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DOUBLE-LOOPED PALSTAVES FROM THE LATE BRONZE AGE / EARLY IRON AGE OF THE WESTERN IBERIAN PENINSULA: NEW TECHNOLOGICAL INSIGHTS FROM SANTA JUSTA (NORTH OF PORTUGAL)

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ABSTRACT

Palstaves are one of the most common types of copper-based tool spread out during the Late Bronze Age (LBA) and the Early Iron Age (EIA), particularly between ca. 10th and 8th century BC, across Western Iberia. Hundreds have been found in hoards and settlements, especially in the Centre and North of Portugal and Galicia (Spain). This paper focuses on the study of two double-looped palstaves from Serra of Santa Justa (Valongo, North of Portugal), with the aim to discuss issues related to their production technology. For this purpose, different analytical techniques, such as X-Ray Fluorescence (XRF), Scanning Electron Microscopy with Energy Dispersive X-Ray Spectroscopy (SEM-EDS), and Optical Microscopy (OM), have been used. The results show that the two palstaves were produced with two operational chains: while specimen MDDS-2010.0069 is a leaded bronze (Cu+Sn+Pb) with an as-cast microstructure, the MDDS-2010.0082 is a binary bronze (Cu+Sn) with grains resulting from the forging and annealing of the metal after the ancient metallurgist took the palstave off from the mould. Based on the data presented in this paper, it is reported that the analytical characteristics of the two palstaves analysed here are consistent on a regional scale with data already known from other similar artefacts.

KEYWORDS: Palstaves, Late Bronze Age/Early Iron Age, Western Iberia, Archaeometallurgy.

1. INTRODUCTION

Palstaves produced with one, two or no loops, sometimes still with the casting jet, are very common in the Late Bronze Age (LBA) and the Early Iron Age (EIA) (10th and the 8th century BC) of Western Iberia. The vast majority of these tools were discovered accidentally in the late 19th- and first half of the 20th-century, generally by agricultural workers, which is why the precise location where most of them were found and their archaeological context is, as a rule, uncertain or poorly known.

Because of these circumstances, the investigation of palstaves has traditionally been based on typological approaches (Monteagudo, 1977; Díaz-Andreu García, 1988). L. Monteagudo´s catalogue published within the *Prähistorische Bronzefunde* series (Monteagudo 1977), for example, although no longer fully updated, still provides a valuable source of information, having the merit of systematising data otherwise dispersed in papers published in journals with a limited circulation.

In terms of their geographical distribution, palstaves are mostly concentrated in central and northern Portugal, and Galicia (Spain). South of the Tagus River, they are extremely rare, and the discovery of a palstave with casting jet at Veiros (Estremoz), for example, is one of the few exceptions known so far (Monteagudo, 1977: 165).

Palstaves are usually found concentrated in up to dozens of specimens in small or medium-sized hoards, deposited with other types or alone, in both wet and dry locations (Vilaça, 2006; Bottaini, 2013). Some of the largest hoards known so far in Western Iberia are composed only by double-looped palstaves, just like in the cases of Abelheira (also known as São Martinho de Bougado) (Sarmento, 1888), Ferreira de Aves (Sótão) (Veiga, 1891: 224), Paúl (Covilhã) (Vasconcelos, 1917: 328), Vilar de Mouros (Caminha) (Sarmento, 1888: 158), Carpinteira (Melgaço) (Fortes, 1905a), Fromariz (also known as Castelo) (Paredes de Coura) (Pereira, 1898: 133), Cobidalto (Viana do Castelo) (Bettencourt et al., 2014), Vila de Punhe (Viana do Castelo) (Viana, 1938: 8), Catelinha (a.k.a. Moreira) (Monção) (Cortez, 1951), and Ganfei (Valença) (Fortes, 1905b). In addition, palstaves were also deposited together with other types of objects, such as at Viatodos (also known as Fonte Velha) (Fortes, 1905c), Barrenhas (also known as Vilela Seca) (Villas-Bôas, 1948), Solveira (Montalegre) (Costa, 1963; Bottaini et al., 2015), Travasso (Leitão et al., 1984; Leitão et al., 1985; Cruz et al., 2014), and Moura da Serra (Nunes, 1957).

Furthermore, palstaves were found in several archaeological contexts, such as mines, e.g., Mina da Quarta Feira (Sabugal) (Veiga, 1891: 225); karst formations, e.g., Penedos Altos (Alvaiázere) (Rocha, 1904: 13); creek banks, e.g., Vidual (Carrazeda de Ansiães)(Botelho, 1899); cliffs, e.g., Vilar de Mouros (Camina) (Sarmento, 1888: 158), Paul (Covilhã) (Vasconcelos, 1917: 328); or even rocky cracks, e.g., Corvite (Guimarães) (Sarmento, 1898: 162), Cobidalto (Viana do Castelo) (Bettencourt et al., 2014), Quinta da Commenda (Arcos de Valdevez) (Pereira, 1898: 89), etc. Others were also discovered inside or close to settlements, e.g., Castro da Senhora da Guia (São Pedro do Sul) (Silva et al., 1984), Castro da Senhora do Bom Sucesso (Mangualde) (Kalb, 1980: 30), Castro de Medeiros (Montalegre) (Veiga, 1891: 231), and Tapada das Argolas (Vilaça et al., 2002-2003: 178).

Regarding their technological characteristics, palstaves have been investigated discontinuously since the beginning of the 20th century. After the pioneering analyses carried out by L. Siret in 1913, new contributions mainly focusing on their chemical composition were made in the 1980s (Harrison & Craddock 1981; Sierra Rodríguez et al. 1984). However, most of the available data has only been obtained in the past two decades in both Spain (Montero-Ruiz et al., 2003; Montero-Ruiz et al., 2014; Montero-Ruiz, 2016; Rovira, 2016), and Portugal (Bottaini et al., 2012a: 24-26), as in the case of specimens found at Tapada das Argolas (Vilaça et al., 2002-2003: 178), Baiõies (Valério et al., 2006: 300-303), Vila Cova de Perrinho (Bottaini et al., 2012b), and Solveira (Bottaini et al., 2015).

Considering the variety of the depositional patterns, the diversity of environments in which they were found, and the differences in terms of production technology, it is likely that ancient societies attributed palstaves special meanings, not just considering them as tools related to agricultural activities (Fontijn, 2002).

In order to shed new light on palstaves and their meaning, this paper reports the results of metallurgical and metallographic analyses of the two previously unstudied double-looped palstaves from Santa Justa. The present analyses were first performed within the doctoral thesis of this paper's author (Bottaini, 2013: 105-112), but analyses have been recently revised and improved. For this purpose, a multi-analytical approach combining X-ray Fluorescence (XRF), Electron Scanning Microscopy with Energy Dispersive X-Ray Analysis (SEM-EDS) and Optical Microscopy (OM) was adopted. Results are discussed and compared on a regional scale, providing new insights into technological issues.

2. THE PALSTAVES

The two double-looped palstaves presented in this paper (MDDS-2010.0069 and MDDS-2010.0082), were found in the Serra de Santa Justa (Fig.1).

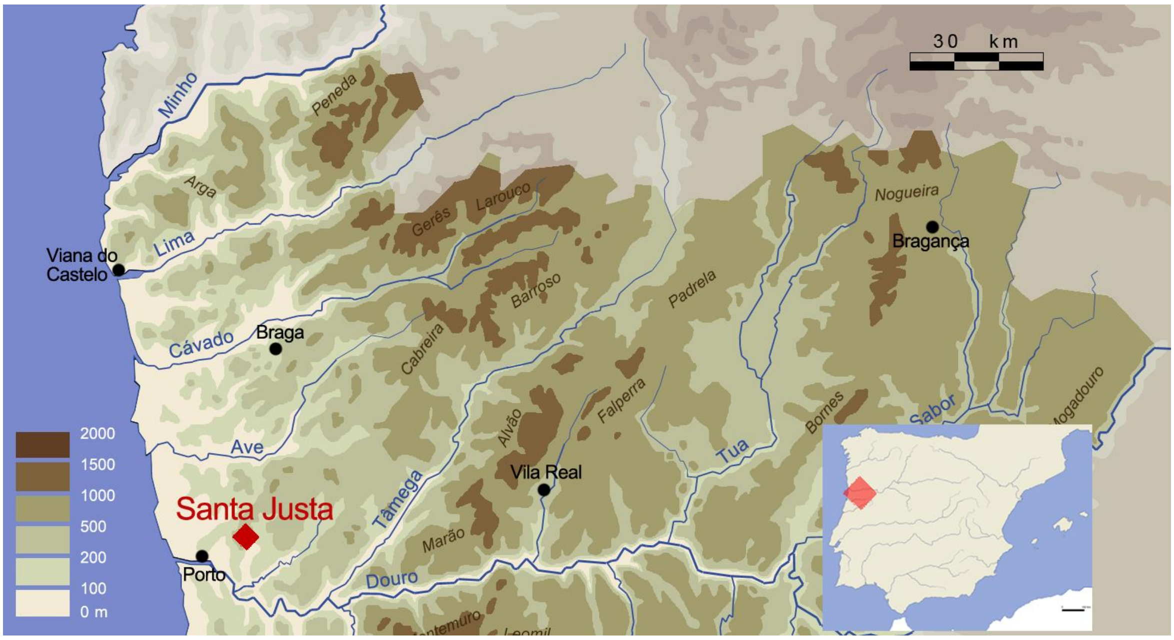

Figure 1. Location of the two palstaves (municipality of Valongo, Porto district)

They are similar in size and weight (Table 1), but show clear differences in morphological terms (Fig. 2). According to Monteagudo's typology, for example, MDDS-2010.0069 is included in the type 29H (Monteagudo, 1977: 181), while MDDS-2010.0082 in the type 35A (Monteagudo, 1977: 208). It should be noted that the latter type consists mostly of palstaves from central Portugal.

Table 1. Morphological characteristics of the two palstaves from Santa Justa. L: Length (cm); W: Width (cm); T: Thickness (cm); Wt: Weight (g).

ID	Previous ID numbers	L	W	T	Wt
MDDS-2010.0069	MMP 134, CMP 43-134, MNSR 219, MEP 7127	23,1	6,4	2,7	1151
MDDS-2010.0082	MMP 133, CMP 43-133, MNSR 218, MEP 7128	23,4	7,2	2,8	1123

The two palstaves from Santa Justa have been frequently mentioned in the literature since the beginning of the 20th century (Peixoto, 1902: XIV; Pinto, 1929; Cortez, 1946: 61–62; Monteagudo, 1977; Kalb, 1980: 28). Although information on the circumstances and context of the find are unknown, Savory (1951: 362) speculated that they were part of a hoard. More recently, it has been argued that their find-spot would be related to the Castro de Santa Justa (Santa Justa hillfort), also known as Alto do Crasto or Cavadas dos Castros (Silva, 2006: 137). In his monograph on Iberian axes, Monteagudo also referred the occurrence of another double-looped socketed axe from the Serra de Santa Justa (Monteagudo, 1977: 246), but did not reveal any relationship with the finding of the double-looped palstaves studied here.

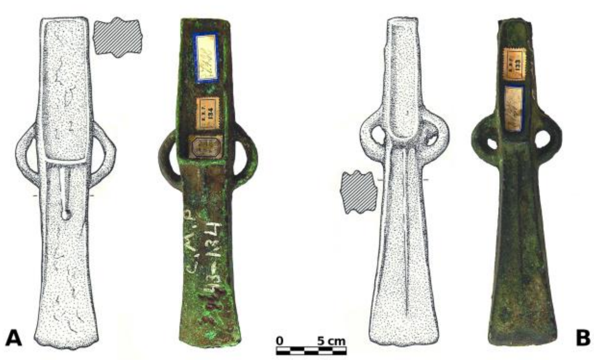

Figure 2. Palstaves (A) MDDS-2010.0069, and (B) MDDS-2010.0082 (Drawings according to Monteagudo 1977).

During the 20th century, the two palstaves were incorporated into various museums. In fact, they were part of the *Museu Municipal do Porto* (M.M.P./C.M.P.: *Câmara Municipal do Porto*) (Peixoto 1902: XIV), probably until its extinction in 1940 (Almeida, 2008). Later, they were incorporated in the *Museu Nacional dos Soares dos Reis* (M.N.S.R.) (Cortez, 1946), and, finally, passed to the *Museu de Etnologia do Porto* (M.E.P.) (Monteagudo, 1977: 181, 208), where they were kept until the museum closed in 1992 (Table 1). Since then, the palstaves were inaccessible to the public until 2010, when they were finally incorporated in the *Museu D Diogo de Sousa* (Braga). In this paper, the two axes are identified with the inventory number given by the latter museum.

3. METHODOLOGY

3.1 X-ray Fluorescence (XRF)

XRF analyses were performed with a Bruker Tracer III-SD handheld spectrometer equipped with a Rh anode tube and a silicon drift detector on samples removed from the blades of the two palstaves. The following operating conditions were used: 40 Kv, 12.5 μA current, Al-Ti filter (304.8 μm aluminium, 25.4 μm titanium), 60 seconds acquisition time. The concentration of the various elements was calculated from a calibration validated by five certified standards (BCR-691).

3.2 Scanning Electron Microscopy with Energy Dispersed X-ray Spectroscopy (SEM-EDS)

SEM-EDS was carried out with a Hitachi S3700N interfaced with a Quantax EDS microanalysis system equipped with a Bruker AXS 5010 XFlash Sillicon Drift Detector (129 eV Spectral Resolution at FWHM/Mn kα). The operating conditions for EDS analyses were as follows: backscattered electron mode (BSEM), 15-20 kV accelerating voltage, at a ~10 mm working distance and 90 μA emission current.

3.3 Optical Microscopy (OM)

For metallographic observations, the two samples removed from the blade of the palstaves were mounted in epoxy resin, grinded with sandpaper up to 1200 μm and polished with 6 μm, 3 μm, and 1μm polycrystalline diamond powder. They were then etched with an aqueous ferric chloride solution, following Scott (1991). Finally, they were observed with a microscope Leica DM-2500-P combined with a Leica MC170-HD camera, using the Leica Application Suite software platform.

4. RESULTS AND DISCUSSION

As shown in Table 2, the two palstaves were produced with different alloys, namely, leaded bronze (Cu+Sn+Pb) (MDDS-2010.0069) and binary bronze (Cu+Sn) (MDDS-2010.0082).

When observed by SEM, the two samples revealed a microstructure with differences reflecting their composition. In fact, MDDS-2010.0069 (Figure 2A) showed a microstructure scattered by the presence of the tin-rich α+δ eutectoid phase and Cu-S and Pb globular inclusions (Figure 3). In contrast, MDDS-2010.0082 (Figure 2B) displayed a more homogeneous microstructure with the presence of a reduced number of globular Pb segregates and elongated Cu-S inclusions (Figure 4).

Table 2. Results of the XRF analysis (wt.%)

ID	Cu	Sn	Pb	Fe
MDDS-2010.0069	78.80	16.10	5.05	0.05
MDDS-2010.0082	89.75	9.20	1.00	0.05

The amount of tin and lead has a deep impact on the mechanical properties of a metal and affects the thermo-mechanical response of the alloy to forging and annealing processes. A bronze with ~10/14-15% Sn, for example, exhibits optimal mechanical properties (Rovira, 2004: 26; Bottaini et al., 2016). In contrast, when tin exceeds 14-15%, the metal becomes more brittle and harder to forge due to the formation of the α+δ eutectoid phase. Similarly, brittleness increases when Pb exceeds a certain amount (Philip, 1991: 99), making the alloy much more difficult to deform plastically without cracking due to the presence of Pb-rich interdendritic globules scattered throughout the metal structure.

Table 4 summarises the data available so far on the chemical composition of palstaves from the Portuguese territory. The problem of correlating data obtained with different methodologies and analytical techniques is a long-debated and controversial issue in archaeometallurgy (Müller et al., 2009). Unfortunately, some of the data presented in the table has been published with little information on the analytical methodology adopted, the specifications of the equipment used, the way how data were processed and the quantifications obtained, the area of the palstave that was analysed, etc. We are therefore aware that comparing data such as those reported in the table may be difficult, especially with heterogeneous materials such as leaded alloys (Hughes et al., 1982). Nevertheless, at the moment, this is the only possibility we have to draw some conclusions of technological relevance on a regional scale.

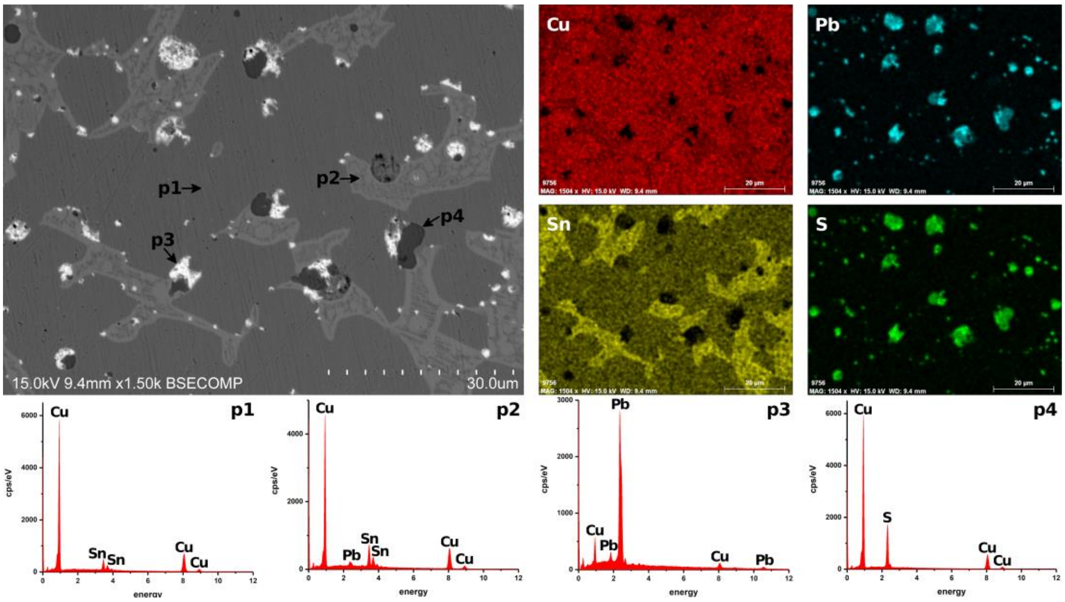

Figure 3. SEM-EDS mapping of the sample MDDS-2010.0069, showing the a+δ eutectoid phase richer in Sn (p2), and Pb (p3), and S (p4) inclusions.

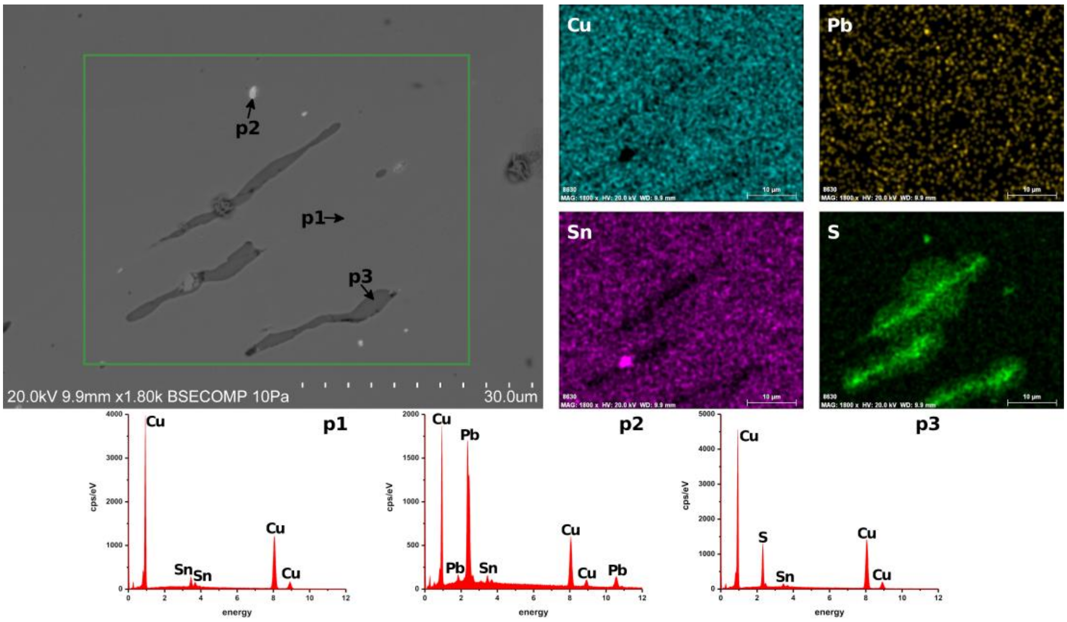

Figure 4. SEM-EDS mapping of the sample MDDS-2010.0082, showing Pb (p2), and S (p3) inclusions.

Table 4. Composition (wt%) of double-looped palstaves from the Portuguese territory; n.d.: not detected; tr.: traces. (*) "believed to have been excavated N. of Oporto" according to Harrison & Craddock 1981: 138. (**) Bibliography: [1] Bottaini et al. 2012a; [2] Lobato 1992-93; [3] Harrison & Craddock 1981; [4] Siret 1913; [5] Bottaini et al. 2015; [6] Valério et al. 2006; [7] Coffyn 1976; [8] Vilaça et al. 2002-03; [9] Leitão & Lopes 1985; [10] Bottaini et al. 2012b.

N.	Provenance		Cu	Sn	Pb	Other elements	(*)
1	Barcelos	North	85.1±0.4	11.0±1.0	4.3±0.5	n.d.	[1]
2	Chaves	North	88.8±0.4	11.0±1.0	0.5±0.1	n.d.	[1]
3	Cortiços	North	67.7	6.8	5.4	Fe: 0.01; Ni: 0.06; Ag: 0.02; Sb: 0.01	[2]
4	Minho	North	85.9±0.4	14.0±1,0	0.4±0.1	As: <102 ppm	[1]
5	Minho	North	86.0±0.4	12.0±1.0	1.9±0.2	n.d.	[1]
6	Monte da Virgem	North	68.8	4.4	16.40	Fe: 0.01; Ni: 0.03; Sb: 0.13	[2]

7	Monte da Virgem	North	58.06	8.7	24.02	Fe: 0.01; Ni: 0.05; Sb: 0.10	[2]
8	Monte da Virgem	North	60.1	8.8	28.04	Fe: 0.008; Ni: 0.008; Sb: 0.08	[2]
9	Monte da Virgem	North	60.8	9.01	28.3	Fe: 0.01; Ni: 0.04; Sb: 0.10.	[2]
10	North of Portugal (**)	North	66.5	7.7	24.5	Fe: 0.03; As: 0.10; Ni: 0.002; Ag: 0.07; Sb: 0.07; Bi: 0.001; Zn:0.008	[3]
			67.5	8.3	24.6	Fe: 0.025; As: 0.015; Ag: 0.06; Sb: 0.07; Bi: 0.001; Zn: 0.01	
11	North of Portugal (**)	North	62.00	6.5	31.1	Fe: 0.25; As: 0.02; Ni: 0.005; Ag: 0.085; Sb: 0.03; Bi: 0.001; Zn: 0.02	[3]
12	North of Portugal (**)	North	62.0	6.9	31.2	Fe: 0.45; As: 0.03; ni: 0.10; Ag: 0.50; Bi: 0.002; Zn: 0.05	[3]
			59.0	6.4	35.1	Fe: 0.03; As: 0.025; Ni: 0.01; Ag: 0.05; Bi: 0.002	
13	North of Portugal	North	80.6±0.4	n.d.	19.0±2.0	Fe: 0.06±0.02	[1]
14	S. Mamede de Ribatua	North	79.6	11.5	0.06	Fe: 0.007; Ni: 0.05; Sb: 0.04.	[2]
15	S. Mamede de Ribatua	North	78.9	8.36	2.99	Fe: 0.01; Ni: 0.07; Sb: 0.01.	[2]
16	Abelheira	North	59.32	9.67	28.13	Sb: 2.50	[4]
			n.d.	n.d.	97.0	n.d.	[4]
17	Abelheira	North	63.32	7.98	24.73	Sb: 1.25	[4]
18	Abelheira	North	56.05	5.34	33.60	Sb: 1.67	[4]
			25.72	2.83	67.83	Sb: 1.25	[4]
19	Abelheira	North	51.7	8.1	40.02	Sb: 0.75	[4]
			n.d.	n.d.	96.6	n.d.	[4]
20	Abelheira	North	50.62	11.01	26.29	Sb: 1.83	[4]
			38.05	10.07	51.12	Sb: 0.20	[4]
			n.d.	n.d.	97.35	n.d.	[4]
21	Abelheira	North	7.18	tr. (?)	84.18	Sb: 0.94	[4]
22	Abelheira	North	50.6	3.3	35.44	Sb:1.00	[4]
			n.d.	n.d.	98.37	n.d.	[4]
23	Abelheira	North	73.86	11.17	13.66	Sb: 1.18	[4]
24	Abelheira	North	61.48	8.65	25.75	Sb: 0.39	[4]
25	Solveira	North	84.1±0.9	12.0±2.0	4.0±0.9	Ni: 700±200 ppm	[5]
26	Unknown	Unknown	66.7±0.3	7.6±0.8	26.0±3.0	n.d.	[1]
27	C. Senhora da Guia	Centre	81.2	18.0	<0.1	Fe: 0.35; As: 0.14; Sb: 0.04	[6]
28	C. Senhora da Guia	Centre	69.4	29.7	<0.1	Fe: 0.34; As: <0.10; Sb: 0.08	[6]
29	C. Senhora da Guia	Centre	54.6	44.0	0.3	Fe: 0.40; As: 0.38; Sb: 0.19	[6]
30	C. Senhora da Guia	Centre	62.8	36.2	<0.1	Fe: 0.28; As: 0.46; Sb: <0.02	[6]
31	C. Senhora da Guia	Centre	80.2	19.20	<0.1	Fe: 0.10; As: 0.22; Sb: 0.06	[6]
32	C. Senhora da Guia	Centre	66.3	32.8	<0.1	Fe: 0.30; As: 0.46; Sb: <0.02	[6]
33	C. Senhora da Guia	Centre	65.8	33.0	<0.1	Fe: 0.40; As: 0.48; Sb: <0.02	[6]
34	C. Senhora da Guia	Centre	62.6	36.2	<0.1	Fe: 0.43; As: 0.53; Sb: 0.08	[6]
35	C. Senhora da Guia	Centre	78.1	21.2	<0.1	Fe: 0.12; As: 0.20; Sb: 0.06	[6]
36	C. Senhora da Guia	Centre	61.8	37.1	0.18	Fe: 0.32; As: 0.28; Sb: 0.17	[6]

37	Quinta do Ervedal	Centre	86.5	~7.0	0.02	Fe: 0.003; As: 1.50; Ni: 0.10; Ag: ~1.0; Sb: ~3.0; Bi: 0.15; Mn: tr	[7]
38	Tapada das Argolas	Centre	86.1	12.20	0.5	As: 0.70; Ag: 0.10; Sb: 0.10; Au: 0,30	[8]
39	Travasso	Centre	84.0	12.0	n.d.	n.d.	[9]
40	Travasso	Centre	88.5	9.5	n.d.	n.d.	[9]
41	Travasso	Centre	88.0	10.0	n.d.	n.d.	[9]
42	Vila Cova de Perrinho	Centre	90.02±0.21	9.92±0.03	tr.	Fe: 0.061±0.003	[10]

The first aspect to note concerns the geographical distribution of binary (Cu+Sn) and leaded (Cu+Sn+ >3% Pb) palstaves. In fact, while we can observe a certain uniformity in the distribution of binary palstaves throughout Western Iberia, those produced with leaded alloys are concentrated exclusively in the North of Portugal (and Galicia) (Figure 5). Furthermore, only a small number of palstaves fall within the range of 10-14% Sn and <3% Pb (Figure 6A, green area), which is theoretically considered as the optimal range providing alloys with the most appropriate mechanical properties.

In all the palstaves analysed, Sn does not exceed 16.1% (palstave MDDS-2010.0069 from Santa Justa), varying between 7% and 12.2% in Central Portugal (Figure 6B1) and from 0 to 16.1% in the North (Figure 6C1). The 10 axes from Castro da Senhora da Guia de Baiões (São Pedro do Sul) have an amount of Sn much higher than the rest of the palstaves, in the range of 18-44%, but this is because the analyses were performed without removing the corrosion layers (Valério et al., 2006: 300-303).

Lead has a more pronounced variability than tin, especially in the North of Portugal, where it is found mixed to both Cu+Sn and, although much more rarely, Cu alone (Bottaini et al., 2012A: 26), ranging up to around 40%. Of the 42 palstaves reported in Table 3, 19 from North of Portugal have a Pb content higher than 3%. This suggests that Pb was added voluntarily at some point of the production cycle and given its high content not with the intention to make the axes more efficient touse (Figure 6C2). The high and unpredictable variability of the lead is a common trait also in the neighbouring Galicia (Harrison et al., 1981, Montero-Ruiz, 2016), where a large number of high leaded palstaves is also attested, e.g., Samieira (Sierra Rodríguez et al., 1984), Vara (Montero-Ruiz et al., 2003), and Distriz (Montero-Ruiz et al., 2014).

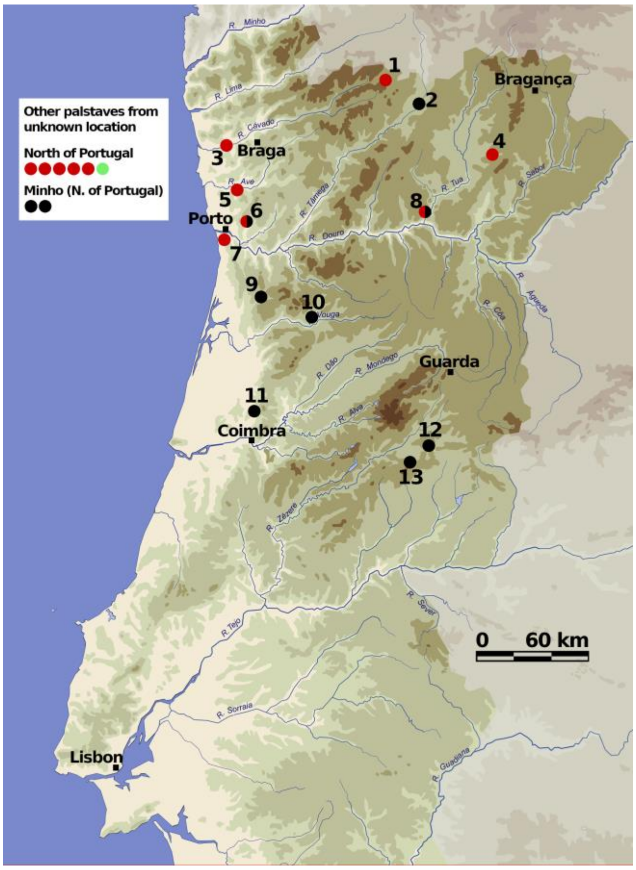

Figure 5. Map of distribution of double-looped palstaves according to their chemical composition showing that leaded bronze palstaves are so far exlusively concentrated in the North of Portugal, while binary bronzes are distributed in a more balanced way across North and Centre of Portugal (black dots: binary bronzes; red dots: leaded bronzes; green dot: leaded copper). Sites: 1) Solveira; 2) Chaves; 3) Barcelos; 4) Cortiços; 5) Abelheira; 6) Santa Justa; 7) Monte da Virgem; 8) São Mamede de Ribatua; 9) Vila Cova de Perrinho; 10) Castro da Senhora da Guia de Baiões; 11) Travasso; 12) Tapada das Argolas; 13) Quinta do Ervedal.

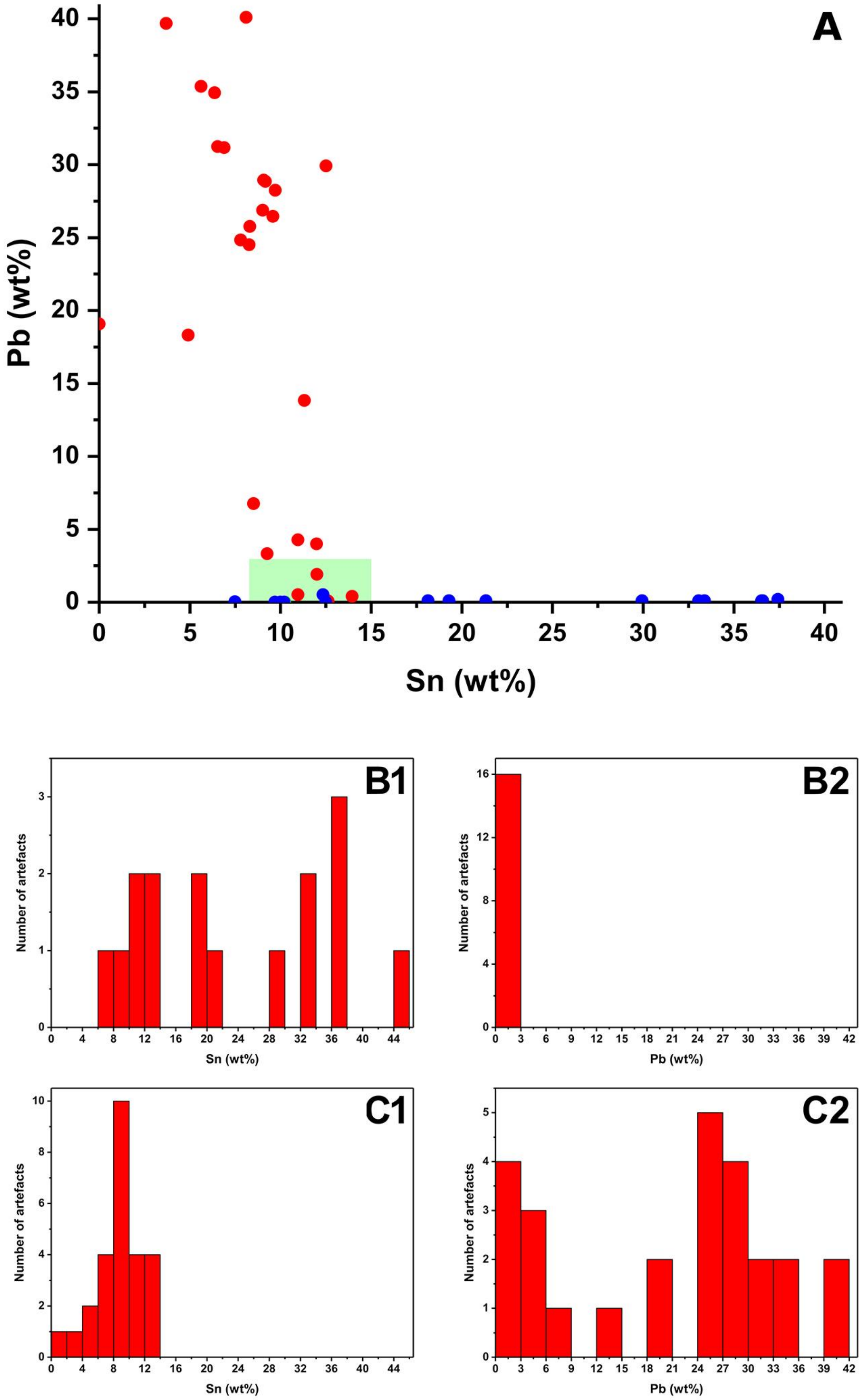

Figure 6. Elemental distribution of the double-looped palstaves from Centre and North of Portugal. A) Scatterplot concerning the Sn and Pb values detected in Central (blue dots) and Northern Portugal (red dots); B) Histogram of Sn and Pb variability in the Centre of Portugal (B1 and B2 respectively); C) Histogram of Sn and Pb variability in the North of Portugal (C1 and C2 respectively). Data has been normalised.

To this respect, an intriguing aspect is the composition of the casting jets when present. Analyses conducted by Siret (1913) on a group of palstaves from Abelheira (North of Portugal) indicated that the casting jets consist of almost pure lead (data have not been included in Figure 6), while in the body of the axes it ranges from about 25% to 40% Pb. This situation, which requires further investigation, is due to the presence of Pb spheroid globules placed inside the casting jet (Figure 7), as also discussed in Harrison et al. (1981: 153-154).

In contrast to the north-west of the Iberian Peninsula, the palstaves from central Portugal are characterised by an absence or a very low amount of lead, which does not exceed 0.5%. Low Pb metallurgy is typical of the LBA from Central Portugal, generally characterised by binary alloys (Cu + 8-15% Sn), with reduced impurities (Vilaça, 1997; Bottaini et al., 2016).

Figure 7. Detail of the casting jets of two double-looped palstaves from the Abelheira hoard (North of Portugal), analysed by L. Siret (1913), showing the presence of Pb spheroid globules placed in their inside (Photo © Carlo Bottaini).

Overall, the data collected in Table 2 suggest that the addition of Pb was not a systematic practice in the production of palstaves. In fact, lead appears to be employed erratically and randomly, often mixed in amounts too large to provide metal any technological benefit. A recent experimental work has showed that high-lead alloys have a different colour than binary or low leaded alloys (Devogelaere, 2017). Therefore, it is very likely that, based on the colour of the metal itself, ancient metal craftsmen (and eventually metal traders and customers) might have been able to distinguish different types of alloys, not being led to mistake a binary palstave for a leaded one. In this scenario, the possibility that ancient metal craftsmen appreciated the beneficial properties of Pb cannot be dismissed, although we must admit that Pb was not added for merely technological reasons, but rather due to other factors, such as, for example, local or temporal availability of Pb, recycling of lead-rich bronzes, etc.

Furthermore, a recent investigation carried out on two palstaves from Distriz (north-western Spain) determined that the Pb contained in the artefacts has an isotopic fingerprint close to ores of the Almería region (South of Spain) (Montero-Ruiz et al., 2014). According to this data, the authors of the study consider that high-leaded palstaves found in the Atlantic region may have been produced locally with raw material imported from the peninsular region under Phoenician influence, i.e., Iberian Peninsula south/south-eastern (Montero-Ruiz et al., 2014: 155), where copper-leaded axe-like ingots were already circulating at the time (Renzi, 2010). As such, the production of palstaves may be framed within the so-called Western Phoenician sphere system (Frankenstein, 1977), which connected the Atlantic and Mediterranean worlds from the 8th century onward (Arruda, 2009), also allowing for the exchange of metals both as finished objects (Vilaça et al., 2020), and as raw material.

5. MANUFACTURING PROCESS

The metallographic observation of the two palstaves from Santa Justa suggests that they underwent different post-casting treatments after being removed from the mould. The palstave MDDS-2010.0069 has an as-cast dendritic microstructure indicating that the blade did not suffer any post-casting treatment (Figure 8A). In contrast, the microstructure of the palstave MDDS-2010.0082 consists of twinned grains with strain lines, indicating a combination of hammering and heat treatments followed by final forging. In this case, the thermo-mechanical treatment was intended to make the blade harder and more suitable for practical uses that may involve physical impacts against harder surfaces (Figure 8B).

Regionally, few other palstaves have been observed under the metallographic microscope. Three binary axes with unknown find-spot from the North and one from central Portugal (i.e., Vila Cova de Perrinho) displays a microstructure with well-defined grains with annealing twins formed after heating and plastic deformation of the blade. In contrast, two palstaves composed of leaded bronze and leaded copper, both from North of Portugal, show an as-cast microstructure (Bottaini et al., 2012a, Bottaini, 2013).

To be also noted that a large number of palstaves found in the north-western of Iberian Peninsula appear to be poorly finished and the persistence of the casting jet gives the idea that axes were hastily buried immediately after their production. However, when available, data on their microstructure suggests that ancient metalworkers were somehow aware of the mechanical properties of the alloys. In the Portuguese territory, for example, post-cast treatment is so far restricted to the axes with lower amounts of lead.

However, further analyses are needed to get a clearer picture of the situation and to understand whether there is any relationship between the concentration of lead and the type of post-cast treatment applied. Metallography carried out on a leaded palstave from Vara (north-western of Spain), for example, showed that its blade was selectively hammered (Montero-Ruiz et al., 2003), thus revealing that the situation may not be as linear as it appears at first sight.

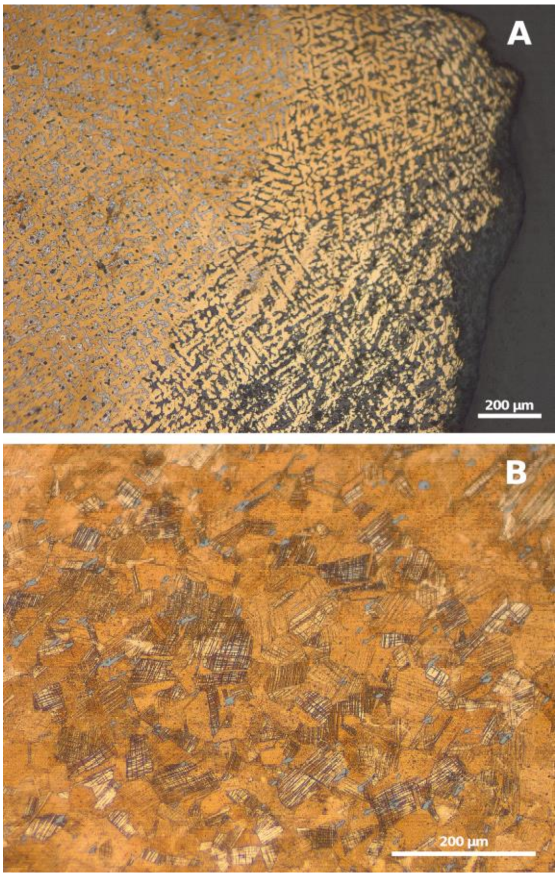

Figure 8. Metallography of MDDS-2010.0069, showing a dendritic microstructure, typical of an as-cast alloy (A), and of MDDS-2010.0082, displaying the presence of twinned grains with strain lines from heating and hammering (B).

6. FINAL REMARKS

The analytical data of the chemical composition and microstructural characteristics of two double-looped palstaves from Santa Justa, North of Portugal, provided new insights into technological issues related to the production of this type of artefacts.

The two palstaves from Santa Justa revealed that they were produced with different technological processes: MDDS-2010.0069 showed an as-cast microstructure produced of 78.8% Cu, 16.1% Sn, and 5.05% Pb, with reduced impurities (0.05% Fe). In contrast, MDDS-2010.0082 is an 89.75% Cu + 9.2% Sn alloy, with 1% Pb and 0.05% Fe as vestigial elements, that revealed twinned grains as result of repeated cycles of hammering and annealing applied along the blade to make it sharper.

The chemical composition of the two palstaves confirms the trend known so far in terms of geographical distribution, in which binary palstaves are scattered throughout the Western Iberia, while those with a higher Pb content are concentrated exclusively in the north of Portugal and Galicia (Spain). The bronzeworkers produced almost standardised palstaves in terms of morphology using different alloys and applying distinct post-casting treatments. They probably knew the mechanical response of a high-leaded alloy when subjected to plastic deformation, and therefore selectively annealed and forged the axes with lower or no lead. The case of the leaded palstave from Vara, whose blade was selectively forged, is so far unique.

Why bronze-smiths used different operational chains to produce the same type of objects is still to be understood. However, this diversity in terms of production technology, together with the variety of depositional patterns in which palstaves were placed, may reflect the multiple functions that such tool had among the FBA/EIA communities of Western Iberia.

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