The cryogenic structure and texture of seasonally freezing soil in the steppe zone of the Trans-Volga-Urals region

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Abstract. The formation of ice lenses and associated frost heave were found in soils the steppe environment with positive mean annual air temperature. The ice lenses due to soil freezing occur in soils with expressed microrelief when they have additional ground moistening. In soils formed on quaternary loam with shallow groundwater the formation of ice was not differentiated across the microrelief; the morphology of the microrelief is similar to thurfur. Soils formed on fine-dispersed limestone (chalky polygons) and on the material of ancient weathering crust (frost mounds) do not have clear evidence of subsoil extramoisterning exhibit the differentiated formation of cryotexture according to microrelief. The ice lenses were found in soils of microhights. The formation of cryogenic lenticular and platy structures occur after to the melting of ice lenses in soils. Local frost heave in steppe soils determines the small-scale differentiation of soil processes and the formation of the complex soil cover.

1. Introduction

A set of cryogenic macro- and micro- features was found in steppe soils formed on limestone parent material characterized by well expressed regular microrelief ("chalky polygons") [1, 2]. These features include the platy structure atypical for steppe soil. The platy structure was prominent and was expressed to a big depth with a gradual increase of the thickness of platy aggregates.

The platy structure can be inherited from parent material [3] or resulted from different soil processes such as eluvial [4], solonetzic-eluvial [5, 6], cryometamorphic [7, 8], caused by anthropogenic compaction [9] or be a relict one [10]. The platy soil structure was described in soils of eastern Trans-Ural before [11] without discussing the mechanism of its formation.

The platy soil structure we have described in soils formed on limestone most likely had cryogenic origin according to its localization and morphology. The winter testing in a small pit confirmed the presence of ice lenses between platy aggregates.

The cryogenic platy soil structure is more common to soils of high latitudes [12-15]; however, it may occur in other regions up to the North Caspian semi-deserts i.e. ~50° N [16, 17].

Other forms of regular microrelief similar to cryogenic tundra microrelief can be found in Trans-Volga-Urals steppe environment where we examined the chalky polygons. The microrelief occurs on various geomorphological positions and rocks. We investigated the soils of the microhills and microdepressions of the regular microrelief formed on various parent materials to evaluate its role in the formation of the complex soil cover, and the role of a modern and paleo- cryogenic processes in pedogenesis. The aim of this study was an analysis of the occurrence, degree of manifestation, and...
peculiarity of the platy structures in soils to clarify its cryogenic origin in Trans-Volga-Urals steppe soils.

2. Materials and Methods
The key-sites are located within Orenburg region on the Pre-Urals plateau (the East-European plain) and the Ural-Tobol plateau (the Ural mountains) (figure 1). The Pre-Urals plateau represents a wavy denudation plain formed by red-colored Permian and Triassic deposits in the north, Jurassic and Cretaceous rocks in the central and southern parts. The Ural-Tobol plateau is a denudation pediment plain. It has a leveled relief with weathering crust up to 30-40 m thick, which often occurs at the surface [18]. The Quaternary alluvial and lacustrine deposits are wildly spread generally below the sheet of loess-like loam.

![Figure 1. Location of the key-sites in Orenburg region, Russia.](image)

The climate is continental; the mean annual air temperature (MAAT) is about +4°C, the MAAT of January is -15°C, the MAAT of July is +21°C; evaporation (800-900 mm) predominates over the precipitations (260-390 mm). Most of precipitations (~60-70%) occur from May to September with the maximum in July, and minimum in February. The duration of a frost-free period is ~140 days. The snow cover is ~30 cm. The depth of soil freezing is generally 0.7 – 1.2 m, with the maximal freezing up to 2 m. Soils are represented by black soil and chestnut soil; there are soil and vegetation cover complexity. The area belongs to subboreal continental East European dry-steppe landscapes [19].

Three key-sites with microlief were selected for the study. They are characterized by the alternation of isometric microhighs and hollow depressions (figure 2 a-c). The key-sites differ according to the type of microlief (shape and size of microhighs), geomorphology, parent material, and depth to groundwater. The distance between the centers of knolls is about 5 m on average. The surface of knolls is covered with a light salt encrustation.

Key-site 1 “Chalky polygons”: The Pre-Urals plateau (51°08’10”N, 55°37’16”E), a curved part of the gentle south-west slope to a gully running into the Itchashkan river. Soil are formed on limestone eluvium overlapped by loess-like loam. The downcutting of the gully is 2.5-3 m (figure 2a).

Key-site 2 “Thufurs”: The Pre-Urals plateau (51°15’28.97” N, 56°37’12.50”E), the valley of the Tuzlukkol river (the left bank inflow of the Ural river) joins to a waterlogged lake-shaped opening; the excess over the water level is 0.5-1.5 m, the groundwater is at a depth 0.8-1.2 m (figure 2b).
Key-site 3 “Heave mounds”: The Ural-Tobol plateau (51° 9′22.50″N; 59°23′18.67″), a gentle slope of a vast erosional depression with re-deposited material of weathering crust. The depth of groundwater is expected at a depth > 2.5 m (figure 2c).

![Figure 2. The general view of the key sites: a satellite image (left) and a landscape photo (right): (a) – Chalky polygons, (b) – Thufurs, (c) – Heave mounds.](image)

The morphological study of the structure and cryogenic texture of soil of mounds and depressions was conducted in trenches and soil pits with a depth up to 2 m in the summer and small pits with a depth of 30-40 cm in the winter.

Soil structure was described in summer time, while the cryogenic texture and ice content was examined in winter period. Cryogenic structures were described after [20, 21]; soil structure was described after Guide for soil description [22].

3. Results

3.1. Microrelief

The forms of microrelief investigated at three key-sites have general resemblance but differ by morphometric parameters (table 1, figure 2 and 3).
Table 1. Morphometric parameters of the microhighs.

| Key site         | Shape      | Height, cm | Distance between the tops of microhighs, m |
|------------------|------------|------------|------------------------------------------|
| 1. Chalky polygons | polygonal  | 10-30      | 5-6                                      |
| 2. Thufurs       | tetragonal | 30-50      | 3-4                                      |
| 3. Heaving mounds| rounded    | 40-70      | 6-8                                      |

Key-site 1 “Chalky polygons” has the landscape complexes with isometric polygonal microrelief with a height of about 30 cm. The relatively uniform in size microhighs with d~5 m are surrounded by hollow-shaped depressions forming the large polygonal network. The central parts of polygons are represented by spots of white chalky material (figure 2a, 3a).

Key-site 2 “Thufurs” has the microhighs ~ 2.5 m in diameter with the height of 30 - 50 cm. The microhighs are separated by hollow-shaped depressions alongside the slope. The shape of microhighs is tetragonal, less often they are rounded or slightly elongated (wavy ridges with a width of 0.5 m) with a flattened top and steep sides (figure 2b, 3b).

Key-site 3 “Heaving mounds” is characterized by polygonal hilly microrelief consisting of rounded dome-shaped microhighs of different size (2-7 m in diameter) with the height of 40-70 cm with close to vertical side walls rising above the flat surface. The V-shaped hollow-shaped depressions are marked by cracks 5-10 cm width and 10-20 cm depth (figure 2c, figure 3c).

Figure 3. An external view of microhighs at three key-sites: (a) – Chalky polygons, (b) – Thufurs, (c) – Heaving mounds.

3.2. Cryogenic texture

The Chalky polygons are characterized by lenticular non-parallel and wavy non-parallel cryogenic texture strongly cementing the soil, which could not be dug by shovel in winter (table 2).

Visible ice lenses were found in soils of microhighs formed by finely-dispersed limestone eluvium. Ice lenses are fragmentary and very fine near the surface of microhighs. The clear cryogenic texture is formed deeper. Till the depth of 10 cm the thickness of ice lenses is less than 1 mm; at a depth of 10-25 cm the thickness of ice lenses gradually increases to 1-2 mm and they have more lenticular form. The cryogenic texture disappears in a non-frozen layer at a depth below 25 cm.

The ice lenses were not found within the microdepressions. Soil material can be easily dug by a shovel, except the upper denser layer to a depth of 10 cm from the surface.

The cryogenic texture of the Thufurs is wavy parallel. Ice segregations are represented by the network of wavy horizontal or slightly inclined ice lenses with similar thickness about 0.5 mm. Visible ice lenses were found in soils both of microhighs and microdepressions (table 2).

In microhighs the ice lenses appear at a depth of ~ 7-10 cm. They are extremely fine. The thickness of ice does not exceed 0.5 mm even at a depth of 30 cm. In microdepressions the ice lenses start to appear from the surface. They are hardly visible and their thickness does not increase with depth. The
The distance between ice lenses is less than 1 mm both in microhighs and microdepressions, and does not change with depth. Frozen soil material is so solid on each element of the microrelief.

Table 2. Characteristics of cryogenic texture.

| Key site            | Depth, cm | Type                      | Thickness of ice lenses, mm | Thickness of mineral mass between the ice lenses, mm |
|---------------------|-----------|---------------------------|-----------------------------|------------------------------------------------------|
|                     |           | micro high                | micro depression            | micro high                                          | micro depression |
| 1. Chalky polygons  | 0-10      | no                        | lenticular non-parallel     | no                                                   | <0.5             |
|                     | 10-25     | no                        | wavy non-parallel           | no                                                   | 0.5-1.0          |
|                     | 25-35     | thawed soil               | wavy non-parallel           | no                                                   | 1.0-2.0          |
| 2. Thufurs          | 7-30      | 2-30                      | wavy parallel               | ~0.5                                                | ~1               |
| 3. Heave mounds     | 0-8       | no                        | lenticular non-parallel     | <0.5                                                | 1.2              |
|                     | 8-20      | no                        | wavy non-parallel with      | ~0.5                                                | 1.2              |
|                     | 20-30     | thawed soil               | wavy non-parallel with      | 0.5-1.0                                             | 2.4              |

The cryogenic texture in soils of the Heaving mounds is lenticular non-parallel in the upper layer of the earth. With depth it transforms into a wavy non-parallel and with elements of regular reticulate (table 2). Visible ice lenses were found within microhighs only. The clear cryogenic texture appear at a depth below 8-12 cm. The thickness of ice lenses is 0.5 mm and gradually increases to 1 mm at a depth of 30 cm. Together with the thickness of the ice lenses the soil material in-between the ice lenses increases in thickness. The soil material in microhighs is extremely dense.

The ice lenses were not found within microdepressions; the soil can be dug with a shovel from the surface.

3.3. Soil structure

Soil structure in the three key-sites generally reflects the pattern of cryogenic texture (table 3).

Platy and wedge-shaped-platy soil structures were described within the microhighs in soils of the Chalky polygons till the depth of 90 cm. There was a gradual trend from strong plates 1 mm thick at a depth of 5-10 cm to moderate platy aggregates 10-12 mm thick at a depth of 50-90 cm. The soil mass within microdepressions was less structured (crumbly and cloddy aggregates) without evidence of platy aggregates.

The soils of the Thufur were structured into fine plates and clods; the plate were slightly better expressed in the microhighs. The clear and thicker platy structures appeared at a same horizontal level which was about 70 cm depth from the surface of the microhighs and ~ 30 cm in the microdepressions due to the amplitude of the microrelief. The thickness of platy structures was the same without any change with depth.
The structure in the soils of the Heave mounds was platy. In the microhighs it appeared at a depth ~8 cm, was clear and strong. Their thickness increased from 1-2 mm up to 15-20 mm at a depth of 140-180 cm. The soil structure in microdepression combined crumbly, cloddy and granular aggregates.

**Table 3.** Characteristics of soil structure.

| Key site          | Depth, cm | Soil structure* | Thickness of platy structure, mm | Depth to platy structure, cm |
|-------------------|-----------|-----------------|----------------------------------|-------------------------------|
|                   | MH        | MD              | MH                              | MD                            |
| 1. Chalky polygons| 0-10      | Cr+Pl           | Cr                              | ~1 abs.                       | ~90 abs.                     |
|                   | 15-25     | Pl+We           | Cr+Cl                           | 1-2 abs.                      | abs.                         |
|                   | 25-35     | Pl+We           | Cr+Cl                           | 2-4 abs.                      | abs.                         |
| 2. Thufurs        | 7-30      | Pl              | Pl                              | ~1 ~1                         | ~120 ~70                     |
| 3. Heaving mounds | 0-8       | Pl              | Cr+Cl+Gr                        | 1-2 abs.                      | ~180 abs.                    |
|                   | 8-20      | We+Pl           | Cr+Cl+Gr                        | 1-2 abs.                      | abs.                         |
|                   | 20-30     | We+Pl           | Cr+Cl+Gr                        | 2-4 abs.                      | abs.                         |

* MH – microhigh, MD – microdepression; Cr – crumbly, Cl – cloddy, Gr – granular, Pl – platy, We – wedge-shaped

**4. Discussion**

The winter formation of ice lenses was found in soils of accumulative and trans-accumulative landscapes with polygonal microlief in Trans-Volga-Urals region. The intensity and degree ice formation (the morphology and thickness of ice lenses) was variable at different key-sites and depending on the position in microlief.

Formation of ice lenses was caused by water saturation. In the most waterlogged conditions of the Thufurs key-site, the ice lenses were found without regard to the position in the microlief allalong the frozen layer up to a depth of 30 cm in soils. The soils both of the microhighs and microdepressions, had practically similar cryogenic texture. In less humid landscapes (Chalky polygons and Heave mounds key-sites) the cryogenic texture was better expressed within the microhighs, while within the depressions the ice lenses were absent. The thickness of soil material between the ice lenses was minimal (~1 cm) in the most humid conditions (Thufurs), and it was increasing with depth from 1 to 4 cm in soils the Chalky polygons and Heave mounds, in drier pedoenvironment. The increasing size of the ice lenses with depth is known and corresponds to the decrease of temperature gradient with the depth [23].

The grade of platy soil structure correlates with the cryogenic texture (figure 4) that confirms the cryogenic mechanism of its formation in all investigated soils. The most prominent platy structure was discovered in the Heave mounds key-site. We expect this is related to most clayey texture of these soils comparing with other key-sites.

The differences in hydrothermic regimes are expected to be responsible for the various grade or development of platy structure between the microgighs and microdepressions. To confirm this hypothesis we initiated the measurements of temperature regime and moisture dynamics in soils of microhighs and microdepressions on the key-sites. However in soil of microdepressions from the Chalky polygons key-site we found the inclined platy microstructure in the thin-sections [1] that can indicate either weak process of ice lenses and platy aggregates formation in the microdepressions or more rare, not perennial ice formation there.
The winter formation of ice lenses leads to the differentiated frost heaving of tops of the microhighs and the off-freezing of coarse fraction (gravel) that we have registered in the Chalky polygons [2]. However, this phenomenon is widespread in the region.

Figure 4. The cryogenic texture (left) and soil structure (right) of the upper horizons: (a) – Chalky polygons; (b) – Thufurs; (c) – Heave mounds.

5. Conclusion
The platy structure is not typical for the soils in steppe environment, meanwhile it is well developed in soils at all investigated key-sites in Trans-Volga-Urals region.

Morphological analysis and the correlation of the cryogenic texture and soil structure confirmed our expectation that the platy structure could be generated in soil of steppe environment due to the
formation of ice lenses. The thickness of the layers with cryogenic structure corresponds generally to the average depth of soil freezing.

The formation of ice lenses is related to the additional moisture. The polygonal microrelief is a factor of subsoil water redistribution and of differentiation of the hydrothermal regime of soils on microhighs and microdepressions. The subsoil moisture moves upward toward the soil surface in the microhighs which promotes to the more active formation of ice lenses and platy structure there. Parent material is also significant for the morphology of the microrelief, cryogenic texture, and cryogenic soil structure. The most prominent platy structure was found in more clayey soils.

As a result our investigation has shown that the formation of segregated ice and cryogenic soil structure could be active and prominent in in mid-latitudes under a favorable combination of climate and local factors.

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References

[1] Kovda I, Ryabukha A and Polyakov D 2019 Cryogenic processes in soils of chalky landscapes in steppe zone south of the Orenburg region IOP Conference Series: Earth and Environmental Science 368 012026 doi:10.1088/1755-1315/368/1/012026

[2] Kovda I, Polyakov D, Ryabukha A, Lebedeva M and Khaydapova D 2021 Microrelief and spatial heterogeneity of soils on limestone, SubUral plateau, Russia: attributes and mechanism of formation Soil &Till. Res. 209 104931 doi:10.1016/j.still.2021.104931

[3] Khitrov N B and Rogovneva L V 2014 Vertisols and vertic soils of the middle and lower Volga regions Eurasian Soil Science 47 pp 1167-1186 doi:10.1134/S1064229314090063

[4] Zaidel’man F R, Ustinov M T and Pakhomova E Yu 2010 Solods of the Baraba Lowland and the Priobskoe Plateau: their properties and genesis and the methods of their diagnostics Eurasian Soil Science 43(10) pp1069–1082

[5] Lebedeva M P and Konyushkova M V 2011 Temporal changes in the microfabrics of virgin and reclaimed solonetzes at the Dzhanbybek Research Station Eurasian Soil Science 44 pp 753-765 doi: 10.1134/S1064229311070106

[6] Shabanova N P, Kolesnikov A V and Bykov A V 2015 Morphological and chemical properties of soils on the eastern shore of Lake Bulukhta, northern Caspian region Eurasian Soil Science 48 pp 781-791 doi:10.1134/S1064229315080074

[7] Tarnocai C and Bockheim J 2011 Cryosolic soils of Canada: Genesies, distribution, and classification Canadian Journal of Soil Science 91(5) pp 749-762 doi:10.4141/cjss10020

[8] Gubin S V and Lupachev A V 2017 Soils of loamy watersheds of coastal tundra in the north of Yakutia: pedogenetic conditions and processes Eurasian Soil Science 50 pp 133-141 doi:10.1134/S1064229317020041

[9] Gorbok S N, Bezuglova O S, Abrosimov K N, Skvortsova E B, Tagiverdiev S S and Morozov I V 2016 Physical properties of soils in Rostov agglomeration Eurasian Soil Science 49 pp 898-907 doi:10.1134/S106422931606003X

[10] D’Amico M E, Pintaldi E, Catoni M, Freppaz M and Bonifacio E 2019 Pleistocene periglacial imprinting on polygenetic soils and paleosols in the SW Italian Alps Catena 174 pp 269-284 doi:10.1016/j.catena.2018.11.019.

[11] Pobedintzeva I G 1975 Soils on ancient weathering crusts (Moscow: Moscow State University Press) p 191

[12] Ping C L, Michaelson G J, Kimble J M, Romanovsky V E, Shur Y L, Swanson D K and Walker D A 2008 Cryogenesis and soil formation along a bioclimate gradient in Arctic North America Journal of Geophysical Research 113(G3) doi:10.1029/2008jg000744
[13] Lebedeva I I and Gerasimova M I 2009 Factors of soil formation in soil classification systems *Eurasian Soil Science* **42(12)** pp 1412-1418 doi: 10.1134/S1064229309120138

[14] Goryachkin S V 2010 *Soil cover of the North (patterns, genesis, ecology, evolution)* (Moscow: GEOS) p 414

[15] Bockheim J G 2015 *Cryogenic Soil Processes Cryopedology* (Heidelberg-New York-Dordrecht-London: Springer Press) p 177

[16] Verba (Lebedeva) M P, Kulakova N I and Yamnova I A 2006 Genesis and Properties of Dark-Colored Chernozem-Like Soils of Mesodepressions under Fallow in the Northern Caspian Region *Eurasian Soil Science* **39 (9)** pp 990-1001

[17] Shabanova N P and Lebedeva M P 2016 Properties of solonetzes on terraces of salt lakes Bulukhta and Khaki in the Caspian Lowland *Eurasian Soil Science* **49** pp 591-605 doi: 10.7868/S0032180X16060113

[18] Voskresensky S S, Leontiev O K and Spiridonov A I 1980 *Geomorphological zoning of the USSR and adjacent seas* (Moscow: Higher School) p 343

[19] *Geographical Atlas of the Orenburg Region* 2020 (Orenburg: Institute of Steppe) p 159

[20] Popov A I, Rozenbaum G E and Tumel N V 1985 *Cryolithology* (Moscow: Moscow State University Press) p 239

[21] French H and Shur Y 2010 The principles of cryostratigraphy *Earth-Science Reviews* **101(3-4)** pp 190-206 doi:10.1016/j.earscirev.2010.04.002

[22] FAO 2006 *Guidelines for soil description/ 4th edition* (Rome: FAO) p 97

[23] Badu Yu B 2010 *Cryolithology* (Moscow: Moscow State University, University book house) p 528