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TARTALOM – INDEX

FROM LOCAL TO MICROREGIONAL AND BEYOND: SPATIAL STRUCTURES IN AND AROUND THE EARLY MEDIEVAL CARPATHIAN BASIN

Papers submitted to the session organised at the 28th EAA Annual Meeting, Budapest, Hungary, 31 August–3 September 2022

Edited by Ivan Bugarski – Erwin Gáll – Gergely Szenthe

RECENSIONES

X-RAY AND NEUTRON RADIOGRAPHY OF LATE BRONZE AGE WEAPONS AND ARMOUR FROM WESTERN HUNGARY

János Gábor Tarbay[1] – Zoltán Kis[2] – Boglárka Maróti[3]

The study introduces 2D images of X-ray and neutron radiography analyses carried out on Late Bronze Age Transdanubian combat weapons, a potential shield fragment, armour, and helmet fragments. The results were provided in the framework of the 'Technology, Use and Manipulation of Weapons from Late Bronze Age Transdanubia' research programme (2020–2024). The studied finds originate from different sites and contexts: a rapier (Keszthely), swords (Nagydém A-B, Tab), spearheads (Bonyhád area, Budakeszi A-B, Celldömölk Ság Hill II, Keszőhidegkút, Pölöske), an arrowhead (Pázmándfalu III), a 'helmet' (Keszőhidegkút), a cuirass (Pázmándfalu I/II), a 'cuirass/helmet' (Szentgáloskér), a 'shield' (Szentgáloskér), and a dagger (Tahitótfalu). Using methods less applied in Bronze Age research in Hungary, we provided new results on the casting technology of these objects, casting defects, and production techniques and repairs of sheet metal objects.

A tanulmány dunántúli, késő bronzkori támadófegyverek, lehetséges pajzstöredék, páncél és sisaktöredékek röntgen- és neutronradiográfia módszerével előállított 2D felvételek eredményeit teszi közzé. A vizsgálatok elvégzésére a „Késő bronzkori dunántúli fegyverek technológiája, használata és manipulációja" (2020–2024) c. kutatási program keretében került sor. A tanulmányozott leletek köre különböző kontextusokból és lelőhelyekről származik: tőrkard (Keszthely), kardok (Nagydém A-B, Tab), lándzsahegyek (Bonyhád vidéke, Budakeszi A-B, Celldömölk-Ság-hegy II, Keszőhidegkút, Pölöske), nyílhegy (Pázmándfalu III), sisak (Keszőhidegkút), vért (Pázmándfalu I/II), „vért/sisak" (Szentgáloskér), „pajzs" (Szentgáloskér), tőr (Tahitótfalu). A magyarországi bronzkori kutatásban kevésbé alkalmazott módszerek segítségével a szóban forgó tárgyak öntéstechnológiájáról, öntvényhibáiról, továbbá a lemeztárgyak megmunkálásáról és javításáról szolgáltattunk új eredményeket.

Keywords: *X-ray radiography, neutron radiography, Late Bronze Age, weapons, Western Hungary*

Kulcsszavak: *röntgenradiográfia, neutronradiográfia, késő bronzkor, fegyverek, Nyugat-Magyarország*

Introduction

While radiographic techniques are widely used to study Bronze Age metal finds, a relatively few bronzes from Hungary, such as swords, spearheads, knives, helmets, an axe, a flesh hook, and a mega spiral, have been subjected to similar analysis or advanced methods, e.g., neutron tomography (see Driehaus 1961, 30, Pl. 13. 3–5; Born, Hansen 2001, 186–205, Figs. 143, 145, 152, 154; Hellebrandt 2011, 133, Fig. 13; Dani et al. 2013; Mödlinger et al. 2014; Kiss et al. 2015; Tarbay 2015; Tarbay 2018, Pl. 319; Tarbay et al. 2021; Tarbay et al. 2023). X-ray and neutron radiography (henceforth NR) can provide 2D images of the object's inner structure; thus, they provide a great benefit for use-wear analysis of ancient bronze objects and are effective in further characterising the bronzes' production technological traces, particularly casting traces and defects that are difficult to evaluate on the surface (Dolfini, Crellin

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2016). These analytical methods are available in Hungary in the laboratory of the Nuclear Analysis and Radiography Department of the HUN-REN Centre for Energy Research (Szabó et al. 2019, 3, Tab. 1). Furthermore, X-ray and XCT analysis with comparable results is widely available in private and public medical institutions throughout the country, and some museums can also perform X-ray analysis with their own instruments. For these reasons, it is surprising that the use of these methods has not been more widely spread in Hungary for the examination of Bronze Age metal objects.

In this paper, we aim to change this situation by publishing a small series of X-ray and NR results on Late Bronze Age weapons from the territory of Western Hungary. These artefacts were analysed in the laboratory of the Nuclear Analysis and Radiography Department of the HUN-REN Centre for Energy Research in the framework of the 'Technology, Use and Manipulation of Weapons from Late Bronze Age Transdanubia' (2020–2024) research programme of the Hungarian National Museum. The new series includes different types of weapons, mainly spearheads and swords, but also a rapier, an arrowhead, a dagger, sheet metal armour and a potential shield and armour parts.

The selected artefacts can be dated between the Br B2/C1(C2) and the Ha B2 period of the Hungarian Late Bronze Age. The oldest find is the eponymous Sauerbrunn-Boiu-Keszthely type rapier from a tumulus excavated in the Legelő-dűlő at Keszthely (Neumann 2009, List 1. 31–43; Godiš, Styk 2019) (*Figs. 1–2*). In chronological order, this remarkable find is followed by a 'Peschiera style' (Merlara type) dagger from the shore of the River Danube at Tahitótfalu-Szentendre Island, dated around the Br D–Ha A1 based on its fine parallels (Tarbay 2020) (*Fig. 3. 17*). The series includes several emblematic finds from the Transdanubian Kurd type hoards (Ha A1) (Mozsolics 1985), such as a spearhead with a long, straight sword-like blade from the Bonyhád area hoard that belongs to a special combat weapon group, namely spearheads used with slashing movements (Schauer 1979; Mozsolics 1985, 102–104, Pl. 36. 2) (*Fig. 4. 1*) and the spearhead with stepped blade from Pölöske, which belongs to a widely distributed weapon type in Central Europe, the parallels of which are distributed between the Carpathian Basin and the Alps (Mozsolics 1985, 177–178, Pl. 124. 4; Hansen 1994, 66–67, Fig. 35; Bader 2015, 382–383) (*Fig. 4. 13*). The bent and broken ribbed sword from Tab finds its parallels in Transdanubia (Kemenczei 1988, 61, Pl. 36. 328; Makkay 2006, Pl. 10. 52), Transylvania (Bader 1991, Pl. 25. 253, Pl. 26. 264), the northern Balkans (Harding 1995, Pl. 9. 58, Pl. 18. 139), and Austria (Schauer 1971, Pl. 91. 596).

Fig. 1. The rapier from Keszthely and its X-ray image (Photo: József Rosta; Appendix 9)
1. kép. A keszthelyi tőrkard és röntgenfelvétele (Fotó: Rosta József; Appendix 9)

We also had the chance to include a few newly found objects from the Pázmándfalu funerary hoards, owing to the generosity of the leader of the excavation and first publisher of the finds, Gábor

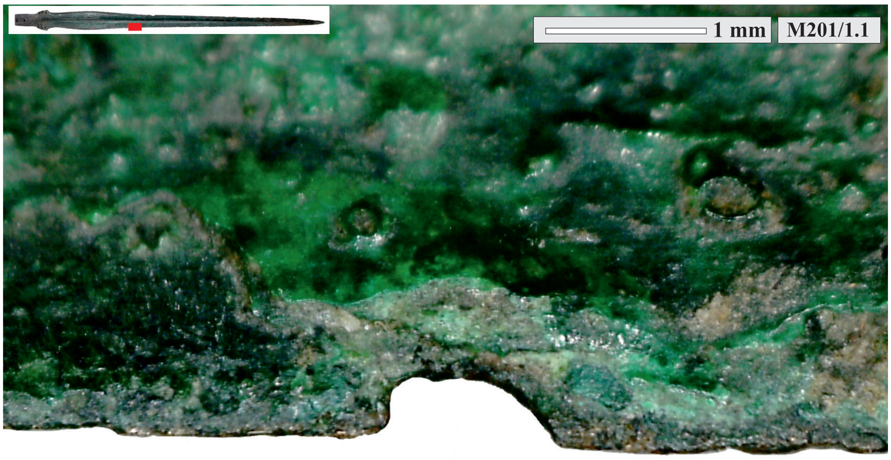

Fig. 2. U-shaped notch on the edge of the Keszthely rapier (Appendix 9)
2. kép. U alakú csorbulásnyom a keszthelyi tőrkard élén (Appendix 9)

V. Szabó. The first object to be mentioned is a socketed, barbed arrowhead from Pázmándfalu Hoard III, which belongs to a widely distributed hunting and combat weapon group throughout the area occupied by the Urnfield culture and beyond (Clausing 2005, 63–65; V. Szabó 2019, 62–64, Fig. 48) (*Fig. 4. 12*). An exceptional find in the studied series is the Carpathian-style cuirass side fragment from Pázmándfalu Hoard I/II. It consists of the back and front plates of the armour attached by a serrated sheet metal band and two ribbed rectangular-shaped cast and hammered rivets (*Fig. 3. 11*). The best analogue of such armour can be found in Čaka, Čierna nad Tisou, Šarišské Michaľany, Ivančice IV, Farkasgyepű and Saint-Germain-du-Plain (Reinach 1921, 234, Fig. 129. 7257; F. Petres, Jankovits 2014, 57; Mödlinger 2017, 182–186, 212; Salaš 2018, 59–60, Fig. 22, Pl. 4. 96, 96a; Salaš, Msallamová 2019, 29–32, Fig. 2. 1A; V. Szabó 2019, 60–71). Smaller, similar-shaped rivets were excavated from the 6th burial with weapons from Balatonfűzfő, which may also be part of similar sheet metal armour (Ilon 2015, Fig. 9. 23–24, 26–27).

There is a ribbed sheet metal fragment from Szentgáloskér, a potential shield fragment, according to Mozsolics (Mozsolics 1985, 28, 194–195, Pl. 115. 7), which could be part of a Lommelev-Nyírtura type shield, whose group of parallels is well-known in Hungary, northern Croatia, and Denmark (Patay 1968; Uckelmann 2012, 14–21) (*Fig. 3. 15*). Another curious sheet metal fragment from the same hoard was included in the series. This find was interpreted as a metal vessel part, part of a metal cuirass, or a bronze collar of an organic cuirass (Hampel 1886, Pl. 118. 27–28; Paulík 1970, 50, Fig. 7. A1; Schauer 1978, 124–125; Bouzek 1981, 26; Bouzek 1985, 110; F. Petres 1982, Fig. 11b; Schauer 1982, Fig. 1. 25; Mozsolics 1985, 26; Kytlicová 1988, 310–311, Fig. 5; Jankovits 1992, 71; F. Petres, Jankovits 2014, 60, Fig. 15. 1) (*Fig. 6*). Recently, Mödlinger rejected this idea based on technological arguments (Mödlinger 2017, 193), as did Jankovits, who earlier argued for its identification as an armour part (Jankovits 2016, 66). Based on their sides, it is likely that small, perforated sheet metal rim fragments with ribs from the same hoard (*Fig. 6. 14/7–14/10*) also belong to this object, suggesting that this sheet was a lower part of the sheet metal product. Although we still do not have enough evidence to identify this object typologically, we think it is likely that it could have been part of some kind of armour, of which the helmet or, more likely, cuirass seems most likely, as such dense rivet holes are more characteristic of Carpathian cuirasses (Mödlinger 2017, Pl. 25. 128).

The youngest objects selected for analysis were deposited between the Ha B1 and Ha B2 periods. Two objects were selected from the Keszőhidegkút hoard. One of them is a sheet metal fragment with perforated edges, a potential conical-shaped or bell helmet, according to Mozsolics (Mozsolics 1985, 24–25; Mödlinger 2017, 33–42; Tarbay 2021, 113, Fig. 9. 29) (*Fig. 3. 8*). The other is a blade fragment of a large spearhead with a willow-shaped blade and outline grooves (see Tarbay 2023, 482–485, Fig. 7) (*Fig. 4. 7*). The content of the Keszőhidegkút hoard represents multiple periods, which most likely closed around the Ha B1 (Tarbay 2021, 99–117, Fig. 8. 7). The two objects examined are more likely to belong to the Ha A1 group. Four spearheads with leaf-shaped blades, one of them with a protruding midrib, were chosen for analysis from the recently published

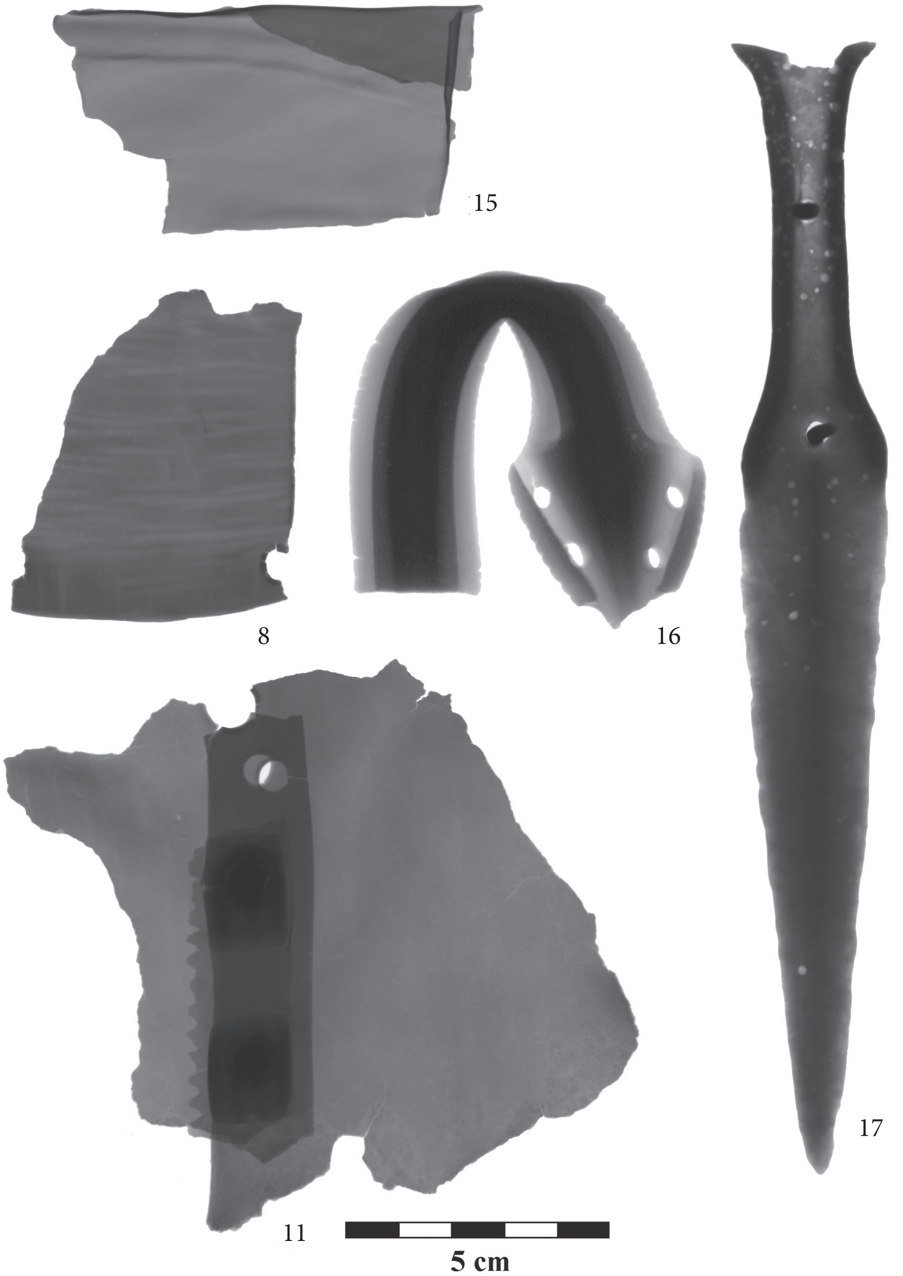

Fig. 3. X-ray images of a dagger, sword, and sheet metal objects. 8: Keszőhidegkút; 11: Pázmándfalu I/II; 15: Szentgáloskér; 16: Tab-Csabapuszta; 17: Tahitótfalu-Szentendre Island (Appendix 8, 11, 15–17)
3. kép. Tőr, kard és lemeztárgyak röngtenfelvételei. 8: Keszőhidegkút; 11: Pázmándfalu I/II; 15: Szentgáloskér; 16: Tab-Csabapuszta; 17: Tahitótfalu-Szentendrei-sziget (Appendix 8, 11, 15–17)

Budakeszi A and B hoards (*Fig. 4. 2–5*). The production and use of these weapons span multiple periods. Typo-chronological analysis of the Budakeszi hoards showed that they were deposited in the Ha B1 (reviewed by Tarbay 2022, 33–35, 52–53, Fig. 2. 1). The list also includes one of the Liptov-Högl-type metal-hilted sword fragments from the Nagydém A-B hoards (Kemenczei 1991, 40, Pl. 33. 139) (*Fig. 7. 10*), a mixed dual hoard, probably deposited around the same time. Such weapons are most common in the northeastern Carpathian Basin; their appearance in Transdanubia is considered rare and probably a result of warrior mobility (Müller-Karpe 1961, 22–29; Bader 1991, 128–133; Stockhammer 2004, 180–183; Novotná 2014, 49–66; Tarbay 2018, 20–22, List 3. 3, Map 4). The last object is a spearhead with a leaf-shaped blade from Hoard II discovered in Ság Hill at Celldömölk. This object is the youngest of the selected finds, dated to Ha B2, according to Amália Mozsolics (Mozsolics 2000, 37–38, Pl. 12. 8) (*Fig. 4. 6*).

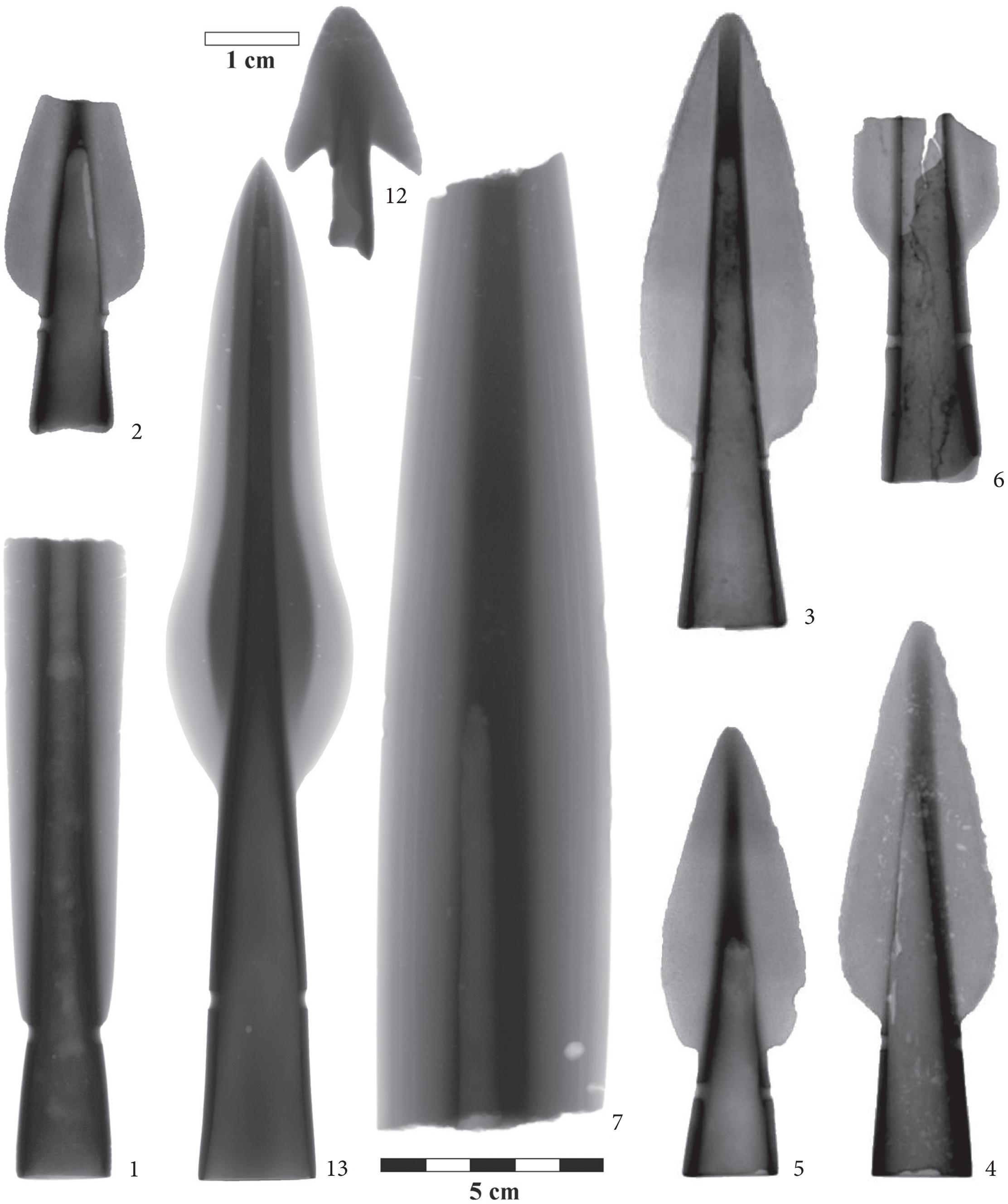

Fig. 4. X-ray (1, 7, 12–13) and NR (2–6) images of spearheads and an arrowhead. 1: spearhead from Bonyhád area; 2: spearhead from Budakeszi Hoard A; 3–5: spearheads from Budakeszi Hoard B; 6: Celldömölk-Ság Hill; 7: spearhead from Keszőhidegkút; 12: arrowhead from Pázmándfalu; 13: spearhead from Pölöske (Appendix 1–7, 12–13)
4. kép. Lándzsahegyek és egy nyílhegy röntgen (1, 7, 12–13) és neutronradiográfiás (2–6) felvételei. 1: Bonyhád vidéki lándzsahegy; 2: lándzsahegy a Budakeszi A depóból; 3–5: lándzsahegyek a Budakeszi B depóból; 6: lándzsahegy Celldömölk-Ság-hegyről; 7: keszőhidegkúti lándzsahegy; 12: pázmándfalui nyílhegy; 13: pölöskei lándzsahegy (Appendix 1–7, 12–13)

X-ray and neutron radiography

X-ray and neutron imaging usually reveal the macro- and microscopic structure of an object by non-destructive tests. Radiography (2D imaging) or tomography (3D imaging) can be used to visualise the attenuation of the beam capable of penetrating the object (such as X-rays and electrically neutral neutrons). According to the principle of radiography, material placed in the path of the beam casts a ‘shadow’ on the screen which is sensitive to a given radiation (projection image or projection). Imaging (i.e. the formation of a contrast pattern) is made possible by detecting different amounts of radiation that reach different points on the screen. Both types of radiation can pass through several centimetres of material, so the interior of a larger object can be successfully examined.

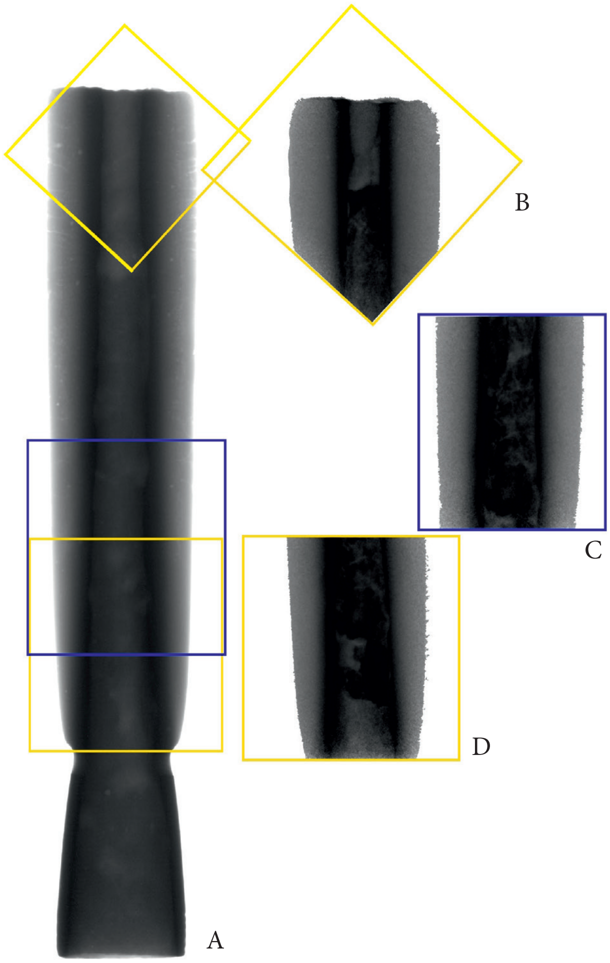

Fig. 5. X-ray (A) and NR (B–D) images of the spearhead from Bonyhád area (Appendix 1)
5. kép. A Bonyhád vidéki lándzsahegy röntgen- (A) és neutronradiográfiás (B–D) felvételei (Appendix 1)

With bimodal imaging, it is possible to generate both X-ray and neutron data sets for the same object. The different interaction of the two types of radiation (X-ray – with electron shell, neutron – with nucleus) gives complementary information. X-ray imaging is a widely used basic method compared to neutrons, with spatial resolution down to nanometres. However, neutron imaging is very useful for examining materials made up of elements with low atomic numbers, as X-ray imaging of these materials is poor. In addition, neutron imaging is particularly sensitive to hydrogen content. Its disadvantages compared with X-ray imaging are lower spatial resolution (some 10s – 100s of μm) and longer exposure times. The triad of spatial resolution, exposure time and field of view should always be optimised.

The X-ray and neutron imaging were performed at the RAD and NORMA facilities operated by the Nuclear Analysis and Radiography Laboratory of HUN-REN Centre for Energy Research, respectively. For X-ray radiographic images, an ERESCO 42 MF3.1 X-ray tube was used, placed 106 cm away from the scintillator screen. The tube voltage was set to 200 kV with a current of 4.5 mA, and a 2 mm thick Al-filter was used during the acquisition of the images. The spatial resolution achieved is approximately 250 μm. The neutron imaging was performed on the horizontal channel No.2 of the reactor. The achieved spatial resolution is about 350 μm. Image processing was done using routines and plugins from the latest version of the FIJI open-source programme (Schindelin et al. 2012; www.fiji.sc).

The radioactivity that is generated in the object from neutron irradiation decays after a while, therefore tests should be planned so that this time is acceptable, whereas with X-ray imaging this problem does not occur.

Results and Discussion

X-ray and NR results and their interpretation will be presented below by object types, starting with spearheads, and ending with sheet metal objects. Spearheads dated to the Ha A1–Ha B2 made up the largest group of finds that was studied *(Fig. 4.1–7, 13)*. These objects were made in two-piece casting moulds with two negatives and a long casting core inserted between the mould halves (Trommer, Bader 2013). Much of the phenomena observed by the 2D X-ray and NR images can be associated with the above production technology. The most common observation is the occurrence of different pores, which can be associated either with gas porosity or with shrinkage porosity (Tarbay et al. 2021, 7–8, Fig. 6). Pores inside the castings are observable in six out of the eight spearheads. In many cases, their distribution, size, and quantity do not seem to be significant, even on a 2D image (*Fig. 4. 1, 2, 4, 6–7, 13*). Porosity certainly did not make these weapons dysfunctional. An apparent exception is a spearhead from Budakeszi B (*Fig. 4. 4*). Here, the pores are distributed near the midrib and the hole inside the object, as well as along the socket. Some of the pores also

Fig. 6. The fragmented sheet-metal object from Szentgáloskér and its X-ray image (Appendix 14)
6. kép. A szentgáloskéri töredékes lemeztárgy és röntgenfelvétele (Appendix 14)

have an elongated shape, suggesting they could have been formed by shrinkage porosity. The object was nevertheless manufactured and probably used based on combat traces (see Tarbay 2022, 64–65). The second category of phenomenon observable inside the spearheads is associated with the socket, or more precisely, the casting core. Information on production technology can be obtained from the depth and position of the spearhead sockets. Ideally, the sockets are situated at the exact centre of the weapon, and they are long and almost fill the entire cavity of the midrib section. The studied findings show how hard it was to achieve such symmetry during casting. Except for one spearhead from Budakeszi B (*Fig. 4. 3*), all the other complete spearheads and one fragment had a core shift defect in a lateral or longitudinal direction (*Fig. 4. 2, 4–5, 7, 13*). There could be many causes of these defects, including the imprecise and asymmetrical shape of the casting cores, inadequate fixing of the cores with a fixing rod through the pegholes, or the insufficient preheating of these mould parts, which could lead to gas formation and shrinkage, eventually displacing the casting core. The latter scenario is highly likely for some of the Budakeszi spearheads (*Fig. 4. 2, 4*), where core shifts combine with pores. The third phenomenon is cracking caused by shrinkage that can be observed in the images. This was only present in the lower section of the spearhead from Celldömölk-Ság Hill (the upper cracks were caused by mechanical stress, probably a hammer impact) (*Fig. 4. 6*). The arrowhead from Pázmándfalu (*Fig. 4. 12*) was produced using similar technology to the spearheads. Inside the arrowhead, one can observe a minor core shift in the longitudinal direction, which was probably associated with a large, incomplete defect along the socket. Near-tip longitudinal crack-like traces are observable, whose origin is unclear to us, but they can probably be associated with the use of the weapon. On the NR images, remnants of organic material can be observed on the inner wall of the Bonyhád spearhead socket. These could be detached parts of the wooden shaft that corroded into the wall of the socket, but their precise identification requires further sampling and elemental composition analysis (*Fig. 5*). The swords (*Fig. 7. 10, Fig. 3. 16*), the rapier (*Fig. 1*), and the dagger (*Fig. 3. 17*) form the second category of objects that are technologically comparable and can be discussed together. Swords and daggers are made in two-piece moulds with two negatives cast in a vertical position from the handle or the tip of the blade (Siedlaczek 2011). There are some special variants, such as the metal-hilted swords (*Fig. 7*) which are cast separately in a two-piece mould with two negatives and a core or with a lost-wax casting technique. On the X-ray images, trapped gas pores were identified inside all weapons (see gas pores in swords: Quilliec 2002, 100, Fig. 17; Quilliec 2007, 406, Fig. 8; Tarbay et al. 2023, 9, 16). In two cases, one can observe the densification of the pores in one direction: near the lower blade part – Keszthely rapier (*Fig. 1*) or near the handle – Tahitótfalu dagger (*Fig. 3. 17*). The concentration of pores can indicate the direction of casting (Mödlinger et al. 2009, 53–54). The Keszthely rapier was probably cast from the direction of the tip, while the Tahitótfalu dagger was cast from its hilt. A breakage at the end of the hilt that may be associated with the removal of the casting jet is also visible on the latter object (Tarbay 2020, Fig. 3). The pores near the end of the Keszthely rapier may seem serious on a 2D image, but this did not make the weapon a dysfunctional object. Doubts on functionality can be easily dispelled by comparing the results of the X-ray and the use-wear analysis (Dumont, De Mulder 2020). The eponymous rapier from Keszthely shows characteristic traces of heavy wear in the form of worn-out patterns, micro edges, and tip damage (*Fig. 2*).

The metal-hilted sword from Nagydém showed that the cavity of the handle is hollow; no stuck ceramic mould parts were visible inside (*Fig. 7*). The terminal of the blade is situated in the middle of the handle (Bunnefeld 2016, 30, Fig. 6), but it does not fit completely into the hilt's cavity, especially around the area of the shoulders. The blade also has a small hilt plate, shaped like the broken lower part of a casting jet. Unlike most metal-hilted swords, the blade handle is attached to the metal hilt by pegs punched through the peg holes. In this case, the pegs are only just halfway into the blade's shoulders. The sword from Nagydém is not the only one with such traces; similar ones were identified by X-ray on Central European swords with ribbed hilts or cup-shaped pommels from Bohuslavice, Komjatná and Zlatná na Ostrove, Mecklenburg, Milavče C4 (Říhovský 2000, 151, Pl. 7, 12; Wüstemann 2004, Pl. 64. 441; Novotná 2014, Pl. 19. 83, Pl. 29. 131A; Winiker 2015, Pl. 8. 19). Born interpreted this phenomenon as a riveting error (see Born, Hansen 2001, 190–191, Fig. 143). Wüstemann and Sicherl proposed that the shoulder area of the hilt plate be broken off when the blade was punched through (Wüstemann, Sicherl 2015, 92, Pl. 8. 19) or

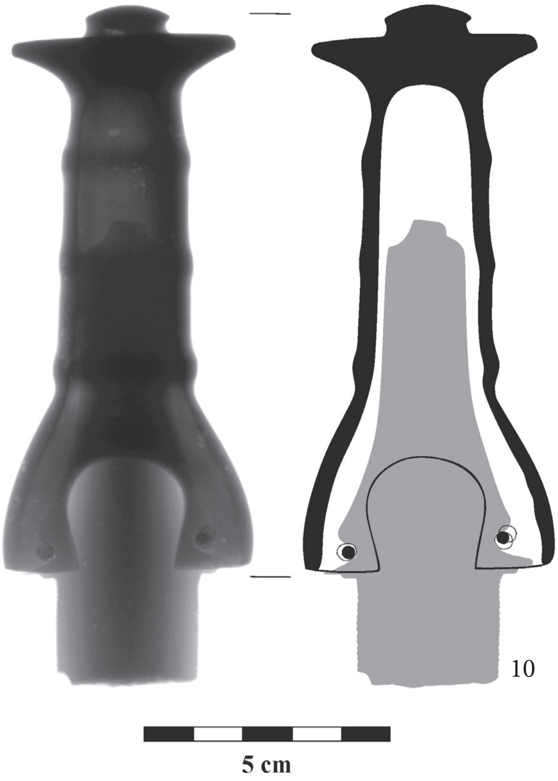

Fig. 7. X-ray image of the sword from Nagydém (Appendix 10)
7. kép. A nagydémi kard röntgenfelvétele (Appendix 10)

that the piercing point be so far along the edge that only an edge notch was created (Wüstemann 2004, 143, Pl. 64. 441). Bunnefeld described sword handles as having broken-out rivet holes (Bunnefeld 2016, 348, Pl. 117. E2, Pl. 118. E4) from which an interpretation was given by Horn on the example of halberds (Horn 2014, 185–187, Fig. 113). There are also several other possibilities for how this phenomenon could have occurred. The hilt plate of the blade is significantly narrower than the cavity of the metal handle; it does not fit completely and perfectly. This blade could originally have been made for another, narrower metal-hilted sword; what we see is an improvised solution to fit into a narrow hilt plate, a large metal hilt originally made for another sword. Another scenario is that the hilt plate was cast incompletely and therefore became narrower than the handle. A third possibility is that a previously used blade with a damaged handle and worn-out peg holes was inserted into a metal handle, which is not an unknown phenomenon of the period (Born, Hansen 2001, 202). The rounded surfaces around the peg holes could indicate such extensive wear. However, this should be further characterised by advanced 3D methods (neutron tomography or CT) for an exact determination.

The last group of objects is armour (*Fig. 3. 11*), potential armour (*Fig. 3. 8, Fig. 6*), and shield parts (*Fig. 3. 15*). In the case of sheet metal objects treated by cold hammering and annealing, the traces usually observable on the radiography images of these finds are lateral and perpendicular hammer impacts related to the tools used for stretching and raising the sheets. Such hammer traces were observed by X-ray on Late Bronze Age bronze cups and helmets (Born 1997, 79–80, Figs. 22–25; Born, Hansen 2001, 247–248, Fig. 198). Elongated oval-shaped hammer traces parallel to the rim of the sheet metal objects are best observable on the sheet from Keszőhidegkút (*Fig. 3. 8*). Along the edges of this sheet, perpendicular hammering traces that helped to shape this part of the object are also well-observable. Faint hammering traces are also present on the much thinner sheets from Pázmándfalu (*Fig. 3. 11*). The X-ray images also help us to characterise an enigmatic sheet metal object from the Szentgáloskér hoard (*Fig. 6*). On the X-ray image, it is clearly visible that the edge of the object is covered with one punched patch-like sheet that covers an additional small rectangular sheet in the middle of the object's upper edge (*Fig. 6*). The punched sheet fastened together the two main sheets using small pegs with rounded heads and bent shafts, which are for helmet and cuirass fastening (Mödlinger 2017, Pl. 3. 16, 21, Pl. 25. 128). Elongated chisel or axe cut marks are also visible on the edge of the preserved main sheet, suggesting that part of the main sheet was removed prior to the riveting of the punched, patch-like sheet. We believe that this punched sheet was a repair trace that held together two previously damaged sheet metal parts. Repairing sheet metal products was a common practice for metal vessels (Gogâltan 1993) and armour during the Late Bronze Age. This type of decorative and fine repair, as we can see on the Szentgáloskér sheet, has its best analogues among the group of armour. A fine counterpart is the bell helmet from Pişcolt, Romania, whose body was repaired with a small, rounded piece of sheet metal with punched decoration and attached with rivets to the main sheet (Marta 2017, 195–197, Fig. 4. 1). This does not indicate that it was a sheet metal helmet because the Pişcolt helmet is younger than the Szentgáloskér sheet, and it serves merely as a technological parallel. At present, it seems more likely that these sheet metal objects, and their potential fragments could be edge parts of repair armour, a helmet, or a cuirass.

Conclusions

The study introduced a new X-ray and NR series of Late Bronze Age combat weapons and armour, and a shield fragment dated between the Reinecke Br B2/C and Ha B2 periods. Our results contributed to the characterisation of cast and sheet metal object production technology. The interior and internal structure of the studied objects revealed different technological information and general and type-specific production technological traces. The list of observed phenomena includes various core shift defects, which can be described mainly in the case of spearheads. On several objects, casting defects such as pores caused by gas, shrinkage porosity, and internal cracks were observed. In some cases, the densification of pores at one end of the cast also indicates the direction of casting, as can be observed in the case of the Keszthely rapier cast from the tip or the Tahitótfalu dagger cast from the handle. Complex, multi-part objects, such as the metal-hilted sword from Nagydém, could also provide new information on the way in which these weapons were hilted. In the case of sheet metal objects, X-ray and NR images mainly revealed hammering marks connected to the formation of these objects by cold hammering and annealing, which are difficult to see with the naked eye. New data was also provided on the assembly of the complex sheet metal object from Szentgáloskér, which may be part of a repaired armour or helmet.

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Appendix

No.	*Site*	*Type*	*Inv. No.*	*References*	*Figs.*
1	Bonyhád area	spearhead	HNM, 1889.95.102	Mozsolics 1985, 102–104, Pl. 36. 2	*Fig. 4. 1, Fig. 5*
2	Budakeszi A	spearhead	HNM, 2021.8.2	Tarbay 2022, 187, Pl. 1. 2	*Fig. 4. 2*
3	Budakeszi B	spearhead	HNM, 2021.8.69	Tarbay 2022, 187, Pl. 1. 2	*Fig. 4. 3*
4	Budakeszi B	spearhead	HNM, 2021.8.70	Tarbay 2022, 190, Pl. 11. 70	*Fig. 4. 4*
5	Budakeszi B	spearhead	HNM, 2021.8.71	Tarbay 2022, 190–191, Pl. 11. 71	*Fig. 4. 5*
6	Celldömölk-Ság Hill II	spearhead	HNM, 1949.25.26	Mozsolics 2000, 37–38, Pl. 12. 8	*Fig. 4. 6*
7	Keszőhidegkút	spearhead	HNM, 1926.66.92	Tarbay 2021, 99–117, Fig. 8. 7	*Fig. 4. 7*
8	Keszőhidegkút	'helmet'	HNM, 1926.66.71	Tarbay 2021, Fig. 9. 30a–b	*Fig. 3. 8*
9	Keszthely-Legelő-dűlő, Mound 1/ Feature 1	rapier	HNM, 1885.114.1	Kemenczei 1988, 38, Pl. 13. 156, Pl. 59A	*Fig. 1. 9*
10	Nagydém A-B	sword	HNM, 2020.8.1	Kemenczei 1991, 16, Pl. 33. 139	*Fig. 7. 10*
11	Pázmándfalu I/II	cuirass	ELTE IAS	V. Szabó 2019, 174–178, Fig. 47	*Fig. 3. 11*
12	Pázmándfalu III	arrowhead	ELTE IAS	V. Szabó 2019, 174–178, Fig. 48	*Fig. 4. 12*
13	Pölöske	spearhead	HNM, 1887.9.12	Mozsolics 1985, 177–178, Pl. 124. 4	*Fig. 4. 13*
14	Szentgáloskér	'cuirass'/ 'helmet'/ 'sheet'	HNM, 1886.4.90	Mozsolics 1985, 194–195, Pl. 115. 6,9–10	*Fig. 6*
15	Szentgáloskér	shield	HNM, 1886.4.97	Mozsolics 1985, 28, 195–195, Pl. 115. 7	*Fig. 3. 15*
16	Tab-Csabapuszta	sword	HNM, 1880.105.33	Kemenczei 1988, 61, Pl. 36. 328	*Fig. 3. 16*
17	Tahitótfalu-Szentendre Island	dagger	HNM, 2023.11.1	Tarbay 2020, 2, Fig. 3	*Fig. 3. 17*

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KÉSŐ BRONZKORI, NYUGAT-DUNÁNTÚLI FEGYVEREK ÉS PÁNCÉLOK RÖNGTEN ÉS NEUTRONRADIOGRÁFIÁS VIZSGÁLATA

Összefoglalás

Munkánk dunántúli, késő bronzkori (Bz B2/C–Ha B2) támadófegyverek, lehetséges pajzstöredék, páncél és sisaktöredékek röntgen és neutronradiográfia módszerével előállított 2D felvételek eredményeit teszi közzé. A vizsgálatok elvégzésre a „Késő bronzkori dunántúli fegyverek technológiája, használata és manipulációja" c. kutatási program után (2020–2024) került sor. A tanulmányozott leletek köre különböző kontextusokból és lelőhelyekről származik: tőrkard (Keszthely), kardok (Nagydém A-B, Tab), lándzsahegyek (Bonyhád vidéke, Budakeszi A-B, Celldömölk-Ság-hegy II, Keszőhidegkút, Pölöske), nyílhegy (Pázmándfalu III), sisak (Keszőhidegkút), vért (Pázmándfalu I/II), „vért/sisak" (Szentgáloskér), „pajzs" (Szentgáloskér), tőr (Tahitótfalu).

Az eredményeink elsősorban a tárgyak öntéstechnológiájáról, öntési hibáiról, illetve a lemeztárgyak megmunkálásához és javításához köthető jelenségről szolgáltattak új adatokat. A megfigyelt jelenségek közé sorolhatunk különféle öntőmag elmozdulási hibákat, melyek alapvetően a lándzsahegyek esetén voltak megfigyelhetők. A fentieken kívül a röntgen- és neutronradiográfiás felvételeken leírhatók voltak gyakoribb öntvényhibák is, mint a gáz vagy zsugorodási porozitás által okozott pórusok vagy a valószínűleg zsugorodási hibaként értelmezhető belső repedések. Néhány esetben, mint a keszthelyi tőrkard vagy a tahitótfalui tőr, a pórusok sűrűsödése kirajzolta az öntés irányát is, mely előbbi esetén a hegy, míg utóbbinál a markolat volt. Az alkalmazott módszerek lehetőséget nyújtottak arra is, hogy az olyan összetett, többrészes öntvények illesztését is megvizsgáljuk, mint a nagydémi fémmarkolatos kard, melynek belsejében kitörött vagy a használattól kikopott szegecslyukakat lehetett megfigyelni. A röntgen- és neutronradiográfiás felvételek segítségével a lemeztárgyakon a lemezek nyújtásához és alakításához köthető kalapácsnyomokat is meg lehetett határozni, melyek valószínűleg hidegkalapáláshoz és hőkezeléses lágyításhoz köthetők, s szabad szemmel a tárgyakon nehezen különíthetők el. Új adatot szolgáltattunk az egyik különös, a kutatástörténet során eltérően értelmezett, Szent-

gáloskérről származó lemez-tárgyról. Eredményeink alapján ezen a tárgyon látható poncolt, lekerekedő, szegecsekkel rögzített lemezszalag egy foltszerű javítás lehet, melynek analógiáit Kárpát-medencei sisakok között láthatjuk (Piskolt). A poncol, szegecselt lemezszalag egy alá-rakott második lemez segítségével fogta össze az újravágott, javított tárgy testét. A szentgáloskéri lelet tipológiai értelmezése kapcsán továbbra is finoman fogalmazunk, véleményünk szerint vagy vért, vagy sisak része volt.