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Forging a New World Order? Interdisciplinary Perspectives on the Management of Metalworking and Ideological Change in the Late Bronze Age Carpathian Basin

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Abstract

The Carpathian Basin was a highly influential centre of metalworking in the 2nd mil. BC. Nevertheless, despite the abundance of metal objects from the Late Bronze Age, the scarcity of contextually associated metalworking remains representing distinct phases of the metalworking cycle from this region is striking. Here, we explore Late Bronze Age metalworking through the lens of a uniquely complete metalworking assemblage from the site of Șagu from contexts spanning the sixteenth to early thirteenth century BC. This material provides insights into changes in craft organisation following socio-political change after the collapse of Middle Bronze Age tell-centred communities. Our approach combines analytical and experimental data together with contextual analysis of technical ceramics (crucible, mould, and furnace fragments) to reconstruct the metalworking *chaîne opératoire* and place Șagu in its broader cultural context. Analyses demonstrate clear technological choices in ceramic paste recipes and strong interlinkages between metallurgy and other crafts practised on site, from domestic pottery production to building structures. Experimental replications reveal important intrinsic and experiential aspects of metallurgical activities at Șagu. Evidence on the spatial organisation of metallurgical workflows (routine sequence of actions and decisions) suggests they incorporated a high degree of visibility, which marks a distinct change in the use of craft space compared to the context of densely occupied Middle Bronze Age tells nearby. Combined, our archaeometric, experimental, and contextual results illustrate how changes in metalworking activities in the Late Bronze Age Carpathian Basin were deeply embedded in an ideological shift in the aftermath of the breakdown of Middle Bronze Age tells and the emergence of new social structures.

Keywords Late Bronze Age · Carpathian Basin · Crucible metallurgy · Technical ceramics · Experimental archaeology

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Introduction

Following hundreds of thousands of years of stone tool use, metal took as little as 3000 years to progress from a rare, prestige material to a staple resource defining routine social practices. By the mid-2nd mil. BC, Europe was defined by these metal-using societies. Wider social strategies of wealth, power, display, and control facilitated this transformation through craft environments. The choices made by past craftspeople extended beyond raw materials or tools used, as they were also socially and culturally defined (Pfaffenberger, 1992). The latter places the transfer of technological know-how at the heart of social networks. Thus, the management of metalworking can reflect differentiated political and ideological thought packages (*e.g.* see Zori, 2019), as much as technological decision making within its human–environment interaction context (Sofaer, 2006). Here, we present analysis of a uniquely complete Late Bronze Age (LBA) metalworking assemblage to provide new insight into how changes in craft organisation were instrumentalised following a period of significant social change. This covers the collapse of the political infrastructures of the Middle Bronze Age in the southeastern Carpathian Basin ca. 1600–1550 BC and the reconfiguration of societies in the following LBA I and II (1600/1550–1200 BC) periods.

Recent research has shed new light on the origins of global metallurgy in southeastern Europe during the Neolithic. The transformative potential of metallurgy as a craft fosters creative and cultural expressions through its practice, along with the activities metal products enable (Jørgensen et al., 2018; Radivojević et al., 2021; Sofaer, 2006). By the Late Bronze Age, metalwork had become ubiquitous to the extent that it shaped lifeways through routine activities while also forming a core component of economic and ritual expressions of power across Europe (Brück & Fontijn, 2013; Earle et al., 2015; Fontijn, 2019). Archaeometric research has revealed insights into the circulation of metal as a resource and into object biographies (through metallography, metalwork wear analysis, and fragmentation studies) that explore specific human-object interactions over time (*e.g.* Dolfini & Crellin, 2016, Horn & von Holstein, 2017, Knight, 2019, Ling et al., 2019, Mödlinger & Trebsche, 2021, Mödlinger, 2011, 2021, Molloy, 2018, Nørgaard et al., 2021, Radivojević et al., 2019, Radivojević et al., 2021, Tarbay et al., 2021). Fewer studies have focussed on craft choices through the lens of particular technical ceramics, and these typically focus on specific components of the *chaîne opératoire* (Amicone et al., 2020b, Binggeli, 2011; Eklöv Pettersson, 2012; Ó Faoláin 2004; Needham 1980; Sahlén, 2013). Considering Ottaway's (2001: Fig. 1) or Molloy and Mödlinger's (2020: Table 1) models of the metalworking cycle, there are notable gaps in our knowledge because much focus has been placed on the finished products and less on the creative, organisational, and power dynamics which can elucidate the social context enabling the metal consumption revolution that characterised the Late Bronze Age (Vandkilde, 2016). While this is often a limitation dictated by the archaeological record itself, the study of the role of Bronze Age metalwork and metalworking has nonetheless gravitated towards finished objects and their social roles. The status and identity of bronze workers in prehistory, and how the organisation of their craft articulated with elite agendas of resource management, has often been built on ethnography, theory, or mortuary archaeology, though recent work takes greater account of Budd and Taylor's call to better integrate theory

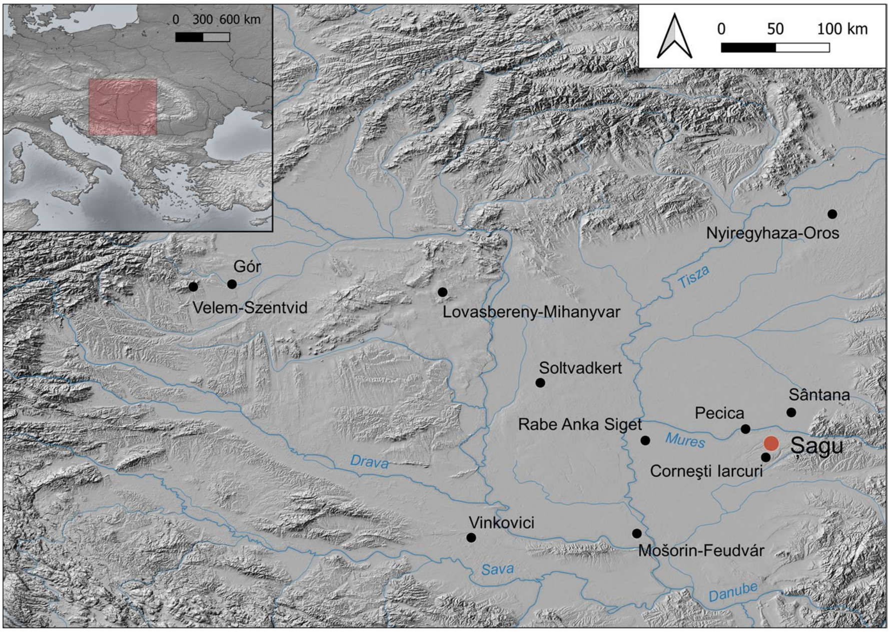

Fig. 1 Map of the Carpathian Basin showing the locations of sites mentioned in the text and major rivers (base map from The European Environment Agency; www.eea.europa.eu)

with archaeometric approaches (Budd & Taylor, 1995; see also Brandherm, 2009; Iles & Childs, 2014; Jantzen, 2008; Jockenhövel, 2018; Neipert, 2006; Nessel, 2013; Rowlands, 1971). Broader studies of the Bronze Age metalworking *chaîne opératoire* have focussed on regional overviews, theoretical reflections on practice, or general technical principles, which provide top-down perspectives on the period in Europe (Kuijpers, 2018a; Molloy & Mödlinger, 2020; Ottaway, 2001).

The study of the social context and relevance of metallurgy in the Late Bronze Age can benefit from an integrated, multi-scalar approach that begins with a more complete understanding of socially situated craft practice—particularly in the cases where the archaeological record provides clues for the various steps of the metallurgical cycle, and not just the finished objects (for a later period example see Orfanou et al., 2021). Along with the structural components of the processes of copper-based metallurgy bound by technology, the nuances of how craft was organised in a particular Bronze Age society are fundamental to understanding technique, knowhow, integration, organisation, and ultimately the meaning of metallurgy for that society (*e.g.* Kuijpers, 2018a, 2018b; Norgaard 2018; Sofaer & Budden, 2013). Such a scalar approach requires us to focus on well-preserved datasets where many steps of the *chaîne opératoire* are preserved together, to provide insights into specifics that can inform our general understanding of craft practice. We explore this theme using a combined contextual, archaeometric, and experimental approach to metal production at the Bronze Age site of Şagu in the Carpathian Basin, where such a diverse assemblage is preserved. The Şagu assemblage provides a unique opportunity to employ such an interdisciplinary approach and, thus, enables a dialectic in

Table 1 List of ceramics (crucibles, moulds, furnace fragments, domestic pottery) from Şagu analysed during this study ("Y" = yes/analysed with the respective technique mentioned in the column; "-" = not analysed)

Sample ID	Description	Context and feature	hhXRF (surface)	Petrography (thin sections)	RLM and SEM (mounted cross-sections)	XRPD and SEM (firing estimation)
C1	Crucible	cx. 198	Y	Y	Y	-
C2	Crucible	cx. 182	Y	Y	Y	-
C3	Crucible	-	Y	Y	Y	-
C4	Crucible	cx. 198	Y	Y	Y	-
C5	Crucible	cx. 198	Y	Y	Y	Y
C6	Crucible	-	Y	Y	Y	-
C7	Crucible	cx. 71	Y	Y	Y	Y
C8	Crucible	cx. 71	Y	Y	Y	-
F1	Furnace	cx. 194	Y	Y	-	Y
F2	Furnace	cx. 72	Y	Y	-	Y
F3	Furnace	cx. 85	Y	Y	-	-
F4	Furnace	cx. 92	Y	Y	-	-
F5	Furnace	cx. 177	Y	Y	-	-
M1	Mould	cx. 195	Y	Y	-	Y
M2	Mould	cx. 198	Y	Y	-	Y
DP1	Domestic	cx. 91	Y	Y	-	-
DP2	Domestic	cx. 91	Y	Y	-	Y
DP3	Domestic	cx. 35	Y	Y	-	Y
DP4	Domestic	cx. 35	Y	Y	-	-
DP5	Domestic	cx. 236	Y	Y	-	-
DP6	Domestic	cx. 236	Y	Y	-	-
DP7	Domestic	cx. 198	Y	Y	-	Y
DP8	Domestic	cx. 198	Y	Y	-	Y
DP9	Domestic	cx. 198	Y	Y	-	-
DP10	Domestic	cx. 198	Y	Y	-	-

our analyses whereby feedback loops between distinct methods enrich our understanding of the social context of metalworking.

The Carpathian Basin, centrally located in Europe, is geographically advantageous as it is connected via long-distance river routes, enabling the creation of extensive trade and communication networks (Fischl & Kiss, 2015; O'Shea, 2011). Its flat interior, the Pannonian Plain, was home to extensive and often densely spaced settlements during the Bronze Age. This region became a well-known centre of innovation in metalworking in the 2nd mil. BC (Vandkilde, 2014). The progression from prestige to more commonplace use of metals in the Carpathian Basin occurred in the context of complex tell-centred polities, which were at their height (ca. 2200–1550 BC) in the later Early and Middle Bronze Age (MBA). Though unfolding over decades, the tell settlement network had collapsed between 1600 and 1500 BC with the abandonment of virtually all tells and the breakdown of the supporting social infrastructures (Staniuk, 2021).

To better understand the technological and social context of LBA metalworking, we adopt a multidisciplinary approach to study the Şagu assemblage. We explore the technological context and the workflows of activities through the properties of the metallurgical remains (crucibles, moulds, furnace fragments) by combining analytic and experimental approaches. The set of analyses addressed questions about the raw materials and the technological processes involved. The experimental reproductions were modelled after the analytical results and aimed, firstly, to confirm the nature of metallurgical activities and, secondly, to provide parallels for the long-term preservation of metallurgical traces, as low-fired ceramics are often under-represented in the archaeological record. The social context of metalworking is investigated through depositional patterns and the implications these have for the use of space. Using these combined approaches, we aim to reconstruct key elements of the *chaîne opératoire* of LBA crucible metallurgy in southeastern Europe for the first time by offering detailed insights into the spatial and technological attributes of this craft and its cross-craft interlinkages with other local industries. We further explore how changes in metallurgical activities between the MBA and LBA reflect broader social and ideological changes taking place in communities in the Pannonian Plain. Publication of the excavation is ongoing, and we present a selected sample of the pyrotechnical material recovered based on state of completeness, function, and accessibility.

Archaeological Context

Metallurgical Activities in the Middle Bronze Age Pannonian Plain

The management of craft and material resources of metalworking were central to MBA tell political economies (Demény et al., 2019; Duffy et al., 2019; Earle et al., 2015; Fischl et al., 2013b; Gogâltan et al., 2019; Nicodemus & O'Shea, 2019; Vicze, 2013). Metallurgical remains, mostly in the form of moulds (clay, stone) and tuyères, have been found in a number of MBA tells, whereas fewer structures with a clear metallurgical character, such as hearths, are identified (Găvan, 2012; Gogâltan, 2005). The occasional presence of metallurgical remains from MBA Carpathian flat settlements may suggest that access to this pyrotechnology, its knowhow, and resources was available, yet still limited. Sites defined as MBA primary centres, such as Pecica or Mošorin-Feudvár (Fig. 1), were also the foci of metalworking, consolidating political, economic, and ideological power (Falkenstein et al., 2016; Nicodemus & O'Shea, 2019). Available evidence confirms that most known metalworking debris comes from "fortified, central, and tell settlements", though excavation bias towards central sites may play a role (Fischl et al., 2013a). Metalworking traces at tell sites include collectively most of the metalworking *chaîne opératoire* including moulds, tuyères, and casting cores and debris, though these are often found with either poor stratigraphic definition or in secondary contexts (Găvan, 2015, 2020). Even though excavations at tells reveal them to be locations for metallurgical activities, occasional finds of moulds from flat settlements are a reminder of the bias created by the long prioritisation of fieldwork at tells. Nonetheless, without contextual data, it is impossible to tell if refractory ceramics or stone moulds at a site relate to craft activities or the widely attested practice of re-using these items for other types of activity, such as placing them in foundation deposits of structures (Găvan, 2015; Molloy & Mödlinger, 2020, p. 183). For this reason, we do not regard the presence of moulds recovered in isolation and/or without contextual information as implicitly demonstrating metalworking took place at a site. Thus, of the many sites with evidence of clay or stone moulds, such as Gór (Biró, 1995; Ilon, 2018), Soltvadkert (Gazdapusztai, 1958), or Vinkovici (Ložnjak Dizdar, 2013), they must remain possible rather than probable workshop locations.

A metal workshop within the tell at Mošorin-Feudvár is among the few sites where various elements of the metallurgical *chaîne opératoire* have been found in proximity or direct association. This is the only site with considerable spatial data for metalworking debris, thereby relating objects, spaces, and structures to each other (Găvan, 2015, p. 72; Hänsel & Medović, 2004). It includes evidence for mould making, various casting technologies (lost wax, bivalve moulds) and making a range of types of objects, which suggests a specialised craftsperson or small group operated within, and near to, a building identified by the excavators as a workshop (Găvan, 2015, p. 73). At another MBA site on the Pannonian Plain, Lovasbereny-Mihanyvar, hearths, crucibles, and two casting moulds were documented along with Vatya pottery, fitting the criteria for probable metalworking (Fischl et al., 2013a). Various metal casting remains are found across the tell at Pecica and though specific workshop installations have not been found in situ, concentration of finds in one area is noteworthy (Gogăltan, 1999; Nicodemus & O'Shea, 2019, Fig. 3.2). Craftwork at Pecica included the production of high-status objects, particularly axes. For other sites with available stratigraphic information, most metallurgical evidence is found in the core settled area of tells and rarely within the surrounding lower settlement (Găvan, 2015, 2020, p. 471).

Metallurgical Activities in the Late Bronze Age Pannonian Plain

Looking to the communities themselves, during and immediately following the MBA period of crisis, a new network of massive and frequently enclosed LBA sites emerged in the southeast of the Carpathian Basin (Harding, 2017; Molloy et al., 2020). Most sites were 10–40 ha, while they commonly reached up to 100 ha and, in exceptional cases, up to 1750 ha (see Molloy et al., 2020, Fig. 1). These sites represent a fundamentally new mode of inhabiting and managing the landscape and a novel means to monumentalise and defend settlements. Alongside the LBA settlements, flat cemeteries were established, and cremations became more prevalent. In many ways, the LBA world represented a fundamentally new social order.

At this time, a rich and diverse metalworking tradition, the so-called Koszider horizon (Vicze, 2013), flourished across the wider area. LBA settlements provided the context for metalworking activities as they transitioned to open settlements extending over 10s of hectares from the cramped confines of densely occupied tells of ca. 1–2 hectares. Despite the LBA Carpathian metalwork styles being influential across Europe, research into Bronze Age Carpathian societies has so far focused primarily on the MBA tells and their inhabitants, evident in fieldwork investment since the nineteenth century (Dani et al., 2019; Găvan, 2012; Kienlin et al., 2017; Staniuk, 2021). Over the past 10 years, this situation is changing with greater focus on the LBA. Nevertheless, based on current data we have limited knowledge of the organisation and social context of LBA metalworking. Given the central importance of metalworking in the geographic and political networks of

MBA societies, technological reorganisation in the new context of LBA settlement networks can inform us about processes of social change and resilience across a well-known horizon of rapid social transformation.

Bronze consumption in LBA Europe was integrated into all levels of society, being used widely for both utilitarian and prestige items (Earle et al., 2015, p. 634; Molloy & Mödlinger, 2020, p. 170; Nicodemus, 2014, p. 309). In contrast with the massive volume of known LBA metal finds, excavated bronze workshop locations are exceptionally rare anywhere in Europe (Molloy & Mödlinger, 2020, pp. 170, 183–188). While data from regions networked with the Carpathian Basin, such as the eastern Mediterranean, the Po Valley, or Scandinavia, inform us about the basic character of the bronze casting technology (Asderaki-Tzoumerkioti et al., 2017; Eklöv Pettersson, 2012, p. 201; Evely et al., 2012; Iaia, 2015; Jantzen, 2008), the culturally specific techniques and conventions of local smiths in the LBA have not been addressed. The presence of pyrotechnical ceramics at a site in isolation is minimally informative for the technical or spatial organisation of metalworking practice. Instead, contextual information on the find spot and associated finds and the co-deposition of various interlinked elements of the *chaîne opératoire* is important for identifying metalworking locations. For example, a possible furnace recovered at Soltvadkert, dated to BzC-D (ca. 1400–1200 BC), ca. 155 km northwest of Şagu, with moulds placed inside it, is clearly a structured deposit and the co-location of these objects suggests a workshop near or at this site (Gazdapusztai, 1958).

The well-known LBA site of Velem-Szentvid, excavated in the early and mid-twentieth century, has provided various metalworking remains including tuyères, crucibles, mould fragments, furnace fragments, bronze hammers, and bun ingots, though unfortunately with poor contextual information. While deposition of moulds was widespread across the site, most are said to be from domestic contexts and there is no distinct focal point of activity on the basis of available records (Ilon, 2018, pp. 115–116). While it is probable that metalworking took place at Velem-Szentvid, spatial and temporal patterns are disturbed and some findspots were clearly not related to metalworking, emphasising the need for caution in using the presence of objects to link sites and craft practice in cases where they are stray finds. Mould production is documented at the site of Gór, though it is unclear if such specialised craft was co-located in a settlement where casting was taking place (Biró, 1995; Dietrich, 2012a). Stray finds of LBA moulds or more rarely crucibles or tuyères are not uncommon, and Ilon identifies some 95 probable LBA sites with mould finds (Ilon, 2018; see also Kovács, 1986). At some sites, such as Nyiregyhaza-Oros, the various types of metallurgical remains can co-occur, but not in contextual association or in sufficient numbers to identify a definite workshop (Marta et al. 2010).

The recent discovery of crucibles, moulds, furnaces, ground-stone tools, and metal scraps from the site of Şagu in Romania is a rare case from the Carpathian Basin of a site with clearly defined contextual associations between different components of the bronze crafting process (Fig. 1). Due to the extensive excavations, spatial data are also available from this site to provide insights into organisation within the settlement and how this related to other functional spaces. In particular, the presence of heavy and relatively fragile (if moved) low-fired furnaces, and large fragments of these, strongly suggests that they were deposited close to where they were used. Located in the High Vinga Plain, at the foothills of the Carpathian Mountains, Şagu was discovered and comprehensively excavated in advance of motorway construction, and remains partially published (Sava et al., 2011). The material from Șagu represents thus-far a uniquely complete in situ evidence of metalworking and covers several technological steps from melting of ingots to the casting of finished objects. The preservation of this assemblage is exceptional because the occupants of LBA Șagu saw fit to deposit materials in the protected environment of pits.

Excavations at Șagu

Situated in the hinterland of larger and more complex sites such as Corneşti Iarcuri or Sântana (and close to the earlier centre of Pecica), there is no evidence to suggest that the unenclosed site of Șagu (Fig. 1), covering ca. 23 ha, was a primary political centre. During developer-led excavations, more than 300 LBA pits were excavated in a 2.88 ha transect of 720×40 m (Fig. 2) through the site (Sava et al., 2011). Most excavated features

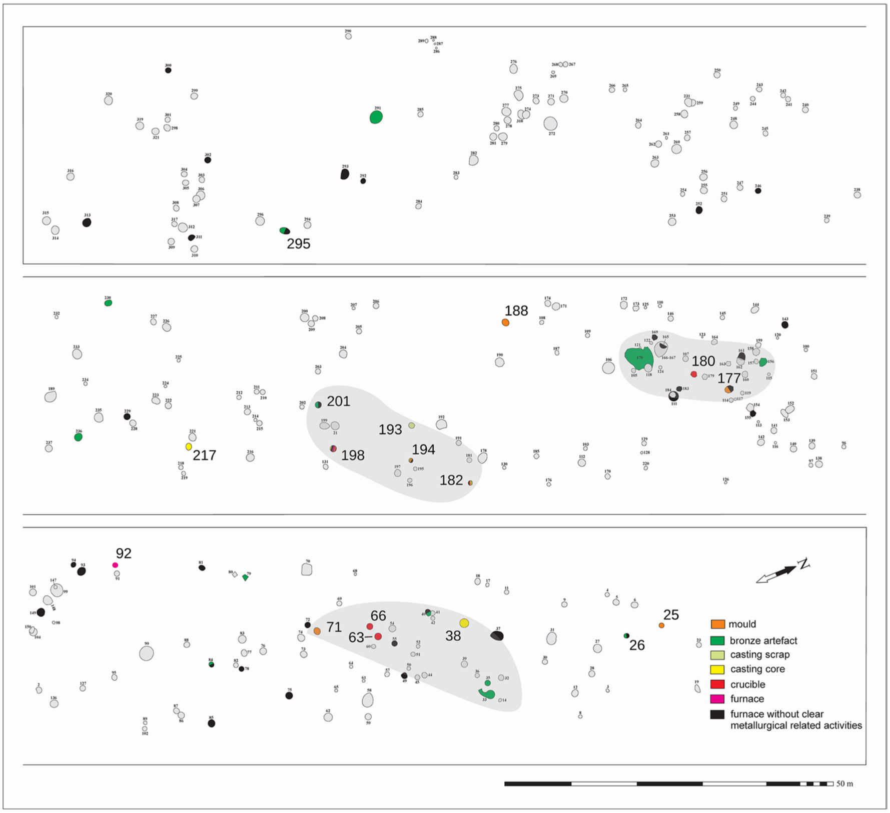

Fig. 2 Plan of the long trench excavated at Șagu (720 m in length, 40 m in width) showing the exposed pits. Due to the large length of the trench, it is presented in three continuous segments: the top being the westernmost part and the bottom the easternmost part of the same trench. The pits with identified metallurgical material are highlighted and the grey areas indicate the loci with evidence of concentrated metallurgical activities. Cx 194 has possible furnace frags, moulds, and casting cores. Cx 198 has possible furnace frags, furnaces, moulds, crucibles, casting cores. Cx 182 has casting metal residue, casting core, crucible, and possible furnace fragments

(contexts, Cx) at Șagu contained domestic refuse, including characteristic channel-decorated LBA pottery. Absolute dates indicate the settlement was occupied from the sixteenth to the late fourteenth–early thirteenth century calBC (Fig. 3), thereby just overlapping with the abandonment phase at nearby MBA tells, with absolutely dated abandonment horizons at Pecica, Feudvar, and possibly Rabe Anka Siget, which may have been abandoned in the previous century (Nicodemus et al., 2015; O'Shea et al., 2019, p. 614, Fig. 7; Staniuk, 2021). Additional finds from Șagu demonstrate that metalworking was situated within a multi-craft milieu including food preparation (quern stones; butter churn) and pottery production (Sava et al., 2011, pp. 60–79).

Methodology

Contextual Evidence of Metalworking Activities at Șagu

Three general areas within the excavated trench showed concentrations of pyrotechnical materials, including clusters of furnaces, crucibles, and moulds (see highlighted grey areas in Fig. 2). The large assemblage of technical ceramics, representing different stages of the metallurgical *chaîne opératoire*, was recovered from at least 13 pits spread across the site (Sava et al., 2011, pp. 50–59). These include 28 tempered clay and 14 sandstone mould fragments primarily for socketed axes and chisels (Figs. 4 and 5), 18 crucible fragments with traces of crucible slag, and 9

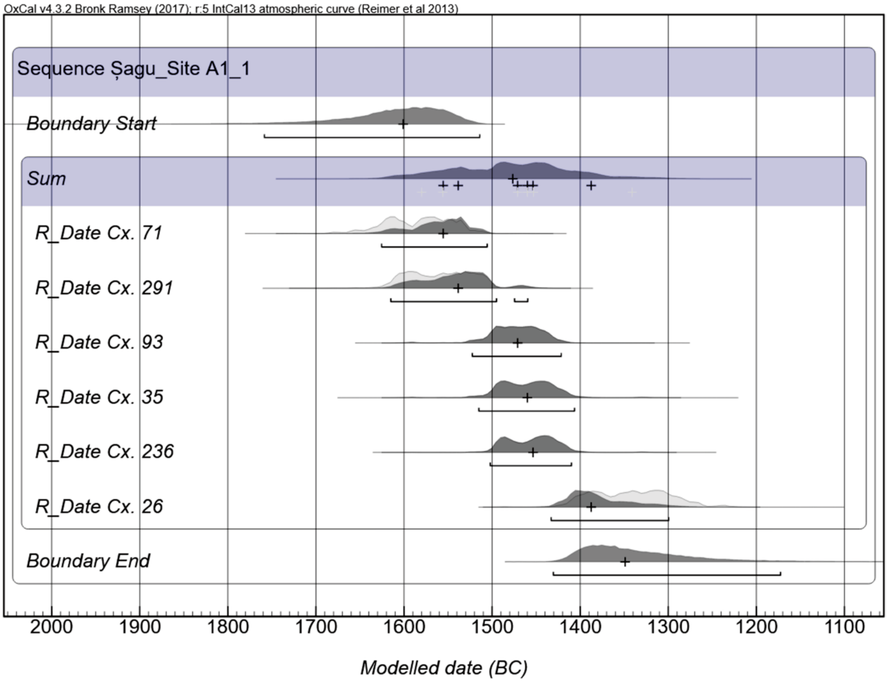

Fig. 3 Calibrated radiocarbon dates (C14 calBC) from Șagu. Samples used for the model were recovered from Cx 26, 35, 71, 93, 236, and 291 (after Sava, 2020)

Fig. 4 Photograph of in situ moulds and mould fragments found in Cx 194 (courtesy of Victor Sava, Arad Museum)

cores for casting socketed objects. A well-preserved crucible in the shape of an open shallow bowl (Fig. 6A) has dimensions of 7×8 cm and a thickness of ca. 5 mm. A total of 19 copper-alloy objects recovered weighed collectively just 45 g (Sava et al., 2012). A well-preserved furnace with a height of 31 cm, maximum diameter of 30 cm, walls of 4 cm in thickness, and a platform attached to its base for above-ground use shows clear signs of its use during metallurgical activities, based on its design, fabric and firing pattern (Fig. 7). Occasionally, fragments of objects with decoration ranging from simple pale slips to plastic decoration can be defined based on fabric and firing traces as probable furnaces. These were published together with mobile hearth fragments in the preliminary publication of Șagu (see Sava et al.,

Fig. 5 Photos of moulds for socketed axes. Mould **A** is from Cx 5 and moulds **B** and **C** from Cx 194 (courtesy of Victor Sava, Arad Museum)

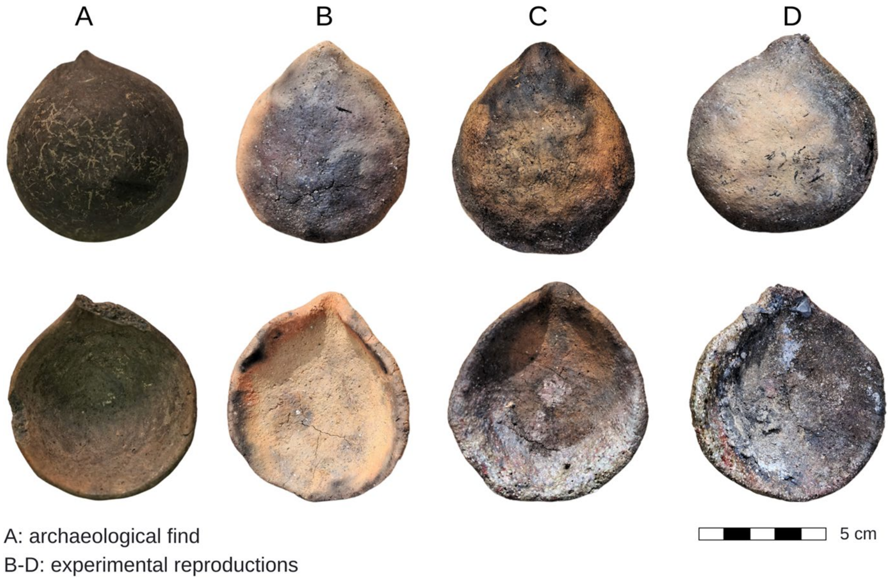

Fig. 6 Photographs of the exterior (top) and interior (bottom) surfaces of an almost complete crucible from Cx 281 at Șagu (**A**) and three (**B**–**D**) experimental reproductions of crucibles used during the tests with variable degrees of vitrification: Crucible B used in 1 test, B in 3 tests, and C used in 5 tests. The crucible from Cx 281 (**A**) was not sampled during the study due to its excellent preservation. **A**: courtesy of Victor Sava, Arad Museum; **B**–**D**: courtesy of UCD CEAMC

2011, pp. 32–45). Further analyses of all relevant fragments will take place to differentiate elements from these visually similar but functionally different constructions. Some features in Fig. 2 are marked as containing possible furnace fragments

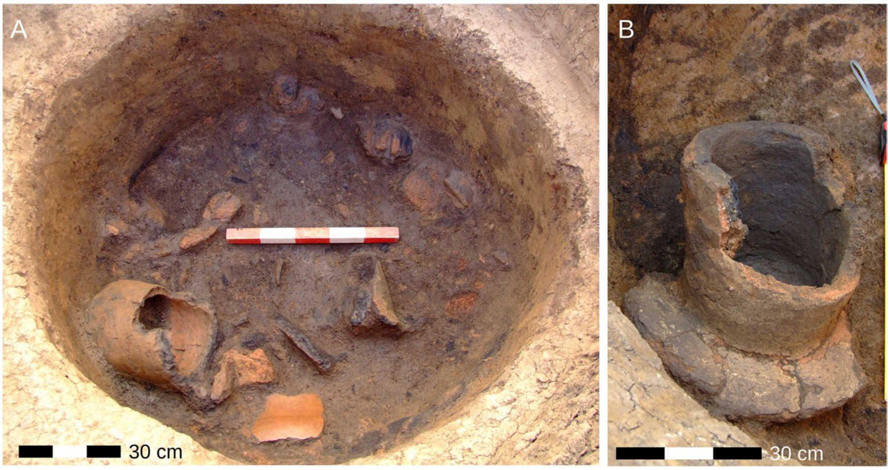

Fig. 7 Photographs of (**A**) the Cx 92 showing fragments of a cylindrical furnace from Șagu and (**B**) a round ceramic structure identified as a tempered clay casting furnace at Cx 198 (courtesy Victor Sava, Arad Museum)

(in the figure key: furnace without clear metallurgical related activities) due to both their poor state of preservation—some are often amorphous lumps—and the need for extensive analysis of all material from the site.

Analytical methods

Study materials

We selected 25 archaeological ceramic fragments for analytical examination, including 8 crucible sherds, 5 furnace fragments, 2 mould fragments, and 10 sherds of domestic pottery (Table 1). The technical ceramics were selected after scanning with a handheld X-ray fluorescence spectrometer, enabling targeting of samples with strong signals of metallic residues. Macroscopic observation of crucible fragments showed oxidised copper residues and a vitrified crucible slag lining their interiors. The domestic pottery sherds were selected for comparison of raw materials and fabric recipes with the technical ceramics. Analytical methods included further detailed, non-destructive hhXRF analysis of all 25 ceramic fragments, followed by removing samples for petrographic analysis, estimation of firing temperatures, and the identification of metallic residues on the cross-sections of crucibles.

Analytical Techniques

Handheld X-ray Fluorescence

We used an Olympus Vanta M-Series handheld (portable) X-ray fluorescence (hhXRF) instrument for surface, non-destructive analysis during the selection of ceramic samples at the initial stage of the study—a method that has been proven potent for identifying suitable technical ceramics for additional destructive analysis (Orfanou et al., 2021). The initial surface hhXRF scanning allowed us to identify 25 samples of technical and domestic ceramic samples for more detailed study (Table 1). We tested the precision and accuracy of a custom application for tin- and arsenic-rich copper alloys with integrated calibration software (AlloyPlus-BronzeAsFix) against copper alloy certified reference materials (CRMs) by MBH Analytical (2 bronzes, 2 leaded bronzes, and 1 phosphor bronze). Analysis of CRMs shows excellent precision with typical coefficient of variation (CV) values of ≈ 1 and ≈ 3 for major (> 1 wt%) and minor (1–0.1 wt%) elements, respectively; and accuracy with relative distance (δ rel.) values of ≈ 1 and ≈ 10 for major and minor elements, respectively (full set of data in Online Resource 1). Detection limits for most elements were found at the level of 0.1 wt%. During initial sample screening of technical ceramics, we used the AlloyPlus-BronzeAsFix calibration as we were more interested in the metallic residues than the composition of the ceramic body and we adopted a presence or absence approach for copper and tin residues. Analysis of domestic pottery, in which no copper or tin was detected, provided a baseline for the selection of samples of technical ceramics.

Once the metallurgical and domestic pottery samples were selected, we ran a second round of surface analysis with hhXRF for obtaining more detailed information on the bulk ceramic compositions aided by the large analytical area of the instrument (collimated beam ca. 3 mm) with the built-in GeoChem-Extra application suitable for geological materials. The precision of this method was tested with repeated analysis on the same spots of the ceramic fragments and was found satisfactory. As we used these results to identify qualitatively compositional groups between the 4 classes of ceramics in the sample, this method was not tested against geological CRMs. Three measurements were obtained for each fragment, both on the interior and exterior surfaces, and means are presented in the results.

Petrography

Thin sections were prepared from the selected 25 ceramic fragments and observed with a Leica DM 2500P polarisation microscope in transmitted light to obtain information on their composition and technology. The colour and optical activity of the matrix provided indications on the firing conditions and temperatures at which the samples were exposed (Quinn, 2013, pp. 23–33; Whitbread, 1989).

X-ray Powder Diffraction

Ten samples (Table 1) were further analysed with X-ray powder diffraction (XRPD) with a Bruker D8 Advance instrument with a Cu-sealed tube (40 kV/20 mA), a Göbel mirror optics, a 0.2-mm divergence slit, a fixed knife edge to suppress air scatter, sample rotation and a VÅNTEC 1-detector. XRPD provides a detailed mineralogical characterisation that informs on firing procedures by making use of the presence and absence of mineral phases that form or disappear at specific temperatures and atmospheric conditions (Gliozzo, 2020; Maggetti, 1982; Maritan, 2004; Nodari et al., 2007; Rice, 2015, pp. 99–115). The 2006 PDF database from the International Centre for Diffraction Data-Joint Committee of Power Diffraction Standards (ICDD-JCPDS) was used to identify the crystalline phases.

Reflected Light Microscopy

The 8 crucible fragments in the sample were further sampled and embedded in epoxy resin blocks. The crucibles' cross-sections were polished to 1 µm with standard metallographic procedures and were examined with a Huvitz HRM 300 optical microscope in reflected light mode (RLM) to obtain spatial information of any metallic remnants in the crucible slag layers on their interior surfaces.

Scanning Electron Microscopy with Attached Energy Dispersive Spectrometer

Two scanning electron microscopes (SEM) were used at different stages of the study. A Hitachi TM3030+instrument using an accelerating voltage of 15 kV, an operating current of 110 µA, and a variable working distance at 1000×and 2000×magnifications, was used for observations on 10 cut samples (2 crucibles, 2 moulds and 2 furnace fragments, and 4 domestic sherds) to assess the degree of vitrification. This technique, in combination with XRPD, helped to reconstruct aspects of ceramic pyrotechnology such as the temperatures in which our samples were exposed to during their production and use (Faber et al., 2009; Maniatis & Tite, 1975; Mentesana et al., 2019; Tite & Maniatis, 1975a, 1975b). The samples were platinum coated and the analysis was carried out on the samples' core. Additionally, the cross-sections of the 8 embedded crucible fragments were examined with a Hitachi TM3030Plus instrument (operating at 15 kV, a working distance of 8.5 mm, and a deadtime of 20–25%) targeting the metallic remains within the crucible slag and the metal oxides and silicates in the slag matrix. Analysis of 3 certified reference metallic materials show detection limits from 0.1 wt% such as for tin and lead, and ≈ 0.2–0.3 for sulphur, manganese, iron, nickel, arsenic, silver, and bismuth (see full results in Online Resource 2).

Experimental Replications

Five experimental tests were conducted in 2021 at the Centre for Experimental Archaeology and Material Culture (CEAMC) at University College Dublin (UCD). Tests 1–3 were conducted in a laboratory environment with a controlled propane fuel heat source, and tests 4–5 were field experiments using a furnace and bellows set up (see below). Tests focused on the practicalities and sensorial aspects of the metallurgical practice with an emphasis also on actualistic approaches, as well as on generating semi-quantitative data (Hurcombe, 2008, p. 85; Molloy, 2008, p. 118).

The replica technical ceramics for this project were handmade, modelled after analytic data from this study, and the dimensions of well-preserved crucibles from Șagu with an illitic clay retrieved locally from Ireland. The clay was levigated to remove unwanted organic and inorganic components and combined with inclusions to reproduce crucible fabric 1 mentioned in Table 2. We selected one fabric for replication purposes in line with keeping a manageable timeframe for the experiments. All replica crucibles were made from 85 g of wet clay. Crucibles used in the three initial tests were pre-fired to 800 °C in a Carbolite chamber furnace, while during the final two tests the crucibles were used unfired and became fired through use in the metallurgical furnace. For the replica furnace, 30% dried and finely chopped grass was added to an illitic clay almost completely free of natural inclusions. The use of an organic, fibrous inclusion has a number of advantages, not least that it adds strength to the walls of large vessels (Taylor, 2013, p. 124). Once built, the furnace was allowed to air dry for 2 weeks before being used in an unfired state during the experiments.

A grog-tempered fabric, made by combining a crushed illitic vessel (fired at 750 °C) sieved through an 800-μm mesh and workable clay was used for the bivalve moulds. These additions speeded drying by increasing porosity and they limited shrinkage and increased refractoriness (Hamer, 1977, p. 150). Two fabrics were made, namely one based on the petrographic results with 10% grog and a second one with 30% to mitigate against the risk of unfired clay bursting (following health and safety protocols at UCD CEAMC). This was particularly important for the tests casting into unfired moulds. We used the moulds to cast small bronze heart-shaped pendants similar to objects recovered at Șagu (Sava et al., 2011, p. 91). In order to evaluate the potential preservation of technical ceramics in archaeological contexts, experimental clay-based samples were immersed in water after use to assess if unfired clay replicas had incidentally become ceramic during melting, preheating, or casting of the metal charge, following O'Neill's (2019) protocols.

Results

Contextual Analysis

Finds of moulds and casting cores and metal spillage, possibly associated with the production process, are more widely distributed either at the margin of activity or in isolation, see for example Cx 25, 38, 71, 188, and 217. This suggests that post-casting metalworking was more distributed or, at least, less tightly focussed around the furnace areas. However, moulds co-occur with furnaces in Cx 194 and 198, showing deposition of technical ceramics from each manufacturing step could occur within the same context. A probable furnace in Cx 92 is not found in association with other pyrotechnical materials and this apparent separation of melting activity may also be reflected in the wide distribution of possible furnaces in isolation from other materials. A pottery kiln, Cx 180, was located within the central concentration of metalworking technical ceramics. While it is unclear if this was precisely contemporary, it indicates that industrial activity of various forms was set within the heart of the settlement. Due to the architectural traditions of this period which leave typically faint or no archaeological footprints, it was not possible to associate features containing technical ceramics with the built environment of the settlement. This significantly hampered contextual analysis at this site. However, the spatial distribution of "activity areas" at nearby contemporary sites in Serbia and at the enclosed site of Sântana indicate that buildings were not tightly clustered (Molloy et al., 2020; Sava et al., 2019).

Surface hhXRF Analysis

Sample Selection

During initial screening of samples, all fragments suspected to be crucibles showed copper and tin readings well above our 1 wt% threshold on their interiors (full set of data in Online Resource 3). All crucible fragments with copper also showed tin. Surface analyses of the furnaces did not indicate the presence of metallic traces.

Ceramic Bulk Elemental Compositions

Further surface hhXRF analysis of the selected 25 fragments (domestic and crucible sherds, mould, and furnace fragments) aimed to investigate the nature of bulk ceramic compositions in the four groups of ceramics (full table of results in Online Resource 4). Any copper, tin, and lead amounts detected on the crucibles have been

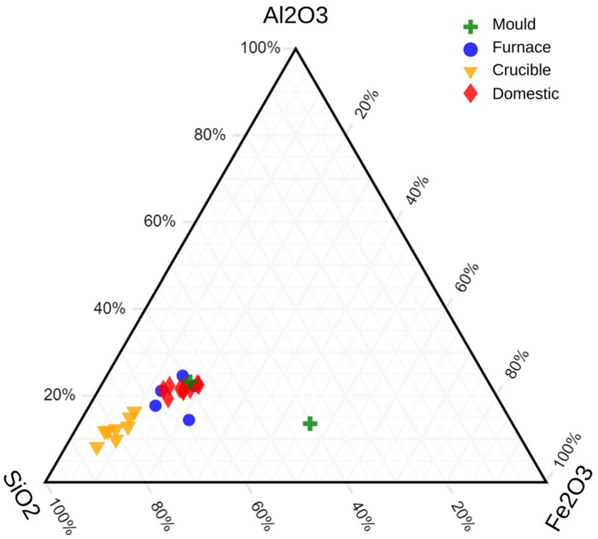

Fig. 8 Ternary plot of Al2O3, SiO2, and Fe2O3 for crucibles (orange triangles), moulds (green crosses), furnace fragments (blue circles), and domestic pottery (red diamonds). Crucible fragments cluster with overall higher SiO2 values

excluded and results were renormalised to 100% to allow a comparative discussion of bulk ceramic compositions. Results showed comparable compositions for all four ceramic groups with mean values for silica 58 wt%, alumina 16 wt%, and iron oxide 13 wt%. Figure 8 shows the crucibles with increased silica contents (mean 70 wt%) and lower alumina and iron oxide compared to the rest of the groups. However, the alumina to iron oxide ratio for domestic pottery, furnace, and crucible fragments (moulds excluded due to small sample size with 2 fragments) is consistent at 1.3–1.4.

Metallic Traces

Surface analysis of the 25 fragments revealed metallic traces only in the crucibles, with typically < 10 wt% copper, < 2 wt% tin, and < 1.5 wt% lead. In crucible fragment C1, traces of silver were also detected. No arsenic was found.

Ceramic Compositional and Technological Characterisation

The petrographic analysis of all 25 samples revealed the presence of 6 different fabrics as seen in Fig. 9 and described in Table 2. Results from the petrographic observations show various tempering strategies at Şagu used in connection with different functions of the ceramic objects produced. Relining of the crucibles was not clearly visible petrographically, but not disproved either.

Estimation of Firing Temperatures

Results of the XRPD analysis revealed a mineralogical assemblage of quartz and feldspar in all 10 samples. Some samples (F2, M1, M2, DP2, DP8) also include illite (Figs. 10B, 11A and B), though the identification of this clay mineral could

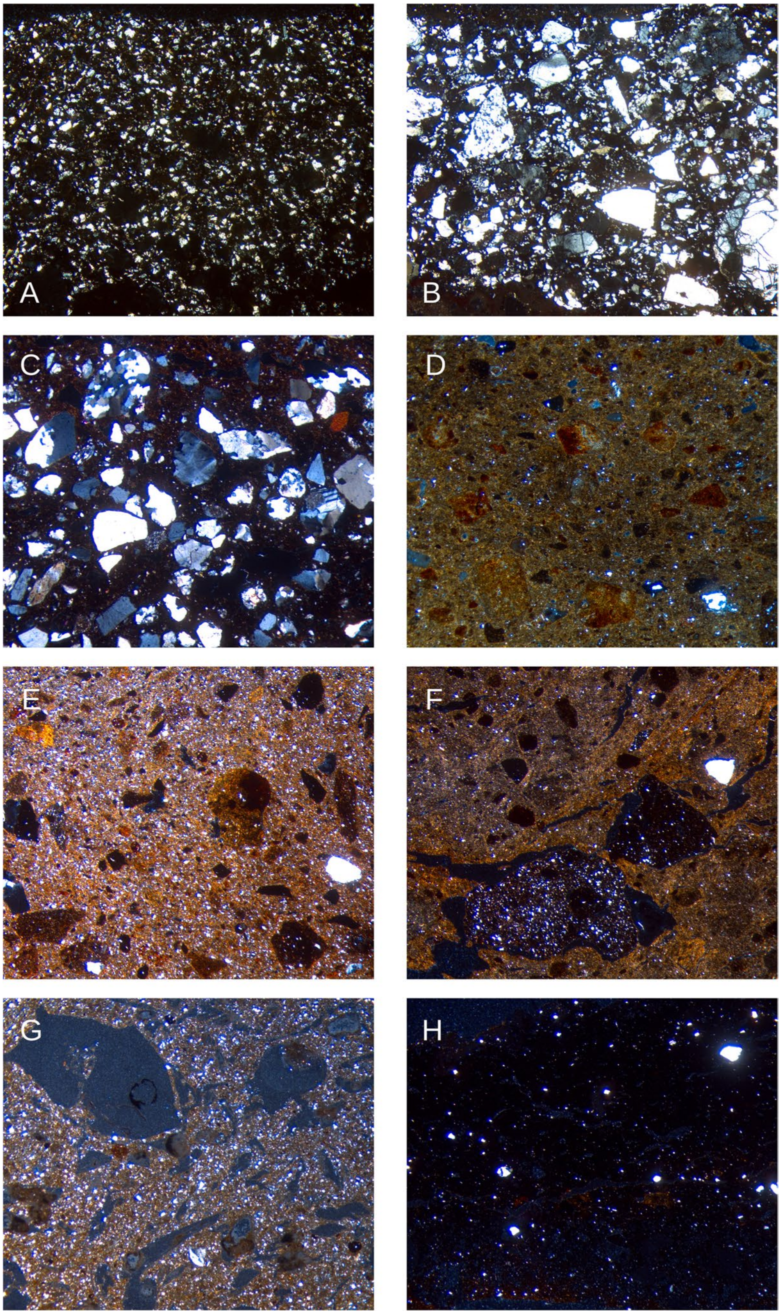

Fig. 9 Thin section micrographs of selected ceramic samples: (**A**) fabric 1 tempered with fine quartzy sand (C2); (**B**) fabric 2 tempered with metamorphic rocks fragments (C3); (**C**) fabric 3 tempered with metamorphic and sedimentary rocks fragments (DP3); (**D**) fabric 4 tempered with grog (M1); (**E**) fabric 4 tempered with grog (DP4); (**F**) fabric 4 tempered with grog (DP8); (**G**) fabric 5 plant tempering (F1); (**H**) fabric 6 un-tempered (DP7). Field of view: 8 mm

Table 2 Summary of the petrographic analysis with detailed observations for the 6 ceramic fabrics identified. *AS* average size, *FT* estimated firing temperature(s)

Fabric	Fragments	Description	Inclusions (%) Average size (AS)	Clay tempering	Firing temperatures (FT)
1	**Crucibles:** C2, C7, C8	Presence of quartz, feldspars and minor quantity of muscovite, chert, and pyroxene	Abundant (40%) AS: 0.3 mm	Fine sand rich in quartz	Optical activity: Low FT: Relatively high
2	**Crucibles:** C1, C3, C4, C5, C6	Presence of foliated metamorphic rocks, quartz, and feldspars. Quartz and felspars are also main constituents of the metamorphic rocks identified	Abundant (40%) AS: 0.8 mm, some rock fragments reach up to 1.6 mm	Sand rich in metamorphic rocks	Optical activity: Low FT: Relatively high
3	**Domestic:** DP3	Presence of metamorphic rocks (as in fabric 2) but it also contains sedimentary rocks		Metamorphic rocks	Optical activity: High FT: Relatively low
4	**Moulds:** M1, M2 **Domestic:** DP1, DP2, DP4, DP5, DP6, DP8, DP9, DP10	Marked by grog (fragments of broken sherds) that has been added as temper	Not very abundant (ca. 10%) AS: 0.8 mm, but some fragments can reach 1.6 mm Other naturally occurring inclusions include quartz, feldspars, muscovite (AS 0.2 mm), and rarely metamorphic rock fragments (AS 0.8 mm)	Grog	Optical activity: High FT: Relatively low (For most samples)

Table 2 (continued)

Fabric	Fragments	Description	Inclusions (%) Average size (AS)	Clay tempering	Firing temperatures (FT)
5	**Furnaces:** F1, F2, F3, F4, F5	Marked by abundant planar voids sometimes filled with charred material	Abundant planar voids (20–30%) AS: 2.4–4.8 mm Other naturally occurring inclusions include quartz and feldspars, more rarely calcite, muscovite (AS 0.2 mm), and fragments of metamorphic rocks (AS 0.8 mm)	Voids from the combustion of plant materials	Optical activity: Variable (per sample, even within a single sample) FT: Variable
6	**Domestic:** DP7	Presence of quartz, feldspars, few little fragments of metamorphic rocks, and very rarely muscovite			Optical activity: Absent FT: High

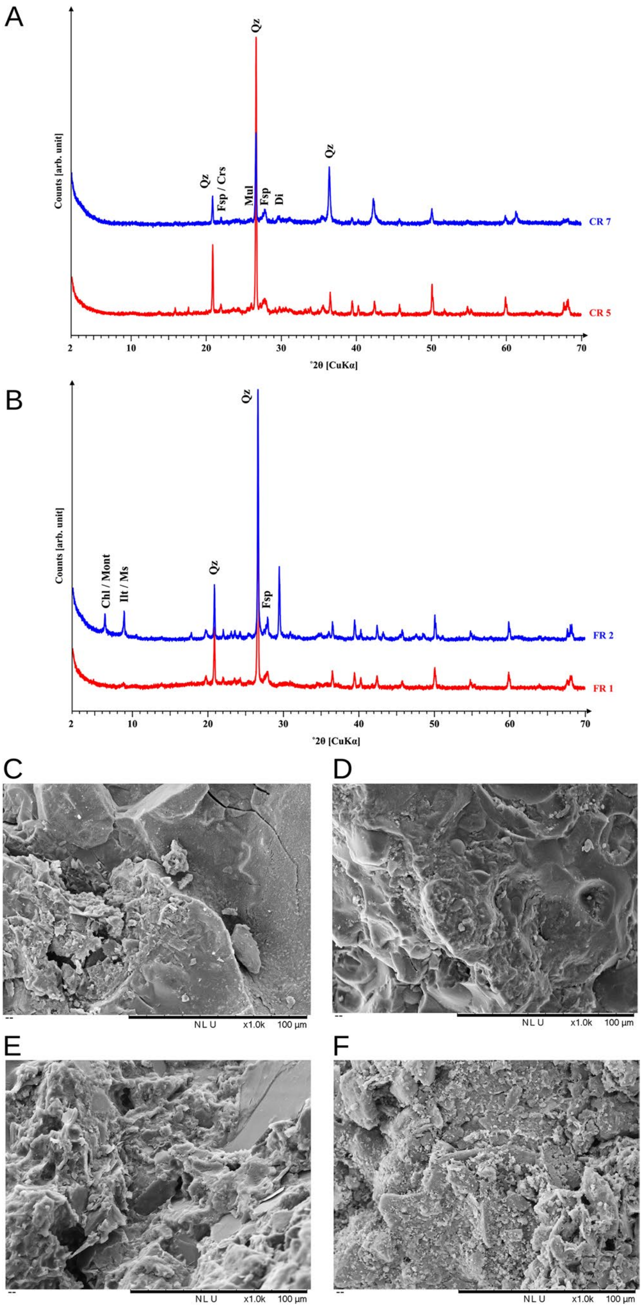

Fig. 10 X-ray powder diffractograms showing the mineralogical composition of selected samples from Șagu: (**A**) Crucibles; (**B**) Furnace fragments. SEM photomicrographs under secondary electron imaging: (**C**) CR 5; (**D**) CR 7; (**E**) FR 1; (**F**) FR 2. Mineral abbreviations after Whitney and Evans (2010). See Table 3 for interpretation of vitrification stage

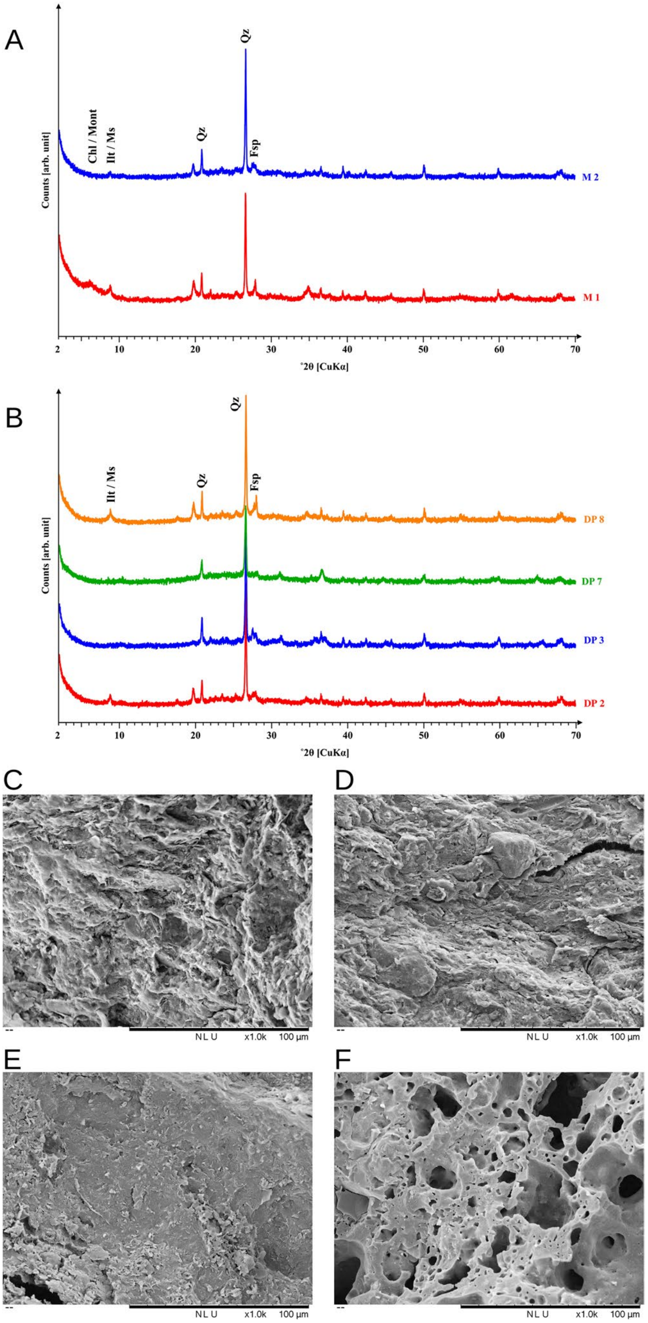

Fig. 11 X-ray powder diffractograms showing the mineralogical composition of selected samples from Șagu: (**A**) Clay moulds; (**B**) Domestic pottery fragments. SEM photomicrographs under secondary electron imaging: (**C**) M1; (**D**) M2; (**E**) DP2; (**F**) DP7. Mineral abbreviations after Whitney and Evans (2010). See Table 3 for interpretation of vitrification stage

Table 3 Summary of results of petrographic, XRPD, and SEM observations. Mineral abbreviations after Whitney and Bernard (2010). Determination of degree of vitrification (last column) during SEM analysis (*CV* continuous vitrification, *IV* initial vitrification, *NV* no vitrification, *NV+* intermediate between NV and IV, *V* extensive vitrification)

	Petrography			XRPD							SEM
Sample ID	Colour	Description	Optical activity	Qz	Fsp	Ilt/Ms	Chl/Mont	Mul	Crs	Di	Degree of vitrification
C1	Reddish-dark grey	Coarse metamorphic	Absent								
C2	Reddish-dark grey	Fine quartz	Absent								
C3	Reddish-dark grey	Coarse metamorphic	Absent								
C4	Reddish-dark grey	Coarse metamorphic	Absent								
C5	Reddish-dark grey	Coarse metamorphic	Absent	X	X			X?	X?	X?	CV
C6	Reddish-dark grey	Coarse metamorphic	Absent								
C7	Reddish-dark grey	Fine quartz	Absent	X	X			X?	X?		CV
C8	Reddish-dark grey	Fine quartz	Absent								
F1	Reddish-dark grey	Chaff tempered	Low	X	X	X (weak)					NV/V
F2	Reddish-dark grey	Chaff tempered	Moderate	X	X	X	X				NV+/IV
F3	Reddish	Chaff tempered	Absent								
F4	Light brown-grey	Chaff tempered	High								
F5	Light brown-grey	Chaff tempered	Moderate								
M1	Dark brown	Grog tempered	Low	X	X	X	X				NV/IV
M2	Reddish to black	Grog tempered	Moderate	X	X	X					NV + /IV
DP1	Black core and light brown edges	Grog tempered	Moderate								
DP2	Black core and light brown edges	Grog tempered	Moderate	X	X	X					NV+/IV
DP3	Black core and light brown edges	Metamorphic rocks	Moderate	X	X						V
DP4	Dark brown	Grog tempered	High								
DP5	Red	Grog tempered	Moderate								
DP6	Black core and light brown edges	Grog tempered	High								
DP7	Black	Untempered	Absent	X	X						V
DP8	Yellowish	Grog tempered	High	X	X	X					NV+/IV

Table 3 (continued)

	Petrography			XRPD							SEM
Sample ID	Colour	Description	Optical activity	Qz	Fsp	Ilt/Ms	Chl/Mont	Mul	Crs	Di	Degree of vitrification
DP9	Black core	Grog tempered	High								
DP10	Dark brown	Grog tempered	High								

be hindered when muscovite is present, due to the overlap between the main illite and muscovite peaks ($2\theta = 8.8°$, $d = 10$ Å). Nevertheless, muscovite is quite rare in the samples examined here. The presence of illite indicates that the maximum firing temperature in these samples must have been below 850–900 °C, when the crystalline structure of this mineral is destroyed (Gliozzo, 2020). One furnace (F2) and one mould (M1) fragment exhibit the main peak of chlorite/montmorillonite (around $2\theta = 6°$, $d = 14$ Å), which could indicate exposure to lower temperatures (< 700 °C). Clay minerals were not detected in any of the crucibles, but the latter probably display cristobalite and mullite, that develop at temperatures above 1000 °C, as well as diopside (Fig. 10A).

A selection of fragments (2 crucibles, 2 moulds, 2 furnace, and 4 domestic fragments) was further examined by SEM for estimating the degree of vitrification (see Table 3). Results showed that only crucibles (C5, C7) display a continuous vitrification (Fig. 10C and D). Furnaces and moulds showed no vitrification or initial vitrification (Fig. 10E and F, Fig. 11C and D), except for extensive vitrification found in some parts of furnace fragment F1. The degree of vitrification of the 4 domestic pottery fragments ranges from initial vitrification in DP2 and DP8 to extensive vitrification in DP3 and DP7 (Fig. 11E and F). Overall, the results of the analyses carried out on the ceramic samples (Table 3) suggest that crucibles were exposed to high firing temperatures (ca. 1000 °C), while the domestic pottery, moulds, and furnace fragments examined were exposed to lower temperatures in comparison to the crucibles. Nevertheless, some portions of the furnaces could have also been exposed to relatively higher temperatures.

Metallic Remains in Crucible Slag

Reflected Light Microscopy

Examination of polished cross-sections of all 8 crucible fragments showed a layer of crucible slag in the interior surfaces of the fragments, namely a highly vitrified layer of fused ceramic mixed with metallic traces both as metals and oxides (red cuprite identified under cross polarised light). All slag layers included metallic traces in the form of bright prills (Fig. 12 and Fig. 13). These metallic prills with diameters of just a few microns (Fig. 12) or larger ones (up to 1.5 mm wide), such as indicated by bright colour in fragment C1 (Fig. 13A). In fragment C8 (Fig. 13C), two crucible slag layers were found, one trapped between two clay layers and a second one in the interior surface of the fragments.

Scanning Electron Microscopy with Attached Energy Dispersive Spectrometer

Further examination of the crucible fragments with an SEM–EDS revealed in more detail the various phases present in the metallic and metal oxide remnants in the slag layers. A total of 114 area analyses were obtained with a mean of 14 analyses per sample both from metallic areas and the slag matrix (full results available in Online Resource 5). Copper, in its metallic or oxide form, was detected in all 8 fragments, tin (mostly as an oxide) in 7 (C1–3 and C5-8), and lead in three (C1–3). Traces of

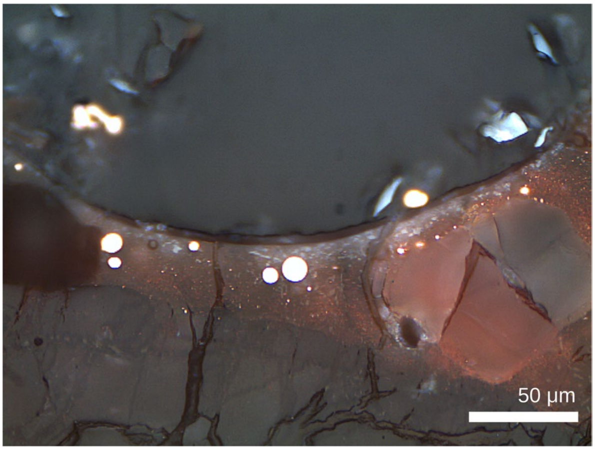

Fig. 12 Photomicrograph of crucible C3 (500×, plain polarised) showing part of the crucible slag with embedded metallic prills identified by their bright, highly reflective colour

silver were detected in fragment C4. Figure 14 shows four representative areas from the crucible slag layers in fragments C1, C2, C6, and C7. Phases with both copper and tin oxides were often found, such as in C1, and form the main components of the less corroded phase (Fig. 14A). Copper silicate phases such as the prill in C2 (Fig. 14B) are also often present. Copper and tin oxides fused with the ceramic

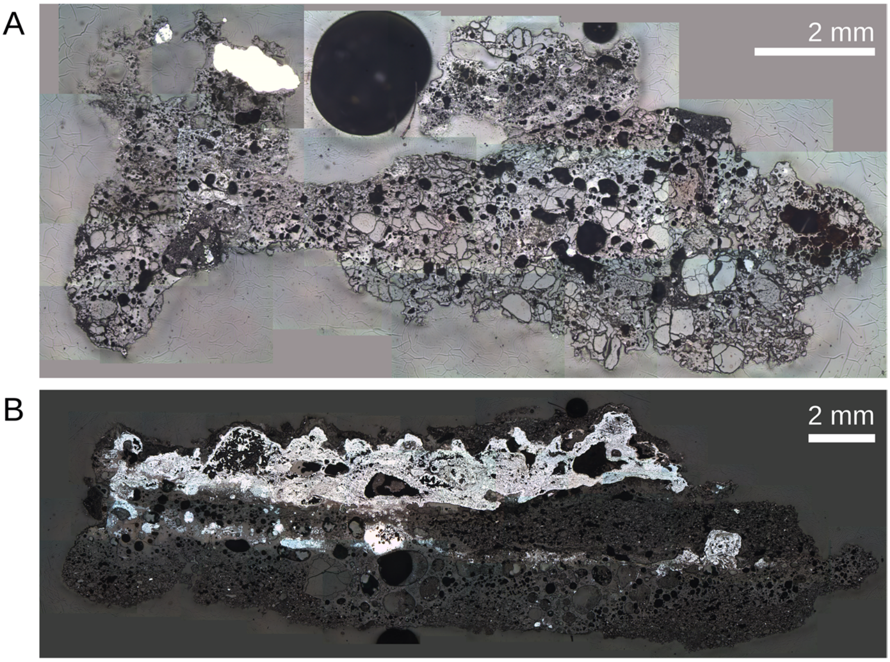

Fig. 13 Collated photomicrographs (each photomicrograph: 50x) showing the overview of the cross-sections of crucibles (**A**) C1, and (**B**) C8. A vitrified layer of crucible slag is visible at the top part (interior surfaces) of both fragments. In fragment C8 two slag layers are visible, one trapped between two layers of ceramic and second one on the outmost interior surface (top of fragment in figure)

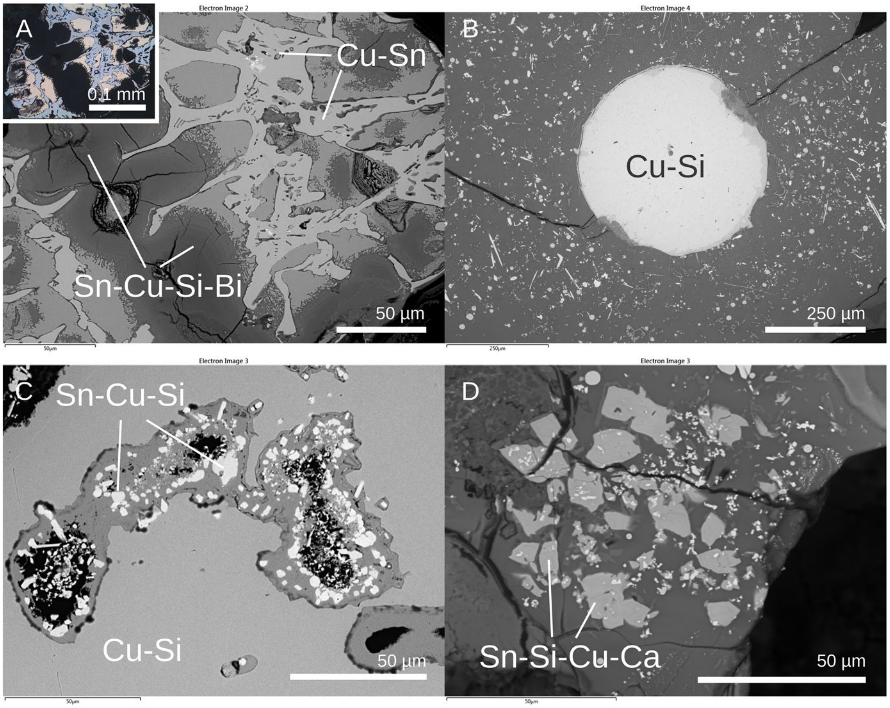

Fig. 14 Scanning electron images (backscattered, BSE) of (**A**) crucible fragment C1 (800×) with insert photomicrograph of the same area (500×, plain polarised) showing rich-tin phases in a metal prill (the darker phases are corroded); (**B**) crucible fragment C2 (180×) showing a copper silicate prill and some thin elongated needles in the slag matrix; (**C**) crucible fragment C6 (1200×) showing copper silicates and tin oxides in the slag matrix—Ta_2O_5 was detected in the Sn-Cu-Si phase indicated in the BSE image; (**D**) crucible fragment C7 (1500×) showing crystals rich in tin and copper oxides, as well as silica and lime. The areas annotated in the BSE images include the elements (excluding oxygen) present in the respective phases starting with the element in highest concentrations, including all elements > 5 wt%

compounds such as silica and lime are also often present in C6 and C7 (Fig. 14C, D). In two areas in crucible fragments C6 (in the Sn-Cu-Si phase, Fig. 14C) and C8 (throughout the top layer of slag) traces of tantalum pentoxide (Ta_2O_5) at around 0.2 wt% were detected alongside tin oxide.

Experimental Tests of LBA Crucible Metallurgy

During 5 experimental tests, 31 crucibles, 5 moulds (in tests 4 and 5), and a furnace were used with three charges, namely a) copper, b) readymade bronze, or c) copper and tin introduced as separate metals. All copper and tin used were clean metals as certified by the supplier and as confirmed further by hhXRF, namely pure copper (100 wt% copper, any impurities were below the detection limits) and > 99 wt% tin with traces of copper (0.5 wt%) and silver (0.3 wt%). Selected crucibles were relined between repeated uses. Table 4 shows an overview of the experiments, crucibles (re) used and relined, and the charge for each test.

Table 4 List of experimental tests and crucibles (Cr) used. Tests 1–3 were conducted in laboratory conditions replicating a smithy and tests 4 and 5 were field experiments using the replica furnace. In the "Charge" columns, Bronze refers to a readymade bronze alloy added in the crucible, Cu and Sn to the addition of the copper and tin as separate metals, and Cu to only copper metal used

Cr ID	Cr no. at test	Test 1		Test 2		Test 3		Test 4		Test 5	
		Action	Charge	Action	Charge	Action	Charge	Action	Charge	Action	Charge
1	C1	Melt	Bronze	–	–	–	–	–	–	–	–
2	C2	Melt	Bronze	–	–	–	–	–	–	–	–
3	C3	Melt	Bronze	–	–	Relined; alloying	Cu and Sn	–	–	–	–
4	C4	Melt	Bronze	–	–	–	–	–	–	–	–
5	C5	Melt	Bronze	–	–	–	–	–	–	–	–
6	C6	Melt	Bronze	–	–	–	–	–	–	–	–
7	C7	Alloying	Cu and Sn	–	–	Relined; alloying	Cu and Sn	–	–	–	–
8	C8	Alloying	Cu and Sn	–	–	Relined; melt	Cu	–	–	–	–
9	C9	Alloying	Cu and Sn	–	–	–	–	–	–	–	–
10	C1	–	–	Melt	Cu	–	–	–	–	–	–
11	C2	–	–	Melt	Cu	–	–	–	–	–	–
12	C3	–	–	Melt	Cu	–	–	–	–	–	–
13	C4	–	–	Melt	Bronze	–	–	–	–	–	–
14	C5	–	–	Melt	Bronze	–	–	–	–	–	–
15	C6	–	–	Melt	Bronze	–	–	–	–	–	–
16	C7	–	–	Alloying	Cu and Sn	–	–	–	–	–	–
17	C8	–	–	Alloying	Cu and Sn	–	–	–	–	–	–
18	C9	–	–	Alloying	Cu and Sn	–	–	–	–	–	–
19	C1	–	–	–	–	Alloying	Cu and Sn	–	–	–	–
20	C2	–	–	–	–	Alloying	Cu and Sn	–	–	–	–
21	C4	–	–	–	–	Melt	Cu	–	–	–	–
22	C5	–	–	–	–	Melt	Bronze	–	–	–	–

Table 4 (continued)

Cr ID	Cr no. at test	Test 1		Test 2		Test 3		Test 4		Test 5	
		Action	Charge	Action	Charge	Action	Charge	Action	Charge	Action	Charge
23	C6	–	–	–	–	Melt	Bronze	–	–	–	–
24	C1	–	–	–	–	–	–	Melt	Bronze	–	–
25	C2	–	–	–	–	–	–	Melt	Bronze	–	–
26	C3	–	–	–	–	–	–	Melt × 4 (relined)	Bronze	–	–
27	C4	–	–	–	–	–	–	Melt (bottom heating)	Bronze	–	–
28	C1	–	–	–	–	–	–	–	–	Melt × 2	Bronze
29	C2	–	–	–	–	–	–	–	–	Melt × 3	Bronze
30	C3	–	–	–	–	–	–	–	–	Melt × 5 (relined)	Bronze

Fig. 15 **A** Photo of B. O'Neill and L.E.F. Brown in the field during the experiments at UCD CEAMC using bellows to pump air into the cylindrical furnace. **B** Close-up photo of the furnace structure with charcoal and an experimental crucible charged with copper and tin. The area directly heated by the bellows' nozzle is the hotspot, which reaches highest temperatures

Once the clay mix was prepared, forming each crucible (7–8-cm width, 8–9-cm length, max. 6-m thickness in the base) and the furnace (31-cm internal diameter, 20–30-cm height, 4-cm thickness) by hand took ca. 5 and 20 min, respectively. The furnace was then placed into a pit with the rim at ground level (Fig. 15). A bellows and an unfired right-angled clay tuyère at the top of the furnace introduced air into the feature and heated the crucible from above. The lower half of the furnace was filled with charcoal and the crucible was placed beneath the tuyère and then covered by another layer of charcoal bringing the level of the fuel to 2–3 cm below the tuyère.

During the tests, charges typically of 40 g of bronze, and occasionally up to 125 g, were fed successfully into a crucible. The furnace configuration worked efficiently with melting copper and bronze. Feeding the metal in small quantities directly into the hot spot to be collected by the open crucible was also efficient and only required light bellowing. It is also possible that some form of blow pipe was alternatively used, perhaps with multiple participants contributing to a single hot spot. Given the difference between the crucible and furnace diameter, it was possible to place moulds within the furnace away from the hot spot to preheat prior to pouring. Once molten, the metal was poured either into a standby shallow ceramic vessel or mould.

All crucibles were sufficiently refractory to withstand the temperatures needed to melt the various charges (Cu, Cu, and Sn, Bronze; Table 4). Both fired and unfired crucibles displayed little cracking or degradation during use, though thermal impacts increased over successive uses (Fig. 6B–D). Following the first use, all crucibles displayed mottled (red to black) colourations. The main areas of reduction (black) were on the external base. The most pronounced use-wear indicator occurred on the internal base beneath the molten metal (Fig. 6B–D). Due to its low reactivity (Dungworth, 2000, p. 85; Kearns

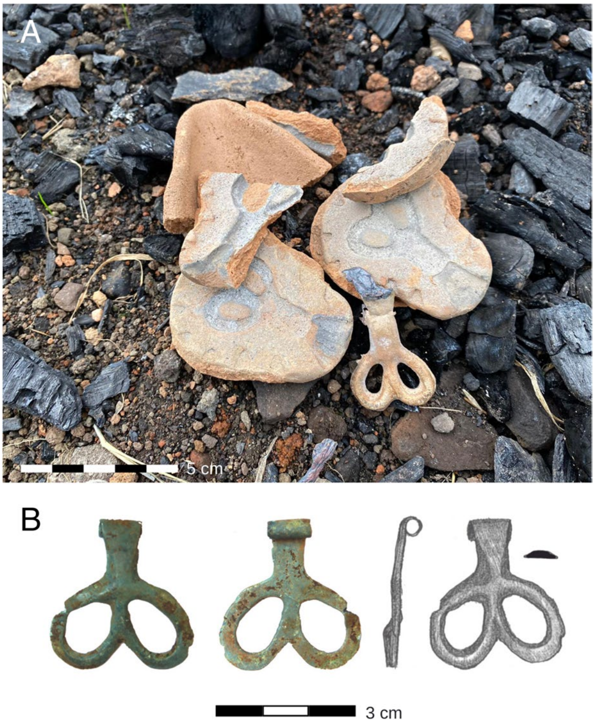

Fig. 16 **A** Bi-valve mould made and used during experimental tests with cast bronze pendant. **B** Bronze pendant recovered from Cx. 236 at Șagu (after Sava et al., 2011, p. 51, Fig. 9.1)

et al., 2010, p. 50), molten copper (alloy) tends to roll over the surface of refractory clays/ceramics without sticking. Over successive uses, vitrification begins to develop and progressively trap greater amounts of the metal. Ultimately, this accumulation and corresponding loss of metal impede the crucible's function, rendering it useless. Relining this surface with a thin layer of refractory fabric rejuvenated it and allowed one or two additional casts. Three crucibles were used in tests 4 and 5; one was used once, one three times, and the third five times and then relined (Fig. 6B–D). Of note, relinings applied in advance and allowed to air dry before re-use cracked and detached in the heat of the furnace. Alternatively, those that were relined and placed immediately into the hot furnace when wet best resembled the archaeological examples, as the fabric's porosity limited clay shrinkage by allowing water vapour to easily release.

Moulds were used unfired but preheated by placing upright within the lit charcoal and by the hot spot in the operating furnace. Of the 5 moulds used, 3 casts were successful, the other 2 failing due to a casting error when charcoal fell into the pouring cup. While we noticed some patterns of relatively light oxidation and reduction resulting from the preheating process, few other alterations were observed, aside from a scorch mark at the pouring cup (Fig. 16).

Following over 20 successful melts, we immersed in water selected experimental fragments to gauge the degree of preservation in the archaeological record. After 12 h of use during experiments, the initially unfired tuyère broke down in water, leaving only a tiny portion of hardened clay from the nozzle intact. Similarly,

Table 5 Table of the hhXRF analyses (AlloyPlus-AsBronzefix application, 2-phase) of a cast bronze pendant and a bronze droplet produced during the experimental tests. All values reported in wt%. LODs (limits of detection) are defined as per Online Resource 1. Only detected elements are reported. The value of 0.1 wt% for arsenic is at the detection limit and is considered semi-quantitative

Description	Cu	As	Sn	Pb
Pendant	92.3	0.1	7.4	0.2
Droplet	92.1	< LOD	7.8	0.2

fragments from the upper portions of the furnace immersed in water quickly disintegrated, suggesting that none had turned into ceramic and, thus, leaving no diagnostic features of the furnace or technology. Following casting and recording, mould fragments of both fabrics were immersed in water and behaved similarly as they disintegrated within ca. 13 min, indicating they had not converted to a ceramic. This is in line with previous experimental work (O'Neill, 2019, p. 81) and highlights the importance of the depositional environment to the preservation of low-fired or unfired technical ceramics.

Non-destructive Analysis of Experimental Samples with hhXRF

Upon completion of the experimental tests, we examined non-destructively the interior and exterior surfaces of the replica crucibles (full table of results in Online Resource 6). Results showed traces of copper and tin in the interiors of the crucibles used primarily in tests 4 and 5 (field experiments). More abundant metallic traces were noted in the reused crucibles, which also featured more vitrified interior surfaces compared to crucibles used once. Analyses of crucibles used in tests 4 and 5 also showed traces of zinc and lead oxides (see below the discussion for an explanation of this). Finally, we analysed non-destructively with hhXRF a cast pendant and a metallic droplet resulting from the experiments. Analysis of both the pendant and the droplet showed a bronze 92 wt% copper and 7–8 wt% tin with lead impurities (Table 5).

Discussion

Technology, Function, and Use of Ceramics

Our combined surface and destructive analysis, and the quantitative and qualitative results, alongside experimental reproductions revealed critical information about the technology, function, and use of technical ceramics at Șagu, as well as about the cross-craft interlinkages between metallurgical activities and domestic pottery production.

Performance of Ceramic Fabrics

All four ceramic categories, namely fragments of crucibles, furnaces, moulds, and domestic pottery showed comparable chemical compositions. The increase in the silica content of the crucibles is attributed to the addition of quartz in the form of sand, confirmed both from the petrographic examination (Table 2) and the compositional analysis carried out with SEM-EDS, which revealed identical alumina to iron oxide ratios across fabrics used for domestic pottery, the furnaces, and crucibles. Petrographic examination showed distinct recipes for the ceramic fragments analysed, marked by various tempering agents which might have modified their performances (Müller, 2017; Müller et al., 2014). The addition of organic material into the clay used for pyrotechnological installation, such as noted in fabric 5 (used for the furnace fragments), is not surprising as this type of inclusion makes the firing structures much lighter (Skibo et al., 1989), while providing structural support and thermal insulation (Martinón-Torres & Rehren, 2014, pp. 123–124). Crucibles are marked by a fine (fabric 1) and a coarse fabric (fabric 2) tempered with a quartz-rich sand and a metamorphic rock-rich sand (composed of quartz), respectively. In both cases, the dominant mineral inclusion is quartz, the presence of which can modify mechanical (strength, toughness) and thermal shock resistances of the vessel clay's body during heating (Vekinis & Kilikoglou, 1998). The mechanical behaviour of clay during the firing is also influenced by the percentage and size of quartz grain, the optimal percentage being 20% (Kilikoglou et al., 1998; Vekinis & Kilikoglou, 1998). Under this condition, the paste becomes tougher without compromising its strength, with benefits also to thermal shock resistance. In both recipes used for crucibles, inclusions seem to be present in a higher amount (ca. 40%). Though not ideal, this is still an acceptable amount of temper that can depend on the type of clay used. Because of the rather small size of the inclusions in fabric 1, it is possible that this recipe performed better from a mechanical and thermal point of view compared to fabric 2 (see Martinón-Torres & Rehren, 2014, pp. 123–124).

The addition of grog (crushed sherds added into clay paste) as a temper, noted in fabric 4, is typical of the domestic pottery and mould production. This is a common practice among potters in the Balkans at least from the end of the Late Neolithic period (Amicone et al., 2020a, 2021). It is, however, difficult to evaluate whether this tradition continued uninterrupted down to the Late Bronze Age due to the lack of extensive research for later periods. Nevertheless, it is known as one of the common tempering agents in the Bronze Age period in this area (Earle et al., 2011; Kreiter et al., 2007). Grog could have been added into clay paste for functional reasons such as for improving the vessel's mechanical and thermal properties, but its choice as a temper may have been driven also by cultural and symbolic factors (Rice, 2015, p. 80).

Melting or Alloying of Bronze?

Copper and tin were both used in the crucibles at Șagu. Presently, we cannot fully determine whether readymade bronze was worked, copper and tin were added separately during active alloying, or copper was co-smelted with tin/cassiterite during metallurgical activities on site. Results suggest that various of these processes possibly took place at Șagu. The presence of tantalum pentoxide, which belongs to a set of minerals often co-occurring with cassiterite, found alongside tin oxide (Farci et al., 2017, p. 344), as well as potential semi-dissolved cassiterite remnants or naturally derived cassiterite needles, and tin-calcium-silicon oxide phases found in the crucible slag layers could suggest active alloying (pers. com. J. Montes-Landa; Rovira, 2007, p. 33). Nevertheless, the potential cassiterite needles are not fully formed such as the thicker, elongated rhomboidal shapes seen in other LBA contexts (Figueiredo et al., 2010, p. 1628; Rademakers et al., 2018, pp. 511–512). Meanwhile, secondary tin oxides surrounding copper and tin-rich phases were also present as remnants of the oxidation of bronze. This oxidised bronze could have been added to the charge or be the result of the process. Different processes for the making and working of bronze require different know-hows, operation times, and temperatures reached, as well as access to different resources, and are indicative of the level of the technological knowledge available at Șagu.

Traces of silver more suggest the use of different copper minerals (the silver coming as an impurity from the copper ore) or to recycling than to the working of silver metal, further suggesting that possibly various resources (ores, scrap metal) were available at Șagu. Evidence of relining in at least one cross-section (C8), but also the rather thick vitrified layers of crucible slag in all fragments are indicative of the repeated use of these crucibles. This was further supported by the observations during the repeated use and relining of crucibles during the experiments conducted as part of this study. The slag layers, thus, are remnants of the rigorous metallurgical activities at Șagu.

Experimental Tests and the Archaeological Record

Experiments evaluated the fabric composition of crucibles, moulds, and the furnace from Șagu and how these objects could be used together for melting bronze (alloying copper with cassiterite was not tested during the experiments) and making copper-based objects, as well as their preservation rates. Discolouration of experimental crucibles after use (on the external base) matched the patterns found on archaeological examples (compare A with B–D in Fig. 6). Both archaeological and experimental results suggest that the crucibles were reused. During repeated uses, most of the replica crucibles developed small patches of visible vitrification in the interior of their bases, but also on their rims, the latter not identified on the archaeological examples. Relining of crucibles resembled the archaeological evidence most closely when applied to an unheated crucible and directly placed into the heat of the furnace. Relining and reuse of crucibles allowed us to identify changes over their multiple uses and assess the efficiency of the relining. The easy and quick application of the relining in situ (*i.e.* at the casting location) would have prevented further loss of metal.

To assess the function of the furnace, a range of factors were considered. Based on the archaeological finds, air could only be introduced through the top of the feature. Although there were patches of oxidation and reduction on the furnace walls, these suggest relatively low temperatures (O’Neill, 2018, p. 41). Nevertheless, the frequent absence of high-heat indicators, such as vitrification (though one furnace fragment showed traces of vitrification), does not preclude its use as a furnace, but instead provides insights into how this feature might have been used. The shape and size of the furnace allowed the repositioning of the crucibles to control the effect from the heat source, such as for avoiding excess bellowing. The wide opening of the furnace further suggests that more than one crucible could be used simultaneously, each with their own hot spot (though this was not tested during our experiments), and would allow space for metal to be melted in the crucible while a mould was preheated beside it. The furnace's large depth could accommodate the preheating of the moulds of different sizes in an upright position, also for pouring the metal such as seen in Fig. 15B. This is technologically advantageous and makes up for the use of an open crucible (heat loss) by reducing casting time, keeping the crucible and mould close. The furnace configuration with a hot spot close to the rim of the furnace (instead of its base) is consistent with the evidence from the crucibles for top-down heating, with rather localised heat alterations identified macroscopically on experimental crucibles. Considering the above, the clay structures from Șagu are consistent with metallurgical use, possibly as mini-smithies in which both the melting and casting took place.

Experimental work further demonstrated how specific tempered clay recipes impact production choices before and during casting, as well as on the variable preservation of technical ceramics also dependent on the intensity of the heating they have undergone during routine use. The addition of quartz in the crucibles helped to withstand the prolonged high temperatures, complementing the grog from crushed illitic clay. Furnaces and moulds did not need quartz temper as they were not subjected to the same prolonged high temperatures as the crucibles, with much of the heat escaping via the furnaces' wide rims. Instead, increased porosity, such as from the organic temper, was important for the furnaces, aiding the release of free water and gasses during casting. The moulds could be used preheated but still unfired, as temperatures during preheating would be sufficient to harden the clay or convert it to ceramic. Thus, the depositional context is decisive for the preservation of these moulds in the archaeological record. Evidence of the moulds, tuyères, and parts of the furnaces disintegrating in water after the experiments illustrates the fragility of this type of evidence and might, at least partly, explain the sporadic retrieval of such finds from the archaeological record, leading to another case of absence of evidence not being evidence of absence for Carpathian MBA-LBA metallurgical activities. It is noteworthy that some of the moulds at Șagu required in-situ consolidation with resins because they were too friable to be lifted.

A Note on Contemporary Experiments to Replicate Past Technological Activities

Surface analyses of the interior surfaces of the experimental crucibles after the tests revealed copper and tin, which were added purposefully during the tests, but also, traces of zinc and lead oxides, which were not intentionally added. These rather intruding elements were found in the crucibles used in tests 4 and 5. Notably, no zinc or lead amounts were detected in the finished pendants cast during the tests. During these tests, we used a galvanised (zinc-coated) iron rod (visible in Fig. 15B) to check whether the metal charge was in a solid or liquid state. We believe that the rod's coating reacted with the ceramic, whose interior surface would be rather viscous while undergoing high temperatures (placed under the hot spot), leaving behind zinc and lead traces. With this, we raise caution when archaeological experiments are conducted with contemporary means. Analyses of the experimental features upon completion of the tests and rigorous recording of all materials and tools involved during the tests are needed.

Setting the Stage for Crucible Metallurgy and Craft Intersections in the LBA Carpathian Basin

Șagu does not appear to have been a site of outstandingly high status, particularly when compared to the size and complexity of neighbouring sites such as Sântana or Corneşti Iarcuri (Gogâltan et al., 2019; Lehmphul et al., 2019). Considering the scale of metalworking evidence, based on current evidence, this appears to mark a point of departure from the MBA tradition in terms of the status of major metal-producing sites and the spatial, and perhaps ideological, organisation of craft within settlement contexts.

Following the procurement of clay, temper, charcoal, and ingots, metal production loci can be broken into spaces or stages for (1) carving wood or stone for mould templates, (2) crucible and mould making using wooden templates, stone, clay, and tempers, (3) the construction and use of furnaces, (4) mould opening and/or disposal, and (5) finishing the cast objects. Available spatial data from Șagu indicate that the crucible fragments are mostly found in association with furnaces. Find locations of moulds are more varied as they were in some cases deposited in features at some distance way from crucibles and/or identified furnaces, as well as together in separate pits with other metallurgical remains (see Online Resource 7 for details of the assemblage of each context represented in the study). These material traces relate to post-production disposal of materials. Some of the earlier stages which do not leave archaeological footprints could have been co-located with other crafts where cross-craft interactions would take place, such as pottery workshops. This is suggested by the compositional similarities between technical ceramics and domestic pottery at Șagu. This brings into the foreground recent discussions around the varying degrees of craft specialization. In the absence of a potters wheel, the production of domestic pottery and moulds required similar tactile skills and experiences, with complex shapes being made in a manner where forms were retained as objects dried. We might envisage people particularly skilled in that arena specializing in shaping clay irrespective of end-function, something the shared recipes may indicate. Alternatively, we might consider some individuals engaged in metalworking primarily focusing on these forming, shaping and melting stages while others were involved in the fettling and polishing of bronze and/or carving and affixing organic elements such as handles. Essentially, the workflow may have drawn upon specialised skills of individuals variably according to needs or the complexity of particular objects, even if many of those involved had sufficient skill to complete most tasks to an adequate degree (Kuijpers, 2015, 2018b; Nørgaard, 2018, p. 9, 2015). Specialisation of craftspeople in specific aspects of the metal working cycle, such as mould and crucible making (Dietrich, 2012b; Eklöv Pettersson, 2013), is supported for the case of Șagu considering the specific fabrics used for the crucibles (fabrics 1 and 2) compared to the moulds and domestic pottery as shown during the petrographic examination.

The prominent role that primary centers had played in the management of metalworking during the MBA appears to have been lessened during the LBA, with the case of Șagu providing an example of a settlement of modest status, though still relatively large, in which multiple crafts were practiced. This may indicate a loosening of control over the production and circulation of metalwork in the LBA. Furthermore, in the case of the southeastern Pannonia Plain, this shift may express a physical and ideological change from the densely packed closed environs of a tell, where metalworking was guarded by default or design, to a context defined by enabling greater visibility amidst less densely spaced structures. The conspicuous decoration of some furnaces suggests a spatial context of metalworking inviting visibility and community engagement via means of visual cues. This attention to aesthetics suggests a metallurgical stage was set for new theatrics of craftwork in this LBA social environment. This has further repercussions for understanding the visibility of the craft itself within communities, as well as the way access and redistribution of resources, know-how, and products were managed.

In a landscape where stone is exceptionally rare, prehistoric communities relied on clay for covering various needs (Sofaer, 2015; Sofaer et al., 2013). Clay is immensely versatile and can be further manipulated using inclusions and thermal treatment. Despite the collapse of preceding social systems in the Carpathian Basin, knowledge of and dependence on clay remained, revealing shared material experiences over time. At Șagu, the specific qualities of the different ceramic paste recipes and various tempers (grog, quartz/sand, metamorphic rocks, organics) were well understood. Once ceramic fabrics were prepared, complex shapes were conceived and materialised through manual work. Ceramic recipes were then used appropriately for vessels intended for different functions such as domestic uses, moulds and furnaces involving exposure to lower temperatures, or crucibles involving higher temperatures. It is, thus, important that the same familiar clay with distinct inclusions was used at Șagu for moulds and domestic pottery, and with added quartz for the crucibles. This highlights at once a shared, cross-craft materiality for making complex shapes in the former two cases, yet a deep understanding of the technological demands for the crucibles, which were destined to undergo significantly higher temperatures for longer periods. Furnaces used a ceramic fabric recipe seen also in wattle-and-daub structures, thus underlying additional materiality crossovers at Șagu. As installations, furnaces materially articulated with the built environment and reflected knowledge of buildings' structural properties and of other technical structures, such as kilns, thermal shock resistance, and thermal insulation properties. The above observations suggest similar material engagements and experiences across different technical activities and/or technologies but also specialised technical know-how in production and manipulation of available resources.

The performance space of metallurgy is important for its impact on material preservation (Doonan, 2013). The cylindrical furnaces operating as mini-smithies focus the performance of the melting and casting into a tightly constrained space, whereby movement circulates around a small central point. Firing conditions, execution of casting, opening of moulds, and discarding of debris show varied patterns for these technical ceramics at Șagu. Taken together, these data show that casting routinely took place within the settlement and frequently close to the pits in which metallurgical debris was deposited. This reveals multi-stage practices sometimes taking place in the same and sometimes in different loci throughout the site, which often ensured high visibility of the production activities within the community. If moulds or crucibles were discarded close by upon their last use, they would be largely crushed underfoot during working routines. This is attested by the fragmentary state of crucible fragments recovered at Șagu which are typically small and not refitting. The inclusion of crucible fragments in pits alongside furnace fragments further suggests that used crucibles were deposited during routine cleaning of spaces when furnaces eventually went out of use. While a similar pattern is seen for moulds in some instances, moulds and casting cores were also opened and discarded in a different setting at Şagu. The wider distribution of the metalworking paraphernalia indicates that, at least occasionally, the routines for post-casting processing occurred in different spaces (Fig. 2). Clay-based moulds rarely survive due to the low temperatures involved in their use (as also shown by our experiments here, the moulds were used unfired and only preheated), and many of those that did survive were so poorly preserved that they required in-situ conservation (see also: O'Neill, 2019; Ottaway, 2003). Furnaces by virtue of their unfired nature, as also confirmed by our experiments, and their relative fragility were poorly suited to archaeological preservation. It appears that careful effort was rarely extended in removing their remains from workshop environments to dispose of them in pits at Şagu. When such efforts were not expended here or at other sites, furnaces and moulds would rapidly degrade and survive poorly or not at all in archaeological contexts. This presents a challenge for excavators to identify such amorphous and degraded elements in the field, which may present simply as oxidised spreads with few visible object surfaces preserved within the debris.

Looking to the broader context of metalwork consumption, the shift from production in tell-settlements in the MBA to production at open-sites like Şagu in the LBA is reflected in the increased diversity of object types. Once termed the Koszider horizon and associated with a Tumulus Culture invasion, the change is now seen as more gradual. A diversification in the range of objects being produced at tells begins in the eighteenth century BC (Găvan, 2015, pp. 180–183). With the so-called Koszider horizon of metalworking contemporary to the final decades of the activity at nearby tells, this diversity increases further from the sixteenth century along with the volume of material being produced in bronze. We can see in this a shift in the status and role of metalwork, and by extension metal management strategies, in society. Thus, the site of Şagu stands at a crossroad in the control and role of bronze as evident in the material culture itself. Further excavation is needed at other sites to resolve if the presence of metalworking at Şagu is exceptional or typical for LBA settlements. While not characterising the settlement and its community as a whole, this was an important component of its routine operations. The location of Şagu in the immediate hinterland of the monumental megasite of Corneşti Iarcuri suggests that just as metalwork itself became increasingly accessible, so too may have been the capacity to produce it within communities.

Conclusion

In this paper, we set out to examine the evidence for metal production at the site of Şagu in Romania to get new insights into changes in technological and, by extension, social organisation between the Middle and Late Bronze Age in the southeastern Carpathian Basin. Şagu is the most extensively excavated LBA site in the wider region and technical ceramics were recovered from 2 to 5% of the excavated features (pits). Here, we aimed to provide a technical and experimental study of the site-specific dataset and to use this as a vehicle to explore how craft organisation and cross-craft interactions related to society more widely.

Șagu reveals a wealth of community knowledge of the materiality of clay which ran through the entire metalwork production sequence, drawing upon knowledge of clay performance, pottery production, and architecture. This indicates the deep integration of metalworking within the Șagu community, while the performance and depositional patterns further reveal this extensive and inclusive experience of metalworking. Additionally, the working, if not making / alloying, of bronze, followed by casting bronze objects and further circulating them, makes Șagu an important node in the bronze artefact production network as a receiver and manipulator of resources and distributor of finished products in the Carpathian Basin and possibly beyond.

The restricted range of mould fragments, with impressions of mostly axes and chisels, may suggest that metalworkers at Șagu specialised in the production of specific artefact types. However, the likelihood that moulds for smaller objects more rapidly degraded and the existence of cores suited to manufacturing spearheads means we should not exclude that other object types were made at Șagu. More complex objects, such as swords, could have been made elsewhere or possibly by specialised craftspeople of a different status. Such a distributed organisation of craft would work in the context of large-scale community building in which multiple sites formed single communities. At the same time, evidence for various production activities including food (butter churn), cloth (spindle whorls), pottery (kiln), carpentry (chisel and axe moulds) as well as metalworking, demonstrates that the Șagu community was self-sufficient in many regards, while also feeding some needs of a wider network. This co-location of skillsets demonstrates the capacity for cross-craft interaction (Brysbaert, 2007, 2014) and the diverse skillsets available within or to the Șagu community. This in turn means that metalworking as a practice could be less clearly differentiated or specialised and need not have been linked to an individual or individuated identity.

The model of re-organisation of LBA societies following the MBA tell-centred system, and based on our evidence from Șagu, may suggest that less control was being exerted over where metal was made and who could participate either as a craftsperson or even as an audience. In the LBA, hosting craft workers was not the preserve of central sites and the capacity for cross-craft interaction is clearly demonstrated in the remains from Șagu. In a society in which clay was a fundamental resource, it is important that the range of technical knowhow was distributed across multiple crafts, revealing a pool of shared rather than exclusive expertise. In spatial terms, the craft environment at LBA Șagu was a marked departure from the boutique craft work at MBA tells. In organisational terms, this integrated and accessible metalworking tradition articulates well with increased levels of metalwork production that characterised the Late Bronze Age of the Carpathian Basin and beyond.

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Author Contribution All authors contributed to the manuscript and VO integrated authors' contributions into the original manuscript. VS conducted the original excavation and secured access to the study materials from Arad Museum, Romania. BM conceptualised the research design of the present study and all authors contributed to the methodology and to the research objectives thereafter. CB conducted the hhXRF analysis during sample screening and with BM and VS selected the samples. VO conducted additional hhXRF analysis on all samples, and targeted RLM and SEM–EDS on the crucibles, processed and visualised the results. SA conducted the petrography on all samples, SEM–EDS and XRPD on selected samples, processed and visualised the results. BON designed, planned and with LEFB conducted the 5 rounds of experiments for this project. They also made all experimental replicas, including moulds, crucibles, furnace, the tuyère, etc. in line with analytical results. BON wrote/contributed to the experimental sections, including infield methods and results. CB conducted the hhXRF analysis of the experimental samples and with VO processed the results. BM contributed the social context content, discussion, and editorial oversight. All authors reviewed, edited, and approved the final manuscript.

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Declarations

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