Micromorphological features of cryogenesis in the structure of taiga soils on the West Siberian Plain

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Abstract. Morphological descriptions of cryogenic soils of the taiga zone are very important for diagnostics and classification of soils of northern regions. The development of geocryogenic processes depends on locally specific climatic and lithological factors. Previous studies on cryometamorphic soils (svetlozems) formed on Mid-Pleistocene loamy parent materials have been focused on their hydrological and thermal regimes. This article presents the results of meso- and micromorphological analyses of mesomorphic loamy soils formed in autonomous (interfluve) areas under seasonal freezing conditions. The permafrost features of the studied soils were formed during cold climatic cycles of the Pleistocene-Holocene period. The modern pedogenesis develops under increasingly hydromorphic conditions untypical for autonomous soils of the taiga zone of the West Siberian Plain. As a result, processes of peat accumulation and gleyzation have developed in such soils. However, gley features are absent in cryometamorphic soils. In their upper layers, iron undergoes oxidation and concentrates within granular peds during freezing. In their lower horizons (from the 40 cm depth), Fe-nodules are assimilated within platy peds (as a result of cryogenic restructuring of silty-clayey groundmass) and relic clay coatings are fragmented. The vertical differentiation of cryogenic features within the studied soil profiles can be associated with changes in climatic conditions during the Pleistocene-Holocene period.

1. Introduction

Soil cryogenic processes in the contemporary areas of continuous, discontinuous, sporadic permafrost and intergelisol of the West Siberian Plain are poorly expressed. In modern soils north of 62° north latitude, frost wedges in the form of albeluvic tonguing in Podzol and ice lenses in peat soils are recorded. South of 62° north latitude in the soils of the middle taiga subzone the signs of cryoturbation and the signs of permafrost of soils at the macro level are not found. Features of the cryogenic processes are only distinguishable at meso- and micromorphological levels (in practically undifferentiated loam and sandy loam soils). Here, these cryogenesis features can either be features of relict cryogenic process
[1] and influence the evolutionary development of soils, or they can show seasonal soil freezing. There is no doubt that the morphological features of geocryogenic processes are markers of natural-climatic conditions [2, 3]. Accordingly, their presence and transformation suggest evolutionary development of soil properties [4]. Comprehensive research on structural changes in soils affected by active freezing-thawing processes is highly relevant for the understanding of genesis and taxonomy of poorly studied soils of Siberia.

2. Materials and methods
All genetic horizons of the investigated profile were examined and characterized in the field as specified by the FAO Guidelines for Soil Description (2006) [5]. Recording an automatic monitoring system for field measurements of soil temperature called “SAM-N2” was applied. During the research, morphological features of autonomous metamorphic soils on loamy neopleistocene deposits were studied using the multi-level morphological diagnostics method. This method includes morphological field description, mesomorphological study under a binocular microscope and micromorphological study in thin sections under a polarizing microscope in transmitted and reflected light. Samples for micromorphological analysis were taken in early September, when the upper soil horizons had temperatures below 0 °C, but the lower horizons were still saturated with unfrozen moisture.

Currently, pedogenesis takes place in cold, humid conditions. Precipitation is 500 mm/y that prevails over evaporation. The average annual air temperatures in different years range from 3 to 0.6 °C. Climate is the main factor in the occurrence of the cryogenic process, but the role of parent material is equivalent. The development of autonomous mesomorphic soils is associated with the change of climatic conditions in the Pleistocene-Holocene period, as well as with the fine texture composition.

The studied soils were formed on terraces, under the regenerating spruce-cedar forest with a ground cover dominated by mosses, on Mid-Pleistocene (Neopleistocene and Eopleistocene) loamy parent materials [6]. Based on micromorphological features, these soils are classified as cryometamorphic soils [7]. The upper layers of the studied soils are developed from material which has obvious signs of frost action: wedges and cryoturbation.

The soil has a weak differentiation along the horizons. Generalized morphological features of soils indicate the presence of an active layer in soils up to a depth of 30–40 cm. It is the ochre colour BF horizon with a large number of iron nodules [8]. At the top of the pit, the structure is caviar with small aggregates which have a rounded shape. At a depth of 40 cm and below, the structure becomes angular. Horizontal scaly arrangement of aggregates in the middle horizons Cw according to the WRB [9] or a cryometamorphic horizon (CRM) according to the Russian Classification and Diagnostics [7] indicates that the soils are affected by frost action and that the below-freezing temperatures influence the formation of the cryogenic structure. Deeper, it is visible that the enlargement of angular-coarse aggregates and the colour do not change. In the spring, at a depth of 100 cm, thixotropy may appear. There are no signs of coatings on aggregates in the layers.

3. Results
The results of "SAM-N2" temperature measurements are shown in figure 1. Temperature gradients change according to a depth level. The coldest horizons are located at a depth of 20 cm. The average below freezing temperature is 1.07 °C. Temperatures of the cryometamorphic horizon from February to June are in the subzero range with the average values of 0.2 °C, the maximum sum of below-freezing temperatures is recorded in March and is 8 °C.

Special conditions for soil hydrological regime are created due to below-freezing temperatures during six months. The average annual moisture is 21% for depths from 40 to 100 cm. Water content at these depths is stable during the year. The hydrological regime is dynamic in the active layer.

The mesomorphological study of the mesomorphic soil profile revealed the following features of structural differentiation: 1) the diameter of rounded aggregates increased with depth from 1–2 mm to 5 mm (interestingly, there was a tendency for a subparallel orientation of those aggregates, figures 2 and...
3a); 2) a platy microstructure with plane voids and silty coatings was observed in the middle part of the profile (figure 2).

Figure 1. Annual temperature of horizons.

Figure 2. Mesomorphology study of the mesomorphic soil: a) the caviar or granular structure; b) the scaly formation in aggregates and crystalline silica coatings, upper facets of gravels are covered by cryogenic clayey-silt-sand cappings.

Figure 3. A specific granular microstructure with Fe-nodules inside of the eluvial horizon, 10–13 cm: a) 2-II-N, b) 2-X-N.

Upper facets of gravels are covered by cryogenic clayey-silt-sand cappings [10]. Sharp edges of aggregates are found in soil structure, and ice crystals are found in interaggregates space in June. Deeper
in soil profile starting from 60 cm depth and below, mutually parallel layers of mineral aggregates of the angular-coarse structure are formed, overlaid with light silty coatings, which can be connected with separation and movement of particles towards the surface of aggregates in the course of cryogenesis.

The micromorphological analysis showed that the upper 40-cm-thick layer has a specific granular microstructure with Fe-nodules inside (figure 3). The permafrost features are detected at a depth of 40 cm and below. The horizons have platy microstructure, with silt grains extruded into pores-fissures (figure 4) [11]. Fe-nodules are assimilated into platy peds due to the cryogenic re-structuring of silty-clayey groundmass. Parallel horizontal plane voids are formed due to the gradual movement and freezing of water in interstitial space. Deeper in soil profile, starting from 60 cm depth, angular and rounded microstructures are formed. Within the cryogenic horizon, thin clay coatings undergo fragmentation due to cryogenic restructuring and, subsequently, the fragments (papules) are gradually assimilated into aggregates (figure 5).

**Figure 4.** Platy structure of the cryogenic horizon, 30–40 cm, a) 10-II-N, b) 10-X-N.

**Figure 5.** Angular-coarse structure with silica coatings on the surface of plates of cryogenic horizon, 90–100 cm, a) 4-II-N; b) 4-X-N.

### 4. Discussion

In micromorphological descriptions, it is noted that the upper layers of automorphic mesomorphic loam soil differ from cryometamorphic horizons in a more defined structure and the presence of iron nodules. The marked rounded aggregates (small in horizon E and larger in layer horizon BF) may be associated with microbiological activities that are involved in the formation of aggregates by releasing substances into the soil that glue individual particles into crumb microstructure. Separate studies of microbiological activity in this soil have shown that microfungi play the dominant role and there is a process of
decomposition of organic material. The activity of processes is moderate, the microbial system can be described as conservative, located in the homeostasis zone.

Rounded aggregates of a larger size are present in the illuvial-ferruginous horizons. The soil fine material in this horizon has a thin-plate horizontal orientation. Parallel horizontal pores are formed due to the gradual movement of water and the formation of ice schlieren. Platy aggregates also contain ferruginous nodules.

The transition of the iron-illuvial horizon to the cryometamorphic horizon at a depth of 25–30 cm is represented by the fine soil texture with weakly aggregated rounded forms and a high interpedal porosity. The studied soils had an iron-illuvial horizon similar to that in svetlozems [7]. The high mobility of iron was probably due to high (68%) saturation of this horizon with moisture prior to its rapid freezing. When such material was exposed at the surface, it had a thixotropic behavior.

The amount of moisture in the svetlozems profile determines the microstructure of soil aggregates. Due to low moisture at the depth of 50 cm and below, the structure of aggregates is formed. The impact of below-freezing temperatures on poorly waterlogged finely-dispersed cryometamorphic horizon leads to cracking of aggregates, creating an angular structure with sharp edges. Formed ice lenticular has a horizontal orientation, creating large blocks.

The transition from the cryometamorphic horizon to the buried illuvial-textural horizon (at a depth of 90–100 cm) is represented by compressed fine soil, divided into large angular-blocky aggregates covered with silty coatings with fine quartz-feldspar grains and quasi-hypo-coatings. Papules are formed due to cryogenic restructuring and assimilation of clay coatings into intrapedal mass (figure 5b). Presumably, such clay coatings do not result from recent clay illuviation, but they can be inherited from earlier stages of pedogenesis of the Pleistocene-Holocene period.

It is assumed that the mechanism of formation of the cryogenic structure is associated with earlier severe freezing that was occurring in this area too. The penetration of below-freezing temperatures into poor moistly fine loam cracked units. The existing deeper freezing caused the formation of segregational ice and the migration of water vapor and extrusion of fine particles to the freezing front, forming discontinuous block structures with sharp, wedge-shaped angles.

5. Conclusion
Cryogenic processes in the studied soils occur in the system (parent material, water in the liquid and solid states of matter and solution) and lead to changes in the mechanisms of pedogenetic processes. The main morphological features of the cryogenic process in the cryogenic horizons are the presence of silt and cracks that are covered with fine silica. They were formed during partluation, as evidenced by the fine porosity of aggregates associated with the pull of moisture to the freezing front. Allegedly, the clay coatings formation in the middle horizons of soils occurs due to the migration of gravitational water. Soil freezing is accompanied by changes in the structure of soil material, e.g., relic clay coatings (inherited from earlier stages of pedogenesis) are transformed into quasi- and hypo-coating and/or papules within the lower soil horizons.

The soils formed on loamy deposits are differentiated by temperature and moisture. The upper horizons with rounded aggregates up to a depth of 30–40 cm appear in the active layer and have early freezing-thawing cycle, which depends on the current climatic conditions. Platy structure in the middle horizons represented by the horizontal position of the aggregates, corresponds to the depth of modern freezing; the lower part represented by angular form of structures with obvious discontinuous interpore spaces, that do not correspond to modern freezing. The average below-freezing temperature is 0.2 °C, that indicates cold conditions in the past.

Multi-level morphological diagnostic conducted in conjunction with seasonal study of soil freezing and moisture on loamy deposits of Western Siberia Plain, allowed us to clarify the formation of specific soil structures and coatings in different genetic horizons of autonomous metamorphic soils.
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