RESEARCH ARTICLE – VÝZKUMNÝ ČLÁNEK

PIXE analysis of Late Bronze Age situlae from the eponymous Hajdúböszörmény-Csege-halom I hoard and Sényő-Dajkahegy, Northeastern Hungary

PIXE analýza pozdně bronzových situl z eponymního depotu Hajdúböszörmény-Csege-halom I a Sényő-Dajkahegy, severovýchodní Maďarsko

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The paper introduces the particle-induced X-ray emission analysis (PIXE) of two Hajdúböszörmény-type situlae from the eponymous Hajdúböszörmény I hoard (collection of the Hungarian National Museum, Budapest) and Sényő (collection of the Jósa András Museum, Nyíregyháza). Both situlae are representative types of the period between 1080 and 960 BC, Ha B1, or the 'Hajdúböszörmény hoard horizon' of the Hungarian Late Bronze Age. The obtained results are significant in that they are the very first to characterise the classic Hajdúböszörmény-type situla from their core distribution area, i.e., the region where this metal vessel type was presumably produced. The paper is focused on a description of the elemental composition of these tin bronze vessels, with particular attention on the grouping of their accompanying elements and the ratio of tin. The PIXE results suggest that a rather homogenous raw material was used to produce and repair these objects, which can be correlated with the CG16 Copper Group. The ratio of tin was relatively high, mostly around 9–10 wt%; low values were only identified on one of the repaired parts of the Sényő situla and a secondarily attached copper rivet.

PIXE – elemental composition – Late Bronze Age – Ha B1 period – Carpathian Basin – Hajdúböszörmény-type situla

Příspěvek představuje analýzu metodou částicově indukované rentgenové emise (PIXE) dvou situl typu Hajdúböszörmény ze stejnojmenného depotu Hajdúböszörmény I (sbírka Maďarského národního muzea, Budapešť) a z lokality Sényő (sbírka Muzea Jósy Andráse, Nyíregyháza). Obě situly reprezentují období 1080 až 960 př. n. l., tedy stupeň Ha B1, neboli tzv. horizont depotů Hajdúböszörmény pozdní doby bronzové v Maďarsku. Získané výsledky jsou významné tím, že vůbec poprvé charakterizují klasické situly typu Hajdúböszörmény z jádrové oblasti jejich rozšíření, tj. z oblasti, kde se tento typ kovových nádob pravděpodobně vyráběl. Příspěvek je zaměřen na charakteristiku prvkového složení těchto nádob z cínového bronzu, přičemž zvláštní pozornost je věnována seskupení doprovodných prvků a poměru cínu. Výsledky PIXE analýzy naznačují, že k výrobě a opravám těchto předmětů byla použita poměrně homogenní surovina, kterou lze korelovat se skupinou mědi CG16. Poměr cínu byl poměrně vysoký, většinou kolem 9–10 hm.%; nízké hodnoty byly zjištěny pouze na jedné z opravovaných částí situly ze Sényő a na druhotně připojeném měděném nýtu.

PIXE – prvkové složení – pozdní doba bronzová – stupeň Ha B1 – Karpatská kotlina – situla typu Hajdúböszörmény

Introduction

A distinct metallurgical tradition emerged within the distribution of the Gáva pottery style in the eastern part of the Carpathian Basin during the Ha B1 period dated between 1080

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and 960 BC. Among the items of the 'Hajdúböszörmény horizon', the most valuable were prestigious objects manufactured for the elite, such as elements of the lavish metal feasting sets, e.g. bronze situlae, cauldrons, cups, or strainers, and unique bronze weaponry, such as bell helmets and metal-hilted swords with a cup-shaped pommel (*Mozsolics 2000*, 23–25). The importance of these Late Bronze Age symbols of power can be best illustrated by their spatial distribution, particularly in the case of metal objects linked with banqueting. Different metal vessels bearing the distinctive Hajdúböszörmény style appeared not only in their core area in the Carpathian Basin, from where they originated, but also in distant parts of Europe, including southern Scandinavia, eastern France, and northern Italy. Between the end of the Late Bronze Age and the beginning of the Early Iron Age, they not only reached far but also tended to appear in lavish and unique ritual hoards or burial contexts, which usually contain numerous symbols of the male or female elite, such as metal vessels of local origin, gold, weaponry, and ostentatious ornaments (*Tarbay 2023*, 100–109).

The Hajdúböszörmény-type situlae are the most emblematic elements of the new elite set. These objects are likely to be preferred exchange items, diplomatic gifts that may have been desired by leaders of communities far from the Carpathian Basin. Situlae able to hold several litres of a liquid were probably used for serving beer (*Jósa 1902*, 278; *Szabó 2017*, 59–63; see herbal millet beer in the Kladina situla: *Jílek et al. 2022*) and thus played an essential role in community rituals and ceremonial banquets organised by the elite. Their symbolic importance is indicated by their decorated wall sheets embellished with sun and bird pair motifs, a mythological scene interpreted differently by various authors (see *Kaul 2005*, 135–148; *Wirth 2010*, 7–12; *Valent et al. 2021*).

Despite the large amount of archaeological data available on the typology, relative dating, and distribution of these Hajdúböszörmény-type situlae, only three studies have addressed their archaeometallurgical characterization. Concerning the Hajdúböszörmény--type situlae themselves, only the vessel from Unterglauheim has been analysed (*Jacob 1995*, tab. 23: 305, pl. 49: 305), accompanied by analyses of two comparable finds from Hajdúböszörmény II and Kladina that belongs, however, to different and rather specific subtypes of these situlae (Hajdúböszörmény- or Kurd-type – Obišovce variant: *Angyal et al. 2017*, 69–77, tab. 1; Kurd-type – Kladina variant: *Jílek et al. 2022*, 456). Meanwhile, the examples of the eponymous and most typical Hajdúböszörmény-type situlae remain unanalysed. Important questions that may help us refine the historical interpretation of these finds have still not been addressed at the required level.

Since Vere Gordon Childe's brief note in the 1926 issue of the journal *Man*, it has been hypothesised that Hajdúböszörmény-type situlae were made in a northeastern Carpathian workshop (*Childe 1926*, 132). Many researchers, including *Åberg* (*1935*, 86–87), *Lindgren* (*1938*, 78), *Patay* (*1990*, 42–43; *1996*, 408–409), *V. Szabó* and *Bálint* (*2017*, 14) hypothesised based purely on the assessment of the distribution of Hajdúböszörmény-type situlae that their origin may have been in the present-day territories of Hajdú-Bihar and Szabolcs-Szatmár-Bereg counties of Hungary. But what kind of workshop can we imagine? Could the seemingly very uniform vessels, deposited between the end of the Late Bronze Age and the beginning of the Early Iron Age, really have come exclusively from one Carpathian elite workshop, or was the production much more complex than that, with several intra- and extra-Carpathian workshops, imitations of the original vessels, and generations of highly skilled craftsmen existing during this time? How can we even characterise the Late Bronze Age Hajdúböszörmény-type situlae in terms of their elemental composition

No.	Site	Context	Collection	Inv. No.	Relative Dating	References
1	Hajdúböszörmény-Csege-halom (I)	hoard	Hungarian National Museum	1858.33.1	Ha B1 (ca. 1080–960 BC)	*Patay 1990*, 41, Pl. 30.57; *Tarbay 2022*, Fig. 10. No. 1
2	Sényő-Dajkahegy	individually deposited vessel	Jósa András Museum	86.31.1	Ha B1 (ca. 1080–960 BC)	*Patay 1990*, 41, Pl. 33.62

Tab. 1. The studied metal vessels.

if only single cases of special types (Hajdúböszörmény II) or vessels dated to the Early Iron Age and outside the Carpathian Basin (Kladina) have been studied so far? What relationship can we assume between the individual objects, and what technological and archaeological aspects are involved in the elemental composition of the finds?

To answer these questions, collaboration was started between three museums (Déri Museum, Debrecen; Hajdúsági Museum, Hajdúböszörmény; Hungarian National Museum, Budapest) and the HUN-REN Institute for Nuclear Research ('ATOMKI', Debrecen). In this paper, we present the first results of a particle-induced X-ray emission analysis (PIXE) examining the elemental composition of the eponymous situla from the first Hajdúböszörmény-Csege-halom hoard (Hajdú-Bihar County) held at the Hungarian National Museum and the Sényő-Dajkahegy (Szabolcs-Szatmár-Bereg County) situla in the collection of the Jósa András Museum (*Tab. 1*; *Fig. 1*). Both artefacts belong to the classical period of Hajdúböszörmény-style metal vessels, the Ha B1 phase (1080–960 BC), and were found in the core distribution area. These unique vessels have outstanding historical significance, and they can be considered extremely valuable museum artefacts. Therefore, methods using drilling sampling were not allowed; only the removal of the patina on the examined spots by a professional restorer was possible. Our research team applied external (in-air) PIXE analysis to reveal more information on the raw materials and production techniques of these important vessels. We also aimed to characterise the composition of the main matrix (Cu and Sn) and identify accompanying elements, e.g. As, Ag, Ni, Pb, Sb, and Zn.

Archaeological background

The situla from the first, eponymous Hajdúböszörmény-Csege-halom hoard (Hajdú-Bihar County, Hungary) is one of the most emblematic objects from the Hungarian Late Bronze Age. It comes from a lavish assemblage that contained two bell helmets, 30 flange-hilted and metal-hilted swords, and a banquet set of two cauldrons, a cup, a situla, and four vessel handles (*Patay 1990*, 21–22, 41, 61, pl. 4: 7, pl. 5: 8, pl. 30: 57–59, pl. 41: 94). These finds were discussed in numerous studies throughout the history of research involving the consideration of the entire array of objects, or the analysis of individual types (review in *Tarbay 2023*). The artefacts in the Hajdúböszörmény hoard were deposited in a symbolical manner in three layers in the surroundings of the prehistoric Csege-halom kurgan (*Mozsolics 1984*, 81–93). According to recent field research, this area was an uninhabited zone in the Late Bronze Age and part of a potential mythological-sacred landscape that might have been important for local communities and their elites (*V. Szabó – Bálint 2017*, 9–44).

Fig. 1. A – The situla from the Hajdúböszörmény-Csege halom I hoard (Hungarian National Museum, Budapest; drawing by Anna Mária Tarbay); B – The situla from Sényő-Dajkahegy (after *Patay 1969*, Pl. 47.2; *Patay 1990*, Pl. 30.57, Pl. 33.62; *Tarbay 2023*, Fig. 10; drawing by Panna Tolvaj and Tibor Szekeres).

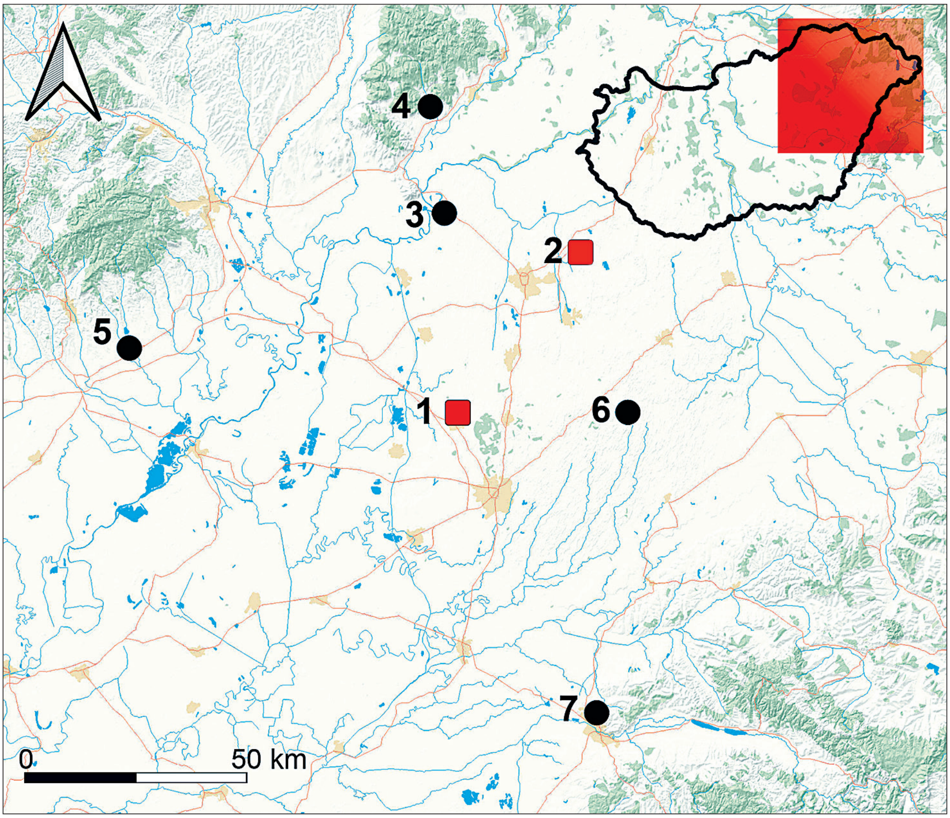

Fig. 2. Location of Hajdúböszörmény-Csege-halom, Sényő-Dajkahegy, and other finds of the Hajdúböszörmény-type situlae in northeastern Hungary and West Romania: 1 – Hajdúböszörmény; 2 – Sényő; 3 – Tiszanagyfalu; 4 – Tolcsva; 5 – Mezőkövesd; 6 – Nyírlugos; 7 – Oradea (after *Tarbay 2023*).

The content of this hoard is usually associated with the northeast Carpathian elites and their armed military escorts, who deposited these unique artefacts on a historically significant occasion.

The Sényő-Dajkahegy situla (Szabolcs-Szatmár-Bereg County, Hungary) was found in 1900. The only information known about the object's discovery is that it originates from the field of János Molnár and was found during grape rotation. According to András Jósa, no additional finds were made on the site when he examined the find spot by excavating an area of 15 × 15 m (*Jósa 1902*, 277–278, pl. 3). Since then, the situla was studied by several scholars, who address its typological characteristics, a group of parallels, and dating (*von Merhart 1952*, 70, pl. 20: 8; *Patay 1969*, 175, no. 7, pl. 47: 2; *Patay 1990*, 41, pl. 33: 62; *Jósa – Kemenczei 1965*, 26, pl. 64; *Mozsolics 2000*, 73–74, pl. 90: 1). It cannot be ruled out that the situla was deposited as a single-object hoard. Archaeological evidence for such a scenario in the Carpathian Basin comes from the excavated contexts of the Gáva pottery-style settlement of Pócspetri (*Kalli 2017*, 175–192). As Pál Patay has already pointed out, the bottom part of the Sényő situla was repaired, suggesting a long period of use prior to deposition (*Patay 1990*, 11).

Both metal vessels are representatives of the 'Hajdúböszörmény-type' situla. Its core distribution area is located in the Northeast Carpathian Basin, in areas that comprise the Hungarian counties of Szabolcs-Szatmár-Bereg and Hajdú-Bihar (*Fig. 2*). They have also appeared in several parts of Europe, probably because of the supra-regional network in which the local elite in the Northeast Carpathian Basin played an important role. Their westernmost appearance is in eastern France. The northernmost extent of their distribution is Denmark. A handful of Hajdúböszörmény metal vessels were discovered in the territory of Germany, Switzerland, Poland, Italy, Slovenia, Slovakia, West Ukraine, the Northern Balkans, and Transdanubia (distribution reviewed by *Tarbay 2023*, 100–108, fig. 13). While most of these metal vessels were produced and deposited during the Ha B1 period, there are several examples of later Ha B2–Ha B3 depositions (960–800/780 BC), suggesting that these situlae were produced and circulated until the beginning of the Early Iron Age (e.g., Ochtendung, Nedilys'ka, Rivoli Veronese, Saint-Romain-de-Jalionas; *Tarbay 2019a*, 313–359).

Situlae were apparently composite objects consisting of sheet parts, cast parts and cast/hammered parts (handles), which were assembled by conical-shaped rivets and flat-hammered pegs. Recently, the production technological properties of the Hajdúböszörmény situla from hoard I have been comprehensively discussed in relation to the manufacturing of this type by *Szabó* (*2017*, 45–68). The sheet metal parts of the vessel were made out of a single as-cast disc (situla bottom) or more as-cast plates (wall sheets) by cold hammering and probably annealing. The manufacturing technology of situlae and comparable metal vessels was thoroughly discussed based on archaeological experiments (*Pietzsch 1968*, 237–283), systematic macroscopic observations (*Patay 1990*, 7–15), and advanced analytical techniques (*Pernot 2015*, 65–93).

Method

Sample preparation

Prior to the PIXE analysis, the patina of the situla from Hajdúböszörmény was removed in 1 cm^2 areas to avoid distorting the elemental composition. The cleaned spots were re-patinated and completely restored after analysis in the laboratory of the Works of Art Conservation and Restoration Department of the Hungarian National Museum (*Fig. 3*; *Fig. 4*).

PIXE analysis

The particle-induced X-ray emission analysis is a non-destructive and non-invasive multi-analytical method and is therefore widely used in heritage science (*Chiari et al. 2021*). PIXE analysis is considered a surface-sensitive technique that does not require prior sample preparation (except in special cases such as corrosion layer) and can be applied to a wide range of object sizes. As the PIXE analysis is basically carried out in very small areas and is inherently sensitive to the surface layers of thickness up to tens of microns, it is worth performing multiple measurements on the artefact. The real advantage of PIXE is that it can be used in parallel with a number of other ion beam analysis (IBA) techniques (PIGE, RBS, NRA), allowing a full range of elemental analysis to be carried out. Quantitative analysis is straightforward, based on physical parameters, and does not require standards. The main limiting factor is the need for a complex technical background including a particle accelerator.

The quantitative elemental analysis of different parts of situlae (a total of 26 measurements) was performed by in-air micro-PIXE at the Oxford-type microprobe facility (*Rajta et al. 1996*, 148–153) at the HUN-REN Institute for Nuclear Research (ATOMKI) in Debrecen, Hungary (*Török et al. 2015*, 167–171). In our external beam set-up, the beam was delivered to the air through an ultrafine (200nm) Si_3N_4 window. The characteristic X-rays were collected by two detectors located on either side at 45° from the object surface. A 25 mm^2 SDD X-ray detector with 8 µm Be window was used to measure low Z elements. This detector was mounted with a permanent magnet (1 T magnetic field) which protected the detector from scattered protons. A 50 mm^2 Si(Li) detector, with an additional 8 mm Co and 375 mm kapton filter at the front to attenuate the copper contribution to the detector energy spectrum, detected medium and high Z elements. The proton beam of 3.2 MeV energy focused down to 60 × 60 µm with a current of 200–400 pA was used to irradiate the artefacts. Elemental distribution maps and summed-up X-ray spectra on 1 × 1 mm areas were recorded. In the case of inhomogeneity, the 'selected raster' mode was applied. The accumulated beam charge was monitored by the in-vacuum chopper (*Barta – Uzonyi 2000*, 339–343) and for each measurement, the accumulated charge was 0.1-0.15 µC.

The PIXE spectra were evaluated with the GUPIXWIN software package (*Campbell et al. 2010*, 3356–3363). The analytical procedure was checked with standard reference materials such as ERM-EB375 and CTIF B10 bronze standard and a series of mono-elemental thick targets.

Results

Material composition

The analysed objects can be classified as tin bronzes, featuring percentages of 4.31 wt% up to 16.5 wt% Sn ratios (*Tab. 2*). Depending on the cooling condition of the casting process in the mould, different metallic phases may be formed, increasing the appearance of dendritic structures. If the alloy is too rich in Sn, the formation of two different phases (alpha and delta) cannot be avoided, which resulted in the maximum solubility of Sn in Cu. Thus, the Sn percentage in the solid state is about 14–15%. Additionally, eutectic alloys are always found when a higher percentage of Sn occurs (*Tylecote 1990*, 89–97).

To facilitate the interpretation of the results, the measurements were classified according to the scheme of the Oxford Copper Groups, which was later applied in the EU-financed FLAME project (*Pollard et al. 2018*, 5–10). This classifies the bronze artefact according to four trace elements: arsenic, antimony, silver, and nickel. The presence or absence of these elements is most likely to reveal geographical, typological, technological, functional, or chronological patterns. All possible combinations of these elements give 16 possible copper groups (*Pollard et al. 2018*, 85–114). The cut-off value was 0.1% for As and Sb, 0.08% for Ni, and 0.07% for Ag. The elemental composition results for each vessel are presented in more detail below.

		Samples	wt%							ppm			
			Cu	Sn	Ni	As	Sb	Ag	Pb	Fe	Co	Zn	Bi
Hajdúböszörmény I	H1	wall sheet	88.6	10.06	0.11	0.16	0.26	0.08	0.60	510	480	870	
	H2	wall sheet	89.2	9.54	0.12	0.16	0.20	0.09	0.49	390	480	890	350
	H3	handle	89.0	9.88	0.11	0.14	0.18	0.09	0.40	320	430	640	320
	H4	conical rivet	89.6	9.19	0.09	0.16	0.17	0.09	0.57	530	480	600	
	H5	conical rivet	89.1	9.57	0.09	0.16	0.15	0.09	0.61	1410	660	450	200
	H6	conical rivet	89.3	9.51	0.09	0.16	0.21	0.10	0.52	460	520	280	160
	H7	flat rivet	89.4	9.36	0.12	0.16	0.22	0.09	0.48	660	490	700	160
	H8	flat rivet	89.4	9.36	0.12	0.16	0.24	0.10	0.41	570	520	660	210
	H9	base sheet	88.6	10.08	0.11	0.15	0.28	0.10	0.43	330	530	1110	190
	H10	flat rivet bottom	88.5	10.21	0.10	0.15	0.23	0.09	0.46	650	550	900	180
	H11	flat rivet bottom	88.4	10.31	0.11	0.15	0.21	0.11	0.45	660	540	680	290
	H12	flat rivet bottom	88.4	10.33	0.11	0.12	0.25	0.09	0.45	690	580	700	250
	H13	flat rivet bottom	88.9	9.85	0.12	0.16	0.25	0.09	0.43	700	590	780	310
Sényő	S1	base sheet	87.2	10.48	0.47	0.24	0.91	0.14	0.41	510	830		
	S2	bottom (n=2)	81.4	16.05	0.52	0.58	0.92	0.13	0.21	770	380	500	
	S3	wall sheet flat rivet	85.2	12.88	0.21	0.22	0.64	0.15	0.52	1470	340		
	S4	flat rivet	88.7	9.12	0.47	0.26	0.79	0.11	0.41	660	850		
	S5	conical rivet	99.9							90	70	500	
Sényő repair	S6	repair on the wall sheet	92.2	4.31	0.37	1.21	1.04	0.03	0.18	4960	1200		
	S7	repair bottom	86.0	11.93	0.26	0.20	0.32	0.20	0.88	310	650	830	
	S8	repair bottom	83.8	13.97	0.26	0.22	0.40	0.22	0.94	200	660	970	
	S9	repair rivet bottom	88.3	9.59	0.46	0.26	0.64	0.13	0.42	610	820	780	
	S10	bottom (sec. repair)	84.5	13.83	0.44	0.36	0.58	0.08	0.15	100	270		
	S11	repair flat rivet bottom	88.2	9.68	0.45	0.28	0.67	0.14	0.46	570	780		
	S12	repair bottom rivet	87.5	10.02	0.45	0.36	0.75	0.17	0.57	640	810		
	S13	repair conical rivet	99.7				0.28			590			
		LOD (ppm)	50	130	40	100	110	60	510	50	30	250	120

Tab. 2. List of results for PIXE measurements carried out on Late Bronze Age situlae, including sample code (H1–H13, S1–S13) and elemental compositions in wt% (Cu, Sn, Ni, As, Sb, Ag) as well as in ppm (Fe, Co, Zn, Bi). The uncertainty of the measurement is 1–3% for the main components (Cu, Sn) and 15–20% for the trace elements (Ni, As, Ag, Pb, Sb). The limit of detection (LOD) values is in ppm.

Hajdúböszörmény I situla

Different parts of the fragmented situla from the Hajdúböszörmény I hoard were studied. These are in succession: two spots on the wall sheet (H1, H2), one on the handle (H3), three spots on the conical rivets (H4, H5, H6), two spots on the flat rivets (H7, H8), one spot on the bottom (H9) and four spots on the bottom's flat rivets (H10, H11, H12, H13) (*Fig. 3*). We observed no significant difference between the alloying ratios at the examined metal vessel parts; this eponymous artefact revealed an Sn ratio between 9.19 wt% and 10.82 wt%. Similar accompanying elements were indicated by the PIXE analysis, such as Mn, Fe, Co, Ni, Zn, As, Ag, Sb, Pb, and Bi. Except for Bi, these were present in all parts of the vessel in different ratios. The Oxford Copper Group classification of the vessel

Fig. 3. Measured spots on the situla from Hajdúböszörmény-Csege-halom I hoard (Hungarian National Museum).

parts showed a homogenous result. All the studied parts belong to CG16, which suggests that they were made of the same material. The PIXE results on the different parts of this vessel also seem to be quite similar to each other with respect to accompanying elements (Pb, Zn, Fe, Ni, Ag, Sb, As, Bi, Co) and the percentage of Sn in the wall sheets and handles (8.14–11.82 wt%) (*Jacob 1995*, tab. 23: 305, pl. 49: 305).

Sényő situla

The PIXE results of the primary part of the Sényő situla are very similar to those obtained from the Hajdúböszörmény I vessel. From a technological perspective, this vessel has at least two main biographical phases of production, which emerged at different times.

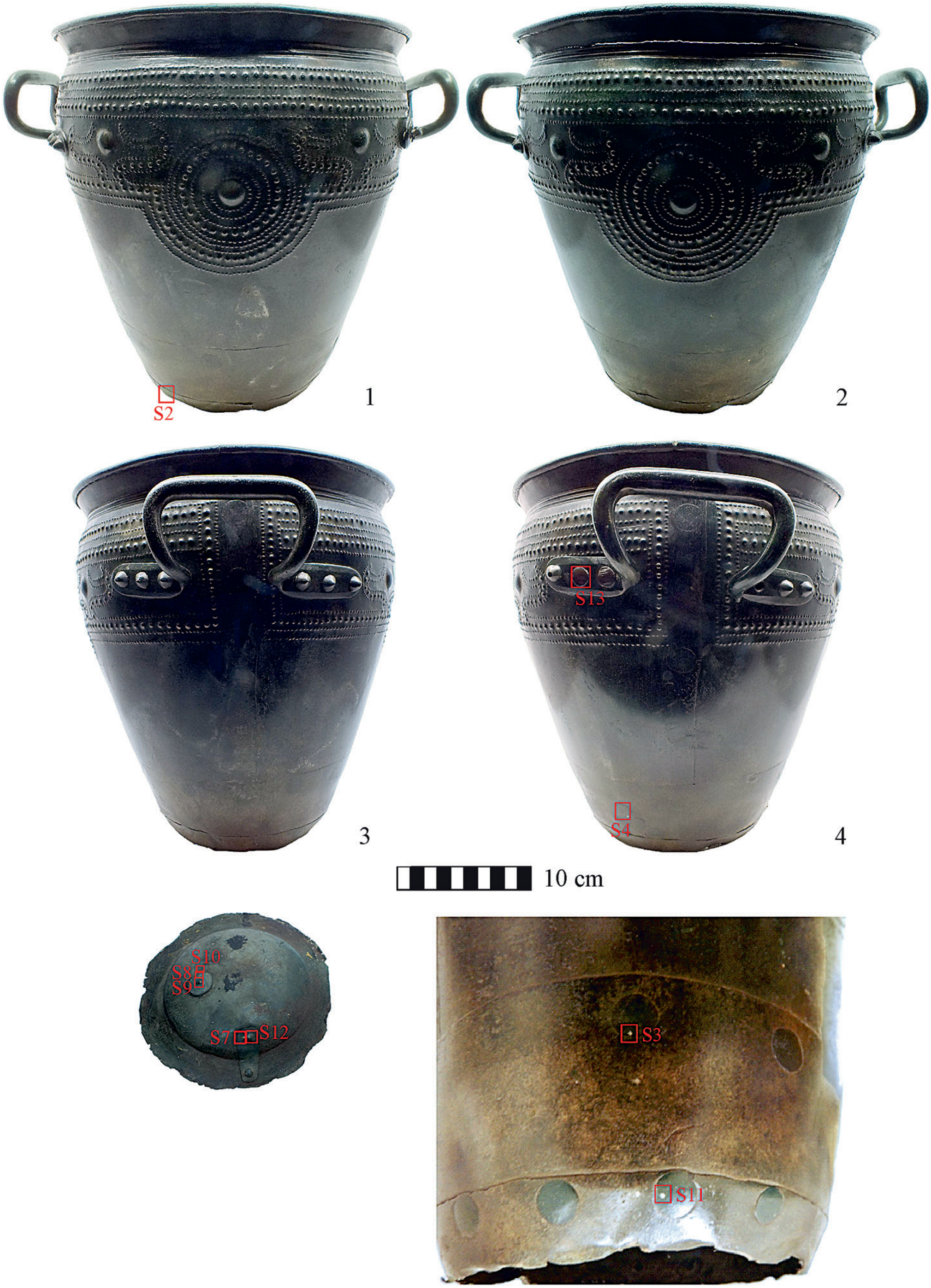

Fig. 4. Measured spots on the situla from Sényő-Dajkahegy (S1, S5–6 were unidentifiable) (Jósa András Museum).

One is the time of production, and the other is probably linked to repair after a long period of use. The Sn ratio ranges between 4.31 wt% and 16.05 wt%, which are, however, two extreme values obtained at specific parts of the vessel. The lower value was generated by a flat rivet, the higher value by the base sheet. The Sn ratio ranges between 9.12 and 13.97 wt% in other parts. We do not see any difference between the Sn ratio of the elements made during the first production phase (*Tab. 2*: S1–S5) and the repaired parts (*Tab. 2*: S6–S13; *Fig. 4*). Two conical rivets are made of copper with different combinations of a few low-level accompanying elements. They fall into unique CG groups, such as CG1 (*Tab. 2*: S5) and CG3 (*Tab. 2*: S13). The accompanying elements observed in the different parts are Mn, Fe, Co, Ni, Zn, As, Ag, Sb, and Pb. The Oxford Copper Group classification revealed that most of the base and repaired parts are made of CG16 raw material. At the same time, one repaired flat rivet falls into the group of CG14 (*Tab. 2*: S6).

Discussion

The PIXE measurement series of the two situlae from Hajdúböszörmény I and Sényő provided new results on the elemental composition of these metal vessels from the classic Ha B1 period and the core area of their distribution. Both objects are tin bronzes with a relatively low impurity level, with a few exceptions below 1 wt%, which seem to be unique compared to the generally high Sb and Pb content of ingots (*Czajlik 2012*, 94–96) and finished products (*Liversage – Pernicka 2002*, 417–431, tab. 2) circulated in this period.

Based on the tradition in the shape of the vessel parts, the way they were assembled, and their stylistic features, one would expect a uniform pattern of raw material use and a standard ratio of Sn in different parts of the objects. In this sense, the situla from the Hajdúböszörmény I hoard is the most emblematic example. All its measured sheet metal parts and rivets revealed the use of the same copper raw material belonging to CG16 and a similar ratio of Sn between 9 and 10 wt%. This reflects the possibility that the metalworkers who cast and formed these vessel parts had access to the same raw material and relatively abundant Sn, with which they alloyed in approximately the same ratio. Results on most measured parts of the Sényő situla fall into CG16, the same copper group as the Hajdúböszörmény situla. The CG classification also showed that most repaired parts belong to the same material group as the originals. This may imply that the object was brought back to the same workshop at one point in its life for repair, or the craftsmen who carried out this work used the original damaged sheet to repair the vessel. Different results from CG16 can be seen in three cases – two conical rivets (CG1, CG3), which are technically copper pegs, and one wall repair sheet containing a higher amount of copper. The above-described conclusions on the Sényő situla can be refined by the impurities (*Fig. 5*). Thus, while the Hajdúböszörmény I measurements form a homogenous group, the Sényő measurements are less coherent and do not reflect a homogenous use of raw materials. Despite this small variability, our results suggest that the workshop in which these situlae were made probably relied on the same raw material, whose origin should be verified by lead isotope analysis in the future.

The ratio of Sn was an attribute that a metalworker could influence in a direct way. Although some new trends may unfold in the future, in the current series, we cannot

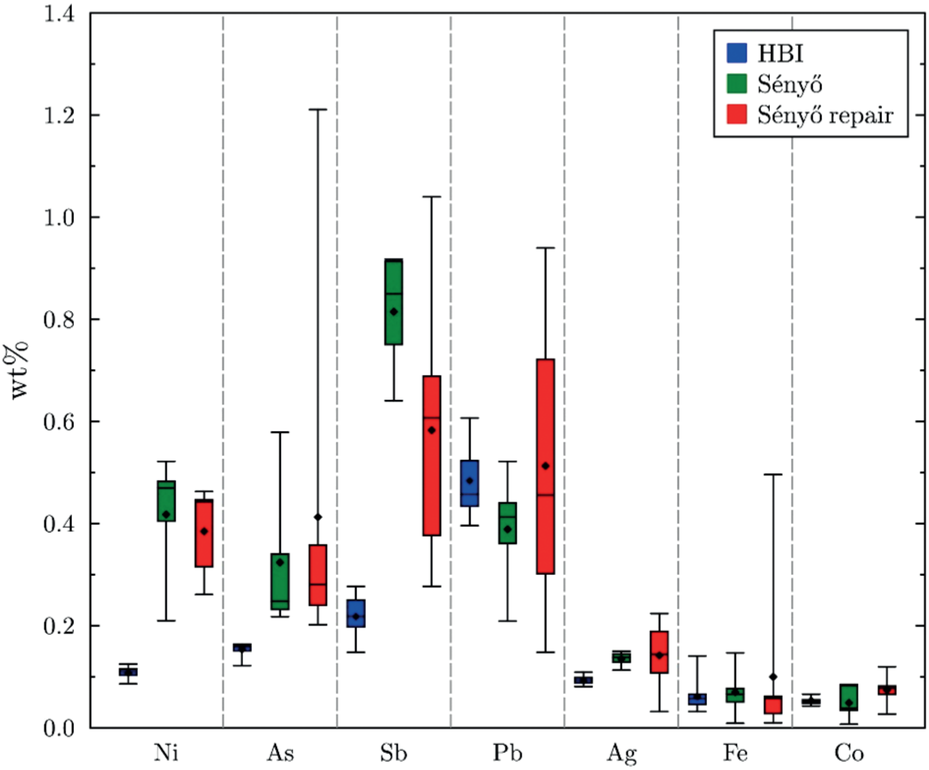

Fig. 5. Box plot showing the distribution of Ni, As, Sb, Ag, Fe, Co and Pb weight content of the situlae.

observe intentionality in the alloy ratio of the different situla parts. It seems that for wall sheets, a value around 9–10 wt% was preferred, but higher values in the case of the Sényő situla original and repaired parts are also observable. It should be noted that a higher Sn (ca. 12–17 wt%) was also identified in the previously measured situla from the Hajdúböszörmény II hoard (*Angyal et al. 2017*, 77). These data are generally higher than the so-far studied Ha B1 north-east Carpathian bronzes (e.g., axes, sickles, swords) from the Nagykálló (*Mozsolics – Hegedűs 1963*, 259–262), Terpes/Szajla (*Tarbay 2019b*, 277, fig. 2), and a large series published by *Liversage* and *Pernicka* (*2002*, tab. 2). It suggests that workshops making prestigious metal vessels had better access to tin raw materials that were not available locally. Conical and flat rivets also have a similar Sn ratio, except for the pure Cu examples. The application of copper rivets does not signify a lack of access to Sn, as it is a technologically logical choice due to its easier shaping during the assembling process. As an analogue, the rivet of the Hart an der Alz Kurd-type situla should be mentioned, which contained only 0.61 wt% Sn with 98.75 wt% Cu (*Jacob 1995*, tab. 23: 305, pl. 49: 305). Since the rivets of this vessel are hammered completely flat, the choice of malleable material – a copper peg – was preferable during the production phase. It is also observed that some rivets of the Unterglauheim situlae contain a low amount of Sn between 5.23 and 7.52 wt%; unfortunately, it is not clarified from which rivet type these values were obtained (*Jacob 1995*, tab. 23: 305, pl. 49: 305).

Conclusion

The paper introduced the PIXE elemental composition analysis of two Hajdúböszörmény-type situlae. This small series is unique since it is the first time that these emblematic vessels coming from the presumed workshop centre in the north-eastern part of Hungary have been analysed. Based on the PIXE results, it appears that these tin-bronze vessels were made of a relatively homogenous composition of materials, especially the eponymous situla of the Hajdúböszörmény I hoard. Sheet metal and handle parts, as well as most of their rivets and flat-hammered pegs, have a 9–10 wt% ratio of tin. This tin content is higher than the relatively low tin and higher lead and antimony (above 2 wt%) values observed in Ha A2/Ha B1 and Ha B1 bronze artefacts from Hungary. This may mean that the presumed northeastern Hungarian situla workshop or workshops that produced these two vessels had good access to tin from long distances. They did not experiment with the addition of other alloying elements, even during the period of Ha B1 (see *Liversage – Pernicka 2002*; *Czajlik 2012*, 94–98, 103). Based on their grouping according to the Oxford Copper Group scheme, the raw material most similar to CG16 appears to be common for these vessels. This material group also appears in the Sényő situla; however, here, vessel parts belonging to different CG groups (CG1, CG3, CG14) can also be observed in the case of two rivets and a repaired part. Of particular interest are the almost completely pure Cu content of conical rivets (S5, S13) and the high Cu content repair piece (S6), which may be related to technical or technological issues (easier crafting). In the case of the Sényő situla, different raw materials may indicate repairs made at consecutive times and perhaps by different bronzesmiths. The fact that some of the repairs have the same CG group as the original parts (CG16) in the Sényő situla indicates different biographical scenarios. The prestigious metal vessel could have been brought back to the same workshop using similar raw materials, or the craftsmen could have used the original damaged sheets to make these repairs to the vessel. It is a biographical event whose exact course in the Bronze Age cannot be determined, but all of this suggests a long period of use, possibly for profane and ritual purposes on feasts, and the high value of the Sényő bronze situla.

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