Towards direct casting: Archaeometallurgical insight into a bronze mould from Elgiszewo, Poland, 900–700 BC

K přímému odlévání: bronzová licí forma z Elgiszewa, Polsko, 900–700 př. n. l.

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This study reports the results of archaeometallurgical investigations performed on a complete two-part bronze casting mould discovered in the village of Elgiszewo (north Poland). The mould was part of the so-called Lusatian founder's hoard deposited on the southern borders of the Chełmno group territory between 900 and 700 BC. The investigations involved the employment of spectral (ED XRF, SEM-EDS, X-ray) and microscopic (SEM-EDS, OM) analyses. The experimental casting of the model mould and socketed axe was carried out in this study as well. The chemical composition of the mould indicates the use of fire-refined (oxidized) fahlore scrap bronze, which could originally be composed of North Tyrolean copper fahlores. The metallographic results furthermore indicate deliberate tin abandonment by the Lusatian metalworker to maintain a thermal resistance of the mould during direct metal casting. Having analysed the results of the performed research, we can state that the mould from Elgiszewo was capable of ensuring direct casting and was in fact used by the Lusatian metalworkers for this purpose before the mould was finally deposited.

casting mould – Lusatian culture – Urnfield complex – Late Bronze Age – archaeometallurgy

Studie prezentuje výsledky archeometalurgického výzkumu kompletní dvoudílné bronzové licí formy nalezené v obci Elgiszewo (Kujavsko-pomořské vojvodství). Forma pochází z depotu zlomků, který byl uložen na jižních hranicích územní skupiny Chełmno mezi lety 900 a 700 př. n. l. Průzkum formy zahrnul spektrální (ED XRF, SEM-EDS, rtg.) a mikroskopické (SEM-EDS, OM) analýzy. V rámci studie bylo provedeno i experimentální odlití modelů formy a tulejkovité sekerky. Chemické složení formy nasvědčuje užití žárově (oxidačně) rafinovaného zlomkového bronzu získaného hutněním sulfidických měděných rud (řady tetraedrit-tennantit), jejichž původ lze hledat nejspíše v severním Tyrolsku. Metalografické výsledky ukazují i na skutečnost, že kovolitci lužické kultury záměrně pominuli příměs cínu z důvodu zachování tepelné odolnosti formy pro přímé lití. Po analýze výsledků výzkumu lze konstatovat, že forma z Elgiszewa umožňovala přímé lití a že toto zařízení bylo skutečně využíváno.

licí forma – lužická kultura – komplex popelnicových polí – pozdní doba bronzová – archeometalurgie

1. Introduction

The complete two-part bronze casting mould (*figs. 1* and *2*) was discovered by chance in 2013 in the village of Elgiszewo (Golub-Dobrzyń district, north Poland) during an illegal metal detector survey conducted along the peated part of the Okonin Lake shore (*Gackowski 2016*, 168–170, fig. 2). The mould was part of the so-called founder's hoard deposited on the southern borders of the territory occupied by the Chełmno group of the Lusatian culture between 900 and 700 BC.[1]

Fig. 1. Casting mould from Elgiszewo (Poland; courtesy of the Province Historical Monuments Conservation Office in Toruń).
Obr. 1. Licí forma z Elgiszewa.

Nine bronze shell-moulds for multiplying the looped socketed axes dated to the Late Bronze Age (further LBA) are reported from Poland so far: (1) Brzeg Głogowski, (2) Gaj Oławski, (3, 4) Kiełpino, (5) Nowe Kramsko, (6) Pawłowiczki, (7, 8) Rosko, and (9) 'from the Sieniocha River area' (*Machajewski – Maciejewski 2006*; *Sałat et al. 2006*; *Baron – Miazga – Nowak 2014*; *Baron et al. 2016*; *Kłosińska – Sadowski 2017*; *Lubuski Wojewódzki Konserwator Zabytków 2018*). The specimen from Elgiszewo is another such find (*fig. 3*).

A widely held belief in Polish archaeology has been that metal moulds, due to their low thermal resistance, were used only for preparing wax or lead models (*Machajewski – Maciejewski 2006*; *Sałat et al. 2006*; *Baron – Miazga – Nowak 2014*; *Baron et al. 2016*; *Lubuski Wojewódzki Konserwator Zabytków 2018*). Hopefully, the recent detailed work on the mould from Gaj Oławski performed by *Baron et al.* (*2016*; *Baron – Miazga – Nowak 2014*) shed further light on the functionality of the casting moulds from Poland.

The artefact from Elgiszewo fits the hoarding trend observed in other parts of Poland (Gaj Oławski, Kiełpino, Rosko, and perhaps 'from the Sieniocha River area') and Euro-

[1] A general criticism against tendentious interpretations of burials and/or hoards containing tools used in metalworking (see *Ježek 2015* for a detailed (re)evaluation of 'the smith's burial' and 'founder's hoard' concepts; see also *Ježek 2017*; *Ježek – Holub – Zavřel 2018*) provides grounds for the construction of a contrary model proposing that the metal finds from the Elgiszewo hoard were gathered (and perhaps also partially manufactured) by the Chełmno group community and the deposition act was a demonstration of their local identity (see, e.g., *Kaczmarek 2017b*, 279–280). Choosing the southern borders of their own territory as a hoarding place could have had a decisive impact on the marking of local borders and passages, and left, perhaps, a characteristic landmark on the regional and interregional routes maintained by the Chełmno group in the final stage of the Bronze Age (see *Maciejewski 2016* for contextual studies on the LBA metal hoards).

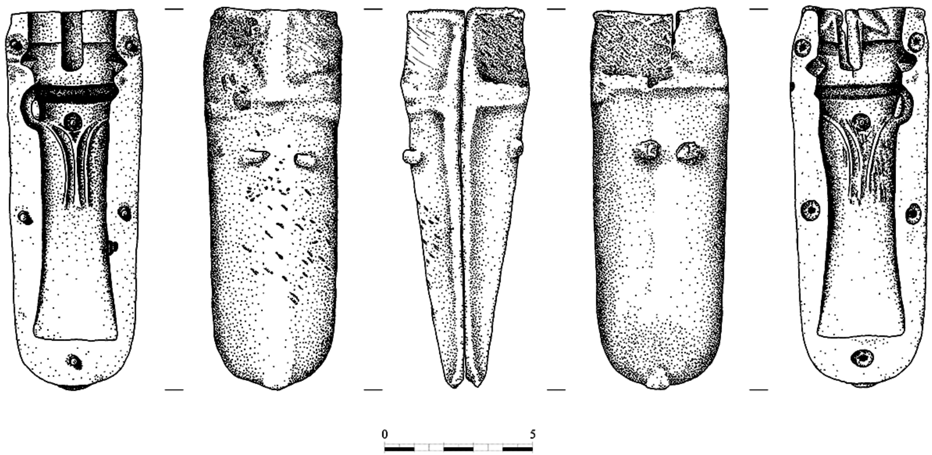

Fig. 2. Casting mould from Elgiszewo.
Obr. 2. Licí forma z Elgiszewa.

pe, where most of the moulds are wetland finds. It is also symptomatic that the casting moulds and the bronze axes had similar cultural status and were thus deposited similarly (*Baron – Miazga – Nowak 2014*; *Baron et al. 2016*, with refs.). This is consistent with the cultural phenomenon outlined by *Kaczmarek* (*2012*), who claims that transferring the metal from the grave to the deposit context became evident during the LBA and therefore might reflect a change of the bronze function in social practice.

2. Typological background

The hoard from Elgiszewo consists of 34 bronze artefacts (including, equestrian gear, several bracelets and necklaces, a *Spindlersfeld* fibula, handles and attachments of bronze kettles and an antennae knife) with a total weight of 2.67 kg. An oval 'metallurgical stone' with a poorly marked fluting running around it (and bronze drops attached to its structure) was also deposited in the hoard. Before the deposition act was performed, all the artefacts were probably wrapped in some kind of organic packaging, no remains of which were preserved.

The typological structure of the artefacts indicates a 900–700 BC date range, which corresponds to the transition period Ha B2–B3 (= Montelius V). Such chronological placement is well supported by two bronze handles with cross attachments, which were probably removed from Eastern Carpathian bronze kettles (*Gackowski 2016*, 168, figs. 2: 5 and 29). It is important to mention that a similar bronze kettle (possibly originating from the Gáva-Holihrad metal workshops) was discovered in Głowińsk near Rypin (*Gedl 2003*), which is about 30 km east of Elgiszewo. A bronze knife in the hoard is highly similar to Silesian knives of the *Szymocin* type (*Gedl 1984*, 58–59, Taf. 14: 139 and 139A), and, together with a poorly preserved fragment of a *Spindlersfeld* fibula (linked to the West Pomeranian – Oder variant *Chłopowo*), pushed the dating of the Elgiszewo hoard back into the final stage of the Bronze Age (*Gedl 2004*, 29–30, Taf. 13).

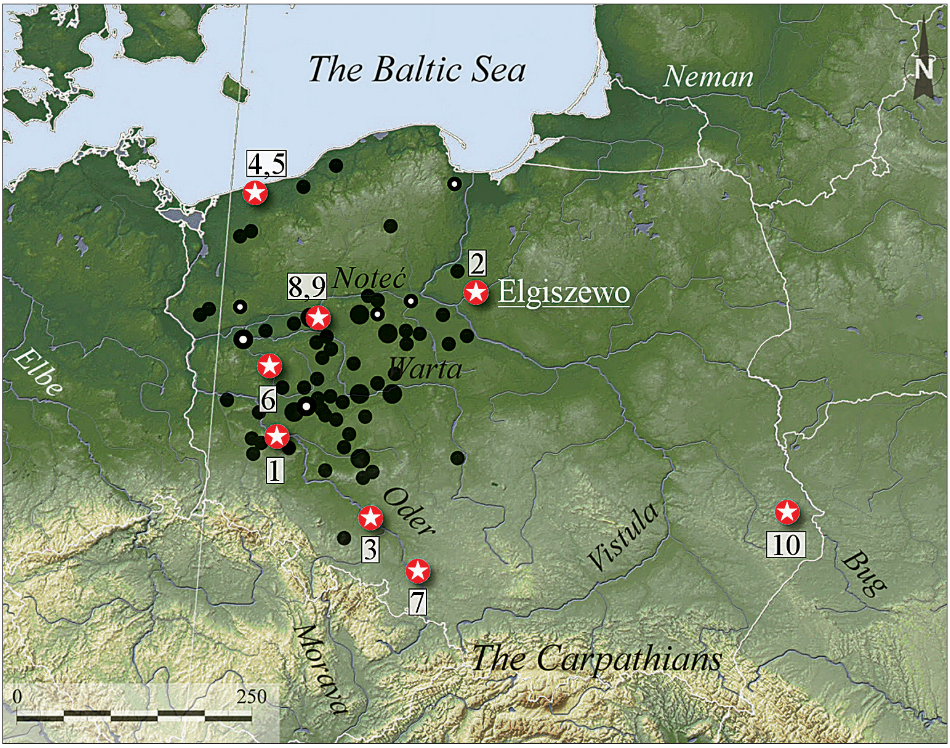

Fig. 3. Distribution of the Przedmieście type socketed axes ● including variant G ⭘ against the backdrop of the LBA metal casting moulds from Poland ✪. Large spots stand for three or more axes found together (*Kuśnierz 1998*, 43–51, Taf. 43: B; *Baron – Miazga – Nowak 2014*, 327, fig. 1; *Kłosińska – Sadowski 2017*; *Lubuski Wojewódzki Konserwator Zabytków 2018*, adapted; map background: Yarr65/Shutterstock.com).
Obr. 3. Prostorové rozšíření tulejkovitých seker typu Przedmieście ● včetně varianty G ⭘ na pozadí nálezů licích forem mladší a pozdní doby bronzové z Polska ✪. Velké body označují hromadné nálezy tří a více seker (*Kuśnierz 1998*, 43–51, Taf. 43: B; *Baron – Miazga – Nowak 2014*, 327, fig. 1; *Kłosińska – Sadowski 2017*; *Lubuski Wojewódzki Konserwator Zabytków 2018*, upraveno).
1 Brzeg Głogowski, Głogów dist.; 2 Elgiszewo, Golub-Dobrzyń dist.; 3 Gaj Oławski, Oława dist.; 4, 5 Kiełpino, Gryfice dist.; 6 Nowe Kramsko, Zielona Góra dist.; 7 Pawłowiczki, Kędzierzyn-Koźle dist.; 8, 9 Rosko, Czarnków-Trzcianka dist.; 10 'from the Sieniocha River area'.

The well-preserved negative parts indicate that the mould was designed to multiply the looped socketed axes of the *Przedmieście G* type. The *Przedmieście* axes are exclusive to the metallurgical practice shared by Lusatian metalworkers from Greater Poland (with some examples coming from Silesia and Pomerania) during the end of the LBA (*Kuśnierz 1998*, 50–53, Taf. 20: 380 and 390).

Few casting moulds are reported from the Chełmno land. Apart from the specimen from Elgiszewo, only a few others have been discovered, and these were clay mould fragments from the Lusatian settlement in Ruda near Grudziądz. Nonetheless, socketed axes were relatively common in the Chełmno group, as may be exemplified by the finds of the *Przedmieście* type (Czarnowo, Kałdus, Wałdowo Królewskie), *Czarków* type (Papowo Toruńske, Rogowo) and *Kopaniewo* type (Rudnik; *Gackowski 2005*).

3. Methods

3.1. ED XRF

The alloy profile (= chemical composition) of the mould was established by means of energy dispersive X-ray fluorescence (ED XRF); the instrument used for analyses was a Spectro Midex spectrometer equipped with a molybdenum X-ray tube and a Si Drift Detector (SDD) with 150 eV resolution at 5.9 keV. The analytical conditions used were 44.6 kV, 5.9 mA, and 180 s of live time. The ED XRF quantification was performed with the use of the fundamental parameter program FP+ for the elemental analysis of the alloys. Surfaces of the mould were prepared by mechanical removal of the corrosion products (exposing the metallic core) and followed by degreasing with $O=C(CH_3)_2$ (acetone). The alloy profile of the mould was determined on the basis of a series of 15 measurements taken from the metallic core of each part.

3.2. SEM-EDS

The elemental composition of the mould was determined as a result of investigations with the use of a Hitachi S3400N scanning electron microscope (SEM). The surface observations were carried out by means of a BSE detector with 28 kV accelerating voltage and environmental vacuum mode (chamber pressure of 50 Pa). The X-ray microanalyses were conducted using a NORAN 986B-1SPS EDS spectrometer (Thermo Noran) coupled with the Hitachi S3400N scanning electron microscope. The EDS investigations were performed on the outer parts of the mould in a semi-quantitative, surface and standardless mode complemented by non-conducting material imaging with the use of a BSE detector operating at a pressure of 50 Pa.

3.3. Microstructure analysis

A microstructure analysis was performed with the use of the Nikon Eclipse LV150 metallographic microscope (OM) equipped with a Nikon Digital Sight DsFi1 microscopic camera and the Nis-Elements system for image analysis. The observations were made in the outer part of the mould (knob), which was polished with diamond paste (1 μm), and etched in HCl (30 ml) + $FeCl_3$ (30 g) in C_2H_5OH (120 ml) solution.

3.4. Macrostructure analysis

The macrostructure observations were carried out with a Nikon SMZ 745Z stereoscopic microscope (OM) equipped with the Nikon Digital Sight DsFi1 microscope camera.

3.5. X-ray defectoscopy

The X-ray defectoscopy was determined as a result of investigations with the use of an industrial X-ray radioscopy system, Y.MU2000-D (YXLON), comprising an X-ray tube (160kV) coupled with a digital panel detector with the active area of 200 mm by 200 mm at a frame rate of 15 fps and a pixel size of 200 μm. Data imaging was performed with the use of the YXLON Image 2500/3500 system.

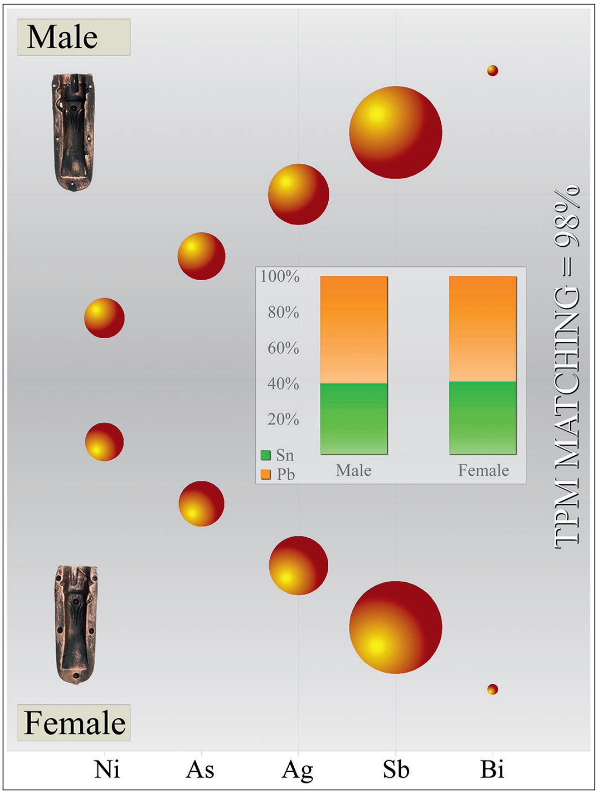

Fig. 4. The alloy profile of the casting mould from Elgiszewo by means of the ED XRF.
Obr. 4. Chemické složení licí formy z Elgiszewa stanovené pomocí ED XRF.

3.6. 3-D model visualization

The 3-D scanning based on the reverse engineering method was used to visualize the geometry of the *Przedmieście* type socketed axe, which was compatible with the investigated mould. The 3-D model visualization involved triangulation with the use of the 3-D laser scanner (MetraSCAN 3-D) equipped with an optical tracking system (C-Track 780) by Creaform. The entire scanning process was supported with VXelements software. The geometry achieved by the 3-D laser scanning was subsequently transferred to the Geomagic Studio 2013 software and processed further in the 3ds Max software to simulate the inner part of the axe. In order to remodel the triangular mash of the object, the model was re-imported into Geomagic Studio 2013. The final geometry of the axe was conducted with the ZBrush 4R7 software. The 3-D model visualization was completed by selecting the rendering parameters and creating the appropriate texture of the axe with the use of the 3ds Max software.

3.7. Experimental casting

The experimental casting was divided into two stages and carried out in the Metal Color Starachowice foundry. In the first stage, a model alloy similar in chemical composition to the mould from Elgiszewo was used to cast an experimental mould. The mould was shaped in the sand mass. The melts were carried out in a graphite crucible and a NABER TERM resistance electric furnace. An organic coating was applied. The bath was mixed with a ceramic body and the temperature was monitored. The pouring was completed with the use of a thermocouple. The alloy was composed of pure ingredients which were successively introduced. After the chemical composition and temperature were stabilized, the sand form was poured at the temperature of 1180 °C. The second stage of the experiment involved casting the socketed axe which fit the reconstructed mould. The hardness (HB) of the axe model alloy was controlled. The HB testing was conducted on samples cut perpendicularly to the direction of casting and measured with a universal Brinell hardness tester at the temperature of 20 °C.

4. Results

4.1. ED XRF

The ED XRF analyses show that distribution of the minor and trace elements in both parts of the mould is highly consistent[2] (*tab. 1* and *fig. 4*). Some minor differences were noticed in the content of iron and antimony, the latter of which may be due to the phenomenon of reversed segregation (*Romankiewicz 1995*, 136–143; *Kowalski – Garbacz-Klempka – Dobrzański 2017*, 561). On the other hand, the accuracy of ED XRF is not very high, and it is possible that these differences are not significant.

Part	Fe	Co	Ni	Cu	As	Ag	Sn	Sb	Pb	Bi
Male	0.04	0.06	0.59	93	0.83	1.4	0.36	3.1	0.55	0.04
Female	0.06	0.06	0.58	93	0.81	1.4	0.36	3.4	0.52	0.04
Mean	0.05	0.06	0.59	93	0.82	1.4	0.36	3.2	0.53	0.04

Tab. 1. Chemical data, obtained by ED XRF for the casting mould from Elgiszewo. Data are mean values, calculated from 15 measurements.
Tab. 1. Prvkové složení licí formy z Elgiszewa stanovené pomocí ED XRF. Uvedené hodnoty jsou průměry 15 měření.

Antimony and silver dominate the alloy profile making up 3.2 wt% and 1.4 wt%, respectively, while the nickel oscillates at a level around 0.6 wt%. The lead content measured in the mould only slightly exceeds a value of 0.5 wt%.

Remarkably, tin is below 0.4 wt%, which is much too far from the LBA metallurgical practice, where the tin content in mainstream genuine bronze is expected to fall in the range of 5–15 wt%. This may indicate a deliberate tin abandonment by the LBA metalworker to maintain the thermal resistance of the mould during direct metal casting.

The ED XRF results also indicate that the mould from Elgiszewo was cast in the fire refined (oxidized) fahlore scrap bronze.[3]

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[2] Total profile markers (TPM) matching for the male and female part (estimated using the values of relevant standard deviation) makes up to 98%.

[3] If we deny the use of the scrap bronze, the low tin and lead contents in the mould from Elgiszewo must be considered not as the remnants of the previous genuine bronze alloy, but only as the original impurities of the used ore.

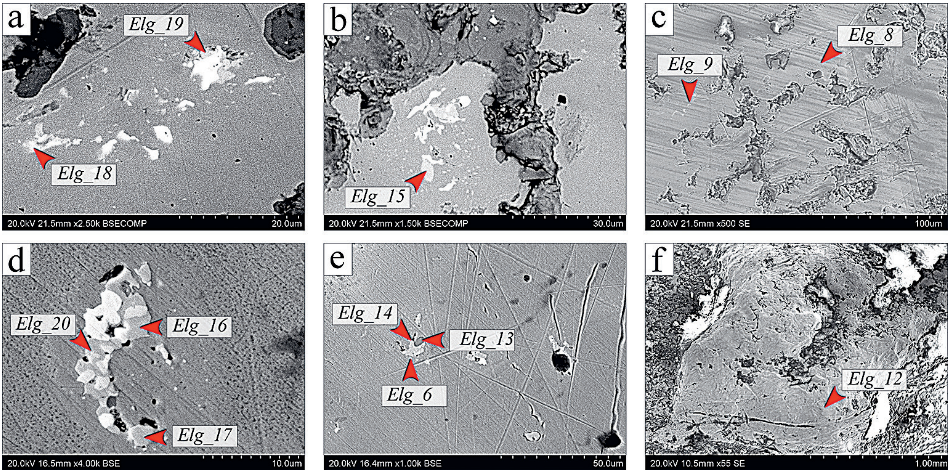

Fig. 5. The SE and BSE images of the casting mould from Elgiszewo with the EDS micro-areas spots.
Obr. 5. Mikrofotografie (SE a BSE) licí formy z Elgiszewa s vyznačením analyzovaných míst (EDS).

4.2. SEM-EDS

The SEM-EDS investigations displayed dendritic α-phase micro-areas associated with cored dendrites forming a solid solution with copper of A and B composition. The subordinate amaeboidal inclusions of α+δ eutectoid were recognized as the composition C (*tab. 2* and *fig. 5*). Final A composition is mostly copper (Cu = 95.5-100 wt%) agglomerating with antimony (Sb = 1.4–4.5 wt%) and nickel (Ni = 1.3 wt%). Apparently, the A composition precludes the beginning of the dendritic crystallization process, whereas the B composition containing from 82.1 wt% to 95.4 wt% of copper (with subordinate Sb, Ag, As and Ni) marks its termination. The eutectoid is dominated by copper varying between 55.3 wt% and 72.9 wt% (with significant Sb, Ag, Ni, and Pb contents) (*Baron et al. 2016*, 192–194).

The significant sulphur content ranging from 1.5 wt% to 17.9 wt% (*tab. 2*: Elg_12, Elg_13 and *fig. 5: e, f*) is noteworthy. While elements such as antimony, silver, and arsenic tend to agglomerate on the grain boundaries, iron, lead (up to 1 wt%) and sulphur usually concentrate as inclusions (Fe-rich copper sulphides or Pb nodules), usually forming $Cu_{2-x}Fe_xS$ (*Mödlinger et al. 2013*, 31). It is commonly assumed that bronze containing sulphur was produced by smelting chalcopyrite ore (*Ashkenazi – Iddan – Tal 2012*, 532–533). However, this is not the case with the investigated mould, since neither ED XRF nor SEM-EDS investigation confirmed any significant iron content (see *tab. 1* and *2*). The copper-sulphur atomic weight ratio, which is about 2÷1 (Cu = 69.8 at% ÷ S = 30.2 at%) in the Elg_12 EDS micro-area indicates that tetrahedrite (fahlore) ore was used by the LBA

According to the standard free energy of reaction, iron, tin, and lead are preferentially oxidized before copper during fire refining, unlike nickel, which could not be readily removed from the re-melted fahlore (*Davis 2001*, 175). A noticeable amount of nickel (0.59 wt%) measured in the mould, together with low contents of iron (Fe=0.05 wt%) and lead (Pb = 0.53 wt%) offer a suggestive indication of this.

Micro-area	S	Ni	Cu	As	Ag	Sb	Pb	*Comp.*
Elg_1	...	...	100	...	...	...	...	A
Elg_2	...	...	100	...	...	...	...	A
Elg_3	...	1.3	98.7	...	...	...	...	A
Elg_4	...	...	98.6	...	...	1.4	...	A
Elg_5	...	...	96.1	...	...	3.9	...	A
Elg_6	...	...	95.5	...	...	4.5	...	A
Elg_7	...	1.5	95.4	1.5	...	1.6	...	B
Elg_8	...	1.5	94.6	1.2	...	2.7	...	B
Elg_9	...	1.4	93.9	...	1.3	3.4	...	B
Elg_10	...	1.4	93.3	...	1.5	3.8	...	B
Elg_11	...	...	93.2	...	2.6	4.2	...	B
Elg_12	1.5	...	90.7	2.9	1.2	3.7	...	B
Elg_13	17.93	...	82.1	...	...	...	...	B
Elg_14	...	...	72.9	...	...	...	27.13	C
Elg_15	...	...	71.3	...	...	28.65	...	C
Elg_16	...	2.2	71.1	...	...	26.68	...	C
Elg_17	...	3.2	69.1	...	...	27.69	...	C
Elg_18	...	...	62.9	...	37.12	...	...	C
Elg_19	...	9.0	56.3	...	...	34.65	...	C
Elg_20	...	8.2	55.3	...	...	36.47	...	C

Tab. 2. Chemical data, obtained by SEM-EDS for the casting mould from Elgiszewo. Comp. – composition of the investigated micro-area: (A, B) cored dendrites, (C) eutectoid.
Tab. 2. Prvkové složení licí formy z Elgiszewa stanovené pomocí SEM-EDS. Comp. – složení zkoumaných mikrooblastí: (A, B) dendrity, (C) eutektoid.

metalworker during the manufacturing of the mould from Elgiszewo (*Garbacz-Klempka et al. 2017*, 176). The evidence for this comes from the thermal decomposition of tetrahedrite, which can be expressed by two simplified equations (*Baláž 2000*, 125):

$$2Cu_{12}Sb_4S_{13} \rightarrow 8Cu_3SbS_3 + S_2\uparrow \qquad (1)$$

$$4Cu_3SbS_3 \rightarrow 6Cu_2S + 4Sb + 3S_2\uparrow \qquad (2)$$

4.3. Microstructure analysis

In the exposed micro-area, an as-cast structure preserved, which may suggest that the mould was not subject to any plastic working or heat treatment (*Baron et al. 2016*, 193; *Garbacz-Klempka et al. 2016b*, 31–32; *2017*, 176). It is important to mention that some microstructures indicating an incipient recrystallization process are also evident in the investigated micro-area (*fig. 6: c*).

The cored dendrites are indicative of fast liquid metal cooling, whereas diversified arm-spacing of dendrites suggests that the cooling rate was graded throughout the entire volume of the liquid metal during its solidification (*Baron et al. 2016*, 196).

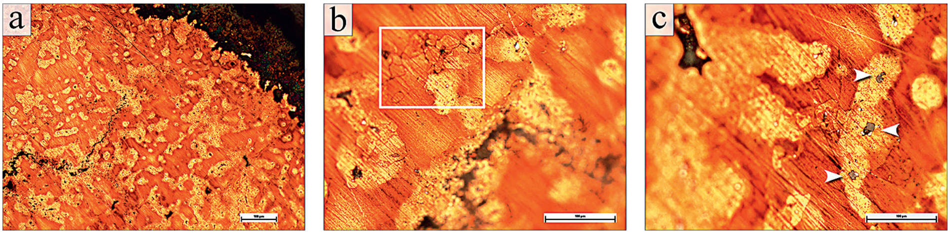

Fig. 6. The OM images of the microstructure of the casting mould from Elgiszewo: a – 100x; b, c – 500x.
Obr. 6. Mikrostruktura licí formy z Elgiszewa (optická mikroskopie): a – 100x; b, c – 500x.

Optical microscopy (OM) also displayed some porosity partially affecting grain boundaries (*fig. 6: a*; see also *fig. 5: b, c*). The intergranular corrosion could lead to a significant reduction in the tensile strength and ductility of the mould (*Garbacz-Klempka et al. 2017*, 178), but did not actually limit its functionality in the past.

4.4. Macrostructure analysis

The find from Elgiszewo is a complete two-part casting mould designed for multiplying *Przedmieście* type socketed axes. The object is preserved in a good condition. The surface of the mould is covered with a dark brown bog patina and some corrosion marks are also visible (*fig. 7: i*; see also *fig. 1*). The weight of the male and female part of the mould seems to be standardized and equals 298 g and 314 g, respectively, with a total weight of 612 g. The male part is 13.9 cm long and 4.2 cm wide at the blade negative and metrically refers to the female part, which is 13.8 cm long and 4.3 cm wide. The mould from Elgiszewo was suitable for casting the *Przedmieście* type axe, which could have been 10.8 cm long, 3.2 cm wide at the blade part with an outer socket diameter of about 3 cm (*figs. 1* and *2*).

On the inner side of the male part, four pegs which fitted into four holes in the female part (*fig. 7: e, h*; see also *figs. 1* and *2*) are evident. The pegs were meant to provide a proper joining and stabilization for the both parts of the mould during casting. Two broken knobs, which are visible on the outer side of the mould (*fig. 7: g*; see also *figs. 1* and *2*), tied both parts together and were used to open the mould (cf. *Baron et al. 2016*, 189). It was also essential for the LBA metalworker to provide the mould with smooth walls and well-developed pattern negatives such as grooves of the central orante motif with the raised arm gesture (*fig. 7: b*) or the axe loop (*fig. 7: a*). All this was intended to add smoothness and precision to the final axe casting.

The split with a total length of 2.5 cm is discernible on the feeding channel of the mould (*fig. 7: f*). The character of this damage, together with its location, may both confirm that the mould was used in the past. Further evidence comes from the broken knobs (*fig. 7: g*; see also *figs. 1* and *2*) and pancake-like smoothing above the knobs (see *fig. 1*).

It is essential to stress that longitudinal and parallel cracks cluster around the blade, socket, and neck part on the inner side of the mould (*fig. 8*). This damage oscillates around a few tenths of a millimetre in depth and their length varies between 1 mm up and 9 mm. If the mould from Elgiszewo was indeed used for direct casting, it would have been expo-

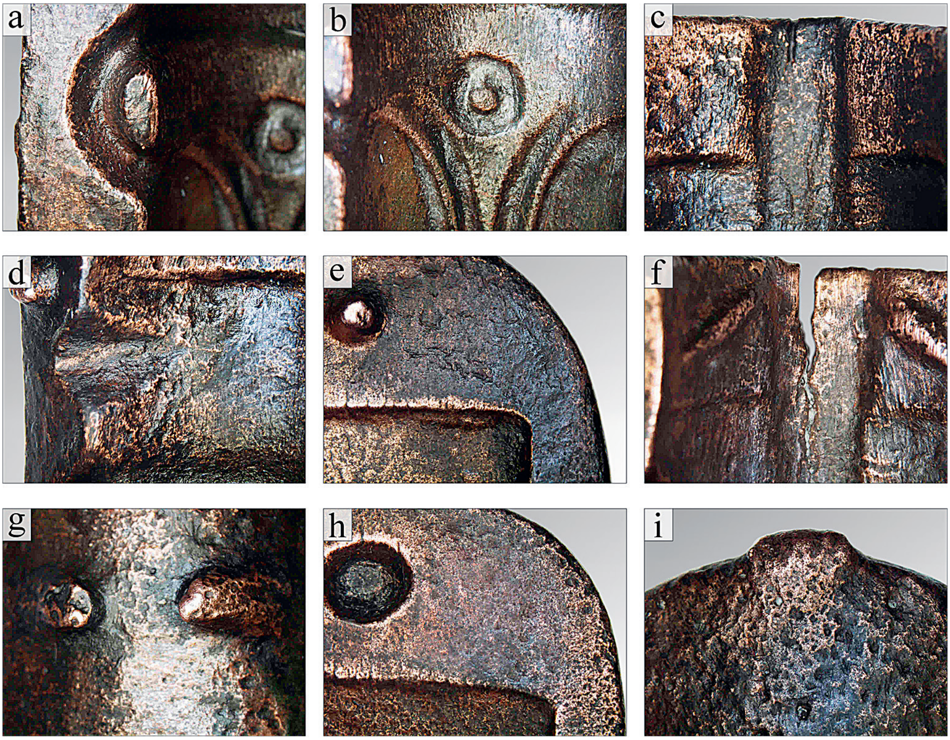

Fig. 7. The macrostructures of the casting mould from Elgiszewo: a – loop negative; b – orante motif negative; c – feed channel; d – neck part with a cut-off line; e – peg; f – split; g – broken knob; h – peg hole; i – casting porosity.
Obr. 7. Makrostruktura licí formy z Elgiszewa: a – negativ poutka; b – negativ motivu 'oranta'; c – nálitek; d – část krčku s dělící rovinou; e – vodící kolík; f – prasklina; g – zalomený výstupek na vnější straně formy; h – vodící jamka; i – pórovitost odlitku.

sed to thermal stress, which may lead to the conclusion that the mentioned macrostructures are thermal fatigue cracks.

4.5. X-ray defectoscopy

The X-ray defectoscopy revealed serious corrosion resulting in cracks and splits around the neck and socket part of the mould (*fig. 9: a*). Some damage is visible on the edges of the female part (*fig. 9: c*). Although the metal core of the neck part has been heavily disturbed (*fig. 9: a, c*), the remaining casting volume is generally complete. Inside the mould, the negative of the *Przedmieście* type axe, with its noteworthy central orante motif, is still visible and well-preserved (*fig. 9: a, c*).

4.6. 3-D model visualization

Casting defects are barely noticeable on the 3-D model (*fig. 10: a, c*). The final geometry of the axe confirms its typological attribution to the *Przedmieście* type (see Chapter 2).

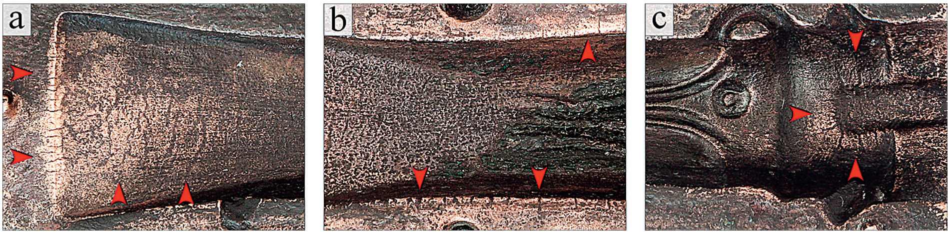

Fig. 8. Thermal fatigue cracks left on the inner side of the casting mould from Elgiszewo: a – blade part; b – socket part; c – neck part.
Obr. 8. Tepelné trhliny ponechané na vnitřní straně odlévací formy z Elgiszewa: a – část pro čepel; b – část pro tulejku; c – část pro krček.

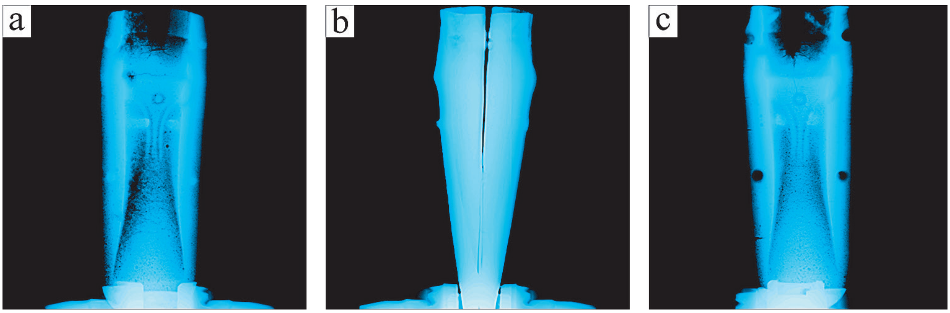

Fig. 9. The X-ray images of the casting mould from Elgiszewo.
Obr. 9. Rentgenogramy licí formy z Elgiszewa.

Assuming that the Lusatian metalworker could ensure an adequate alloy and was able to maintain the proper conditions during the casting, he/she could have obtained a cast of good compactness, as is shown in *fig. 10*.

4.7. Experimental casting

In the first stage, a model alloy consistent with the chemical composition of the mould from Elgiszewo was used to cast an experimental mould (*tab. 3* and *fig. 11: a*). The second stage of the experiment involved casting a socketed axe that would fit the reconstructed mould. The alloy used for the model axe (*tab. 3*) was composed with reference to other LBA socketed axes (*Przedmieście* and *Czarków* type) recognized in terms of chemistry (*Sałat et al. 2006*, 148, tab. 1).

Casting	Cu	Ag	Sn	Sb
Model alloy IV (Mould)	96	1	...	3
Model alloy V (Axe)	92	...	8	...

Tab. 3. The model alloy profiles of the experimental mould and axe castings.
Tab. 3. Chemické složení experimentálních odlitků licích forem a sekery.

Fig. 10. The 3-D visualization of the casting mould from Elgiszewo and the compatible Przedmieście type axe.
Obr. 10. 3-D vizualizace licí formy z Elgiszewa a odpovídající sekery typu Przedmieście.

Fig. 11. The stages of the experimental casting of the Przedmieście type axe compatible with the casting mould from Elgiszewo: a – casting the mould; b – pre-heating the mould; c – knocking the casting out of the mould.
Obr. 11. Fáze experimentálního odlití sekery typu Przedmieście, která je kompatibilní s licí formou z Elgiszewa: a – licí forma; b – předehřev licí formy; c – vyklepnutí odlitku z formy.

Two parts of the mould were covered with a layer of organic coating (composed of milled charcoal mixed with animal fat and ash in a 1:1 ratio) to prevent welding with the poured liquid metal. The coating was mechanically applied on the mould surface and fired in the flame of the burner. Next, both parts were matched together and pre-heated to the temperature of 130–150 °C (*fig. 11: b*). The casting temperature was 1150 °C. The alloy solidification proceeded very quickly due to the rapid dissipation of heat from the mould which was allowed to cool, and after 10 minutes, the casting was knocked out (*fig. 11: c*).

The Brinell hardness for the CuSbAg ternary alloy (= model alloy IV) reached the value of 70 HB (*tab. 4*), which is most likely due to the lack of the tin component in the model alloy. A similar result was obtained for pure copper (= model alloy I).

Model alloy	***Alloy profile***	**HB**
Model alloy I	Cu	65
Model alloy II	CuSn11(PbNi)1(SbAsAg)0.5	107
Model alloy III	CuSn10(PbNiSbAsAg)1	122
Model alloy IV (Mould)	CuSbAg	70
Model alloy V (Axe)	CuSn8	83

Tab. 4. The comparison of the Brinell hardness (HB) values for the experimental mould and axe castings, and the model alloys.
Tab. 4. Srovnání hodnot tvrdostí (HB dle Brinella) základních typů modelových slitin užitých k experimentálnímu odlití licích forem a sekery.

The casting temperature of the axe model alloy (= model alloy V) reached 1150 °C, which was significantly higher than the temperature routinely recommended for bronze casting. Consequently, gas porosity and other numerous casting defects occurred (*fig. 12: c*) but, nevertheless, the mould did avoid apparent damage (*fig. 12: a*).

5. Discussion

5.1. General remarks

The alloy profiles of the casting mould from Poland (Elgiszewo, Gaj Oławski, and Rosko) are broadly similar (*tab. 5*). The mould from Elgiszewo has the lowest content of tin (Sn = 0.36 wt%; see *tab. 1*), which was due to the deliberate treatment by the Lusatian metalworker to maintain a thermal resistance of the mould during direct metal casting. According to *Baron et al.* (*2016*; *Baron – Miazga – Nowak 2014*), the same can be true for the mould from Gaj Oławski. The same authors have acknowledged that the find from Gaj Oławski only provided a service for lost-wax casting. *Sałat et al.* (*2006*) came to similar conclusions working on the mould from Rosko. It seems that such application was not the predominant use of the mould from Elgiszewo. We believe that there would have been no apparent need for the Lusatian metalworker to abandon a genuine (standard) bronze alloy if the mould had been intended only for preparing single-use wax models.

Mould	*Compatibility*	Fe	Co	Ni	Cu	As	Ag	Sn	Sb	Pb	Bi
Rosko	*Przedmieście*	0.01	*N/A*	0.27	89	0.59	*N/A*	8.4	1.4	0.66	0.01
Gaj Oławski	*Kowalewko*	*N/A*	*N/A*	0.46	90	0.67	*N/A*	6.9	2.0	0.12	*N/A*
Elgiszewo	*Przedmieście*	0.05	0.06	0.59	93	0.82	1.4	0.36	3.2	0.53	0.04

Tab. 5. Chemical data for the LBA metal casting moulds from Poland (*Machajewski – Maciejewski 2006*; *Sałat et al. 2006*, 148, tab. 1; *Baron – Miazga – Nowak 2014*, 334, tab. 1, as amended).
Tab. 5. Prvkové složení licích forem mladší a pozdní doby bronzové z Polska (*Machajewski – Maciejewski 2006*; *Sałat et al. 2006*, 148, tab. 1; *Baron – Miazga – Nowak 2014*, 334, tab. 1, upraveno).

The chemical signatures reported for the moulds from Poland indicate a low lead content varying between 0.12 wt% and 0.66 wt% (see *tab. 5*). Interestingly, lead should not be present in amounts greater than 0.005 % if the copper alloy is meant to be processed with heat treatment. This is due to the fact that upon heating in the range from 500 °C to 900 °C, such an alloy remains in the two-phase area and lead-rich liquid is existent in equilibrium with the copper-rich terminal solid solution. Hence, the liquid wets the grain boundaries and forms a film on them, leading to alloy disintegration. This phenomenon is known as a hot shortness (*Davis 2001*, 34). Apparently, the disadvantages of introducing lead[4] (and tin) to an alloy must have been recognized by the metalworkers who fashioned the casting

[4] The intentional addition of lead has been confirmed for the phalerae and some armbands found in the hoard from Elgiszewo (*Gackowski 2016*, 168–170, fig. 2). Since the research on the hoard is still in progress, a strict reference to chemical data on the remaining metal finds is not currently possible.

Fig. 12. The experimental Przedmieście type axe casting compatible with the casting mould from Elgiszewo.
Obr. 12. Experimentální odlitek sekery typu Przedmieście odpovídající licí formě z Elgiszewa.

moulds found in Elgiszewo, Gaj Oławski, and Rosko (see e.g. *Garbacz-Klempka et al. 2016a* for evidence of modifying the alloy composition by the Lusatian metalworkers).

5.2. Towards direct casting implementation

Several types of inclusions were found in the microstructures of the mould from Elgiszewo, but special attention should be paid to those recognized as copper sulphides. One of these, displayed in the Elg_12 EDS micro-area (see *tab. 2* and *fig. 5: f*), is a product of the tetrahedrite thermal decomposition (Cu_2S). The other, visible in the Elg_13 EDS micro-area as a spherical particle (*fig. 5: e*) had been completely molten and solidified into a sphere, which implies that the melting temperature of the ore was 1100–1150 °C (*Niehuis – Sietsma – Arnoldussen 2011*, 59). Since the sulphide-rich ores resist smelting (and thus cannot be reduced directly), it was essential for the LBA metalworker to implement roasting (oxidation) prior to smelting (reduction) in order to remove most of sulphur from the fahlore. Usually, this process is accomplished at around 700 ºC (*Niehuis – Sietsma – Arnoldussen 2011*, 59; *Ashkenazi – Iddan – Tal 2012*, 532–533; *Pernicka 2014*, 253; *Garbacz-Klempka et al. 2017*, 176–179).

The investigated mould preserves the as-cast structure (see *fig. 6*), which may suggest that no heat treatment (annealing) was implemented after the mould had been cast. Following the same line of reasoning, *Baron et al.* (*2016* and *Baron – Miazga – Nowak 2014*) concluded that the mould from Gaj Oławski was never used for direct metal casting. Such a scenario may be, however, diminished. Here, if the bronze moulds indeed provided a service for direct casting in the past, they actually do not have to be expected to act in a similar manner upon annealing. The microstructural changes accompanying annealing in bronze were described in detail by *Rawdon* (*1916*, 13–14), who claims that the diffusion process is a relatively slow one because the interior dendritic pattern of the crystals loses its identity and becomes homogeneous. During recrystallization, soft and strain-free crystals tend to nucleate and grow in a plastically-deformed matrix, and once such a matrix is absorbed by these new crystals, further annealing would only be followed by grain growth (*Davis 2001*, 243). The consumption (absorption) of the eutectoid is dependent on the cooling rate during casting solidifying (*Rawdon 1916*, 14–15). In terms of LBA metalworking practice, the solidification of the alloy is believed to have proceeded readily due to the rapid dissipation of heat from the mould, and consequently, such an object should generally appear an as-cast structure. The microstructure adjacent to the mould surface might possibly be affected upon heat treatment (preheating and filling the mould), but the cooling rate was quick enough to protect the metal from a high temperature factor, allowing the mould to be preserved an as-cast structure. A striking result of the OM examinations of the mould from Elgiszewo was the fact that the presence of isolated nuclei in the dendritic matrix was confirmed (see *fig. 6: c*), which is indicative of an incipient recrystallization process. It is important to stress that the OM observations were made on the broken knob, which is located on the outer part of the mould. Since the knobs were only used to open the mould, the investigated micro-area could not have been affected by the liquid metal directly during mould filling. Ultimately, the lack of a homogeneous microstructure in the outer parts of the bronze mould does not necessarily exclude the possibility of its use for direct metal casting.

The presence of the thermal fatigue cracks on the inner side of the mould (see *fig. 8*) can be explained by the phenomenon of thermal stress.[5] In the early stage of casting, the liquid metal flowed into the mould causing a sudden increase in temperature on the inner surfaces, which were simultaneously constrained by the cooler material beneath them and therefore exposed to the compressive stress. As soon as the mould was opened, the cooling stage began (*Kayikci et al. 2009*, 145). Temperature gradients had initiated the thermal stress, which resulted in the accumulation of local plastic strains on the mould surface and lead to the occurrence of the thermal cracks.

The microstructure adjacent to the mould surface was exposed to gradual softening due to intense heating by the liquid alloy (*Muhič et al. 2010*). Apparently, this caused defects discernible around the neck part of the mould (see *fig. 9: a, c*), namely, a split running through the feeding channel (see *fig. 7: f*). *Muhič et al.* (*2010*) noticed that thermal cracks tend to also occur on locations with higher stress concentration (i.e. edges and corners with small radiuses), which corresponds well to the cracks affecting the blade and socket part of the mould (see *figs. 7: e, h* and *8: a, b*).

An experimental approach (see Chapter 4.7) proved that the mould from Elgiszewo could have been successfully employed by the Lusatian metalworker for direct casting. If the mass of the mould was adequately high in comparison to the casting, there was no danger of melting the mould (*Tylecote 1987*, 210; *Kuijpers 2008*, 89). However, direct casting required an extremely short cast time of about 3 s. Otherwise, the final product would be incomplete in the edge parts (*Wirth 2003*, 84; *Baron et al. 2016*, 188). It is reported that the casting of fifteen socketed axes in one bronze mould is possible with no apparent damage to the mould (*Drescher 1957*; *Kuijpers 2008*, 89; *Baron et al. 2016*, 188).

5.3. Raw-material provenance and possible (re-)distribution channels

The casting mould from Elgiszewo was made of fire refined (oxidized) fahlore scrap bronze (see Chapter 4.1). Yet, after taking a closer look at the chemical signature of the analysed object, it appears that the mould has a distinct tendency towards the LBA (1100–700 BC) metalwork from the Nordic zone reported by *Ling et al.* (*2014*, 118–119, tab. 1)

[5] The fahlore copper is advantageous in direct metal casting inasmuch as the antimony and arsenic addition increases the tensile stress of copper (*Junk 2003*, 19–34). Perhaps, this was also noticed by the Lusatian metalworkers. In this context, it is worth to recall the chemical data on the hoard from Rosko reported by *Sałat et al.* (*2006*, 148, tab. 1) demonstrating that the casting mould ('ON'–'ONA') has a distinct tendency towards fahlore, while some other accompanying socketed axes seem to share different (non-Fahlerz) chemical signatures.

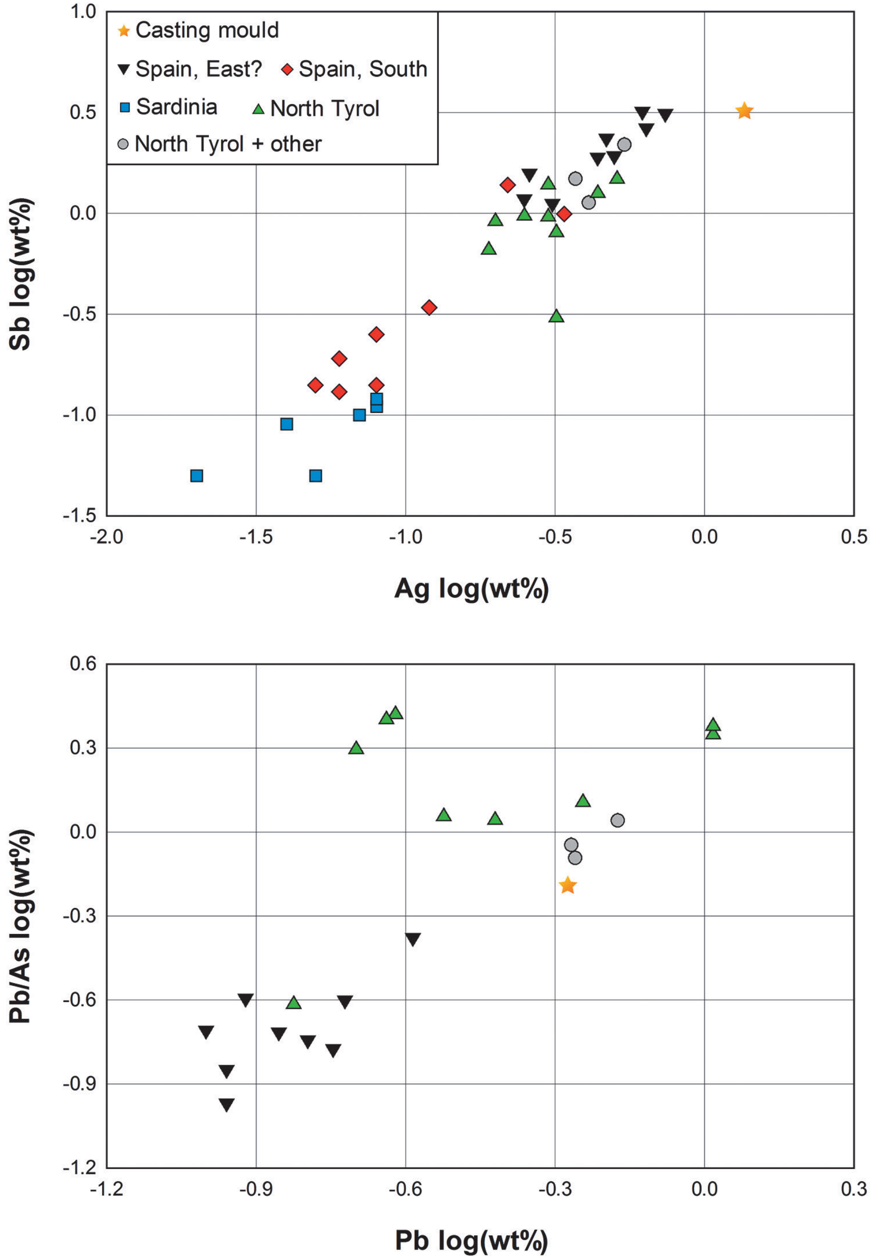

Fig. 13. Chemical characteristics of the LBA (1100–700 BC) metalwork from the Nordic zone and the casting mould from Elgiszewo. The diagrams Ag vs. Sb and Pb vs. Pb/As show chemical correlation between the casting mould and the North Tyrolean copper fahlores (*Ling et al. 2014*, 118–119, tab. 1, adapted).
Obr. 13. Chemické charakteristiky odlitků mladší a pozdní doby bronzové (1100–700 př. n. l) ze severské zóny a licí formy z Elgiszewa. Diagramy Ag vs. Sb a Pb vs. Pb/As ukazují chemickou korelaci mezi licí formou a sulfidickými měděnými rudami ze severního Tyrolska (*Ling et al. 2014*, 118–119, tab. 1, upraveno).

as cast from North Tyrolean copper. To validate this correlation, we used the principles formed by *Pernicka* (*1999* and *2014*) that silver and nickel are quite stable in the *chaîne opératoire* applied during ore processing (i.e. extraction, smelting, and casting) and correlate with the metal source. The content of arsenic and antimony may be reduced during ore processing, but they are still useful in fingerprinting the metal source (see also *Ling et al. 2013* for geochemical fingerprints).

Plotting the content of silver against the corresponding quantities of antimony kept the mould from Elgiszewo closely to the North Tyrolean fahlore and some of those originating from the Iberian Peninsula line (*fig. 13*). Ultimately, the Pb vs. Pb/As diagram tied up the analysed mould with the the North Tyrolean fahlores (see *fig. 13*); this chemical correlation needs to be confirmed by the lead isotope analysis.

It is important to mention that 40 % (n = 8) of the artefacts analysed by *Ling et al.* (*2014*, 120–121, Tab. 3) and dated to the Montelius V correlate well with the copper fahlores and slags from Schwaz-Brixlegg in North Tyrol.[6] This corresponds to the findings made by *Lutz* and *Pernicka* (*2013*, 126), who have stated that in the LBA the exploitation of copper ores was continued across all of the Austrian mining districts and was marked by the large-scale extraction of fahlores resumed at Schwaz-Brixlegg region. This statement was reasserted by *O'Brien* (*2015*, 183).

According to *O'Brien* (*2015*), copper distribution across the LBA Europe was monopolized by large mining centres, notably those in the eastern Alps, and due to limited supplies, the metal circulation may have been strongly allied with exchange networks and recycling systems. Concerning the 'Urnfield Barbaricum', this found an echo in some regions lacking metal resources that became able to establish metalworking practices of their own. Good examples are Eastern Pomerania and Silesia – Greater Poland – Lubusz land metallurgical pan-province (*Bukowski 1998*; *Blajer 2001*).

Emerging from these assumptions is an image of possible (re-)distribution channels for the North Tyrolean fahlores. It does seem that this was strictly connected with the central European amber routes established already by the North Alpine Danubian/Únětice communities and maintained during the Tumulus and Urnfield periods (*Ling et al. 2014*, 128). Via those routes (*Handelskorridor*), the Nordic zone of the Urnfield complex was supplied with Tyrolean metal (*Kaczmarek 2012*, 378–387; *Ling et al. 2014*; *O'Brien 2015*). This exchange network is likely to have been channelled through the Danubian route towards Silesia. Consequently, the Silesia – Greater Poland – Lubusz land metallurgical pan-province could become a secondary centre from which the Tyrolean copper fahlores (and also metalwork) were further redistributed (*fig. 14*; *Bukowski 1981*; *Kaczmarek 2012*; *2017a*).

6. Final remarks

The distribution of the bronze casting moulds in Poland reflects the process of integrating the Chełmno group community with the southwestern ecumene of the Lusatian culture at the end of the Bronze Age. The active role of the Silesia – Greater Poland – Lubusz land

6 The copper fahlores from Schwaz-Brixlegg have significant amounts of As, Sb, Ag, and Bi but low contents of Co and Ni (*Lutz – Pernicka 2013*, 123).

Fig. 14. Distribution of the LBA metal casting moulds from Poland ✪ against the backdrop of the North Tyrolean copper fahlores exchange network ● with possible (re-)distribution in the Lusatian culture ecumene (*Gardawski 1979*, 197, ryc. 44; *Kaczmarek 2012*, 378–387, ryc. 156; *2017a*, 95, ryc. 5; *Baron – Miazga – Nowak 2014*, 327, fig. 1; *Ling et al. 2014*, 129, fig. 21; *Kłosińska – Sadowski 2017*; *Lubuski Wojewódzki Konserwator Zabytków 2018*, adapted; map background: Yarr65/Shutterstock.com).
Obr. 14. Prostorové rozšíření licích forem mladší a pozdní doby bronzové z Polska ✪ na pozadí obchodních cest umožňujících směny sulfidických měděných rud ze severního Tyrolska ● s možnou (re-)distribucí v lužické oikumeně (*Gardawski 1979*, 197, ryc. 44; *Kaczmarek 2012*, 378–387, ryc. 156; *2017a*, 95, ryc. 5; *Baron – Miazga – Nowak 2014*, 327, fig. 1; *Ling et al. 2014*, 129, fig. 21; *Kłosińska – Sadowski 2017*; *Lubuski Wojewódzki Konserwator Zabytków 2018*, upraveno).
1 Brzeg Głogowski, Głogów dist.; 2 Elgiszewo, Golub-Dobrzyń dist.; 3 Gaj Oławski, Oława dist.; 4, 5 Kiełpino, Gryfice dist.; 6 Nowe Kramsko, Zielona Góra dist.; 7 Pawłowiczki, Kędzierzyn-Koźle dist.; 8, 9 Rosko, Czarnków-Trzcianka dist.; 10 'from the Sieniocha River area'.

metallurgical pan-province in shaping the metalworking practice of the northern Lusatian peripheries must be acknowledged. However, there is little archaeological evidence proving that the Chełmno group had the capacity to drive this metalworking trend forward and carry out local bronze smithing during the LBA (see e.g. *Gackowski 2016*). There are also strong indications that Chełmno group metalworkers did not develop their own local style. Rather they focused on imitating foreign metalwork (*Gackowski 2016*, 174–175; see also *Garbacz-Klempka et al. 2016a*; *2017*), which strongly diminishes the local origin and use of the casting mould from Elgiszewo.

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