Soil & Tillage Research 209 (2021) 104931

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Microrelief and spatial heterogeneity of soils on limestone, Sub Ural plateau, Russia: Attributes and mechanism of formation

Irina Kovda [a,*], Dmitry Polyakov [b], Anna Ryabukha [b], Marina Lebedeva [a], Dolgor Khaydapova [c]

[a] Dokuchaev Soil Science Institute, 119017, Moscow, Russia
[b] Institute of Steppe, Ural Branch of Russian Academy of Sciences, 460000, Orenburg, Russia
[c] Soil Science Faculty, Moscow State University, 119992, Moscow, Russia

ARTICLE INFO

Keywords:
Steppe zone
Polygonal microrelief
Complex soil cover
Cryoturbations
Involutions and intrusions
Macro and micromorphology
Texture
Coarse fraction
Rheology
Modern and relict cryogenic features and processes

ABSTRACT

Complex soil cover and microrelief are common for arid environments. Understanding of the genesis and functioning of complex soil cover associated with microrelief is important to ensure optimal land use.

We studied "chalk polygons" formed on the shallow limestone in the south of the European part of Russia including microrelief and soil morphology, and the main physical and chemical properties of the representative horizons.

The microrelief consists of regular microhighs separated by polygonal network of elongated microdepressions. The soil cover includes Rendzic Endoleptic Calcaric Phaeozem (Relictiturbic, Tonguic) in microdepressions, Skeletic Calcaric Regosol (Relictiturbic, Raptic, Ochric) in microslopes and Skeletic Calcaric Regosol (Relictiturbic, Raptic, Nudiyermik) in microhighs. The soils consist of three main layers with abrupt boundaries: dark grey and grey, brownish-pale turbated, and white soft and hard limestone. Hard limestone from the bottom of microdepressions is connected with the surface white "chalk caps" on the microhighs via the soft limestone intrusions across the microslopes. Morphological analysis and micromorphology revealed a number of cryogenic features such as large wedge-shaped structures in microdepressions, mosaic profile, turbated horizons, involutions and intrusions, platy soil structure. In the absence of permafrost a number of macromorphological attributes are apparently relict, while meso- and microcryogenic features could be modern, formed during winter freezing.

Limestone intrusions being relict determine the modern structure and functioning of the soil complex. They consist of disintegrated limestone gravel incorporated into soft powdery limestone, and exhibit plastic behavior when wet. Rheological characteristics confirm that the material of limestone intrusion has reduced shear resistance, and a lower range of elastic behavior and yield strength. Intrusions are the channels of water migration from the wettest microdepressions to the dry microhights. Ice lenses form in wet limestone intrusions in winter. Ice formation inside the limestone intrusions induces the frost lift and refreshment of the "chalk cap". Thus, intrusions support the spatial and intra-profile heterogeneity, especially of morphology, texture and particle-size distribution.

Active "chalk polygons" have local distribution in steppe areas with shallow limestone and concave topography, and demonstrate unique morphology, and physical and chemical attributes. The arid climate, insufficient precipitation, and annual self-restoration make grazing the optimal agricultural use of these landscapes. Otherwise relict genesis of "chalk polygons" and their unique attributes suggest their preservation as conservation areas.

1. Introduction

Rational agricultural use of soils is based on a scientific approach and use of optimal agricultural technologies to provide the greatest profitability and preservation of soil fertility and diversity. Heterogeneity or spatial variability of the soil cover i.e. soil morphological, chemical and physical attributes complicates the agricultural use and requests new technologies.

* Corresponding author.
E-mail address: ikovda@mail.ru (I. Kovda).

https://doi.org/10.1016/j.still.2021.104931
Received 22 July 2020; Received in revised form 12 December 2020; Accepted 30 December 2020
Available online 24 January 2021

One of the main factors resulting in the complexity and diversity of soil cover is the microrelief, which occurs widely in the world, may have various abiotic or biotic origins, a random or regular pattern. Cramer et al. (2012) overviewed regularly spaced non-anthropogenic earth mounds, which are known under various local names over large areas in different continents and countries such as campos de murundus in Brazil, pimple mounds, hogwallow mounds, prairie mounds, and mima-mounds in north America, heuweltjies in eastern and southern Africa. The age of these mounds was found to be mostly ancient, from 0.7 to 30 kyrs, and they can be inherited and relict (Cramer et al., 2012; Diaz et al., 2016). Biological (termite, vegetation, small vertabrates), geological and pedogenic (shrinking/swelling, limestone faulting, erosion, and aeolian processes), seismic or frost-induced hypotheses are known amongst others to explain its genesis (Cramer et al., 2012; Cramer and Barger, 2014). In some cases only complex and polygenetic origin with combination of bioturbation, seasonal frost action, and erosion processes, with occasional eolian inputs may explain the mounded landscape with well sorted stone borders, and the poorly sorted rubbly soil intermound pavements, such as described in low prairie in northern California (Johnson and Johnson, 2012).

Microrelief of various origin and related complex soil cover are common in Russian landscapes. Microrelief gilgai, associated with clayey soils (Vertisols), results from shrinking-swelling and lateral shearing (Kovda et al., 2003; Khitrov, 2016). Microrelief and complex soil cover on loess can be related to suffusion depressions (Kutovaya et al., 2016). Microrelief in the arid environment of the Caspian Lowland is explained by the subsurface redistribution of salts and changes in density of soils with the formation of microdepressions in areas of leaching and microhighs in the zones of evaporation and salt accumulation (Konyushkova and Abaturov, 2016), or by the zoogenic origin. The digging activity of little souslik (*Spermophilus pygmaeus* Pall.) may form microhighs (Shabanova et al., 2014), otherwise its vertical burrows lead to stronger wetting, desalinization, and suffusion resulted in the formation of microdepressions (Abaturov, 2010).

Microrelief associated with cryogenic processes is common in northern Russia (tundra and northern taiga) or cryoarid steppes in the East of the Asian part of Russia. Various forms and mechanisms of cryogenic microrelief are known related mainly to the alternation of freezing and thawing of water-saturated ground masses (French, 2018). The diversity of the cryogenic microrelief is determined by a combination of regional and local conditions (Garankina, 2013). Polygonal microrelief associated with cryogenic processes and permafrost is characteristic for periglacial tundra landscapes (Kravtsova et al., 2019).

Paleocryogenic microrelief was discovered in the southern taiga and forest-steppe zone of the European part of Russia and is almost not recognizable at present (Velichko et al., 1996). However paleocryogenic microrelief is reflected in the complexity of the soil cover and spatial differentiation of modern soil processes (Velichko et al., 1987; Alifanov et al., 2010). Late Pleistocene cryogenic processes with the formation of polygonal wedge ice about 22−14 kyrs ago were largely identified in central Russia. Modern surface microtopography is controlled by the buried paleocryogenic polygonal network of alternating blocks and hollows (Ovchinnikov et al., 2020).

Nowadays paleocryogenic microrelif is known to be a common feature for large territories of the whole East European Plain and many countries of the northern and central Europe such as in France, Poland, Spain, Ukraine, United Kingdom etc. (Bateman et al., 2014; Bertran et al., 2014; Novak and Fedorovych, 2015; Rodríguez-Ochoa et al., 2019). Vandenberghe et al. (2014) have summarized and shown on the maps the former extent of permafrost in Northern Hemisphere at the time of Last Permafrost Maximim 25−17 ka BP, and extended the permafrost zone almost to the Mediterranean Sea in the Western Europe, Black and Caspian seas in the Eastern Europe, plains of Kazakhstan, north-east, north and west of China in Asia, Mid-Atlantic Coastal Plain of the USA.

Microrelief of any genesis leads to the spatial diversity of soil properties, including water and temperature distributions in the soil cover, other physical, chemical, and morphological attributes, which are important for the practical problems of the land use and the distribution of agricultural practices, as well as the approaches to the assessment of the spatial heterogeneity of the soil properties and the development of threedimensional models of the heat and water transfer (Shein and Troshina, 2012). Microrelief strongly impact the physical processes and influence the process of water infiltration, runoff and erosion (He et al., 2018). Paleocryogenic microrelief, even being non-prominent or buried, impacts the surface soil cover pattern and the degree of soil erosion (Ovchinnikov et al., 2020; Khudyakov et al., 2020).

Specific landscapes with complex vegetation cover and pronounced polygonal microrelief occur locally on shallow Cretaceous limestone within the steppe zone in the South of the European part of Russia (Fig. 1). Their genesis is still insufficiently studied and remains debatable. Polygonal microrelief there was explained by the seasonal cryogenesis combined with dissolution and mechanical destruction of limestone rocks by ground water (Mikhno, 1993; Kliment'ev et al., 2001), as well as by swelling of clay after seasonal moistening (Chibilev et al., 2000). Both hypotheses were based on the external configuration of polygonal microrelief without examination of the internal structure.

The aim of our research was to study the morphology of polygonal microrelief on limestone and its internal structure in order to understand their genesis, modern functioning and optimal land use.

2. Materials and methods

2.1. Location and physiography

The key site "Novopavlovsky chalk polygons" is located to the east of the Novopavlovka village of the Akbulak district, Orenburg region (51°08′10″ N, 55°37′16″ W) and covers an area of about 6 ha on the gentle concave slope of Akmola valley at an abs. height of ~185 m a.s.l. (Fig. 1).

The territory is located in the extreme South-East of the East European Plain. This part of the Podural-Ilek Upland steppe province belongs to subboreal continental East European dry-steppe landscapes (Bekhterev, 2000).

The climate is continental with a mean annual air temperature of +4°C. Winter is cold (mean T_{Jan} -15°C, shallow snow cover up to 30 cm, strong soil freezing up to 140 cm). Summer is hot and dry with mean T_{july} +21°C. Evaporation (800−900 mm) prevails over precipitation (260−390 mm) (Sokolov, 2020).

The steppe vegetation comprises bunchgrasses with *Festuca* sp. and *Stipa* sp. domination (Sokolov, 2020). The density of vegetation cover is heterogeneous: sparse vegetation on the mounds and dense vegetation cover in the depressions. Soil-forming material is loess-like loam underlain by hard limestone of the Maastrichtian layer (biogenic limestone or chalk). The ground water is generally at a depth of 3−4 m.

Several areas with similar surface features (microtopography with white spots on the surface) were identified on the satellite images. During the field observations we found that polygonal microrelief differ by lateral size, vertical amplitude, surface (with our without vegetation), presence or absence of fresh limestone on the surface. For this study we chose the key site 'Novopavlovsky" as an "active" and typical one, having the prominent network of regular polygonal microrelief characterized by high vertical amplitude and "fresh" white surface.

2.2. Field methods

The soils of "chalk polygons" were studied in the trench (400 × 120 cm, 120 cm depth) across the depression located between the tops of two "chalk" microhighs. Small pits, to a depth of 0.6−0.8 m, were additionally studied on the various elements of the microrelief around the trench. Additional trench was excavated across the shallow "passive chalk polygons" with less prominent and more turfed

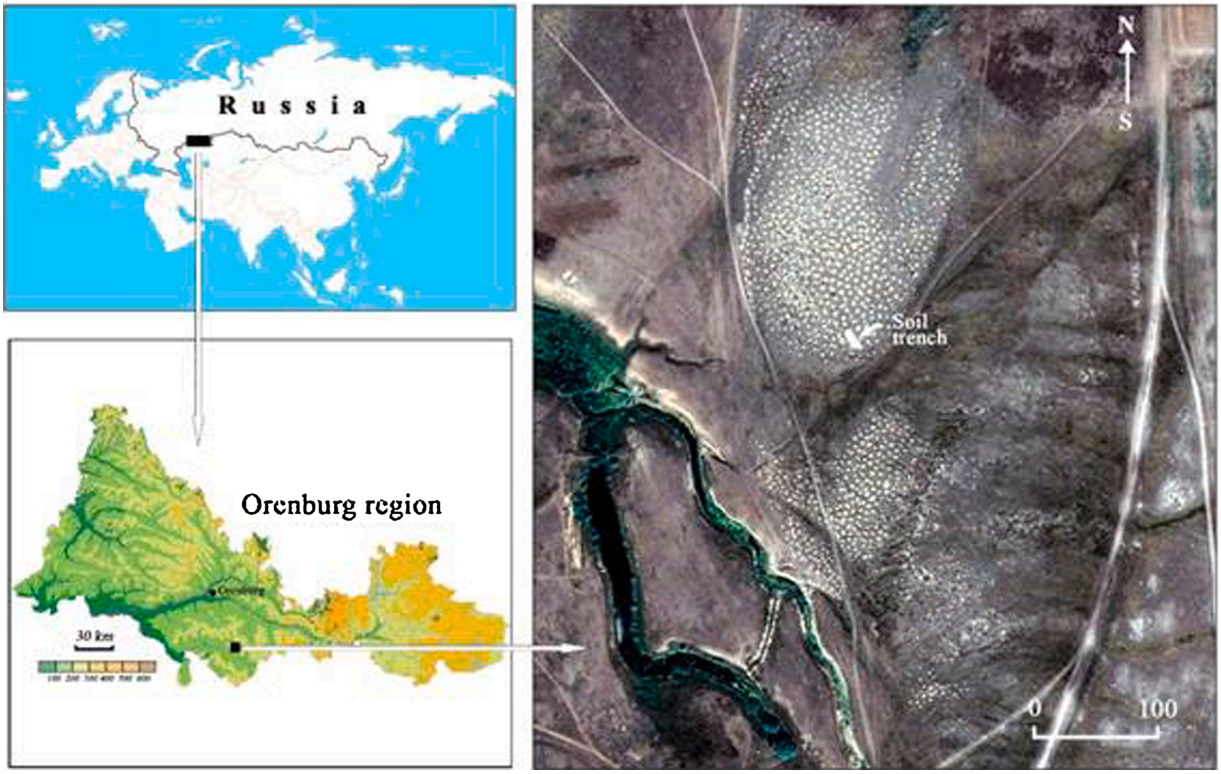

Fig. 1. Location and aerial photograph of the key-site with polygonal microrelief on Cretaceous limestone, Subural plateau, Orenburg region, Russia.

microrelief located at a distance on the less concave geomorphological position.

Soils were classified using the World Reference Base (IUSS WG WRB, 2015). Soil morphology was described according to Guidelines for Soil Description (FAO, 2006). Strong differences in soil morphology were found between four soil profiles from the frontal, back, left and right walls of the trench. The four profiles were described and fixed in the schemes and photos. Two horizontal sections of the trench were fixed and studied at depths of 30 cm and 60 cm. Bulk samples for physical and chemical analyses, and undisturbed soil clods for thin sections, were taken from the main morphological elements of the upper subsoil in the microhigh, microslope and microdepression.

2.3. Laboratory methods

Total carbon (STC) was determined by dry combustion at 900–1000 °C in the current of pure oxygen using the Express analyzer AH-7529 (Russia); inorganic carbon (SIC) – by the release of CO_2 formed when interacting with hydrochloric acid. The concentration of organic carbon (SOC) was calculated as the difference between total and inorganic carbon.

The particle size distribution was determined by two methods. The fractions > 0.25 mm were obtained by sieving (d 0.25, 1, 2, 3, 5, 7, 10 mm); the fractions <0.25 mm – by pipette method based on the rate of sedimentation of particles in standing water (Shein et al., 2001). The texture was classified according USDA (Ditzler et al., 2017).

The form of rock fragments (fine and medium limestone gravel 2–20 mm) was estimated according to shape (isometric, elongated and flat) and degree of roundness (angular, subangular, subrounded and rounded) (Schoeneberger et al., 2012). Subangular and angular fine gravel was combined into an "edged with prominent faces" group. Subrounded and rounded gravel was combined into a "smoothed with smooth or missing edges" group. The amount of gravel fraction in the specimens was calculated in pieces and normalized per kg of soil.

The rheological properties were determined by the amplitude sweeps method on the MCR-302 rheometer (Anton Paar, Austria) in: 1) the material of the limestone ("chalk") intrusion from the middle part of the microslope (30–67 cm), 2) the darkest humus horizon (0–10 cm) of the microdepression, and 3) the material at three depths on the microhigh; the upper dark grey and grey humus horizon (0–13 cm), and two brownish-pale turbated horizons (30–48 and 108–124 cm). Specimens were located between two parallel plates and subjected to shear deformation in an oscillatory mode with an increasing amplitude (Mezger, 2011).

The measurements were performed in grounded 3 g specimens sieved through a sieve of 1 mm diameter, at the humidity of the daily capillary moisture saturation with a control of normal pressure force of the upper plateau <1 N, in triplicate. The other technical conditions were the same as in Markgraf et al. (2006). Statistical processing was performed using Excel. The following parameters were determined: linear viscoelasticity range (LVE-range), elastic modulus (storage modulus G') in the linear viscoelasticity range, maximum shear stress, structure failure point (crossover).

Swelling was assessed indirectly from the thickness of the samples at the beginning of the experiment, to determine the rheological properties. An equal amount of air-dry material (3 g), absorbed a different amount of water as a result of capillary daily settling and acquired a different thickness. The change of thickness allow us to estimate, indirectly, the degree of swelling of the studied soils.

Undisturbed oriented blocks were impregnated with polysynthetic resin, mounted on glass slides (4 × 4 cm size), polished to 30 μm thickness and covered by glass for micromorphological examination in thin sections according to Stoops (2003). Optical examination of microfabric was performed under plane (PPL) and crossed-polarized (XPL) light modes at magnifications of 25x to 100 × .

3. Results and discussion

3.1. Morphology and Structure of "Chalk landscapes"

"Polygonal chalk landscapes" represent the parallel rows of white limestone microhighs in the form of convex polygons (pentagons or hexagons) and are known under the local name "chalk polygons". The average size of polygonal microrelief is ~5 m with the height about 0.3–0.5 m. Polygonal microhighs are separated by prominent elongated narrow depressions with the depth 0.1–0.15 m and 0.6–0.8 m width. Where depressions intersect at the corners of polygons they enlarge to 0.8–1.2 m width (Fig. 2A).

The highest parts of the microhighs are represented by white spots without vegetation rising 10–15 cm above the surface. We suggested to call these white spots the "chalk caps" (Fig. 2B). "Chalk caps" are the dense fine-dispersed crusts of disintegrated limestone with scattered inclusions of hard limestone gravel and belemnite fragments (Fig. 2C), covered with salt efflorescence (Fig. 2D) and subdivided by cracks into several large triangular fragments. The combination of these fragments resulted in the clear image of five- to six-pointed white stars (Fig. 2B)

The soil excavated in the trench is characterized by a mosaic profile instead of normal horizonation with a complex combination of three main layers: dark-grey and grey humus layer (fragments of A and Ah horizons), brownish-pale layer (combination of A/R'@, AC@,ACh@, AC/R'@ and R'/AC@ horizons) and white "chalk" material of limestone intrusion (R'@) and hard limestone eluvium (R) with various degrees of weathering, density and structure (Fig. 3).

The dark grey and grey layer is highly variable in thickness and color. Munsell colors (dry) within the humus horizon vary across the microrelief from 10 YR 8/1 (white) to 10 YR 7/1&7/2 (light grey) and 10 YR 5/1, 5/2 and 6/1 (grey and grayish brown). The humus horizon is poorly developed in the soil of the microhigh, and gradually increases in the microslope soil. The humus horizon is the darkest in soil in the microdepression, has the maximal thickness there, and penetrates into the limestone eluvium to a depth of ~ 100 cm in the form of a wedge with a fringed tail terminus. Horizontal sections fixed at a depth of 30 and 60 cm confirmed the lateral extension of the humus wedge across the trench. The loose sod horizon 1–2 cm thick on the microhighs increases to up to 2–4 cm in the microdepression. The structure is lumpy, organized into the medium prisms in the upper part with no evidence of platy structure. A few rare inclusions of dull fine limestone gravel occur in the humus horizon.

The white layer has a very bright color with abrupt irregular boundaries, complex configuration and consistence. At the bottom of the trench at the depths below 95–130 cm it consists of coarse, extremely hard, limestone eluvium (R). To the left and to the right of the dark wedge-shaped structure in the center of the frontal wall the white material arises towards the surface at an angle of ~45° forming the convoluted structures (Fig. 3). It consists of fine-dispersed limestone material with abundant inclusions of very fine to coarse limestone gravel and fragments with various degrees of roundness. Gravel accumulations follow the boundaries with the brownish-pale material.

In contrast to the dark grey and grey layer the white structures have limited lateral dimensions and the general image of curved veins or intrusions that break through the brownish-pale layer towards the "chalk cap" on microhighs. Additional study of the intrusions in the small pits confirmed their inclined orientation within the brownish-pale material, gradual narrowing towards the surface, and merging with the "chalk caps" (Fig. 3). The fine-grained mass of intrusions under the "chalk caps" has strong platy structure 2–4 to 8–10 mm thick, increasing with depth.

The brownish-pale soil horizons around the white limestone material are located mainly within microhighs and microslopes (Fig. 3) and characterized by: a turbulent pattern; the presence of thin vertical,

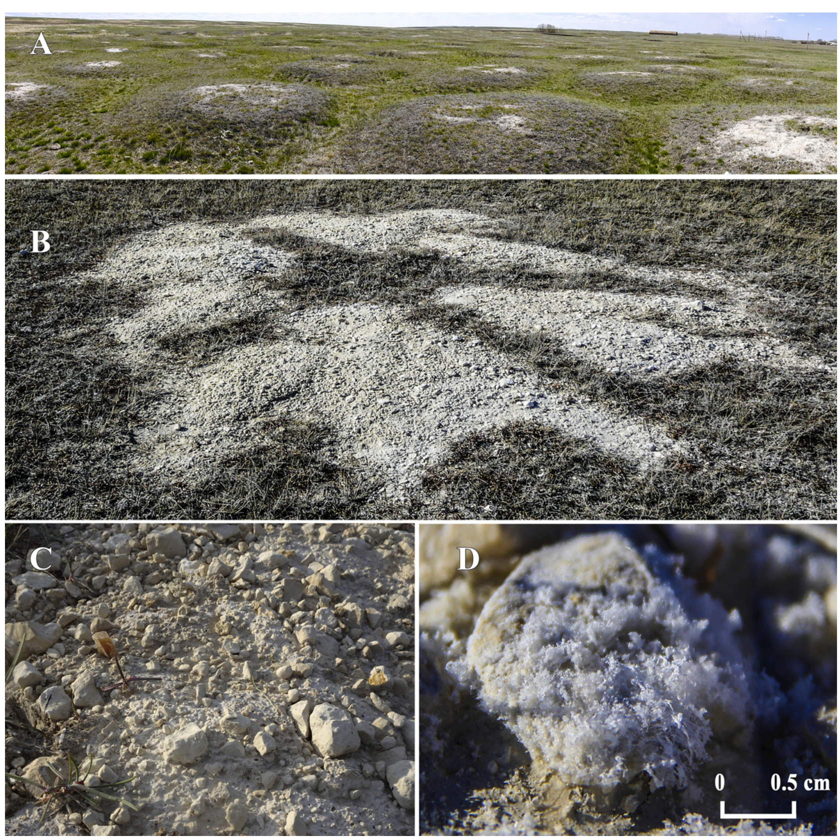

Fig. 2. A - General view of the "chalk polygons"; B - Fragmented limestone spot ("chalk cap") in the center of the microhigh; C – Surface crust consisting of disintegrated limestone with inclusions of limestone gravel and belemnite fragments; – D - Salt crystals at higher magnification on the surface of "chalk cap".

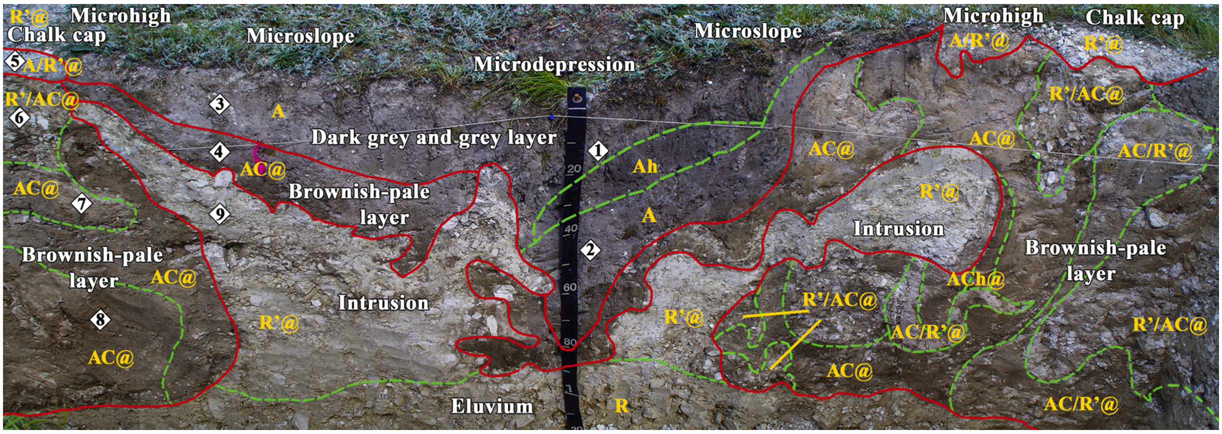

Fig. 3. Mosaic profile of the front wall of the trench across the "chalk polygons" (white diamonds indicate the sampling; red solid lines separate the main layers; green dashed lines separates mosaic morphological units).

inclined, or folded, brownish humus bands; rare limestone gravel; and a less pronounced platy structure <1 to 3–5 mm thick, increasing with depth. Upon drying brownish-pale material brightened strongly (Munsell color dry 10 YR 8/2, 8/1, 8.5/2 8.5/1, 7.5 YR 8.5/2) and acquired color very similar to dry white material (10 YR 8/1 and 9/1).

The distribution and the degree of roundness of the limestone gravel were extremely variable within the trench. The maximum correlation of limestone gravel was found in the limestone eluvium and "chalk caps". The amount of gravel decreased in the intrusions where the gravel is the most rounded. In the dark grey and grey layers, including the lower part of the wedge-shaped structure and turbated brownish-pale horizons, the amount of limestone gravel was minimal.

A weak salt effervescence appeared on the wall of the trench upon drying.

3.2. *Interpretation of morphological attributes*

Microrelief of the "chalk polygons" is characterized by a complex vertical and lateral structure. The soil profile combines the features of horizonation and mosaic organization, and this combination varies across the microrelief. Dark grey and grey humus horizons are most developed in the microdepression. The most monotonous brownish-pale material prevails in the soil profile of the microhighs. The transitional microslopes, which are intersected by limestone intrusions, have the most complex turbated and mosaic structure with involutions.

The different manifestation of morphological attributes and soil horizons, and their strong interdependence indicate the complex soil cover of "chalk polygons". According to the results of the field investigations the soils were preliminarily identified as Rendzic Endoleptic Calcaric Phaeozem (Relictiturbic, Tonguic) in microdepressions, Skeletic Calcaric Regosol (Relictiturbic, Raptic, Ochric) in microslopes and Skeletic Calcaric Regosol (Relictiturbic, Raptic, Nudiyermik) in microhighs.

Morphological attributes characteristic of Vertisol (vertic properties i.e. slickensides, wedge-shaped aggregates, clayey texture, stickiness and plasticity), Solonetz (natric horizon), or Solonchak (ground water, gleyic features, salic horizon), were not found in the trench which excludes a number of possible mechanisms of the microrelief formation, such as vertic, biogenic, suffusion, or high salt concentration.

However, a number of morphological features appear to be cryogenic. These are the polygonal pattern of the surface, the internal morphology of microrelief, selected soil attributes such as the wedge form of the humus horizon in the microdepression, the platy structure of several horizons, the mosaic structure of the soil profile, and the involutions, turbations, and intrusions.

The increased thickness of the humus horizon in microdepressions is characteristic of any microrelief and is usually associated with the redistribution of precipitation and related increase in plant biomass (Khitrov and Loiko, 2010). However, the clear wedge form of the humus horizon in the microdepression, and its large lateral size, are similar to pseudomorphs formed during frost dessication of soils into polygons in permafrost areas (Vandenberghe; et al., 2014; Streletskaya, 2017). Since the Orenburg region is out of permafrost area we interpret the formation of microrelief and humus wedges as relict.

The other cryogenic features we have described can be relict as well, or can form at the present time as consistent with the severe winters and deep freezing. Mosaic soil profiles are related to the physical deformations that may be the result of cryogenic processes in a permafrost environment (Ping et al., 2013; Bockheim, 2015; Gubin and Lupachev, 2017) or of shrink-swell processes in clayey smectite-rich soils (Williams et al., 1996; Kovda and Wilding, 2004; Khitrov et al., 2015; Pal, 2017). The shrinking/swelling mechanism was excluded, this is why we were interested to confirm if the microrelief, mosaic profile, involutions and intrusions can form by cryogenic processes at the present time.

The merging of limestone intrusions with the surface "chalk caps" indicates that intrusions are or used to be the source and provider of the limestone material to the microhighs and formed the microrelief. To answer what is their current functioning and does the limestone material arrive to the surface at the present time we investigated the attributes of the intrusions and the surrounding (hosting) groundmass.

3.3. *Analytical characteristics of intrusions and groundmass*

3.3.1. *Carbon*

The total carbon content (STC) is high and slightly variable from 9.7 % in turbated horizons to 10.5 % in the limestone intrusion. The high STC is related to the incorporation of limestone material into the groundmass of every soil horizon and corresponds to the visible changes in limestone concentrations in the soils. Converted to $CaCO_3$ equivalent it exceeds 57 % even in the humus layer of the microdepression and reaches ~93 % in the intrusion. The concentration of SOC has maximum in humus horizons (1.29–3.6 %) and is minimal in the brownish-pale horizons up to total absence in the white limestone material of intrusion and "chalk cap" (Table 1).

3.3.2. *Texture of fine material*

Soil texture is mainly silty clay (Fig. 4A) with the predominance of fine fractions and small amount of sand. Maximum of silt (up to ~48 %) was found in the turbated brownish-pale horizons of microhigh (specimens 6 and 7). At the top of the dark-grey horizon there is a slight increase of sand (~10 %) and silt (up to 55 %) and the texture is silty clay loam. The material of the intrusion has no evident differences from the

Table 1
Total, inorganic and organic Carbon concentrations in soils of "chalk polygons".

Specimen N°	Position in microrelief	Horizon, Munsell color (dry)	Depth, cm	STC %	SIC	SOC	$CaCO_3$. equiv.
1	Microdepression	A, 10YR 5/2	5–15	10.44 ± 0.4	6.84 ± 0.04	3.60 ± 0.08	57.0 ± 0.3
2		A, 10 YR 6/1	43–53	9.73 ± 0.05	8.44 ± 0.01	1.29 ± 0.05	70.3 ± 0.0
3	Microslope	A, 10 YR 7/2	3–13	10.27 ± 0.01	8.49 ± 0.01	1.78 ± 0.02	70.7 ± 0.1
4		AC@, 10 YR 8/2	15–25	10.24 ± 0.02	9.48 ± 0.24	0.76 ± 0.26	79.0 ± 1.9
5	Microhigh	A/R'@, 10 YR 8/1	0–10	10.35 ± 0.05	10.35 ± 0.05	–	86.2 ± 0.4
6		R'/AC@, 10 YR 8.5/1	10–20	10.43 ± 0.01	10.43 ± 0.01	–	86.9 ± 0.1
7		AC@, 10 YR 9/1	40–50	9.7 ± 0.08	9.34 ± 0.04	0.36 ± 0.12	77.8 ± 0.3
8		AC@, 10 YR 8.5/2	57–67	10.16 ± 0.04	10.16 ± 0.04	–	84.7 ± 0.3
9	Limestone intrusion	R'@, 10 YR 9/1	35–45	11.13 ± 0.05	11.13 ± 0.05	–	92.7 ± 0.4

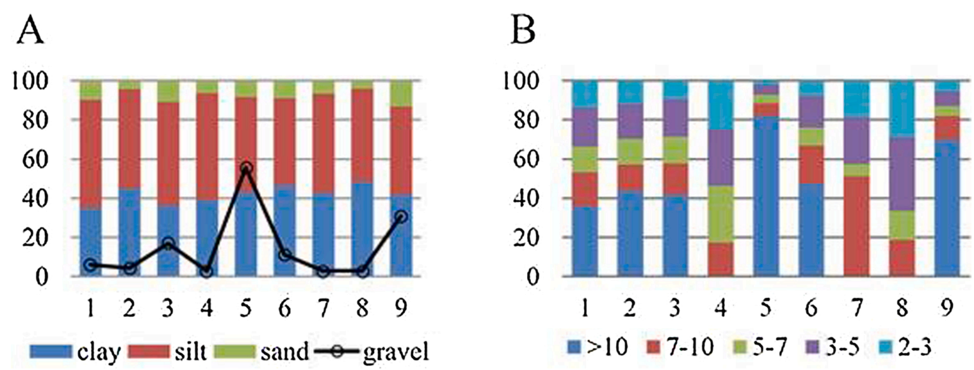

Fig. 4. A - Particle size composition of the fine earth and the proportion of rock fragments in the bulk samples,%; B - Size (mm) of rock fragments, %. Numbering of specimens (1-9) corresponds to Tables 1 and 2.

hosting brownish-pale groundmass except for the increased sand fraction to a maximum concentration of 13.3 %.

3.3.3. Distribution and size of rock fragments

The distribution of parent rock fragments (limestone gravel and stones) is highly variable. The maximal concentration of rock fragments was found in the intrusion (30.8 %), limestone material in the surface i.e. the "chalk cap" (55.5 %) and the subsurface horizon in the microhigh (11.2 %) (Fig. 4A). Some enrichment in rock fragments was found in the upper dark-grey humus layer of the microslope adjacent to the microhigh (16.9 %). The brownish-pale layer adjacent to the intrusion and the grey horizon in the lower part of the wedge-shaped humus horizon in the microdepression contain minimal rock fragments.

In contrast to the faint spatial differentiation of the fine earth texture and particle-size distribution, there is a strong spatial variation in rock fragment size (Fig. 4B). We identified the following groups of horizons: 1) limestone intrusions and "chalk cap" in the microhigh; 2) upper dark-grey part of humus horizon in the microslope, dark-grey and grey wedge-shaped structure in the microdepression, and the turbated brownish-pale material under the "chalk cap" in the microhigh; 3) turbated brownish-pale horizons and the lower part of the dark-grey horizon on the microslope – i.e. the groundmass hosting the limestone intrusion.

Rock fragments in the limestone intrusion and "chalk cap" (specimens 5 and 9) are characterized by medium to coarse (>10 mm) gravel. The dark-grey humus horizons of the microslope and wedge-shaped structure in the microdepression (specimens 1–3) show almost equal distribution of all fractions with domination of medium to coarse gravel. The turbated, brownish-pale, material of the microhigh under the "chalk cap" (specimen 6) tends to this group, but demonstrates an increased proportion of medium to coarse gravel. The brownish-pale horizons hosting the intrusion (specimens 4, 7 and 8) are characterized by the complete absence of medium to coarse gravel and the maximum of fine (3–5 mm) gravel.

3.3.4. Concentration and forms of fine and medium gravel

The concentration of gravel is highly variable from ~790 to 2840 pieces per kg of soil within the soils across the microrelief (Table 2). The limestone intrusion, "chalk cap" and the upper dark grey horizon in the microslope are enriched and contain the highest content of gravel (> 2425 pc kg^{-1}). The minimum of gravel was found in the horizons which are the most far from the "chalk cap" (791–1578 pc kg^{-1}).

Isometric gravel prevails everywhere. The maximum (78–80 %) concentration of isometric gravel was found in the limestone intrusion and the "chalk cap", the minimum was in the deepest subsoil (39–52 %). Decreasing of isometric gravel resulted in the increased proportion of elongated and flat forms. The maximum of elongated form corresponds to the lower part of the wedge-shaped structure (34 %). An increased portion of flat forms occurred in the lower, dark grey and turbated, brownish-pale, horizons (27–37 %).

The roundness of fine and medium gravel was also variable (Table 2). Predominating edged form (55–83 %) decreased in the intrusion to 33 %, while the smoothed form increased to 67 %. The dark-grey and grey layers of the microdepression and the microslope (specimens 1–3) are characterized by the maximum amount of edged gravel with a predominance of angular forms. The limestone intrusion and the "chalk cap" have the maximum of smoothed gravel; but the degree of roundness in the "chalk cap" was noticeably lower than in the limestone intrusion. Brownish-pale horizons immediately adjacent to the limestone intrusion and the "chalk cap" (specimens 4 and 6) are characterized by a relatively high concentration of smoothed gravel. The turbated brownish- pale layer of the microhigh (specimens 7 and 8) have a high concentration of edged mostly subangular fine gravel.

3.3.5. Rheological properties

Rheological studies were determined using the method of amplitude sweep, which allows estimation of the viscoelastic behavior of soils before the transition to viscous flow (Ghezzehei and Or, 2001; Markgraf et al., 2006; Khaidapova et al., 2016; Holthusen et al., 2017).

The upper dark grey horizons of the microdepression and the

Table 2
Amount and shape of fine and medium gravel (d 2−20 mm).

Nº of specimen*	Total	Isometric	Elongated	Flat	Edged			Smoothed		
					Total	including		Total	including	
						Angular	Subangular		Subrounded	Rounded
	PCs/kg	%								
1	1204	58	19	23	72	39	33	28	20	8
2	791	39	34	27	78	45	33	22	16	6
3	2843	61	26	13	83	55	28	17	13	4
4	969	49	22	29	67	27	40	33	23	10
5	2425	78	12	10	55	17	38	45	39	6
6	1578	58	23	19	63	23	40	37	28	9
7	861	41	22	37	75	28	47	25	22	3
8	1304	52	20	28	70	31	39	30	25	5
9	2787	80	17	3	33	13	20	67	44	23

* numbering of specimens corresponds to Table 1.

microhigh absorbed the largest amount of water (74 and 59 %), while the material of the limestone intrusion absorbed the least of water (Table 3). The absorbed water corresponds to the thickness of the specimens after daily capillary wetting and free swelling. The maximum swelling occurred in the dark grey and grey horizons of the micro-depression and microhigh. The swelling was minimal in the limestone material of the intrusion.

The range of linear viscoelastic behavior (LVE-range) characterizes the structural resistance to stress. The highest LVE-range was in the dark-grey and grey organic carbon enriched horizons of the micro-depression and the microhigh (Fig. 5A). These horizons also provided maximum shear resistance (300 and 280 Pa), while the other tested specimens (brownish- pale turbated layer and the limestone intrusion) were characterized by 4–5 times smaller values (Fig. 5C). Material from the limestone intrusion had the smallest LVE-range which means that the material from the intrusion was less resistant to stress (Fig. 5A). The crossover values that characterize the overall range of elastic-plastic behavior before the transition to the viscous flow area are also greatest in the upper dark grey and grey horizons of the microdepression and the microhigh (Fig. 5B). The brownish-pale turbated layer (108−124 cm) had the highest modulus of elasticity with maximum shear resistance; the limestone intrusion material had the weakest shear resistance (Fig. 5E).

Thus, the highest resistance to stress was shown by the dark grey and grey upper horizons, most affected by pedogenesis, and richest in organic matter, regardless of their location in the microdepression or in the microhigh. We expect this phenomena is probably due to the structuring influence of the organic matter. The elastic Modulus of the brownish-pale turbated horizons is slightly higher than the other variants in the LVE (undeformed state) and limestone material of the intrusion is the smallest both in the LVE-range state and at the maximum shear resistance (Fig. 5D). It is possible that the more elastic behavior of the brownish-pale turbated horizons and its greater swelling in comparison with the intrusion material contribute to the extrusion of the less resistant limestone material to the surface. The difference in the deformation behavior of adjacent soil materials appears to be the reason for the observed mosaic profiles due to uneven deformation and shearing.

Table 3
Daily absorbed water and estimated free swelling.

Position in microrelief	Horizon	Depth, cm	Humidity, %	Thickness of specimen, mm
Microdepression	A	0−10	73.95 ± 1.95	4.89 ± 0.23
Microhigh	A/R'@	0−10	59.08 ± 4.36	4.27 ± 0.19
	AC@	30−48	36.78 ± 0.48	3.07 ± 0.61
	AC@	108−124	44.18 ± 1.92	3.55 ± 0.03
Microslope	R'@	30−67	30.80 ± 4.96	1.85 ± 0.63

3.3.6. Micromorphology

Micromorphological investigation in thin sections revealed strong changes in microstructure and aggregation of limestone eluvium under pedogenesis. The lower horizon of limestone eluvium consists of dense homogeneous non-aggregated calcareous groundmass with chalk fragments with very weak degree of pedality and porosity, few ferriferous nodules and diffuse mottles, biogenic residuals, and calcitic b-fabric (Fig. 6A).

The groundmass of surface and subsurface soil horizons became highly aggregated due to soil formation, with strongly developed pedality and voids. "Chalk cap" consists of simple lenticular shaped, accommodated, peds separated by parallel subhorizontal plane voids (Fig. 6B). Dark micromass of the upper horizon in the microdepression is rich in organic fine material and fresh residues, is organized in well-developed inclined plates consisting of isometric and prolate aggregates (Fig. 6C–D). Upper soil horizons in the microslope and microhigh have distinctly less organic material and more carbonates than the microdepression. The groundmass in the microslope is more compact and less aggregated, with limestone inclusions and very fine isolated microfossils. Porosity is low; the voids are almost completely filled by secondary micritic calcite coatings (Fig. 6E–F). The microstructure in the upper horizon of microhigh is heterogenous. Calcite-rich large dense angular and subangular blocky peds are separated by large voids infilled by very fine peds and excrements (Fig. 6G–H). At the same time subangular blocky microstructure with dense angular aggregates separated by planar voids also occur in the microhigh (Fig. 6I–J). Abundant micrite calcite coatings are typical for microhigh despite the heterogeneity.

3.4. Interpretation of analytical data

The material of limestone intrusions consists almost entirely of inorganic carbon, i.e. crashed limestone, represented by coarse (sand and gravel) fractions incorporated into strongly disintegrated limestone material. The gravel fraction of the intrusion is characterized by the large size of the rock units, high degree of roundness, and the predominance of the isometric gravel, compared with the host groundmass. Rheological properties indicate that the limestone material of the intrusion has reduced shear resistance, reduced range of elastic behavior and yield strength.

The micromorphology indicates that initially dense and consolidated limestone is becoming disintegrated and reorganized in soil horizons affected by pedogenesis (dark-grey and grey, brownish-pale horizons, and intrusions). Hard limestone fragments with various degrees of roundness occur inside the loose strongly carbonate groundmass. The horizontal and inclined fracturing, lenticular and acute-angle aggregation of the groundmass suggest gradual ice formation in the wet, but unsaturated, soil (VanVliet Lanoe and Fox, 2018).

The sharp color contrast and abrupt boundaries of the limestone intrusions with the hosting brownish-pale material indicate that mixing

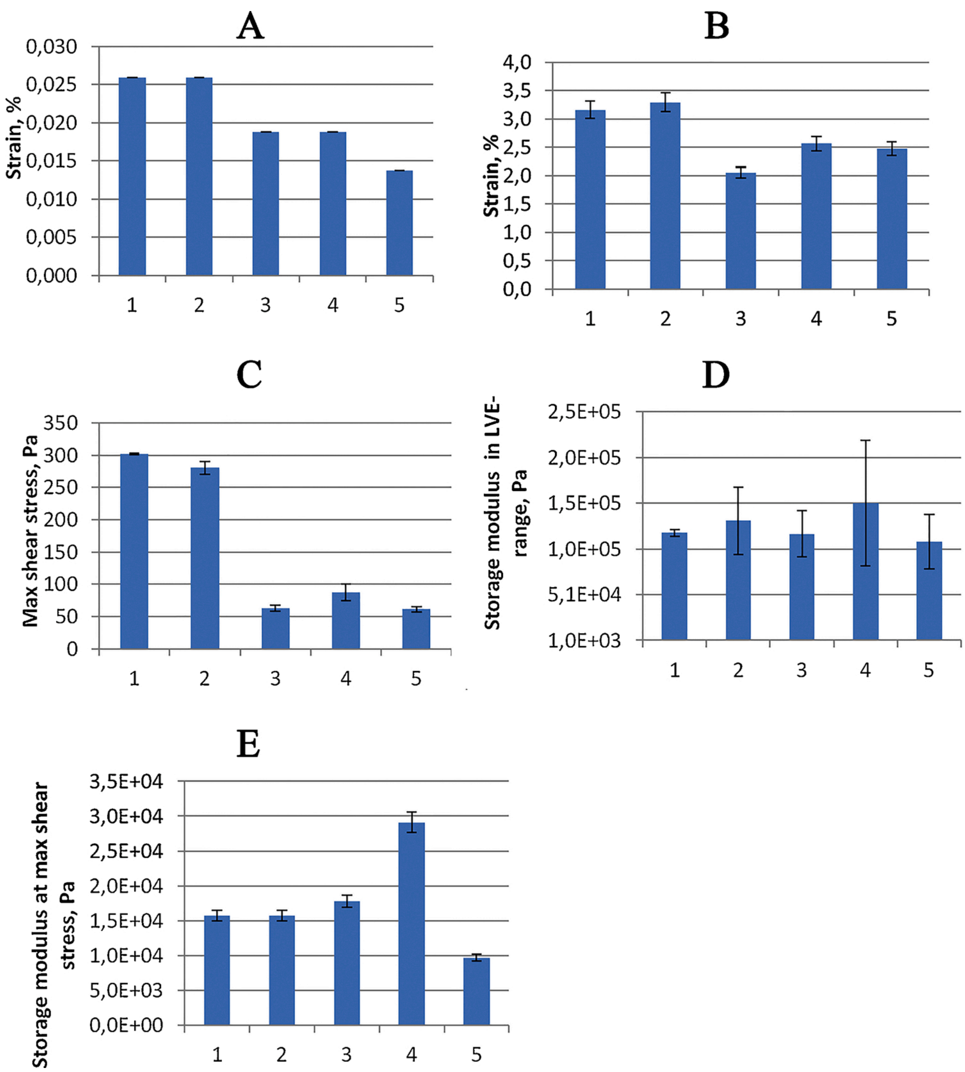

Fig. 5. A) - linear viscoelastic range (LVE-range),%; B) – crossover; C)- maximum of shear stress, Pa; D)- Storage modulus in LVE-range; E) – storage modulus at maximum shear stress obtained from rheological curves. 1) dark grey and grey horizon (A), microdepression 0-10 cm; 2) dark grey and grey horizon (A/R'@), microhigh 0-13 cm; 3) brownish-pale turbated horizon (AC@), microhigh 30-48 cm; 4) brownish-pale turbated horizon (AC@), microhigh 108-124 cm; 5) limestone intrusion (R'@), microslope 30-67 cm.

of these materials practically does not occur. At the same time intrusions are evidently the sources of limestone eluvium to the surface of microhighs, which resulted in the formation of the "chalk caps". In the process of translocation the edged limestone fragments became erased, and they gradually transformed into isometric rounded gravel with more or less smoothed edges.

What is the mechanism of formation of the limestone intrusions and microrelief? We suppose that originally the "chalk polygons" have been formed during the last stage of glaciation at the Late Pleistocene when Orenburg region was a part of a permafrost area. Although this region has not been known previously as permafrost or paleo-permafrost, this could be because of insufficient knowledge of this territory, while for the western, better studied territories of the central Russia (East European Plain), the permafrost and cryogenic landforms including hummocks, basins and polygonal microrelief with ice wedges have been already identified; and the permafrost area expanded over the major part of the East European Plain, north of 48–49 °N with periglacial steppe in the south (Velichko, Zelikson, 2005). The affiliation of Orenburg region with paleo-permafrost zone corresponds as well with conception of Vandenberghe et al. (2014) about wide distribution of permafrost during the late glacial maximum in Northern Hemisphere.

We believe that the network of cryogenic ice wedges contributed the initial formation of the intrusions of wet disintegrated limestone mass the same way as the formation of cryogenic microrelief occurs in the modern cryolithozone. Cryoturbated non-permafrost soils are known meanwhile out of the permafrost zone, but they have "gelic" or "cryic" temperature regimes and are located mainly at higher altitudes in the mountains (Kabala, 2013), unlike the Orenburg region.

Modern cryogenic processes maintain the activity of the microrelief and mosaic morphology of the relict "chalk polygons" locally in the areas with concave topography. Due to the concave topography these territories have additional ground moisture and are wetter than the other steppe territories around. It is known that the hardness of biogenic limestone (chalk) is decreased upon wetting and it becomes soft and plastic (flowing) when wet. At the same time biogenic limestone does not have frost resistance and becomes fragmented after few cycles of freezing/thawing.

At this point limestone intrusions play the role of channels for subsoil moisture migration from the wettest lower horizons of the microdepressions to the surface of drier microhighs. As it was found during the field examinations, in summer the material of limestone intrusions was wetter and more plastic than the hosting brownish-pale groundmass, while in winter it had the ice lenses or segregation ice. The evidence of segregation ice was also confirmed by platy aggregation found at macroscale and in the thin sections. Winter ice formation also explains the sorting, isometric shape, and roundness of limestone gravel in the intrusions as cryogenic.

The formation of ice lenses inside the limestone intrusions leads to increased volume, and contributes to the spring refreshment of the "chalk cap" on the surface of the microhighs. The fresh limestone gravel

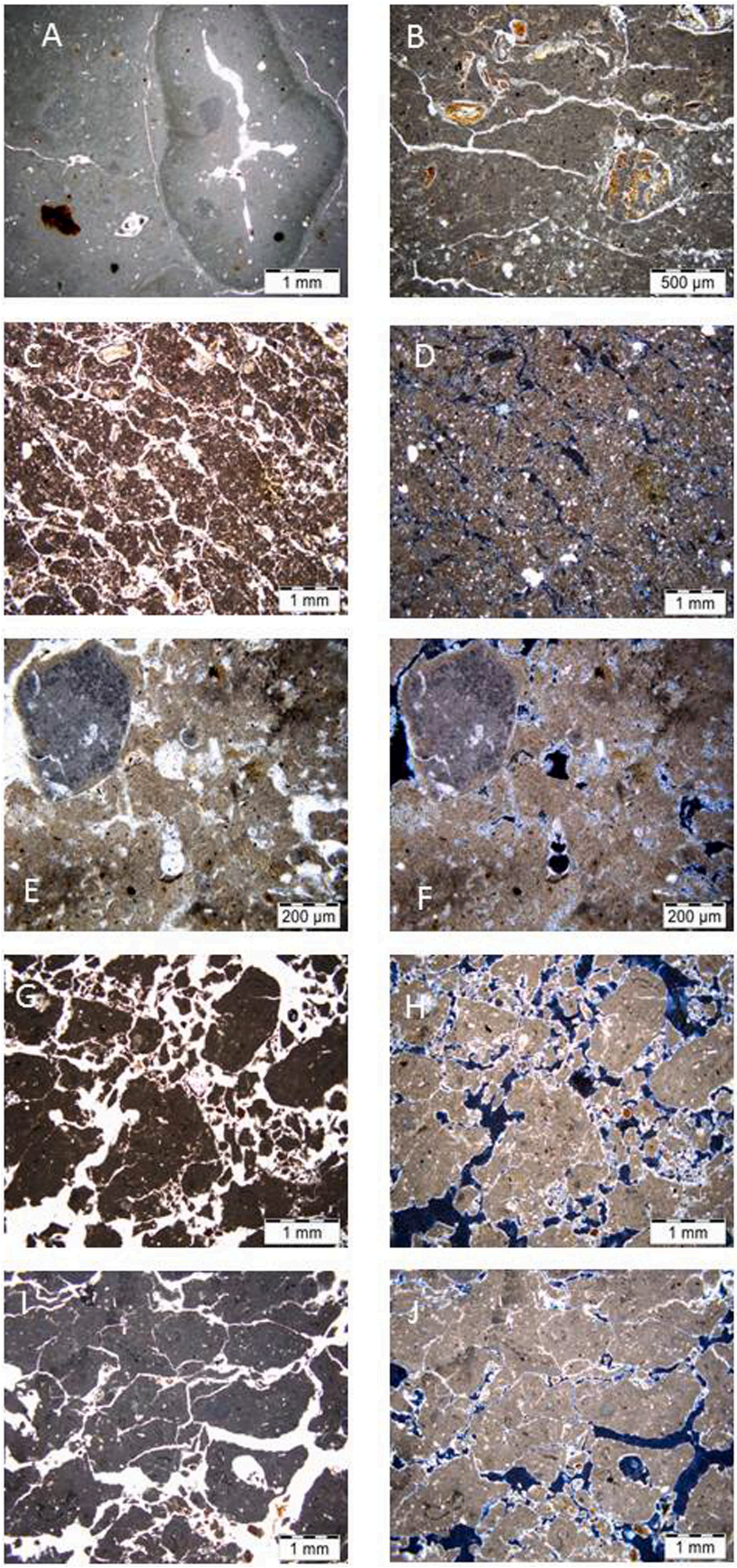

Fig. 6. A) Massive microstructure of compact calcite micromass with inclusions of fine Fe-nodules and a shell. The oval septaric nodule with dark organo-algal rim in the right upper corner (microslope, 95-100 cm; PPL); B – Lenticular-plates of variable composition with common weakly decayed organ residues; micro-zones of pure calcite aggregates and peds enriched in fine silt (microhigh, chalk cap; PPL); C, D –Grayish Brown calcite-rich groundmass with crystallitic b-fabric (in XPL) enriched in fine organic materials; strongly aggregated in crumbs and plates with numerous plant residues of variable size. Open porphyric c/f related distribution pattern, C/F limit at 30 μm, ratio of 10:90. Inclined subparallel planes are expected to follow the inclination of the paleocryogenic wedge filled by organic rich material (microdepression, 3-8 cm; C – PPL; D – XPL); E, F – Light brown calcite-rich groundmass with rounded limestone inclusion and fossils. Crystallitic b-fabric in XPL with clear micrite coatings and infillings in the voids. (microslope, 5-10 cm, E– PPL; F – XPL); G, H –Highly separated subangular peds consisting of calcite-rich groundmass with high concentration of organic fine material; abundant excrements and very fine angular aggregates in interaggregate pores (microhigh, 7-13 cm; G – PPL; H – XPL); I, J – Fractionation of calcite-rich groundmass into platy aggregates with angular and isometric subdivision; few thin roots residues and excrements in the bottom part (microhigh, 7-13 cm; I – PPL; J – XPL).

entering the "chalk cap" is subjected to cryogenic crushing with a decreasing in size and formation of edged morphology; surface erosion from microhigh to microdepression resulted in the redistribution of fine limestone gravel along the microrelief.

Thus, intrusions act as a factor that forms spatial and intra-profile heterogeneity of the morphology and physical attributes, especially texture and particle-size distribution, of "chalk polygons". At the same time microrelief and intrusions determine the modern functioning of these landscapes and impact the spatial differentiation of water and temperature regimes.

4. Conclusions

The soil cover of "chalk polygons" is complex and consists of three paragenetic soils: Skeletic Calcaric Regosol (Relictiturbic, Raptic, Nudiyermik), Skeletic Calcaric Regosol (Relictiturbic, Raptic, Ochric) and Rendzic Endoleptic Calcaric Phaeozem (Relictiturbic, Tonguic). The formation of the microrelief and soil complexes was determined by frost heaving, intra-soil movement of plastic limestone material via limestone intrusions from microdepressions to microhighs, and surface redistribution of the material along the microrelief from microhighs to microdepressions.

Morphological analysis of the soil complex revealed the relict cryogenic genesis of microrelief. Such morphological features as polygonal microrelief with a network of wedges, currently filled by dark humus horizons, turbated brownish-pale horizons and mosaic profile could be formed in the presence of permafrost only, which is absent at the present time in the Sub Ural plateau and European part of Russia in general except in the far north.

Passive and active "chalk polygons" currently occur in the steppe zone of the Sub-Ural plateau depending the topography. The active "chalk polygons" being in wetter concave landscape positions function as seasonal frost heave mounds due to the internal formation of ice and annual heaving in the subsurface parts of the intrusions. "Chalk polygons" stay passive in more flat positions where they do not have winter ice growing, self-restoration and annual refreshment of the syrface "chalk caps".

The soils of "chalk polygons" have unique morphology, physical and chemical attributes, and require special attention as special paleoenvironmental markers. At the same time "chalk polygons" demonstrate a set of features hampering productive agricultural use related to microrelief, subjacent limestone rock, and arid environment with moisture deficit during vegetation period: complex soil cover, mosaic profile, unfavorable physical and chemical attributes including low organic matter and high rockiness.

The soils of microhighs are especially unfavorable for crop plants. Their surface and subsurface horizons have highest proportion of gravel, limestone crust, and salt effervescence on the surface. The elevated pH and carbonate content are not suitable for crops cultivated in Orenburg region, and require specific physiological adaptation typical of calciphytes. In addition the microhights are colder and have abundant ice lenses in winter time, which contribute to the breaking of the roots; the intrusions act as the channels for the input of chalk gravel to the surface.

The relict cryogenic spatial and vertical organization of soils and self-maintenance of active "chalk polygons" via seasonal frost/thaw and heaving processes require extra actions for agricultural use. Taking into consideration the uniqueness of these landscapes and large areas of lands, available for agriculture in Orenburg region, it seems that the best economic utilization of "chalk polygons" is the organization of natural conservation areas for the preservation of their ecosystems. An alternative way of their use could be rangeland. Limited pasture could preserve the native steppe vegetation and landscape, and could be a good strategy for such landscapes to keep them as centers of biodiversity conservation.

Funding

This research was supported by Russian Foundation for Basic Research grant № 20-05-00556, Institute of Steppe of the Ural Branch of the Russian Academy of Sciences (project № AAAA-A17-117012610022-5), and V.V. Dokuchaev Soil Science Institute (project № AAAA-A19-119081690029-4).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.still.2021.104931.

References

Abaturov, B.D., 2010. Microdepressions microrelief of Caspian lowland and mechanisms of its formation. Aridnye Ekosistemy 16 (5), 31–45 (in Russian).
Alifanov, V.M., Gugalinskaya, L.A., Ovchinnikov, A.Yu., 2010. Paleocryogenesis and a Variety of Soils on the Centre of East European Plain. GEOS, Moscow (in Russian).
Bateman, M.D., Hitchens, S., Murton, J.B., Lee, J.R., Gibbard, Ph.L., 2014. The evolution of periglacial patterned ground in east Anglia. UK. J. of Quaternary Sci. 29 (4), 301–317. https://doi.org/10.1002/jqs.2704.
Bekhterev, I.A., 2000. Encyclopedia "Orenburg region". Nature. Golden Alley, Kaluga (in Russian).
Bertran, P., Andrieux, E., Antoine, P., Coutard, S., Deschodt, L., Gardere, P., Hernandez, M., Legentil, C., Lenoble, A., Liard, M., Mercier, N., Moine, O., Sitzia, L., Van Vliet-Lanoë, B., 2014. (July): distribution and chronology of Pleistocene permafrost features in France: database and first results. Boreas 43, 699–711. https://doi.org/10.1111/bor.12025.
Bockheim, J.G., 2015. Cryopedology. Springer, Cham. https://doi.org/10.1007/978-3-319-08485-5.
Chibilev, A.A., Musikhin, G.D., Pavleichik, V.M., Petrishchev, V.P., Sivokhip, Zh.T., 2000. Geological monuments of nature of the Orenburg Region. Orenburg Book Publishing House, Orenburg (in Russian).
Cramer, M.D., Barger, N.N., 2014. Are mima-like mounds the consequence of long-term stability of vegetation spatial patterning? Palaeogeogr., Palaeoclimat., Palaeoecol. 409, 72–83. https://doi.org/10.1016/j.palaeo.2014.04.026.
Cramer, M.D., Innes, S.N., Midgley, J.J., 2012. Hard evidence that heuweltjie earth mounds are relictual features produced by differential erosion. Palaeogeogr., Palaeoclimat., Palaeoecol. 350-352, 189–197.
Diaz, N., Dietrich, F., Cailleau, G., Sebag, D., Ngounou Ngatcha, B., Verrecchia, E.P., 2016. Geomorphology 261, 41–56.
Ditzler, C., Scheffe, K., Monger, H.C. (Eds.), 2017. Soil Science Division Staff. 2017. Soil Survey Manual. USDA Handbook 18. Government Printing Office, Washington, D.C.
FAO, 2006. Guidelines for Soil Description, 4th edition. FAO, Rome.
French, H.M., 2018. The Periglacial Environment, 4th edition. John Wiley & Sons, Chichester, UK, and Hoboken, New Jersey.
Garankina, E.V., 2013. Evolution of cryogenic microrelief in the low mountans of subarctic. Kriosfera zemli. 17 (3), 3–16 (in Russian).
Ghezzehei, T.A., Or, D., 2001. Rheological properties of wet soils and clays under steady and oscillatory stresses. Soil Sci. Soc. Am. J. 65, 624–637. https://doi.org/10.2136/sssaj2001.653624x.
Gubin, S.V., Lupachev, A.V., 2017. The role of frost boils in the development of cryozems on coastal lowlands of northern Yakutia. Euras. Soil Sci. 50, 1243–1254. https://doi.org/10.1134/S1064229317110072.
He, S., Quin, F., Zheng, Z., Li, T., 2018. Changes of soil microrelief and its effect on soil erosion under different rainfall patterns in a laboratory experiment. Catena 162, 203–215. https://doi.org/10.1016/j.catena.2017.11.010.
Holthusen, D., Pertile, P., Reichert, J.M., Horn, R., 2017. Controlled vertical stress in a modified amplitude sweep test (rheometry) for the determination of soil microstructure stability under transient stresses. Geoderma 295, 129–141. https://doi.org/10.1016/j.geoderma.2017.01.034.
IUSS Working Group W.R.B, 2015. World reference base for soil resources 2014 update 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No 106. FAO, Rome.
Johnson, D.L., Johnson, D.N., 2012. The polygenetic origin of prairie mounds in northeastern California. Horwath Burnham. In: Horwath Burnham, J.L., Johnson, D. L. (Eds.), Mima Mounds: The Case for Polygenesis and Bioturbation: Geol. Soc. of Am. Special Paper 490. https://doi.org/10.1130/2012.2490(06).
Kabala, C., 2013. Cryoturbated non-permafrost soils: origin, occurrence and classification problem. In: Szymanski, W. (Ed.), Frost- Affected Soils – Dynamic Soils in the Dynamic World, 6th Int. Conf. on Cryopedology, Inst. Of Geography and Spatial Management. Jagiellonian Univ., Krakow, Poland.
Khaidapova, D.D., Chestnova, V.V., Shein, E.V., Milanovskii, E. Yu., 2016. Rheological properties of typical Chernozems (Kursk oblast) under different land uses. Euras. Soil Sci. 49, 890–897. https://doi.org/10.1134/S1064229316080044.
Khitrov, N.B., 2016. Properties and regimes of Vertisols with gilgai microtopography (a review). Euras. Soil Sci. 49, 257–271. https://doi.org/10.1134/S1064229316030054.
Khitrov, N.B., Loiko, S.V., 2010. Soil cover patterns on flat interfluves in the Kamennaya Steppe. Euras. Soil Sci. 43, 1309–1321. https://doi.org/10.1134/S106422931012001X.

Khitrov, N.B., Vlasenko, V.P., Rukhovich, D.I., Bryzzhev, A.V., Kalinina, N.V., Rogovneva, L.V., 2015. The geography of vertisols and Vertic soils in the kuban-azov lowland. Euras. Soil Sci. 48, 671–688. https://doi.org/10.1134/s1064229315070042.
Khudyakov, O.I., Alifanov, V.M., Pletnev, P.A., Ovchinnikiv, A.Yu., Reshotkin, O.V., Bukhonov, A.V., 2020. Paleocryogenesis as a factor of heterogeneity of Agro-gray soil. Euras. Soil. Sci. 53 (10), 1437–1445.
Kliment'ev, A.I., Chibilev, A.A., Blokhin, E.V., Groshev, I.V., 2001. The Red Book of Soils of the Orenburg Region. UrO RAN, Yekaterinburg (in Russian).
Konyushkova, M.V., Abaturov, B.D., 2016. The specificities and properties of soils of solonetzic complex on the latest stages of development in the area of Caspian sea region. Dokuchaev Soil Bull. 83, 53–76. https://doi.org/10.19047/0136-1694-2016-83-53-76 (in Russian).
Kovda, I.V., Wilding, L.P., 2004. Vertisols: problems of classification, evolution, and spatial self-organization. Euras. Soil Sci. 37 (12), 1341–1351.
Kovda, I.V., Morgun, E.G., Williams, D., Lynn, W., 2003. Soil cover of gilgai complexes: peculiarities of the development in subtropical and temperate climates. Euras. Soil Sci. 36, 1168–1182.
Kravtsova, V.I., Pizhankova, E.I., Kizyakov, A.I., Gavrilov, A.V., 2019. Satellite images in the new Atlas «Russian Arctic». Ice and Snow 59 (3), 411–422 (in Russian).
Kutovaya, O.V., Tkhakakhova, A.K., Cheverdin, Yu.I., 2016. Effects of surface flooding on biological properties of meadow Chernozems in Kamennaya steppe. Dokuchaev Soil Bull. 82, 56–70. https://doi.org/10.19047/0136-1694-2016-82-56-70 (in Russian).
Markgraf, W., Horn, R., Peth, S., 2006. An approach to rheometry in soil mechanics – structural changes in bentonite, clayey and silty soils. Soil Tillage Res. 91 (1-2), 1–14. https://doi.org/10.1016/j.still.2006.01.007.
Mezger, T.G., 2011. The Rheology Handbook. For Users of Rotational and Oscillatory Rheometers, 3rd Revised Ed. Vincentz Network, Hanover.
Mikhno, V.B., 1993. Cretaceous Landscapes of the East European Plain. Petrovskiy Skver, Voronezh (in Russian).
Novak, T., Fedorovych, M., 2015. Morphology and genesis of the postcryogenic polygonal microrelief of the Volyn upland. Naukovi zapiski 1, 64–70 (In Ukranian).
Ovchinnikov, A.Yu., Alifanov, V.M., Khudyakov, O.I., 2020. The impact of paleocryogenesis on the formation of Gray Forest soils in central Russia. Euras. Soil. Sci. 53 (10), 1354–1364.
Pal, D.K., 2017. A Treatise of Indian and Tropical Soils. Springer, Cham. https://doi.org/10.1007/978-3-319-49439-5_2.
Ping, C.-L., Clark, M.H., Kimble, J.M., Michaelson, G.J., Shur, Yu, Stiles, C.A., 2013. Sampling protocols for permafrost-affected soils. Soil Horiz. 54 (1), 13–19. https://doi.org/10.2136/sh12-09-0027.
Rodríguez-Ochoa, R., Olarieta, J.R., Santana, A., Castañeda, C., Calle, M., Rhodes, E., Bartolomé, M., Peña-Monné, J.L., Sancho, C., 2019. Relict periglacial soils on Quaternary terraces in the Central Ebro Basin (NE Spain). Permafr. Periglac. Process. 30 (4), 364–373. https://doi.org/10.1002/ppp.2005.
Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Soil Survey Staff, 2012. Field Book for Describing and Sampling Soils, Version 3.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.
Shabanova, N.P., Lebedeva Verba, M.P., Bykov, A.V., 2014. The effect of digging activity of little souslik on soils of the first terrace of Khaki Sor in the Botkul'sk-Khaki depression. Euras. Soil Sci. 47, 141–152. https://doi.org/10.1134/S1064229314030065.
Shein, E.V., Troshina, O.A., 2012. Physical properties of soils and the simulation of the hydrothermal regime for the complex soil cover of the Vladimir Opol'e region. Euras. Soil Sci. 45, 968–976.
Shein, E.V., Arkhangel'skaya, T.A., Goncharov, V.M., Guber, A.K., Pochatkova, T.N., Sidorova, M.A., Smagin, A.V., Umarova, A.B., 2001. Field and Experimental Analysis of Physical Properties and Regimes of Soils. Moscow State University, Moscow (in Russian).
Sokolov, A.A. (Ed.), 2020. Geographical Atlas of the Orenburg Region. Institute of Steppe, Orenburg (in Russian).
Stoops, G., 2003. Guidelines for Analysis and Description of Soil and Regolith Thin Sections. Soil Sci. Soc. of Am., Inc., Madison, Wisconsin, USA.
Streletskaya, I.D., 2017. Soil wedge structures in the southern coast of the Finland gulf. Earth`s Cryosphere 21 (1), 3–10. https://doi.org/10.21782/EC2541-9994-2017-1(3-10).
Vandenberghe, J., French, H.M., Gorbunov, A., Marchenko, S., Velichko, A.A., Jin, H., Cui, Z., Zhang, T., Wan, X., 2014. The Last Permafrost Maximum (LPM) map of the Northern Hemisphere: permafrost extent and mean annual air temperatures, 25–17 ka BP. Boreas. 43 (3), 652–666. https://doi.org/10.1111/bor.12070.
VanVliet Lanoe, B., Fox, C.A., 2018. Frost action. In: Stoops, G., Marcelino, V., Mees, F. (Eds.), Interpretation of Micromorphological Features of Soils and Regoliths, 2nd edition. Elsevier, pp. 575–603.
Velichko, A.A., Morozova, T.D., Berdnikov, V.V., Nechaev, V.P., Tsatskin, A.I., 1987. Paleogeographic background of differentiation of the soil cover and development of erosion processes. Pochvovedenie 10, 102–112 (in Russian).
Velichko, A.A., Morozova, T.D., Nechaev, V.P., Porozhnyakova, O.M., 1996. Paleocryogenesis, Soil Cover Patterns, and Farming. Nauka, Moscow (in Russian).
Velichko, A.A., Zelikson, E.M., 2005. Landscape, climate and mammoth food resources in the East Euoropean Plain during the Late Paleolithic epoch. Quat. Int. 126-128, 137–151. https://doi.org/10.1016/j.quaint.2004.04.019.
Williams, D., Cook, T., Lynn, W., Eswaran, H., 1996. Evaluating the field morphology of Vertisols. Soil Survey Horizons 37, 123–130.