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STATISTICAL ANALYSIS OF TRACE ELEMENT CONTENT IN NEOLITHIC, ENEOLITHIC AND BRONZE AGE METAL ARTEFACTS FROM CENTRAL AND SOUTH-EASTERN EUROPE [1]

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The prehistoric metal artefacts have been at the centre of archaeological research for over a century. Archeometallurgical analysis largely focused on determining the geological origin of metal and its distribution patterns throughout Europe. For this purpose, among others, analysis of the content of trace elements was used. From 1954 to 1974 in Stuttgart, S. Junghans and E. Sangmeister conducted the largest project to study the chemical composition of copper and bronze artefacts. During the study, 22,000 items from almost all parts of Europe were examined, dated mainly from the Eneolithic period to the Middle Bronze Age. In order to perform the statistical analysis, which was the main purpose of this thesis, items from central and south-eastern Europe were selected from the published data set. The main goal is to compare the results of metal composition analysis with the formal classification of metal artefacts. Based on the content of four elements (arsenic, antimony, silver, and nickel), cluster analysis was performed to divide the material under study into groups. It resulted in the determination of 15 groups (and 17 subgroups of group 1 and five of group 2). Each of the groups has been characterised, taking into account the location, dating, cultural context, and typological category of artefacts. They represent production centres based on copper deposits from a given region. Statistical analysis of the content of trace elements provided relevant information on the general origin of the raw material, changes occurring from the Neolithic to the Bronze Age, differences and similarities between the metallurgy of archaeological taxonomic units, and the level of metallurgical knowledge in prehistory.

INTRODUCTION

The problem of metal use and the spread of related skills has always been one of the priorities for researchers studying the archaeology of the Eneolithic and Bronze Age. The two most important issues related to this are the reconstruction of the technology used to produce bronze and make objects from it, and obtaining the most accurate knowledge of the distribution of metal (reconstruction of exchange networks, location of sites of metal origin; *Hauptmann 2007*, 8). Already in the 19th century, as soon as the analysis of the chemical composition of metal artefacts became possible, the question arose whether it would be able to provide new information on these topics (*Hauptmann 2007*, 27). Initially, it was hoped that the new technology would allow to accurately matched objects to specific metal deposits. However, the content of trace elements in a finished object is not only due to the chemical composition of the deposit but also to compositional changes occurring during the smelting and metalworking processes and to conscious decisions made by prehistoric metallurgists to obtain alloys with given properties (*Hauptmann 2007*, 27, 28). Therefore, the study of the trace element content of metal objects conducted in Stuttgart between 1954 and 1974 by S. Junghans and E. Sangmeister, was not aimed at determining the origin of the metal. Instead, these researchers decided to use the analyses performed as an additional classification criterion. In this way, they intended to identify metallurgical centres and workshops. Sangmeister and Junghans assumed that if one workshop used the same raw material deposit and the same smelting, processing and alloying technologies, the metal produced in it would be characterised by particular chemical composition (*Radivojević et al. 2018*, 10).

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Their work resulted in 22 thousands analyses of trace elements content in Bronze Age metal objects and statistical analysis of 12 thousands of them. This is one of the largest projects related to analyses of the chemical composition of archaeological artefacts conducted so far. It has therefore produced a huge database on the chemical composition of Bronze Age metal objects from across Europe. These data have been confirmed to be comparable with data obtained using modern methods – are so precise and accurate that they can be successfully used for contemporary research (*Krause 1998*, 168). The statistical classification of information obtained from chemical composition analyses is an essential tool for sorting large amounts of data into groups with similar characteristics. Because of the developments in technology, new software is now available that allows such analyses to be conducted more quickly and accurately. Therefore, there is an opportunity to reuse the results of studies conducted in the last century in order to obtain new information (*Krause/Pernicka 1996*, 274). The main aim of this paper is to compare the results of trace element analyses with the formal classification of bronze artefacts.

For this purpose, 8597 artefacts were analysed. Objects from central and south-eastern Europe were selected from a published dataset (*Junghans/Sangmeister/Schröder 1968*; *1974*). To the information on the location and typology of the artefacts, derived from the aforementioned publication, data on the dating and cultural context of the analysed objects were also added. Then, based on the content of four elements (arsenic, antimony, silver, and nickel), a cluster analysis was conducted to divide the studied material into groups.

The groups distinguished are not intended to indicate the source of the raw material used to manufacture the items assigned to them. Statistical analysis served as a starting point for further research, allowing for the organisation of a large amount of data. Then, each of the separated groups was characterized, taking into account the location, dating, cultural context, and typological category of the artefacts included in it. The aim of the research was to test the relationship between the above-mentioned characteristics and the chemical composition of the objects. It was assumed that this would enable to observe patterns regarding the use and distribution of metal with similar trace element contents. Analysis of the geographical spread of individual groups can indicate the general place of origin of the raw material. Dating the artefacts should help indicate changes over time. The cultural context, on the other hand, can show differences and similarities between the metallurgy of individual archaeological taxonomic units. The number of specific artefact types in particular groups could indicate the level of metallurgical knowledge and possible preferences with regard to the choice of raw material for the manufacture of a given category of artefacts.

THE SAM PROJECT

The invention of atomic emission spectroscopy in 1930 made it possible to measure the content of trace elements in a relatively small sample (weighing a few milligrams), which definitely contributed to the development of research on the chemical composition of metal archaeological artefacts. The most extensive study of trace element content by spectrometry was conducted at the Würtembergisches Landsmuseum in Stuttgart between 1954 and 1974, under the direction of S. Junghans, E. Sangmeister and M. Schröder, in the project "Studien zu den Anfängen der Metallurgie" (SAM; *Slater/Charles 1970*, 207). Over the course of the project, 22,000 artefacts from almost the whole Europe, dating mainly from the Eneolithic to the Middle Bronze Age (the majority from the Early Bronze Age), were examined. A significant advantage was the use of the same equipment and the same research methodology for all analyses, ensuring that the results obtained are consistent (*Pearce 2016*, 47). In contrast to previous studies, it was assumed from the outset in the SAM project that the aim would not be to match the raw material used to produce artefacts to specific deposits (*Pernicka 2014*, 242). This decision was made due to the vast size of the area from which the analysed artefacts came – a great amount of sampling from all known copper deposits in Europe would have been necessary to infer their origin (*Radivojević et al. 2018*, 8). In addition, the aforementioned researchers were also aware that the chemical composition of the finished artefact is affected not only by the raw material from which it was made, but also the technological process by which it was created (*Krause/Pernicka 1996*, 275). Instead of trying to determine the origin of the metal, they decided to use the analyses conducted as a classification criterion (*Pernicka 2014*, 242).

To this purpose, statistical analyses were conducted in 1968 upon 12.000 results (*Junghans/Sangmeister/Schröder 1968*, 13). Their basis was developed together with the analyst and statistician H. Klein (*Krause/Pernicka 1996*, 276). He initially divided the material into groups, so the content of each trace element in the artefacts in a given group could be represented by a Gauss curve, thus separating 12 groups. He then refined this method by adding a further stage of analysis in which two different elements were juxtaposed (so that for each analysis all the elements were compared), making the maxima of the frequency plots more clearly identifiable, and therefore easier to separate, than if each element was considered separately. The grouping was based on 5 elements: arsenic, antimony, silver, bismuth and nickel (*Junghans/Sangmeister/Schröder 1968*, 13). Tin was omitted because in many cases its occurrence was not related to its content in the ore but was the result of an intentional addition, in order to obtain a specific alloy. On the other hand, the content of other elements (Pb, Co, Zn, Au and Fe) was detected only in a few samples and therefore they were also excluded from the analyses (*Krause/Pernicka 1996*, 279). The classification was conducted in two stages: initially, on the basis of As and Sb contents, 5 basic groups were separated (reflecting different ore types), and then, based on the contents of the remaining elements, further subdivisions were made.

The result was a chart showing the diversity of artefacts within 29 groups (*Junghans/Sangmeister/Schröder 1968*, 13; *Krause/Pernicka 1996*, 279). These groups represent production centres or regions based on a particular deposit, in line with Sangmeister's assumption that objects produced by one metallurgist (one workshop) had a similar composition if he always used the same source of raw material, always combined different raw materials in the same proportions and used the same smelting and casting technologies (*Radivojević et al. 2018*, 10). By plotting the data on maps in order to study the spread of the given copper groups, additional information about the production and distribution of copper in the early Bronze Age could be obtained (*Pernicka 2014*, 242).

METHODOLOGY

Chemical analyses in the SAM project

The data on the content of trace elements in metal objects used in this paper come from the above-described publication "Studien zu den Anfängen der Metallurgie". The method used by these researchers to measure the content of individual trace elements was optical emission spectroscopy (OES; *Pearce 2016*, 47). This consisted of photographically recording the spectrum emitted by the substance under study when subjected to an electrical pulse (*Pollard 2018*, 63). A sample weighing approximately 0.2 g was taken from each artefact examined, ensuring that the metal taken was not transformed in any way (e.g. by corrosion). The collected sample was then melted to form two electrodes, between which a high-voltage electrical impulse was transmitted. This resulted in the emission of light, the wavelength of which depended on the presence of particular chemical elements in the sample. The intensity of the emitted light in turn provided information on the amount of each element contained in the sample (*Pollard 2018*, 19).

The advantage of the method used is that it allows the content of all the elements contained in the sample to be measured (*Pollard 2018*, 63). The limitations of optical emission spectroscopy are also known: the low reproducibility of the results and the tendency to underestimate the content of some elements at high concentrations (*Pollard/Bray/Gosden 2014*, 233). However, studies conducted in the 1990s by Krause and Pernicka dispelled existing doubts about the precision and detection limits of elements using the OES method. They showed that in these respects the results of the SAM project researchers are comparable to modern methods and can therefore be used in present-day research (*Krause/Pernicka 1996*, 279).

Database

The SAM project measured the content of 11 elements (tin, lead, arsenic, antimony, silver, nickel, bismuth, gold, cobalt, zinc and iron). Of these, arsenic, antimony, silver, nickel and bismuth were considered by Junghans and Samgmeister to be the most useful in separating individual copper types (*Junghans/Sangmeister/Schröder 1968*, 57). This choice was confirmed as the most reasonable also by later researchers dealing with the problem of archaeometallurgy (*Krause/Pernicka 1996*, 279; *Liversage 1994*, 61). Tin should be excluded from the analyses, because in many cases it was added intentionally, in order to obtain bronze, so it cannot be considered as a deposit contaminant, and therefore taking it into account together

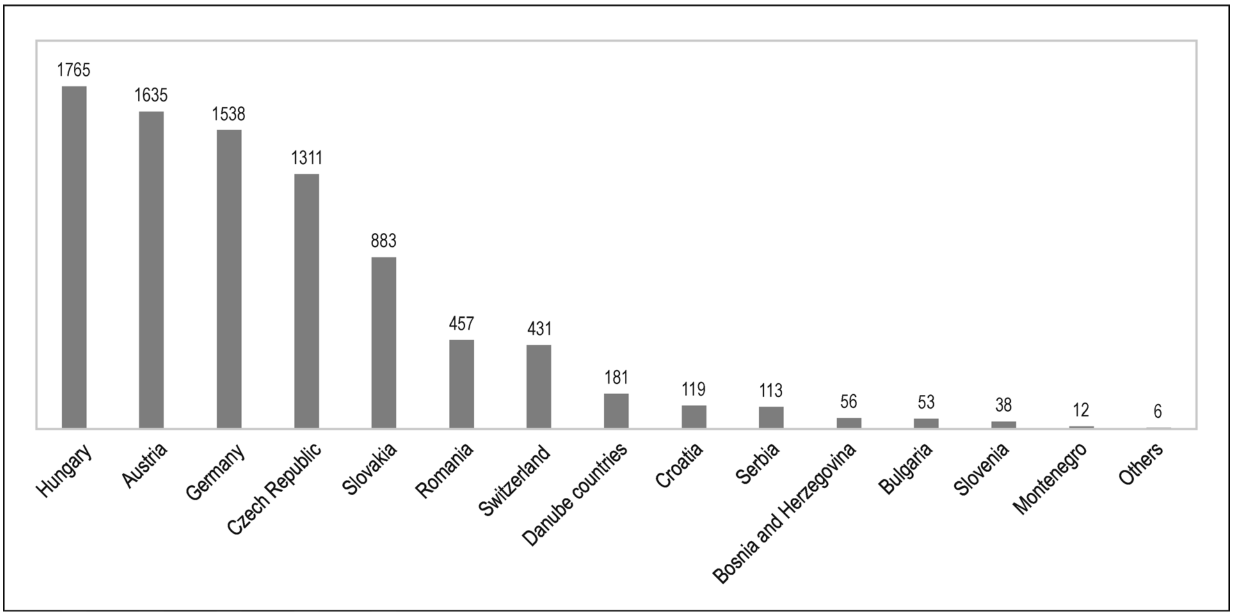

Fig. 1. Number of artefacts from the territories of present-day countries.

with trace elements would distort the results of the analyses (*Krause/Pernicka 1996*, 279). The content of gold, zinc, cobalt and iron only in a small number of samples exceeded the detection threshold; additionally, even if the presence of these elements was detected, it is most often indicated without a specific numerical value (especially in the case of iron), which makes it impossible to include these elements in the statistical analysis (*Junghans/Sangmeister/Schröder 1968*, 57). Lead, on the other hand, is characterised by a tendency to "sink" during the solidification of the metal, as a result of which it accumulates in certain areas of the object, so its content largely depends on the part of the artefact from which the sample was taken for analysis. Bismuth also exhibits the same characteristic, which is why (despite being included in similar analyses in some cases) it was excluded from the database (*Pearce 2016*, 47). Therefore, the statistical analysis conducted is based on the content of four elements: arsenic (As), antimony (Sb), silver (Ag) and nickel (Ni).

In order to conduct a statistical analysis of the trace element content, it was necessary to create a database containing all the necessary information on individual artefacts. Of the 22,000 artefacts analysed by the team of researchers from the SAM project, 8597 were included in the database. Some of the artefacts were excluded due to their origin outside the area to which it was decided to restrict the analysis. The area under study (Central and Southeast Europe; artefacts discovered on the territory of present-day: Germany, Switzerland, Liechtenstein, Austria, Czech Republic, Slovakia, Hungary, Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, Serbia, Kosovo, Bulgaria, and Romania; Fig. 1) was chosen for analysis because it encompasses two main metallurgical centres operating during the Bronze Age – Alpine and Carpathian – and their surrounding areas. The analysis of these particular artefacts could therefore show whether there are differences in the trace element contents of bronze objects produced in the aforementioned centres. In addition, it also offers the possibility of tracing the spread of particular metal groups in the surrounding areas. It was also necessary to discard those objects for which the content of at least one of the four elements was not expressed by a numerical value (e.g. it was specified as "Spur" or "+") because a specific numerical value is necessary to conduct a mathematical analysis. Also, items in which the content of all trace elements was equal to 0 were not included in the database.

Statistical analysis

The material was divided into groups, based on the trace element content of the individual items. For this purpose, cluster analysis, a method of so-called unsupervised classification, was used. It allows the analysed material to be divided into homogeneous classes. The basis for grouping objects is the similarity between them, expressed using a similarity metric (*Kowalik 2014*, 123). The main aim of the analysis was to reduce a large amount of data to a number of basic categories, which were treated as subjects for further inference about the spread of particular metal types in the Bronze Age in Europe.

Cluster analysis is conducted using MatLab, a computer programme for performing scientific and engineering calculations and creating graphs and computer simulations. The functions needed to perform this analysis are contained in the toolbox called "Statistics and Machine Learning Toolbox". The first step when performing a cluster analysis is to calculate the distance between the individual elements of the set, for which the procedure "pdist" is used. To employ it, the following formula has been used:

$$y = pdist(X, \text{'metryka'}) \quad (1)$$

X defines the set of elements to be analysed, the second output parameter is the distance metric. In my analysis, I have used the Euclidean ("Euclidean") distance because it is the most direct method of calculating the distance between objects. It is calculated using the formula:

$$d(x, y) = \sqrt{\sum_{i=1}^{p}(x_i - y_i)^2} \quad (2)$$

Where x and y are the set points in n-dimensional space, and and are the coordinates of these points (*Kowalik 2014*, 125). When running the "pdist" procedure, the distance between each pair of data is measured.

The second stage of cluster analysis is to link the objects that are closest to each other. This is done using the "linkage" procedure, which uses information about the distance between elements in the set to determine the proximity of individual objects. First, the objects are combined into pairs consisting of the two most similar objects from the entire set, then these pairs are combined with the next, until the connections between all elements are determined. To conduct the procedure described, the formula used was:

$$z = linkage(y, \text{' metoda\_grupowania'}) \quad (3)$$

Where y is the result of the "pdist" procedure and the second output parameter specifies the method by which the clustering is to be performed (*Kowalik 2014*, 126). In the analysis conducted, the unweighted pair-group method using arithmetic averages (UPGMA) was applied. In this method, the distance between two clusters is calculated using the arithmetic mean distance between all pairs of objects belonging to two different clusters (*Kowalik 2014*, 127). The results of the cluster analysis are presented by a dendrogram, which illustrates the multi-level hierarchical structure of the data set. Initially, each element is a separate group, then they are combined according to the degree of similarity (the lower the objects are connected to each other, the higher the similarity between them).

The final step is to divide the data set into groups. An inconsistency coefficient is used to determine where they should be "cut off". This is calculated by comparing the height of each connection in the dendrogram with the average height of all connections under it. The result is a numerical value to be inserted in the place of "cut off" in the formula:

$$dendrogram(Z, \text{'ColorThreshold'}, cutoff) \quad (4)$$

This provides a graph in which the different groups are marked with different colours, giving a clear picture of the results of the cluster analysis conducted.

The result of the analysis of the data on trace element content was the division of the collected material into 20 groups. The vast majority of artefacts (95%) were in the first two groups (65% in Group 1, 30% in Group 2). This is due to the fact that the database contains a large number of objects with a relatively low content of trace elements and a much smaller number of those with much higher content. I have therefore further subdivided groups one and two into subgroups (17 and 5, respectively), by means of further analysis in MatLab (also conducted according to the procedure described above, but taking into account only the artefacts allocated to a particular group in the first analysis). The last five groups containing objects with a very high content of at least one of the elements, indicating an intentional addition or error during testing, were combined into one group (Group 15). As a result, 15 groups were finally separated and formed the basis for further research on Eneolithic and Bronze Age metallurgy.

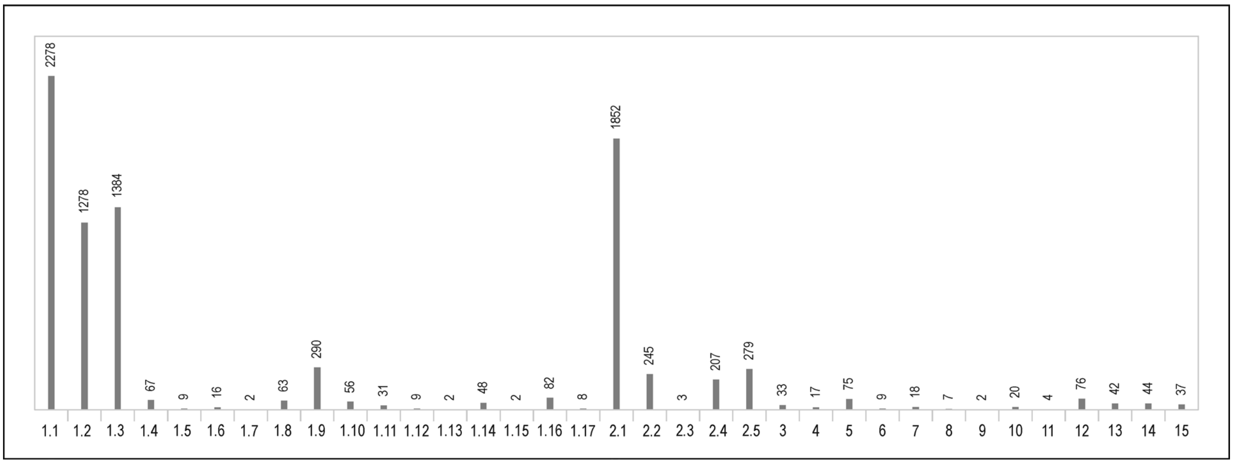

Fig. 2. Number of artefacts in each group and subgroup.

RESULTS OF THE CLUSTER ANALYSIS – METAL GROUPS

The number of artefacts assigned to each group is shown in Fig. 2. The distinguished groups do not reflect specific deposits or places of origin of a particular metal. The artefacts within one group may come from different locations, and different types of copper may have been produced from ore from one mine (*Pollard 2018*, 104). The analysis and grouping presented here serves as a tool to detect patterns of trace element content in a large dataset. It is a starting point for further analyses leading to the detection of changes over time, differences between different regions, and categories of artefacts. This method can also indicate patterns in the distribution of objects made from a single metal type, which can help determine the general region from which the metal originated. Changes in the frequency of occurrence of particular types over time may also indicate the abandonment of certain deposits and the discovery of new ones, as well as changes in the smelting and processing of the metal (*Liversage 1994*, 119).

The following table (Tab. 1) presents information on each group. It shows the number of artefacts assigned, the range of content of each trace element, information on which categories of artefacts are most frequent, as well as data on their dating and the cultural context from which they came. In the case of Groups 1 and 2, both data for the groups as a whole (under the sections described as "Group 1" and "Group 2") and their individual subgroups are provided. The geographical spread of the artefacts assigned to each group is shown on the maps (Fig. 3–14).

INTERPRETATION OF THE RESULTS

The statistical analysis provided a division into groups, characterised by a specific composition of trace elements. Some of these are very common and widely distributed. Others appear to be smaller, local traditions existing alongside the main metal groups. In addition, groups containing only a few objects are also present. It was noted in the previous chapter that the analysis conducted was not intended to identify specific metal provenance locations. The distinguished groups, analogous to the groups resulting from the SAM project, represent centres of production based on deposits from a particular region (*Junghans/Sangmeister/Schröder 1968*, 20, 21). On the basis of information about the origin of the artefacts assigned to a particular subgroup or group, it is possible to make a general determination of the region in which a particular type of metal was most common. It can therefore be assumed that the metal originated from deposits sourced in this region.

The four largest subgroups, each with more than a thousand artefacts, represent the most common Bronze Age metal types in the area under study. Of all objects analysed, 79% were assigned to them. Two subgroups – 1.1 and 1.2 – appear to be associated with the Carpathian metallurgical circle, as the vast majority of the artefacts come from the Hungarian area (Fig. 3; 4). In addition, group 1.1 also included

Tab. 1. Characteristics of distinguished metal groups.

Group/subgroup number	Number of artefacts	Trace elements content	The most frequent types of artefacts	Archaeological cultures (arranged by number of artefacts)	Chronology (dating of the majority of the artefacts)
Group 1	5624	As: 0–3.1% Sb: 0–1. 85% Ag: 0–2% Ni: 0–2.6%	hatchet	Unětice, Straubing, Otomani, Unterwölbling, Bodrogkeresztúr, Vinča	Neolithic – Bronze Age B
1.1	2278	As: 0–0.93% Sb: 0–1.03% Ag: 0–0.52% Ni: 0–1%	hatchet	Unětice, Vatya, Bodrogkeresztúr,Vinča	Neolithic – Bronze Age B
1.2	1278	As: 0.19–1.6% Sb: 0–1.1% Ag: 0–0.74% Ni: 0–2.1%	bracelet, hatchet, ingot	Otomani, Straubing, Unětice, Suciu de Sus	Bronze Age A-B; also Bronze Age C/D–D
1.3	1383	As: 0–1.15% Sb: 0–1.5% Ag: 0.01–1.4% Ni: 0–0.89%	loop-ended, ring-shaped ingot, hatchet	Unětice, Unterwölbling, Vatya	Bronze Age A
1.4	67	As: 0–0.37% Sb: 0–0.73% Ag: 0.81–1.75% Ni: 0–0.097%	hatchet, ring, axe	Bubanj-Hum III, Kisapostag, Unětice	Eneolithic – Bronze Age A
1.5	9	As: 0–0.45% Sb: 0.98–1.5% Ag: 0.79–1.65% Ni: 0–0.14%	hatchet, bracelet	Bubanj-Hum III	Eneolithic
1.6	16	As: 0–0.5% Sb: 0.005–0.58% Ag: 0.01–0.8% Ni: 1–1.45%	rib-shaped ingot, bracelet	Unětice, Straubing	Bronze Age A
1.7	2	As: 0.17–0.32% Sb: 0.08–0.26% Ag: 0.01–0.27% Ni: 2–2.1%	dagger, spearhead	Culture du Rhône, Nitra group	Bronze Age A
1.8	63	As: 1.8–2.9% Sb: 0–0.64% Ag: 0–0.68% Ni: 0–0.42%	hatchet, pin, ingot	Wieselburg-Gáta, Straubing, Bodrogkeresztúr	Eneolithic – Bronze Age A

Tab. 1. Continuation.

Group/subgroup number	Number of artefacts	Trace elements content	The most frequent types of artefacts	Archaeological cultures (arranged by number of artefacts)	Chronology (dating of the majority of the artefacts)
1.9	290	As: 0.96–2.4% Sb: 0–0.8% Ag: 0.001–1.1% Ni: 0–1.45%	rib-shaped ingot	Straubing, Unětice	Bronze Age A
1.10	56	As: 0.55–1.45% Sb: 0.69–1.5% Ag: 0.01–0.5% Ni: 0.42–1.45%	hatchet, pin, ingot	Straubing, Otomani, Vatya,Suciu de Sus	Bronze Age A–C/D
1.11	31	As: 1.3–2.1% Sb: 0.72–1.15% Ag: 0.01–0.82% Ni: 1–1.7%	rib-shaped ingot	Straubing	Bronze Age A
1.12	9	As: 1.35–1.75% Sb: 1.2–1.85% Ag: 0.01–0.53% Ni: 0.3–1.15%	bracelet, ring	Straubing	Bronze Age A
1.13	2	As: 1.4–1.6% Sb: 1.5–1.85% Ag: 0.48–0.56% Ni: 0–0.05%	rib-shaped ingot	Straubing	Bronze Age A
1.14	48	As: 1.1–2.2% Sb: 0.03–0.84% Ag: 0.07–0.57% Ni: 1.45–2.4%	rib-shaped ingot	Unětice, Straubing, Otomani	Bronze Age A–B
1.15	2	As: 1.2–1.3% Sb: 0.32–0.57% Ag: 0.74–0.92% Ni: 1.8–2.05%	awl, ring	Cortaillod, Nitra group	Neolithic, Bronze Age A
1.16	82	As: 1.8–3.1% Sb: 0.09–0.7% Ag: 0.01–0.71% Ni: 0.79–2.2%	rib-shaped ingot	Unětice, Straubing	Bronze Age A
1.17	8	As: 0–1.15% Sb: 0–0.86% Ag: 0.71–2% Ni: 1.2–2.6%	rib-shaped ingot, ornaments	Unětice, Straubing	Bronze Age A
Group 2	2586	As: 0–3% Sb: 0.42–3.4% Ag: 0.01–2.2% Ni: 0–2.2%	loop-ended, ring-shaped ingots	Unětice, Straubing, Unterwölbling, Nitra group	Bronze Age A

Tab. 1. Continuation.

Group/subgroup number	Number of artefacts	Trace elements content	The most frequent types of artefacts	Archaeological cultures (arranged by number of artefacts)	Chronology (dating of the majority of the artefacts)
2.1	1852	As: 0–2.9% Sb: 0.42–3.3% Ag: 0.01–1.8% Ni: 0–2.1%	loop-ended, ring-shaped ingots	Unětice, Straubing, Unterwölbling	Bronze Age A
2.2	245	As: 0.12–3% Sb: 1.2–3.4% Ag: 0.01–1.47% Ni: 0–0.45%	rib-shaped ingot, loop-ended, ring-shaped ingots	Unětice, Straubing, Unterwölbling	Bronze Age A
2.3	3	As: 1.1–1.65% Sb: 1.65–2.15% Ag: 1.3–2.2% Ni: 0.022–0.49%	bracelet, chisel, loop-ended, ring-shaped ingots	Straubing, Urnfield	Bronze Age A, Hallstatt A
2.4	207	As: 0–2.2% Sb: 1–3.3% Ag: 0.01–1.7% Ni: 0–2.2%	ring	Unětice, Nitra group	Bronze Age A
2.5	279	As: 0–1.9% Sb: 0.55–3.3% Ag: 0.14–1.52% Ni: 0–2.2%	ring	Nitra group, Unětice	Bronze Age A
Group 3	33	As: 1.17–3.7% Sb: 1.25–2.75% Ag: 0.04–1.15% Ni: 0.54–1.85%	rib-shaped ingot	Straubing, Unětice	Bronze Age A
Group 4	17	As: 0–1.3% Sb: 0–1.7% Ag: 1.65–3.1% Ni: 0–0.82%	axe, hatchet	Unětice, Bubanj-Hum III	Eneolithic – Bronze Age A
Group 5	75	As: 2.5–5.4% Sb: 0–1.6% Ag: 0.01–0.77% Ni: 0–2.8%	rib-shaped ingot	Unětice, Straubing	Bronze Age A
Group 6	9	As: 2.3–3.8% Sb: 0.2–2.2% Ag: 0.68–2.4% Ni: 0–1.15%	rib-shaped ingot, loop-ended, ring-shaped ingots	Unětice	Bronze Age A

Tab. 1. Continuation.

Group/subgroup number	Number of artefacts	Trace elements content	The most frequent types of artefacts	Archaeological cultures (arranged by number of artefacts)	Chronology (dating of the majority of the artefacts)
Group 7	18	As: 0.37–1.35% Sb: 1.2–1.85% Ag: 0.06–1.4% Ni: 1.45–3.2%	earing, spiral	Unětice, Unterwölbling	Bronze Age A
Group 8	7	As: 0.35–2% Sb: 1.3–3.4% Ag: 0.59–1.85% Ni: 3.6–4.2%	ring, pin	Unětice	Bronze Age A
Group 9	2	As: 1.1–1.4% Sb: 2.6–3% Ag: 2.2–2.6% Ni: 2.65–3.3%	dagger	Straubing	Bronze Age A
Group 10	20	As: 1.3–3.1% Sb: 0–0.66% Ag: 0–1% Ni: 2.5–4.3%	rib-shaped ingot	Unětice	Bronze Age A
Group 11	4	As: 2.7–3.3% Sb: 2.7–3.3% Ag: 0.28–0.6% Ni: 2.1–2.7%	rib-shaped ingot, bracelet	Straubing	Bronze Age A
Group 12	76	As: 0.07–2.45% Sb: 2.2–4.35% Ag: 0.25–2.95% Ni: 0.8–3.25%	ring, bracelet	Unětice, Nitra group	Bronze Age A
Group 13	42	As: 0.2–3.3% Sb: 3.8–6% Ag: 0.39–1.6% Ni: 0.49–2.9%	bracelet, hatchet, ring	Unětice	Bronze Age A
Group 14	44	As: 0–2.7% Sb: 2.2–5% Ag: 0.02–1.4% Ni: 0–1.4%	rib-shaped ingot	Straubing, Unětice	Bronze Age A
Group 15	37	As: 0.1–6.4% Sb: 0–10% Ag: 0.01–5% Ni: 0–9.18%	ring, dagger	Unětice, Straubing	Bronze Age A

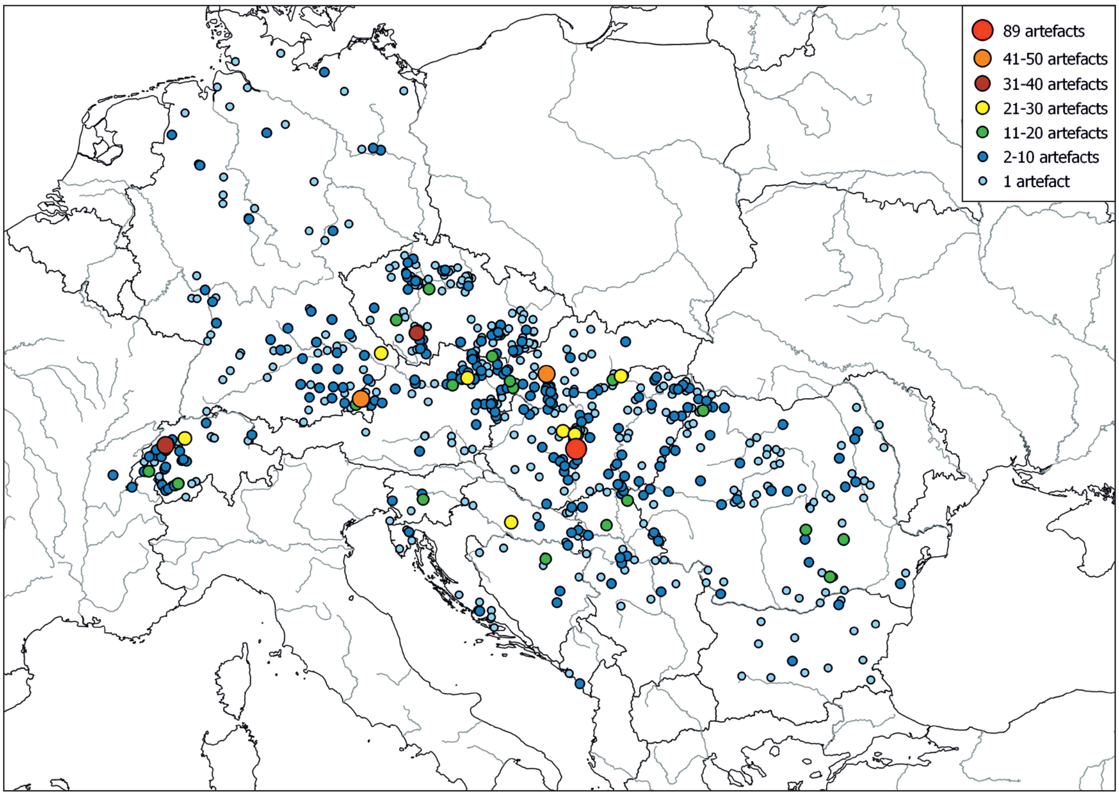

Fig. 3. Distribution map of the objects in group 1.1. Scale: 1 : 10,000,000 (source of a basemap: QuickMapServices – ESRI World Topo).

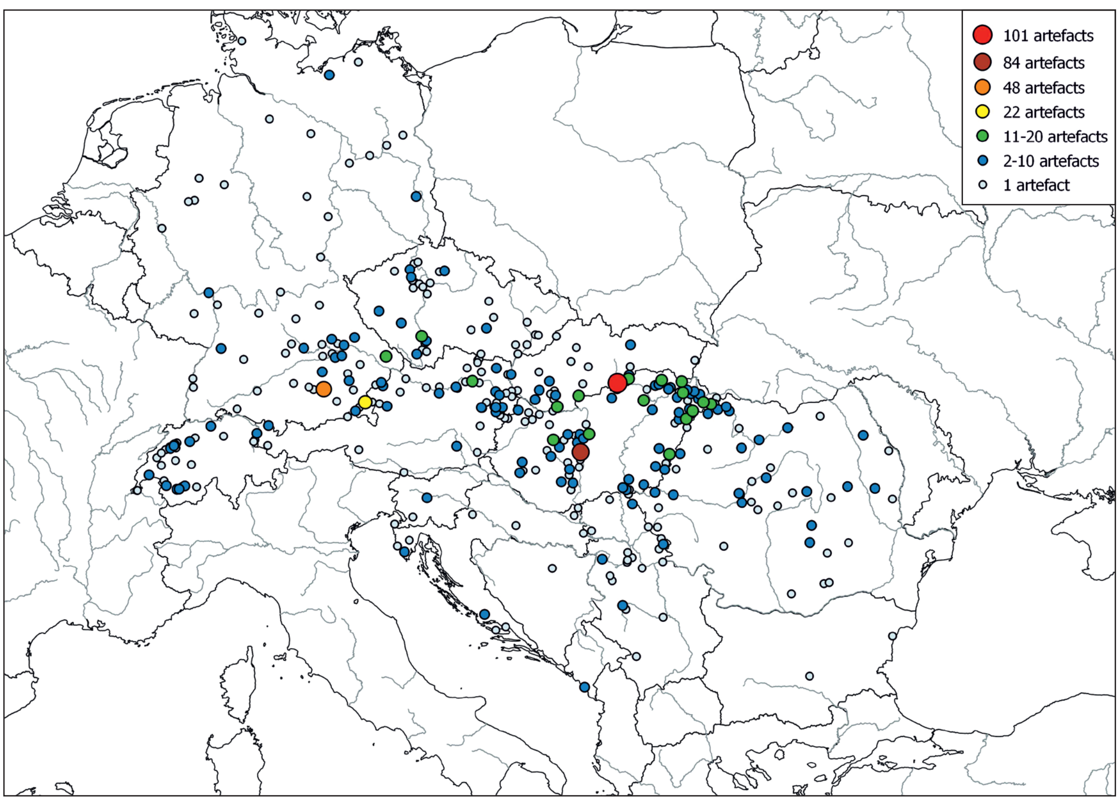

Fig. 4. Distribution map of the objects in group 1.2. Scale: 1 : 10,000,000 (source of a basemap: QuickMapServices – ESRI World Topo).

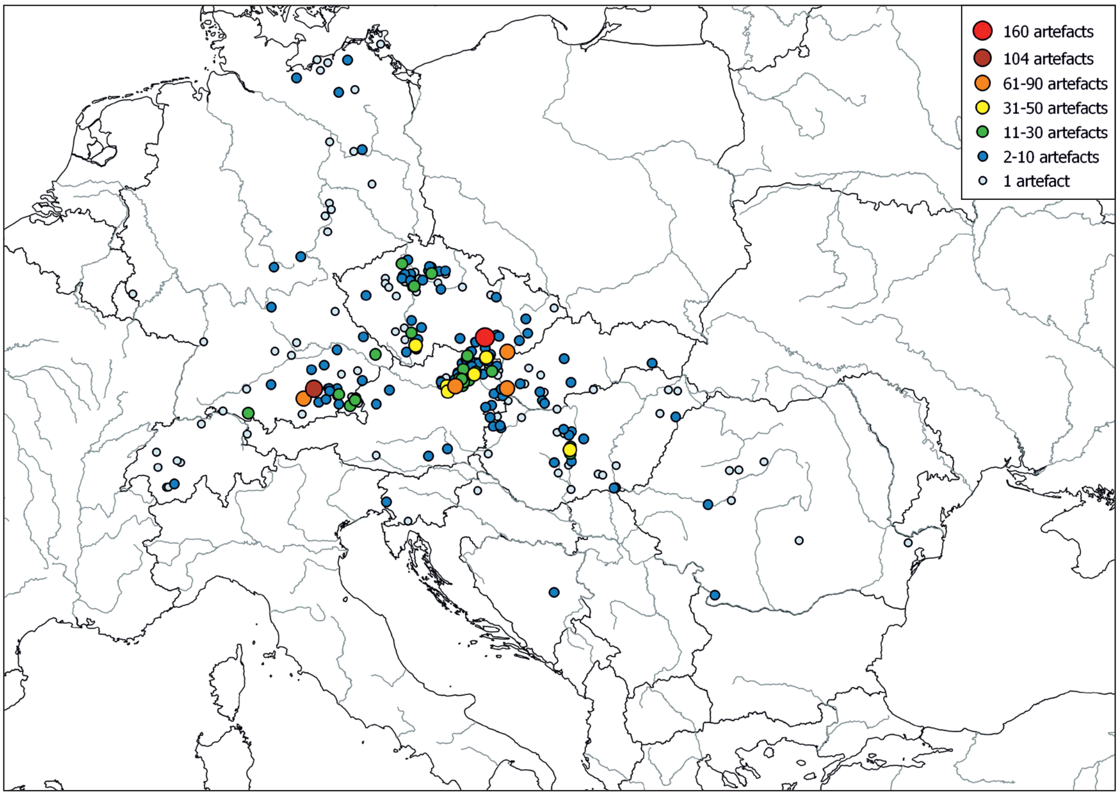

Fig. 5. Distribution map of the objects in group 2.1. Scale: 1 : 10,000,000 (source of a basemap: QuickMapServices – ESRI World Topo).

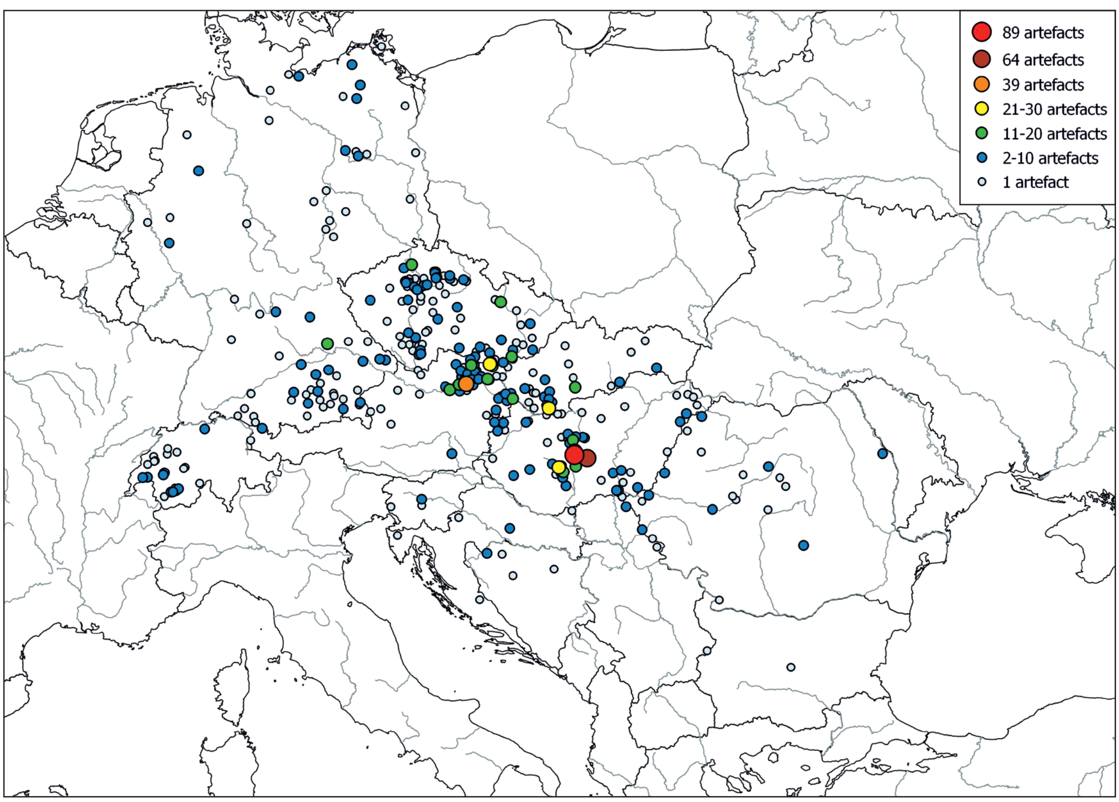

Fig. 6. Distribution map of the objects in group 1.3. Scale: 1 : 10,000,000 (source of a basemap: QuickMapServices – ESRI World Topo).

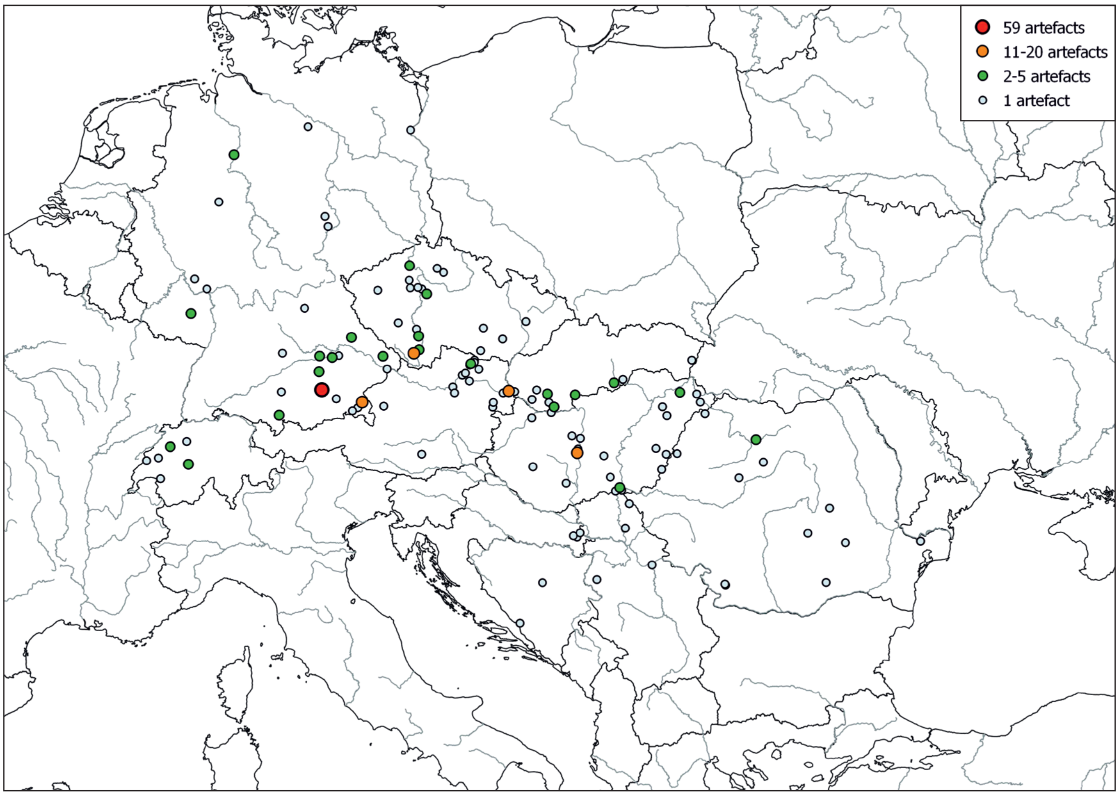

Fig. 7. Distribution map of the objects in group 1.9. Scale: 1 : 10,000,000 (source of a basemap: QuickMapServices – ESRI World Topo).

a large number of Balkan artefacts, particularly from Bulgarian sites. Subgroup 2.1, on the other hand, represents the Alpine metallurgical circle, with most of the objects assigned to it coming from Austria, southern Germany, and the Czech Republic (Fig. 5). In the fourth of the most numerous subgroups, 1.3, there are many artefacts from both Carpathian and Alpine areas, so the type of metal characteristic for this group seems to be widespread throughout Central Europe (Fig. 6). Of the subgroups, containing between 200 and 300 artefacts, two – 1.9 and 2.2 – are associated with the Alpine metallurgical centre, both of which have the vast majority of artefacts from southern Germany (Fig. 7; 8). In the other two groups – 2.4 and 2.5 – objects from Germany and Slovakia predominate, so it is impossible to link them exclusively to one of the two main centres (Fig. 9; 10). Among the smaller groups, numbering a few dozen objects each, in nine the majority of the artefacts are from Alpine sites (subgroups 1.8, 1.11, 1.14, 1.16, and groups 3, 5, 13, 14, 15; Fig. 11–14). Two subgroups – 1.4 and 1.10 – are associated with the Carpathian metallurgical centre (Fig. 11). The artefacts assigned to group 12, on the other hand, come from both Alpine and Carpathian sites (Fig. 13). Of the remaining groups, comprising fewer than 20 artefacts, eight contain artefacts exclusively or almost exclusively from Alpine areas (subgroups 1.13, 1.17, 2.3 and groups 6, 7, 8, 9, 11). In the others – 1.5, 1.6, 1.7, 1.12, 1.15, 4, and 10 – the objects are not concentrated in one area.

Early Bronze Age artefacts are by far the most prevalent in the database, and therefore objects dating to this period also dominate in almost all groups. However, it is possible to observe some dependencies, especially in the largest subgroups. The majority of Neolithic and Eneolithic artefacts were assigned to the first of these, 1.1, which included artefacts with the lowest trace element content. In sub-group 1.2, on the other hand, in addition to a large number of Early Bronze Age artefacts, objects from the Middle and Late Bronze Age are also represented in significant numbers. The other two of the four largest subgroups – 1.3 and 2.1 – contain almost exclusively artefacts dating to the Early Bronze Age. A clear predominance of artefacts from this period can also be observed in sub-groups 1.9, 2.2, 2.4, and 2.5.

It is also possible to reach certain conclusions about the metallurgy of specific archaeological cultures. Correspondence analysis was performed to illustrate the relationship between the cultures and the metal groups (Fig. 15). Those cultures for which the number of objects in the database exceeded 1% of all artefacts analysed were considered. Of the metal groups, those with more than 20 objects were included.

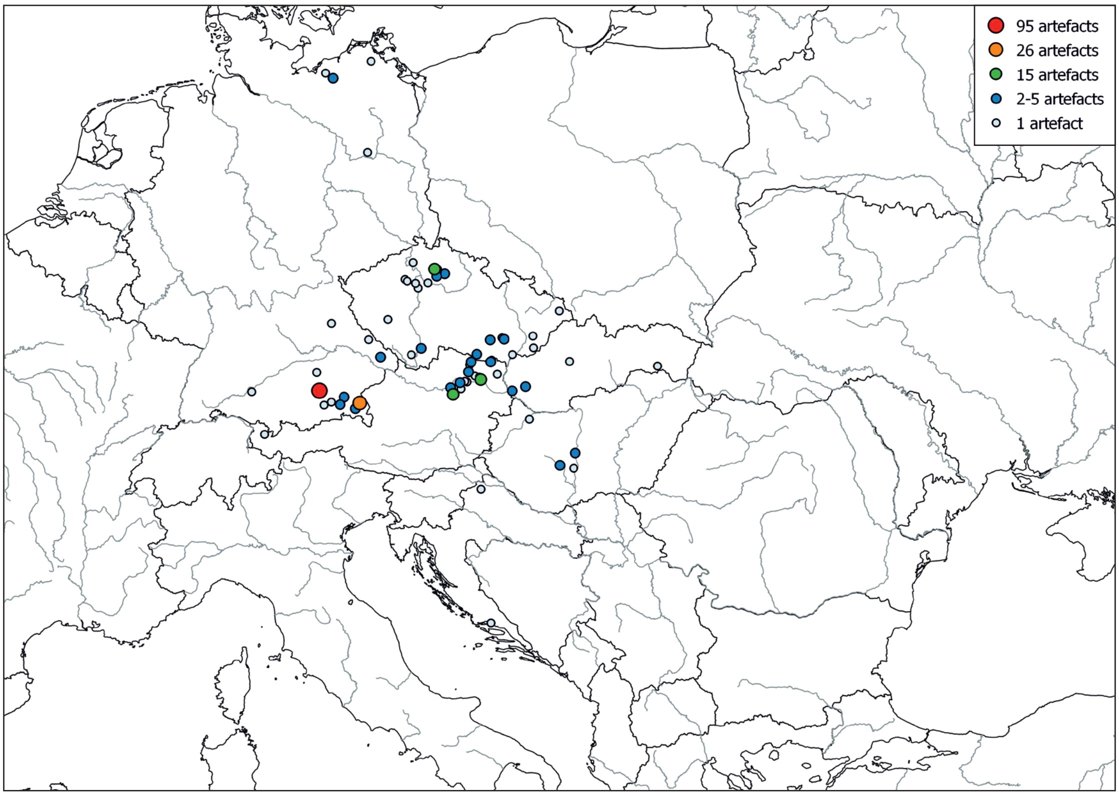

Fig. 8. Distribution map of the objects in group 2.2. Scale: 1 : 10,000,000 (source of a basemap: QuickMapServices – ESRI World Topo).

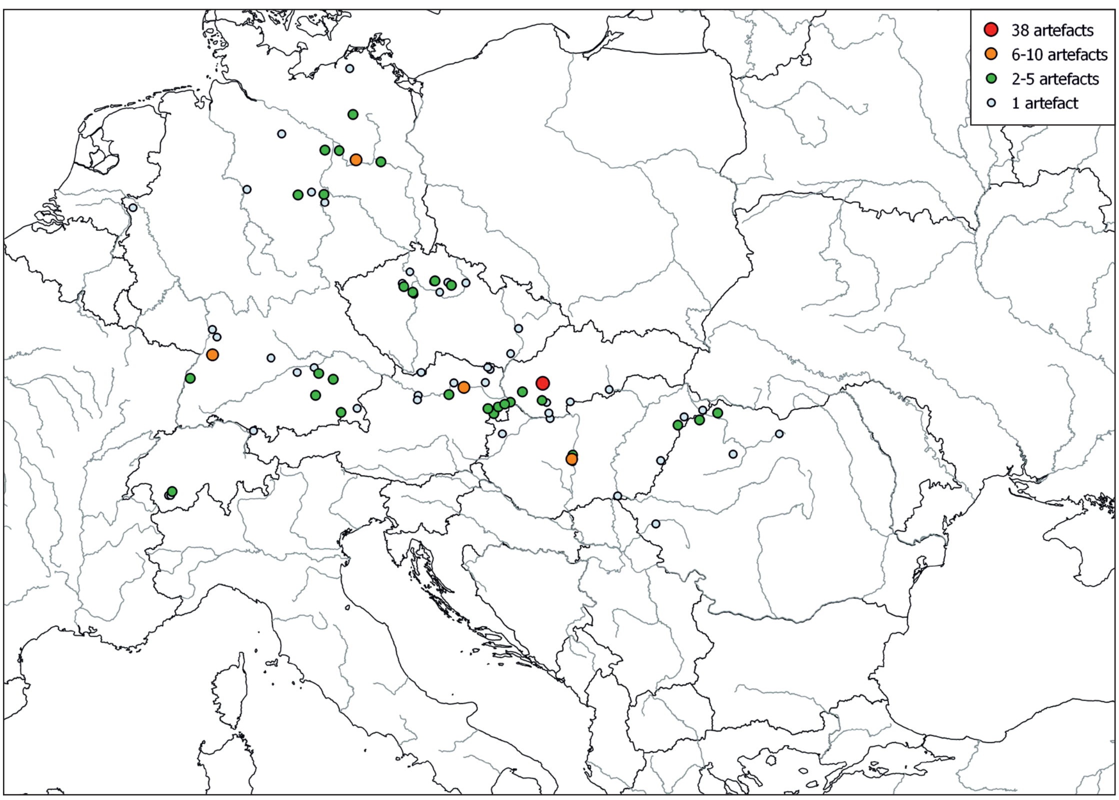

Fig. 9. Distribution map of the objects in group 2.4. Scale: 1 : 10,000,000 (source of a basemap: QuickMapServices – ESRI World Topo).

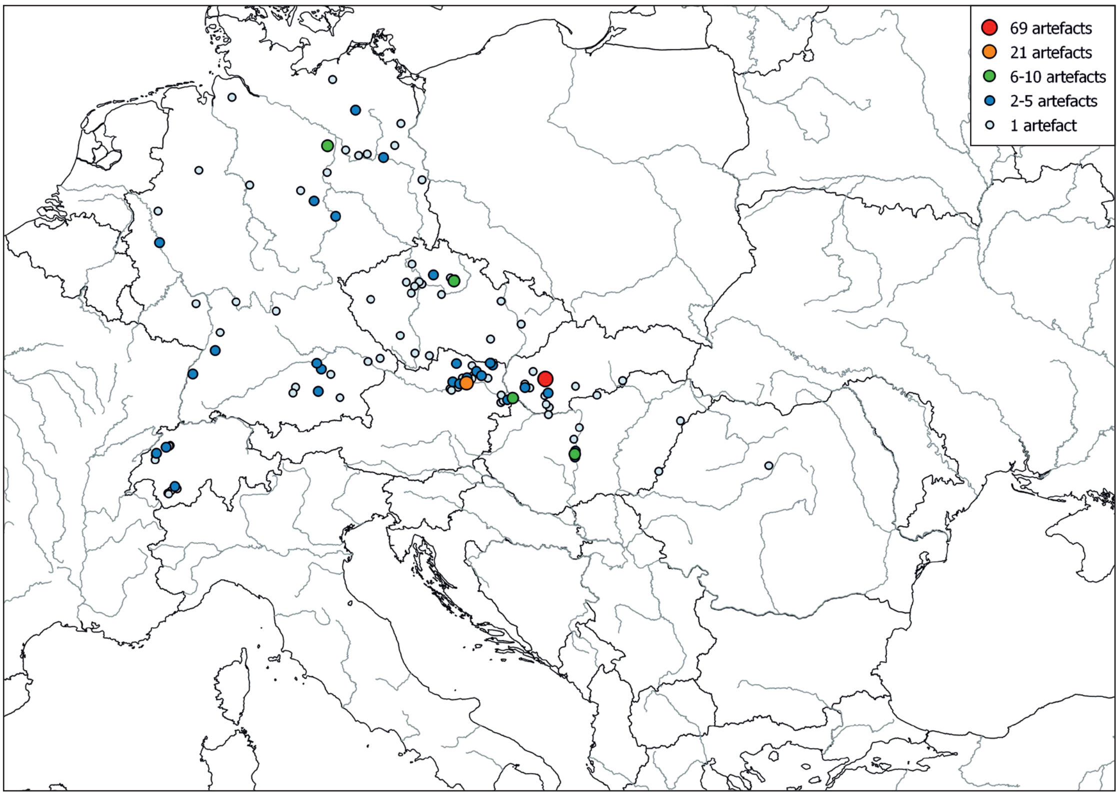

Fig. 10. Distribution map of the objects in group 2.5. Scale: 1 : 10,000,000 (source of a basemap: QuickMapServices – ESRI World Topo).

The most numerously represented culture in the analysed database is the Unětice culture. Its position close to the centre of the chart is due to the fact that artefacts related to it are present in large numbers in almost all metal groups. However, it can be observed that it is most closely associated with groups 2.1, 1.3 and 13. The most similar to the Unětice metallurgy, in terms of trace element content of metal objects, is the metal production of the Unterwölbling group (proximity of both groups in the chart). Here too, groups 2.1 and 1.3 are clearly dominant. In addition, groups 1.9 and 2.5 are also represented in large numbers. The artefacts of the Straubing group, which metalwork is also linked to this of Unětice culture, differ slightly in composition from the two cultures mentioned above, with groups 2.2, 1.9 and 2.4 being most characteristic. Numerous loop-ended, ring-shaped and rib-shaped ingots associated with these cultures (mainly the Unětice and Straubing) were placed in the same groups (mainly 2.1, 2.2, 1.9, 1.10, 3, 5). Ornaments and parts of costume from the Carpathian Basin area (also dated to the Early Bronze Age) are usually found in these groups too, although in smaller numbers. This may indicate the export of copper and bronze from the Alpine area.

The metal artefacts of the Nitra group are characterised by a composition similar to the Unětice artefacts from Germany. Ornaments and parts of costume associated with these groups were assigned to the same sub-groups (2.4 and 2.5). This may be a result of the smelting and processing process, which produced metal of the same composition from different deposits. However, it may be that the raw material came from a single deposit, in the area of one of these cultures. In this case, the absence of this type of metal in the Czech Republic is surprising. The Wieselburg-Gáta culture, which occupies the Lower Austrian and north-western Hungarian areas, is characterised by the presence of metal types, associated with both Alpine and Carpathian centres, at a similar level. This is confirmed by the findings of *E. Duberow*, *A. Krenn-Leeb* and *E. Pernicka* (*2009*), who, by means of lead isotope analysis, established the origin of the raw material used to produce artefacts from the sites of this culture. They proved that some of the artefacts were made of metal from the Western Carpathians (probably from Slovakia) and some from the Eastern Alps (*Duberow/Krenn-Leeb/Pernicka 2009*, 343, 344).

In addition to the correspondence analysis, it was also useful to trace the proportion of objects made of metal of a respective group among all the artefacts associated with a particular culture, especially in the case of items from the Carpathian Basin, that are represented in the database in large numbers.

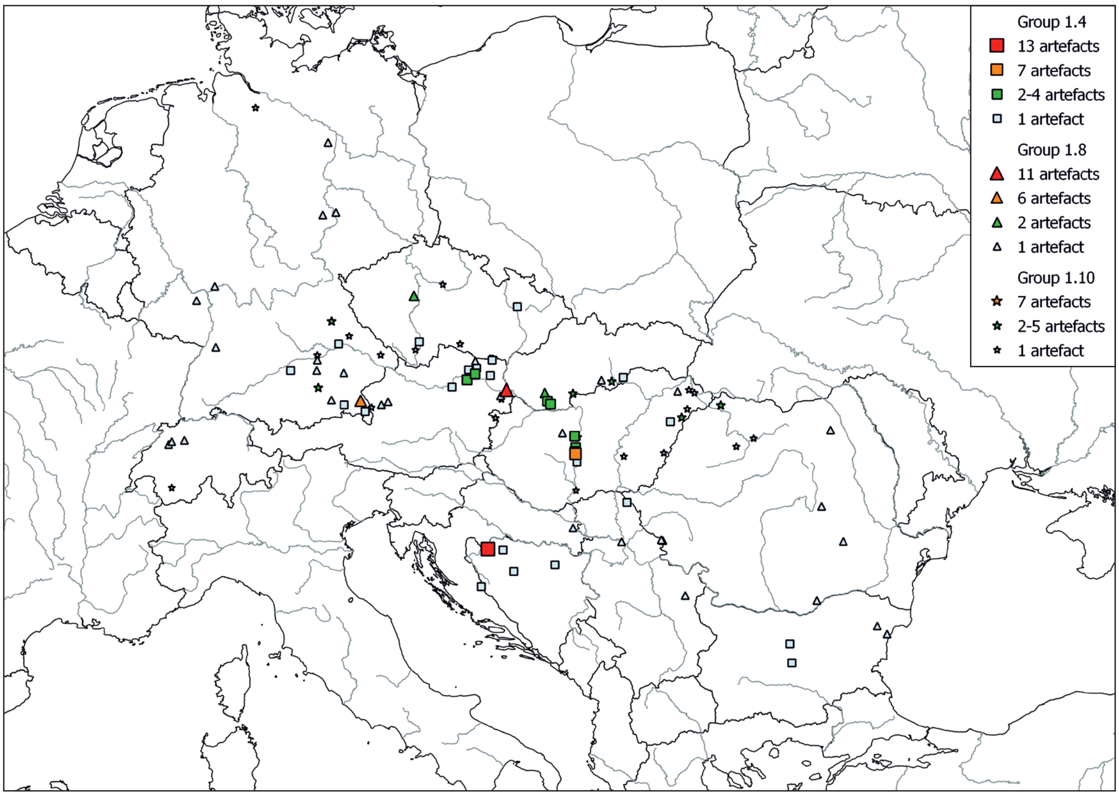

Fig. 11. Distribution map of the objects in groups 1.4, 1.8 and 1.10. Scale: 1 : 10,000,000 (source of a basemap: QuickMapServices – ESRI World Topo).

Fig. 12. Distribution map of the objects in groups 1.11, 1.14 and 1.16. Scale: 1 : 10,000,000 (source of a basemap: QuickMapServices – ESRI World Topo).

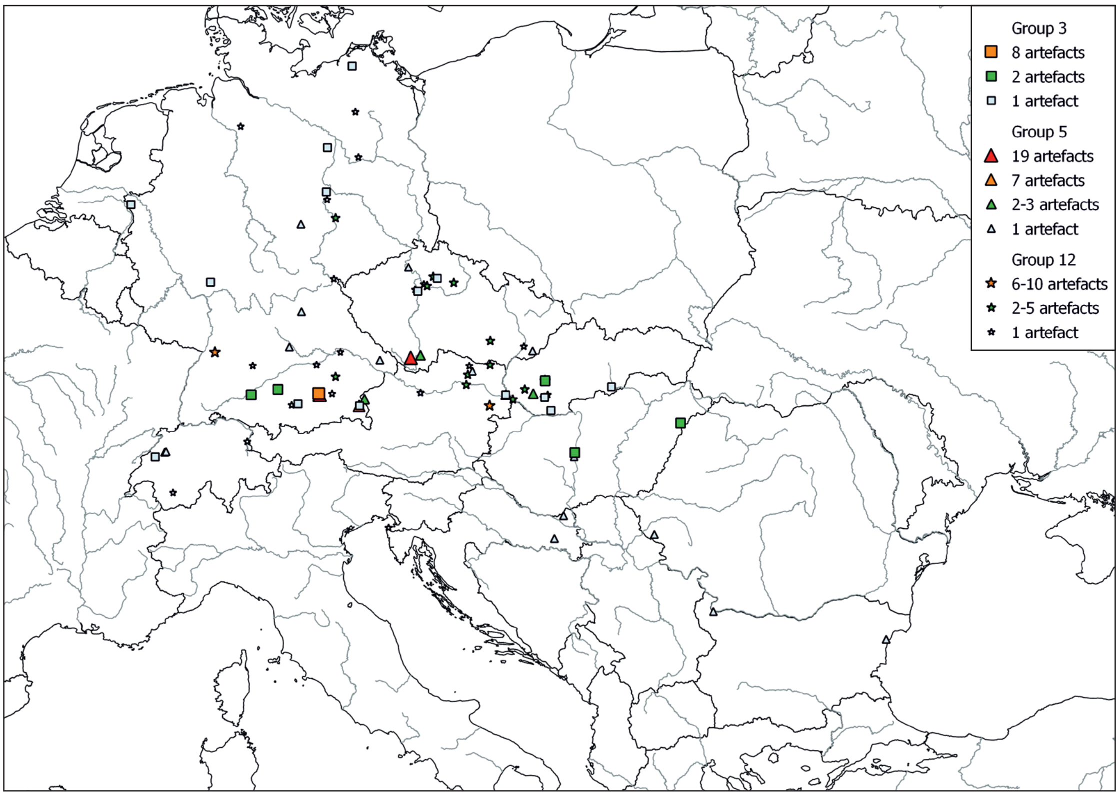

Fig. 13. Distribution map of the objects in groups 3, 5 and 12. Scale: 1 : 10,000,000 (source of a basemap: QuickMapServices – ESRI World Topo).

Thanks to the fact that for this region, the analyses included not only Early Bronze Age artefacts, but also those dated from the Eneolithic to the Late Bronze Age, it is possible to trace the characteristics of bronze metallurgy in this region throughout the Bronze Age. Eneolithic artefacts, associated with the Bodrogkeresztúr culture, are mainly assigned to subgroup 1.1. Objects associated with the Kisapostag culture were produced from metal with compositions characteristic of subgroups 1.3 and 1.4. The metallurgy of the Vatya culture is also dominated by artefacts with trace element contents typical of subgroup 1.3, however, there are also numerous artefacts assigned to subgroups 1.1 and 1.2. In the Otomani culture, these subgroups became the most popular, while the number of artefacts in group 1.3 decreases. Artefacts dating to the Late Bronze Age are produced from metal with a composition characteristic of subgroups 1.2 and 1.1, while subgroup 1.3 is completely disused. It therefore appears that Carpathian metallurgy was mainly based on regional deposits. Only in the case of the Early Bronze Age a small proportion of metal from the Alpine region could be observed. Changes in the use of particular metal types (the appearance and disappearance of certain groups) may indicate both the discovery of new deposits and the abandonment of old ones, as well as changes in the smelting and metalworking process and therefore the development of metallurgical knowledge.

On the basis of the distinguished groups, it is also possible to identify some relationships between metal groups and categories of artefacts that were produced from a given type of raw material. The problem, however, is that the quantities of each type of object in the database are not equal. The most numerous are ornaments and elements of costume, as well as ingots. Weapons and tools are almost three times less frequent. Nevertheless, this arrangement is not maintained in all groups. In subgroups 1.1 and 1.2, ornaments and elements of the costume are the most numerous, tools and weapons form almost equal groups, while ingots are the least frequent. The distribution is similar in subgroup 1.3, with the difference that ingots constitute a more numerous group than tools and weapons. In the fourth of the largest subgroups – 2.1 – ingots (mainly in the form of loop-ended, ring-shaped ingots) have a distinct prevalence over all other types of objects. By analysing the percentage contribution of each category of artefacts in the distinguished groups, it is also possible to observe the relationship between the type of raw material and the types of artefacts that were produced from it, even despite the differences in the

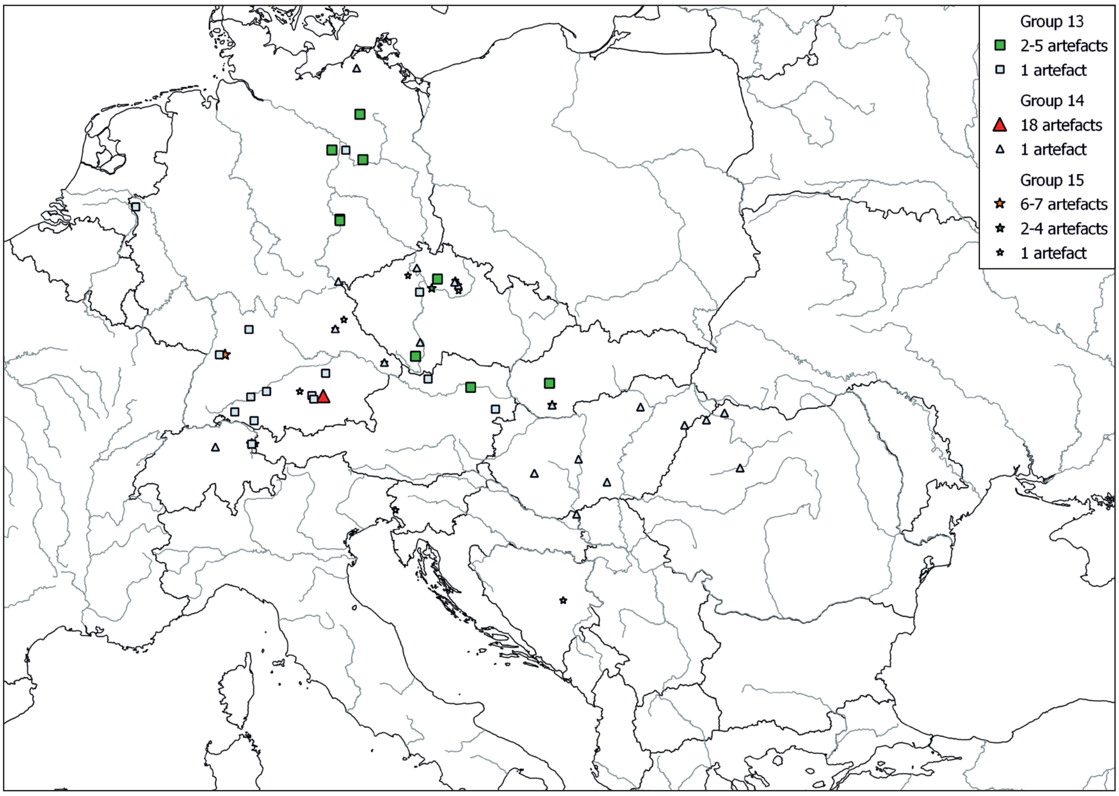

Fig. 14. Distribution map of the objects in groups 13, 14 and 15. Scale: 1 : 10,000,000 (source of a basemap: QuickMapServices – ESRI World Topo).

size of the groups. A significant surplus of weapons and tools in relation to their percentage proportion in the whole database is found in subgroups 1.1, 1.2, and 1.9 (in the last case only tools). The proportion of these categories of artefacts, on the other hand, is smaller in subgroups 2.1 and 2.2. Ornaments and parts of the costume are statistically more frequent in subgroups 1.2, 1.3, 2.4, and 2.5, while their proportion in groups 1.9, 2.1, and 2.2 is smaller than their quantity in the whole database would suggest. A surplus of ingots can be observed in subgroups 1.9, 2.1, and 2.2. This category of artefacts, on the other hand, is much less numerous in subgroups 1.1, 1.2, 1.3, 2.4, and 2.5. As a result of the analysis conducted, there appears to be a correlation between the categories of artefacts and the raw material used in their manufacture. This may therefore suggest that prehistoric metallurgists were aware of certain properties of different groups of metals (resulting from their composition).

The statistical analysis also confirmed the difference in the chemical composition of loop-ended, ring--shaped ingots and rib-shaped ingots, as shown in earlier studies (*Radivojević et al. 2018*, 32). The former form is also more homogeneous from the perspective of trace element content (Junk/Krause/Pernicka 2001, 357) – 70% of all loop-ended, ring-shaped ingots were in the same subgroup (2.1). These are characterised by high levels of arsenic and antimony, lower silver content, and no or only a small admixture of nickel. Rib-shaped ingots, on the other hand, although also present in fairly large numbers in subgroup 2.1, are also present in the same quantity in subgroups 1.1, 1.2, 1.9, and 2.2. The chemical composition of this type of bar is therefore much more varied than that of the former. The contents of all trace elements analysed range from very low (<0.1%) to very high levels (maximum value for: arsenic – 6.2%, antimony – 4.5%, silver – 2%, nickel – 4.2%).

DISCUSSION

The results of the trace element analyses performed by the SAM project over the 50 years since their publication numerous studies have been conducted, using, to a greater or lesser extent, the results obtained from this project (e.g. *Pernicka et al. 2016*; *Sangmeister 1973*; *Tylecote 1970*). One of the largest studies,

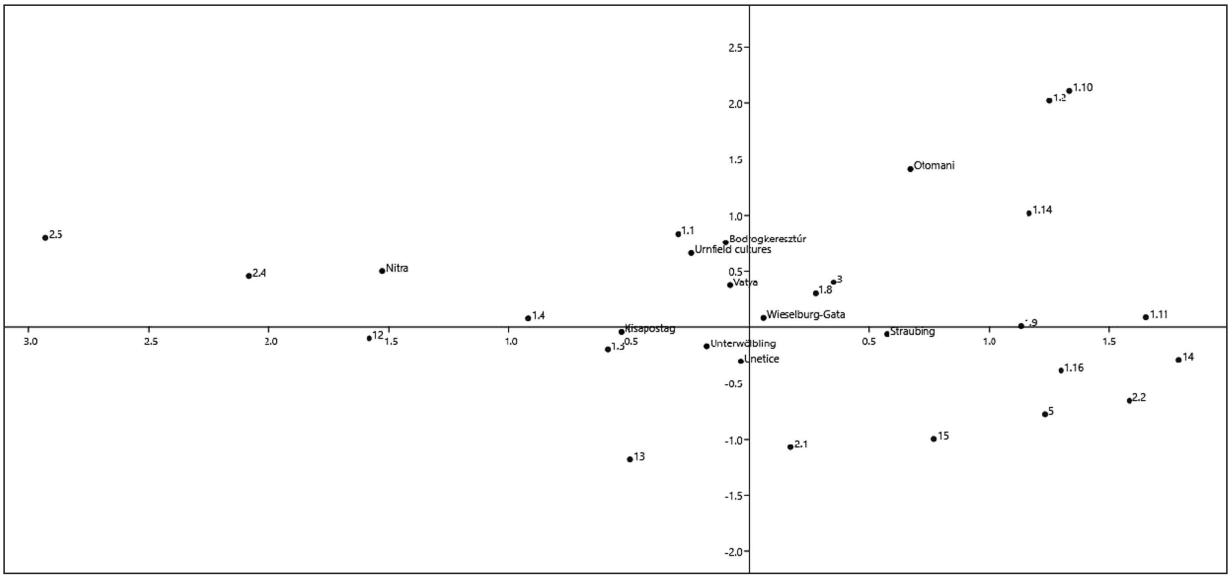

Fig. 15. Correspondence analysis results illustrating relationships between archaeological cultures and metal groups.

based partially on these analyses, was conducted in the early 1990s as part of the SMAP project. In this case, cluster analysis was used to separate initially 8, and later 24 and 40 groups. In both of these projects, the division into groups was a two-step process – first, the material was divided on the basis of its arsenic and antimony content (in the case of the SMAP project, partly also nickel) into five and eight groups, respectively. These groups were then divided into smaller subgroups based on the content of the other elements analysed. The groups formed as a result of the first stage were intended to represent the type of ore, while those separated during the second stage were expected to represent the metallurgical workshops (*Krause/Pernicka 1996*, 280). Despite the use of different statistical methods, the SMAP study confirmed the validity of the groups separated in the earlier project (*Pernicka 1990*, 98). The analysis performed in the present study, in contrast to the studies described above, was a one-step analysis. The cluster analysis conducted involved all the material at once, including all the elements analysed. Despite this difference, a partial comparison of the separated groups is possible. The most distinctive of these, identified as "Fahlerz-Metall ohne Ni", corresponds to subgroups 2.1, 2.2 and 2.3. The other two subgroups of group 2 (2.4 and 2.5), on the other hand, correspond to the type "Fahlerz-Metall mit Ni". The metal type identified by the SMAP project researchers as "Reinkupfer", on the other hand, appears to be analogous to subgroup 1.1. A more detailed comparison of the groups distinguished by the SMAP research with the results of the current study is presented in Tab. 2 (*Krause 2003*, 89, 91).

Tab. 2. Comparison of the groups separated by SMAP project and D. Liversage with those of the present study.

Groups from the SMAP project	Liversage's groups	Groups from current study
Reinkupfer (Cluster 2)	'Lhag', 'LSz', 'Lp'	1.1
Fahlerzkupfer mit Ni (Cluster 17)	'dAsNi'	1.2
Arsenkupfer (Cluster 6)	'ev'	1.3
Reinkupfer mit Silber (Cluster 13)	'hAg'	1.4
Antimonkupfer (Cluster 28)	'SAB'	1.5
Fahlerzkupfer mit Ni (Cluster 4)	'AsNi'	1.11, 1.14, 1.16
Fahlerzkupfer ohne Ni (Cluster 1)	'Ösenring' metal	2.1, 2.2, 2.3
Fahlerzkupfer mit Ni (Cluster 8)	'Singen' metal	2.4, 2.5, 12

The researchers involved in the SAM and SMAP projects confirmed the validity of such studies through their analyses. In both cases, it was assumed from the outset that it was not possible to identify the geological source of the metal, due to the amount of analysis that would be required to do so – samples would have to come from all known copper deposits in Europe. In addition, smelting the metal from the ore and its subsequent processing also affect the chemical composition of the finished object, which would have made it even more difficult to match the artefacts to specific deposits. They therefore decided to separate copper groups based on trace element content and analyse their distribution in time and space (*Radivojević et al. 2018*, 17). Researchers working on both projects have shown that the information thus obtained on the use of copper in the Bronze Age provides new aspects for interpretations of the archaeological material (*Krause/Pernicka 1996*, 288). The use of statistical methods to group together the large amounts of data obtained through trace element studies has made it possible to create a typology of copper types. Despite the existence of a certain "blurring" at the edges of the distinguished groups, they provide important information on metal usage in the Bronze Age. Researchers from the SMAP project have also shown that, although the group boundaries can shift depending on the amount of material analysed, there are also metal types that are so characteristic that they remain constant (especially the so-called "Ösenhalsring metal"; *Krause 1998*, 172).

Research on the content of trace elements in Bronze Age metal objects was also conducted in the 1990s by D. Liversage. On the basis of analyses of 2,500 artefacts from the Carpathian Basin, he separated 21 metal groups. He used the histogram method of creating bar charts, which allowed the composition of the metals belonging to each group to be visualised. The content of each of the elements analysed by D. Liversage (arsenic, antimony, silver, nickel, cobalt and bismuth) was assigned to one of six columns, reflecting respectively: the absence of a given element, thousandths, hundredths, decimals, the range from 1 to 10% and values above 10%. Thanks to the description of the separated groups in the paper "Interpreting Composition Patterns in Ancient Bronze: The Carpathian Basin" (*Liversage 1994*), it is possible to partially match them with the groups resulting from the present work. This comparison is shown in Tab. 2.

Liversage's research also did not aim to identify the specific deposits from which the raw material used to produce the analysed objects came. In his paper, he outlined that matching raw material to deposits required methods other than trace element analysis (e.g. lead isotope studies). Instead, he identified distribution patterns of objects made from one type of metal to determine the general region from which they may have originated (*Liversage 1994*, 60, 61). He also noted that the metal groups used changed over time, which can be explained by the assumption that new deposits were discovered and used during the Bronze Age, while others were abandoned. This is also confirmed by the present research. By also taking into account the dating and cultural context of the artefacts analysed in his research, he observed changes in the distribution of metal types in the Carpathian Basin. In the Eneolithic, small-scale exploitation prevailed and no clear patterns are visible. In the Early Bronze Age, two main groups ("Ösenring" metal and "Singen" metal) predominate, and several smaller groups are also present. In the Middle Bronze Age, almost all artefacts have a very similar composition and may have come from a single deposit (*Liversage 1994*, 75).

In his research, D. Liversage also considered the tin content of the objects analysed. This made it possible to derive conclusions about alloy-making technology and metallurgical knowledge in prehistory. In the Eneolithic, artefacts with an admixture of tin are very few. In the Early Bronze Age, it is possible to observe a tendency to aim for a high content of it in bronze objects (around 10%). The study also shows that tin was more often added to copper with a low content of impurities. From around the 18^{th}–17^{th} c. BC, there is an increase in bronzes with a lower tin content (6–7%). In the Late Bronze Age, as a result of secondary re-melting of bronzes, artefacts are characterised by very different tin contents (*Liversage 1994*, 75–79).

The metallurgy of the northern Carpathian Basin based on the research of the SAM project was also addressed by *E. Schalk* (*1998*). The aim of her work was to trace the typological, chronological, and compositional development of metal artefacts from this area. The author of this research did not conduct her own statistical analysis of the material studied, relying instead on the groups proposed by SAM. Schalk's evaluation, however, allowed her to observe relationships between the different types of artefacts, their dating, cultural context, location and chemical composition (*Schalk 1998*).

In 2015, work began on the Flow of Ancient Metal across Eurasia (FLAME) project. Its aim is to collect and organise all trace element analyses of Bronze Age metal objects published to date. The aim is to help better understand the uses and distribution of metal and to provide new information on the development of the metallurgical tradition. The FLAME project researchers based their analysis on the content of the same four elements considered most important in earlier studies: arsenic, antimony, silver and nickel. However, the grouping methodology they used differs markedly from the statistical methods used in other studies. They separated 16 groups based on the presence or absence of each element, setting the cut-off at 0.1% (*Pollard 2018*, 86). However, this approach has been criticised by E. Pernicka, who questions the geochemical and metallurgical justification for setting a fixed group boundary threshold at 0.1% (*Radivojević et al. 2018*, 17). The method used in the FLAME project differs so much from the methods used in other projects and in the present study that it is not possible to compare the results. The researchers involved in the described project state that the study they are conducting serves as a tool for detecting trace element patterns in a large data set and provides a reference point for further analyses leading to the detection of changes in metallurgy during the Bronze Age, regional differences and the relationship between copper types and artefact categories (*Perucchetti et al. 2021*, 655).

CONCLUSION

The research on the chemical composition of Bronze Age artefacts that has been undertaken since the beginning of the last century has led to a Europe-wide network of analyses. Their statistical compilation provides an overview of the types of copper used in different geographical areas and at different times. It also allows inferences to be made about the development of early metallurgy (*Krause 1998*, 164). The statistical analysis conducted in the present paper resulted in the separation of 15 groups (as well as 17 subgroups of Group 1 and 5 of Group 2). Each of these is characterised by a specific chemical composition, which was influenced both by the raw material used and the technological process leading to the final object manufactured from it (*Krause/Pernicka 1996*, 289). The resulting groups vary considerably in the number of objects they contain. The four largest subgroups appear to reflect the copper types most characteristic of the Early Bronze Age. Statistical analysis also revealed the presence of a number of smaller groups that represent minor, local "workshops". The artefacts assigned to each group and subgroup were also analysed in terms of their geographical spread, dating, cultural affiliation and typological categories. This allowed to associate each group with one of the major metallurgical centres operating in the Bronze Age in the area under study.

It has also been shown that the determination of copper types can be used as an additional criterion when inferring the metallurgy of specific cultures and the relationships between them. Tracing the contribution of individual groups to the material of archaeological cultures provides the opportunity to demonstrate similarities in their metallurgy. These relationships are evident both in space and in time. The chemical composition of the finished object is influenced by the raw material and the manner in which it is processed, so the occurrence of artefacts belonging to the same group in the material of different archaeological taxonomic units may indicate contacts between them. In addition, in the case of the Carpathian Basin area, changes in the metallurgy throughout the Bronze Age can also be demonstrated. This shows that trace element analyses are not only useful for the Early Bronze Age. Several groups have also shown the co-occurrence of ingots from Alpine sites with ornaments and elements of costume from the Carpathian Basin, dating from the same chronological phase. This may indicate an exchange of raw material or finished objects between these regions.

In addition, an analysis of the occurrence of particular categories of artefacts in the distinguished groups showed that, in many cases, this differs from the distribution in the entire database. So, it is likely that a particular type of raw material was consciously selected according to the type of object it was intended to produce.

In conclusion, chemical composition analyses of Bronze Age artefacts have an important role in archaeological research and are an essential part of the description of archaeological material. The identification of areas with occurrence of objects with the same trace element contents is extremely important when inferring the origins and development of metallurgy. Due to the uneven distribution of copper deposits across Europe, chemical composition analyses can also provide information on the exchange networks that existed during the Bronze Age (*Pernicka 2014*, 262).

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Štatistická analýza obsahu stopových prvkov v neolitických, eneolitických a bronzových kovových artefaktoch zo strednej a juhovýchodnej Európy

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Súhrn

Výskum chemického zloženia artefaktov z doby bronzovej, ktorý sa uskutočnil od začiatku minulého storočia, viedol k vytvoreniu celoeurópskej siete analýz. Ich štatistické spracovanie poskytuje prehľad o druhoch medi používaných v rôznych geografických oblastiach a v rôznych obdobiach. Umožňuje tiež vyvodiť závery o vývoji ranej metalurgie (*Krause 1998*, 164). Výsledkom štatistickej analýzy vykonanej v tomto príspevku bolo vyčlenenie 15 skupín (ako aj 17 podskupín skupiny 1 a 5 podskupín skupiny 2). Každá z nich sa vyznačuje špecifickým chemickým zložením, ktoré bolo ovplyvnené použitou surovinou, ako aj technologickým postupom vedúcim k finálnemu predmetu z nej vyrobenému (*Krause/Pernicka 1996*, 289). Výsledné skupiny sa výrazne líšia počtom predmetov, ktoré obsahujú. Zdá sa, že štyri najväčšie podskupiny odrážajú typy medi najcharakteristickejšie pre staršiu dobu bronzovú. Štatistická analýza odhalila aj prítomnosť viacerých menších skupín, ktoré reprezentujú menšie, lokálne „dielne“. Artefakty priradené ku každej skupine a podskupine boli analyzované aj z hľadiska ich geografického rozšírenia, datovania, kultúrnej príslušnosti a typologických kategórií. To umožnilo priradiť každú skupinu k jednému z hlavných metalurgických centier pôsobiacich v dobe bronzovej v skúmanej oblasti.

Ukázalo sa tiež, že určenie typov medi možno použiť ako ďalšie kritérium pri odvodzovaní metalurgie konkrétnych kultúr a vzťahov medzi nimi. Sledovanie príslušnosti jednotlivých skupín k materiálu archeologických kultúr poskytuje možnosť preukázať podobnosti v ich metalurgii. Tieto vzťahy sú zrejmé v priestore aj v čase. Chemické zloženie hotového predmetu je ovplyvnené surovinou a spôsobom jej spracovania, takže výskyt artefaktov patriacich tej istej skupine v materiáli rôznych archeologických taxonomických jednotiek môže naznačovať kontakty medzi nimi. Okrem toho možno v prípade oblasti Karpatskej kotliny preukázať aj zmeny v metalurgii v priebehu doby bronzovej. Z toho vyplýva, že analýzy stopových prvkov sú užitočné nielen pre staršiu dobu bronzovú. Viaceré skupiny preukázali aj spoločný výskyt ingotov z alpských lokalít s ozdobami a prvkami kroja z Karpatskej kotliny, ktoré pochádzajú z rovnakej chronologickej fázy. To môže naznačovať výmenu surovín alebo hotových predmetov medzi týmito regiónmi.

Okrem toho analýza výskytu jednotlivých kategórií artefaktov v rozlíšených skupinách ukázala, že sa v mnohých prípadoch líši od rozloženia v celej databáze. Je teda pravdepodobné, že konkrétny typ suroviny bol vedome vybraný podľa typu predmetu, ktorý bol určený na výrobu.

Záverom možno konštatovať, že analýzy chemického zloženia artefaktov z doby bronzovej majú dôležitú úlohu v archeologickom výskume a sú nevyhnutnou súčasťou opisu archeologického materiálu. Identifikácia oblastí s výskytom predmetov s rovnakým obsahom stopových prvkov je mimoriadne dôležitá pri odvodzovaní pôvodu a vývoja metalurgie. Vzhľadom na nerovnomerné rozloženie ložísk medi v Európe môžu analýzy chemického zloženia poskytnúť aj informácie o výmenných sieťach, ktoré existovali v dobe bronzovej (*Pernicka 2014*, 262).

Obr. 1. Počet artefaktov z teritórií súčasných štátov.
Obr. 2. Počet artefaktov v každej skupine a podskupine.
Obr. 3. Mapa rozmiestnenia objektov v skupine 1.1. Mierka: 1 : 10 000 000 (zdroj základnej mapy: QuickMapServices – ESRI World Topo).
Obr. 4. Mapa rozmiestnenia objektov v skupine 1.2. Mierka: 1 : 10 000 000 (zdroj základnej mapy: QuickMapServices – ESRI World Topo).
Obr. 5. Mapa rozmiestnenia objektov v skupine 2.1. Mierka: 1 : 10 000 000 (zdroj základnej mapy: QuickMapServices – ESRI World Topo).
Obr. 6. Mapa rozmiestnenia objektov v skupine 1.3. Mierka: 1 : 10 000 000 (zdroj základnej mapy: QuickMapServices – ESRI World Topo).

Obr. 7. Mapa rozmiestnenia objektov v skupine 1.9. Mierka: 1 : 10 000 000 (zdroj základnej mapy: QuickMapServices – ESRI World Topo).
Obr. 8. Mapa rozmiestnenia objektov v skupine 2.2. Mierka: 1 : 10 000 000 (zdroj základnej mapy: QuickMapServices – ESRI World Topo).
Obr. 9. Mapa rozmiestnenia objektov v skupine 2.4. Mierka: 1 : 10 000 000 (zdroj základnej mapy: QuickMapServices – ESRI World Topo).
Obr. 10. Mapa rozmiestnenia objektov v skupine 2.5. Mierka: 1 : 10 000 000 (zdroj základnej mapy: QuickMapServices – ESRI World Topo).
Obr. 11. Mapa rozmiestnenia objektov v skupinách 1.4, 1.8 a 1.10. Mierka: 1 : 10 000 000 (zdroj základnej mapy: QuickMapServices – ESRI World Topo).
Obr. 12. Mapa rozmiestnenia objektov v skupinách 1.11, 1.14 a 1.16. Mierka: 1 : 10 000 000 (zdroj základnej mapy: QuickMapServices – ESRI World Topo).
Obr. 13. Mapa rozmiestnenia objektov v skupinách 3, 5 a 12. Mierka: 1 : 10 000 000 (zdroj základnej mapy: QuickMapServices – ESRI World Topo).
Obr. 14. Mapa rozmiestnenia objektov v skupinách 13, 14 a 15. Mierka: 1 : 10 000 000 (zdroj základnej mapy: QuickMapServices – ESRI World Topo).
Obr. 15. Výsledky korešpondenčnej analýzy ilustrujúce vzťahy medzi archeologickými kultúrami a skupinami kovov.

Tabela 1. Charakteristika rozlíšených skupín kovov.
Tabela 2. Porovnanie skupín rozdelených podľa projektu SMAP a D. Liversagea so skupinami tejto štúdie.

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