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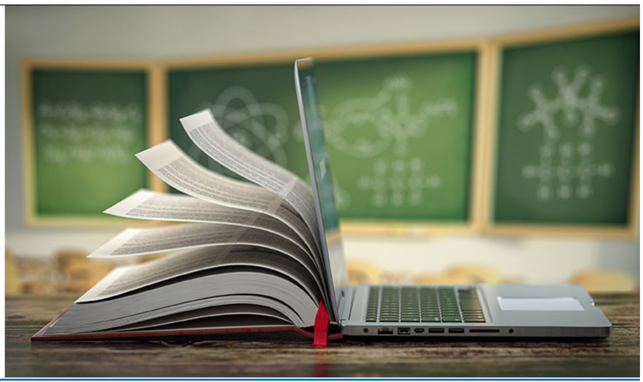

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Relict cryogenic structures in the landscapes of Orenburg region, Russia

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Abstract. The evidence of Neo-Pleistocene and possibly Holocene paleopermafrost was found in Orenburg region, Russia. Large polygons are clearly visible in relief, which indicate the existence of continuous low-temperature frozen rocks in the past. We found and studied the structure of the ground wedges formed in sediments of different composition and genesis. Ground wedges in loess-soil formations indicate several stages of permafrost expansion at the end of the Neo-Pleistocene. Freezing of ground was accompanied by the formation of polygonal-wedge ice and initially-ground wedges. During the warming periods the permafrost melted and pedogenesis restarted together with active thermokarst processes and formation of pseudomorphs along the wedge ice.

1. Introduction

In the Middle and Late Neo-Pleistocene, during cryochrones, the territory of Northern Eurasia was repeatedly subjected to cryogenic processes and long-term freezing, followed by stages of permafrost degradation [1, 2, 3]. This is evidenced by a number of relict cryogenic morphologic features in the outcrops and soil pits and paleocryogenic polygonal relief.

Paleocryogenic relief and relic features are unequally studied within the Northern Eurasia. They were most thoroughly studied in the central part of the East European Plain in the Upper Volga River basin by A Velichko and V Berdnikov [4, 5, 6]; in eastern part of the East European Plain by G Butakov, V Berdnikov, and A Illarionov [7, 8]; in Ukraine by A Bogutsky, A Velichko, and V Nechaev [9]; in the Northern and Central Kazakhstan by A Gorbunov, E Seversky and I Gorbunova [10, 11]. Currently S Larin, S Laukhin, V Alekseeva, and others investigate the relict cryogenic relief and paleocryogenic structures in south-western part of western Siberia [12, 13, 14].

Paleocryogenic studies both in geohorizons and in the landscape morphological structures are carried out in western Europe by Vandenberghe et al. [3], Fábián et al. [15], Zielinski et al. [16], in North America by French and Millar [17], in China by Yang et al. [18], Cui and Xie [19]; Dong et al. [20], Tong [21], Cui et al. [22], Vandenberghe et al. [23], Jin et al. [24], Harris and Jin [25], and in other countries. Large-scale work is currently underway in order to summarize and form a database of relict periglacial forms in western Europe by French scientists Bertran et al. [26] and Andrieaux et al. [27].

Paleopermafrost has not been previously known and investigated in Orenburg region. We initiated the complex field studies aimed to find the relict cryo-geological features in the geological outcrops, soils and relief in this area. We were looking for the most striking cryogenic features such as polygonal relief, wedge-shaped structures (pseudomorphs on polygonal wedge ice, initially-ground wedges, fine-polygonal crack formations), plastic deformations (involutions and cryoturbations) [28, 29].

2. Material and Methods

The field studies in Orenburg region were carried out in 2018-2020 within the territory of the elevated erosional denudation uplands of the East European Plain (Obshchy Syrt and Sub-Ural Plateau) and denudation socle plains of the southern Trans-Urals (Uralo-Tobolsk plateau). The study area has a diverse geological structure. The East European Plain is composed of clay shales, marls, sandstones, limestones, argillites and aleurolites of Permian and Triassic age in the north, Jurassic and Cretaceous deposits consisting of shingle bed, sandstones, sands, clays and limestone (chalk) in the south. Plains of the Trans-Urals are composed of dislocated Paleozoic and Proterozoic sedimentary and igneous rocks. Paleozoic rocks in depressions are overlapped by Mesozoic and Cenozoic sediments with a heterogeneous composition ranging from clays to conglomerates. Weathering crust of Mesozoic-Cenozoic age with a thickness of 30-40 m is exposed at the surface on watershed areas [30]. Irregularities and depressions in the bedrocks are filled with Quaternary loess-like loams. The thickness of Quaternary sediment varies from 0.5-1.0 m on watersheds and upper slopes to 45.0 m in the river valleys and ravines [31].

The climate is continental. The mean annual air temperature varies between +4°C and +1.5°C from south-west to the east of the Orenburg region. The distribution of precipitation is uneven. Mean annual precipitation decreases from 450 mm in the north-west to 260 mm in the south-east. Duration of the frost-free period is about 140 days [31].

Chernozems and Kastanozems dominate in zonal soil cover, and the complexity is characteristic for soil and vegetation cover. The depth of soil freezing reaches 1.2-1.4 m (in February), the snow cover in winter is about 0.3 m [31].

The territory belongs to bunchgrass steppe, which is generally strongly disturbed by plowing. Meanwhile the soil pits were have been dug under native vegetation.

Satellite images were analyzed before the prior to field work. We used the satellite images of high resolution (2-10 m) from GoogleEarth, BingMaps, and YandexMaps resources. DJI Mavic Mini Combo mini drone was used for aerial survey in the field.

Field studies were carried out at eight key-sites (figure 1, table 1) with different geomorphology. Soil pits and trenches, and natural outcrops were examined. A detailed morphological studies of vertical outcrops and horizontal sections at different depths were carried out; cryogenic features and host sediments were described together with schematic sketches, photo-fixation and sampling.

3. Results and Discussion

The field studies in Orenburg region revealed the features that have been interpreted as evidence of relict cryogenic structures.

The satellite images clearly show meso- and microrelief, similar to the microrelief widespread in modern cryolithozone. Regular grid of polygons from 5x5 m to 40x40 m and larger in diameter is detectable on flat watersheds and valleys; elongated depressions (dells) are visible along the slopes with an interval of 20 to 60 m; bead-shaped channels inherited from the ancient polygonal ice grid in the bottoms of small valleys [32, 33]. Evidence of soil cryoturbation, ground wedges and cryotextures were found in the pits and outcrops. The description of these features according to the key-sites is presented below.

Figure 1. Map of the key-sites location in Orenburg region.

Table 1. Location of the key-sites.

№	Key-site	Coordinates	Absolute height, m	Location
1	Pervomaisky	51°50'31,61"N 51°39'49,30"E	82	Ponomarevka gully, 6.5 km south-east of Pervomaysky village, Pervomaysky district.
2	Ivanovka 1	51°40'37,76"N 55°05'24,71"E	110	Quarry outcrop, southern outskirts of Orenburg, 10th km of Orenburg-Soliletsk bypass road.
3	Ivanovka 2	51°40'36,20"N 55°05'23,50"E	110	Quarry outcrop, southern outskirts of Orenburg, 10th km of Orenburg-Soliletsk bypass road.
4	Podgorodnyaya Pokrovka	51°49'23,98"N 54°56'55,17"E	187	Quarry outcrop, 1 km southwest of Podgorodnyaya Pokrovka village, Orenburg district.
5	Itchashkan	51°08'1,12"N 55°43'43,70"E	217	Right bank of the Itchashkan River, 8 km east of Novopavlovka village, Akbulak district.
6	Tuzlukkol	51°15'28,97"N 56°37'12,50"E	195	Lake-like extension of the Tuzlukkol River, 12 km southwest of Burlyksky village, Belyaevsky district.
7	Akzharsky	51°09'22,35"N 59°23'27,52"E	286	Erosion hollow, 6.2 km north of Akzharskoye village, Yasnensky district.
8	Ozerny	51°01'07,28"N 61°04'43,41"E	317	Slope of erosion hollow, 15 km south-east of Ozernoye village, Svetlinsky district.

Pervomaisky key-site. The narrow ground wedge was found in the natural exposure on the slope of Ponomarevka gully. The groundmass filling the ground wedge has bright ochre color contrasting with the host brown-yellow horizontally layered sediments (figure 2). The ground wedge can be traced along the exposure from 0.5 m to 1.85 m depth; its width narrows from 0.1-0.12 m in the upper part to 0.04 m at a depth of 0.9 m. At a depth of 1.35 m, the wedge splits into “tails” 0.02-0.03 m width. The “tails” gradually narrow to 1 mm at a depth of 1.87 m. The groundmass filling the structure is represented by non-compacted ferruginous sands with vertical layering. The host sediments are dense loess-like loams, which are replaced by dense sands with inclusions of Jurassic mollusk shells at a depth of 1.87 m. Five bright wavy horizontal interlayers with orange iron staining are traced in the gray-brownish compacted loam; their thickness decreases with a depth from 0.05 to 0.01 m. The layer contains reticulate fine carbonates veins 1-2 mm width with angular-discontinuous texture. The platy structure appears below the depth of 0.50 m with the increasing thickness of individual plates with a depth from 1-2 mm to 10 mm.

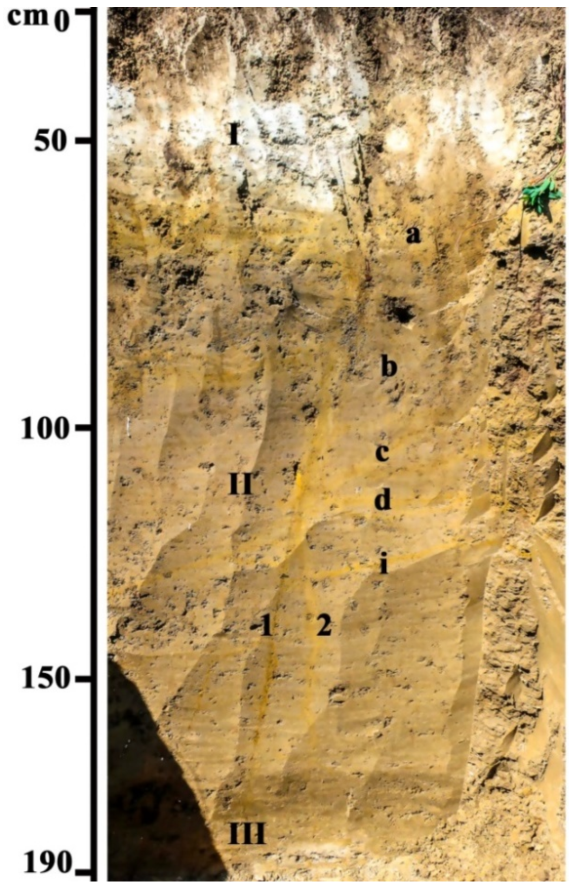

Figure 2. Pervomaisky key-site: Morphology of the ground wedge: I – pale loess-like loam; II – gray-brownish compacted loam; III – dense cemented sand with Jurassic mollusk shells; a-i – horizontal-wavy interlayers with orange iron staining; 1, 2 – “tails” of the ground wedge.

Ivanovka 1 and 2 key-sites are situated in abandoned quarry 100 x 200 m in size and 4-5 m deep. The satellite image of the area demonstrates the clear polygonal blocky relief of the territory adjacent to the southern side of the quarry (Ivanovka 1). This relief is easily identified by a spotty pattern and a polygon network with an average grid size of about 30 meters (figure 3a).

The outcrop of the quarry demonstrates the packages of pale-yellow loess and dark brown buried soils. The lower part of the bright yellow loess in the outcrop contains the prominent ground wedge 0.1 m a width and a visible height of about 1.0 m filled with dark brown humus material (figure 3b). The estimated vertical size of the ground wedge is 2.0-2.6 m. The lower part of the wedge is devided into four “tails” with a thickness of 0.01-0.001 m. The “tails” are incorporated into underlying rocks.

The opposite wall of the quarry (Ivanovka 2) demonstrates the two-meter package of yellow rocks (presumably loess) below the modern soil at a depth of 0.70-0.65 m. Underneath is a 0.10 m layer of dark brown humus horizon (paleosol) under which a number of elongated dark brown humus-rich ground wedges are located inside a package of orange-yellow material. The wedges have variable orientation with domination of a vertical one. The lower parts of ground wedges are splitted into several “tails”. Their width decreases with depth from 0.10 m to 0.01 m. All ground wedges appear below the paleosol and terminate at the same depth. Visible height of the ground wedges is ~2.0 m (figure 3c).

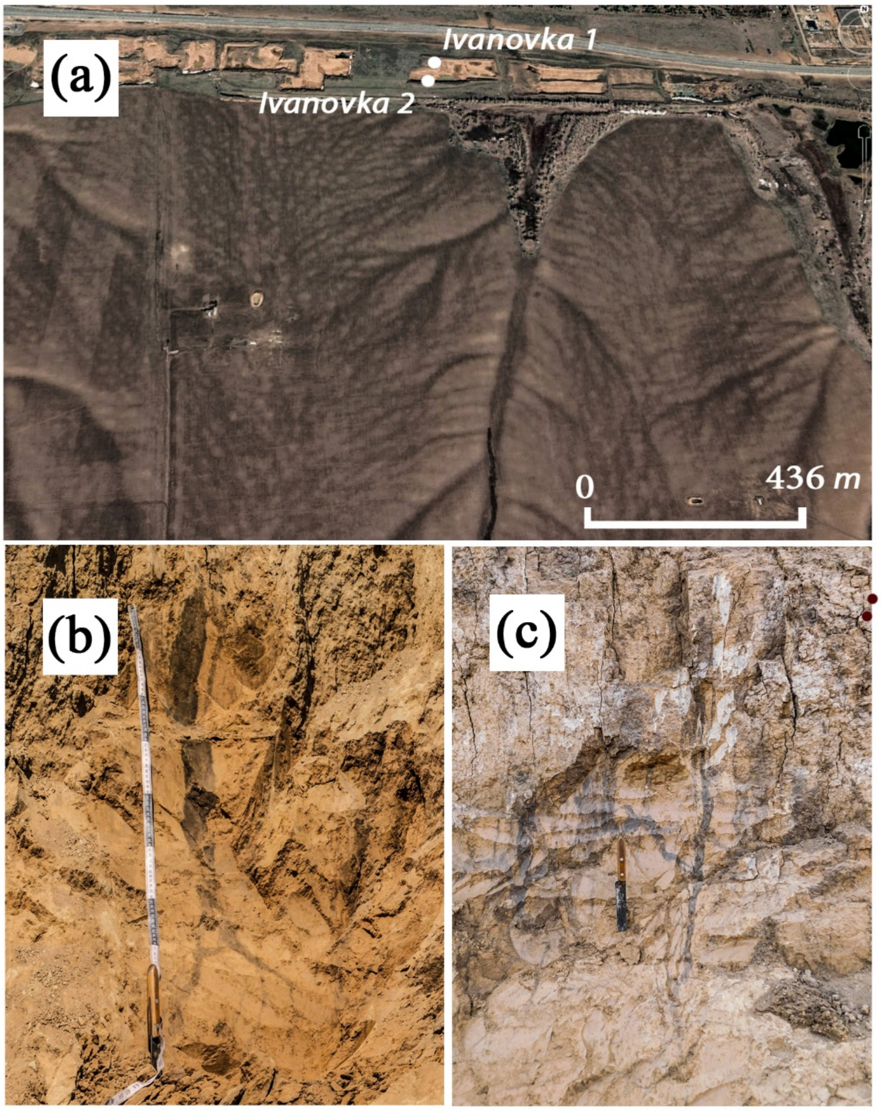

Figure 3. Ivanovka 1 and Ivanovka 2 key-sites: (a) Fragment of the satellite image depicting polygonal blocky microrelief; (b) Morphology of the ground wedge from Ivanovka 1 key-site; (c) Morphology of the ground wedges from Ivanovka 2 key-site.

Podgorodnyaya Pokrovka key-site. The large quarry is 600 x 500 meters in size and 50 m depth. It represents the reference geological section of the loess-paleosol formation, and became well-known recently as a reference section for out-glacial part of Russia. The section was first described by V K Shkatova in 1988 [34]; it was well studied, has a paleomagnetic reference, teriofaunistic and other characteristics. The section with a total thickness of about 50 m demonstrates the loess-paleosoils interchange, which overlaps Akchaghylian marine sediments. Two complexes are clearly distinguished in the quarry. The lower complex with a thickness of about 15.0 m is associated with the Eopleistocene, the upper complex with a thickness of about 40.0 m pertains to the Neo-Pleistocene epoch and includes ten paleosols separated by loess horizons. The boundary of the Middle and Upper Neo-Pleistocene is marked by pedocomplex including two paleosols: the lower brownish-black Chernootrozhskaya paleosol and the upper reddish-brown Pyanenskaya paleosol with loess-like loam in-between. Stratigraphic position of the Chernootrozhskaya paleosol is defined by fauna of small mammals and corresponds to Eemian Interglacial (MIS 5e) [34].

Polygonal blocky relief is well defined on satellite image of the area surrounding the quarry. This relief can be identified by spotted pattern and polygon network. The grid size is about 30-40 meters (figure 4b).

The south-western wall of the quarry demonstrates the ground wedges associated with an erosional depression at the absolute level of 139 m (figure 4a). The ground wedges of light yellow color with a height of ~1.30 m appear in loess sediments below modern soil (0.60-0.90 m) and penetrate into the dark brown horizon of paleosol with an apparent thickness of ~ 1.2 m. In contrast to loess horizons and modern soil, the paleosol is non-carbonate.

The distance between the ground wedges is about 0.60 m, their thickness in the upper part is 0.11 m. They are multiterminus with the reduced width of the “tails” ~ 0.01-0.03 m. Ground wedges are infilled by overlying yellow loess groundmass and have white calcific rim layer with 1.0-1.5 cm thick.

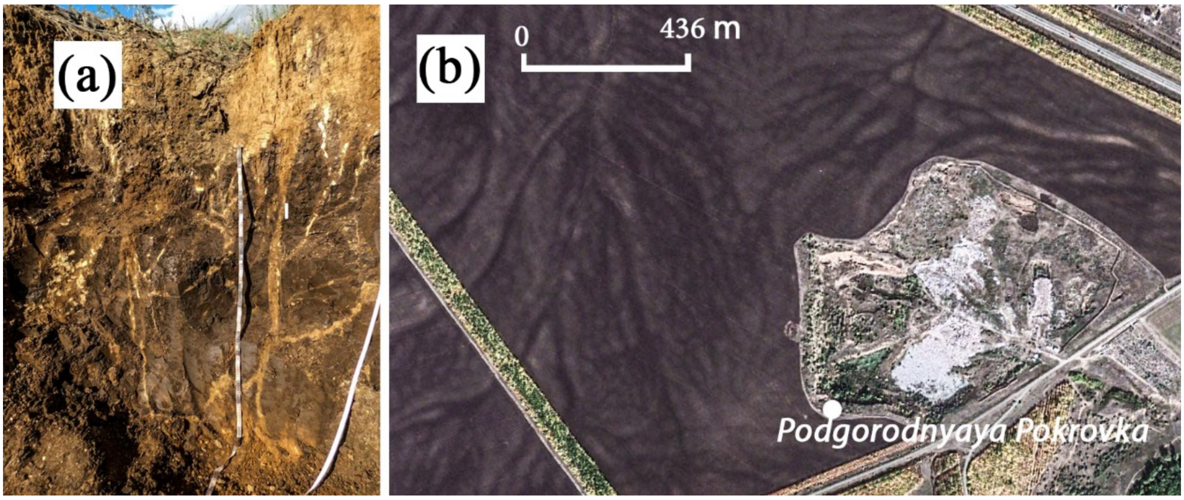

Figure 4. Podgorodnyaya Pokrovka key-site: (a) Morphology of the ground wedges; (b) Fragment of satellite image with polygonal blocky microrelief.

Itchashkan key-site. The satellite image shows prominent polygonal microrelief. In the terrain it is represented by a regular alternation of flat polygons with white spots of chalk without vegetation (figure 5a, c, d). The diameter of the spots in central part was 1.5-2.0 m with the distance between them ~5 m. The depressions in-between the white chalk spots were about 0.3 m deep and 1.5-1.0 m width, covered by grass vegetation and filled with loose organic-rich limestone material.

The soil pit in the central part of the depressions (between chalk spots) discovered the dark humus-rich ground wedge just below the topsoil (0.08 m). The ground wedge consisted of mixed groundmass with darker and lighter material in the upper part, while the deeper part of the wedge was monotonous dark. The ground wedge with vertical size ~ 1.15 m was well pronounced and prominent against the light background of the limestone material (figure 5a). Its morphological structure consisted of two parts: an extended upper one up to the depth of 0.35 m, and a lower one which was more narrow splitting into several “tails”. At a depth between 0.6 and 0.85 m, the thickness of the wedge was 0.05-0.07 m narrowing deeper to 0.01 m. Loose groundmass filling the ground wedge had biogenic features including several krotovinas up to the depth of 0.85 m, and common plant roots. The groundmass of the wedge was represented by the limestone of different degrees of dispersion: from very fine chalk silt to dense chalk gravel. The boundary between disintegrated and dense limestone at a depth of 1.0 m was marked by the presence of large ferruginous mottles 0.04-0.07 m in diameter with the interval between the mottles of about 0.15 m. Very fine (< 0.1 mm) ferruginous veins were noticed also up to the depth of 1.0 m in the ground wedge. Disintegrated limestone layer had increased thickness in the depression comparing to its thickness below the white chalk spots. The cryoturbation features were also found in the upper part of the soil pit.

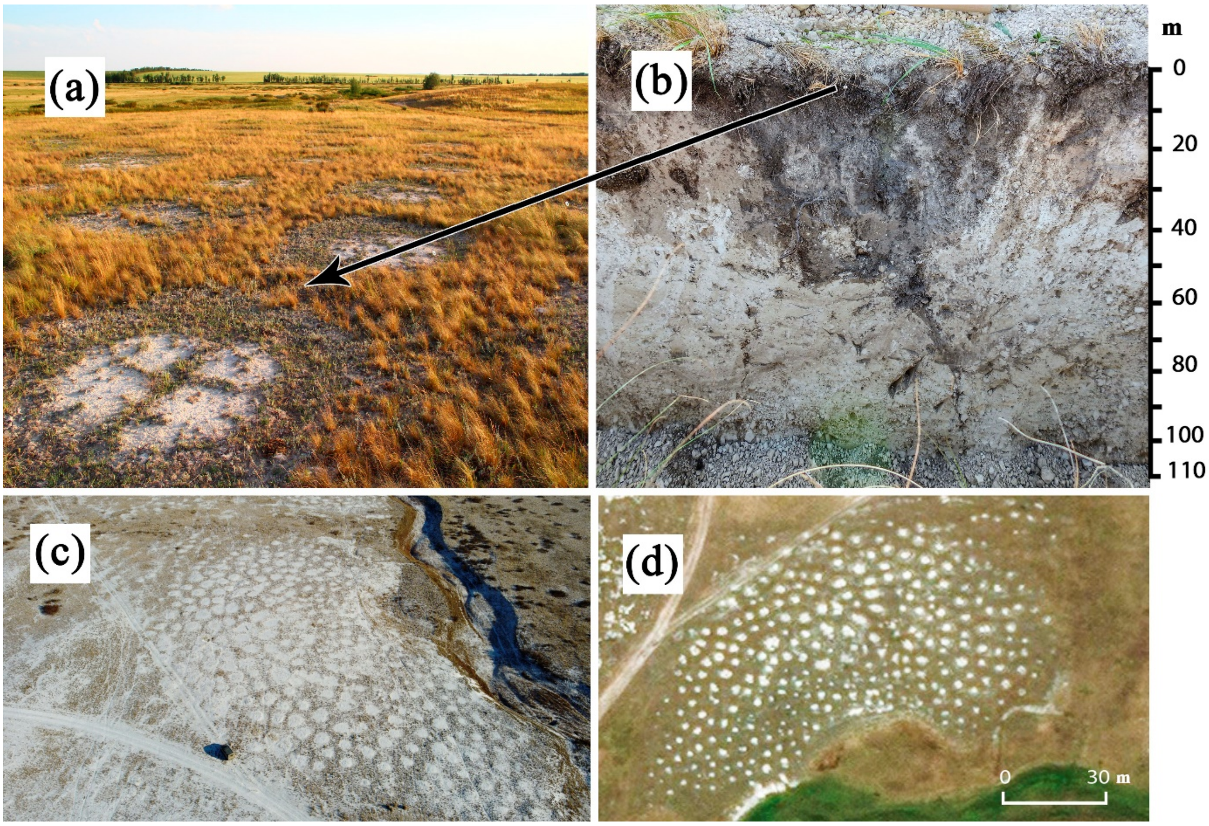

Figure 5. Itchashkan key-site: (a) Landscape of the key-site; (b) Morphology of the relict permafrost ground wedge in the depression; (c) Quadcopter photo of key-site; (d) Fragment of satellite image showing polygonal microrelief.

Tuzlukkol key-site. The microrelief is represented by grassed tetragonal hummocks 1.5-2.5 m in size. Hummocks are divided by hollow-shaped depressions with a width of 0.3 to 0.6 m, oriented along and across the general slope. The height of the hummocks is 0.3-0.5 m. Depressions are characterized by dense vegetation cover. Quadcopter images identified well-ordered hummocky-polygonal microrelief with clear network pattern (figure 6b, c, d).

Soil pit at the intersection of hollow-shaped depressions (between four hummocks) revealed the well-defined humus-filled ground wedge which can be traced to a depth of 0.8 m (figure 6a). The ground wedge had a two-tiered structure with large and narrow lower parts. The width of the ground wedge decreased from 0.12 m at a depth of 0.15 m to 0.05 m at a depth of 0.2 m; at a depth of 0.45 m the wedge turned into curved hair-like terminus. The boundary between the ground wedge and host deposits was gradual; the ground wedge was filled with dark gray organic-rich loam, which differed from the host sediments by more light texture and loose consistence. Host material was dark gray heavy loam with fine (1-2 mm) platy structure turning at a depth into bluish-gray mottled clay with dark fine layers and gravel inclusions, lightening to the bottom. Similar ground wedges forming a polygonal network were revealed in soil pits in upper and lower positions along the slope.

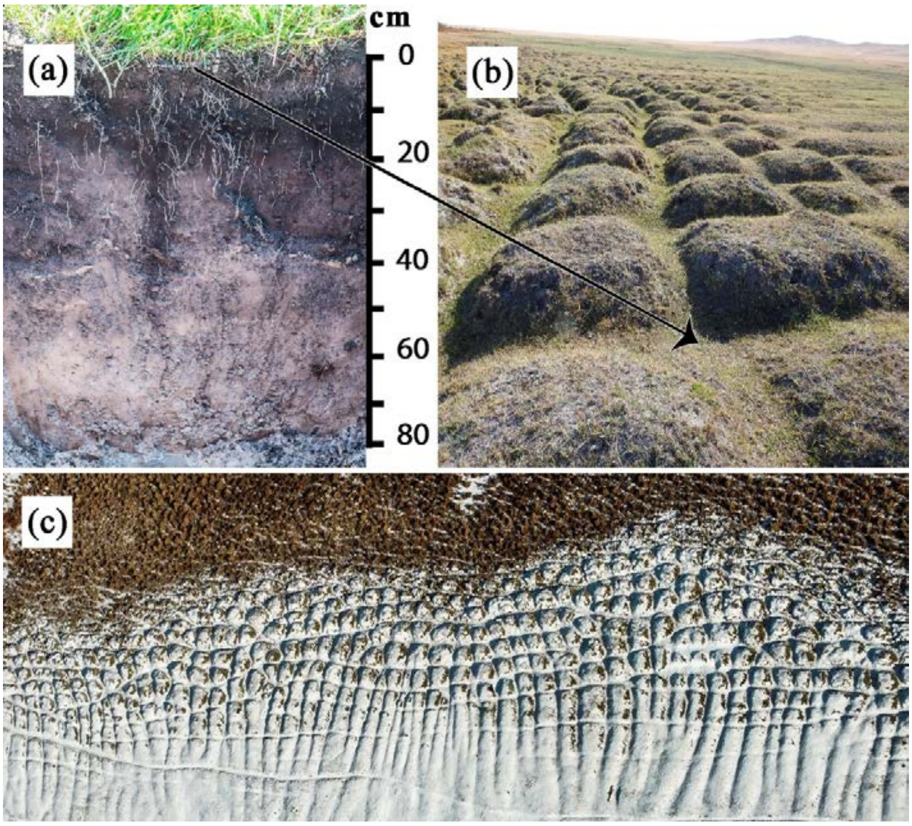

Figure 6. Tuzlukkol key-site: (a) Morphology of the ground wedges; (b) Landscape view with regular microrelief; (c) Quadcopter image of the key-site.

Akzharsky key-site. The erosional remnant located in the hollow contained a polygonal crack network represented by humic wedge-shaped structures with a height of 0.8 m and a width of 0.3 m at the top (figure 7). The distance between the axial parts of these ground wedges was 0.5 m. Ground wedges had an extended upper part reaching up to the depth of 0.6 m and the narrow lower part going underneath the exposed wall of the remnant. The silty loam humic material of the ground wedges had lumpy structure and open fissures. The host material was represented by a dense brownish loess-like loam with very fine (1-1.5 mm) platy structure.

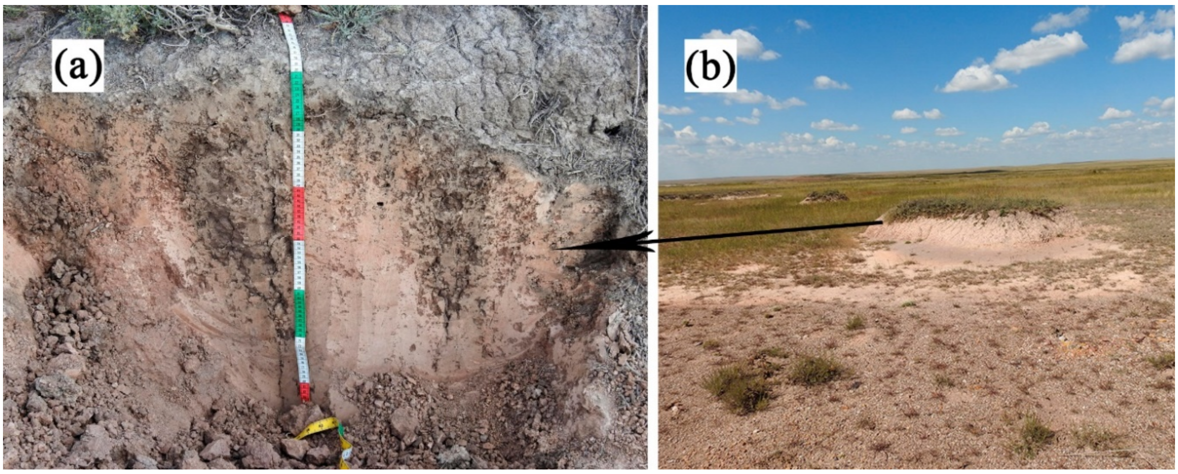

Figure 7. Akzharsky key-site: (a) Morphology of the ground wedges; (b) Landscape with erosional remnants in the hollow.

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Ozerny key-site. The microrelief consisted of rounded microhighs with gentle slopes free of vegetation with flat top surfaces and bowl-shaped small depressions in the middle. Microhighs are divided by narrow valley-like microdepressions 0.15-0.2 m deep and 0.3-0.4 m wide overgrown with vegetation. On satellite images the microrelief could be detected as a network of hexagonal polygons (figure 8b). Microhighs were composed of yellowish-brown clayey material; they had dense and strongly fissured crust on the surface in dry seasons.

In the side wall of a trench across the microhigh to the microdepression we excavated a part of a complex ground wedge (figure 8a). It consists of several vertically oriented tortuous fissures filled by dark brown humic groundmass penetrating up to 1.2 m into the yellowish-brown clayey sediments. The ground wedge had an extended upper part, partially excavated in the trench, and had a number of tortuous “tails” starting at a depth of ~ 0.2 to 0.3 m. The width of the “tails” narrowed from 0.1-0.15 m to 0.04 m at a depth of 0.6 m, up to few mm in the very bottom. The upper part of the soil was cryoturbated.

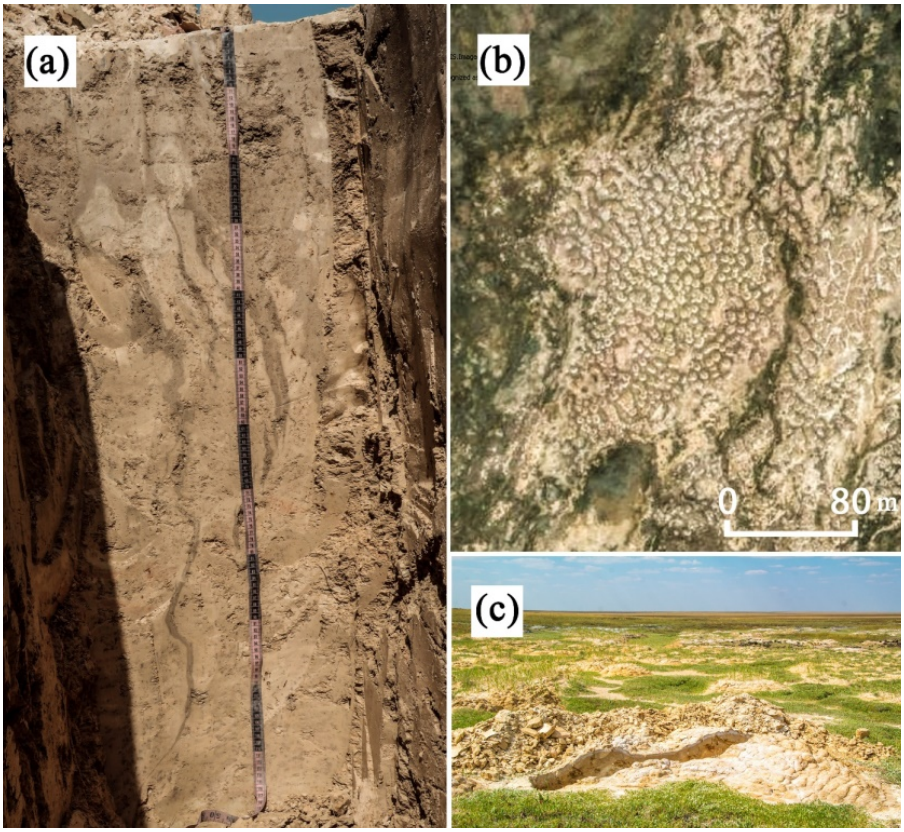

Figure 8. Ozerny key-site: (a) Morphology of the ground wedges; (b) Fragment of satellite image with polygonal microrelief; (c) Landscape and open soil trench across the microhigh.

4. Conclusion

The number of morphological features found and described in Orenburg region apparently could not be formed in modern climatic conditions. These features include polygonal meso- and microrelief, ground wedges, cryoturbated soil profiles, and platy soil structure resulted from ice lenses. These features suggest the presence of paleopermafrost, which could be expected to exist in this region during Neo-Pleistocene and possibly at the initial cold stages of Holocene.

Both large polygons up to 30 m in diameter and smaller polygonal microrelief are prominent in the geomorphology in the terrain and could be detected on the satellite images. Large polygons indicate severe permafrost conditions and the existence of continuous low-temperature frozen rocks in the past.

Ground wedges were investigated in the natural exposures, outcrops and soil trenches. They are assumed to be relicts of frost cracking. It was found that the ground wedges in polygonal systems were confined to inter-polygonal depressions. The permafrost genesis of the ground wedges instead of desiccation cracking is expected to be confirmed by their complex structure and morphology with large expanded upper part and narrow tails. The height of expanded upper part is expected to indicate the thickness of the active layer and the depth to the permafrost in the past, while the numerous narrow terminus or "tails" were formed via cracking and penetration into the frozen groundmass. The ground wedges demonstrated typical character of infillings. Several exposures and soils demonstrated various dislocations, involutions and turbations, which were also interpreted as paleocryogenic. Processes of active cryoturbation could take place in the seasonally thawed layer, above the permafrost. Ferruginous mottles and interlayers found in the chalk rocks could mark the water impermeable barrier at the paleopermafrost level, and very fine reticulate iron veins could indicate the existence of cryogenic texture and ice lenses in the past.

Paleocryogenic morphological structures (ground wedges, cryoturbations, post-cryogenic textures), found in the soil pits, outcrops and exposures, and characteristic polygonal paleorelief point to a deeper seasonal freezing, compared to modern environment, and paleopermafrost occurrence. According to our investigation in the Orenburg region the permafrost existed at least to the latitude of 51°N here in the past. The territory had a continuous and /or sporadic permafrost with rock temperatures up to -3°C and colder.

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