium myrtillus*) and lingonberry (*Vac-*

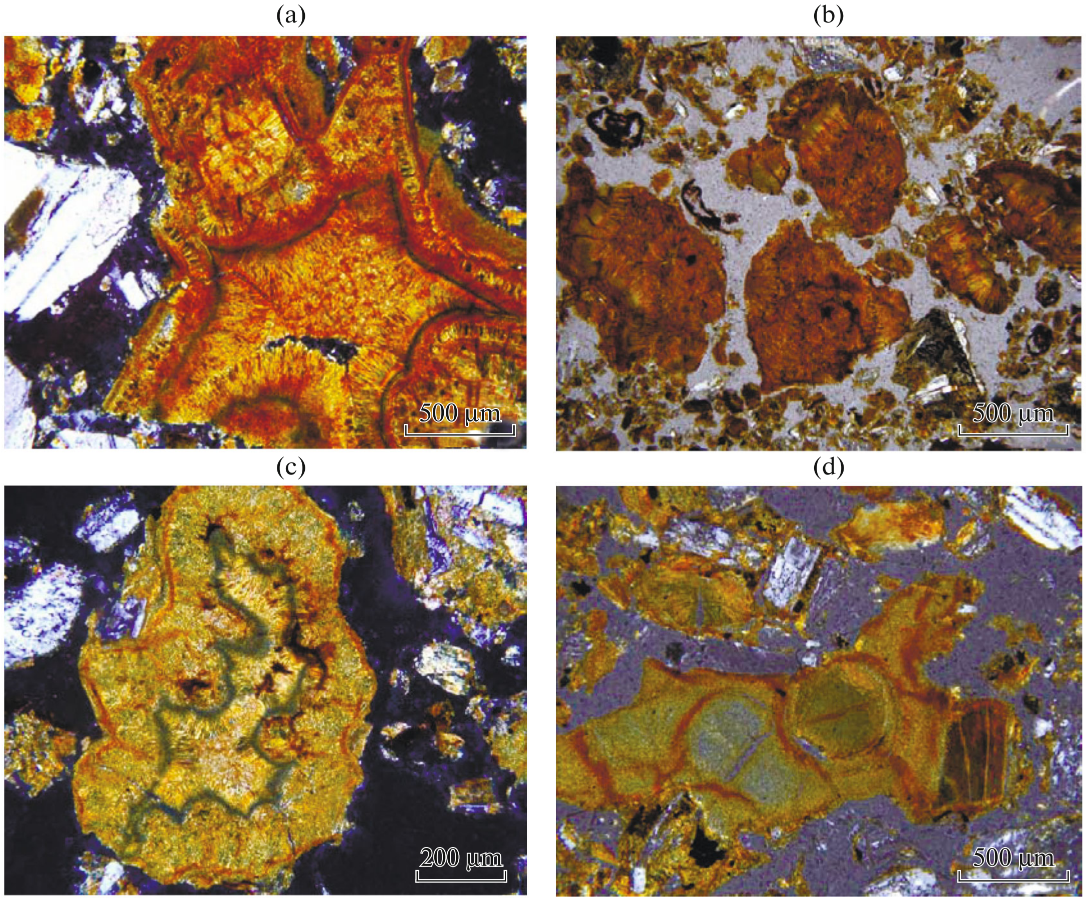


Fig. 2. Microfabrics of polymineral clayey aggregates of organic rzhavozem (pit 1-Zh, BFM1 horizon) differing in their optical characteristics: (a) slightly altered fragment of iddingsite (XPL), (b) fragments of iddingsite differing in size and iron content among clods of plasmic material (PPL), (c) large aggregate of bowlingite with local ferrugination, and (d) fragmentation of bowlingite and iron depletion from central zones of its fragments (X N).

cinium vitis-idaea) predominated in the dwarf shrub layer. Boreal herbs—maianthemum (*Maianthemum bifolium*), wood cranesbill (*Geranium sylvaticum*), starflower (*Trientaliseuropaea*), fern (*Gymnocarpium dryopteris*), aconite (*Aconitum septentrionale*), and various grasses (*Gramineae*).The moss cover is slightly developed and is represented by sparse patches of green mosses (*Pleurozium schreberi*).

O, 0–5 cm. Brown (5YR 4/2-5/2) loose weakly decomposed litter consisting of the remains of herbs with fresh needle and leave litter on the surface. Clear uneven boundary.

AY, 5–10 cm. Brownish dark gray (10YR 4/3–5/3; 4/2) silt loam; fine crumb structure, relatively loose. Abundant roots of dwarf shrubs and trees of 4–8 mm in diameter. Distinct transition is seen from changes in the color.

In thin sections, the soil mass has a yellowish gray color; it is microaggregated into round aggregates of 0.5–1.5 mm in size (Figs. 3a and 3b). The organic material is represented by fresh and weakly decomposed roots and by brownish gray microforms of humus impregnating the soil mass. Large pores contain silty infillings ruptured in some loci (Fig. 3d). Fissured sericitic debris of plagioclases and pyroxenes are seen in the soil mass.

BFM1, 10–20 cm. Grayish brown (10YR 4/4) to brown (10YR 5/6–6/6) silt loam with indistinct fine crumb structure; slightly compacted; contains the inclusions of charcoal; roots are less abundant. Small (2–3 cm) altered doleritic pebbles are present; some of them can be crushed by hand. The transition is seen from changes in the color of fine earth and from an increase in the amount of bedrock detritus.

In thin sections, the mass of fine earth is unevenly colored with yellowish gray and yellowish brown microzones; rounded and angular-rounded microaggregates are clearly seen. Fresh and ruptured plant remains preserving their cellular structure and ferruginated plant tissues are present; there are also small iron concentrations of 0.2–1 mm in size. The skeletal part consists of the altered and fissured grains of plagioclases and pyroxenes and of black opaque ore minerals (titanomagnetite) of irregular shape. Ruptured silty infillings are seen is the pores, which attests to the illuviation of fine silt material from the upper horizons.

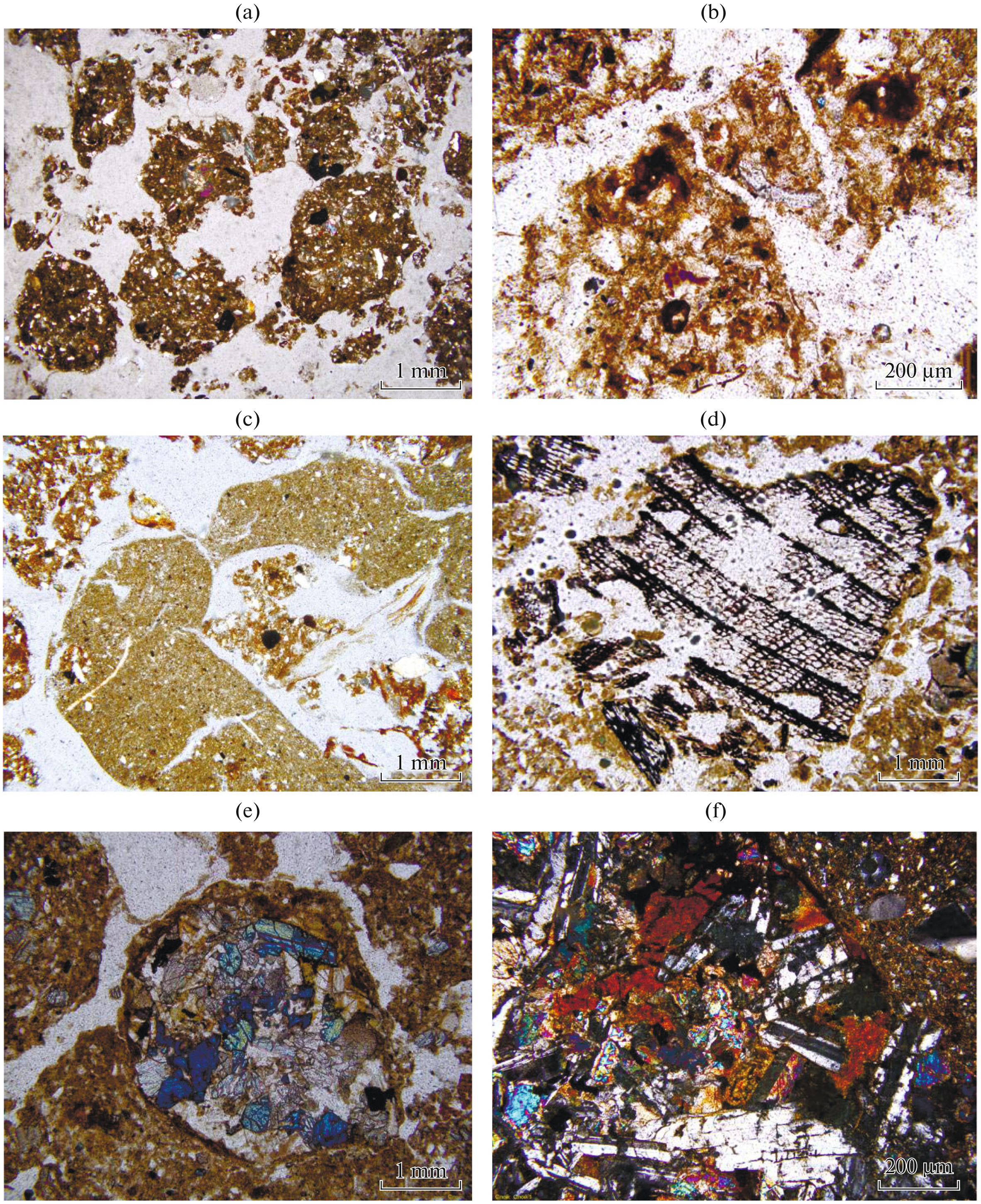
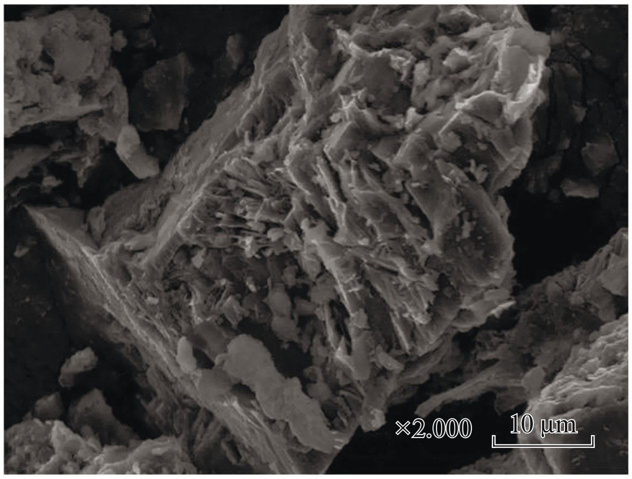


Fig. 3. Microfabrics of genetic horizons of rzhavozems (PPL): (a) rounded microaggregates (coprolites), AY horizon, pit 34-Zh; (b) rounded aggregates with humus–iron nodules, AY horizon, pit 34-Zh; (c) fine silty biogenic infillings, AY horizon, pit 34-Zh; (d) coarse coalified tissues with cellular structure, AY horizon, pit 36-Zh; (e) and (f) slightly altered minerals in fragments of dolerite with in situ silty–clay–iron films (BFM horizon, pit 36-Zh ((e) PPL, (f) XPL).

BFM2, 20–30 cm. Yellowish brown (10YR 6/6–6/8) light loam with unstable crumb structure; at the contact with the underlying bedrock, fine earth material acquires reddish brown color. Abundant rock fragments of 10–15 cm in size and small (1–2 cm) angular debris of hard bedrock are present. Some of small weathered pebbles can be crushed by hand. The surface of pebbles is covered by the brown films (<1 mm)

(a)



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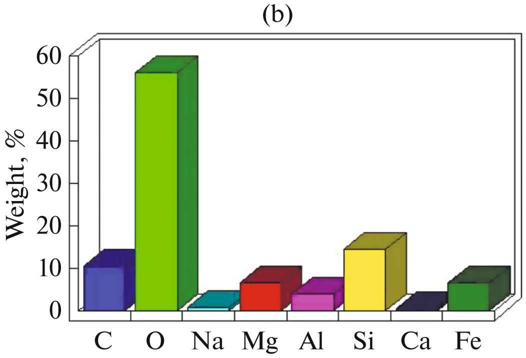

Fig. 4. Packing of clay minerals in the aggregate of iddingsite (a) and its elemental composition (b).

of weathering. Rock chips are dark-colored; under the films of weathering, a thin zone of increased fissuring of the rock is seen. The walls of the fissures are marked by bright brown concentrations of iron hydroxides. Fine earth material constitutes about 20–30% of the mass of the horizon and is allocated to spaces between coarse rock fragments and to the silty clay coatings (silt caps) on the upper sides of pebbles. The content and size of rock fragments sharply increase from the depth of 36–40 cm. Most of rock fragments have a horizontal orientation, though some small rock fragments are oriented in the vertical direction.

In thin sections, the soil material has an even yellowish brown color. Angular and angular–rounded microaggregates of 0.5 to 1–2 mm in size are characterized by the tight packing of fine-earth material. Mineral grains of plagioclases, pyroxenes, and olivine with different degrees of alteration are seen in the soil mass. Fissured angular quartz grains are also present in small amounts. Some fragments of dolerite bedrock are covered by thin ocherous weathering films.

BC, 30–50 cm. Coarse (15–20 to 30 cm) angular rock fragments; spaces between them are filled by the silt loamy fine earth (about 10% of the mass of the horizon). Bedrock fragments are weakly touched by weathering processes; weathering films on their surface are very thin or absent. Strongly fissured bedrock with the minimum content of fine earth underlies the soil profile from the depth of 48–50 cm.

Tis soil was classified as a raw-humus rzhavozem [19] or as a Hyperskeletic Leptosol [31].

Pit 36-Zh (64°20′ N, 51°09′ E) was also studied in the southeastern part of the Chetlasskii Kamen massif in the central Timan, on the upper part of a slope (5°–7°) of southwestern aspect at 294 m a.s.l. under spruce forest with an admixture of larch. Boreal herbs—wood geranium (*Geranium sylvaticum*), starflower (*Trientaliseuropaea*), fern (*Gymnocarpium dryopteris*), and aconite (*Aconitum septentrionale*)—predominate in the ground cover. Green mosses (*Pleurozium schreberi*) are found in small patches. The soil described in this pit was classified as a raw-humus rzhavozem [19] or as a Hyperskeletic Leptosol [31].

Its morphological and micromorphological features are generally similar to those described in pit 34-Zh. In this context, a detailed description of this pit is not presented.

The study of thin sections prepared from large rock fragments sampled in the studied soils attests to the predominance of mafic and intermediate rocks of different geneses, including olivine dolerite (pit 1-Zh) and lava breccia and volcanic tuff (pits 34-Zh and 36-Zh) with relict inclusions of the ophitic and microporphyric textures. Plagioclases predominate in the rocks (50%) and are represented by andesine (An40–45) in the form of platy crystals of up to 0.2 mm in thickness and phenocrystals of 1–1.2 mm in size. The grains (0.05–0.1 mm) of monocline pyroxene constitute about 30% of the rock mass. Magnetite (about 10%) is present in the form of well-shaped crystals of 0.5–0.7 mm in size. The predominant size of mineral grains in olivine dolerite is from 0.2 to 1.2 mm. The weathering of such rock yields coarse-textured (loamy sand) fine earth material. It is important that olivine dolerite found in pit 1-Zh displays clear features of its postmagmatic alteration. Some of the initial grains of plagioclases were completely replaced by these pseudomorphs. The grains of pyroxenes and olivine were partially replaced by magnetite and/or by fine-scale light green or yellow-brown phyllosilicates with pleochroism.

The analysis of particle-size distribution data attests to certain differences in the fine earth material of the studied pits. Thus, fine earth in pit 1-Zh is characterized by the sandy or loamy sandy texture, whereas fine earth in pits 34-Zh and 36-Zh has the silt loamy or clay loamy texture with a predominance of the coarse silt fraction and a relatively high content of the clay (<0.001 mm) fraction (Table 1).

The analysis of mineralogical composition of sand fractions from the studied soils also attests to significant differences between them. The soils in pits 34-Zh

Table 1. Particle-size distribution in rzhavozems

Horizon	Depth, cm	Loss on HCl treatment, %	Fraction content, %; particle size, mm						Sum of particles <0.01 mm
			1.0–0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	
Pit 1-Zh, organic rzhavozem									
BFM1	6–15	3.39	5	56	20	5	5	9	19
BFM2	15–25	2.14	4	60	20	3	3	10	16
BC	25–30	2.84	10	64	17	1	1	7	9
C	30–40	3.00	9	62	14	2	4	9	15
Pit 34-Zh, rzhavozem									
AY	5–10	1.02	19	22	22	7	10	20	37
BFM1	10–20	1.60	15	21	29	7	11	17	35
BFM2	20–30	1.90	32	23	25	1	10	9	19
BC	30–50	1.58	12	14	39	10	12	13	35
Pit 36-Zh, rzhavozem									
AY	4–10	1.20	30	13	29	5	11	12	28
BFM1	10–20	0.82	17	11	34	6	14	18	38
BFM2	20–30	0.85	18	10	30	8	12	22	42
BC	30–50	0.93	13	14	27	7	12	27	46
C	50–60	1.57	10	15	32	7	8	28	43

and 36-Zh contain maximum amounts of the admixture of allochthonous glacial till material of more acidic composition. In particular, their sand fractions contain significant amounts of quartz grains that absent in mafic rocks.

At the same time, no significant differentiation of the soil profiles has been diagnosed. In the lightweight fraction of organic rzhavozem, specific rock debris were found in the fine sand fraction. These debris represented clayey aggregates, whose diagnostics required additional microscopic studies.

According to their optical properties, these aggregates were attributed to two types of polycrystalline clay formations: iddingsite (Figs. 2a and 2b) and bowlingite (Figs. 2c and 2d). As shown in several studies, iddingsite and bowlingite represent oriented aggregates of trioctahedral iron–magnesium smectites replacing pyroxenes and olivine in mafic rocks in the course of their hydrothermal alteration [10, 21, 30]. Though iddingsite is a fully crystalline rock, it appears as a homogeneous substance under the microscope, which is explained by the even orientation of the minerals “inheriting the oxygen carcass of the initial olivine” [30, p. 54].

In the soil of pit 1-Zh, iddingsite in thin sections is present as a brightly colored reddish brown substance of the scaly–fibrous structure with pleochroism (from dark brown to yellow color) and with a relatively high birefringence (about 0.050) (Figs. 2a and 2b). The debris of bowlingite in thin sections have greenish tints in their color; their optical relief is low or medium, and their birefringence (about 0.025) is lower than that of iddingsite (Figs. 2c and 2d).

Bowlingite and iddingsite are fully crystalline substances consisting of the mixture of smectite and chlorite with some admixture of micas and quartz. However, they differ from one another in their chemical compositions. Bowlingite is characterized by the higher contents of aluminum and magnesium and by the lower content of iron. It is known that iddingsite usually forms pseudomorphs over iron-rich olivines and pyroxenes, whereas bowlingite develops over pyroxenes and olivines with a lower iron content in effusive mafic [30].

Electron microscopy with the use of a microanalyzer proved that aggregates of iddingsite are polycrystalline (according to [30]) substances representing the packs of thin sheets (scales) with honeycomb structure (Fig. 4a). The X-ray microanalysis of iddingsite proved that these sheets consist of predominant silicon, magnesium, and iron with small amounts of sodium and calcium (Fig. 4b).

The analysis of the state of these polymineral aggregates in different horizons of pit Zh-1 demonstrated their fragmentation to finer debris in the upper and middle-profile horizons, which may be due to the physical comminution under the impact of cryogenic processes in the cold season (fall–winter) [1]. The presence of angular and strongly fissured quartz grains in pits 34-Zh and 36-Zh also attests to the activity of cryogenic processes in the studied soils.

The soils studied in pits 34-Zh and 36-Zh are formed on the highest parts of the interfluves in the central Timan. They are developed from the intermediate to mafic rocks and are characterized by the presence of the gray-humus (AY) horizon. At the microlevel, this horizon is specified by the microaggregation of the humus–iron–clayey plasma into granular microaggregates with the high interaggregate porosity (Fig. 3a). Crumb aggregates in this horizon may be attributed to coprolites attesting to the activity of soil micro- and mesofauna. Thick fine silty infillings attest to the mobility of fine silt fractions and their illuviation (partluvation) in the profile (Fig. 3c). The AY horizon is characterized by relatively high contents of the humus–iron–clayey plasma and plant residues of different degrees of decomposition.

The middle-profile iron-metamorphic (BFM) horizons in both of these soils are characterized by the presence of abundant strongly weathered and fissured fragments of dolerite with preserved grains of plagioclases. The surface of these half-rounded rock debris is covered by silty–clay–iron coatings from the enclosing material, which does not attest to the active interhorizon migration of iron (Figs. 3e and 3f).

The obtained mineralogical and micromorphological characteristics of these soils allow us to gain better insight into their physicochemical properties that have been partly described in earlier studies [9].

The studied soils on the intermediate and mafic rocks are characterized by the high organic matter content in the upper horizons. Micromorphological characteristics of this organic matter attest to its raw-humus nature in the organic rzhavozem (the more type of humus) with minimal indications of the biogenic transformation of plant residues and to its mull–moder nature in typical rzhavozem, in which various forms of plant remains and coprolites are present (Figs. 3a and 3d). The loss on ignition in the litter horizon of organic rzhavozem (pit 1-Zh) reaches 60–80%. According to the content and properties of humus, the studied rzhavozems belong to high-humus soils (in agreement with the criteria suggested by Orlov and Grishina [17]): the humus content in the AY and BFM horizons reaches 10–12% and 4–6%, respectively. The distribution of humus has an accumulative pattern. Humic substances impregnate the entire mineral part of the soils (Table 2), which has been confirmed by the micromorphological analysis. In the strongly gravelly and stony lower horizons, the humus content reaches 1–1.5%. The presence of significant amounts of humus in the entire profile is explained by the shallow thickness of the soil underlain by the hard bedrock.

Organic rzhavozems and rzhavozems are characterized by the acid reaction; the degree of acidity decreases downward through the soil profiles. A somewhat lower actual acidity in the litter of pits 34-Zh and 36-Zh is explained by a higher content of the residues of herbs enriched in ash elements in comparison with that in pit 1-Zh. In the mineral part of the soils, the gray-humus AY horizon is characterized by the increased values of all the forms of acidity. In the lower part of pit 36-Zh (C horizon, 50–60 cm), a sharp rise in pH values is observed, which may be due to the presence of an admixture of calcareous moraine. The maximum values of hydrolytic (total) acidity—(43–54 cmol(+)/kg soil)—are in the litter horizons. In the mineral horizons, the hydrolytic acidity gradually decreases downward through the soil profile.

The content of exchangeable bases constitutes 10–15 cmol(+)/kg soil in the upper horizons and increases to 22 cmol(+)/kg soil in the BC horizon. The degree of base saturation is about 50–60%; it increases up to 75% in the lowermost horizon, which may be related to the high content of specific polycrystalline aggregates consisting of bowlingite and iddingsite. The analysis of analogous formations in the soils of the Valaam Island [4] proved the presence of smectite in them [4].

The contents of oxalate- and dithionite-extractable iron compounds in the studied soils (pits 1-Zh, 34-Zh, and 36-Zh) are characterized by the accumulative distribution patterns with the maximum (2.2–2.8%) in the upper horizons, where the maximum accumulation of humus is also observed (Table 2). We failed to fine clear micromorphological indications of the interhorizon migration of iron–humus compounds in the studied soils. Most probably, iron coatings on pebbles in the BFM and BC horizons were formed in situ.

Among the studied soils, the chemical composition of fine earth in the organic rzhavozem (pit 1-Zh) differs from that in typical rzhavozems of pits 34-Zh and 36-Zh. In pit 1-Zh, it is close to the chemical composition of dolerite. We conclude that the this soil does not contain significant admixtures of allochthonous felsic material. It was developed from the ancient eluvium of dolerite, for which the increase content of dark-colored minerals is typical. This is reflected in the bulk elemental composition of the soil, i.e., in the increased contents of iron, aluminum, calcium, and sodium and in the decreased content of silicon. Rzhavozems described in pits 34-Zh and 36-Zh were developed from the eluvium–colluvium of volcanic tuff with the admixture of allochthonous felsic material of glacial till. In pit 36-Zh, this heavy loamy material also contained the admixture of calcareous moraine in the deep horizons. It is characterized by the increased content of silicon owing to the presence of significant amounts of silt- and sand-size grains of quartz and plagioclases.

Thus, a comparative assessment of elementary pedogenetic processes in the studied soils indicates that the development of soil profiles in the substrates differing in their mineralogical and petrographic compositions (paleotypal and cenotypal rocks) is specified by the two major horizon-forming processes: (1) income/transformation of organic matter and (2) in situ iron metamorphism (ferrugination) of the

Table 2. Physicochemical properties and bulk elemental composition of rzhavozems

Horizon	Depth, cm	pH		Ac_{tot}, cmol(+)/kg	V	Humus	Bulk contents, %					Fe_2O_3, (Mehra–Jackson), %	Tamm's extraction, %	
		H_2O	KCl		%		SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO		Fe_2O_3	Al_2O_3
Pit 1-Zh, organic rzhavozem														
O	0–6	6.25	4.95	19.50	73	35.4*	–	–	–	–	–	–	–	–
BFM1	6–15	6.42	4.61	3.48	92	1.31	56.4	12.22	15.71	6.63	2.63	2.28	1.91	0.74
BFM2	15–25	6.47	4.30	3.96	92	1.22	57.4	11.79	16.28	6.43	2.60	1.88	2.23	0.80
BC	25–30	6.73	4.55	3.40	93	0.75	56.1	13.76	15.39	7.05	2.34	1.87	2.33	0.84
C	30–40	6.55	4.36	4.05	91	0.74	57.3	12.29	15.92	6.11	2.69	2.23	2.14	0.79
Dolerite	–	–	–	–	–	–	58.9	11.06	16.38	5.03	4.71	0.56	1.66	0.66
Pit 34-Zh, rzhavozem														
O	0–5	5.60	4.81	54.14	46	56.1*	–	–	–	–	–	–	–	–
AY	5–10	4.87	3.82	17.30	56	9.86	64.03	11.60	16.32	2.58	1.63	2.87	1.98	1.16
BFM1	10–20	5.23	4.04	12.80	63	6.07	63.95	10.55	17.35	2.88	1.88	2.97	1.68	1.81
BFM2	20–30	5.52	4.21	10.80	71	1.63	62.67	9.90	19.61	2.77	1.90	2.35	1.18	2.52
C	30–50	5.61	4.11	8.11	75	1.08	65.69	8.46	17.51	3.20	2,07	1.53	0.84	1.01
Dolerite	–	–	–	–	–	–	56.51	9.69	17.74	8.61	3.52	0.47	0.52	0.31
Pit 36-Zh, rzhavozem														
O	0–4	5.93	5.17	23.9	–	48.4*	–	–	–	–	–	–	–	–
AY	4–10	5.24	4.18	10.5	–	9.18	69.54	5.37	14.04	1.12	1.79	–	–	–
BFM1	10–20	5.47	4.09	9.23	–	2.72	69.22	6.40	13.50	1.17	1.98	–	–	–
BFM2	20–30	5.60	4.20	7.92	–	2.34	66.27	7.78	14.01	1.42	2.09	–	–	–
BC	30–50	5.73	4.25	6.53	–	1.31	65.96	8.18	14.68	1.48	2.22	–	–	–
C	50–60	7.44	6.60	0.78	–	1.29	69.30	6.49	13.27	2.36	2.20	–	–	–
Dolerite	–	–	–	–	–	–	55.45	7.54	15.81	8.21	2.85	–	–	–

Ac_{tot} is the total (hydrolytic) acidity, V is the base saturation, * is the loss on ignition, and dashes stand for "not determined."

Table 3. Comparative assessment of elementary pedogenetic processes in the studied soils

Elementary pedogenetic process	Organic rzhavozem		Rzhavozems	
	Pit 1-Zh		Pits 34-Zh and 36-Zh	
	macro- and microfeatures	degree of manifestation	macro- and microfeatures	degree of manifestation
Metamorphism (in situ transformation) of organic matter				
Input and transformation of plant residues	Raw-humus and peaty horizons Raw humus of the mor type without indication of the biogenic processing of plant litter Predominance of coalified root residues	+ *	Raw-humus and gray-humus horizons. Humus of the mull–moder type; the presence of coprolites Root residues of different degrees of decomposition; coarse coalified tissues	+++
Migration of humus–silty particles (partluvation)	Grayish light yellow humus–fine silty infillings of different sizes (up to the sand size)	++	Light gray humus–silty thick slightly fissured infillings	+++
Organic matter	Organic matter in the form of separate cells slightly bound with the clay matter	+	Disperse and impregnating forms of humus of the brownish gray color	++
Metamorphism of mineral matter				
Disintegration	Small gravels are easily crushed by hand Fragmentation of iddingsite and bowlingite to sand-size particles	++	Small gravels can be crushed by hand. Fissured sericitic debris of plagioclases and pyroxenes predominate; fissured quartz grains are also present	+
Metamorphic ferrugination	Reddish brown color (2.5YR 4/6) of fine earth; Predominance of bright yellow and yellow-red fragments of iddingsite and bowlingite	+++	Brown and yellowish brown color (10YR 6/6; 6/8) of fine earth and coatings on pebbles and skeletal grains; Impregnation of the soil mass with iron hydroxides and numerous fine iron nodules	+++
Soil structuring				
Formation of organomineral aggregates	Small aggregates—fragments of infillings	+	Angular-rounded aggregates with not sharp boundaries and coprolites	++

* Expert evaluation of the degree of manifestation of particular features: (+) weak, (++) moderate, and (+++) strong (characteristic feature).

mineral soil mass. (Table 3). Other elementary pedogenetic processes (disintegration, partluvation, and aggregation) are moderately and weakly manifested in the studied soil profiles.

CONCLUSIONS

In the northern taiga subzone of the Timan Range, two types of soils with brown nonpodzolized profile have been described on the eluvium and eluvium–colluvium of intermediate and mafic magmatic rocks. According to the new Russian soil classification system [19], they can be attributed to rzhavozems and organic rzhavozems in the order of iron-metamorphic soils. They are characterized by similar diagnostic middle-profile (BFM) and lower horizons. The differences between these soils are manifested in the upper horizons. In rzhavozems, a gray-humus AY horizon is formed; in organic rzhavozems, this horizon is absent. This may be due to differences in the character of plant cover, plant litter decomposition, and biogenic processing of organic materials coupled with differences in the amount of allochthonous silty and clayey material.

The conducted mineralogical and micromorphological studies demonstrated certain differences in the mineralogical compositions of separate particle-size fractions attesting to differences in the genesis of parent materials. In turn, these differences are reflected in the physicochemical properties of the studied soils. In the case of soil development from the parent material with a considerable admixture of allochthonous fine-dispersed material to the coarse-textured gravelly eluvium of mafic rocks (without their considerable alteration in the form of pseudomorphs over olivine and pyroxenes), the gray-humus horizon is formed in rzhavozems (pits 34-Zh and 36-Zh). Its development is favored by active transformation of the litter of herbs by the soil meso- and microfauna and pronounced fixation of forming humic substances in the fine earth of heavier texture. These rzhavozems of well-drained soils, in which partluvation—illuviation of fine silt particles with the formation of silty infillings—is developed. Some of these infillings are then transformed by the soil biota. Small iron nodules inside unstable crumb aggregates with the clay–humus–iron composition of plasmic material attest to some intra-horizon migration of iron in the rzhavozems.

Organic rzhavozem (pit 1-Zh) is developed from the ancient weathering crust of olivine dolerites. The aggregates in this soil are smaller, which is related to the abundance of specific polycrystalline substances—iddingsite and bowlingite debris consisting of smectitic clay and silicate minerals—in the coarse particle-size fractions. Such debris represent specific "clayey aggregates." At the microlevel, they are strongly fractured into sand-size particles under the impact of physicochemical and cryogenic disintegration. As a result, this soil has a low content of the fine silt and clay fractions and has a low capacity for binding the products of decomposition of plant residues in the mineral mass. Thus, the gray-humus horizon is not pronounced, and the litter horizon is immediately underlain by the BMF horizon.

The major horizon-forming pedogenetic process in the studied soils is the in situ ferrugination—the release of iron from the preprocessed mineralogical matrix of the iron-rich mafic rocks and the accumulation of nonsilicate iron compounds in the BMF horizon. Thus, the studied soils belong to the order of iron-metamorphic soils in the Russian soil classification system.

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