Structural organization and composition peculiarities of soil neoformations in some types of automorphic soils in the south-east of the Bolshezemelskaya tundra

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Abstract. Automorphic tundra soils of different gleying degree and various permafrost table depth were studied. The chemical composition and distribution of different structural components, including skeletans (sandy-silty cutans), clay cutans, and Fe-Mn concretions in Dystric Cambisol and Turbic Cryosol profiles (permafrost table occurs 2–5 m and 0.9 m depth) were investigated. It is shown that the upper part of the profile of Dystric Cambisol forms under the current active processes of pedogenesis (gleying, Al-Fe-humus illuviation, specific cryogenic organization), signs of previous stages of soil genesis are preserved (the presence of humus pedorelicts, fragments of clay deposits) in the lower part. The chemical composition of the intraped mass reflects the eluvial-illuvial differentiation of Dystric Cambisol profile. The maximum amount of Fe-Mn concretions is observed in the middle profile part. This is due to redox processes in this type of soil. Turbic Cryosols is characterized by insignificant profile differentiation of structural components by chemical composition, weak intensity of pedogenic processes, cryoturbations, inherited signs of earlier stages of pedogenesis (fragments of clay cutans, humus pedorelicts) in the lower horizons. Gleying is one of the leading soil-forming processes. Cryogenic transformation of the soil layer affects the distribution of small amount of skeletans and concretions.

1. Introduction

Arctic and Subarctic soils and specific features of their formation induce specific interest of researchers. It is caused by the need in assessment of the environmental consequences of both climate change at the global and regional levels, and the increasing rates of human impact. Features of soil morphology, chemical composition and soil profile distribution of different neoformations play an important diagnostic role in soil research [1–4]. The study of the composition and properties of neoformations allows answering many questions of soil genesis in the past and at the present stage of their formation [3, 4]. On the territory of Russia, soil neoformations have been studied mainly in the soils of the taiga and forest-steppe zone (sandy-loamy soils, loamy and clayey podzolic soils, soddy-podzolic soils, boggy-podzolic soils, gray forest gley soils, chernozem-like gleyed soils, soddy-gley soils, floodplain soddy granular gley soils) [4–6]. For soils of the tundra zone, especially for soils with texture-differentiated profile, such studies are rare [7–9]. The objective of study is to reveal the regularities of the distribution and chemical composition of soil formation products (sandy-silty and clayey cutans,
concretions, pedorelicts) in two types of loamy soils that form under the bioclimatic conditions of the southern tundra.

2. Objects and methods
The study area is located on the territory of the Komi Republic (European North-East of Russia, southeast of the Bolshezemelskaya tundra). The structural organization of automorphic loamy soils of this area under different types of tundra vegetation was studied. The first object is located on an easy slope of a moraine hill (67° 31' 47.60" N 63° 7' 52.89" E). The permafrost table occurs on 1.5 m depth and below. Vegetation cover is with dwarf birch-shrub, moss and lichen. The soil is Dystric Cambisols. Soil horizons: Oi–OB–G–Bt–BC. The second object is located on the naked upwind slope of the moraine sloping hill (67° 35' 26.27" N 64° 9' 57.37" E). Permafrost table occurs at the 90-cm depth. Vegetation cover is moss-lichen with rare shrub. The soil is Turbic Cryosols. Soil horizons: Oi–OAc–Gtx–Bg–BCg.

Observation of morphological characteristics of soil structure on macro-, meso- and micro levels was done; the physicochemical properties of soils were analyzed according to generally accepted methods in soil science. Under laboratory conditions, structural components of soils were prepared from undisturbed monoliths – skeletans (Sk), clay cutans (Cc), as well as groundmass (GM) and intraped mass (IM) [1]. Fe-Mn concretions (IMC) were selected from the soil mass by the wet sieving method [10]. The determination of total carbon (Ctot) and nitrogen (Ntot) is done using an "EA-1110 CHNS-O" elemental analyzer (Carlo Erba, Italy). Oxalate extractable fractions of iron (Feo) and aluminum (Alo) were determined according to the Tamm method; dithionite extractable fractions of iron (Fed) were determined according to the Mehra and Jackson method. The bulk composition of groundmass and neoformations was made by X-ray fluorescence spectrometry. The names of the horizons and soils are given in according to the World Reference Base for Soil Resources [11].

3. Results and discussion

3.1. Dystric Cambisols
Dystric Cambisols are most common soils of the southeastern Bolshezemelskaya tundra. They form in drained automorphic landscapes (on the naked slopes of moraine hills), in the shrub-moss tundra. Combination of an organogenic, gleied, and textural horizon is a specific feature of the soil profile structure. Structured textural horizons (Bt) are characterized by angular-oval shaped aggregates and an abundance of whitish skeletans (SK), especially for the middle part of the textural horizon. The formation of the upper part of the profiles is a result of both current cryogenesis and soil processes of the tundra stage of soil forming (gleying process, Al-Fe-humus illuviation, biochemical transformation). The specific cryogenic organization of the soil mass appears as a result of cryogenesis, due to the agglutination of particles during rotation, as well as pressure of ice schliers and segregation and coagulation structuring [12]. The fragments of pedorelicts (clay coating) retained in lower horizons are preserved from earlier period of pedogenesis [12].

Particle size distribution analysis data shows the removal of silt particles. This process occurs mainly in the upper half-meter soil layer [12]. Total elemental analysis of structural components (skeletans and intraped mass) indicates the profile differentiation under the eluvial-gleying and eluvial-illuvial processes (table 1). A weakly expressed eluvial-illuvial distribution of Fe2O3 and CaO was revealed in the intraped soil mass (accumulation in the Bt1 horizons, where aggregates with a ferruginous center are present). The profile distribution of Al2O3 and MgO displays a similar picture, but the removal of these elements is less expressed. This is explained by various redox processes in these profile parts or under an evident effect of Al-Fe-humus illuviation. Inverse distribution of total elemental content of R2O3 was revealed for skeletans: accumulation in the Bt1 horizons, a decrease in the Bt2 horizon. Possibly, intraped mass isolated by cutans from leaching and preserving properties more exactly indicates the eluvial-illuvial differentiation of the profile.
Fe$_o$ and Fe$_d$ (table 2) are accumulated in the skeletans on the surface of aggregate, interped spaces and intraped pores which are the paths of chemical compound migration at the profile’s middle part (Bt horizon). The total content of Fe$_o$ and Fe$_d$ is higher in IM. The content of Fe$_o$ and Fe$_d$ is regularly distributed in IM down the soil profile and effectively correlates (the correlation coefficient (r) is 0.87 and 0.98) with ω(C) profile distribution in IM. Close correlation (r = 0.99) was noted only between Fe$_o$ and Ctot in skeletans. It indicates the predominant migration of organo-mineral complexes in the composition of skeletans and reflects the process of Al-Fe-humus illuviation as a phase of an integrated macroprocess – Al-Fe-humus differentiation of soils [13].

**Table 1.** Total concentrations of major elements of soil structural components, %.

| Horizon | Depth, cm | Sample | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | MgO | MnO | K$_2$O | P$_2$O$_5$ | TiO$_2$ |
|---------|-----------|--------|--------|-------------|-------------|-----|-----|-----|--------|---------|--------|
| G       | 19–29     | IM     | 74.20  | 13.12       | 5.00        | 1.07| 1.37| 0.11| 2.18   | 0.10    | 0.90   |
| Bt1     | 37–47     | SK     | 78.955 | 11.05       | 3.06        | 0.74| 0.81| 0.04| 2.11   | 0.07    | 0.81   |
| Bt2     | 52–77     | SK     | 73.36  | 13.38       | 5.26        | 1.17| 1.43| 0.09| 2.25   | 0.10    | 0.84   |
| BC      | 77–97     | SK     | 77.04  | 11.45       | 3.43        | 0.74| 0.96| 0.04| 2.05   | 0.09    | 0.72   |
| OAcR    | 7–15(17)  | IM     | 72.0   | 13.57       | 5.34        | 1.35| 1.10| –   | –      | 0.18    | 0.88   |
| Gtx     | 15(17)–   | IM     | 72.1   | 13.20       | 5.07        | 1.35| 0.94| –   | 2.11   | 0.16    | 0.91   |
| Bg      | 26–38     | IM     | 72.6   | 13.24       | 5.37        | 1.36| 1.02| –   | 2.18   | 0.17    | 0.91   |
| BCg     | 38–42     | IM     | 72.3   | 13.62       | 5.35        | 1.35| 1.12| –   | 2.14   | 0.17    | 0.88   |
| BCG     | 42–65     | IM     | 72.9   | 13.11       | 5.43        | 1.36| 0.96| –   | 2.12   | 0.16    | 0.93   |

* According to Sloboda [7].

| Horizon   | Depth, cm | Sample | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | MgO | MnO | K$_2$O | P$_2$O$_5$ | TiO$_2$ |
|-----------|-----------|--------|--------|-------------|-------------|-----|-----|-----|--------|---------|--------|
| Turbic Cryosol |         |        |        |             |             |     |     |     |        |         |        |
| OAcR      | 7–15(17)  | IM     | 72.0   | 13.57       | 5.34        | 1.35| 1.10| –   | 2.20   | 0.18    | 0.88   |
| Gtx       | 15(17)–   | IM     | 72.1   | 13.20       | 5.07        | 1.35| 0.94| –   | 2.11   | 0.16    | 0.91   |
| Bg        | 26–38     | IM     | 72.6   | 13.24       | 5.37        | 1.36| 1.02| –   | 2.18   | 0.17    | 0.91   |
| BCg       | 38–42     | IM     | 72.3   | 13.62       | 5.35        | 1.35| 1.12| –   | 2.14   | 0.17    | 0.88   |
| BCG       | 42–65     | IM     | 72.9   | 13.11       | 5.43        | 1.36| 0.96| –   | 2.12   | 0.16    | 0.93   |

The upper part of Dystric Cambisol profile has a maximum content of concretions (table 3). They have an irregular oval shape. Tubular concretions also occur. The color is reddish-brown and rusty-brown. In the Bt horizon, rare concretions are crumbly, dark brown color with uneven edges. Fine concretions (< 2 mm diam.) prevail down the profile. The greatest number of concretions with bigger diameter (> 2 mm diam.) occurs in the lower part of the Bt horizon.

The main components of concretions are different compounds of iron and manganese. Concretions (especially in the Bt horizons) actively accumulate Mn (Kx is from 6.5 to 22.5) and Fe (Kx is from 1.8 to 4.0) compared to the groundmass. Accumulation factor is < 1 (table 4) for the rest of the elements. The exception is for concretions in the upper horizon, in which the accumulation of biophilic elements, such as Ca, Mg, K, Na (Kx is from 1.3 to 2.1), is observed. This may be due to the mineralization of plant litter, migration of biophilic elements from the organogenic horizons of Dystric Cambisol down the profile and their accumulation in concretion bodies.

3.2. Turbic Cryosols

Turbic Cryosols are formed in the dwarf-moss tundra with close occurrence of permafrost. This soil type is characterized by profile gleying. Gleied G horizons are thixotropic, weakly aggregated in the lower profile part. Rounded and angular aggregates are rare, slightly whitish skeletans (SK); single skeletal grains are present only in pores of both Bg and upper Gtx horizons. The weak distribution of skeletans in tubular pores characterize cryogenic sorting of skeletal grains, and morphologically pronounced spots in the profile (ocher zones on bluish background) indicate the redox processes of Fe. The OAcR horizon is characterized by aggregation of biogenic and cryogenic (aggregation of fine-dispersed mass) character.
Table 2. Selected chemical properties of soil structural components, %.

| Horizon | Depth, cm | Sample | Fe<sub>o</sub> | Al<sub>o</sub> | Fe<sub>d</sub> | C<sub>tot</sub> | N<sub>tot</sub> |
|---------|-----------|--------|---------------|-------------|--------------|--------------|--------------|
| G       | 8–24      | SK     | _            | _           | _            | _            | _            |
|         |           | IM     | 0.64         | 0.02        | 0.94         | 0.64         | _            |
| Bt1     | 24–52     | SK     | 0.54         | 0.02        | 0.56         | 1.10         | _            |
|         |           | IM     | 0.47         | 0.13        | 0.72         | 0.42         | _            |
| Bt2     | 52–77     | SK     | 0.21         | 0.01        | 0.33         | 0.35         | _            |
|         |           | IM     | 0.52         | 0.41        | 0.65         | 0.36         | _            |
| BC      | 77–97     | SK     | 0.25         | 0.05        | 0.62         | 0.42         | _            |
|         |           | IM     | 0.55         | 0.09        | 0.71         | 0.46         | _            |
|         |           |        |              |             |              |              |              |
|         |           |        |              |             |              |              |              |
| OAc     | 7–15(17)  | IM     | 0.18         | 1.16        | 0.47         | 0.18         | 0.03         |
|         |           | GM     | 0.17         | 1.03        | 0.45         | 0.53         | 0.05         |
| Gtx     | 15(17)–26 | IM     | 0.19         | 0.73        | 0.51         | 0.17         | 0.03         |
|         |           | GM     | 0.21         | 0.68        | 0.47         | 0.74         | 0.07         |
| Bg      | 26–38     | IM     | 0.20         | 1.06        | 0.37         | 0.18         | 0.03         |
|         |           | GM     | 0.18         | 1.01        | 0.36         | 0.35         | 0.04         |
| BCg     | 38–42     | IM     | 0.21         | 1.08        | 0.40         | 0.24         | 0.04         |
|         |           | GM     | 0.19         | 1.08        | 0.39         | 0.24         | 0.03         |
| BCg     | 42–65     | IM     | 0.20         | 1.09        | 0.39         | 0.30         | 0.04         |
|         |           | GM     | 0.15         | 0.96        | 0.29         | 0.28         | 0.04         |

<sup>a</sup> According to Sloboda [7].

<sup>b</sup> Has not been revealed.

This is evidenced by the presence in thin sections of small plant residues with silt particles and coagulative humus curds forming rounded-angular aggregates. Curved dark brown fragments enriched with organic matter at a 40–60 cm depth are the result of cryoturbations. Arched dark-brownish fragments enriched with organic matter are located in sections at a 40–60 cm depth are the result cryogenic mass transfer (cryoturbations). They are more expressed in the Turbic Cryosol than in the Dystric Cambisol profile.

As opposed to Dystric Cambisol, the profile of Turbic Cryosols is not differentiated by the total content of sesquioxides and silicon oxides (table 1). An analysis of the soil groundmass and intraped mass was done to assess the special aspects of the element redistribution within the soil aggregates for each horizon (table 2).

The gleied G horizon is characterized by lower content of Al<sub>o</sub> and Fe<sub>d</sub> for both GM and IM. This may occur due to the gley-mobilization of Al<sub>o</sub> and Fe<sub>d</sub> compounds. By indirection, the presence of iron and aluminum compound mobilization processes confirms the difference in their content in GM and IM, especially in the upper horizons of the profile. The clear predominance of the Fe and Al content in the intraped mass of soil aggregates compared with the groundmass, indicates the removal of iron-aluminum coatings from the aggregate surfaces and the migration of these compounds to oxidative barriers and the freezing front in the upper part of the profile. These processes occur in the form of inorganic Fe and Al compounds migration, since humic substances, as opposed to Fe and Al compounds, are localized mainly on the aggregate surface in Dystric Cambisol. This is evidenced by an almost 3–4-fold increase.
of the $C_{ceg}$ content in the groundmass of the soil compared to its content in the intraped mass of soil aggregates.

### Table 3. Composition and fractional content of concretions of tundra soils.

| Horizon | Depth, cm | Composition of concretions, % of soil mass | Fractional content, % of total mass of concretions |
|---------|-----------|---------------------------------------------|--------------------------------------------------|
|         |           |                                             | < 1 mm  | 1–2 mm | 2–3 mm | > 3 mm |
| Dystric Cambisol |          |                                             |         |        |        |        |
| OB      | 5–13      | 0.36                                        | 31      | 56     | 5      | 8      |
| G       | 13–22     | 0.45                                        | 69      | 29     | 2      | 1      |
| Bt1     | 22–38     | 0.10                                        | 25      | 65     | 3      | 7      |
| Bt2     | 38–60     | 0.04                                        | 10      | 72     | 12     | 5      |
| BC      | 80–100    | 0.01                                        | 64      | 36     | –c     | –      |
| Turbic Cryosol |        |                                             |         |        |        |        |
| OAc    | 7–15(17)  | 0.16                                        | 57      | 36     | 4      | 3      |
| Gtx    | 15(17)–26 | 0.06                                        | 12      | 50     | 28     | 10     |
| BCg L  | 38–65     | 0.10                                        | 11      | 54     | 14     | 22     |
| BCg R  | 38–42     | 0.02                                        | 17      | 76     | 7      | –      |
| BCg L  | 42–65     | 0.18                                        | 32      | 58     | 9      | 1      |

*Left side of the soil profile.

*Right side.

*Has not been revealed.

### Table 4. Accumulation factor* (Kx) of elements in concretions (< 2 mm diam.) of the soils.

| Horizon | Depth, cm | Extraction | Mn  | Fe   | Al  | Ca  | Mg  | K   | Na  |
|---------|-----------|------------|-----|------|-----|-----|-----|-----|-----|
|         |           |            |     |      |     |     |     |     |     |
| Dystric Cambisol |          | Total    | 6.5 | 1.8  | 1.3 | 2.1 | 1.3 | 1.5 | 1.7 |
| OB      | 5–13      | Total    | 19.7| 4.0  | 1.0 | 0.8 | 0.9 | 0.8 | 0.9 |
| G       | 13–22     | Total    | 22.5| 2.3  | 1.0 | 0.5 | 0.7 | 0.7 | 0.8 |
| Bt1     | 22–38     | Total    | 18.2| 1.8  | 0.9 | 0.6 | 0.7 | 0.7 | 0.8 |
| Bt2     | 38–60     | Total    | 9.8 | 4.6  | 1.1 | 1.0 | 1.1 | 1.0 | 1.5 |
| Turbic Cryosol |        | Total    | 7.5 | 3.9  | 1.3 | 0.7 | 1.1 | 1.2 | 1.2 |

*Accumulation factor calculates as relation of element content in concretions to its content in groundmass.

In Turbic Cryosol, the processes of concretion formation are less expressed than in Dystric Cambisol (table 3). The profile gleying under prolonged effect of surface water saturation makes it difficult to form concretions. Fine concretions (< 2 mm diam.) are also formed mainly in Turbic Cryosol. They have different density, colors (dark gray, ocher, rusty-brown) and shapes (roll, round, oval, tubular). There is a relatively high share (10–22%) of coarse concretions (2–3 mm and > 3 mm in diam.) in the Gtx and BCg horizons of Turbic Cryosol compared to Dystric Cambisol. The material composition of concretions is characterized by the pattern similar to Dystric Cambisol such as accumulation of major
Fe and Mn. The accumulation of Mn is less expressed in Turbic Cryosol than in the concretions of Dystric Cambisol (table 4).

Consequently, the Turbic Cryosol profile is characterized by weak transformation of the soil mass under effect of pedogenic processes; by chemogenic differentiation of Fe oxides; by slow profile migration of soil formation matter; marked cryogenic mass transfer (cryoturbation).

4. Conclusion
The structural organization, qualitative and quantitative composition of neoformations in two mostly common soil types in the permafrost zone of the European Northeast was investigated.

Analysis of skeletons (which occur on the pathways of current migration of solutions) diagnoses the process of Al-Fe-humus illuviation. Analysis of the intraped mass (which preserve the properties) reflects eluvial-illuvial differentiation inherited from earlier stages of soil formation.

Turbic Cryosol profile has weakly expressed eluvial-illuvial differentiation.

Concretions are formed in both studied soils, but they are distributed to a 2.5–7.5-fold lower extent in Turbic Cryosol than in Dystric Cambisol. Concretions are loose, with irregular edges, brown or rusty-ocher color, fine size (<2 mm diam.). Accumulations of Mn and Fe compounds are dominant in their composition. The relative accumulation of biophilic elements, such as Ca, Mg, K, Na, is the feature of concretions in upper part of the District Cambisol profile.

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