Tracking Roman lead sources using lead isotope analysis. A case study from the imperial rural estate at Vagnari (Puglia, Italy)

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Introduction

Lead was used widely in the Roman world, most notably to line aqueducts and water tanks, for water pipes, in toiletries, in shipping and fishing -for hull sheathing, anchors, and net sinkers-, in soldering, and occasionally for fashioning slingshot in siege warfare, among other things (Boulakia 1972; Retief and Cilliers 2006; Rosen and Galili 2007; Paparazzo 1994; Müller *et al*. 2014; Schinco and Small 2019). Several strands of evidence make it clear that lead ores were exploited on an immense scale during the Roman period, far more than in any preceding era, including the sixth and fifth centuries BCE when the cupellation of argentiferous lead to extract silver for Athenian coinage played an important political role (Hopper 1968; Conophagos 1980; Aperghis 2013).

Cores drilled in the ice in the French Alps and in Greenland, and in peatlands in western Europe, document clear lead pollution peaks in the Roman period (Preunkert *et al*. 2019; Hong *et al.* 1994; Rosman et *al*. 1997; McConnell *et al*. 2018; Allan *et al*. 2018). Roman shipwrecks containing cargoes of lead ingots confirm that by the late first century BCE the Romans were mining lead on a grand scale, particularly in Spain, but also in Sardinia, and they were transporting this commodity throughout the whole of the western Mediterranean (Pinarelli *et al.* 1995; Trincherini *et al*. 2001; Tisseyre *et al*. 2008). From the first century CE, lead ores in Germany began to be mined for use in the Roman occupation of the newly conquered region and possibly for export elsewhere (Hanel and Rothenhöfer 2005; Durali-Mueller *et al.* 2007; Bode *et al*. 2009).

A recent analysis of lead isotopes in sediments from Rome's harbour system in the later first and early second century CE at Portus revealed a strong anthropogenic lead component in the Tiber river that flowed into it (Delile *et al.* 2014). Isotopic studies of the sediments in the neighbouring harbour at Ostia suggest that the lead pipes (*fistulae*) of the water distribution system of the capital upstream from both ports represent the main contributory factor to this contamination as early as the second century BCE (Delile *et al.* 2017). Roman mining districts in the western Mediterranean (Spain) and western Europe (Britain, Germany, France) provided the ores for the city's *fistulae*, underscoring the importance of lead mining outside Italy and the trade in this material between Rome and the western provinces (Delile *et al*. 2014a: 6597; Delile *et al*. 2017: 10062).

These studies utilise isotopic analysis for an understanding of the supply sources of lead in a major urban environment -the capital of the Empire- to good effect. Other investigations of sediments and artefacts in Naples, Pompeii, and Herculaneum also have concentrated on urban and densely populated sites on the Italian peninsula (Delile *et al*. 2016; Keenan-Jones *et al*. 2011). Far less attention has been focused on contemporary rural sites in Roman

Italy and the evidence for lead ore sources and the use and processing of lead in those locations. Furthermore, almost all the published isotopic analysis of lead objects relates to *fistulae* and ingots, not, however, to processing and recycling debris from workshops in either towns or villages. In the following, and in order to at least partially remedy this situation, the archaeological and isotopic evidence for the sourcing and working of lead at an important rural settlement of Roman imperial date at Vagnari in south-east Italy is presented.

Historical and Archaeological Background

Field-walking, survey, and excavations about 75 km west of the Adriatic coastal town of Bari in Italy revealed a Roman village (*vicus*) and an associated cemetery at Vagnari in ancient Apulia that was occupied from the early first to the fourth century CE (Small 2011; Brent and Prowse 2014; Carroll 2014; Carroll 2019; Prowse *et al*. 2014) (Fig. 1). Ceramic roof tiles at Vagnari and in the vicinity, that were stamped with the name of an imperial slave, indicate that this settlement was a central part of a very large rural estate belonging to the Roman emperor and operating as a source of revenues. The period between the late first and the end of the third century CE was the most active and productive phase of occupation in the *vicus*.

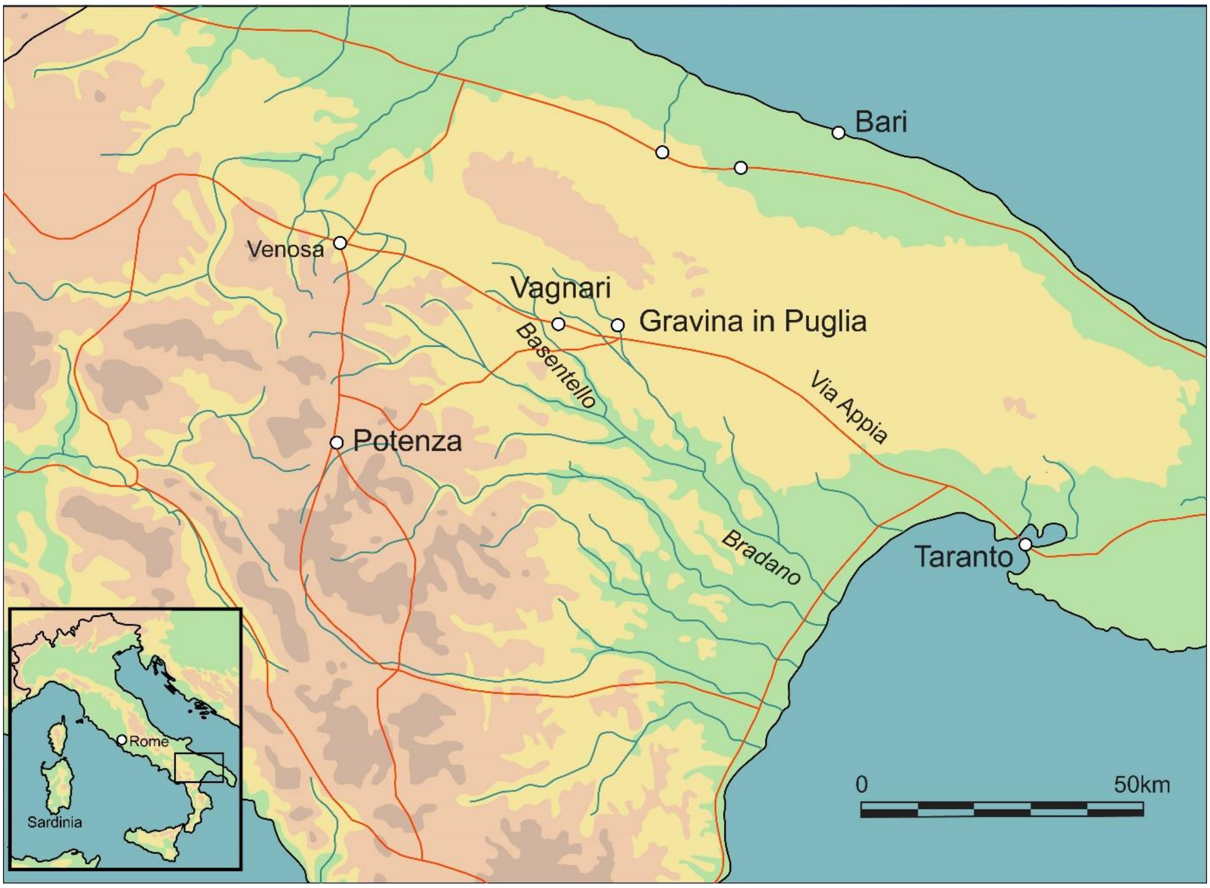

Fig. 1 Map of south-east Italy showing the location of Vagnari (drawn by Irene De Luis).

A major goal of the archaeological fieldwork by the University of Sheffield since 2012 has been to investigate the mobilisation of natural and man-made resources on the Vagnari estate, with a focus on the networks that were established to develop and maintain the imperial property and the connectivity between this region and others in and beyond Italy.

In addition to agricultural activities, such as cereal cultivation and viticulture, the excavations have revealed various industries in the settlement, including pottery and tile production, iron-working, and lead processing. It is on the latter that we focus here.

Fig. 2 Clipped pieces of thin lead sheet (photo Maureen Carroll).

A total of 4.5 kg of lead was retrieved in deposits, pit fills, floors, and drain fills in the *vicus*. No particular room or space in the buildings at Vagnari could be identified as a workshop dedicated to the processing of lead. All lead artefacts and manufacturing debris found in the Roman settlement and in field-walking surveys around Vagnari have been catalogued and studied; a selection of artefacts retrieved in the McMaster University excavation of the cemetery also has been included in this study (Table 1). The lead objects can be grouped into three main artefact categories. The first artefact group consists of small square or rectangular pieces cut from rolled lead sheet only 2-3 mm in thickness, weighing between 3 and 11 g (Fig. 2). These pieces were found only in the *vicus* and on the field-walking survey. The second artefact group comprises material from the processing of lead, such as lead droplets formed during melting or re-melting (Fig. 3, 1F-1H). These look like solidified liquid drops or spills, and the underside of these pieces are flat and often slightly rough, as a result of the molten liquid falling on the ground or some other level surface. The group also includes pieces of cut and torn lead from objects destined for re-melting and recycling; presumably also the scrap that is deliberately (and sometimes quite neatly) folded in on itself once or multiple times represents the collection and convenient preparation of the material for re-melting (Fig. 3, 1B and 1G). The third artefact group is made up of manufactured artefacts such as weights for scales, fishing net weights, attachments, hinges and decorations once fixed to parts of buildings and furniture, and other utilitarian items (Fig. 3, 1A, 1C-1D and 1I). Also present in this third group are the lead clamps or tenons used in repairing cracked or broken ceramic vessels (Fig. 3, 1E), a phenomenon that was especially common in the context of large and costly vessels such as *dolia* or vats used for the storage of wine or oil (Peña 2007: 216-227, figs. 8.2-8.7). These tenons were inserted in a slot cut into the vessel wall to straddle the crack, rendering the vat stable and functioning. Given that we have a second-century CE winery with *dolia* at Vagnari, such repair tenons are rather appropriate finds (Carroll 2016).

Fig. 3 Overview of some of the lead artefacts selected for analysis. 1A. sieve (*in situ* on top of a ceramic libation pipe in the cemetery); 1B. scrap; 1C. weight; 1D. rod or ingot; 1E. ceramic repair tenon; 1F. melted droplet; 1G. folded scrap; 1H. melted droplet; 1I. fishing net weight (photos M. Carroll and T. Prowse).

Object Number	Object Type	Context	Date
43-10-00-12-2	Cut sheet	vicus, overlying demolition	3rd-4th c.?
54-10-xx-17	Cut sheet	vicus	?
58-10-00-12-5	Cut sheet	vicus, overlying demolition	3rd-4th c.?
9-10-1002-12	Cut sheet	vicus, demolition	3rd c.
11-10-1001-12	Cut sheet	vicus, demolition	3rd c.
43-10-00-12-1	Cut sheet	vicus, overlying demolition	3rd-4th c.?
43-10-00-12-3	Cut sheet	vicus, overlying demolition	3rd-4th c.?
43-10-00-12-4	Cut sheet	vicus, overlying demolition	3rd-4th c.?
43-10-00-12-6	Cut sheet	vicus, overlying demolition	3rd-4th c.?
43-10-00-12-8	Cut sheet	vicus, overlying demolition	3rd-4th c.?
43-10-00-12-12	Cut sheet	vicus, overlying demolition	3rd-4th c.?
43-10-00-12-13	Cut sheet	vicus, overlying demolition	3rd-4th c.?
43-10-00-12-15	Cut sheet	vicus, overlying demolition	3rd-4th c.?
58-10-00-12-1	Cut sheet	vicus, overlying demolition	3rd-4th c.?
12-10-1001-12	Appliqué	vicus, demolition	3rd c.
13-10-1002-12	Droplet	vicus, demolition	3rd c.
10-10-1001-12	Droplet	vicus, demolition	3rd c.
43-10-00-12-16	Droplet	vicus, overlying demolition	3rd-4th c.?
43-10-00-12-17	Droplet	vicus, overlying demolition	3rd-4th c.?
43-10-00-12-18	Droplet	vicus, overlying demolition	3rd-4th c.?
52-10-1003-12-1	Scrap	vicus, demolition	3rd c.
43-10-00-12-19	Scrap	vicus, overlying demolition	3rd-4th c.?
43-10-00-12-20	Scrap	vicus, overlying demolition	3rd-4th c.?
43-10-00-12-21	Scrap	vicus, overlying demolition	3rd-4th c.?
43-10-00-12-22	Scrap	vicus, overlying demolition	3rd-4th c.?
25-10-1002-12	Net weight	vicus, demolition	3rd c.
29-10-00-12	Net weight	vicus, overlying demolition	3rd-4th c.?
27-10-00-12	Shell weight	vicus, overlying demolition	3rd-4th c.?
26-10-00-12	Weight	vicus, overlying demolition	3rd-4th c.?

61-10-00-12	Weight	vicus, overlying demolition	3rd-4th c.?
43-10-00-12-23	Weight	vicus, overlying demolition	3rd-4th c.?
43-10-00-12-24	Weight	vicus, overlying demolition	3rd-4th c.?
28-10-00-12	Cap/lid	vicus, overlying demolition	3rd-4th c.?
10-10-2001-13	Nail/pin	vicus, demolition	3rd c.
54-10-1004-12	Strip	vicus, roof collapse	mid-3rd c.
360/6062 P1390	Rod (ingot?)	survey, surface	?
P1071	Ceramic clamp	cemetery (Tomb F104)	mid-2nd c.
P6984	Sieve fragment	cemetery (Tomb F333)	late 2nd c.

Table 1. Analysed lead objects from the *vicus*, the cemetery and the survey (Maureen Carroll). All dates are CE.

In order to understand the implications of accessing lead ores in Italy, for example from mines in Tuscany on the Italian peninsula or the island of Sardinia (Stos-Gale *et al*. 1995: 411-412), or from potentially distant sources, and to follow the movement of resources necessary for lead-working at Vagnari, it was important to determine the origins of the ores present in the material used on the estate. Thirty-eight pieces representing all three artefact groups were sampled, including 35 objects from the *vicus*, two from the cemetery, and one from surface collection during the field-walking survey. The lead objects selected for lead isotope analysis were sampled in 2014 in the store rooms of the Centro Operativo per l'Archeologia di Gravina in Puglia (Soprintendenza Archeologia, Belle Arti e Paessagio) and submitted to the British Geological Survey for analysis. All the objects (apart from two) from the *vicus* were retrieved in the 2012 excavations, many from the upper layers of the site, including an extensive demolition layer dating to the period after the middle of the third century CE and the soil above it which had been churned up by the plough for modern cereal cultivation; the latter context has been assigned to the third-fourth century CE, as no material in this disturbed context post-dates this period. The objects themselves, however, might very well be older, and since the sampling season in 2014, we have excavated more lead belonging to all three object categories in securely dated stratified contexts ranging from the early first to the late third century CE.

Analytical Procedure

Isotope analysis

Ultrapur Nitric acid was used to clean off any surface contamination from a small area of each sample. This was then washed off with de-ionized water and the surface allowed to dry. A further drop of Teflon distilled 8MHNO3 was then allowed to sit on the cleaned surface for a couple of minutes. This was then pipetted off the sample into a clean vial.

Pb isotope analysis of the samples was conducted using a Nu Instruments Nu Plasma, MC-ICP-MS. Prior to analysis, each sample was filtered (Millipore 0.25um PFA) and spiked with a Thallium solution (added to allow for the correction of instrument induced mass bias). Samples were then introduced into the instrument via an ESI 50ul/min PFA micro-concentric nebuliser attached to a desolvating unit (Nu Instruments DSN 100). For each sample, five ratios were simultaneously measured ($^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{206}Pb$) (Table 2). Each individual acquisition consisted of 60 sets of ratios, collected at 5-second integrations, following a 60 second de-focused baseline.

The precision and accuracy of the method was assessed through repeat analysis of an NBS 981 Pb reference solution (also spiked with Thallium). The average values obtained for each of the measured NBS 981 ratios were then compared to the known values for this reference (Thirlwall 2002). All sample data were subsequently normalised, according to the relative daily deviation of the measured reference value from the true. Normalisation to an international standard in this way effectively cancels out the effects of slight daily variations in instrumental accuracy and allows the direct comparison of the data obtained during different analytical sessions. Internal uncertainties (the reproducibility of the measured ratio) were propagated relative to the external uncertainty (i.e. the excess variance associated with the reproducibility of the reference material analysed during the session).

Methodology

The method used to assess the source of the Vagnari Pb artefacts using Pb isotope composition is adapted from the method recommended on the OXALID website. Firstly, the $^{206}Pb/^{204}Pb$ ratios from the Vagnari samples are plotted using a Kernel Density Plot, with 0.015 Kernal bandwidth, to provide a visual representation of the data structure. The groups/peaks are then characterized by specific values in all three Pb isotope axes, and these values are used as the basis for searching published data for matches. Searching was undertaken using the galena data compilation of Blichert-Toft *et al.* (2016) which contains >6700 Pb isotope analyses from across Europe. This compilation was searched using +/ 0.1% ranges simultaneously on three isotopes ratios $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$, using the mean, or representative sample, of the data group as the central point. The data are then discussed, and the interpretation refined, using archaeological attributes and the results are displayed on binary Pb isotope diagrams.

Kernal Density Assessment

The Vagnari data breaks into four sections. There are two clear peaks at $^{206}Pb/^{204}Pb$ = 17.8 and $^{206}Pb/^{204}Pb$ =18.1, then a complex data structure with several internal peaks, and finally a high point with a value of $^{206}Pb/^{204}Pb$ =18.89 (Fig. 4). We have named these data concentrations as population groups 1-4 respectively and these are used to focus the search criteria.

Database searching

The essentially normally distributed population groups 1 and 2 are characterized, for searching, by their mean values. Population group 3 is more complex in structure and so the upper, lower and mid-point peaks were all modelled. The single sample that comprises population group 4 is searched on its singular composite. See Table 3 for search values used. As an example, population group 1, which comprises three samples, has mean values of $^{206}Pb/^{204}Pb$ = 17.8538, $^{207}Pb/^{204}Pb$ =15.5959, and $^{208}Pb/^{204}Pb$ =37.8717. The search criteria used were, therefore, $^{206}Pb/^{204}Pb$ is >17.83 and < 17.87; $^{207}Pb/^{204}Pb$ is > 15.62 and <15.52 and $^{208}Pb/^{204}Pb$ is >37.83 and < 37.91. The resulting search data sets all conformed to the 3D Euclidean test that the LI ratios were < one relative to the test samples.

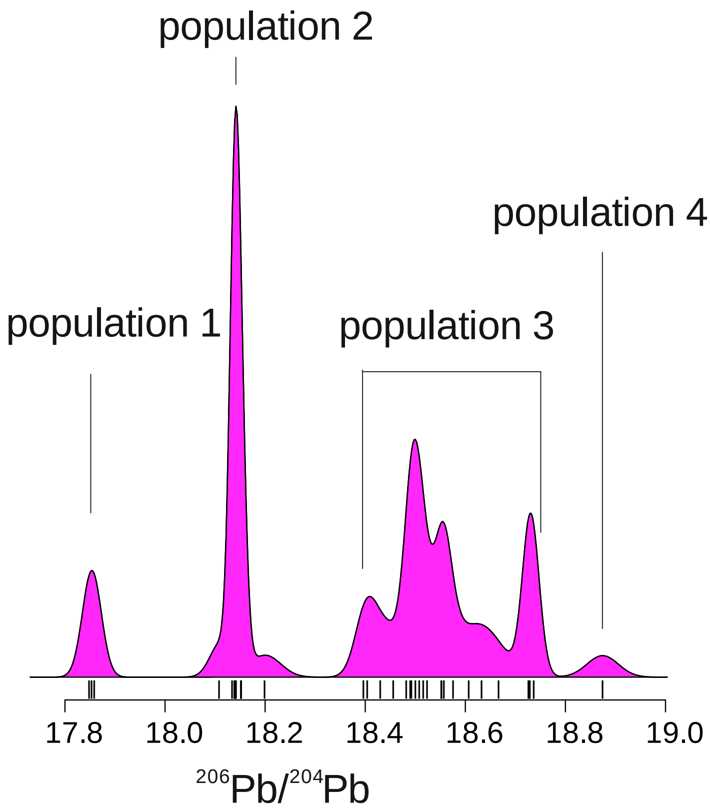

Fig. 4 Lead concentration peaks as population groups 1-4 (Jane Evans).

	206Pb/204Pb	207Pb/204Pb	208Pb/204Pb
Peak 1 mean	17.854	15.596	37.872
Peak 2 mean	18.145	15.641	38.214
Peak 3, group 1 low point 43-10-00-12-21 Pb scrap	18.398	15.683	38.621
Peak 3, group 1 mid-point 10-10-1001-12 Pb droplet	18.516	15.671	38.691
Peak 3, group 1 high point 26-10-00-12 Pb weight	18.738	15.693	39.037
Peak 4, sample: SF TR 19-050 P1071	18.874	15.698	38.900

Table 3 Peak values used in searching the database (Jane Evans).

Peak 1

This assemblage comprises three samples of cut sheet Pb (artefact group 1), which generate a normally distributed curve on the KDE plot (54-10-xx-17, 58-10-00-12-5, 43-10-00-12-2). The search of galena data within 0.1% uncertainty on the combined $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and the $^{208}Pb/^{204}Pb$ yielded nine galena source matches. Six of these were from the Iglesiente region of Sardinia, Italy (OXALID: Italian ores), and the remaining three were single samples from France (Marcoux *et al*. 1986), Greece (OXALID: Greek ores), and Spain

(Tornos *et al*. 1996). The most probably origin of Pb from these sheets, both from the highest number of hits and the most proximal source, is thus Sardinian galena.

Peak 2

This assemblage also from artefact group 1 comprised 12 samples predominantly of lead sheet (43-10-00-12-1, 43-10-00-12-3, 43-10-00-12-4, 43-10-00-12-6, 43-10-00-12-8, 43-10-00-12-12, 43-10-00-12-13, 43-10-00-12-15, 11-10-1001-12-1, 58-10-00-12-1, 9-10-1002-12), but including also an appliqué strip (12-10-1001-12) from artefact group 3. Forty-six galena analyses fall within the search range for this group and these are dominated by samples from the French Pyrenees (n=13, Marcoux 1986, 1991; Lescuyer *et al*. 1998; Munoz *et al*. 2106) and Wales in the UK (n=16, Rohl 1966; Rohl and Needham 1998). There are also matches from Morocco, (n=5, Bouabdellah *et al*. 2009), Spain (n=4, Marcoux 1986), Romania (n=1, Cook and Chiaradia 1997), and Italy (n=2, OXALID: Italian ores). The likely sources, based on numbers of matching data, are either Wales or the French Pyrenees, of which the latter is geographically closer to Vagnari.

Peak 3 (compound)

This is composed of 23 samples from artefact group 3 of identifiable items such as lids, nails, and weights, pieces of scrap, and Pb droplets or melting debris (13-10-1002-12, 10-10-1001-12, 32-10-00-12-16, 43-10-00-12-17, 43-10-00-12-18, 52-10-1003-12-1, 43-10-00-12-19, 43-10-00-12-20, 43-10-00-12-21, 43-10-00-12-22, 25-10-1002-12, 29-10-00-12, 27-10-00-12, 26-10-00-12, 61-10-00-12, 43-10-00-12-23, 43-10-00-12-24, 28-10-00-12, 10-10-2001-13, 54-10-1004-12, 360/6062 P1390, P1071, P6984). The Pb isotope profile reflects this mixed provenance with a broad range of values. To model this dataset, we have searched for matching data for the top, middle and low point of the array (see Table 2).

Sample 43-10-00-12-21, a piece of scrap, is used to define the low end of the array, and 19 samples provide a match within the uncertainties set. They are dominated by galena from France (n=8, Marcoux 1986) and Italy (n=6, Rottura 1991; Nimis *et al*. 2012; Begemann *et al*. 2001; OXALID), with minor contributions from Greece (n=2, OXALID 29), Austria (n=2, Köppel 1997), and the UK (n=1, Rohl 1996)

The midpoint is taken as the Pb droplet 10-10-1001-12. Matches for this are also dominated by data from France (n=10, Brevart *et al*. 1982; Marcoux 1986; Baron *et al*. 2006), with single samples from each of Bulgaria (Gale *et al*. 1991), Italy (OXALID), Romania (Cook and Chiaradia 1997), Turkey (OXALID), and the UK (Rohl 1996).

The high point of this array is taken as the lead weight 26-10-00-12. There are 11 matches, predominantly from Italy (n=7, OXALID), Spain (n=4, Arribas and Tosdal 1994; Murillo-Barroso 2010), and Romania (n=1, Cook and Chiaradia 1997).

The overall results suggest that these artefacts represent lead predominantly from France, Italy, and Spain.

Peak 4

This single sample from artefact group 3 forms a discrete Pb isotope peak in $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ on the KDE diagrams. The sample is a second-century CE sieve fragment

(P6984) from a libation pipe associated with Tomb F333 in the cemetery (Fig. 3, 1A). When the database is searched, looking for composition matches within 0.1% uncertainty on all three isotope ratios, 36 results are returned, 30 of which are from Greek galena (Stos-Gale *et al*. 1996; Marinos and Petrascheck 1956; and OXALID). The remaining six matches are from Spain (n=1, Arribas and Tosdal 1994), Switzerland (n=1, Guénette-Beck 2005), Romania (n=1, Marcoux *et al*. 2002), and Tunisia (n=2, Skaggs *et al*. 2012; Jemmali *et al*. 2013). Hence, Greece seems the most probably origin of the sieve, based on the observation that most matches are of Greek origin.

Summary of results

The data primarily show that Vagnari was receiving and processing lead from a number of sources (Fig. 5). The normally distributed data from the sheet metal squares and rectangles of the Peak 1 assemblage supports a single source of origin from Sardinia and this could be a first-generation lead production. The rest of the Pb sheet in the Peak 2 assemblage has a more radiogenic signature around $^{206}Pb/^{204}Pb$ = 18.14. The spatially closest single-source match of origin of Pb of this composition is from the French Pyrenees, although the more distant origin of Wales cannot be ruled out on Pb isotope composition. It is possible that this peak is the product of mixing between a Sardinian and a younger source, but the tight grouping of the data makes this less likely. The scrap metal and the finished artefacts (Peak 3) show an associated mixture of Pb isotope signatures which are dominated by French and Italian sources, but mixed sources cannot be discounted. Finally, the sieve fragment (Peak 4) has a distinct Pb isotope nature that is best matched with a Greek source.

Discussion

Although the lead items from the *vicus* retrieved before 2014 are rather late in date, more recent fieldwork in the settlement clearly demonstrates that lead was being worked here already from the early first century CE, and at least until the third century CE. Precise dates also come from the artefacts found in burials of the mid- to late second century CE in the cemetery; these include the ceramic repair tenon and the sieve. The amount of lead waste found at Vagnari is probably small in comparison to the large and ubiquitous quantities of the material that once were used for various purposes in the settlement and to the quantities that were re-melted repeatedly for secondary use.

The lead squares or rectangles cut from rolled lead sheet in artefact group 1 come from Sardinian mines and from a source in the Pyrenees or Wales. The results of the isotopic analysis of these pieces indicates that the lead in them has not been mixed with another source, rather the metal has come directly from the source. The uniformly dark grey colour and lack of corrosion perhaps offers independent confirmation of that simple and unmixed signature. Because the intensity of the degradation process of lead depends on the purity of the metal, a modification of colour and consistency, from bright metallic grey and stable to dull, whitish, and brittle, provides a visual clue of the purity or impurity of the object (Mattias *et al*. 1984). Perhaps only lead that has not been reworked and re-melted would be stable enough to withstand the process of rolling it out to a thickness of only 2-3 mm, without it breaking, cracking or becoming brittle. Whether the sheets were produced at Vagnari, or brought into the site from another manufacturing centre, we cannot say with any certainty.

Sheets of lead, as a valuable commodity, might first have served a purpose as a lining for basins or containers on the site or in architectural cladding. The clipped squares and rectangles could have been offcuts from larger pieces once they had been fitted for their primary purpose, or they might have been cut from lead sheets after the original contexts for the sheets had fallen out of use. The main tool used in the formation of these clipped lead pieces were the shears, while the marks on some of them indicated that talons and burins also had been used. A possible use for such pieces might have been as additives to the smelting of metal alloys.

At least one of the clipped lead squares more recently found can be dated securely to a second-century context, indicating clearly that sheet lead was coming into the site by this date at the latest. Large pieces of sheet lead could have come to Vagnari to be used, for example, in metal tanks in a bath building. A bath complex has not yet been found at Vagnari, but, just to the west of the excavated buildings of the *vicus*, box flue tiles and hypocaust tiles were collected from the surface in the original field survey, suggesting that a bath was situated near here (C. Small 2011: 7). The existence of a second-century CE wine cellar at Vagnari also may be relevant here (Carroll 2019). Basins for pressed grape juice (as yet undiscovered at Vagnari) may have been lined with lead sheet, and ancient authors refer to the sweetening of wine by boiling it down in lead vats and containers (Cato, *On Agriculture* 107; Pliny the Elder, *Natural History* 14.136). Columella (*On Agriculture* 12.20.3), for example, referred to huge lead or lead-lined cauldrons in which unfermented grape juice (must) was boiled down in capacities equalling the contents of 90 amphorae (26 litres each). It is, thus, possible that the sheet lead at Vagnari may have had an original context such as this before it was recovered and recycled at the end of the life of the winery, although the sheet lead does not show any sign of degradation or corrosion from having been heated for boiling liquids.

The objects in artefact groups 2 and 3 at Vagnari are made of lead from heterogeneous sources in France, Italy, and Spain; they include all but one of the finished artefacts, and all the scrap and melting droplets. Almost certainly they were made of lead that had been recycled and mixed in more than one process. All are dull grey or whitish and exhibit various degrees of corrosion and instability, as is to be expected from lead into which impurities might have been introduced through mixing (Mattias *et al*. 1984). Recycling of lead was common in the Roman period and is attested at Pompeii, for example, where lead water pipes (*fistulae*) were recycled to make new ones; the heterogeneity of lead sources is characteristic in this context (Boni *et al*. 2000). Roman salvaging and recycling practices meant that this heterogeneity of lead from mixed sources such as France, Germany, Spain, and Britain was a common phenomenon also in the water pipes at Rome itself, attested by the sediments in the city's harbour basins (Delile *et al*. 2017). Moving away from lead water pipes, recycling of lead occurred also at Herculaneum, where 125 kg of lead droplets, lead offcuts and scrap were found in a workshop (*Insula* VI.12) buried under the debris of the Vesuvian eruption in 79 CE (Monteix *et al*. 2005; Duvauchelle and Monteix 2013). The casting debris, scrap offcuts, and folded pieces at Vagnari, moreover, strongly resemble a similar assemblage found in the settlement at Mathay-Mandeure (*Epomanduodurum*) in Roman Gaul (Dubuis 2013). There is no available isotopic data from Mathay-Mandeure or Herculaneum on the sources of the lead found in these assemblages, and so we cannot conclude anything about the diversity of sources of the lead there. At Vagnari, the sieve from the cemetery stands out from the other artefacts of these two groups of artefacts of recycled lead at the site, not in appearance, because it, too, is of whitish colour and brittle appearance, but because it probably was made of lead sourced in Greece and might not have been a result of repeated mixing of lead objects.

Conclusion

The source of lead used in the production of artefacts found at Vagnari was not uniform, rather the ores stem from various regions within the Roman empire ranging from Italy, Spain, and Greece, to France or possibly Britain. Such variability and heterogeneity are attested also in the water pipes in the cities of Rome, Pompeii, and Naples where one might expect to find a vibrant influx of materials in a populous, urban environment. Although assemblages of waste, recycling, and artefacts from lead processing and lead re-melting have been found at some towns in Italy and Gaul that resemble those at Vagnari, only the material from Vagnari has been subjected to lead isotope analysis to determine the sources of the lead used in architecture, plumbing, fishing, weighing, and daily artisanal production and repairs. The clear isotopic variability of the lead used on this rural site is a primary characteristic of the material, and this variability sheds light on well-functioning supply networks and connections at play here, despite the somewhat remote location of the imperial estate.

The most homogeneous group of lead used for sheet at Vagnari was imported from Sardinia and from the northern Pyrenees region or Wales. There is no overlap with northern Europe's Roman lead array from *Germania* and no evidence that lead from this region was incorporated in the production of material at the site. Because isotope information is limited to the production step of smelting metal from ores, it cannot be proven that the finished artefacts definitively were made at Vagnari from ores directly transported to the site. The craftsmen at Vagnari who produced the scrap or re-melted lead pieces were not necessarily the ones who had produced the sheet metal. But it is clear, based on the considerable amount of casting scrap and debris from melting and re-melting lead in the settlement, that on-site processing was conducted over a few centuries using lead from multiple sources.

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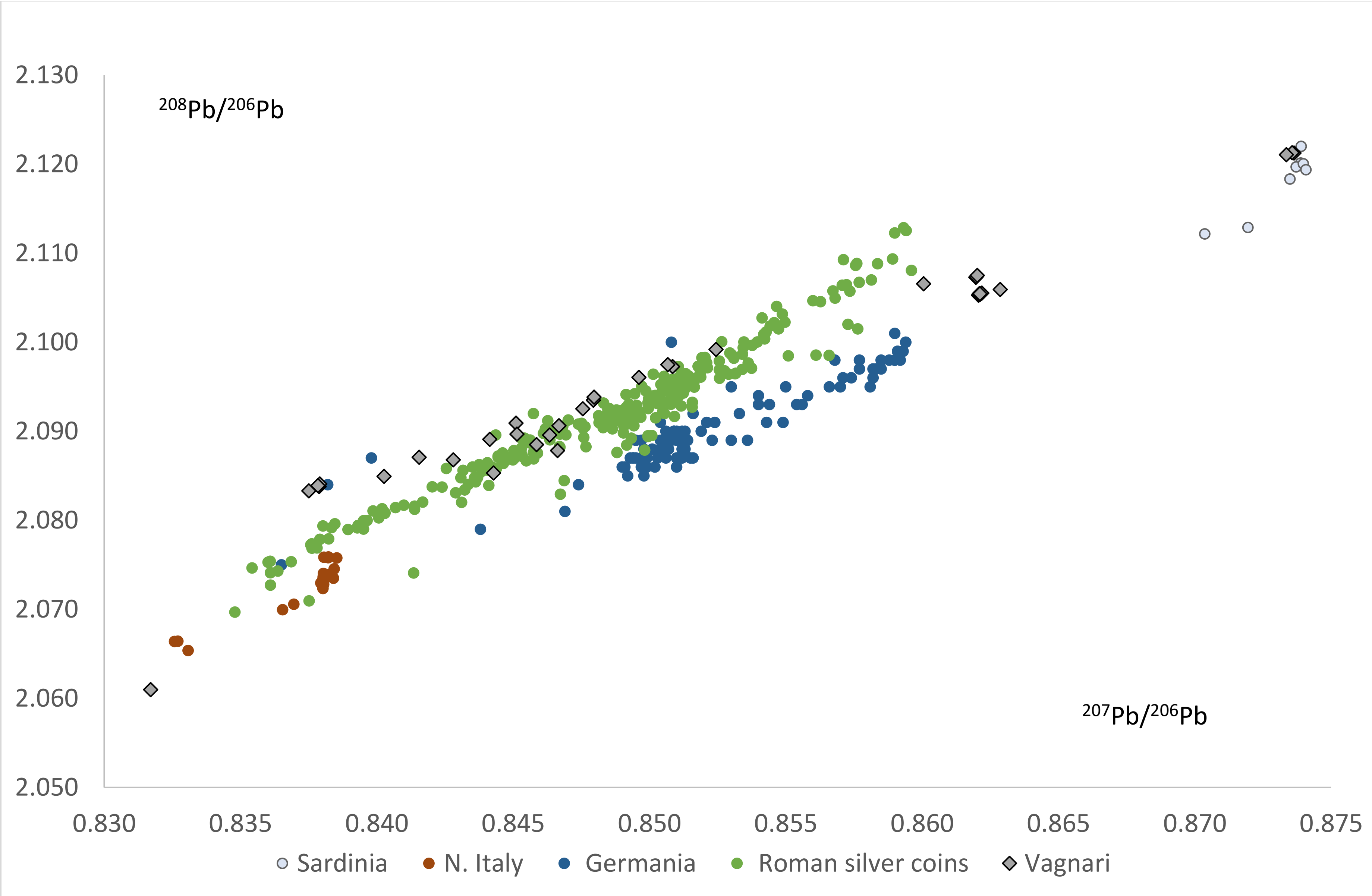
Sample Name	$^{206}Pb/^{204}Pb$	2s %	$^{207}Pb/^{204}Pb$	2s %	$^{208}Pb/^{204}Pb$	2s %	$^{207}Pb/^{206}Pb$	2s %	$^{208}Pb/^{206}Pb$	2s %
54-10-xx-17	17.8494	0.004	15.5944	0.006	37.863	0.007	0.87365	0.003	2.1213	0.003
58-10-00-12-5	17.8539	0.006	15.5961	0.007	37.874	0.008	0.87357	0.003	2.1213	0.005
43-10-00-12-2	17.8582	0.008	15.5973	0.009	37.879	0.010	0.87336	0.004	2.1211	0.006
43-10-00-12-6	18.1096	0.006	15.6265	0.007	38.137	0.009	0.86287	0.003	2.1059	0.006
43-10-00-12-8	18.1357	0.007	15.6362	0.008	38.185	0.009	0.86219	0.003	2.1055	0.006
43-10-00-12-15	18.1390	0.006	15.6372	0.008	38.187	0.008	0.86207	0.003	2.1053	0.006
43-10-00-12-12	18.1391	0.009	15.6380	0.010	38.189	0.011	0.86212	0.003	2.1054	0.006
43-10-00-12-1	18.1397	0.006	15.6375	0.007	38.189	0.007	0.86208	0.003	2.1053	0.006
11-10-1001-12-1	18.1406	0.006	15.6391	0.008	38.194	0.010	0.86210	0.003	2.1055	0.007
43-10-00-12-4	18.1412	0.007	15.6397	0.007	38.194	0.008	0.86210	0.003	2.1054	0.006
43-10-00-12-13	18.1413	0.006	15.6401	0.008	38.195	0.009	0.86212	0.004	2.1055	0.007
43-10-00-12-3	18.1516	0.005	15.6463	0.006	38.250	0.007	0.86197	0.003	2.1073	0.006
58-10-00-12-1	18.1516	0.006	15.6468	0.006	38.252	0.007	0.86199	0.003	2.1074	0.005
9-10-1002-12-1	18.1524	0.007	15.6475	0.009	38.256	0.010	0.86203	0.004	2.1075	0.007
12-10-1001-12	18.2005	0.005	15.6537	0.007	38.341	0.007	0.86006	0.003	2.1066	0.003
43-10-00-12-21	18.3980	0.007	15.6830	0.008	38.621	0.009	0.85244	0.003	2.0992	0.004
P6984	18.4041	0.004	15.6592	0.006	38.598	0.007	0.85085	0.003	2.0973	0.003
43-10-00-12-24	18.4300	0.006	15.6778	0.007	38.656	0.008	0.85067	0.003	2.0975	0.003
28-10-00-12	18.4577	0.005	15.6818	0.005	38.688	0.006	0.84961	0.003	2.0961	0.003
43-10-00-12-16	18.4840	0.007	15.6733	0.008	38.697	0.009	0.84794	0.003	2.0935	0.003
13-10-1002-12	18.4899	0.005	15.6787	0.007	38.715	0.007	0.84796	0.002	2.0938	0.003
43-10-00-12-22	18.4935	0.006	15.6744	0.008	38.698	0.008	0.84756	0.003	2.0925	0.003
29-10-00-12	18.5011	0.004	15.6637	0.005	38.627	0.006	0.84663	0.003	2.0878	0.003
61-10-00-12	18.5080	0.006	15.6700	0.007	38.692	0.008	0.84669	0.003	2.0906	0.003
10-10-1001-12	18.5164	0.005	15.6714	0.006	38.691	0.007	0.84634	0.003	2.0896	0.003
52-10-1003-12-1	18.5251	0.005	15.6691	0.007	38.689	0.008	0.84585	0.003	2.0885	0.003
54-10-1004-12	18.5524	0.008	15.6785	0.009	38.791	0.009	0.84510	0.003	2.0909	0.004
360/6062 P1390	18.5527	0.006	15.6792	0.007	38.769	0.009	0.84514	0.003	2.0897	0.003

43-10-00-12-18	18.5582	0.005	15.6683	0.006	38.699	0.007	0.84428	0.003	2.0853	0.003
25-10-1002-12-1	18.5751	0.008	15.6797	0.009	38.805	0.009	0.84414	0.003	2.0891	0.003
43-10-00-12-17	18.6063	0.005	15.6815	0.005	38.827	0.007	0.84281	0.003	2.0868	0.003
27-10-00-12	18.6336	0.008	15.6812	0.009	38.890	0.009	0.84155	0.003	2.0871	0.003
10-10-2001-13-1	18.6669	0.006	15.6851	0.007	38.920	0.007	0.84026	0.003	2.0849	0.003
43-10-00-12-23	18.7277	0.005	15.6919	0.006	39.024	0.007	0.83789	0.002	2.0838	0.003
43-10-00-12-18	18.7289	0.005	15.6928	0.006	39.032	0.007	0.83791	0.003	2.0841	0.003
43-10-00-12-20	18.7297	0.006	15.6921	0.007	39.030	0.008	0.83784	0.003	2.0839	0.003
26-10-00-12-3	18.7377	0.005	15.6931	0.006	39.037	0.007	0.83751	0.003	2.0833	0.003
P1071	18.8743	0.004	15.6981	0.006	38.900	0.007	0.83171	0.003	2.0610	0.003

Table. 2 Vagnari lead samples and their values (Jane Evans).



2.130
2.120
2.110
2.100
2.090
2.080
2.070
2.060
2.050
$^{208}Pb/^{206}Pb$
$^{207}Pb/^{206}Pb$
0.830
0.835
0.840
0.845
0.850
0.855
0.860
0.865
0.870
0.875
Sardinia
N. Italy
Germania
Roman silver coins
Vagnari

Fig. 5 Lead isotope plot for the sources of analysed lead artefacts from Vagnari (Jane Evans).