



HAL
open science

Continuity of lead-silver production in the area of Cartagena-La Unión (Spain) after the Phoenician trade crisis of the 6th century BC

Céline Tomczyk, Christophe Petit, María Berná, Laurent Costa, Jessica Legendre, Jesús Moratalla, Sidonie Révillon, Pierre Rouillard

► To cite this version:

Céline Tomczyk, Christophe Petit, María Berná, Laurent Costa, Jessica Legendre, et al.. Continuity of lead-silver production in the area of Cartagena-La Unión (Spain) after the Phoenician trade crisis of the 6th century BC. *Journal of Archaeological Science: Reports*, 2024, 59, pp.104742. 10.1016/j.jasrep.2024.104742 . halshs-04718691

HAL Id: halshs-04718691

<https://shs.hal.science/halshs-04718691v1>

Submitted on 3 Oct 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



Continuity of lead-silver production in the area of Cartagena-La Unión (Spain) after the Phoenician trade crisis of the 6th century BC

Céline Tomczyk^{a,*}, Christophe Petit^a, María Berná^b, Laurent Costa^c, Jessica Legendre^d, Jesús Moratalla^e, Sidonie Révillon^f, Pierre Rouillard^c

^a Université Paris 1 Panthéon-Sorbonne, UMR 7041 ArScAn, équipe archéologies environnementales, France

^b Museo Histórico de Aspe, Spain

^c CNRS, UMR 7041 ArScAn, équipe mondes grecs archaïques et classiques, France

^d Ministère de la Communication et de la Culture, Centre de recherche et de restauration des musées de France (C2RMF), France

^e Universidad de Alicante, Spain

^f Laboratoire SEDISOR, UMR 6538 Géosciences Océan, France

ARTICLE INFO

Keywords:

Litharge
Metallurgy
Lead isotopes
Commercial crisis
Phoenician

ABSTRACT

The 6th century BCE is marked by major changes in the Mediterranean trade routes. These changes had a significant impact on the production of silver-lead in the Iberian Peninsula, which was previously thought to have come to an abrupt end.

However, the study of litharge from the early 5th century BCE to the first half of the 3rd century BCE, from three sites in the Alicante region, demonstrates that the types, textures and compositions of litharge remain unchanged after the crisis in Phoenician trade. Thus, although no production workshops have been found in the Cartagena mining district, it is possible to affirm that the cupellation processes used at the beginning of the first millennium BCE continued until the 3rd century BCE.

Lead isotopic analysis of the litharge and two lead artefacts indicate that they come from ores from the very rich mines of Cartagena-La Unión, which were extensively exploited between the 8th and 6th centuries BCE.

Despite a major decline in mining and metallurgical production and considerable changes in the networks of exchange in the Mediterranean, the same production chain persisted from lead extraction to the type of metallurgy practised. The economic crisis does not therefore lead to a cessation of production, but the quantity of lead (and silver) produced would probably be significantly lower.

1. Introduction

Throughout the first millennium BCE, the Iberian Peninsula was the site of rich and complex interactions between indigenous, Phoenician, Greek, Carthaginian and later Roman populations (see in particular [Abad Casal, 1992](#); [Momrak, 2005](#); [Díaz, 2015](#); [Albelda, 2018](#); [Rouillard, 2023](#)).

The coastal regions of the eastern Iberian Peninsula witnessed extensive agricultural production, as evidenced by significant deforestation as early as the 9th century BCE ([Pappa, 2015](#)). Pollen records indicate a specialisation in large-scale cereal, oil, wine ([Buxó, 2008](#)) and fruit production ([Pérez-Jordà et al., 2017](#)). These agricultural activities were sometimes associated with other activities, particularly mining ([Pérez-Jordà et al., 2023](#)), especially of lead-silver. The importance of

metallurgical activity was so important in the early first millennium BC that lead contamination of Phoenician-Iberian origin (~1100–800 BCE) and later of Roman origin has been detected in Greenland ice cores ([McConnell et al., 2018](#)).

However, the flourishing maritime trade from the Iberian Peninsula to the eastern Mediterranean declined in the second half of the 6th century BCE during a Phoenician trade crisis, leading to the abandonment of numerous sites in the Iberian Peninsula ([Aubert, 1995](#); [Ruiz, 2007](#); [Puckett, 2012](#); [Díaz, 2015](#); [Murillo-Barroso et al., 2016](#)). The real impact of this economic crisis remains uncertain. It could manifest itself in a severe recession ([Shefton, 1995](#); [Dietler and López-Ruiz, 2009](#) p.4–49) or even lead to political collapse and the overthrow of the current elites ([Rothenberg and Blanco-Freijeiro, 1981](#); [Díaz, 2015](#)).

It was not until the arrival of the Romans, at the beginning of the 2nd

* Corresponding author.

E-mail address: celine.tomczyk@cnrs.fr (C. Tomczyk).

<https://doi.org/10.1016/j.jasrep.2024.104742>

Received 27 April 2024; Received in revised form 2 August 2024; Accepted 26 August 2024

Available online 6 September 2024

2352-409X/© 2024 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

century BCE, that lead-silver production resumed on a massive scale in Iberia. At that time, the entire southwestern territory of the peninsula was exported to Rome and underwent a political, socio-economic and cultural reorganisation (Keay, 2003; Myers, 2016).

2. Successive phases of intensive exploitation and mining decline in the Alicante region

The Cartagena-La Unión mining area, which is 23 km long and 6.5 km wide, is located in the extreme west of the Murcia region (Spain), amidst gently rolling terrain bordering the Mediterranean coast. Several phases of mineralisation have been identified within these mines, but the dominant facies corresponds to a stratiform deposit within Triassic limestones. Silver-bearing galena (\pm sphalerite) is intercalated within thin bands of calcite and dolomite (Andreazini et al., 2015). The most significant mineralised veins can reach thicknesses of up to 10 m and have the highest lead concentrations in the Iberian Peninsula (Oen et al., 1975). The richness of these deposits, together with their geographical location, which facilitated the export of products via coastal sea routes, contributed to the establishment of the mines of Cartagena-La Unión as a leading mining district from the prehistoric period until their mass exploitation in the 20th century (Vilar, 1986; Rico et al., 2009).

2.1. Periods of intensive exploitation between the 8th and 6th centuries BCE and during the Roman period

These mines are mainly known for their intensive exploitation between the 2nd century BCE and the 1st century CE, during the Roman period (Domergue, 1990; Caparros and del Carmen, 1999; Marín et al., 2010; Fabre et al., 2014; Rico et al., 2018). Lead ingots from Cartagena were exported throughout the Mediterranean during this period (Trincherini et al., 2009; Clemenza et al., 2017; Domergue and Rico, 2024).

However, while the importance of this ancient exploitation is

undeniable, recent discoveries also reveal an earlier phase of intense lead exploitation between the 8th and the second half of the 6th century BCE. The ore from the Cartagena mines was then processed in workshops located close to the coast, less than 100 km from the mines (Fig. 1). Three Phoenician smelting workshops have been discovered:

- at La Fonteta (with smelting activity probably between 800 and 550 BCE (Renzi et al., 2009) but with occupation until the end of the 6th century (Rouillard et al., 2007))
- at Cabezo Pequeño del Estaño (750–650 BCE, Prados Martínez et al., 2018)
- at Punta de los Gavilanes (700–600 BCE, Polzer, 2014).

The presence of a fourth workshop is suspected, as paleopollution identified at the Laguna de Río Seco site suggests extractive lead metallurgy between 1550 and 550 BCE (García-Alix et al., 2013).

While Roman production was usually exported in the form of ingots, Phoenician lead was not typically exchanged in this way, but more often directly as galena or litharge. Litharges are an intermediate stage in lead-silver metallurgy. The reductive smelting of silver-bearing lead ores generates slag and bullion lead. A litharge is formed when this bullion lead is cupelled to separate the silver which is released in liquid metallic form, from the lead (which is then retained in the litharge). The reducing fusion of this litharge produced lead in metallic form.

Ships passed through along the Alicante region loaded with several tonnes of lead, as evidenced by two 7th century BCE shipwrecks discovered off the coast of the lead reduction workshop at Punta de los Gavilanes (Negueruela et al., 2004; Polzer, 2014). The first shipwreck, discovered at Bajo de la Campana, was loaded with over a ton of non-argentiferous galena from Almería (Polzer, 2014) in the form of 10,000 fragments (Polzer, 2012), accompanied by goods of exotic origin (copper and tin ingots, bronze furniture, amber and ivory (Ruiz Cabrero and Mederos Martín 2004; Nantet, 2016 p. 277–279). The second shipwreck, called Mazarrón 2, carried Phoenician amphorae and almost

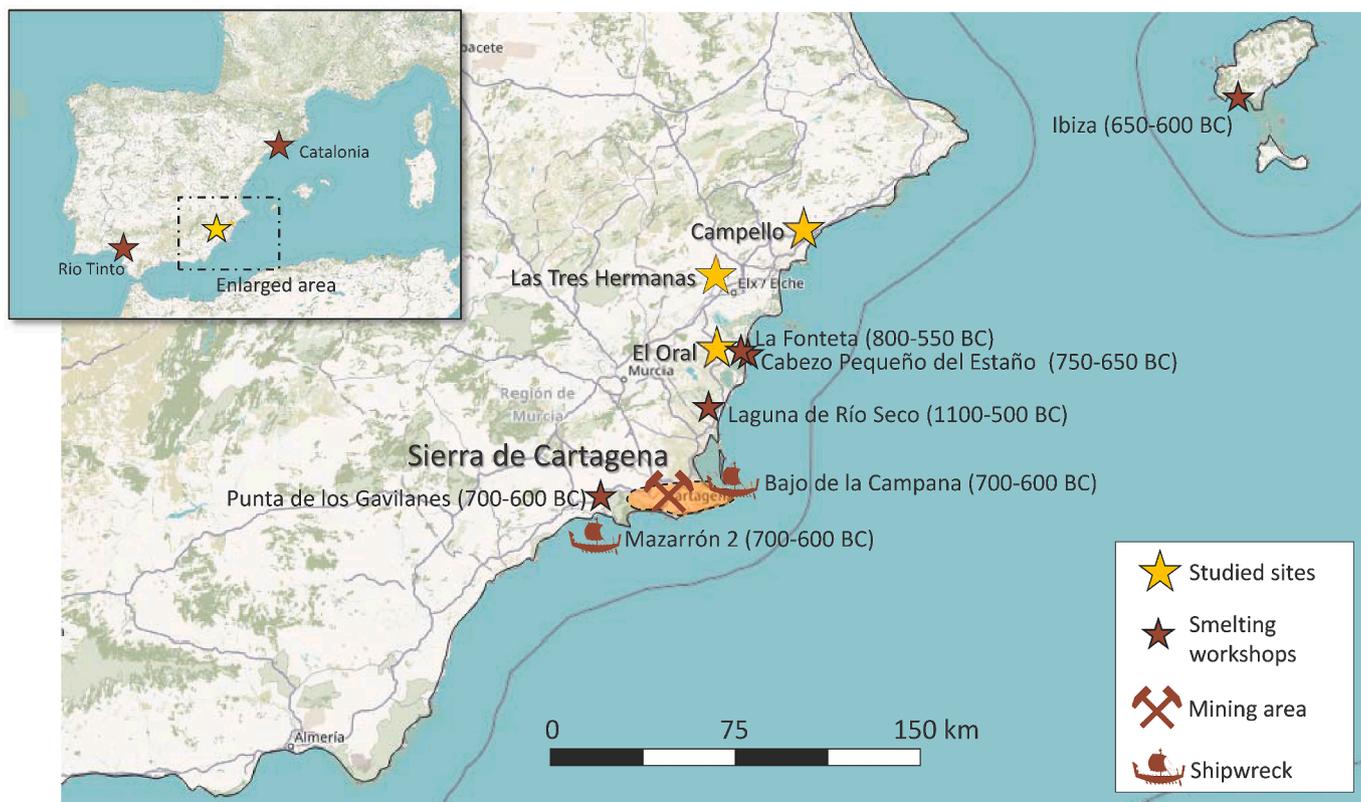


Fig. 1. Lead(-silver) smelting workshops during the Phoenician period and sites studied in this study.

three tonnes of litharges made from lead mined in the Cartagena mining district (Renzi et al., 2009).

The Phoenician coastal navigation system (Renzi et al., 2009; Tejedor, 2018) allowed the spread of lead from Cartagena along the Spanish coasts (Murillo-Barroso et al., 2016). This trade was undoubtedly crucial as lead was used, among other things, to extract silver from jarosites mined in the south of the Iberian Peninsula (Craddock, 2014; Murillo-Barroso et al., 2016). Lead exports to Rio Tinto's mines to extract silver from jarosites were organised as early as the 11th-9th centuries BC (Wood and Montero-Ruiz, 2019) and intensively between the 8th and 7th centuries BC (Neville, 2007 p. 140–141; Kaufman et al., 2016).

Between the 7th and 6th centuries BCE, lead from the Cartagena mines also reached the island of Ibiza, 250 km away. Indeed, isotopic analysis of lead show that lead from Cartagena was smelted there alongside local ores (Ramon Torres et al., 2011).

Silver production from various sites in the Iberian Peninsula was traded throughout the Mediterranean until the 7th century BCE, as demonstrated by isotopic analysis of silver artefacts from the easternmost Mediterranean (Eshel et al., 2019; Wood et al., 2019).

2.2. Few discoveries in the 5th-3rd centuries BC

While it is undisputed that production and export were highly significant before the 7th century BCE, to date, there is little evidence of Iberian mining activity after this period.

In the 6th century BCE, mines in Ibiza ceased activity (Ramon Torres et al., 2011), as did those in Catalonia (Rafel et al., 2010) and Rio Tinto (Fernández Jurado, 1993; Pérez Macías, 1999). Many smelting sites related to the extraction of silver from jarosites also ceased operations during this century (Rothenberg and Blanco-Freijeiro, 1981; Anguilano, 2012; Wood and Montero-Ruiz, 2019). The very limited quantity of silver artifacts discovered in the Iberian Peninsula for the following centuries (5th-3rd centuries BCE) seems to suggest that silver production shifted towards the eastern Mediterranean (Murillo-Barroso et al., 2016).

In the region of Alicante, discoveries of litharges after the 6th century BCE are also very rare, and no metallurgical workshops have yet been discovered. The question of mining remains open. The discovery of rare ceramics dated between 500 and 300 BCE in some mine workings (Domergue, 1987; Salvador, 2012; Bellón Aguilera, 2013) and of litharges cakes and cupels dated from 400 BCE at Punta de Gavilanes (Ros Sala, 1993; Ros Sala et al., 2003) suggest that the Cartagena-La Unión mines may have been exploited. This exploitation, if it took place, would have been of very low intensity: a recent study of palaeopollution in the Bay of Cartagena highlights that anthropogenic lead contamination is barely detectable from around the 6th century BCE until the intense resumption of mining activities in the Roman period (Ortiz et al., 2021).

3. Materials and methods

Our study aims to test whether some lead was indeed produced in the Cartagena mining district between the crisis in Phoenician trade and the Roman mining revival. To this end, litharges from sites dating between the 5th and 3rd centuries BCE were analysed in order to define their composition and deduce their geographical origin. Two lead artefacts from the 5th century BCE were also analysed using EDS (SEM) and lead isotopes to determine whether they were derived from the smelting of the litharges studied (Table 1).

All the material studied comes from the Alicante region, from three sites located approximately 80 km north of the Cartagena mines.

The first of these, El Oral (San Fulgencio, Alicante) is an Iberian settlement located on the north bank of the Segura, 7 km from its mouth. The litharge fragments were found in a dwelling house (first half of the 5th century BCE), in an open-air room, mixed with iron slag, next to a stone anvil. This room probably served as a small metalworking workshop (Casal and Sellés, 1993; Mira, 2001). The second site, Las Tres Hermanas (Aspe, Alicante), is an Iberian settlement dated to between

Table 1

. List of sites from which the archaeological material analysed came. Their dating is based on chrono-typological studies of ceramics.

Site	Datation	Material
El Oral: San Fulgencio	First half of the 5th century BCE	litharge, lead ingot
Las Tres Hermanas	late 5th – middle of the 4th century BCE	litharges, shapeless lead artifact
Campello: La Illeta dels Banyets	end of 4th – first half of 3rd century BCE	Litharge

the end of the 5th century BCE and the middle of the 4th century BCE. A pile of litharge cakes was found in a sloping area, against the wall of a house, but no specific structure was identified (Moratalla Jávega et al., 2023). Finally, the site of La Illeta dels Banyets, in El Campello (Alicante), occupies a small coastal island that has seen various phases of occupation (Bronze Age, Iberian, late Roman). The litharges were recovered from an artisanal facility linked to fishing, in a space dedicated to storage, with no other metallurgical elements. The level has been dated to the late 4th-early 3rd century BCE (Olcina Doménech et al., 2009).

EDS analysis were carried with a Zeiss EVO 10 scanning electron microscope (SEM) on several distinct samples to determine their composition and identify any mineral phases present. Measurements were made on a sawn, flattened surface at an acceleration voltage of 20 kV and a working distance of approximately 8.5 mm.

Lead isotope analyses were then carried out by MC-ICP-MS at the Sedior laboratory to determine the origin of the material studied.

4. Results

4.1. Chemical composition and typology of the material examined

4.1.1. Macroscopic appearance

The litharge cakes come from archaeological contexts dating from after the 6th century BCE. They have similar dimensions, with diameters ranging from 21 to 28 cm and thicknesses not exceeding 2 cm. They have a thin crust of cream-coloured surface alteration. When freshly fractured, their textures are quite similar: they show a more or less laminar structure characterised by parallel bands of whitish minerals and visible greyish spheres homogeneously dispersed in a red–orange matrix (Fig. 2). The most porous portions of the litharges are richer in lead metallic beads.

It is noteworthy that the diameter of the litharges studied corresponds to that of the litharges from the Mazarrón 2 shipwreck, dated to the 7th century BCE (Negueruela et al., 2004) and that the texture and thickness of these litharges are similar to those of the small fragments found in the La Fontena workshop, dated to the 8th to mid-6th century BCE (Renzi et al., 2009).

4.1.2. Chemical composition of the litharge

The presence of silver metal beads on the surface of the litharge cakes indicates a cupellation process (in the case of the litharge from El Oral, the presence of 0.49 % silver had already been noted by Abad Casal and Sellés (1993 p. 265). Analysis not identify the presence of silver in the matrix of the litharge, indicating the efficiency of the separation of lead and silver (with silver present only on the surface).

The composition of the litharge matrices is very homogeneous (Tables 2, 3 and 4) and the litharges from the three sites studied are similar. They have high lead (Pb) contents, ranging from 55 to 68 %.

The lead oxide matrix is always accompanied by silicified calcium carbonates (CaCO₃ ± Si,Al) corresponding to the whitish elements sometimes visible to the naked eye (Fig. 3). Pure lead beads (corresponding to the metallic beads also visible to the naked eye) are abundant in the porosities.

The chemical composition of litharge explains the metallurgical



Fig. 2. Plan view, left: macroscopic appearance of litharge cakes from Las Tres Hermanas; cross-section, right: top – sawn surface of a porous litharge (Las Tres Hermanas), middle – highly altered surface of a non-porous litharge (Las Tres Hermanas), bottom – a fragment of litharge (altered surface) from the Campello site (La Illeta dels Banyets).

Table 2

EDS SEM analysis of Las Tres Hermanas litharges (averages over 6 analyses per sample).

Element	C	O	Al	Si	Pb	Ca	Comment
Weight %	6.97	20.20	2.39	4.66	55.41	10.38	Sample L1 TH, non-porous
	4.78	19.49	0.77	3.03	59.56	11.63	Sample L2 TH, non-porous
	5.11	20.28	1.15	1.62	63.57	8.20	Sample L3 TH, porous
Margin of error	9 %	10 %	9–11 %	8–6 %	2.5 %	5.5–12 %	

Table 3

EDS SEM analysis of litharges found at Campello (sample L CA, average of 6 analyses).

Element	C	O	Al	Si	Pb	Ca
Weight %	4.16	15.76	1.54	2.81	67.5	8.23
Margin of error	9.18 %	11.63 %	13.38 %	9.26 %	3.40 %	9.24 %

Table 4

EDS SEM analysis of El Oral litharges (sample L EO, average of 6 analyses).

Element	C	O	Al	Si	Pb	Ca
Weight %	3.08	22.71	1.21	2.03	59.63	11.22
Margin of error	10.62 %	11.22 %	16.88 %	12.03 %	4.52 %	8.37 %

process employed. A mixture of lead and silver (bullion lead) is melted in a circular reactor about 25 cm in diameter. The lining of the reactor is porous and rich in calcium. It absorbs the lead by capillarity, while the silver (in metallic form) remains on the surface. The process used corresponds to a classical cupellation process (see, for example, Izquierdo De Montes, 1997; Bayley and Eckstein, 2006; Martín-Torres et al., 2008; L'Héritier et al., 2015; Moureau and Thomas, 2016), but the

striking fact here is that the size and the composition of the litharges found at the three sites studied are almost identical.

Finally, the SEM (EDS) analysis of a small, highly altered lead ingot found at El Oral (Fig. 4) and a small drop of shapeless lead (approximately 1 cm wide by 3 cm high) found among the litharge fragments at Las Tres Hermanas indicate that they are composed of pure lead. This again emphasises the effective separation of lead and silver during the cupellation process.

The litharges from the three sites investigated are similar in type, texture and composition. They originate from the same type of cupellation process, probably using ceramic vessels of similar shape.

4.2. Identification of the origin of the lead

Although the lead-silver ore deposits of Cartagena are the closest to the sites, and the litharges have textures similar to those produced from lead from Cartagena one to two centuries earlier (Renzi et al., 2009), it cannot be ruled out that the lead contained in these litharges has other, much more distant, sources. These analyses show a very strong similarity of signatures, confirming the hypothesis of a common origin for these artefacts (Table 5).

Several hypotheses of provenance must be considered:

- The first is a local, i.e. Iberian, origin;

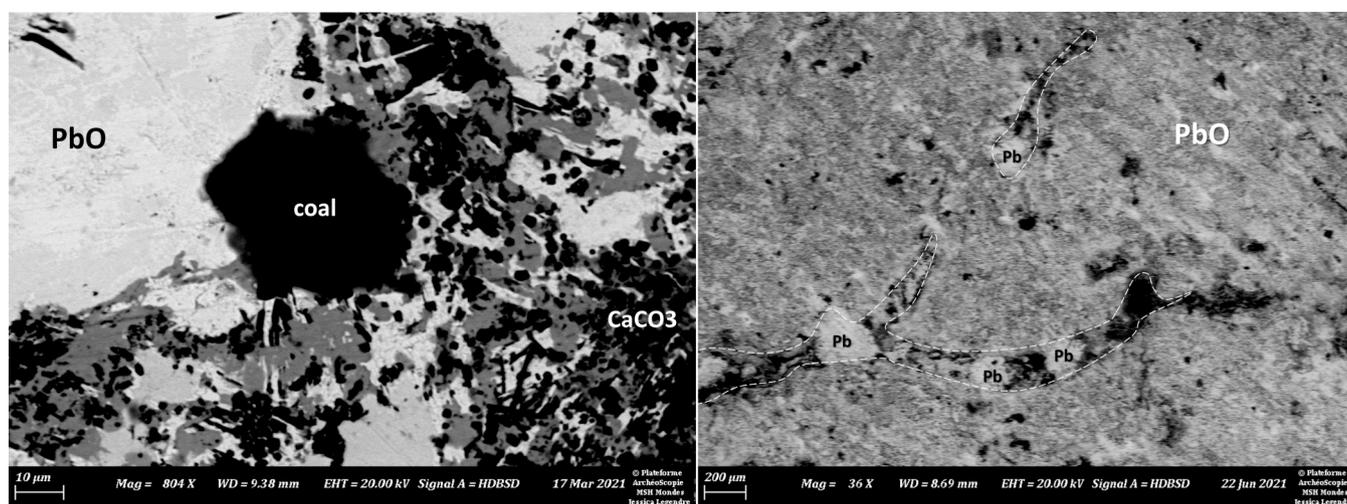


Fig. 3. On the left, texture and structure of a litharge: the bands of whitish minerals visible with the naked eye correspond to calcium carbonates (slightly silicified) organised in large bands, but also to small crystals (dark in EDS) interspersed in the PbO matrix; on the right, presence of pure lead beads (corresponding to the beads visible with the naked eye) in the porosity of the litharge (EDS).



Fig. 4. Lead ingot analysed (weight 8.5 g).

Table 5

Lead isotope analyses carried out as part of this study, results NIST 981 standardised.

Site	ID	Description	$^{206}\text{Pb}/^{204}\text{Pb}$	2σ	$^{207}\text{Pb}/^{204}\text{Pb}$	2σ	$^{208}\text{Pb}/^{204}\text{Pb}$	2σ
Las Tres Hermanas	L1 TH	Litharge	18,7175	0,0004	15,6805	0,0005	39,0188	0,0016
Las Tres Hermanas	L2 TH	Litharge	18,7067	0,0012	15,6851	0,0009	39,0320	0,0124
Las Tres Hermanas	L3 TH	Litharge	18,7045	0,0012	15,6845	0,0008	39,0283	0,0114
Las Tres Hermanas	18 TH	Pb artefact	18,7069	0,0008	15,6824	0,0007	39,0229	0,0112
El Oral	L EO	Litharge	18,7071	0,0014	15,6850	0,0011	39,0325	0,0132
El Oral	P EO	Pb ingot	18,7080	0,0008	15,6792	0,0007	39,0156	0,0134
Campello	L CA	Litharge	18,6943	0,0015	15,6792	0,0011	39,0026	0,0141

- The second is from the Aegean region, where numerous lead-silver mines were in operation in the Cyclades, on the island of Thasos or in the Laurion area (Pernicka et al., 1981; Jones, 1982; Weisgerber and Pernicka, 1995; Mussche, 2006; Papadopoulou, 2011);
- The third hypothesis is Sardinian; indeed, lead-silver metallurgy workshops have been discovered in the Montevecchio mining basin in the south of the island (Caro et al., 2013);

- The last is Anatolian (Taurus Mountains), although the lead-silver exploitations are poorly dated (Pitarakis, 1998).

Bivariate plots normalised to the stable isotope (^{204}Pb) clearly show that a Sardinian origin can be rejected (the $^{206}\text{Pb}/^{204}\text{Pb}$ ratios from these deposits are too low); the hypothesis of an Aegean origin must also be rejected because the $^{206}\text{Pb}/^{204}\text{Pb}$ ratios are slightly too high. Only some

signatures from the Taurus Mountains could be close to the signatures of the artefacts in the diagram $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, but they differ in the ratios $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$; the Anatolian origin can be rejected. The mined ores would therefore be of Iberian origin (Fig. 5).

In order to define their origin more precisely, the lead isotopic signatures of the artefacts can also be compared with different mining areas in the Iberian Peninsula. Six potential mining areas located relatively close (within 150 km) can be considered.

Among the available signatures are those from the mines of Cartagena (Graeser and Friedrich, 1970; Baron et al., 2017; Milot et al., 2021; Domergue and Rico, 2024 p. 25), which were extensively exploited in previous centuries (10th-8th centuries BC to mid-6th century BCE) to produce litharges similar to those studied. In addition, the signatures of neighbouring ore deposits include:

- The closest mining district to Cartagena: Mazarrón (data from the Oxalid database; Graeser and Friedrich, 1970; Milot et al., 2021)
- Sierra Almagrera (data from the Oxalid database; Arribas and Tosdal, 1994; Hunt Ortiz, 2003; Montero Ruiz and Murillo-Barroso, 2010; Murillo-Barroso et al., 2019);
- Sierra de Bedar (data from the Oxalid database; Montero Ruiz and Murillo-Barroso, 2010; Murillo-Barroso et al., 2019);
- Cabo de Gata (data from the Oxalid database; Hunt Ortiz, 2003);
- Sierra de Gador (Arribas and Tosdal, 1994; Montero Ruiz and Murillo-Barroso, 2010)

Furthermore, although located respectively 250 km and over 500 km from the site, the mining areas of Ibiza (data from Hermanns, 2014), Rio

Tinto (Oxalid database; Marcoux, 1998; Pomiès et al., 1998; Hunt Ortiz, 2003), and Catalonia (Rafel et al., 2019; Montero Ruiz, 2017; Canals and Cardellach, 1997) were also considered. This choice is based on the fact that lead mining activity has been previously confirmed in these areas during earlier periods.

This second projection shows that the most probable origin of all the artefacts is the Cartagena- Mazarrón mining area (Fig. 6). This result is interesting for a number of reasons. Firstly, it emphasises that lead objects were produced from the litharges in circulation. In addition, the litharges analysed have signatures comparable to those produced at La Fonteta one to two centuries earlier. These results support those of Renzi et al., (2009), who also attribute a Cartagena-Mazarrón origin to the litharges from the La Fonteta workshop and the Mazarrón 2 shipwreck. Those mines probably provided the lead that led to the production of litharges of comparable typology between the 8th and 3rd centuries BC.

Therefore, although no workshop has yet been discovered, it appears that the production of litharge between the 5th and 3rd centuries BC followed a similar production model that of the period before the commercial crisis: its ore source is similar, as is its texture and chemical composition.

5. Discussion: Low but continuous production

If it is confirmed that the mines of Cartagena were indeed exploited between the 5th and 3rd centuries BCE, it is very likely that the production processes of the litharges remained identical throughout the period from the 8th to the 3rd century BCE, despite the commercial crisis of the 6th century BCE. It was only during Roman exploitation that

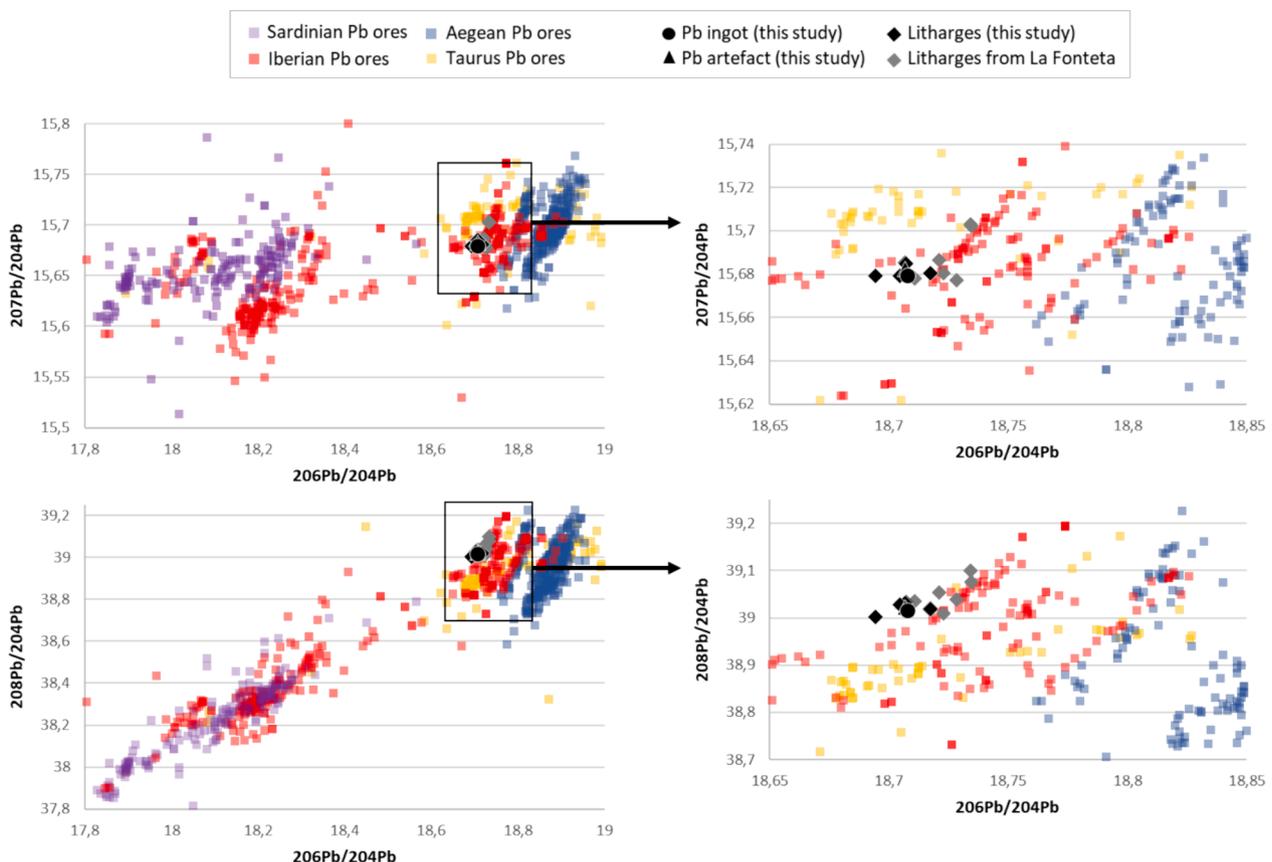


Fig. 5. Bivariate projections of the isotopic signatures of the artefacts analysed in this study and the signatures of lead deposits from the Iberian, Aegean, Sardinian and Taurus Mountains. Data from the Oxalid database (Stos-Gale and Gale, 2009; Graeser and Friedrich, 1970; Boni and Koeppl, 1985; Seeliger et al., 1985; Arribas and Tosdal, 1994; Marcoux, 1998; Hirato et al., 1995; Begemann et al., 2001; Sayre et al., 2001; Ceyhan, 2003; Hunt Ortiz, 2003; Santos Zalduegui et al., 2004; Tornos and Chiaradia, 2004; Valera and Valera, 2005; Koptagel et al., 2007; Montero Ruiz and Murillo-Barroso, 2010; Haniçli and Öztürk, 2011; Hermanns, 2014; Baron et al., 2017; Murillo-Barroso et al., 2019; Milot et al., 2021 and Domergue and Rico, 2024 p. 25, keeping only the lead deposits (see Tomczyk, 2022).

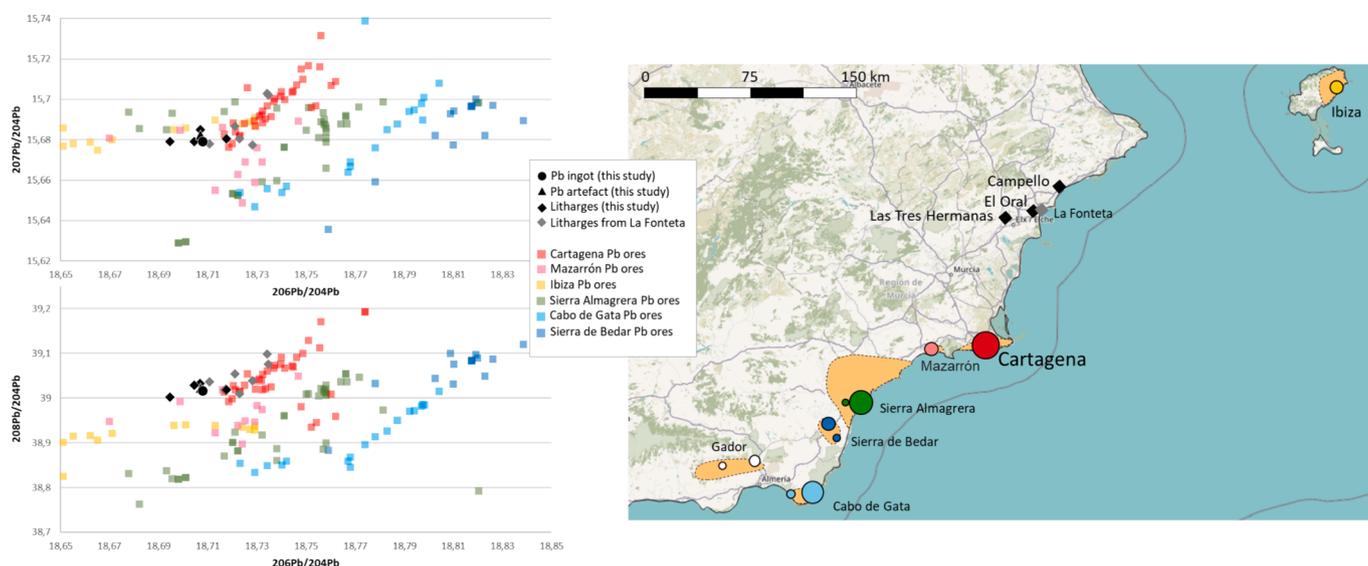


Fig. 6. On the left, bivariate projections of lead isotopic ratios; on the right, localisation of lead-bearing deposits (orange zones) and isotopic analyses of lead from the considered deposits (the colour of the figures corresponds to that of the points representing the deposits in the left diagram, the size of the figures is proportional to the number of analyses available for each mining area). The Sierra de Gador ores are not plotted because they have low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios (average 18.3), as are the Rio Tinto ores ($^{206}\text{Pb}/^{204}\text{Pb} < 18.32$) and Catalonia ores ($^{206}\text{Pb}/^{204}\text{Pb} < 18.55$).

practices changed: the litharges then took the form of small conical rolls, one to two centimetres in diameter (Baron et al., 2017).

The litharges would have circulated on a regional scale, where they would have been used to extract metallic lead, which could have been used to shape lead artefacts or incorporated into ternary bronze alloy compositions. Some of this lead may also have been exported along new trade routes. An argument in favour of the emergence of new exchange networks is based on the analysis of silver objects found at Mas Castellar de Pontós (Catalonia, 500–200 BCE): some of these objects are thought to have the isotopic signature of lead from the mines of Cartagena (Montero Ruiz et al., 2008). Thus, Catalonia, which had previously been a producer of lead, could have imported it at the beginning of the 5th century BCE.

The sudden end of silver production in the Iberian coastal regions (from the Rio Tinto mines to the island of Ibiza) certainly caused a drastic fall in lead production from the Cartagena mines, to the point where it would have been barely perceptible in the pollution of the bay. However, this study shows that production in Cartagena would have continued on a smaller scale. Some silver and lead would have been extracted from the mines and smelted using the same processes as before the crisis, probably by the same population group.

6. Conclusion

The litharges from three sites in the province of Alicante, dated to a period after the Phoenician trade crisis, show strong geochemical similarities with those produced in the same region before this crisis. The diameter, thickness, and texture of the litharges indicate a common manufacturing process involving the absorption of lead through capillarity by a porous and calcium-rich furnace lining. The presence of metallic silver on their surface indicates that they are linked to the same cupellation process.

Lead isotope analysis shows that it came from the Cartagena mines, as did the earlier litharges. This technological continuity, from the deposits mined to the metallurgical processes used to produce standardised litharges, shows that a same *chaîne opératoire* persisted throughout the 8th to 3rd century BCE in the region.

Estimating the production tonnages from the mines is complex, as the mining areas have been extensively reworked from Roman times to the modern period. However, sedimentary archives indicate a sharp

decline in production during the 6th century BCE. Production from the Cartagena mines probably declined after this crisis, but did not cease altogether.

CRedit authorship contribution statement

Céline Tomczyk: Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Christophe Petit:** Writing – review & editing, Funding acquisition. **María Berná:** Resources. **Laurent Costa:** Project administration, Funding acquisition. **Jessica Legendre:** Methodology, Investigation. **Jesús Moratalla:** Validation, Supervision. **Sidonie Révillon:** Methodology, Investigation, Formal analysis. **Pierre Rouillard:** Writing – review & editing, Validation, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

all data are included in the manuscript

Acknowledgements

The SEM equipment used in this study belongs to the MAPS platform - Imagerie des patrimoines et spatialisation et microscopie pour les matériaux anciens de la MSH Mondes (UAR 3225). It was funded by the Île-de-France region as part of the major interest Matériaux anciens et patrimoniaux (DIM – MAP), the CNRS, and the LabEx “Les passés dans le présent”.

The lead isotope analyses were funded by the LabEx Dynamite and the ArScAn laboratory. We would like to thank Zoï Tsrtsioni and Nicole Lozouet for their support in obtaining this funding.

The authors also wish to thank Romualdo Seva Román, María Dolores Landete Ruiz, and Cristina Biete Bañón for the preliminary analyses conducted on the material from Las Tres Hermanas.

References

- Abad Casal, L., 1992. Las culturas ibéricas del área suroccidental de la Península Ibérica. In: *Riuz Zapatero, G., Almagro Gorbea, M. (Eds.), Paleoeología de la Península Ibérica*. Departamento de Prehistoria, Madrid, pp. 151–166.
- Abad Casal, L., Sellés, F.S., 1993. El poblado ibérico de El Oral (San Fulgencio, Alicante) (No. 90). Servicio de Investigación Prehistórica, Diputación Provincial de Valencia.
- Albelda, E.F., 2018. Ethnic and Cultural Identity among Punic Communities in Iberia, in: Cruz Andreotti, G. (Ed.), *Roman Turdetania, Cultural Interactions in the Mediterranean*. BRILL, pp. 70–88. https://doi.org/10.1163/9789004382978_006.
- Andreatini, A., Melgarejo, J., Tauler, E., Torró i Abat, L., Manteca, J., Arnold, M., 2015. Ore Deposits in La Unión-Portmán District: Mineralogical and Geochemical Characterization, in: *Mineral Resources in a Sustainable World*. Presented at the 13th SGA Biennial Meeting, Nancy, pp. 355–358.
- Anguilano, L., 2012. *Roman lead silver smelting at rio tinto - the case study of corta lago* (PhD Thesis). University College London.
- Arribas, A., Tosdal, R.M., 1994. Isotopic composition of Pb in ore deposits of the Betic Cordillera, Spain; origin and relationship to other European deposits. *Econ. Geol.* 89, 10741093. <https://doi.org/10.2113/gsecongeo.89.5.1074>.
- Aubet, M.E., 1995. From trading post to town in the Phoenician-Punic world, in: Cunliffe, B.W., Keay, S.J. (Eds.), *Social Complexity and the Development of Towns in Iberia from the Copper Age to the Second Century AD: Proceedings of a Symposium Entitled "The Origins of Urbanization in Iberia," Proceedings of the British Academy*. Oxford university press for the British academy, Oxford, pp. 47–65.
- Baron, S., Rico, C., Antolinos Marin, J.A., 2017. Le complexe d'ateliers du Cabezo del Pino (Sierra Minera de Cartagena-La Unión, Murcia) et l'organisation de l'activité minière à Carthago Noua à la fin de la République romaine. Apports croisés de l'archéologie et de la géochimie. *Arch. Esp. Arqueol. Ser. Anejos Cons. Super. Investig. Científicas* 90, 147–169.
- Bayley, J., Eckstein, K., 2006. Roman and medieval litharge cakes: structure and composition, in: Pérez-Arantegui, J. (Ed.), *34th International Symposium on Archaeometry*. Institución "Fernando el Católico," Zaragoza, Spain, pp. 145–153.
- Begemann, F., Schmitt-Strecker, S., Pernicka, E., Schiavo, F.L., 2001. Chemical composition and lead isotopy of copper and bronze from nuragic sardinia. *Eur. J. Archaeol.* 4, 43–85. <https://doi.org/10.1177/146195710100400102>.
- Bellón Aguilera, J., 2013. Las minas púnicas de Cala Cocón (Cartagena). *Hastial* 3, 33–44.
- Boni, M., Koeppl, V., 1985. Ore-lead isotope pattern from the Iglesias-Sulcis Area (SW Sardinia) and the problem of remobilization of metals. *Miner. Deposita* 20, 185–193. <https://doi.org/10.1007/BF00204563>.
- Buxó, R., 2008. The agricultural consequences of colonial contacts on the Iberian Peninsula in the first millennium b.c. *Veg. Hist. Archaeobot.* 17, 145–154. <https://doi.org/10.1007/s00334-007-0133-7>.
- Canals, A., Cardellach, E., 1997. Ore lead and sulphur isotope pattern from the low-temperature veins of the Catalan Coastal Ranges (NE Spain). *Miner. Deposita* 32, 243–249.
- Caparros, B., del Carmen, M., 1999. Poblamiento romano en la sierra minera de cartagena. *Pallas Rev. Détudes Antiq.* 50, 183–193. <https://doi.org/10.3406/palla.1999.1549>.
- Caro, T., Riccucci, C., Parisi, E.L., Faraldi, F., Caschera, D., 2013. Ancient silver extraction in the Montevecchio mine basin (Sardinia, Italy): micro-chemical study of pyrometallurgical materials. *Appl. Phys. A* 113, 945–957. <https://doi.org/10.1007/s00339-013-7722-3>.
- Casal, L.A., Sellés, F.S., 1993. Reflexiones sobre la metalurgia protohistórica: el poblado ibérico de El Oral (San Fulgencio, Alicante), in: Ramallo, S., Muñoz, A.M., Ros, M.M., Arana, R. (Eds.), *Metalurgia En La Península Ibérica Durante El Primer Milenio aC: Estado Actual de La Investigación*. Universidad de Murcia, pp. 189–204.
- Ceyhan, N., 2003. *Lead isotope geochemistry of Pb-Zn deposits from eastern taurides* (Mémoire de Master). Middle East Technical University, Turkey.
- Clemenza, M., Contini, A., Baccolo, G., di Vacri, M.L., Ferrante, M., Nisi, S., Carpinelli, M., Cremonesi, O., Enzo, S., Fiorini, E., Mulas, G., Prata, M., Previtali, E., Salvini, A., Sipala, V., 2017. Development of a multi-analytical approach for the characterization of ancient Roman lead ingots. *J. Radioanal. Nucl. Chem.* 311, 1495–1501. <https://doi.org/10.1007/s10967-016-5040-x>.
- Craddock, P., 2014. Production of silver across the ancient world. *ISIJ Int.* 54, 1085–1092. <https://doi.org/10.2355/isijinternational.54.1085>.
- Díaz, A.R., 2015. Landscapes and seascapes of southwest iberia in the first millennium BC. In: Knapp, A.B., van Dommelen, P. (Eds.), *The Cambridge Prehistory of the Bronze and Iron Age Mediterranean*. Cambridge University Press, Cambridge, pp. 488–505. <https://doi.org/10.1017/CHO9781139028387.035>.
- Dietler, M., López-Ruiz, C. (Eds.), 2009. *Colonial Encounters in Ancient Iberia: Phoenician, Greek, and Indigenous Relations*. University of Chicago Press, Chicago, IL.
- Domergue, C., 1990. Les Mines de la péninsule Ibérique dans l'Antiquité romaine. *École Française de Rome*.
- Domergue, C., Rico, C., 2024. *Lateres Plumbei Hispani: Production et commerce du plomb hispanique à l'époque romaine (IIe siècle av. J.-C. – Ier siècle apr. J.-C.)*. Casa de Velázquez, Madrid.
- Domergue, C., 1987. *Catalogue des mines et des fonderies antiques de la Péninsule Ibérique*. Collection de la Casa de Velázquez.
- Eshel, T., Erel, Y., Yahalom-Mack, N., Tirosh, O., Gilboa, A., 2019. Lead isotopes in silver reveal earliest Phoenician quest for metals in the west Mediterranean. *Proc. Natl. Acad. Sci. U. S. A.* 116, 6007–6012. <https://doi.org/10.1073/pnas.1817951116>.
- Fabre, J.-M., Meunier, E., Souhassou, M., Rico, C., Antolinos Marin, J.A., 2014. The silver lead Roman mine of the rambla del Abenque (Sierra Minera de Cartagena): morphology of mining works, mineralization types and chronology of the mine. In: Pulido, L.J.G., Martínez, L.A., García, E.A., Cortés, F.C. (Eds.), *Presente y Futuro De Los Paisajes Mineros Del Pasado: Estudios Sobre Minería, Metalurgia y Poblamiento*. VIIIº Congreso Sobre Minería y Metalurgia Históricas En El Sudoeste Europeo. Granada, Universidad de Granada, Granada, Spain, pp. 131–139.
- Fernández Jurado, J., 1993. Plata y plomo en el comerci fenicio-tartésio, in: Arana Castillo, R., Muñoz Amilibia, A.M., Ramallo, A., Rojo Sala (Eds.), *Metalurgia en la Península Ibérica durante el primer milenio a. C. estado actual de la investigación*. Cuadernos / Universidad de Murcia. Universidad de Murcia, Murcia, pp. 131–165.
- García-Alix, A., Jimenez-Espejo, F.J., Lozano, J.A., Jiménez-Moreno, G., Martínez-Ruiz, F., García Sanjuán, L., Aranda Jiménez, G., García Alfonso, E., Ruiz-Puertas, G., Anderson, R.S., 2013. Anthropogenic impact and lead pollution throughout the Holocene in Southern Iberia. *Sci. Total Environ.* 449, 451–460. <https://doi.org/10.1016/j.scitotenv.2013.01.081>.
- Graeser, S., Friedrich, G., 1970. Zur frage der altersstellung und genese der blei-zink-vorkommen der sierra de cartagena in spanien. *Miner. Deposita* 5, 365–374. <https://doi.org/10.1007/BF00206733>.
- Haniçli, N., Öztürk, H., 2011. Geochemical/isotopic evolution of Pb-Zn deposits in the central and Eastern Taurides. *Turkey. Int. Geol. Rev.* 53, 1478–1507.
- Hermanns, M.H., 2014. La Zona Minera de S'Argentera, Isla de Ibiza (islas Baleares). *CPAG* 24, 301–318.
- Hirato, Y., Enomoto, J., Tachikawa, H., 1995. Lead isotope ratios of copper, zinc and lead minerals in Turkey - in relation to the provenance study of artifacts, in: *Essays on Ancient Anatolia and Its Surrounding Civilizations*. Otto Harrassowitz Verlag, pp. 89–113.
- Hunt Ortiz, M.A., 2003. *Prehistoric mining and metallurgy in south west Iberian Peninsula*. Archaeopress.
- Izquierdo De Montes, R., 1997. Sobre la copelación de la plata en el mundo tartésico. *SPAL Rev. Prehist. Arqueol. Univ. Sevilla* 87–101. <https://doi.org/10.12795/spal.1997.i6.06>.
- Jones, J.E., 1982. The Laurion silver mines: A review of recent researches and results. *Greece Rome* 29, 169–183.
- Kaufman, B., Docter, R., Fischer, C., Chelbi, F., Maraoui Telmini, B., 2016. Ferrous metallurgy from the bir massouda metallurgical precinct at phoenician and punic carthage and the beginning of the North African iron age. *J. Archaeol. Sci.* 71, 33–50. <https://doi.org/10.1016/j.jas.2016.04.002>.
- Keay, S., 2003. Recent archaeological work in Roman Iberia (1990–2002). *J. Roman Stud.* 93, 146–211. <https://doi.org/10.2307/3184643>.
- Koptagel, O., Ulusoy, U., Fallick, A.E., 2007. Sulfur and lead isotope investigations of the carbonate-hosted Pb-Zn deposits in the Yahyalı Region, Kayseri. *Southern Turkey. Turk. J. Earth Sci.* 16, 57–76.
- L'Héritier, M., Baron, S., Cassayre, L., Téreygeol, F., 2015. Bismuth behaviour during ancient processes of silver-lead production. *J. Archaeol. Sci.* 57, 56–68. <https://doi.org/10.1016/j.jas.2015.02.002>.
- Marcoux, E., 1998. Lead isotope systematics of the giant massive sulphide deposits in the Iberian Pyrite Belt. *Miner. Deposita* 45–58.
- Marín, J.A.A., Fabre, J.-M., Rico, C., 2010. Roman mines of Carthago Noua. *Progress of Research on the Rambla Del Abenque (Sierra de Cartagena)*.
- Martinón-Torres, M., Thomas, N., Rehren, T., Mongiatti, A., 2008. Some problems and potentials of the study of cupellation remains: the case of post-medieval Montbéliard, France. *Archeosciences Rev. Archéom.* 59–70. <https://doi.org/10.4000/archeosciences.948>.
- McConnell, J.R., Wilson, A.I., Stohl, A., Arienzo, M.M., Chellman, N.J., Eckhardt, S., Thompson, E.M., Pollard, A.M., Steffensen, J.P., 2018. Lead pollution recorded in Greenland ice indicate European emissions tracked glages, wars, and imperial expansion during antiquity. *Proc. Natl. Acad. Sci.* 115, 5726–5731. <https://doi.org/10.1073/pnas.1721818115>.
- Milot, J., Blichert-Toft, J., Sanz, M.A., Fetter, N., Télouk, P., Albarède, F., 2021. The significance of galena Pb model ages and the formation of large Pb-Zn sedimentary deposits. *Chem. Geol.* 583, 120444. <https://doi.org/10.1016/j.chemgeo.2021.120444>.
- Mira, I.G., 2001. *Poblamiento ibérico en el bajo Segura: el Oral (II) y la Escuera*. Biblioteca Arqueológica Hispana. Real Academia de la Historia.
- Momrak, K., 2005. The Phoenicians in the Mediterranean: Trade, interaction and cultural transfer. *Altorient. Forschungen* 32, 168–181. <https://doi.org/10.1524/aof.2005.32.1.168>.
- Montero Ruiz, I., 2017. La Solana del Bepo from an archaeometallurgical perspective. In: Fontanals, N.R., Soriano, I., Delgado-Raack, S. (Eds.), *A Prehistoric Copper Mine in the North-East of the Iberian Peninsula: Solana Del Bepo (ulldemolins, Tarragona)*. Edicions i Publicacions de la Universitat de Lleida, Lleida, pp. 67–79.
- Montero Ruiz, I.M., Gener, M., Hunt Ortiz, M.A., Renzi, M., Lloréns, S.R., 2008. Caracterización analítica de la producción metalúrgica protohistórica de plata en Cataluña. *Rev. Arqueol. Ponent* 18, 292–316.
- Montero Ruiz, I., Murillo-Barroso, M., 2010. La producción metalúrgica en las sociedades argáricas y sus implicaciones sociales: una propuesta de investigación. *Menga Rev. Prehist. Andal.* 37–52.
- Moratalla Jávega, J., Rouillard, P., Costa, L., Berná García, M.T., 2023. Las Tres Hermanas (Aspe, Alicante). Une résidence ibérique éphémère des Ve-IVe s. av. J.-C., Petracos. *Universidad de Alicante. Instituto Universitario de Investigación en ...*, Alicante.
- Moureau, S., Thomas, N., 2016. Understanding texts with the help of experimentation: The example of cupellation in Arabic Scientific Literature. *Ambix* 63, 98–117. <https://doi.org/10.1080/00026980.2016.1216691>.
- Murillo-Barroso, M., Montero-Ruiz, I., Rafel, N., Ortiz, M.A.H., Armada, X.-L., 2016. The macro-regional scale of silver production in Iberia during the first millennium BC in the context of mediterranean contacts. *Oxf. J. Archaeol.* 35, 75–100. <https://doi.org/10.1111/ojao.12079>.

- Murillo-Barroso, M., Montero-Ruiz, I., Nieto, J.M., Camalich Massieu, M.D., Martín Socas, D., Martín-Torres, M., 2019. Trace elements and lead isotopic composition of copper deposits from the eastern part of the Internal Zone of the Betic Cordillera (SE Iberia): application to provenance of archaeological materials. *J. Iber. Geol.* 45, 585–608. <https://doi.org/10.1007/s41513-019-00111-1>.
- Mussche, H.F., 2006. More about the silver-rich lead of ancient laurion. *Antiq. Class.* 75, 225–230. <https://doi.org/10.3406/antiq.2006.2607>.
- Myers, P.J., 2016. *Developing identities within Roman Iberia: hybridity, urbanism, and economics in southern Iberia in the second and first centuries BC (d.ph)*. University of Birmingham.
- Nantet, E., 2016. *Phortia: le tonnage des navires de commerce en Méditerranée du VIII^e siècle av. l'ère chrétienne au VII^e siècle de l'ère chrétienne (PhD Thesis)*. Archéologie & culture. Presses universitaires de Rennes, Rennes.
- Neguieruela, I., Gonzalez Gallero, R., San Claudio, M., Mendez Sanmartin, A., Presa, M., Marín, C., 2004. Mazarrón-2: el barco fenicio del siglo VII a.C. Campaña de noviembre-1999/marzo 2000, in: *El Mundo Púnico: Religión, Antropología y Cultura Material*. Presented at the Actas II Congreso Internacional del Mundo Púnico, Estudios Orientales, Cartagena, pp. 453–483.
- Neville, A., 2007. *Mountains of silver and rivers of gold: The phoenicians in Iberia*. Oxbow Books.
- Oen, I., Fernandez, J., Manteca, J., 1975. The lead-zinc and associated ores of La unión, sierra de Cartagena, Spain. *Econ. Geol.* 70, 1259–1278. <https://doi.org/10.2113/gsecongeo.70.7.1259>.
- Olcina Doménech, M., Martínez Carmona, A., Sala-Sellés, F., 2009. La Illeta dels Banyets (El Campello, Alicante). Épocas ibérica y romana I. Historia de la investigación y síntesis de las intervenciones recientes (2000-2003). MARQ, Museo Arqueológico de Alicante, Alicante.
- Ortiz, J.E., Torres, T., López-Cilla, I., Galán, L.A., Sánchez-Palencia, Y., Ros, M., Manteca, I., Ramallo, S., Navarro, F., Rodríguez-Estrella, T., Blázquez, A., Gómez-Borrego, Á., Ruiz-Zapata, B., Gil, M.J., Heine, E., 2021. Keys to discern the phoenician, punic and Roman mining in a typical coastal environment through the multivariate study of trace element distribution. *Sci. Total Environ.* 147986 <https://doi.org/10.1016/j.scitotenv.2021.147986>.
- Papadopoulou, Z., 2011. Akrotiraki and Skali: New Evidence for EBA Lead/Silver and Copper Production from Southern Siphnos, in: *Metallurgy: Understanding How, Learning Why: Studies in Honor of James D. Muhly*. INSTAP Academic Press, pp. 149–156.
- Pappa, E., 2015. Changing responses to changing environments: documenting socio-cultural change and demographic evolution through the built environment in south Iberia, circa 900-600 BCE, in: *Housing and Habitat in the Ancient Mediterranean. Cultural and Environmental Responses*, Babesch. Peeters Publishers, pp. 15–30.
- Pérez Macías, J.A., 1999. Pico del Oro (Tharsis, Huelva): Contraargumentos sobre la crisis metalúrgica tartésica. *Huelva En Su Hist.* 71–98.
- Pérez-Jordà, G., Llorio, A.J., López Rosendo, E., Torres Ortiz, M., 2023. Agriculture at the Phoenician site of La Fonteta (Alicante, Spain). *Veg. Hist. Archaeobotany*. <https://doi.org/10.1007/s00334-023-00980-8>.
- Pérez-Jordà, G., Peña-Chocarro, L., García Fernández, M., Vera Rodríguez, J.C., 2017. The beginnings of fruit tree cultivation in the Iberian Peninsula: plant remains from the city of Huelva (southern Spain). *Veg. Hist. Archaeobotany* 26, 527–538. <https://doi.org/10.1007/s00334-017-0610-6>.
- Pernicka, E., Gentner, W., Wagner, G.A., Vavelidis, M., Gale, N.H., 1981. Ancient lead and silver production on Thasos (Greece). *Rev. Archéom.* 1, 227–237. <https://doi.org/10.3406/arsci.1981.1151>.
- Pitarakis, B., 1998. Mines anatoliennes exploitées par les Byzantins : recherches récentes. *Rev. Numis.* 6, 141–185. <https://doi.org/10.3406/numi.1998.2196>.
- Polzer, M.E., 2012. 4. Iron Age Phoenician Shipwreck Excavation at Bajo de la Campana, Spain: Preliminary Report from the Field, in: Günsemin, N. (Ed.), *Between Continents: Proceedings of the Twelfth Symposium on Boat and Ship Archaeology, Istanbul 2009*. Presented at the International Symposium on Boat and Ship Archaeology, Ege Yayınları, Taksim, Istanbul, pp. 27–36.
- Polzer, M., 2014. The Bajo de la Campana Shipwreck and Colonial Trade in Phoenician Spain, in: *From Assyria to Iberia: Crossing Continents at the Dawn of the Classical Age*. Metropolitan Museum of Art, pp. 230–242.
- Pomiès, C., Cocherie, A., Guerrot, C., Marcoux, E., Lancelot, J., 1998. Assessment of the precision and accuracy of lead-isotope ratios measured by TIMS for geochemical applications: example of massive sulphide deposits (Rio Tinto, Spain). *Chem. Geol.* 144, 137–149. [https://doi.org/10.1016/S0009-2541\(97\)00127-7](https://doi.org/10.1016/S0009-2541(97)00127-7).
- Prados Martínez, F., García Menárguez, A., Jiménez Vialás, H., 2018. Metalurgia fenicia en el sureste ibérico: el taller del Cabezo Pequeño del Estañó (Guardamar, Alicante). *Complutum* 29, 79–94. <https://doi.org/10.5209/CMPL.62396>.
- Puckett, N., 2012. *The Phoenician Trade Network: Tracing a Mediterranean Exchange System (Thesis)*.
- Rafel, N., Montero-Ruiz, I., Castanyer, P., Aquilué, X., Armada, X.-L., Belarte, M.C., Fairén, S., Gasull, P., Gener, M., Graells, R., Hunt, M., Martín, A., Mata, J.M., Morell, N., Pérez, A., Pons, E., Renzi, M., Rovira, M.C., Rovira, S., Santos, M., Tremoleda, J., Villalba, P., 2010. New approaches on the archaic trade in the north-eastern Iberian peninsula: Exploitation and circulation of lead and silver. *Oxf. J. Archaeol.* 29, 175–202. <https://doi.org/10.1111/j.1468-0092.2010.00344.x>.
- Rafel, N., Hunt Ortiz, M., Montero Ruiz, I., Soriano, I., Delgado-Raack, S., Marín, D., 2019. *New Bronze Age absolute datings for Solana del Bepo copper mine (Ulldemolins, Tarragona Province, Spain)*. Archéologie Archéom. Méditerranéenne 19, 9–24.
- Ramon Torres, J., Rafel Fontanals, N., Montero, I., Santos, M., Renzi, M., Hunt, M.A., Armada, X.L., 2011. Comercio protohistórico: el registro del Nordeste peninsular y circulación de mineral de plomo en Ibiza y el Bajo Priorato (Tarragona). *SAGVNTVM Papeles Lab. Arqueol. Valencia* 43, 55–81. <https://doi.org/10.7203/SAGVNTVM.43.1644>.
- Renzi, M., Montero-Ruiz, I., Bode, M., 2009. Non-ferrous metallurgy from the Phoenician site of La Fonteta (Alicante, Spain): a study of provenance. *J. Archaeol. Sci.* 36, 2584–2596. <https://doi.org/10.1016/j.jas.2009.07.016>.
- Rico, C., Baron, S., Marín, J.A.A., 2018. Roman mining in Cartagena (Spain). Presented at the 19th International Congress of Classical Archaeology.
- Rico, C., Fabre, J.-M., Antolinos Marín, J.A., 2009. Recherches sur les mines et la métallurgie du plomb-argent de Carthage à l'époque romaine. *Mélanges Casa Velázquez Nouv. Sér.* 291–310 <https://doi.org/10.4000/mcv.343>.
- Ros Sala, M.M., Arana Castillo, R., Antolinos, J.A., 2003. The Metallurgical Furnaces from c. IV-III B.C. of Punta de Los Gavilanes (Mazarrón Port, Murcia, Spain): An Approximation to the Cupellation Process in the West Mediterranean, in: *Proceedings to the International Conference Archaeometallurgy in Europe*. pp. 315–325.
- Ros Sala, M.M., 1993. Minería y metalurgia de la plata en el asentamiento protohistórico de Punta de Los Gavilanes (Mazarrón, Murcia). I: estudio arqueológico, in: *Metalurgia en la Península Ibérica durante el primer milenio a.C.: estado actual de la investigación*, 1993, ISBN 84-7684-447-6, págs. 205-220. Presented at the *Metalurgia en la Península Ibérica durante el primer milenio a.C. : estado actual de la investigación*, Universidad de Murcia, pp. 205–220.
- Rothenberg, B., Blanco-Freijeiro, A., 1981. Ancient Mining and Metallurgy in South-West Spain, The Institute for Archaeo-Metallurgical Studies. ed. London.
- Rouillard, P., 2023. Exchanges between the Greek world and the Iberian Peninsula from the eighth to the fourth century BC. In: Krasilnikoff, J., Lowe, B. (Eds.), *The Greeks in Iberia and Their Mediterranean Context*. Routledge, London, pp. 32–50. <https://doi.org/10.4324/9781003384533>.
- Rouillard, P., Gailledrat, É., Sellés, F.S., 2007. *L'établissement protohistorique de La Fonteta (fin VIII^e - fin VI^e siècle av. J.-C.)*. Fouilles de la Ràbita de Guardamar II. Casa de Velázquez, Madrid.
- Ruiz Cabrero, L.A., Mederos Martín, A., 2004. El pecio fenicio del Bajo de la Campana (Murcia, España) y el comercio del marfil norteafricano. *Zephyrus Rev. Prehist. Arqueol.* 263–281.
- Ruiz, J.A.M., 2007. La crisis del siglo VI a.C. en los asentamientos fenicios de Andalucía. Diputación Provincial de Málaga. Centro de Ediciones de la Diputación de Málaga, Málaga.
- Salvador, A.M., 2012. Evidencias arqueológicas de la minería prerromana en Cartagena: la explotación minero-metalúrgica del Cabezo de la Escucha en Cala Reona (Cartagena, España). *Lucentum* 61–90. <https://doi.org/10.14198/LVCENTVM2012.31.04>.
- Santos Zalduegui, J.F., García De Madinabeitia, S., Gil Ibarguchi, J.I., Palero, F., 2004. A lead isotope database: The los pedroches - alcuía area (Spain); implications for archaeometallurgical connections across south-western and southeastern Iberia*. *Archaeometry* 46, 625–634. <https://doi.org/10.1111/j.1475-4754.2004.00178.x>.
- Sayre, E.V., Joel, E.C., Blackman, M.J., Yener, K.A., Özbal, H., 2001. Stable lead isotope studies of black sea Anatolian ore sources and related Bronze age and phrygian artefacts from nearby archaeological sites. Appendix: new central Taurus ore data. *Archaeometry* 43, 77–115. <https://doi.org/10.1111/1475-4754.00006>.
- Seeliger, T.C., Pernicka, E., Wagner, G.A., 1985. Archäometallurgische Untersuchungen in Nord- und Ostanatolien, in: *Jahrbuch Des Römisch-Germanischen Zentralmuseums Mainz*, 32.1985. pp. 597–659, Abb. Taf.
- Shefton, B., 1995. Greek imports at the extremities of the mediterranean, west and east: reflections on the case of Iberia in the fifth century BC. *Proc. Br. Acad.* 86, 127–155.
- Stos-Gale, Z.A., Gale, N.H., 2009. Metal provenancing using isotopes and the Oxford archaeological lead isotope database (OXALID). *Archaeol. Anthropol. Sci.* 1, 195–213. <https://doi.org/10.1007/s12520-009-0011-6>.
- Tejedor, C.C., 2018. The Mazarrón 1 Shipwreck: an iron-age boat with unique features from the Iberian Peninsula. *Int. J. Naut. Archaeol.* 47, 300–324. <https://doi.org/10.1111/1095-9270.12318>.
- Tomczyk, C., 2022. A database of lead isotopic signatures of copper and lead ores for Europe and the Near East. *J. Archaeol. Sci.* 146, 105657 <https://doi.org/10.1016/j.jas.2022.105657>.
- Tornos, F., Chiaradia, M., 2004. Plumbotectonic evolution of the ossa morena zone, Iberian Peninsula: Tracing the influence of mantle-crust interaction in ore-forming processes. *Econ. Geol.* 99, 965–985. <https://doi.org/10.2113/gsecongeo.99.5.965>.
- Trincherini, P.R., Domergue, C., Manteca, I., Nesta, A., Quarati, P., 2009. The identification of lead ingots from the Roman mines of Cartagena: the rôle of lead isotope analysis. *J. Roman Archaeol.* 22, 123–145. <https://doi.org/10.1017/S1047759400020626>.
- Valera, P.G., Valera, R.G., 2005. *Outline of geology and mineral deposits of Sardinia*. In: *Archaeometallurgy in Sardinia*. Monographies Instrumentum, pp. 35–109.
- Vilar, J.-B., 1986. Carthage et son district minier aux origines du mouvement ouvrier espagnol (1856–1870). *Mélanges Casa Velázquez* 22, 345–372. <https://doi.org/10.3406/casa.1986.2472>.
- Weisgerber, G., Pernicka, E., 1995. Ore Mining in Prehistoric Europe: An Overview, in: *Prehistoric Gold in Europe*, NATO ASI Series. Springer, Dordrecht, pp. 159–182. https://doi.org/10.1007/978-94-015-1292-3_12.
- Wood, J.R., Montero-Ruiz, I., 2019. Semi-refined silver for the silversmiths of the Iron Age Mediterranean: A mechanism for the elusiveness of Iberian silver. *Trab. Prehist.* 76, 272. <https://doi.org/10.3989/tp.2019.12237>.
- Wood, J.R., Montero-Ruiz, I., Martín-Torres, M., 2019. From Iberia to the southern levant: The movement of silver across the mediterranean in the early iron age. *J. World Prehistory* 32, 1–31. <https://doi.org/10.1007/s10963-018-09128-3>.