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ENVIRONMENTAL HISTORICAL ANALYSIS OF YAMNAYA KURGANS BASED ON GEOCHEMICAL, ARCHAEOLOGICAL SOIL SCIENCE AND STATISTICAL METHODS

Theses of the Doctoral (PhD) Dissertation

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1. Background and objectives

Among anthropogenic landforms of lowland landscapes, burial mounds - also referred to as kurgans - are of high importance for both archaeological and environmental science. These several-thousand-year-old, manmade structures are not merely burial or land-use monuments, but complex geoarchives capable of preserving imprints of the environmental conditions prevailing at the time of their construction. Buried palaeosols conserved beneath the mound bodies, together with the sediments and soil layers of various origins composing the mounds, jointly provide an opportunity to reconstruct certain environmental conditions, soil development pathways, as well as geomorphological and geochemical processes characteristic of the period of mound construction.

For a long time, kurgan research was conducted primarily from an archaeological perspective, focusing on the chronological, cultural and ritual interpretation of burials. Over recent decades, however, increasing emphasis has been placed on the recognition that mounds cannot be separated from their natural environment, and that both their formation and subsequent transformation were governed by the close interaction of natural and anthropogenic processes. Accordingly, kurgan research has become an interdisciplinary field, in which methods of Quaternary paleoenvironmental studies, soil science, geochemistry and geomorphology all play an equally important role.

Particularly significant are those palaeosols that became buried at the time when of the mound construction and whose development was interrupted. These buried soil profiles represent time-specific snapshots that enable the investigation of past climatic, vegetation and soil-forming conditions. At the same time, the overlying mound material provides information on construction techniques, raw material procurement strategies and the degree of human-induced landscape modification. The recent surface soils and cultural layers incorporated into the mound body offer further insight into subsequent soil development processes, material translocation and anthropogenic impacts.

Soil science and geochemical investigations are particularly well suited to the exploration of relationships between the mound body and the buried soil. The vertical distribution of elements, variations in macro- and trace-element concentrations, and the depth-dependent trends of salt, carbonate and humus contents all contain information that allows both natural soil-forming processes as well as human-induced effects to be described. Modern laboratory analytical techniques enable the determination of major and trace elements with low detection limits and high precision. The interpretation of the resulting large datasets is supported by multivariate statistical methods, which are capable of revealing complex geochemical patterns and relationships.

The central research problem of the dissertation is to examine how kurgans can be interpreted as complex soil–geochemical systems, and to what extent they are suitable for reconstructing environmental conditions and changes induced by human activity. Particular attention is paid to assessing the degree to which the material used for mound construction reflects the soil characteristics of the surrounding landscape, as well as to evaluating the extent to which buried palaeosols have preserved their original properties beneath the overlying deposits. A further objective of the study is to determine which processes led to the observed geochemical differences within the mound body and the buried soils.

The examples of the Hajdúnánás–Zagolya ETA-01 kurgan and the Boldești–Grădiștea site demonstrate that burial mounds can be interpreted according to similar fundamental principles even under differing environmental conditions. At the same time, local pedological, hydrological and sedimentological settings may have a substantial influence on the direction and intensity of soil development and material translocation processes.

The objectives of the dissertation include the detailed pedological and geochemical characterisation of mound bodies and buried soil profiles, the description of the stratigraphic relationships within kurgans, and the exploration of connections between individual layers and horizons. In parallel, the research aims to apply statistical methods in order to objectively distinguish between processes of natural and anthropogenic origins, thereby contributing to the interpretation of kurgans as complex paleoenvironmental archives.

2. Materials and Methods

Description of the Hajdúnánás–Zagolya site

The ETA-01 site is located approximately 5 km south-southwest of the town of Hajdúnánás, at the boundary between the Hortobágy and the Hajdúhát regions. The area is characterised by a flat plain, with a typical elevation of 88-92 m above sea level. At present, the most prominent landforms are abandoned river channels, infilled oxbows and the associated natural levees, as well as kurgans constructed on these levees and elevated surfaces. During the Pleistocene, sediments transported by water and wind accumulated in the area (Pécsi 1993). Under favourable geomorphological conditions, loess and loess-like sediments were formed (Pécsi 1993; Lindner et al. 2017; Lehmkuhl et al. 2018). The region is characterised by a moderately warm and dry climate (Marosi and Somogyi 1990; Dövényi 2010), and under present-day conditions chernozem soils dominate the surrounding landscape

Description of the Boldești–Grădiștea site

The second investigated kurgan is located in the vicinity of the village of Boldești–Grădiștea, within the Wallachian Plain of Romania. This region extends from the eastern slopes of the Carpathians to the Danube Delta and the Black Sea coast, and is bounded to the south by the Danube valley. Elevation ranges between 5 and 320 m above sea level. The surface of the Wallachian Plain is predominantly covered by loess, with thicknesses ranging from 4 to 40 m in the lowland areas. The investigated site lies between the Buzău and Ialomiţa rivers, in the region commonly referred to as the Bărăgan Plain (Coroban 2013). The climate is moderately continental. The examined kurgan and its wider surroundings are situated within Romania’s chernozem zone (Burcea et al. 2015; Stănilă and Dumitru 2016).

Methodology of Field Soil Investigations

In both cases, investigations were carried out on the central section wall created during archaeological excavation. Prior to sampling, the individual layers of the kurgans, as well as the buried soil horizons and recent surface soils, were characterised based on the methodology of the Hungarian Soil Information and Monitoring System (TIM 1995), supplemented and modified to ensure the adequate documentation of archaeological soil science features (Pető et al. 2019).

In each section wall, the profile of the palaeosol buried during mound construction, the accumulated mound body, and the overlying recent soil profile were clearly distinguished.

Methodology of Sampling

Sampling locations were determined on the basis of field soil observations conducted along the section walls. The primary criterion was that all layers and horizons identified within the mound should be represented within the selected profile wherever possible. In both kurgans, sampling focused on areas close to the mound centre, near the primary burial, where the greatest number of layers and horizons could be observed. For soil science analyses, samples were collected by horizon, whereas for geochemical analyses samples were taken at a higher resolution, at 5 or 10 cm intervals depending on soil properties. Sampling covered both the mound body and the buried soil horizons.

Methodology of Soil Science Laboratory Analyses

Average samples were collected from the soil horizons and layers identified in the exposed section walls for basic soil science analyses. In contrast to the continuous sampling applied for geochemical purposes, soil science sampling targeted morphologically distinct stratigraphic units.

The following basic soil parameters were determined: soil reaction (MSZ-08-0206/2-1978), Arany-type plasticity index (MSZ-21470/51-1983), carbonate content (MSZ-08-0206/2-1978), and total humus content (MSZ-08-0210/2-1977).

Methodology of Geochemical (Laboratory) Analyses

Following homogenisation, samples were processed using aqua regia extraction. Homogenisation was carried out using a porcelain mortar, during which the entire sample mass was crushed and then sieved through a 1 mm mesh. Aqua regia extracts were prepared according to the MSZ 21470-50:2006 standard. Loss-on-ignition analyses were also conducted at 550 °C and 950 °C.

Elemental concentrations in the samples were determined using inductively coupled plasma mass spectrometry (ICP-MS) and microwave plasma atomic emission spectrometry (MP-AES). In both analytical methods, the relationship between signal intensity and concentration was established using external calibration curves.

Statistical Data Processing

Prior to statistical evaluation, concentration data were converted to mg/kg units and their distributions were examined. As most statistical methods assume normally distributed datasets, the data were log-transformed in order to approximate normality (Stanley 2006).

One of the most frequently applied methods in geochemical data analysis is principal component analysis (PCA) (Barczi et al. 2006; Davis 1986; Koinig et al. 2003; Sadeghi et al. 2013), which aids in reducing dataset dimensionality and facilitating interpretation. An important advantage of PCA is that the resulting variables are orthogonal, making Euclidean distance measures well interpretable, which is essential for subsequent cluster analysis (CA).

Cluster analysis was employed to identify patterns within the dataset. Hierarchical clustering using Ward’s minimum variance method (Ward 1963) and Euclidean distance as the metric was applied. To verify the validity of the resulting clusters (Ng and King 2004) and to explore relationships between them, linear discriminant analysis (LDA) was used. Input variables consisted of log-transformed measurement results and cluster group memberships. LDA enables the assessment of classification probabilities and the exploration of differences between groups through examination of relationships between discriminant functions and the original variables (Barczi 2016).

3. Results and Discussion

3.1 Results from the Hajdúnánás–Zagolya ETA-01 Kurgan

3.1.1 Results of soil science investigations

Based on the morphological characteristics observed in the central section, the soil and sediment layers of the kurgan can be described stratigraphically as follows:

0-40 cm	A-horizon
40-60 cm	B-horizon
60-80 cm	BC-horizon
80-110 cm	C1 layer
110-140 cm	A_p-horizon
140-160 cm	B_p-horizon
160-180 cm	BC_p-horizon
180-210 cm	C_p-horizon

The humus-rich topsoil (A horizon, 0–40 cm) of the recent soil developed on the mantle of the kurgan is brownish black in colour (10YR 3/2) and exhibits a crumb structure. Its texture lies at the boundary between the sandy loam and loam textural classes. The A horizon is weakly to moderately calcareous, and only poorly developed carbonate accumulations were observed within the soil material. In accordance with its carbonate status, soil reaction falls within the slightly alkaline range and shows a gradual increase with depth. Humus content decreases vertically, and no abrupt changes were observed along the profile. The A horizon of the recent soil covering the kurgan gradually transitions in colour, with a slight textural change, into the underlying transitional B horizon. This horizon is characterised by a higher carbonate content and, consequently, by a more alkaline soil reaction. The B horizon, which can be classified as sandy loam in terms of texture, shows a decrease in humus content to 0.55%. At the same time, a slight increase in total soluble salt content can be detected within this depth interval in the investigated profile.

Between the C1 layer forming the parent material of the recent soil cover and the overlying B horizon, a short transitional BC horizon was identified at a relative depth of 60–80 cm. The increase in total soluble salt content observed in the B horizon continues with depth within the BC horizon and reaches its maximum in the lowermost sample of the C1 layer. In terms of colour, the BC horizon forms a transition between the B horizon and the C1 layer. With regard to its soil physical and chemical properties, the BC horizon can be classified within the sandy loam textural class. It is characterised by a moderately high total soluble salt content, alkaline soil reaction, moderate carbonate content and low humus content.

The C1 layer constitutes the parent material of the recent soil cover. This structureless sediment, characterised by a grey matrix with locally mixed colours, occurs as a lens-like body within the kurgan. It is not present across the entire cross-section, but is restricted to the area above the central burial. Mixing within the layer is evident as a result of animal burrowing activity. This mixing most likely accounts for the elevated humus content and the abrupt decrease in carbonate content observed within the layer. It is important to emphasise that the total soluble salt content of the C1 layer is higher than that measured in the surface horizons.

The original ground surface buried by the kurgan was identified at a relative depth of 110 cm. The depth interval between 110 and 210 cm within the investigated profile contains a buried former soil profile, which was subdivided during field soil investigation into A_p–B_p–BC_p–C_p horizons.

3.1.2 Results of geochemical investigations

Calcium (Ca) concentration varies considerably both within individual horizons and layers and between them. The Bp horizon of the buried soil exhibits the highest Ca concentration, with an average value of 6.05% between depths of 140 and 160 cm. The C1 layer shows the lowest Ca concentration, averaging 14.2%, but with high variability: minimum and maximum values range from 4.35% to 37.8%. This pronounced variability can be attributed to the mixed nature of the layer (Braun et al. 2022). Aluminium (Al) and iron (Fe) occur at similar concentration levels, and both elements display increased variability within the BC horizon.

In addition to the major elements, significant amounts of barium (Ba), strontium (Sr) and manganese (Mn) were detected in the soil samples. Strontium (Sr) concentrations in the deeper horizons and layers are considerably higher than those observed near the surface; maximum values occur in the BCp horizon, while minimum values are recorded in the B horizon of the modern soil. Barium exhibits a similar trend, although less pronounced than that of strontium (Sr): its maximum concentration is observed in the C1 layer, whereas the lowest values occur in the B horizon of the recent soil.

Among the rare earth elements, lanthanum (La) and cerium (Ce) occur in the highest concentrations in the samples. Heavy metals, including chromium, nickel and copper, reach their maximum concentrations in the modern A horizon developed on the top of the mound (Braun et al. 2022).

3.1.3 Results of statistical investigation

Four principal components were extracted to describe the dataset, together explaining 91.3% of the total variance. The first two components account for 44.4% and 39.9% of the variance, respectively, indicating that a substantial proportion of the information content can be represented by these variables. Examination of the component matrix reveals that the rare earth elements are separated from the other elements within the second principal component.

Based on the dendrogram derived from hierarchical cluster analysis and supported by soil morphological characteristics, the samples were classified into seven groups. To determine group membership probabilities, discriminant analysis was applied. According to the results of linear discriminant analysis (LDA), all samples were assigned to the groups predicted by the cluster analysis.

3.2 Results from Boldești-Grădiștea kurgan

3.2.1 Results of soil science investigations

Based on the morphological characteristics observed in the central section, the stratigraphy of the kurgan can be described as follows:

0-15 cm	A-horizon
15-25 cm	K1 layer
25-100 cm	K2 layer
100-170 cm	K3 layer
170-245 cm	K5 layer
245-250 cm	K5 layer
250-280 cm	A_p-horizon
280-300 cm	B_p-horizon
300-320 cm	BC_p-horizon
320-350 cm	C_p-horizon

The kurgan is covered by a recent humus-rich topsoil with loam texture, dark brown colour and granular structure. The A horizon is densely penetrated by roots, forming a felt-like network, and is characterised by numerous earthworm channels. Although carbonate content was found to be low, a few carbonate concretions filling vertical cracks were observed.

Based on field soil observations, several construction layers could be distinguished beneath the humus-rich topsoil.

- K1 layer: is greyish yellow-brown in colour (10YR 4/2). It thickens towards the centre of the mound. In the central section it occurs between depths of 15 and 25 cm. No anthropogenic inclusions were observed. Its humus content is relatively high (H% = 1.91%), and both its upper and lower boundaries are sharp.
- K2 layer: occurring between depths of 25 and 100 cm, has a greyish yellow-brown colour (10YR 5/2) but it is heterogeneous. Signs of disturbance and well-developed carbonate concretions were observed. The layer is compacted, structureless, and has a high humus content (H% = 1.61%). Krotovinas occur in large numbers.
- K3 layer: is yellowish brown (10YR 4/3), homogeneous in colour, and carbonate concretions are almost completely absent. Total salt content increases to 0.536%, which represents the highest value within the sample series.

- K4 layer: is darker in colour, appears to contain higher amounts of organic matter, and the layer is compacted. Carbonate concretions occur only sporadically, primarily along vertical cracks. The layer is leached and carbonate-depleted, as confirmed by near-zero $CaCO_3$ values.
- K5 layer: is one of the most distinctive stratigraphic units of the kurgan. It is only approximately 5 cm thick (245–250 cm) and is located directly above the buried palaeosol. Charcoal remains and traces of burning were identified within this thin layer. In addition, gleyic discolorations and iron mottling indicate the presence of stagnant water. Humus content is high (H% = 2.17%), approaching that of the present-day surface soil.

Beneath the kurgan earthwork, a buried palaeosol developed on yellowish-brown loess-derived sediment was identified and subdivided into Ap, Bp, BCp and Cp horizons.

A background profile was also described, with the following stratigraphy:

0-40 cm	A-horizon
40-60 cm	B-horizon
60-100 cm	C-horizon

The background profile was identified as a chernozem soil developed on loess-derived sediment.

3.2.2 Results of geochemical investigations

Among the major elements, magnesium (Mg) and potassium (K) exhibit relatively uniform concentrations across all layers and horizons. In contrast, calcium (Ca) concentrations show a clear vertical trend, decreasing from the upper layers downward and then increasing again, reaching maximum values (1.66%) in the BCp and Cp horizons. In general, the more mobile elements (e.g. Ca, Sr and Na) display high variability between layers and horizons. Iron (Fe) concentrations reach their minimum within the K4 layer and their maximum near the surface in the K1 layer. Aluminium (Al) exhibits a similar pattern. The distribution of strontium (Sr) closely follows that of calcium and magnesium. Rare earth element concentrations decrease towards the centre of the kurgan and reach their minimum within the K3 layer. With increasing depth, REE concentrations increase within the buried soil and subsequently show a decreasing trend within the BCp and

Cp horizons. Sodium (Na) concentrations decrease vertically but show a sudden increase within the K4 layer. This increase is accompanied by enhanced heterogeneity, as indicated by increased variance.

3.2.3 Results of statistical investigation

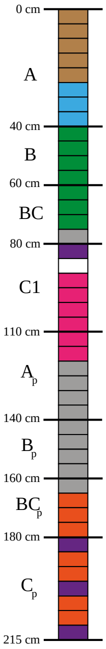
Principal component analysis yielded six principal components that together explain 83.8% of the total variance. The first principal component (PC1) accounts for 31.4% of the variance and correlates with light rare earth elements, thorium, uranium, aluminium, iron, titanium and chromium. The second principal component (PC2) explains 20.5% of the variance and shows correlation with heavy rare earth elements, copper, zinc and potassium. The third principal component (PC3) explains 13.8% of the total variance and correlates positively with sodium, scandium and manganese, while showing negative correlation with carbonate content (LOI950), calcium and magnesium concentrations. Potassium also correlates with PC3, though less strongly than with PC2. The fourth principal component (PC4) explains 6.7% of the variance and correlates with strontium and lead. The fifth principal component (PC5) explains 6.2% of the variance and shows negative correlation with organic carbon content (LOI550). The sixth principal component (PC6) explains 5.2% of the variance and correlates with gallium and barium.

Based on cluster analysis, the samples can be classified into eight groups, the validity of which was confirmed by discriminant analysis.

4. Conclusions and Recommendations

4.1 Hajdúnánás-Zagolya ETA-01

The differentiation of the stratification of the mound body based on morphological observations and the results of soil science investigations made it possible to identify naturally formed soil units (buried palaeosol and recent soil) as well as layers formed as a result of anthropogenic activity. The primary objective of the geochemical analyses was to confirm, refine, or, where necessary, modify the horizon and layer boundaries defined on the basis of morphological features and classical soil science parameters.



*4.1.**Hiba! A(z) 0 itt megjelenítendő szövegre történő alkalmazásához használja a Kezdőlap lapot.**1. ábra Cluster structure identified along the vertical profile of the Hajdúnánás–Zagolya ETA-01 kurgan*

Comparison of the results of cluster analysis with the horizon and layer boundaries defined on the basis of soil morphological characteristics indicates that Clusters 1 and 2 comprise samples belonging to the A horizon of the recent soil cover. Cluster 1 represents the upper approximately 25 cm of this horizon, whereas Cluster 2 includes samples from the lower part of the same A horizon, located at relative depths between 25 and 40 cm.

Cluster 3 can be associated with the B and BC horizons of the recent soil, encompassing a depth interval between 40 and 75 cm. Beneath this zone, between depths of approximately 75 and 90 cm, samples belonging to different clusters occur and do not form a coherent group.

The C1 layer, previously delineated at depths between 80 and 110 cm (Pető et al. 2022), appears vertically shifted based on the current statistical evaluation. The depth interval between 90 and 120 cm forms a well-defined and homogeneous unit, which corresponds to Cluster 6.

The A_p and B_p horizons of the buried palaeosol jointly form Cluster 4, with no pronounced geochemical distinction observed between them based on the available data.

A further transition can be observed at a relative depth of approximately 165 cm, where samples from the BC_p horizon already constitute Cluster 7. The C_p horizon, identified as the soil-forming parent material beneath the mound, exhibits a mixed pattern, as samples belonging to both Cluster 5 and Cluster 7 occur within this horizon.

Overall, it can be concluded that the grouping of samples based on elemental composition is largely consistent with the stratigraphic subdivision established on the basis of morphological characteristics, although minor discrepancies can also be identified. The vertical distribution of clusters along the profile can be fully interpreted only when the sedimentological and soil chemical characteristics associated with each group are also taken into account.

Relationships and differences between the clusters were interpreted using a biplot. This form of representation allows observation of how the samples are separated from one another within the discriminant space. The variables indicated by arrows on the biplot illustrate their pooled correlations with the discriminant functions and indicate the direction and magnitude of the contribution of individual elements to the spatial separation of the samples.

In connection with the complex natural scientific investigation of the mound, the geochemical results complement archaeobotanical, soil science and geological methods (Pető et al. 2022), thereby contributing to a more comprehensive interpretation of the kurgan.

The chernozem character of the buried soil cover is also supported by the geochemical data, as indicated by the homogeneous clustering of the A_p and B_p horizons. The high abundance of palaeokrotovinas points to intensive biological activity in the buried soil prior to mound construction. The elemental composition of the C1 layer and its similarity to the C_p horizon suggest that the initial accumulation of the mound was not derived from the surrounding humus-rich topsoil, but rather from parent material occurring in the wider area.

The geochemical pattern of the recent soil cover is clearly distinguishable from that of the buried layers. The upper, morphologically uniform A horizon exhibits strong anthropogenic influence, whereas the deeper B and BC horizons display a more homogeneous chemical character. Based on the elemental composition data, it is likely that additional humus-rich material was used in the construction of the mound mantle, which subsequently became consolidated and underwent pedogenic development. Overall, the results confirm that interpretation of the stratification and geochemical characteristics of the mound body is only possible through the integrated application of morphological, soil science and statistical methods.

4.2 Boldești-Grădiștea kurgan

Field observations conducted during the excavation of the Boldești–Grădiștea kurgan, together with detailed soil science and geochemical investigations, provided an opportunity to reconstruct individual phases of mound construction and certain aspects of the contemporaneous environmental conditions.

Based on macromorphological observations and laboratory data, the central (primary) grave of the individual belonging to the Yamnaya culture was excavated into a leached chernozem soil. One of the main characteristics of such soils is the absence or low content of carbonates in the A horizon, which indicates that they develop on loess-covered areas where mean annual precipitation exceeds approximately 500–550 mm. The potential vegetation of these environments can be described as a mosaic of temperate grasslands and forest-steppe communities. The burial site was located in a low-lying area (approximately 79 m above sea level) between the eastern slopes of the Carpathians and the western Black Sea coast. Although the climatic influence of the Carpathians may have contributed to increased precipitation, the site nevertheless reflects a clearly steppe-like environment at the end of the 4th millennium BC.

The burial site, and later the area corresponding to the first construction phase of the kurgan, was prepared prior to the burial. The surface was most likely scraped and shaped into a gently outward-sloping platform, which served as the base upon which the mound was erected. The initial mound cover was placed above the primary grave but did not extend beyond the outline of the platform.

Preparation of the ground surface is also reflected in the stratigraphy of the kurgan. The layer designated as K5 (Figure 4.2.1) provides clear evidence of this activity. It appears as a sharply defined boundary at the top of the palaeosurface, indicating deliberate construction. Charcoal remains identified within the layer testify to human-induced environmental modification, which may be explained either by the intentional burning of the platform surface or by the presence of a fireplace located within the area.

This thin layer may have served to seal the burial area. Indicators of stagnant water, together with the enrichment of iron and manganese, suggest that the surface became a trampled and slightly compacted soil layer. However, its geochemical composition and soil properties do not differ markedly from those of the palaeo A_p horizon, indicating that sealing of the platform or burial area was carried out using locally derived material. As the K5 layer is discontinuous and absent from the central part of the mound above the primary burial, it can be inferred that the preparation of the platform took place prior to burrial, as part of the ritual organisation of space.

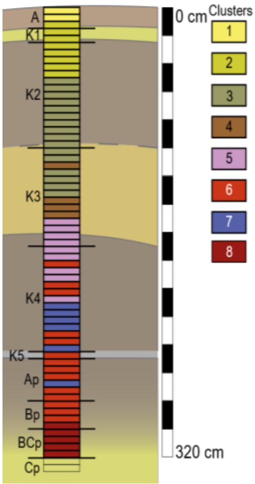


Figure ***Hiba! A(z) 0 itt megjelenítendő szövegre történő alkalmazásához használja a Kezdőlap lapot.****.1. Vertical distribution of clusters along the profile*

The first construction phase of the kurgan is represented by the K4 layer, which, based on macromorphological observations and laboratory data, can be partly compared to an Ap horizon. This supports the hypothesis that the initial mound was built by scraping and accumulating the upper humus-rich soil layer of the surrounding area.

Leaching, compaction and the internal morphological homogeneity of the layer reflect soil-forming processes that require extended periods of time. The duration of this phase can be partly traced through the vertical distribution of Yamnaya burials. While the primary grave was placed deep within the palaeosol and dates to the turn of the 4th–3rd millennium BC, Bronze Age burials located in the south-western quadrant of the kurgan can be dated to the first and second thirds of the 2nd millennium BC. This indicates that the surface of the initial mound structure remained exposed for several centuries. A similar phenomenon was identified at the Hajdúnánás–Lyukas-halom site, where phytolith analyses demonstrated that the surface of the first mound remained exposed for a sufficient length of time to allow the development of dense vegetation (Pető and Scott Cummings 2011). In the case of Boldești–Grădiștea, interpretation is further complicated by the fact that one grave was dated to 2914–2883 cal BC. This grave, however, was excavated into the K4 layer, directly above the central burial. This may indicate that the grave was dug shortly after the construction of the original mound structure, after which the builders abandoned the site. Based on the available data, it is unlikely that the mound was significantly raised at that time; rather, the structure originally created for the primary burial was reused.

As a subsequent step, the structure of the kurgan was modified by additional burials. The spatial extent of the mound expanded beyond the edge of the original platform. Although the stratigraphy of the mound margin differs from that observed in the central area, renewal of the mound can also be traced within the central section.

The second construction phase of the kurgan is indicated by two graves associated with the upper boundary of the K3 layer. However, no radiocarbon dates are available for these burials, and their chronological placement therefore remains uncertain. From a soil science perspective, the material used to raise the mound during this phase differs in character, raising questions regarding its origin. In contrast to the loess-derived material observed at the Hajdúnánás–Zagolya ETA-01 site, the available data indicate that such loess material was not used in the construction of the Boldești–Grădiștea kurgan.

It is more likely that soil material underlying the original palaeosurface (Ap horizon) was scraped, partially mixed, and subsequently used to elevate the mound. Within this layer, total salt content, as well as sodium and potassium concentrations, reached their highest values. In light of these observations, the K3 layer is interpreted as a mixed layer in which sodic factors became enriched. At present, there is no evidence to suggest that this layer was originally constructed from saline soil, as this is not supported by the available salt data. Nevertheless, it should be noted that in several kurgans located in saline regions of the Carpathian Basin, long-term water level rise lasting for centuries or even millennia has been documented, leading to the development of the so-called "salt dome" phenomenon (Barczi et al. 2006; Csanádi and M. Tóth 2011). A similar process cannot be entirely excluded in the case of the Boldești–Grădiștea kurgan.

The history of the kurgan is further complicated by a group of tertiary burials located in the marginal zone, within the north-western sector. Based on radiocarbon dating, these burials can be assigned to the transition between the Middle and Late Bronze Age (1862–1291 BC). In this area, mound height decreases toward the periphery, allowing graves to be excavated down to the palaeosurface, at depths comparable to that of the central burial. Based on the available data, these graves were cut into the shallower material of the K3 layer, which represents the product of the secondary elevation of the kurgan.

The final phase of modification of the kurgan is represented by the K2 and K1 layers and the A horizon developed above them. Within this zone, the presence of a medieval burial has also been confirmed, dated to the turn of the 9th–10th centuries AD, which clearly indicates an intervention associated with a distinct cultural context.

5. New scientific results

In the present doctoral dissertation, two kurgans were investigated. Based on environmental and construction-historical analyses employing geochemical and archaeological soil scientific methods, the following are considered to represent the new scientific results of the research::

1) A complex geoscientific methodology integrating geochemical and archaeological soil science analyses, field-based soil observations, and multivariate statistical methods were developed and tested through two case studies in order to achieve the most accurate possible reconstruction of the stratigraphy and history of anthropogenic structures composed of soil material, sediment and anthropogenic deposits.

2) Through the complex geoscientific investigation of two Yamnaya kurgans, it was demonstrated that burial mounds constructed for funerary purposes are not static features but dynamic systems that evolve over long periods of time, with their development being shaped by both human activity (e.g. cultural reuse) and environmental conditions.

3) It was demonstrated that spatially distant human structures sharing the same cultural affiliation were constructed under similar environmental conditions and comparable conceptual frameworks. Both the Hajdúnánás–Zagolya ETA-01 and the Boldești–Grădiștea kurgans were erected on chernozem soil through the removal and accumulation of the humus-rich topsoil of the surrounding area.

4) It was demonstrated that, in the case of both kurgans, a recent soil developed on the accumulated mound body with properties similar to those of the buried soil. Based on the so-called chernozem–chernozem indication, it was inferred that no shift in soil-forming conditions occurred in the environmental history of the two study sites that would have resulted in the development of a soil type substantially different from the soil cover present at the time of mound construction.

6. Publications by the author related to the topic of the dissertation

Journal articles in English:

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Journal articles in Hungarian:

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