Paleocryogenic traces of climatic peaks of the Late Pleistocene periglacial hyperzone of the mammoth steppe in soils of archaeological sites

L N Plekhanova\textsuperscript{1} ORCID 0000-0002-3611-7783, O S Tupakhina\textsuperscript{2} ORCID 0000-0001-7634-0595

\textsuperscript{1}Institute of physicochemical and biological problems in soil science under Pushchino Scientific Center for Biological Research of the Russian Academy of Sciences, the Federal Research Center, Pushchino, Russia
\textsuperscript{2}Arctic Research Center, the State Public Institution of the Yamal-Nenets Autonomous District (GKU YaNAO) Salekhard, Yamal-Nenets Autonomous District, Russia

E-mail: dianthus1@rambler.ru

Abstract. Recording and accurate dating of paleo-cryogenic processes traces in modern ecosystems can act as a key for understanding the current state and interpreting the history of landscape development. The stage of the existence of glaciers and the accompanying periglacial zone of the tundra-steppes is the milestone in general history of the Russian large areas. The paleo-cryogenic structures in the modern soil cover are the inheritance of this stage. The recording of said structures at deep levels is possible during archaeological excavations. The stratigraphy of the layers of archaeological sites provides a possibility to link paleo-cryostructures’ traces to certain periods of time and archaeologically date the enclosing context. Preservation of the more complete paleosol record relative to past periods of landscape formation is typical for modern natural zones formed under the affection of limiting factors. These zones include steppe (lack of moisture and excess heat) or tundra (excess of moisture and lack of heat). We recorded the third-order soil polygons preserved on sandy loams of the steppe area in the Orenburg region under the earthfill bunds of the Early Iron Age dwelling. We also recorded the third-order soil polygons under the embankment of a Neolithic-Bronze dwelling on sandy loam soils located in the modern northern taiga zone. In both cases the dimensions of the polygons were about 2-3 meters, and their shape was regular or broken hexagons, resulted from the surface slope or terrain roughness. Moreover, we draw parallels in the history of systems formation, and outlined tasks for further research.

1. Introduction
Today, it is significantly complicated to record and date traces of paleoprocesses accurately. However, paleo-cryogenic fracturing inherited from various Pleistocene periods are more amenable for recording. The periglacial zone is characterized by prevailing of cryogenic processes related to frost splitting of soils and are now represented by the relic cryogenic microrelief [1, 2, 3]. Such processes resulted in formation of the block structures, namely microlows and microhights of relief of various orders, which in its turn, defined the deposition rates and redox conditions of soil materials formation. The series of studies clearly demonstrates that the arrangement and composition of the modern soil mantle, which is forming under affection of the current soil formation factors, to the significant extent are defined by paleo-properties and paleoprocesses [4, 5, 6]. For example, there are multiple records of the blocks and interblocks within the territory of the Stone steppe. The particularity
of this preserve is the existence of the open space that provides a possibility to record traces of the ancient cryogenic process visually based using advanced tools; and confirm such records by forming transects through the blocks. It can be said that the paleo-cryogenesis presents everywhere within the territory of Russia, however, in the forested areas the soil blocks of various order are either involved into intensive soil formation or are covered by vegetation canopy, thus recording of such objects is complicated. Modern steppe zone was formed under extreme lack of moisture and excessive heat, while the tundra zones, on the contrary, were formed under excessive moisture and lack of heat. Nevertheless, in both cases such unbalanced influence of limiting factors contributes to preservation of the number of relic properties inherited by the ecosystems from the previous epochs. Whereas, due to intensive interchange, the range of properties of the forested areas will be either unobvious or fully deleted under affection of the new soil formation factors. Thus, the most complete paleopedology records on the surface development history can be found in the zones formed under influence of the limiting factors.

The archeological sites are also the natural monuments and can be studied using the soil-and-archeological method [7, 8, 9, 10]. The principle of this method consists of the adjoint analysis of the modern and old buried soils of the various aged archeological sites, which time of formation is to be determined using the archeological methods. The ecosystem retrospectives are confirmed by the Palynological analysis methods [11, 12]. The ideas that soil achieves dynamic balance (quazi-balance) with the environment, prevail in modern soil science. The soils develop with the course of time in parallel with either changing of the soil formation factors or due to the well-known soil inertia, and thus, its relic properties reflect changes of the environment conditions in the past. Comparative study of soils of the various aged archeological sites between themselves, as well as the modern background soils, makes it possible to simulate changes of paleoenvironmental conditions with the course of time; and moreover, it steps to a new level of studying microbiological and fermentative structure of the soil systems [13-19].

2. Objects
Investigation of soils of Solonchanka IX, the complex consisting of five mounds with “moustache”-grids. The site is located in Kvarakensky District of the Orenburg region in the vicinity of the Alandskoye fortified settlement located at the confluence of the Suunduk River and its tributary Solonchanka River. The Complex occupies the second above floodplain terrace of the left bench of Suunduk. The Complex consists of the central mound and four smaller mounds connected in pairs with stone “moustache”-grids. The length of the northern “moustache” is 86.5 m, and the southern – 103 m accordingly. The mounds’ diameter is 15–20 m, the height is 25–30 cm. the Complex refers to the late 4th century AD, at the boundary between the late Sarmatian-Hunnic period; the age of the site is 1,600 years. Position of the Trans-Ural Plateau within the temperate zone of the West Siberian region defines continentality as the principle trait of the current climate. Softening effect of the Atlantic air mass is weakened by the barrier effect of the Urals. Anticyclones (especially, the Asian anticyclone) provide significant influence. The sum of the mean daily temperatures above 10°C accounts to 1,950–2,300°. The annual amount of precipitation is 250–330 mm, and 130-180 mm of precipitation during the vegetation period. The hydrothermal index is 0.8–1.0.

There was carried out investigation of soils and culture layers of the Multilayered Settlement Yamgort. The settlement comprises fifteen various dwelling hollows referred to different time periods of exploitation. It is located on the right gently sloping terrace of the Synya River (left tributary of the Ob River) on the south of the Yamal-Nenets Autonomous District. The terrace height is 3 m from the sandy shoreline, the surface is gently sloping with moderate elongated ridges and rounded depressions. Excavation site is located on the ridge surface. The ridge is about 280 m length and about 50 m width; and is limited by the Synya river on the north, by the wide floodplain of the spring, and by its bed on the west.

The district relief includes by the dome-shaped uplands, widely spread gently ridged or flatland, and marsh bottomland. The ridges are elongated towards the floodplains of rivers and springs.
rivers’ floodplains length achieves several kilometers. The forest layer of the northern taiga terrain comprises larches, fir trees, birches, and cedars; the mixed open forest is within the settlement area. The main soil materials are the aqueo-glacial sand deposits, which act as the base for illuvial-ferruginous podzols formation. The typical amount of precipitation for this climate is 400-460 mm per year. The mean January temperature is minus 22 °C, the mean June temperature is 14 °C. The relatively low summer temperatures cannot provide significant amount of evaporation that results in high humidity of the both, the atmosphere and the soils.

The 16th dwelling hollow selected for investigation was distinguished for its elongated rectangular aspect ratio and significant dimensions – about 145 sq. m. along the external bund. In the center of the supposed dwelling there was discovered and recorded a foundation pit 3x10 meters. Tentatively, the dwelling was referred to the Eneolithic period. However, during the works it became obvious, that such deep pit was not a part of the dwelling under investigation, but a part of the more ancient construction. Thus, we carried out investigation of two dwellings. The upper one is dated as the Late Bronze Age (based on the ceramics of Kheyakhin culture). The dwelling has the earth-filling one meter wide along the entire perimeter of the construction. The second dwelling is older; its estimated depth is up to two meters, and it had the form of a dugout. The length of the room was 10 m, the width – 3 meters. There were discovered 57 pieces of the well-preserved lower parts of support structures. On the floor, as well as among the residues of the burnt structures there was discovered only the Eneolithic ceramics, referred to the Yasun culture.

The investigation was carried out using comparative-chronological, comparative-geographic, and the soil-archaeologic methods. The morphologic descriptions and determination of the soil chemical properties were performed using the standard practices.

3. Results and Discussions

The background soil of Solonchanka IX has the (tongued) ordinary deeply effervescenced nonsaline residually meadow sandy-loam chernozem soil was formed on alluvial sandy-loam and sandy deposits. The depth of the homogeneous humus horizon amounts to 25–30 cm, the depth of the background soil is about 30 cm, in some places it increases up to 50 cm (the increase is observed on the boundaries of the third order polygons). Humus concentration in buried soils is similar to the current level and is approximately 2%. Humus concentration in the upper horizon of the buried soil after reconstruction amounts to 3.9% [20], which is twice more than the values for the background soil.

We want to draw special attention to the polygonality of ancient soils, which we recorded in all details. The low longue level of the site demonstrated in the A/B horizon, can be explained by the cryo-fracturing under overlapping of the humidity and the frost penetration conditions. Close to the mounds of the 3rd and the 4th complexes, under the stone “mustache”-ridges there were discovered and recorded the third order soil polygons (up to 2–3 m in diameter, figure 1), which were marked by the grey humous bands about 15 cm wide on the brownish-light-grey background of the archaeologic “continent” – AB horizons of the modern soil.

Generation of such polygonal fracturing is typical for the territories with cold or dry climatic conditions, as well as for the sharply continental climate. The first order polygons have relatively small dimensions (10–30 cm for the soils with various grain sizes), small width (up to 2–5 cm), and the fractures depth, normally, does not exceed 20 cm. As the depth of the humus horizon is normally larger, such polygons are not always being recorded due to homogeneity of the material inside the fractures, or on the background of the humus horizon. Several first order polygons form a second order polygon, while its fractures are wider and deeper, and dimensions of such polygons can achieve to 1.5 m in diameter. Several second order polygons form a third order polygon, which dimensions are about 2-3 m, and the fractures depth is up to 0.5-1.0 m. such polygons can be discovered during opening of large areas, for example, under a rag work of the stone “moustache”-ridge.
Below we want to enumerate the factors that were taken into consideration and that are critical for soil formation on various relief elements. The relatively drained clay and clay-loamed terrains are characterized by the gentle reaction to atmospheric humidity changes. This is related to the fact that half of atmospheric precipitations go down together with the surface and subsurface runoff. Undrained surfaces without any runoffs respond to the humidity increase by the rapid growth of the subsurface waters, increase of the hydromorphic feature, and improvement of the biological productivity. The clay and clay-loamed soils require more time than the sandy soils for soils processes and achievement of the quazi-balance with the environment. In sandy-loam and sandy soils such quazi-balance can be achieved much faster. The soil responds to the humidity increase with a rapid increase in bioproductivity, overgrowth, and to aridization – by development of deflation, especially intensively when it is combined with pasture loads.

In general, the weak sensibility is typical for the sandy-loam soils. The traits of the minor changes in soil formation conditions could disappear quickly, as this soil achieves the quazi-balance with the surrounding environment faster than its loaded analogues. The soil buried under the Complex demonstrates the Humid episode of the 4th century AD: the modern soil is less humous, with the carbonate horizon located closer to the surface (“pulled” from the depth of 120–140 cm up to 80–90 cm) and a fully formed thick carbonate cumulating horizon. Based on the data on humus and magnetic sensibility (under calculation of the weighted average indices and their comparison with those of the Solonchanka I Complex), it can be concluded that the humid episode at the boundary between the late Sarmatian-Hunnic period was not long [20], and it is clearly seen that just 100 years later the soils of the low terrace contain the traits of the climate aridization.

In the soils of the Yamgort settlement also formed on a sandy loam soil material, the dominant process is formation of podzol, that is, the eluviation-illuviation horizons are being formed. At that, several buried soils are typical of the different-aged stages of the site functioning. These soils can be seen in the profiles both under the different-aged embankment with fillings, and in the soil of the inter-dwelling space in the contrasting wash-out-wash-in horizons of different thickness. Here, recording of paleo-cryogenic fractures, just as in the steppe, is stipulated by the presence of the contrasting material filled, at the time, the cryogenic fractures. As opposed to the steppe, here the material is rusty-red-grey due to the predominance of sesquioxides, in particular iron and humus. In the northern taiga, humus mainly consists of fulvic acids; their mobility provides formation of a bright illuvial horizon. While

**Figure 1.** Polygonality of the third order soils under the “moustaches” of Solonchanka IX complex.
the fractures are filled with the fixed material from the eluvial and illuvial horizons, thus, the fractures borders in some places have soft outlines, and may be up to 30 cm wide.

Polygonality was recorded at the depth of 60 cm to one meter from the modern surface (figure 2), under fillings of the more ancient and deep dwelling hollow referred to the Neolithic period.

![Figure 2. Schematic layout and dimensions of the third order polygons of the multilayered settlement Yamgort-1. Distinct borders are indicated with solid lines, and smoothed borders of the polygons are indicated with dotted lines.](image)

4. Conclusions
We recorded the third-order soil polygons preserved on sandy loams of the steppe area in the Orenburg region under the earthfill bunds of the Early Iron Age dwelling. Our data supplement the concept of the holocene automorphic loamy chernozem soils in the center of the East European Plain, for which it was established [4] that the differentiation of the modern complex soil cover at the typical and subtypical layers is based on features of soil materials formed under influence of the Late Valday paleo-cryogenesis, namely, the buried paleo-cryogenic polygonal network in the form of the block microheights and separating interblock microlows that form a microrelief on the daylight surface. The block-shaped relief comprises various levels of polygons nested into each other by size.

We recorded the third-order soil polygons located under the embankment of the of a Neolithic-Bronze dwelling on sandy loam soils in the modern northern taiga zone. In both cases the dimensions of the polygons were about 2-3 meters, and their shape was regular or broken hexagons, resulted from the surface slope or terrain roughness. Time period of these polygons’ formation remains under discussion: it can be the Pleistocene relic (as it is generally accepted for any fractures of such depth), or the cryofracturing could repeat in some certain periods, and thus, be preserved under fillings of archaeological sites referred to only certain periods.

In the Pleistocene period (100-10 thousand years ago) in the Northern Hemisphere there was a special biome, which has now almost disappeared; it combined features of the tundra and the steppe. In Russian scientific literature this biome got the name of “tundrosteppe”. In English this term is
usually translated as the “mammoth steppe”. The modern tundra zone is characterized by the high humidity and low air temperatures. The steppes are located closer to the south, in the warmer, however, the dryer (aridic) climatic region. While talking about the “mammoth steppe”, one can tell that it combines tundra’s cold and steppe’s dryness. The mammoth steppe was located farther south than the modern tundra. In that period, the north of the Eurasia was covered with the glacier, and the mammoth steppe terrains spread up to the Spain in the west, Siberia in the south, and China in the east.

The science goes forward, and now it has become possible to compare soil properties of various chronological sections in pairs: “buried soil – background analogue” for not only the soils located on different relief elements, but also remoted spatially, namely, taking the values of the soils indices of the background soil as 100%, and then comparing the relative values. The existing schemes for dating the Late Pleistocene events remain under discussion due to the incompleteness of the records on chronological series of soils related to the East European Plain; it is possible to shed light on these open issues by simple conducting remote comparisons. The mammoth steppe researches is on the rise; a unique scientific experiment is being conducted with the aim to recreate the ecosystems of the mammoth steppe in the northeast of Yakutia in the lower reaches of the Kolyma with the addition of the factor of grazing large animals in the Pleistocene Park reserve [21]. It is supposed that the tundra just as the steppe is a pasture ecosystem [22, 23], i.e., the result of the anthropogenic impact on nature.

It is common practice to pay attention to various aspects of the study and preservation of such a biome as the steppe. However, all the attention is given to the classic steppes on chernozem or chestnut soils of the steppe and dry-steppe zones, which is due to the presence of such natural systems on the territory of Russia. Nevertheless, even now, in local areas, and especially in the past, the so-called cold steppes existed on the territory of the present Russian Federation. A relic site, or a refugium of cold steppes, was discovered in the Altai mountains, where the climate is characterized by dryness and rather low temperatures, which makes it possible for the existence of flora and fauna similar to those that once inhabited the vast spaces of northern Eurasia [24]. Probably, this steppe is a direct "descendant" of the Pleistocene tundra steppe or the mammoth steppe, which successfully escaped extinction.

The zones where the biological component of ecosystems is determined by a limiting factor - a lack of moisture and excess heat for the steppes, and excess of moisture with a lack of heat for the modern Subpolar region are those very ecosystems where relic traits of many natural processes are preserved. In forests or taiga such traits are erased by more modern processes. But it is the steppes and ecosystems of cold regions that retain relic traits for us, where answers to many questions of soil genesis can be found. Probably, the triggering moment for the development of steppe science and a new trend will be construction of parallels in study of soils and ecosystems of the modern cold climatic zones of Russia, since they are territorially prevailing in the country, and this moment may become politically important.

Acknowledgments
This work was supported by the grant from the Russian Foundation for Basic Research (RFFI), project No. 19-49-890003 p_a: "Reconstruction of the paleoecological living conditions of ancient groups in the North of Western Siberia referred to the Eneolithic and Bronze Age", using the resources of the Research Equipment Sharing Center (TsKP) of the Institute of physicochemical and biological problems in soil science under Pushchino Scientific Center for Biological Research of the Russian Academy of Sciences, the Federal Research Center (Pushchino, the Russian Federation) under the State Assignment No AAAA-A18-118013190175-5.

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 Development, Future Prospects and Current Applications Series
"Key Concepts of Soil Physics: Development, Future Prospects and Current Applications" (IOP Publishing) pp 12-26

[2] Ryabukha A 2019 The heritage of pleistocene cryolithzone in the zavolzhye and urals region The successes of modern natural science 10 pp 164-170.

[3] Kovda I, Polyakov D, Ryabukha A, Lebedeva M and Khaydapova D 2021 Microrelief and spatial heterogeneity of soils on limestone, Sub Ural plateau, Russia: Attributes and mechanism of formation Soil & Tillage Research 209 pp 46-54.

[4] Alifanov V, Gugalinskaya L, Ivannikova L and Ovchinnikov A 2008 Effect of paleocryogenesis on the soil cover pattern and properties of chernozems in the Kamennaya Steppe reserve Eurasian Soil Science vol 41 13 pp 1356-1365.

[5] Ovchinnikov A, Alifanov V and Khudyakov O 2020 The impact of paleocryogenesis on the formation of Gray Forest soils in central Russia Eurasian Soil Science 53(10) pp 1354–1364.

[6] Khitrov N and Loiko S 2010 Soil cover patterns on flat interfluves in the Kamennaya Steppe Eurasian Soil Science 43 pp 1309–1321.

[7] Makhonina G and Korkina I 2002 Development of podzolic soils on archaeological sites in the middle taiga subzone of Western Siberia Eurasian Soil Science 8 pp 917-926.

[8] Plekhanova L 2019 Anthropogenic degradation of soils on river terraces in the Volga–Ural region in the Bronze age and its effect on the modern soil–plant cover Arid Ecosystems 9(3) pp 187-192.

[9] Demkin V, Borisov A, Demkina T and Udaltsov S 2012 Soil Evolution and Climate Dynamics in the Steppes of South-East Russian Plain within the Neolith and Bronze Epochs (IV–II MIL. BC) Izvestiya Rossiiskoi Akademii Nauk Seriya Geograficheskaya 1 pp 46-57.

[10] Rusakov A, Popov A, Makeev A, Kurbanova F, Puzanova T, Khokhlova O, Kust P, Lebedeva M, Chernov T and Golyeva A 2019 Paleoenvironmental reconstruction based on soils buried under scythian fortification in the southern forest-steppe area of the East European plain Quaternary International 502 Part B pp 197-217.

[11] Stobbe A, Gummior M, Ruhl L and Schneider H 2016 Bronze Age human-landscape interactions in the southern Transural steppe, Russia - evidence from high-resolution palaeobotanical studies Holocene 26(10) pp 1692-1710.

[12] Ryabogina N, Afonin A, Ivanov S, Nikolaenko S, Li H, Kalinin P and Udaltsov S 2019 Holocene paleoenvironmental changes reflected in peat and lake sediment records of Western Siberia: geochemical and plant macrofossil proxies Quaternary International vol 528 pp 73-87.

[13] Kashirskaya N, Chernysheva E, Plekhanova L and Borisov A 2019 Thermophilic microorganisms as an indicator of soil microbiological contamination in antiquity and at the present time International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM 19(3) pp 569-574.

[14] Zhuravleva A, Demkin V, Blagodatskaya E and Yakimov A 2012 Mineralization of soil organic matter initiated by the application of an available substrate to the profiles of surface and buried podzolic soils Eurasian Soil Science vol 45 4 pp 435-444.

[15] Zhuravleva A, Myakshina T and Blagodatskaya E 2011 The effect of pyrogenically modified substrates on mineralizing activity and growth strategies of microorganisms of grey forest soil Microbiology vol 80 2 pp 194-204.

[16] Evgrafova S, Shibistova O, Zrazhevskaya G, Santrukovka H, Elhottova D, Cerna B and Lloyd D 2008 Phospholipid fatty acid composition of microorganisms in pine forest soils of Central Siberia Biology Bulletin vol 35 5 pp 452-458.

[17] Plekhanova L 2017 Searching for benchmark soils in the steppe zone of the Trans-Ural Plateau to compile the Red Book of soils Arid Ecosystems 7(3) pp 171-177.

[18] Kashirskaya N, Plekhanova L, Udaltsov S, Chernysheva E and Borisov A 2017 The Mechanisms and Time Factor of the Enzyme Structure of a Paleosol Biophysics (Russian Federation) 62(6) pp 1022-1029.
[19] Kashirskaya N, Plekhanova L, Chernisheva E, Yeltsov M, Udaltsov S and Borisov A 2020 Temporal and Spatial Features of Phosphatase Activity in Natural and Human-Transformed Soils Eurasian Soil Science 53(1) pp 97-109
[20] Plekhanova L and Demkin V 2008 Paleosols of kurgans of the Early Iron Age in the Transural steppe zone Eurasian Soil Science 41(1) pp 1-12
[21] Zimov S 2005 Pleistocene park: return of the mammoth’s ecosystem Science vol 308 5723 pp 796-798
[22] Zimov S, Zimov N, Tikhonov A and Chapin F 2012 Mammoth steppe: a high-productivity phenomenon Quaternary Science Reviews vol 57 pp 26–45
[23] Zimov S, Chuprynin V, Oreshko A, Chapin F, Reynolds J and Chapin M 1995 Steppe-tundra transition: a herbivore-driven biome shift at the end of the Pleistocene The American Naturalist vol 146 5 pp 765-794
[24] Chytrý M et al 2019 A modern analogue of the Pleistocene steppe-tundra ecosystem in southern Siberia Boreas vol 48 pp 36–56