

PALEOECOLOGY DURING THE CREATION OF A LARGE BOLDYREVO KURGAN OF THE YAMNAYA CULTURE IN THE SOUTHERN CIS-URALS, RUSSIA

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Abstract: This study focuses on a short-term pedochronosequence of Kurgan № 1 at the Boldyrevo IV kurgan cemetery in the Orenburg Region of the Southern Cis-Urals. According to archaeological findings, the kurgan was built over several decades by people of the Yamnaya (Pit-Grave) culture of the Early Bronze Age (around 5500 BP), with the exact time of its building to be confirmed by radiocarbon dating and further archaeological information. A comparative analysis of the four earthen constructions of the kurgan and the paleosols buried under those constructions was conducted. Results suggest that the kurgan building period was accompanied by the following changes in paleosol morphology and physicochemical properties: the humus horizon acquired a tonguing-like lower boundary, decreased organic carbon content and magnetic susceptibility, while the whole profile was characterized by increasing degree of zooturbation; the impregnation by carbonates in the middle part of the profile and the contents of carbonate carbon, gypsum, and exchangeable sodium increased. Similar trends of morphological and physicochemical changes were observed in the materials of the kurgan constructions. Based on these findings it can conclude that the climate went through aridization rise during the period of the kurgan building. The paleobotanical data from palynological and microbiomorph analyses indicate that there was a tendency for paleoclimate aridization and, possibly a cooling trend during the studied period of the Yamnaya culture, which was probably more arid than the modern climate.

Introduction

Archaeological monuments of steppe regions, particularly, kurgans (burial mounds) represent a unique natural archive, where information on all stages or phases of evolution of the environment is stored. Soils buried under kurgans are isolated from ambient factors from the time of their burial, therefore, they are studied in order to reconstruct the state of different components of the environment such as climate, vegetation and topography prior to the burial (Gimbutas 2000, Barczy et al. 2006, 2009; Rowińska et al. 2010, Petó and Barczy 2011, Szilágyi et al. 2013, Demkin et al. 2014, Barczy 2016, Petó et al. 2016; Dani 2020). There are only very few kurgans of the Early Bronze Age, which corresponds to the late Atlantic and the turn of Atlantic and Subboreal periods of the Holocene (Ecsedy 1979, Horváth 2011, Gerling et al. 2012, Khokhlova et al. 2019).

Only a few studies on such kurgans exist and even less that focus particularly on pedochronosequences (i.e. paleosols sequentially buried under different-age constructions of a kurgan) (Zdanovich et al. 1984; Aleksandrovskii et al. 2004; Golyeva and Khokhlova 2010; Pesochina 2014, Sverchkova et al. 2020). Many kurgans have been lost over time or are still being destroyed due to the development of infrastructure and agriculture. Therefore, during archaeological excavations of a kurgan, it is important to apply the methods of different scientific disciplines and extract the most comprehensive information on both the historico-cultural and environmental contexts of the kurgan's creation.

Paleosols can exhibit a 'memory' of the factors and processes of their formation, which is preserved within their features and properties. The most important characteristics of steppe soils used in paleoenvironmental reconstructions are as follows: a general vertical arrangement of the profile, specific genetic horizons and morphological features (e.g., newly formed pedofeatures), color, fissure network, the vertical distribution of humus, carbonates and soluble salts, indications of biological activity and, in some cases, alkalization (solonetzization) or xeromorphism. A combined analysis of such characteristics has a high informative value. The accuracy of paleoclimatic reconstructions also depends on the duration of soil sealing (Demkin and Demkina 2000).

Apart from paleosols buried under kurgans, materials brought by people for kurgan building and for ritual burial purposes can also carry information on the environmental conditions of the past.

A study on a short-term pedochronosequence buried under consecutive constructions within a single kurgan provides clear identification of trends of changes in paleosol properties and that of paleoclimatic reconstruction of the highest temporal resolution. In other words it provides the most detailed interpretation of climatic fluctuations based on changes in soil properties (Khokhlova 2007). Paleosols of a short-term pedochronosequence are formed under identical topographic-lithological conditions and have a clear chronology of burial (firstly soils in the center and subsequently at the periphery of a kurgan), which is highly advantageous for researchers.

The present study aimed at a paleoenvironmental reconstruction based on a comprehensive analysis of the short-term pedochronosequence and the overlying mound materials of Kurgan № 1 of kurgan cemetery Boldyrevo IV in the Orenburg Region (Russia) using the methods of soil morphology, physico-chemistry and paleobotany.

Materials and Methods

Study site

Excavations of Kurgan № 1 of the kurgan cemetery (KC) of Boldyrevo IV in the Orenburg Region in the Southern Cis-Urals were conducted during the 2019-2020 archaeological expedition of the Orenburg State Pedagogical University under the supervision of Prof. N.L. Morgunova. Kurgan № 1 (N51°37'40.63", E52°42'28.52") is located on the

first terrace of the left (eastern) bank of the Irtek River, which is the right-side (northern) tributary of the Ural River (Figure 1a-c).

The studied kurgan was very large (Figures 1d and 2), i.e. about 4.2 m high and 60 – 62 m wide, being the largest mound not only within this KC, but among all known kurgans of the Yamnaya culture within the Volga-Ural interfluvial area. This kurgan consisted of four earthen constructions built at different times over a short chronological interval. The first three constructions were built over graves and the fourth construction capped the whole structure. Paleosols buried under these constructions were studied in five soil profiles – one profile under each of constructions (I, II and III) and two profiles under construction IV.

The paleosol profiles had the following positions in relation to kurgan 'baulks' (undisturbed slices of the mound's material between trenches excavated by a bulldozer) (Figure 3 a, b):

- paleosol under construction I (grave 3) – profile B11b-19, central baulk, west-facing side, 10 m to the south of the center, where the mound had a total thickness of 2.5 m, the paleosol had a compacted upper layer;
- paleosol under construction II (grave 4) – profile B13b-19, western baulk, east-facing side, 10-12 m to the north of the center, a 15-cm-thick upper layer had been removed by ancient people (topsoil stripping around the grave);
- paleosol under construction III (main grave 5) – profile B14p-19, western baulk, east-facing side, 10 – 12 m to the south of the center, a 25-cm-thick upper layer of paleosol had been stripped by ancient people;
- paleosols under construction IV – profile B12p-19, western baulk, east-facing side, 21 – 24 m to the south of the center, and profile B15p-19, eastern baulk, west-facing side, 15 m to the north of the center, both paleosols had undisturbed surfaces.

The modern surface soil was studied in profile B16s-19, at a distance of 50 m to the southwest of the kurgan's edge, on a post-arable (fallow) field.

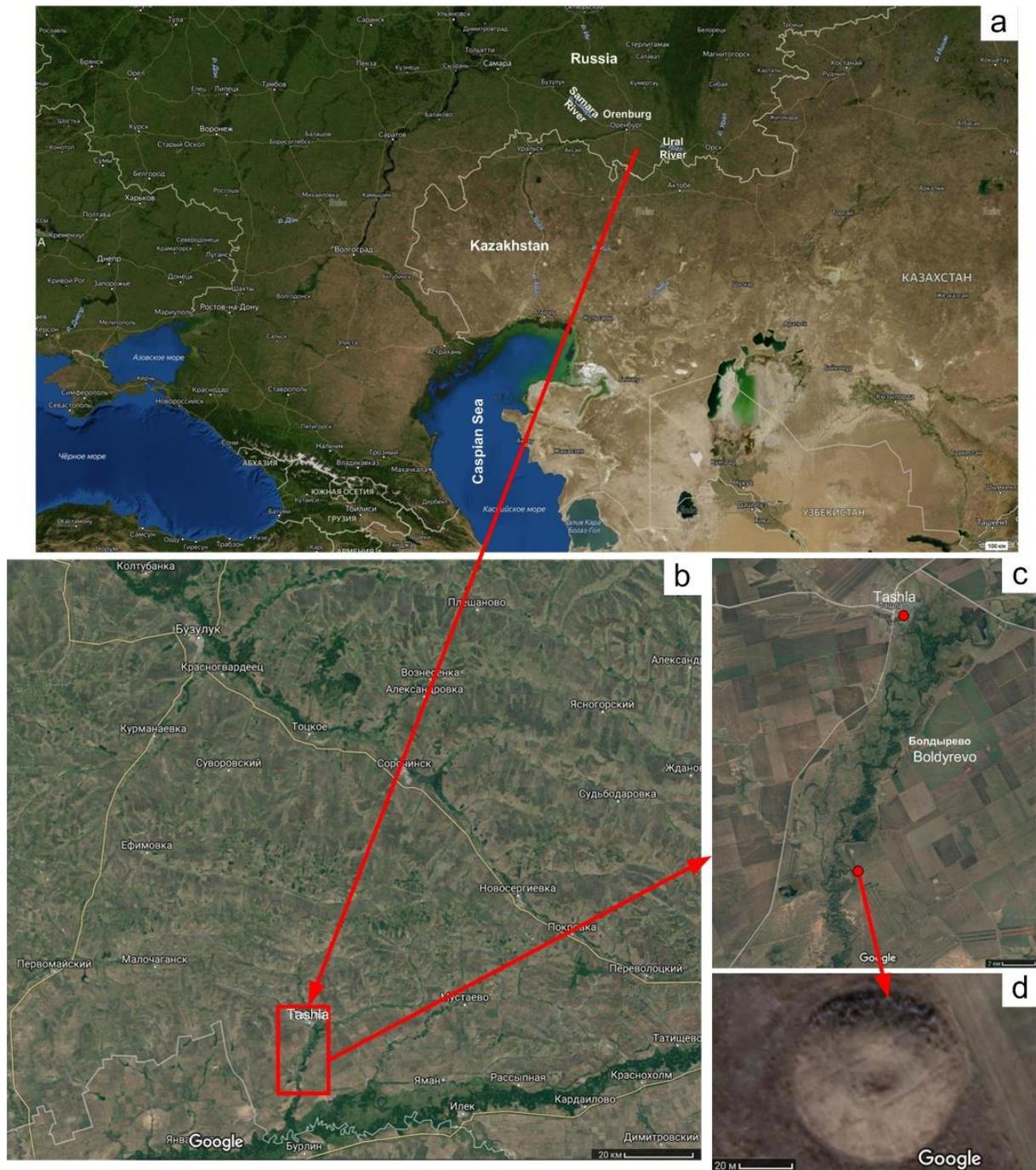


Figure 1. Location of the study site in (a, b) the Tashlinsky District of the Orenburg Region with (c) KCs (red dots) near the villages of Tashla and Boldyrevo and (d) the image of Kurgan № 1 of KC Boldyrevo IV. (Source: Satellite images from [http1\)https://www.google.ru/maps/](http://www.google.ru/maps/)

Geographical setting

The KC of Boldyrevo IV is located on the first terrace of the Irtek River (Ural's northern tributary). This river terrace has an undulating topography with an average height of around 100 m a.s.l. and consists of sandy alluvial deposits that serve as parent material for Calcic Chernozems (southern chernozems, according to the Russian classification system). More specifically, soils of the study site are defined as Protocalcic Chernozems (Arenic), i.e., southern terrace chernozems, according to the Soil Map of the Orenburg Region (Geographical Atlas 1999). The chernozem steppe belt of the Orenburg Region is characterized by a warm and dry climate, with mean temperatures of -15°C and $+22^{\circ}\text{C}$ in January and July, respectively, a mean annual precipitation of about 350 mm and evaporation of 1.5 times higher than precipitation. Undisturbed areas of virgin steppe are dominated by Volga fescue (*Festuca valesiaca*) and feather grass (*Stipa* sp.), although the study site is former arable land that has been abandoned for about 25 years and currently dominated by post-arable weeds (Figure 2).



Figure 2. Kurgan № 1 of KC Boldyrevo IV before the excavation. Photograph by N.L. Morgunova.

Sampling

During the excavation of Kurgan № 1, geoarchaeological investigations included macromorphological descriptions of soils buried under the kurgan and the modern soil near the kurgan. Materials from the soils and kurgan constructions were sampled (in three replications) for different analyses.

From kurgan constructions, undisturbed monoliths of different materials were sampled for mesomorphological investigations and mixed samples were taken for general physicochemical analyses.

All studied soils were sampled for physicochemical analyses. Mixed samples were taken with 10 cm intervals to the depth of 110 cm and further down with 20 cm intervals to the depth of 170 cm.

Carbonate-accumulative horizons from the oldest and the youngest paleosols (profiles B11b-19 and B12b-19, respectively) and the surface soil (profile B16s-19) were sampled for preparation of thin sections for micromorphological analysis.

Profiles B11b-19, B12b-19, B15b-19 and B16s-19, where topsoil had not been stripped, were subjected to palynological and microbiomorphological analyses. For palynological analysis samples from the 0–5 cm depth were used. For microbiomorphological analysis, control samples were taken from 0–2 and 2–5 cm depths and paleosol samples were taken from the following depths: 0–+2 (above the buried surface), 0–2, 2–5 and 5–7 cm.

Analyses

Undisturbed monoliths were described under a binocular microscope and their macrophotographs were taken.

Soil thin sections were investigated and photographed using an AxioScope-A1 microscope (Carl Zeiss, Germany) at the Centre of Collective Use at the Institute of Physical-Chemical and Biological Problems of Soil Science RAS (CCU of IPC & BPSS RAS).

Loose soil samples were air-dried, ground and sieved through a 1 mm mesh for analyses of chemical properties and particle-size distribution and through a 0.25 mm mesh for determinations of organic carbon (C_{org}) and magnetic susceptibility (MS).

The total carbon content was determined using Tyurin's method, content of carbonates (C_{carb}) – manometrically; the content of organic carbon (C_{org}) was determined by subtracting the content of C_{carb} from the total carbon content; the pH_{H_2O} was measured in a 1:2.5 soil:water suspension using a potentiometer; SO_4^{2-} of gypsum – gravimetrically, the total exchangeable bases – using ammonium acetate extraction with the subsequent determinations of K and Na by flame photometry and Ca and Mg by complexometric titration, and loss on ignition (LOI) was determined after exposure of samples to 900°C for 1 h (Arinushkina 1970).

Particle-size distribution was characterized using the Russian system (according to N.A. Kachinkiy, 1965) as follows: coarse and medium sand (1-0.25 mm), fine sand (0.25-0.05 mm), coarse silt (0.05-0.01 mm), medium silt (0.01-0.005 mm), fine silt (0.005-0.001) and clay (<0.001 mm). Particle-size distribution was analyzed using the conventional pipette method after a pre-treatment of samples with sodium pyrophosphate (Vadyunina and Korchagina 1986). The percentage of each fraction was calculated per absolutely dry soil (without hygroscopic moisture).

The magnetic susceptibility (MS) was determined using a KLY-2 Kappabridge magnetometer at the (CCU of IPC & BPSS RAS).

The results of physicochemical analyses were processed using Microsoft Excel and CorelDraw software.

Palynological analysis was performed at the Laboratory of Biostratigraphy of the Voronezh State University using the modified technique developed by Grichuk (1940), and which has previously been described (Khokhlova et al. 2020).

The microbiomorphological analysis involved a consecutive study of the different types of biomorphs under a microscope following the previously described methodology

(Golyeva, 2001). Fifty-gram of each samples were treated with a 30% solution of hydrogen peroxide, and then separated from quartz and other mineral grains by flotation in a heavy liquid (mixed cadmium iodide and potassium iodide solution) with a specific gravity of 2.3. After centrifugation, the floating siliceous and organic biomorphs were collected and washed several times with distilled water, then immersed in glycerine for study under an optical microscope at magnifications 400x. Microbiomorph assemblages were identified and compared between the profiles of the studied pedochronosequence.

All soil samples were studied under a Nikon Eclipse E200 (Nikon Corporation, Japan) optical microscope and selected of them were studied under a JEOL 6610LV (JEOL, Japan) scanning electron microscope (SEM).

The biosilica micro particle distribution diagrams were produced using the C2 (v. 1.5) (Juggins, 2007).

The phytoliths were identified according to ICPN 2.0 (International Committee for Phytolith Taxonomy (ICPT), 2019). Ecological and environmental interpretation of the phytolith assemblages was given according to Golyeva (2007). Since many of the biocenotic groups include several different morphological groups, the cumulative biocenotic component is given on the phytolith distribution graph, and the groups of morphological forms included in it and their codes are given in Table 1.

Table 1. Correlation between biocenotic characteristics and phytolith morphotypes.

Plants	ICPN 2.0 Morphotype	ICPN 2.0 Code
Dicotyledonous and several monocotyledonous herbs	Elongate entire	ELO_ENT
Coniferous	Blocky rectangular	BLO_RES
	Blocky velloate	BLO_VEL
Forest grasses	Acute bulbosus_1*	ACU_BUL_1
Meadow grasses	Acute bulbosus_2*	ACU_BUL_2
	Bilobate	BIL
	Elongate sinuate	ELO_SIN
	Polylobate	POL
Steppe grasses	Rondel conical	RON_CON
	Rondel trapeziform	RON_TRZ
Arid grasses	Blocky polyconal	BLO_POL
	Elongate dentate	ELO_DET
Reed	Bulliform flabellate	BUL_FLA

*1 – with large base; 2 – with small base

Results

Characteristics of the kurgan's construction

Kurgan № 1 was the largest burial mound in KC Boldyrevo IV and consisted of four earthen constructions. Constructions I and II (observed at the central and western baulks, respectively) had heights of about 1.0 and 1.2 m and widths 6 and 7 m, respectively. In the central baulk, construction III completely covered construction I and the outline of construction IV was approximately identified. Constructions III and IV had a maximal total thickness of 3.2–3.5 m and a width of about 60 m (Figure 3 a, b).

The first three constructions were created above graves and surrounded by distinct circular ditches, which occasionally were discontinuous (i.e. consisting of a series of hollows). EC IV did not have any grave underneath and we suppose that it was created as a general reinforcement of the kurgan, which possibly started to crumble or slump back after a short time after building (a likely occurrence in mounds constructed from sandy loams). Although the boundaries of EC IV were indistinct on the faces of baulks, they could be traced by the enlargement of sizes and an increase in the number of carbonates (white spots) in the material on the periphery of the kurgan compared to that in the center. According to our estimations, there was a time lag of only several decades between the building of EC III and EC IV, with the latter being only a reinforcement of the former. Therefore, from an archaeological point of view, EC III and EC IV could be regarded as a single construction, but due to a time interval between their erections, we shall further refer to them separately for the practical convenience of data presentation and discussion.

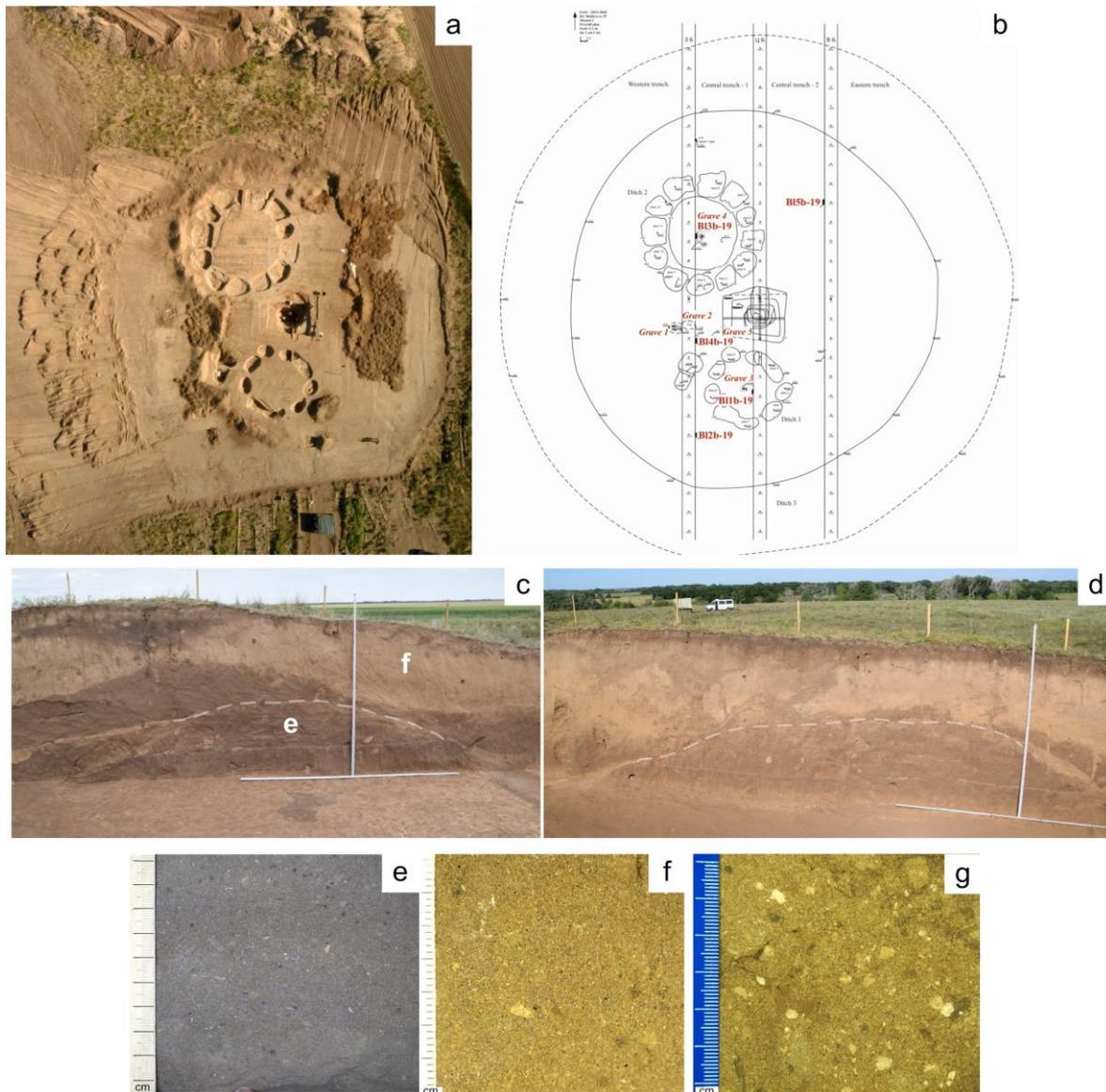


Figure 3. Earthen constructions (EC) of Kurgan № 1 of KC Boldyrevo IV: (a) top view of the ditches of the construction I (small) and II (large); (b) sketch of the baulks and location of the graves, ditches and soil profiles in the excavated Kurgan № 1; (c) construction I, central baulk, western face, and (d) EC II, western baulk, eastern side. Dotted lines mark the boundaries of EC I and EC II, e and f on (c) are sampling points of the materials shown in macro-photographs: (e) gray-brown material from EC I, (f) yellowish-pale material from EC III., (g) yellowish-pale material with prominent whitish mottles from EC IV. Photographs (a) (c) and (d) were taken and sketch (b) was done by N.L. Morgunova and (e), (f) and (g) by O.S. Khokhlova.

Graves 3 and 4 under EC I and EC II, respectively, are burials of children under the age of five and were attributed to the Yamnaya culture based on the typical pottery in grave inventories and the burial ritual. Ancient builders trampled the soil under EC I and stripped soil under EC II. Main grave 5 with remains of four adult people was located exactly between EC I and EC II, where the builders created a squarish plot of stripped soil, with the thickness of the removed humus layer of 10–15 cm on average and up to 25 cm near the central grave. The stripped soil was covered by bluish-whitish clay with rusty mottles and inclusions of plant debris darkened with time (Figure 4 a,

c) and crushed shells of river molluscs (Figure 4b). The clayey cover of this plot partially extended over fills of ditches around EC I and EC II. On this plot the ancient builders were likely to prepare the clay mortar used in the roof of main grave 5. The river mollusk shells and possibly also the plant debris inclusions were likely to indicate either the use of river silt for preparations of the mortar or subsequent additions of river silt to the surface of this plot, possibly, for ritual purposes. The large EC III was created above the main grave and extended far beyond, completely covering EC I and EC II. The main grave's burial chamber was very large (9.5 x 7.5 m wide and about 4 m deep, measured from the level of buried soil) and had a complex stepping structure. Judging from its inventory and burial ritual, the main grave was also ascribed to the Yamnaya culture.

The above-described stratigraphy of earthen constructions unambiguously shows that EC I and EC II were created before EC III (the latter covered the first two). The dating by radiocarbon planned in the near future is likely to help to confirm the observed pattern.

Both constructions I and II consisted of gray-brown material that was capped by a discontinuous layer of yellowish-pale material up to 10 cm thick (Figure 3 a, b). The color of gray-brown material was generally identical to that of the humus horizon (Ahb) of buried paleosols, with additional darker and lighter speckles and mottles (Figure 3 c). Construction III was made predominantly of subsoil materials (mainly B1kb and BCkb horizons, see the paleosol profile description below), with an occasional presence of humified materials from the AhBkb and Ahkb horizons (mostly above constructions I and II, as can be seen in Figure 3 a, b). The subsoil materials of EC III had a yellowish-pale color with small gray-brown (humified) and whitish (carbonate) mottles (Figure 3 d). Construction IV had generally the same yellowish-pale color, but with noticeably larger and more frequent whitish mottles and gray-brown mottles also present (Figure 3 e).

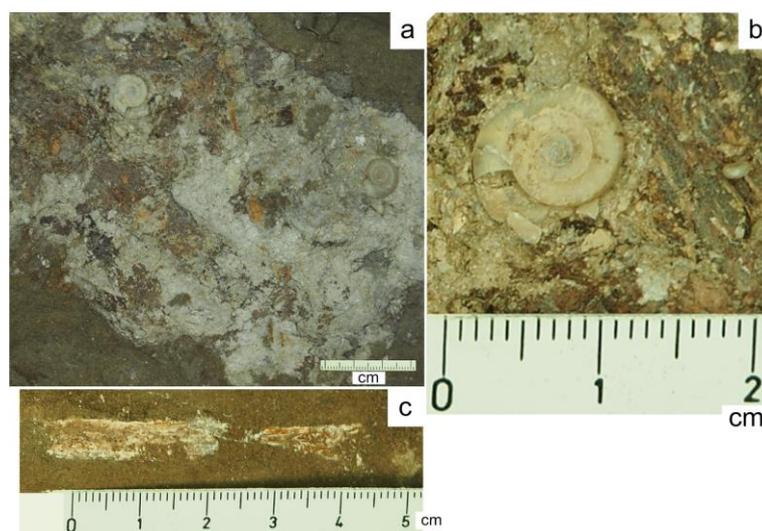


Figure 4. The clayey cover of the plot around the main grave sampled from western baulk, eastern face, Kurgan № 1, KC Boldyrevo IV: (a) general view, (b) closeup of a shell and (c) decomposed debris of plants included in the clay. Macro photographs were taken by O.S. Khokhlova.

The physicochemical analyses showed significant differences in the properties of the materials of constructions I, II, III and IV and the clayey covering of the plot around the main grave (Table 2). The texture classes of both gray-brown and yellowish-pale materials were defined as sandy loams and the clayey cover corresponded to sandy clay loam, close to clay loam. The clayey cover significantly differed from the other materials by all parameters. Its high C_{org} and LOI indicated enrichment in organic matter and its high C_{carb} and pH_{H_2O} (despite the removal of carbonate shells prior to the analysis) indicated possible additions of carbonate powder, e.g., crushed limestone.

Table 2. The physicochemical properties of materials of constructions I, II, III and IV and the clayey cover of the plot around the main grave (Kurgan № 1, KC Boldyrevo IV)

Material of kurgan construction	Particle-size fractions, mm		C_{org} , %	C_{carb} , %	LOI, %	pH_{H_2O}	MS, 10^{-8} units SI
	>0.01	<0.001					
Gray-brown, EC I	81.5±1.5	6.6±0.3	0.34	0.12	2.1±0.1	7.3±0.07	45
Gray-brown, EC II	81.7±1.3	6.4±0.4	0.36	0.16	2.3±0.2	7.6±0.02	40
Yellowish-pale, EC III	83.0±2.6	5.4±1.0	0.25	0.61	3.9±0.1	7.7±0.01	22
Yellowish-pale with whitish mottles, EC IV	82.6±1.7	6.6±0.1	0.23	0.96	4.3±0.1	7.9±0.01	31
Clayey cover of the plot around the main grave	56±2.7	18.8±0.7	2.83	3.61	22.8±1.7	8.3±0.03	13

The gray-brown materials of EC I and EC II as compared to the yellowish-pale materials of EC III and EC IV had higher C_{org} and MS and lower C_{carb} , LOI and pH_{H_2O} . Construction IV had the highest C_{carb} , LOI and pH_{H_2O} values, which correlated with our morphological observations.

Macromorphology of soils of the studied chronosequence

The paleosols buried under kurgan I of KC Boldyrevo IV are shown in Figure 5 a-e. Their profiles generally consisted of the following horizons: Ahb (0–45 cm), Ahkb (45–65 cm), AhBkb (65–90 cm), B1kb (90–120 cm), BCkb (120–160 cm) and R1-R2kb (160–200(245) cm). They were classified as Protocalcic Chernozem (Arenic) according to the WRB or as ordinary chernozem (sandy-loamy migrational-segregational) according to the Russian system. The Ahb humus horizon had color 10YR 4/2–4/4 (referred to as 'gray-brown' in field descriptions) and a smooth lower boundary. Effervescence was observed from the depth of 40–45 cm. The BCkb carbonate-accumulative horizon contained horizontally-oriented dense strips of sandy loam impregnated and cemented with calcium carbonate. Visible accumulations of gypsum were absent. There were numerous holes made by burrowing animals between the depth of 45 and 160 cm, but none of those occurred in the underlying R1-R2kb horizons that consisted of coarse sand.

The surface post-arable soil (Figure 5 f) had the following profile: Ah (0–10 cm), Ah1 (10–28 cm), Ah2 (28–60 cm), Ah3 (60–80 cm), AhB (80–110 cm), Bk (110–130 cm), BCK (130–150 cm), Rk1 (150–180 cm) and Rk2 (180–200 cm). The Ah and Ah1 horizons represented the former plough layer (Ap). This soil was classified as Protocalcic Chernozem (Arenic, Aric) according to the WRB or as common chernozem (sandy-loamy post-agrogenic migrational-segregational) according to the Russian system.

A comparative analysis of the buried paleosols of the studied chronosequence showed that profile B11b-19 (under EC I) was the least disturbed by burrowing animals, its humus horizon had a relatively smooth or wavy lower boundary and its carbonate-accumulative horizon had the most regularly-shaped carbonate impregnation features. The number of burrows increased in pits B13b-19 and B14b-19 (under EC II and EC III, respectively) and reached its maxima in pits B12b-19 and B15b-19 (EC IV). The disturbance by burrowing animals resulted in the formation of an irregular tonguing-like lower boundary of the humus horizon and irregular positions of carbonate strips, especially in the paleosols buried under EC IV. The latter were also characterized by the most developed carbonate impregnation features that also occurred in between the aforementioned horizontal strips.

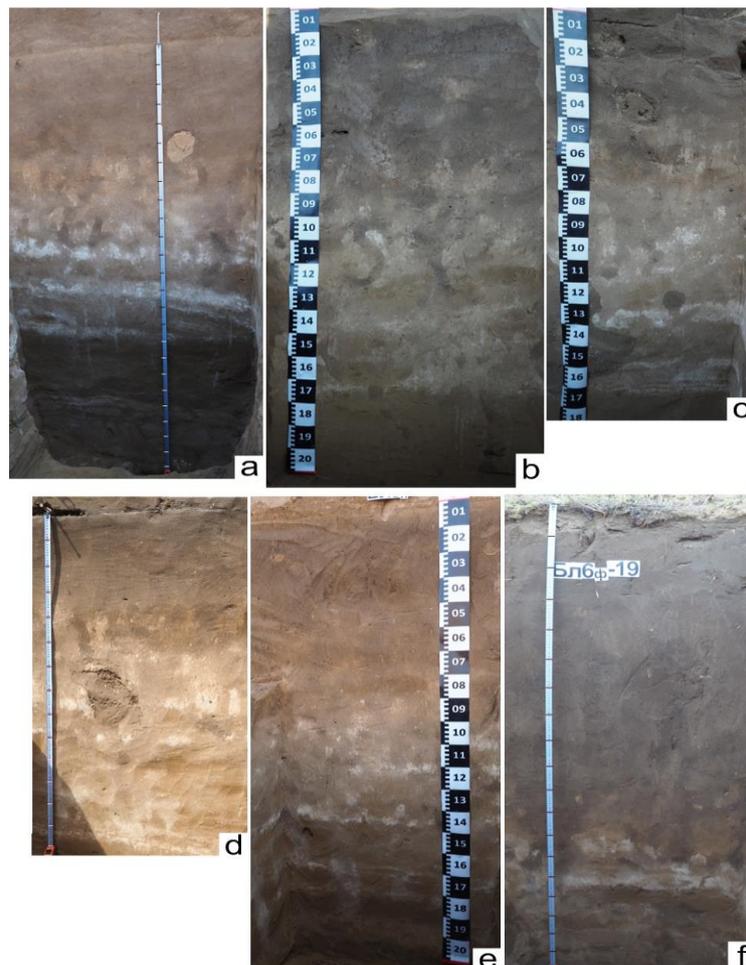


Figure 5. Profiles of the studied pedochronosequence of Kurgan № 1, KC Boldyrevo IV: (a) B11b-19, (b) B12b-19, (c) B13b-19, (d) B14b-19, (e) B15b-19 and (f) B16s-19. Photographs were taken by O.S.

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The modern soil (Bl6s-19) was most similar to the Bl1b-19 paleosol in terms of macromorphology, e.g., it also had a low number of burrows (in this case, due to the recent agricultural use) and clearly visible horizontal strips of carbonate impregnations. However, the modern soil differed by the presence of the former plough layer (Ap) and a much thinner carbonate-accumulative horizon, i.e., the modern BCk (130-150 cm) was half as thick as the ancient BCkb (120-160 cm).

Micromorphology of carbonate-accumulative horizons

The micromorphological analysis of carbonate-accumulative horizons Bkb (paleosols Bl1b-19 and Bl2b-19) and Bk (surface soil Bl6s-19) allowed us to further confirm the results of our macromorphological observations. In the Bkb horizon of pit Bl1b-19, there was micromass characterized by crystallitic b-fabric, which indicated the presence of cryptocrystalline carbonates. Such a calcareous micromass occurred in the form of bridges between silicate grains as well as films on grain surfaces (Figure 6 a). In the Bkb horizon of pit Bl2b-19, a similar calcareous micromass with crystallitic b-fabric occupied a greater area and completely filled the spaces between silicate grains (Figure 6 b). In the Bk horizon of pit Bl6s-19, calcareous micromass bridged silicate grains as in the case of Bl1b-19 and, in addition, carbonates were present in the form of sparite grains scattered among silicate grains (Figure 6 c).

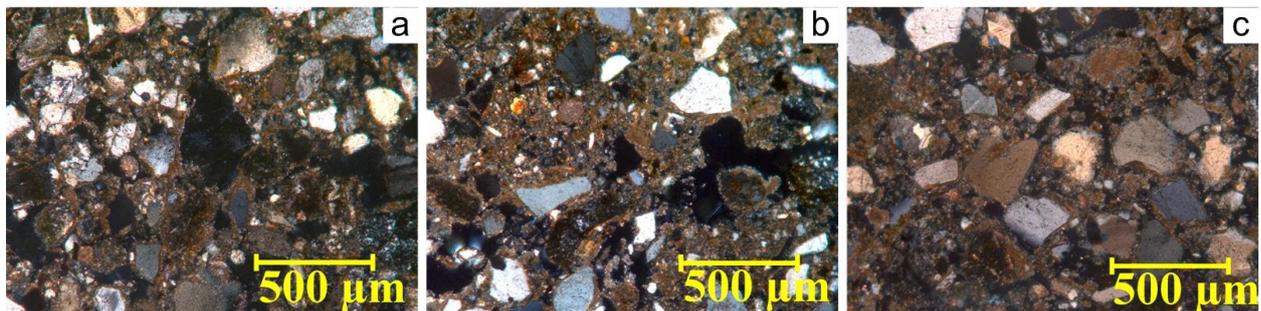


Figure 6. Microfabric of the carbonate-accumulative horizons of soils from the following pits: (a) Bl1b-19, (b) Bl2b-19 and (c) Bl6s-19. Photographs were taken by O.S. Khokhlova.

Physicochemical properties of soils of the chronosequence

The particle-size distribution in the studied paleosols and surface soil was uniform (Figure 7). It was generally characterized by the predominance of particles of >0.01 mm (i.e., so-called 'physical sand', the sum of sand and coarse silt), the content of which ranged from 80 to 85%. The content of particles <0.001 mm (clay) varied mostly from 5 to 10% and occasionally reached 13%. According to the classification of Kachinskiy (1965), soil texture was defined as sandy loam with the predominance of sand (1-0.05 mm) to the depth of 150-160 cm. Lower, in the parent material (R horizons), the sum of coarse and medium sand (1-0.25 mm) varied from 60 to 70%. The uniform particle-size distribution allowed for direct comparisons between the values of the other parameters in the studied soils.

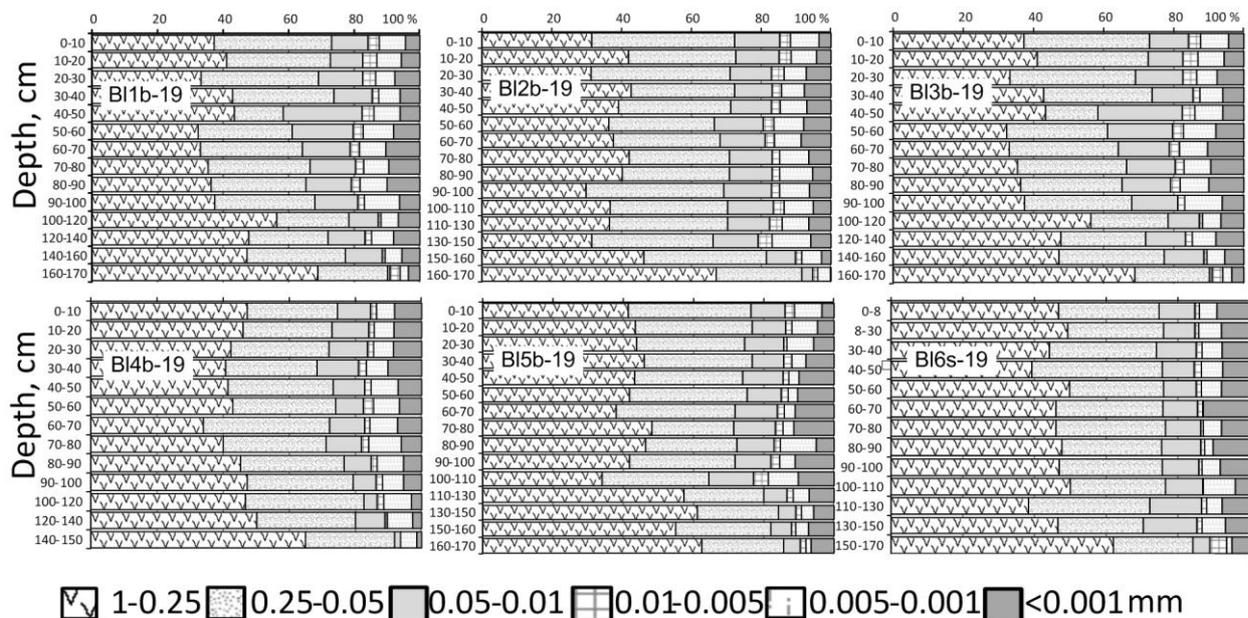


Figure 7. The particle-size distribution in the profiles of the studied pedochronosequence: coarse and medium sand (1-0.25 mm), fine sand (0.25-0.05 mm), coarse silt (0.05-0.01 mm), medium silt (0.01-0.005 mm), fine silt (0.005-0.001 mm) and clay (< 0.001 mm).

Determinations of pH_{H_2O} showed that paleosol BI2b-19 buried under EC IV had a very high pH (8.4–8.7), i.e., a strongly alkaline reaction throughout the profile (Figure 8 a). The other paleosol BI5b-19 buried under the same construction also had very high pH_{H_2O} values, which reached 8.9 within the 0–20 cm layer and did not drop below 8 throughout the whole profile. Paleosol BI3b-19 buried under EC II had pH values close to those in BI5p-19. However, paleosol profiles BI4b-19 and BI1b-19 (EC III and I, respectively) as well as surface soil profile BI6s-19 were characterized by prevailing pH values from 7 to 8, i.e., a weakly alkaline reaction.

The contents of organic carbon (C_{org}) in the upper horizon of paleosols varied from 0.15% in BI2b-19 to 0.3 % in BI1b-19, but reached 0.73% in surface soil BI6s-19 (Figure 8 b). The two paleosols buried under EC IV (BI2b-19 and BI5b-19) were characterized by the lowest C_{org} contents within the upper half-meter-thick layer.

According to Ivanov et al. (2009) soils buried over a period of about 5500 years lose on average 60% of their organic carbon and preserve from 50 to 30% of the original content of C_{org} . A reconstruction of the original C_{org} contents in the studied paleosols, by means of recalculating the data obtained, revealed that paleosols that were relatively poor in organic matter (BI2b-19 and BI5b-19) originally contained 0.4-0.7% C_{org} , whereas relatively rich paleosols (BI1b-19, BI4b-19 and BI3b-19) had contents from 0.7% (BI3b-19) to 1.2% (BI4b-19) that are comparable with the value of 0.73% in surface soil (BI6s-19).

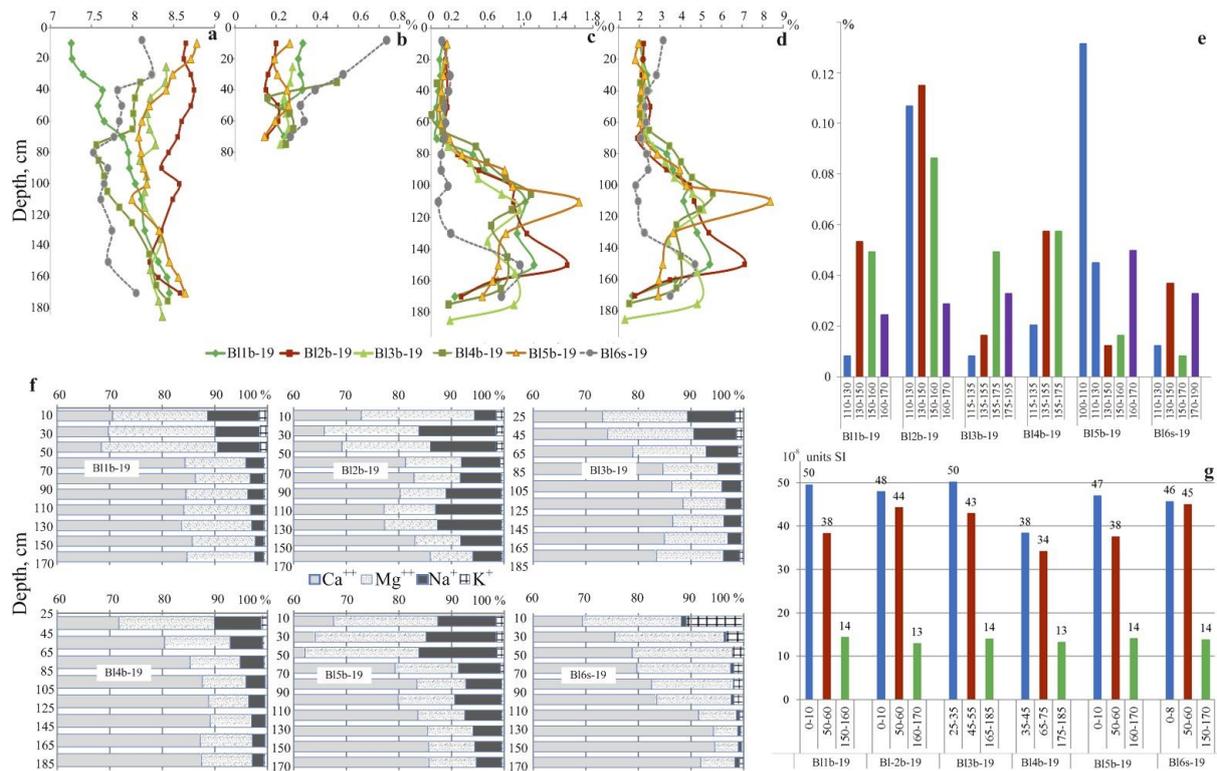


Figure 8. The physicochemical properties in the profiles of the studied pedochronosequence: (a) pH_{H2O}; (b) C_{org} content, %; (c) C_{carb} content, %; (d) LOI, %; (e) SO₄²⁻ of gypsum, %; (f) exchangeable cations, % of the total exchangeable bases; (g) MS, 10⁻⁸ units SI.

The contents of carbonate carbon (C_{carb}) in the studied pedochronosequence had values of around 0.1% within the 0–80 cm depth and increased up to 1.65% in the underlying layers, but dropped to 0.2–0.6% at the bottom, in all profiles (Figure 8 c). Despite the similar patterns of vertical distribution of this parameter, exact depths and values of peak concentrations were different in different profiles. The paleosols buried under the ECs I, II and III (BI1b-19, BI3b-19 and BI4b-19, respectively) had C_{carb} contents of up to 0.9–1.1% within 110–160 cm depths. The paleosols buried under EC IV (BI2b-19 and BI5b-19) had two maxima C_{carb} contents, i.e., 0.9–1.6% at the depth of 110–120 cm and 0.6–1.5% at the depth of 150–160 cm. The modern soil had the C_{carb} maximum of 1% at the depth of 150 cm. Therefore, paleosols BI2b-19 and BI5b-19 had relatively high values of C_{carb} content throughout the profile and the most prominent maxima of this parameter, which is indicative of calcium carbonate accumulation.

Vertical distribution patterns of loss on ignition (LOI) practically repeat those of C_{carb} contents, with maximal values in paleosols BI2b-19 and BI5b-19 (Figure 8 d). Therefore, this analysis furthermore confirmed that paleosols buried under EC IV were characterized by the maximal degree of calcium carbonate accumulation within the studied pedochronosequence.

The content of SO₄²⁻ of gypsum had the highest values (up to 0.13%) within 100–130 cm and 130–150 cm layers of paleosols BI2b-19 and BI5b-19, respectively. Other paleosols and surface soil were characterized by values of up to 0.6%, on average 0.03% (Figure 8 e).

The exchangeable bases were represented mostly by calcium, which had a mean content of 70% of the total exchangeable bases (Figure 8 f). Exchangeable sodium (Na) had variable percentages within soils of the studied pedochronosequence, with relatively high (up to 14.8%) values in the profiles (Bl2b-19 and Bl5b-19) buried under EC IV. The paleosols buried under the first three constructions (Bl1b-19, Bl3b-19 and Bl4b-19) were characterized by exchangeable Na contents from 2 to 9%. Surface soil had the lowest (0.3–0.9%) contents of exchangeable Na throughout the profile, but the highest contents of exchangeable K, especially, within the former plough layer.

Values of magnetic susceptibility (MS) generally decreased with depth (Figure 8 g). The surface horizons had the lowest value of $38 \cdot 10^{-8}$ units SI in profile Bl4b-19, where a 25-cm-thick upper layer had been removed (stripped) by ancient people. Undisturbed upper layers of profiles Bl2b-19 and Bl5b-19 had MS values of 48 and $47 \cdot 10^{-8}$ units SI, respectively, which were comparable with the MS of surface soil ($46 \cdot 10^{-8}$ units SI). However, the highest values of $50 \cdot 10^{-8}$ units SI were detected in both unstripped Bl1b-19 and stripped Bl3p-19 profiles, despite that the latter was missing a 15-cm-thick layer of topsoil. The MS of automorphic soils of the steppe zone is known to increase with an increase of mean annual precipitation, which is due to the reaction of iron-reducing bacteria to the increasing moisture within the humus horizon (Alekseeva et al. 2007, Zavarzina et al. 2003). Therefore, the MS data indicate that the mean annual precipitation decreased at the time of the construction of EC IV.

Palynological analysis of soils

As a result of the palynological analysis of the selected soils (Bl1b-19, Bl2b-19, Bl5p-19 and Bl6s-19, which were not stripped), it was found that samples from Bl1p-19 and Bl2p-19 (buried under EC I and IV, respectively) did not contain any pollen. In order to compare the data obtained on the paleosol buried under EC IV (Bl5b-19) and surface soil (Bl6s-19) in the KC Boldyrevo IV, we used our unpublished data on the paleosol (Tsh8b-19) buried under Kurgan № 1 of KC Tashla IV and surface soil (Tsh7s-19) located near this kurgan. Kurgan № 1 of KC Tashla IV is located at a distance of 10–15 km to the north of Kurgan № 1 of KC Boldyrevo IV (Figure 1) and was also constructed by people of the Yamnaya culture, Repino stage, but presumably a bit later than the kurgan 1 of the Boldyrevo IV.

Paleosols Bl5b-19 and Tsh8b-19 had very similar pollen assemblages (Figure 9).

Tree pollen was dominated by gymnosperm species including predominantly Scots pine (*Pinus sylvestris*), with less abundant Siberian pine (*Pinus sibirica*), Siberian spruce (*Picea obovata*), larch (*Larix* sp.), common juniper (*Juniperus communis*) and sea grape (*Ephedra distachya*). Such a combination of gymnosperms indicated that dark-coniferous forests and pine woods were present within the study region. Angiosperm trees were less abundant and included mostly small-leaved forest species such as birch (*Betula*), aspen (*Populus tremula*) and alder (*Alnus*). There were fewer broad-leaved forest species, e.g., single grains of pollen of common oak (*Quercus robur*) and guelder rose (*Viburnum opulus*) in the Bl5b-19 sample. Both paleosols contained single pollen grains of hazel (*Corylus avellana*), elm (*Ulmus* sp.), and willow (*Sali* sp.). The latter usually

grows by water. As compared to the B15b-19 sample, the Tsh8b-19 sample contained more pollen from *Ephedra distachya* and *Juniperus communis*, which were indicative of aridization and cooling of the paleoclimate within the study region.

The pollen assemblages were generally dominated by grasses (Poaceae) and herbs (*Herbetum mixtum*), the latter including mainly the rose family (Rosaceae) and legumes (Fabaceae). Pollen from grasses and herbs originated from meadow communities. Frequently occurring pollen of the goosefoot family (Chenopodiaceae) originated from ruderal and salt-tolerant species, predominantly *Kochia laniflora* and *Chenopodium album*, which were indicative of the presence of bare ground areas and heavily overgrazed parts of the floodplain in the past. The proportion of *Chenopodiaceae* significantly increased in Tsh8p-19 sample as compared to that in the B15p-19, which also indicated a slight cooling of the paleoclimate.

There were occasional spores that originated from clubmosses (Lycopodiaceae), polypod ferns (Polypodiaceae) and bracken (Pteridium). The presence of polypod ferns and inundated clubmoss (*Lycopodiella inundata*) indicated that regularly flooded areas existed near water courses within the study region. The proportion of Polypodiaceae significantly decreased in Tsh8b-19 sample as compared to that in the B15b-19.

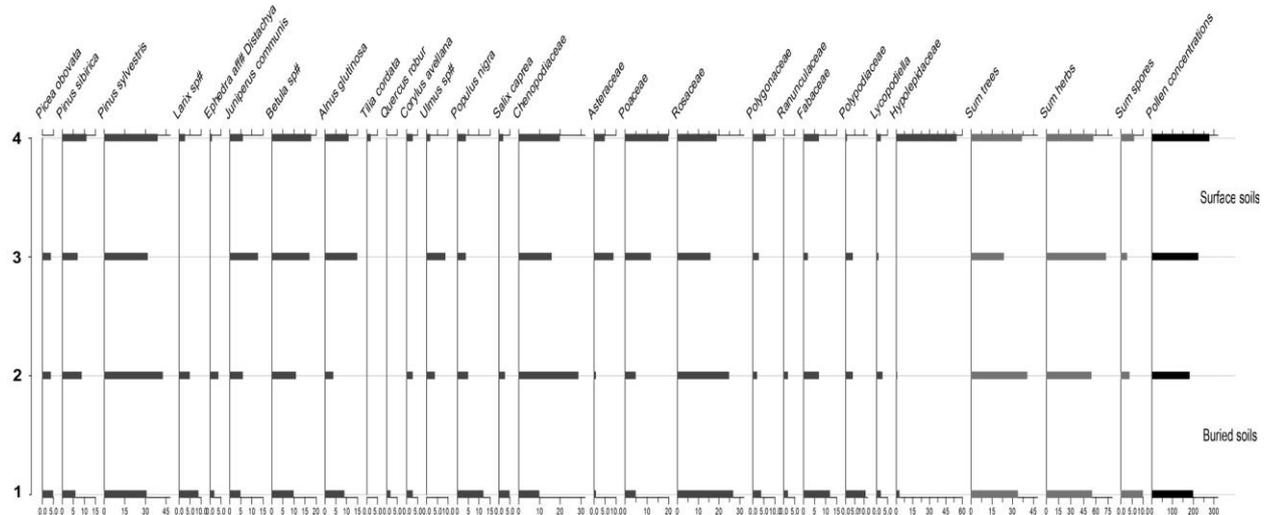


Figure 9. The composition of pollen assemblages from paleosols B15b-19 (1) and Tsh8b-19 (2) and surface soils B16s-19 (3) and Tsh7s-19 (4) from KCs Boldyrevo IV and Tashla IV, respectively.

Thus, the studied pollen assemblages reflected generally cool and dry climatic conditions. A comparison of the B15b-19 paleosol of the study site with the slightly later buried Tsh8b-19 paleosol revealed indications of cooling and aridization as follows: increased proportions of steppe species, increased frequencies of *Ephedra distachya*, *Juniperus communis* and *Chenopodiaceae* and decreased *Polypodiaceae*. These changes happened within the study region just after the completion of the construction of the studied kurgan.

Pollen assemblages from surface (control) soils B16s-19 and Tsh7s-19 were very similar, with the predominance of gymnosperms among tree species and a comparable abundance of grasses, herbs and spores. Within the Ural River valley the oak forests spread far to the north, i.e., up to the latitude of 52° N. To the south of latitude 50° N,

the study region is occupied by the Pontic-Caspian steppe with localized areas of oak forests (Physico-geographical Atlas of the World, 1964). It is not excluded that the area of dark-coniferous forests has quite recently expanded along the slopes of the ridges of Syrt and Melovoi Syrt.

Microbiomorph analysis of soils

The two samples, 0–2 and 2–5 cm, from the surface (control) soil Bl6s-19 contained abundant detritus and occasional grass cuticles, plant roots and fungal hyphae (Table 3, Figure 10). However, the vertical distribution of phytoliths had an unnatural pattern, with the lower sample containing a double number of phytoliths as compared to the upper sample. The lower sample also contained fragments of diatom shells and phytoliths of hydrophilic plants (*Phragmites* and/or *Scirpus*) that were absent from the upper sample. The upper sample contained many phytoliths of arid flora that constituted 15% of its phytolith assemblage, but were absent from the lower sample. These data allowed us to suggest that the modern post-agrogenic soil was irrigated during its arable use in the past, because the observed diatoms and phytoliths of hydrophilic plants are likely to be brought with irrigation waters. The microbiomorph assemblage of the surface sample reflects the current meadow-steppe vegetation at the study site.

Table 3. A comparative semiquantitative assessment of different types of organic matter and silicious microbiomorphs in the studied profiles of paleosols and modern soil

Profile	Depth, cm	Detritus	Amorphous organic matter	Sponge spicules	Diatoms	Phytoliths	Additional information
Bl1p-19	+0+2	+++	+++	-	+	+++	-
	0-2	+++	+++	S.	+	+++	-
	2-5	+++	+++	-	-	+++	-
	5-7	+++	+++	-	+	+++	-
Bl2p-19	+0+2	+++	+++	S.	+	+++	-
	0-2	+++	+++	S.	+	+++	-
	2-5	+++	+++	S.	S.	+++	-
	5-7	+++	+++	-	S.	+++	Cuticles of grasses – S.
Bl5p-19	+0+2	+++	+++	S.	-	+	-
	0-2	+++	+++	-	-	+++	-
	2-5	+++	+++	-	S.	+++	-
	5-7	+++	+++	S.	-	++	-
Bl6f-19	0-2	+++	+++	-	-	++	Grass cuticles, roots, hyphae
	2-5	+++	+++	-	S.	+++	

Note: semiquantitative measures: +++ (many, i.e., over 100 units); ++ (moderate, 40-100 units); + (few, 5-40 units); S. (single, 1-4 units); - (absent)

The paleosol B11b-19 buried under EC I was characterized by the abundance of detritus, amorphous organic matter and phytoliths throughout the sampled layer (from +2 to 7 cm depth). The 0–+2 and 0–2 cm samples contained both entire and fragmented diatom shells, which were more numerous in the 0–+2 sample. The 5–7 cm sample contained only fragmented diatom shells. Single spicules of sponges were observed in the 0–2 cm sample. The phytolith assemblage was generally dominated by meadow-steppe flora, with a small proportion of arid flora (up to 11% in the 2–5 cm sample). However, the 0–2 cm sample had a remarkably high proportion (23%) of phytoliths of hydrophilic flora (*Phragmites* and/or *Scirpus*). The overall abundance of phytoliths, even at the depth of 5–7 cm, indicated that the B11b-19 paleosol had a man-made surface cover of river (or lake) silt, which was at least 7 cm thick. Vegetation of the study site was represented by meadow-steppe communities.

The paleosols B12b-19 and B15b-19 buried simultaneously under EC IV had similar microbiomorph assemblages, with abundant detritus and amorphous organic matter. There were many phytoliths, although not as many as in the B11b-19 paleosol. Although the quantities of phytoliths in 2–5 and 5–7 cm samples from B15b-19 were comparable with typical levels in buried paleosols without allochthonous silt, the qualitative analysis of phytolith assemblages showed that almost all samples from B12b-19 and B15b-19 contained diatom shells and/or sponge spicules to the depth of 7 cm. Vegetation of the study site was represented by meadow-steppe communities, with a tendency for increasing proportions of steppe grasses from the bottom to the top of the studied column.

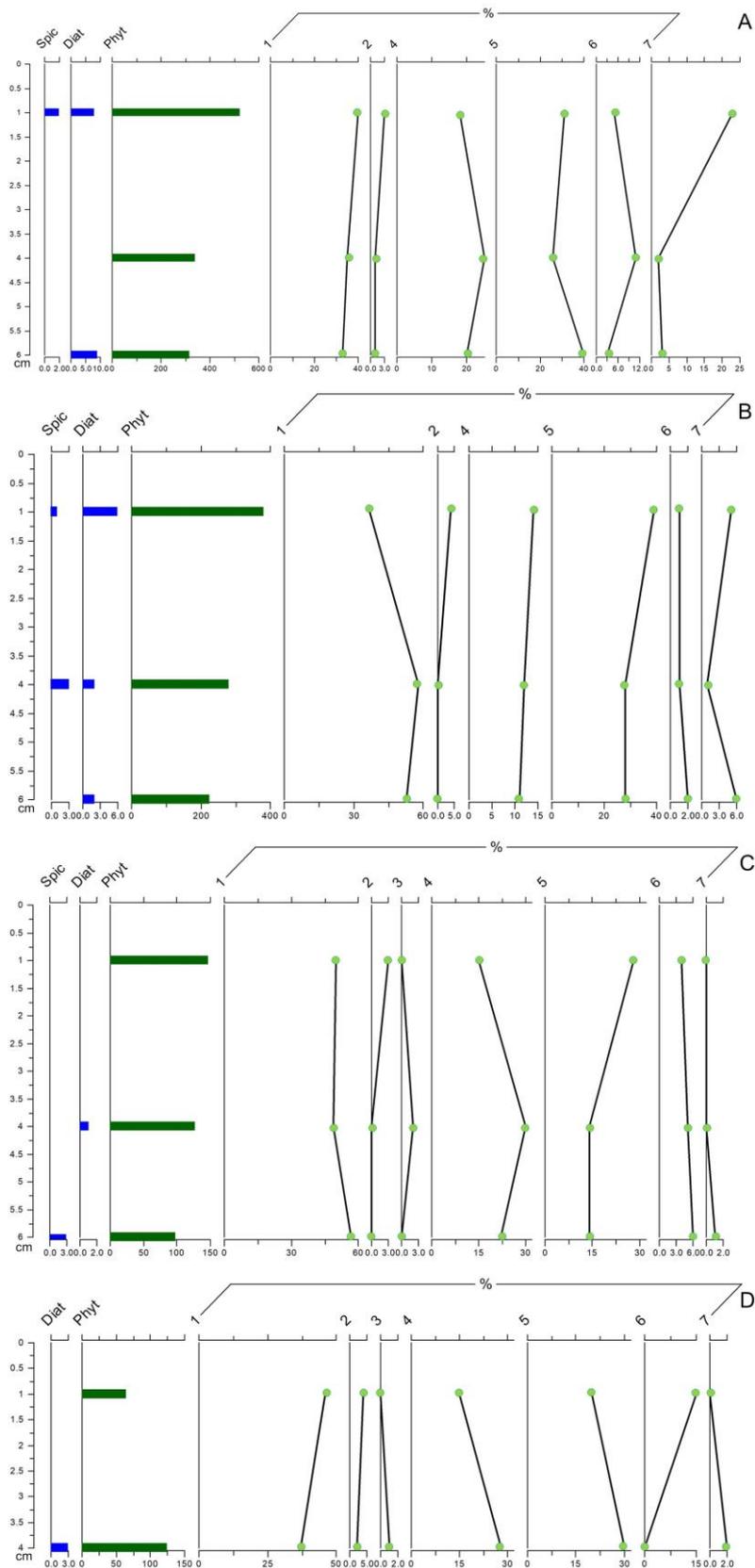


Figure 10. Silica microbiomorphs in buried and surface soils: A – profile B11b-19; B – profile B12b-19; C – profile B15b-19; A – profile B16f-19; 1 – herbs (dicots); 2 – indicator types of conifer species; 3 – trichomes of grasses of forest habitats; 4 – trichomes of grasses of meadow-like habitats; 5 – short sels of grasses of steppe-like habitats; 6 – arid herbs; 7 – reed.

Discussion

The trends of changes in the different soil properties revealed in the present study as well as any changes in the soil cover over time were generally predetermined by climatic fluctuations. As a result of analyzing the short-term chronosequence of paleosols buried under Kurgan № 1 of KC Boldyrevo IV, we identified main paleopedological indicators of changes in climate humidity within the steppe zone. These indicators include the following: the degree of zooturbation of a profile, the content of organic carbon at the upper part of a soil profile, the vertical distribution and depths of peaks (concentration maxima) of carbonate carbon, the contents of gypsum and exchangeable sodium, the value of magnetic susceptibility. In addition to pedogenic properties, information sources stored in the studied soils includes non-pedogenic materials (e.g., pollen and phytoliths) that can be used for reconstructions of paleoenvironments.

It should be emphasized that both the studied paleosols and the surface soil of KC Boldyrevo IV are formed on the same lithogenic basis including soil parent materials and bedrock and have similar topographic positions with comparable elevations, which allowed us to interpret the observed changes in soil properties as a response to climate change.

A comparative analysis of paleosols and surface soil within the short-term pedochronosequence of Boldyrevo IV showed that changes in soil properties over the period of Kurgan № 1 building were as follows: C_{org} content decreased in the upper part of profile, whereas values of C_{carb} , LOI, pH_{H_2O} , SO_4^{2-} of gypsum, exchangeable Na and MS increased. The paleosols B12b-19 and B15b-19 buried under construction IV had the most 'aridic' features including an irregular (tonguing-like) lower boundary of the humus horizon due to a high degree of zooturbation and the micromorphologically detected high degree of carbonate impregnation of micromass within the carbonate-accumulative horizons.

The assumption that the studied kurgan was built from soil materials was confirmed by the findings that the kurgan constructions and the genetic horizons of the buried paleosols had matching textures and colors as well as physico-chemical properties. The observed changes in earthen materials from the first to the fourth constructions mirrored the changes in paleosols buried under those constructions. Materials of constructions I and II were sourced primarily from the Ahb horizon and to a lesser extent from Ahkb and AhBkb and had high C_{org} contents and MS values, but low C_{carb} contents, LOI and pH_{H_2O} . Constructions III and IV were built mainly of material from the Bkb and BCkb horizons with small additions of AhBkb and had relatively low C_{org} contents and MS values, but high C_{carb} , LOI and pH_{H_2O} . The material of construction IV as well as the paleosol buried underneath had the lowest C_{org} contents and the highest C_{carb} contents within the studied chronosequence. Based on all diagnostic properties, we suggest that construction IV was built at the time of increasing aridization of the climate.

The bluish-whitish clayey cover of the plot around the main grave was fundamentally different from all other earthen materials in its morphology and physicochemical

properties. On this plot, it is likely that the ancient builders prepared the clay mortar used in the roof of the main grave. We suggest that the clayey material was prepared with the addition of crushed limestone and, possibly, river silt. Alternatively, river silt could have been applied subsequently for ritual purposes. The microbiomorphic analysis showed that river silt was found at a surface cover of all the paleosols buried under constructions I – IV. Therefore, it is very likely that the entire plot that was further covered by earthen constructions of kurgan was used for the burial clay mortar preparation.

There was a tendency for a decrease in the thickness of silt covering of paleosols from the first to the fourth earthen constructions, which was also observed in the field. The decreasing depth of silt covering was accompanied by a decrease in the proportion of hydrophilic flora and a slight increase in the proportion of steppe species in phytolith assemblages. The latter was probably connected with the general trend of aridization within the study region, when the river water level lowered and the areas occupied by riparian vegetation significantly shrunk.

Soil morphological and microbiomorphic evidence supporting the conclusion on the increasing aridization of the paleoclimate during the construction of the studied kurgan was supplemented by the results of the palynological analysis. The pollen assemblages from paleosols were indicative of not only aridization, but also cooling of the climate during the kurgan construction.

The data obtained in the present study, and in particular, the conclusion about increasing aridization of climate, are in agreement with the results of our previous research on KC Krasikovo I in the same study region of the Southern Cis-Urals (Papkina et al. 2018; Khokhlova et al. 2019). KC Krasikovo I included three kurgans dating back to the early (Repino) stage of the Yamnaya culture, according to archaeological evidence. Kurgan 2 of Krasikovo I is very similar to constructions I and II of Kurgan № 1 of Boldyrevo IV in terms of the morphological and technological characteristics of pottery, which had been recovered from fills of ditches around all those constructions, as well as the shapes of the ditches (discontinuous, i.e., consisting of a series of hollows). Based on the paleopedological analysis of kurgans of Krasikovo I, we have reconstructed an arid episode between 3600 and 3300–3200 years cal BC, i.e. 5600–5300 years BP (Morgunova and Kul'kova 2019, p. 44). This arid episode has been identified from the observed decrease in organic carbon content and cation exchange capacity and increase in the contents of carbonate carbon, gypsum and exchangeable sodium.

In addition to the data from KC Krasikovo I, the conclusion about increasing aridization of the climate within the studied period of Yamnaya culture is confirmed by studies on other archaeological sites within the Orenburg Region in the Southern Cis-Urals, e.g., the Turganik settlement located near to KC Krasikovo I. The cultural layer of Turganik corresponds to the Repino stage of the Yamnaya culture according to archaeological evidence, but it is more ancient than Krasikovo I according to radiocarbon dates. Our reconstruction of the early stage of the Yamnaya culture shows that it was the driest period in the development of this culture. It has been characterized by the

highest percentage of arid flora in pollen assemblages, which were generally dominated by grasses and herb species, and the most 'arid' properties of paleosols (Morgunova et al. 2017, Morgunova and Khokhlova 2020).

The above-described paleosols of the early stage of the Yamnaya culture significantly differ from paleosols of the advanced and late stages of this culture, which have been studied by us in KCs Shumaevo I and II and Mustaevo V and characterized by a stronger humification and stronger leaching of calcium carbonate, soluble salts and alkali (desalinization and dealkalization) (Morgunova et al. 2005; Khokhlova et al. 2004 and 2008).

Thus, the comparative analysis of quantitative and qualitative morphological, physico-chemical and paleobotanical data from the paleosols of a short-term pedochronosequence buried under the Early Bronze Age kurgan allowed us to reconstruct the trends and the scales of fluctuations in humidity and temperature and make the conclusions about the aridization and, possibly, cooling of the paleoclimate of that period.

Conclusions

Kurgan № 1 of KC Boldyrevo IV is a rare surviving monument of probably, the early stage of Yamnaya culture (about 5500 years BP) and a unique monument due to its construction over a relatively short time period (just a few decades). For this reason, the pedochronosequence buried under this kurgan represents an exclusively valuable study material that has a predetermined time scale of changes in the properties of the studied soils.

The data of morphological and physico-chemical analyses indicated that the latest buried paleosols of the studied pedochronosequence had the most 'arid' characteristics. Namely, their humus horizon tended to develop an irregular (tonguing-like) shape of the lower boundary (as opposed to a smooth or wavy boundary in earlier paleosols), the whole profile had the most prominent features of zooturbation and carbonate accumulation, the upper part of the profile was characterized by decreased organic carbon content and magnetic susceptibility together with increased contents of carbonate carbon and gypsum and an increased percentage of exchangeable sodium of the total exchangeable bases. The same trends of changes were observed in the morphological features and physicochemical properties of materials of kurgan constructions, from the earliest to the latest ones.

The palynological data were indicative of decreasing humidity and temperature within the study region. In particular, climate aridization was reflected in the increased proportions of steppe species in meadow-steppe communities, which was also confirmed by the results of phytolith analysis.

The morphological, physicochemical, and microbiomorphical analyses showed that, prior to burial under the kurgan constructions, the paleosol surfaces were covered with river silt. The bluish-whitish clayey cover of the plot around the main grave (under EC III) had a texture of sandy clay loam, close to clay loam, and contained evidence

of additions of crushed limestone. The thickness of the silt covering to the periphery of the kurgan decreased, and among the phytoliths from this material, the proportion of hygrophilous plants decreased, and the proportion of steppe plants increased. That is, climatic changes during the construction of the kurgan were unexpectedly reflected in the composition of the phytolith assemblage of ritual coating.

The comparison of the characteristics of the paleosols with the surface soil at the study site showed that the climate was more arid during the kurgan building period than at the present time.

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