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Provenance of lead ores used for water pipes production in the ancient Roman Gaul (Vienne, France)

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Abstract

The urban fabric of Roman cities developed through the installation of water supply networks, mainly made of lead (Pb). In Gaul, the city of Vienne (France) was central to the manufacturing of Pb artifacts, including large volumes of Pb water pipes. Although Pb artifacts were often labeled with Roman-period stamps indicating the location of manufacturing, our knowledge of the provenance of extracted Pb ore and the way they were imported remains limited. In this study, Roman-period artifacts were analyzed for Pb isotope signatures to document the source of Pb ore used in Vienne's manufactories. Lead isotope signatures were then compared with new local Pb ores data and an updated Pb isotope database using a new algorithm to identify the provenance of Pb. Results indicate that Pb used for artifact manufacturing at Vienne originates mainly from a single source. Data treatment with the new algorithm identifies the Rhenish Massif and the Pennines mining regions as the primary and most probable source, but some artifacts exhibit a similar isotope composition to that of local Pb ores. The similarity of the Pb isotopic signatures of the artifacts produced in Vienne with those of Mainz pipes and lead ingots from the Rhenish massif, as well as the synchronicity of the mining periods in this region, support the Rhenish Massif as the most likely source of Pb for Vienne. Finally, we propose the Rhine and Saone Rivers as the most probable Pb ores conveyance routes to Vienne during the Roman Period.

Keywords:

Lead; Pollution; Roman; Pipe; Lead isotopes

Data availability

A link to the data and/or code is provided as part of this submission.

1 Introduction

Lead (Pb) had considerable industrial importance in the Roman world and was used for the development of urban centers, as well as in the manufacture of ordinary objects (Boulakia, 1972; De Keersmaecker et al., 2018; Delile et al., 2014; Rothenhoefer and Hanel, 2013). Specifically, the production of lead pipes (i.e., *fistulae*) for urban freshwater supply from the head of the aqueducts (castellum) to private and public buildings played a key role in the development of the Empire (Adkins et al., 1999; Deming, 2020; Mays et al., 2007). Lead was also extensively used in an array of public and domestic applications, such as household and cooking utensils [crafted from pure Pb or other alloys like pewter (Arthur and Marsh, 1978; Retief and Cilliers, 2006)], as an ingredient in cosmetics (Welcomme et al., 2006),

medicine (Nriagu, 1983; Rackham, 1938), food [i.e., as sweetener and food preserver (Cilliers and Retief, 2019)], and decoration (Needleman and Needleman, 1985; Nriagu, 1983; Retief and Cilliers, 2006).

Lead was mined and smelted in various places within the Empire (e.g., Hispania, Britannia, Sardinia ...), and its massive extraction has resulted in regional and global Pb contamination recorded in many environmental records around the world (Corella et al., 2021; McConnell et al., 2018; Rosman et al., 1997; Thevenon et al., 2011). Lead could be extracted locally or imported from distant areas as a function of the market price. Hence, to supply urban centers in this strategic metal, numerous terrestrial and navigable (i.e., both maritime and fluvial) transportation routes were developed and mapped (i.e., *Tabula Peutingeriana*) within the Empire (Miller, 1916). In Gaul, Pb extraction by the Gauls predated the Roman invasion. The Greek historian and geographer Strabo of Amasia mentions (3.2.8; 4.1.12; 4.2.2) silver mining in the lands of the *Ruteni* (southern Massif Central) and the *Gabales* (northern Cévennes) (Hirt, 2020). The Romans shaped the Pb mining landscape by expanding existing operations and introducing mining districts like the Cévennes, the Auvergne, and the Alps (Arnaud et al., 2006; Domergue, 2010; Domergue et al., 2006). In parallel, several Roman capitals, such as the city of *Vienne* (Roman Gaul, today France), were central in manufacturing Pb artifacts (Adjajd and Lauxerois, 2014). In particular, large volumes of Pb water pipes labeled with the mention VF (*Vienna Fecit*) were produced in *Vienne* to develop the aqueduct network of regional cities (e.g., Vienne, Lyon) during the High Roman Empire, i.e., between 31 BCE and 235 CE (Brissaud, 2016; Cochet, 2000; Cochet and Hansen, 1986). Although numerous Pb artifacts (i.e., pipes) were labeled with Roman-period stamps indicating the manufacturing location, limited information is available on the origin of extracted lead ore and how they were imported.

Pb isotope signatures are commonly used to assign the provenance of metals used in silver production [e.g., Albarede et al. (2020, 2012)], bronze [e.g., Macfarlane and Lechtman (2016)], and lead artifacts [e.g., Baron et al. (2011), Bode et al. (2009), Durali-Mueller et al. (2007), Repsaet et al. (2015)]. The geolocation of the Pb source ore has been improved by the development of a new algorithm (Albarede et al., 2024a) that statistically measures the distances between the 3-dimensional space of Pb isotope compositions of artifacts and compares them with those of the isotope compositions of the end-members (ores) derived from a new database taking mass-dependent fractionation into account (Albarede et al., 2024b).

In this study, 22 Roman artifacts, including 16 water pipes, recovered in the ancient city of *Vienne* (France) and its surroundings, together with 13 soil samples from two boreholes collected in the Forum place of the city were analyzed for elemental and Pb isotope signatures, to document the source of Pb and the extent of Pb contamination related to *Vienne's* Pb manufacturing activities. In addition, Pb isotope composition was measured in 29 galena ores collected in 9 local mining areas to complement the existing Pb isotope database. Finally, Pb transport routes to *Vienne* during the Roman Period are proposed.

2 Material and methods

2.1 Environmental and archaeological context

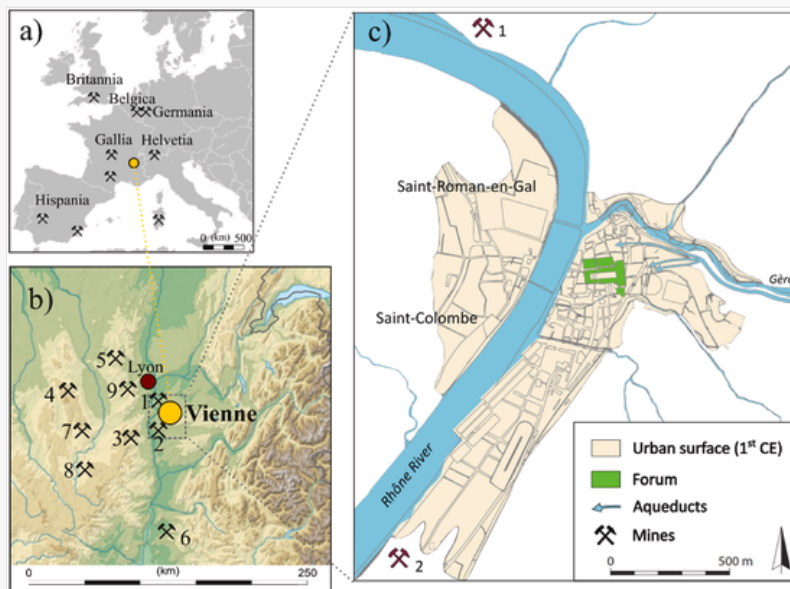
The city of *Vienne* is located in southeast France at the confluence of the Rhône with a small tributary, the Gère River, 35 km south of Lyon (Fig. 1). The city was built on ancient meanders of the Rhône and stretched along both banks of the Rhône River, covering an area of around 200 ha, including the modern cities of *Vienne*, *Saint-Roman-en-Gal*, and *Sainte-Colombe* (Pelletier, 2001). *Vienne's* geological context belongs to the Peri-Alpine domain, between two major geological regions: the Hercynian Massif Central (granitic, metamorphic, and basaltic rocks), west of the Rhône River, and the Alpine foothills of Bas-Dauphiné (Miocene and Pliocene Tertiary soils), east of the Rhône River. The bedrock (mostly schists, micaschists, and gneisses) is cut by the glacial valley, with shreds of Tertiary and Quaternary sedimentary formations, predominantly of glacial origin (Donsimoni, 2008; Helly et al., 2017).



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Fig. 1



a) Map of the western Roman Empire, including the location of Vienne (yellow dot) and known lead extraction areas (mining symbols), including Gallia (Gaul, now France), Britannia (Gales and England), Belgica (Belgium), Germania (Germany), Hispania (Spain and Portugal) and Sardinia. b) Location of Vienne and the local mines where galena ores were collected and analyzed in this study (1: Estressin, 2: La Poype, 3: Saint-Julien-Molin-Molette, 4: Saint-Martin-La-Sauvauté, 5: Beaujolais, 6: Serves, 7: Monistrol-sur-Loire, 8: Versilhac, and 9: Vaugneray). c) Map of the ancient city of Vienne during the 1st century CE [adapted from (Adjajd and Lauxerois, 2014)] with the location of aqueducts and of the Forum in the upper part of the city. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Vienne is one of the oldest cities in eastern France, with abundant water resources, elevated terrains suitable for agriculture, and endowed natural defenses (i.e., surrounded by five hills), which make the city a strategic position. As early as the 5th century BCE, human settlements were identified through archaeological excavations, and in the 3rd century BCE, the city became the capital of the Gallic Allobroges (Adjajd and Lauxerois, 2014). Then, Vienne came under Roman rule in 121 BCE and became a wealthy, well-known port during the High Empire (27 BCE – 235 CE), allowing the connection between the strategic Agrippa and Antoninian Roman road networks (Adjajd and Lauxerois, 2014; Helly et al., 2017). At that time, lead pipe manufacturing was Vienne's hallmark of metallurgical production (Cochet, 2000; Cochet and Hansen, 1986), and numerous Pb pipes have been excavated throughout the whole Allobroge region, i.e., the French Alps (Adjajd and Lauxerois, 2014). Archaeological excavations revealed at least 70 workshops [identifiable by their stamped artifacts (Brissaud, 2016)]. Although Pb mines were exploited locally during the Industrial Revolution (Chermette, 1989), there is no archaeological or historical evidence regarding their exploitation during the Roman times.

2.2 Sample collection and preparation for analysis

Twenty-two Gallo-roman lead artifacts were recovered from the Saint-Roman-en-Gal Museum collection (Table S1). The artifacts stem from Vienne (VI, $n = 8$), Sainte-Colombe (SC, $n = 8$), Saint-Roman-en-Gal (SRG, $n = 3$), and Lyon (LY, $n = 3$), and comprise mostly pipes ($n = 16$), and a diversity of Roman objects like vessels, sarcophagus, and valves ($n = 6$, Table S1). Within the set of artifacts, 19 were dated to the Early Roman Empire (i.e., –27 BCE – 235 CE), and one to Late Antiquity (i.e., 4th century CE, Table S1).

Two 17-m-long boreholes (SC1 and SC4, Table S2) were drilled at the Vienne Forum site during a geotechnical study (2015). The boreholes were re-sampled for the present study every one or 2 m. Samples were freeze-dried and sieved at 2 mm, and the remaining fraction was crushed with an agate mortar to obtain a fraction below 63 μm . The sequence of each borehole covers the last three thousand years, from Quaternary alluvium at the bottom [ca. 6000 year BP (Bravard and Gaydou, 2015),] to contemporary backfill material on top. Their relative chronologies have been established by archaeologists.

To document Pb isotope signatures of local mines, twenty-one galena ores (PbS, Table S3) were sampled from Saint-Julien-Molin-Molette (SJMM, $n = 10$), Saint-Martin-La-Sauvauté (SMLS, $n = 3$), and from the mine of Estressin (ES, $n = 2$) and La Poype (LP, $n = 6$) located north and south of Vienne, respectively (Fig. 1c). However, there is a lack of available information about the history of these mines, except for the 18th and 19th centuries, when some of them were exploited under the Blumenstein mining concession (Chermette, 1989). Four additional mining sites from the Massif Central were also collected to get a regional map of ores, including the Beaujolais (BJ, $n = 3$), Serves (SR, $n = 2$), Versilhac (VH, $n = 1$), Vaugneray (VG, $n = 1$), and Monistrol-sur-Loire (MSL, $n = 1$) (Fig. 1c and Table S3). These data provided a high-resolution focus on the available Pb isotopic data compiled from regional lead ores in the literature (Blichert-Toft et al., 2016).

2.3 Elemental and isotope analysis

Lead artifact samples used for chemical analyses were pried out using metallic pliers. These samples were then leached with 2 ml of double-distilled HCl 7N at room temperature for 1 h and sonicated for 10 min.

Galena ores and borehole samples were ground in ceramic mortars until a fine powder was obtained ($<63 \mu\text{m}$). Then, about 50 mg of powder was digested following a microwave-assisted digestion with concentrated bi-distilled HNO_3 and HCl in a ratio of 3:1 [US EPA Method 3052 (US EPA, 2015);]. Trace element analysis was performed by inductively coupled plasma mass spectrometry (ICP-MS, Agilent, model 7900) within the analytical chemistry platform of ISTERre (OSUG-France) using a modified version of the method published by Chauvel et al. (2011). Be, In, and Bi were used as internal standards to correct for instrumental mass bias. The quality assurance/quality control (QA/QC) are presented in Tables S4 and S5.

Lead isotopic analyses (^{204}Pb , ^{206}Pb , ^{207}Pb , ^{208}Pb) were obtained with a multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS, Nu Instruments, NuPlasma HR) at Ecole Normale Supérieure de Lyon using thallium doping, sample standard bracketing (White et al., 2000) and the values for NIST 981 standard of Eisele et al. (2003). Samples were precisely weighted (around 50 mg) and dissolved using 5 ml of concentrated HNO_3 (double-distilled) and 1 ml of concentrated HF (Merck Suprapur quality) either in Savillex® vessels (galena ores and artifacts) at 120 °C for 72 h or with microwave-assisted digestion (soil) following the US EPA method 3051a (US EPA, 2015). Lead yield (~95 %) was checked on an Agilent 7900 quadrupole ICP-MS within the analytical chemistry platform of ISTERre (OSUG-France). Lead was separated and purified from each sample in an HBr medium using anion-exchange columns loaded with AG1-X8 resin (200–400 mesh, Acros Organics) according to a conventional method (Monna et al., 1997; Weeks et al., 2009). The total procedural Pb blank was $<10 \text{ pg}$. The external reproducibility of the reported Pb isotope ratios, assessed through repeated runs of NIST 981 (performed every two samples), is within the range of 100–200 ppm (or 0.01–0.02 %) for ratios based on 204 ($^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$) and $\approx 50 \text{ ppm}$ (or 0.005%) for $^{207}\text{Pb}/^{206}\text{Pb}$, $^{208}\text{Pb}/^{206}\text{Pb}$, and $^{207}\text{Pb}/^{208}\text{Pb}$.


2.4 Data treatment and calculations

The three geochemically informed parameters (model age T_{mod} , $\mu = ^{238}\text{U}/^{204}\text{Pb}$, and $k = ^{232}\text{Th}/^{238}\text{U}$) were obtained from Pb isotope ratios with the equations given by Albarède et al. (2012) and using the Matlab code found in Delile et al. (2015). Briefly, T_{mod} is related to the tectonic age of the crustal segments in which ore deposits occur, whereas μ and k are related to the crustal depth in which these occur (Delile et al., 2014). Statistical analyses were performed using SigmaPlot version 12.5. Probability values (p) and correlation coefficients (R) are reported for linear regression analyses. In all cases, a p-value of 0.05 was chosen to indicate significance at the 95 percent confidence level. All Pb isotope data and calculations are provided in supplementary tables S1, S2 and S3.

3 Results and discussions

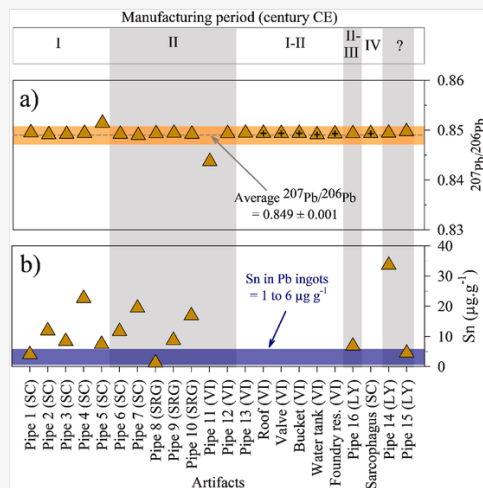
3.1 Singular lead isotope signature of artifacts manufactured in Vienne

Almost all the Pb artifacts analyzed in this study (Table S1) exhibit a tightly clustered isotopic distribution (i.e., $^{208}\text{Pb}/^{206}\text{Pb} = 2.088 \pm 0.003$, $^{207}\text{Pb}/^{206}\text{Pb} = 0.849 \pm 0.001$, $^{204}\text{Pb}/^{206}\text{Pb} = 0.054 \pm 0.0001$, Fig. 2a), independently of the nature of Pb artifact and the period in which they were cast (i.e., first to fourth century CE, i.e., Roman period, Fig. 2).

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Fig. 2




$^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratios of water pipes (open triangles) and other artifacts (cross-hair triangles) retrieved from Saint-Colombe (SC), Saint-Roman-en-Gal (SRG), Vienne (VI), and Lyon (LY), in relation to the period of manufacturing. Dark yellow vertical band in panel a) indicates the average $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratios obtained from all studied artifacts. Blue band in panel b) indicates the Sn concentration in Pb ingots (Baron and Cochet, 2003; Cochet, 2000). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Pipe 5 ($^{208}\text{Pb}/^{206}\text{Pb} = 2.099$, $^{207}\text{Pb}/^{206}\text{Pb} = 0.851$, $^{204}\text{Pb}/^{206}\text{Pb} = 0.0544$, 1st century CE) and Pipe 11 ($^{208}\text{Pb}/^{206}\text{Pb} = 2.081$, $^{207}\text{Pb}/^{206}\text{Pb} = 0.844$, $^{204}\text{Pb}/^{206}\text{Pb} = 0.0539$, 2nd century CE) deviate from the cluster group. A narrow isotopic distribution was previously found for pipes and ingots retrieved at Trier and Mainz (Durali-Mueller et al., 2007). Such narrow distribution can be attributed to two potential causes: i) the sources of Pb remained relatively unchanged over the four centuries of artifact manufacturing, or ii) lead was recycled and fully homogenized, which is not consistent with the long period of production. Consistently, low tin (Sn) concentrations measured in our artifacts ($12 \pm 9 \mu\text{g g}^{-1}$, Fig. 2b) do not support repeated re-melting, as re-melted Pb objects should be enriched (by 0.3–1%) in solder alloy compounds (Sn) over time (Baron and Cochet, 2003). Hence, the clustered Pb isotopic signature of 20 of the 22 artifacts from Vienne supports a single source of Pb ores for their manufacturing.

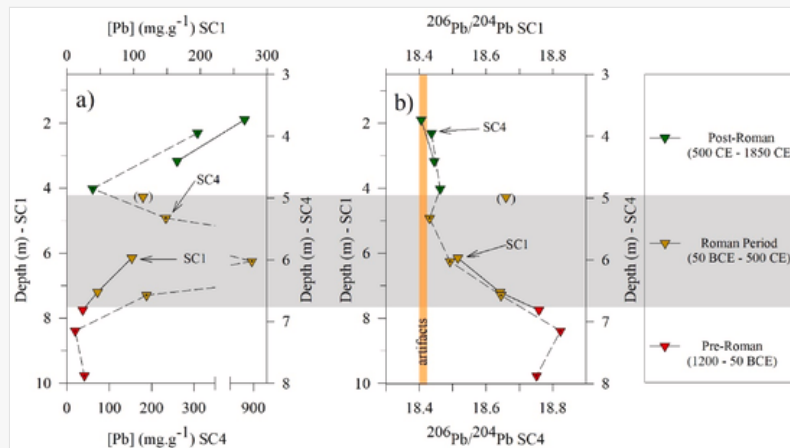
3.2 Inherited lead pollution at Vienne

Total lead concentration and isotope profiles obtained in the forum boreholes (SC1 and SC4, Fig. 3 and Table S2) allow the reconstruction of historical Pb pollution in the city of Vienne. The lowest Pb concentrations are found in the deepest layer dated to the Iron Age (av. \pm SD = $28 \pm 11 \mu\text{g g}^{-1}$, $n = 3$, red symbols Fig. 3a), which are indistinguishable from the local geochemical background of the Rhône [i.e., $17.7\text{--}22.3 \mu\text{g g}^{-1}$ (Cossa et al., 2018; Dendievel et al., 2020)], and the Upper Continental Crust [i.e., $17 \pm 0.5 \mu\text{g g}^{-1}$ (Rudnick and Gao, 2003)]. The associated isotopic signatures exhibit the lowest $^{207}\text{Pb}/^{206}\text{Pb}$ ratios of the record (av. \pm SD = 18.78 ± 0.04 , $n = 3$, Fig. 3 b) and are in the range of reported values for the Upper Continental Crust [i.e., 18.93 ± 0.02 (Millot et al., 2004)]. A major increase in total Pb concentration up to 114 and $893 \mu\text{g g}^{-1}$ is observed in both SC1 and SC4 boreholes, respectively, at a depth corresponding to the Roman occupation (i.e., ca 50 BCE – 400 CE, dark yellow symbols, Fig. 3a). Accordingly, $^{206}\text{Pb}/^{204}\text{Pb}$ ratios shift to lower values (18.56 ± 0.09 , $n = 6$, dark yellow, Fig. 3b), which are in the range found for our set of Pb artifacts manufactured at Vienne (18.42 ± 0.03 , Fig. 2a), testifying to the change in Pb source compared to the previous period, likely related to urban runoff and increased local atmospheric emission of Pb during smelting operation in the city. Pb concentrations remained high with similar isotope ratios during the following post-Roman period (green symbols; [Pb] = $200 \pm 111 \mu\text{g g}^{-1}$, $^{206}\text{Pb}/^{204}\text{Pb} = 18.50 \pm 0.07$, $n = 4$, Fig. 3).

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Fig. 3



Stratigraphic profile (down triangles) of a) total lead concentrations, and b) $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratios of boreholes SC1 (straight line) and SC4 (dotted line) retrieved from Vienne's Forum. Scales between plots were adapted to match ages and periods. Symbol colors indicate the relative age obtained from archeologists' ceramological dating of borehole layers. Red colors refer to the pre-Roman period, dark yellow to the Roman Empire, and dark green to post-roman (i.e., middle age to modern) periods. The average $^{206}\text{Pb}/^{204}\text{Pb}$ isotopic ratios obtained from studied artifacts from the Roman period are also indicated as a yellowish vertical band. The sample in brackets for core SC1 (at 4.2m deep) is considered to be an outlier due to a singular elemental composition characteristic of a backfill sample [see Fig. S2 and Table S2 (extended)]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

In the city of Vienne, around 30 km of Pb pipes were needed to connect the aqueducts to the houses (Fig. S1) during the Roman period (Helly and Delile, 2018). With an average weight of 10.8 kg for each linear meter of pipe, at least 323 tons of Pb was required to craft and set up this web of pipes. Hence, the increase in Pb concentrations, together with the shift to lower $^{206}\text{Pb}/^{204}\text{Pb}$ values from the onset of the Roman period onward, indicates a major non-geogenic Pb contamination consistent with the reported peak of Pb manufacturing activities in Vienne (Arnaud et al., 2006, 2010; Cochet and Hansen, 1986). Lead's tendency to form insoluble minerals and to bind to organic and inorganic soil surfaces limits its mobilization and downstand movement in the soil column (Kushwaha et al., 2018). It is, therefore, expected that Pb can remain in the soil even centuries after the original deposition. Such high Pb levels with similar isotopic signatures after the decline of the Roman Empire suggest the persistence in the soil of historical pollution similar to what has been observed in Rome (Delile et al., 2014).

3.3 Sources of Pb ores used for water pipe production during the Roman period

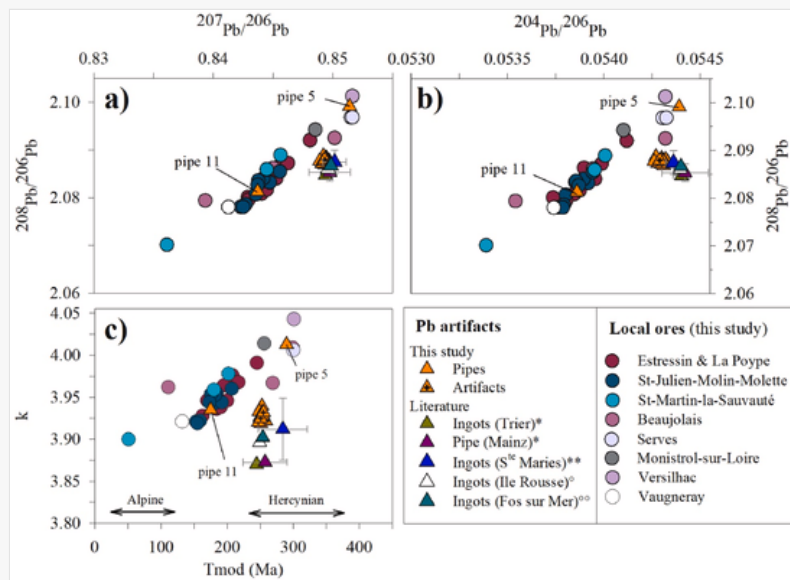
3.3.1 Limited local mining source during the Roman period

In order to determine the main source of Pb used for water pipe production during the Roman period, we compared the isotope ratios ($^{207}\text{Pb}/^{206}\text{Pb}$ vs $^{208}\text{Pb}/^{206}\text{Pb}$ and $^{204}\text{Pb}/^{206}\text{Pb}$ vs $^{208}\text{Pb}/^{206}\text{Pb}$, ^{206}Pb was taken at both denominators to keep mixing relationships linear) of the Pb artifacts with local galena ores (Fig. 4).

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Fig. 4




Lead isotope ratios of Roman lead artifacts (i.e., orange crossed triangles for Vienne, and dark pink triangles for Mainz pipes*), ingots (light brown triangles from Trier*, dark blue triangles for Ste. Maries**, white triangles for Ile Rousse^o, and light blue triangles for Fos sur Mer^{oo}), and local ores (circles, this study) plotted in a) $^{207}\text{Pb}/^{206}\text{Pb}$ vs $^{208}\text{Pb}/^{206}\text{Pb}$, b) $^{204}\text{Pb}/^{206}\text{Pb}$ vs $^{208}\text{Pb}/^{206}\text{Pb}$, and c) geological parameters (k vs T_{mod}). Error bars represent the standard deviation of the average values for lead pipes from Mainz*, and ingots from Trier* (Durali-Mueller et al., 2007), Saintes-Maries-de-la-Mer** (Baron et al., 2011), Ile Rousse^o and Fos sur Mer^{oo} (Raepsaet-Charlier, 2011). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Isotope ratios of the artifacts exhibit distinct signatures from that of the 29 local galena analyzed. Only pipes 5 and 11 overlap, respectively, with the ores from Serves and Monistrol-sur-Loire and Saint-Julien-Molin-Molette, Estressin, and La Poype (Fig. 4a and b). All this suggests that local Pb sources were probably known and exploited occasionally during the Roman times but that local mining only became significant during the 18th and 19th centuries, i.e., a period of intense local mining during the Industrial Revolution (Chermette, 1989).

3.3.2 Identification of the most probable mining source of Pb ores used in Vienne

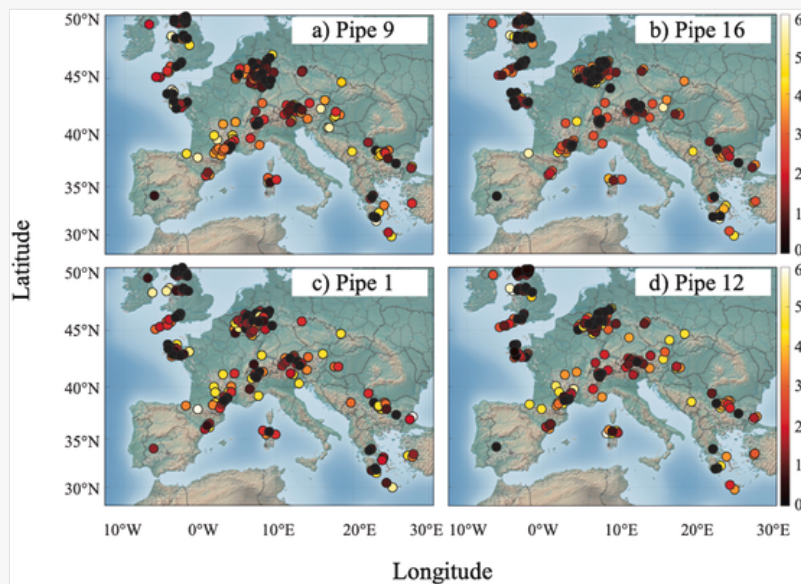
Mining in Gaul experienced a significant boost after the Roman conquests and was mainly focused on iron extraction, whereas Gaul's resources for lead, silver, and copper were of lesser importance when compared with those of other provinces (Domergue et al., 2006). Indeed, within the western Roman Empire, major Pb extraction areas were Spain (Cartagena-Mazarron and Sierra Morena), Belgium/Germany (Rhenish Massif), England (Pennines), and Sardinia (Bode et al., 2009; Domergue and Rico, 2014a). The Iberian region, whose Pb signal is recorded in numerous sediment archives in Europe (Corella et al., 2021; Elbaz-Poulichet et al., 2011, 2020; Martinez-Cortizas et al., 2013; Thevenon et al., 2011) and polar ice (McConnell et al., 2018; Rosman et al., 1997), was mined as early as the sixth century BC, then by the Romans in the first century CE, after which activity declined considerably probably due to high costs and the incorporation of new mining territories such as the British and German mines (Boulakia, 1972).

To test these potential sources and to assign the provenance of Pb ores used at Vienne, Pb isotope signatures of each Pb artifact were individually implemented in a new algorithm (Albarede et al., 2024a) to compare the distances between the 3-dimensional space of their Pb isotope compositions with those of a new reference database of ores Pb isotope (Albarede et al., 2024b). Except for pipes 5 and 11, which match with regional ores (Fig. S3), the algorithm's outputs for the independent analyses of the remaining 20 artifacts converge on 6 possible locations (Fig. 5 and S3) as the main source of Pb ores, i.e., i) the Rhenish Massif (i.e., Gallia Belgica/Germania), ii) the Pennines (i.e., Britannia), iii) the Wallis (i.e., Vallesia), iv) the Cevennes (i.e., Cevenna), v) Sardinia, and vi) the Brittany peninsula (i.e., Armorica).

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Fig. 5



Four outputs of the data treatment obtained with the newly published algorithm (Albarede et al., 2024a) showing the statistical probability of correspondence of Pb isotope compositions of four lead pipes dating from the first and second centuries CE and originating from four different locations; a) pipe 9 from St-Roman-en-Gal, b) pipe 16 from Lyon, c) pipe 1 from Sainte Colombe, and d) pipe 12 from Vienne, compared with the isotope compositions of end-members (ores) derived from a new database (Albarede et al., 2024b). The statistical probability of correspondence increases from white (i.e., low probability = 6) to black (i.e., high probability = 0) dots. The size of dots with a high probability of correspondence (<6) was enlarged to ease the reading, and all data with low probabilities (>6) were removed from the figure. The treatment for all the other artifacts is presented in Fig. S3.

Such matches in isotopic signatures between Pb mineralization from distant regions are common because ores belong to the Hercynian domain. However, several sources can easily be dismissed as their period of exploitation is inconsistent with the Viennese manufacturing period. This is the case for the Armorican Brittany (northwestern France, between the Seine and the Loire rivers) and the Cevennes (south-central France, on the south-east edge of the Massif Central), which all present lower statistical probabilities (Fig. 4 and S3) and were respectively exploited during the first and second centuries BCE, the fourth century CE, and the medieval period [(Baron et al., 2006; Domergue et al., 2006), Fig. S4]. In the case of Sardinia, the statistical probabilities are similar, and although the period of Pb mining is consistent with the period of Viennese artifacts manufacturing, most studies focusing on Pb exportation routes report fluxes centralized towards Italy (i.e., Rome and nearby regions), but there is no mention of export from Italy onwards (Boni et al., 2000; Domergue et al., 2006; Ingo et al., 1996).

Of the three remaining sites with the best statistical matches for the 20 artifacts (Fig. 4 and S3), the Rhenish Massif is one of the most likely sources, given the period of exploitation of the mines and evidence of regional export network for lead ingots in the Roman Empire. This mining region corresponds to both the Eifel district in current Germany (Durali-Mueller et al., 2007) and the Belgian zinc-lead deposits of the Hautes Fagnes Plateau (Cauet et al., 1982; Dejonghe, 1998; Renson et al., 2008). Archaeologists report Roman occupation in this mining district from ca. 50 BCE to 400 CE (Fig. S4) with extensive mining (Domergue and Rico, 2014a; Rothenhoefer and Hanel, 2013), consistently with the period of Pb artifacts manufacturing at Vienne (Allan et al., 2018; Renson et al., 2008). The Rhenish district has been mined since the first century BCE (Domergue, 2010) and isotopically identified as the source of Pb artifacts (Fig. 4) found at numerous archaeological sites of the Rhine basin (Germany), including waterpipes from Mainz and Pb ingots recovered in Trier (Bode et al., 2009; Durali-Mueller et al., 2007). In addition, Roman wrecks discovered in the Mediterranean Sea (first century CE), at Les Saintes-Maries-de-la-Mer (Baron et al., 2011; Baron and Cochet, 2003), Fos-Sur-Mer, and in Corsica (Ile Rousse) or Sardinia (Riccardi, Genovesi, 2002) have revealed Pb ingots stamped “*plumbum Germanicum*”, isotopically matching with the Rhenish massif ores (Bode et al., 2009; Raepsaet et al., 2015; Raepsaet-Charlier, 2011), highlighting a major export network of German Pb within the Roman Empire. In addition, the presence of the Emperor's name in the main seal molded of these ingots indicates that Pb production and export was a direct state management operation, relying, in certain circumstances, on the technical resources of the army and local populations (Raepsaet et al., 2015).

The second most likely source is Britannia. In Roman Britain, ore deposits of Derbyshire and Cumberland (Central and Northwestern England, respectively) produced and exported significant amounts of Pb following the Roman conquest in the second half of the first century CE (Boulakia, 1972; Domergue, 2010; Tylecote, 1964). However, this period of Roman Britain mining appears only in the second half of the production period of Viennese artifacts [i.e., between 31 BCE and 235 CE (Brissaud, 2016; Cochet, 2000; Cochet and Hansen, 1986)] and with a different isotopic signature, as observed in the Romano-British Pb ingot retrieved from the Pennines (i.e., *Perthshire*, Fig. S5) in England (Gardiner, 2001).


In contrast, the silver-lead mines (galena) from the Wallis area in the Swiss Alpine region were active throughout the imperial period but remained relatively small-scale, indicating that this source was certainly secondary, if not minor during the Roman period (Guénette-Beck et al., 2009; Guénette-Beck and Semeels, 2010; Köppel et al., 1993).

Hence, this supports the Rhenish Massif and the Pennines as the most probable mining areas that provided large amounts of Pb for the manufacturing of Pb artifacts in Vienne during at least the first two centuries CE.

3.4 Potential routes of Pb export to the Gallo-roman city of Vienne

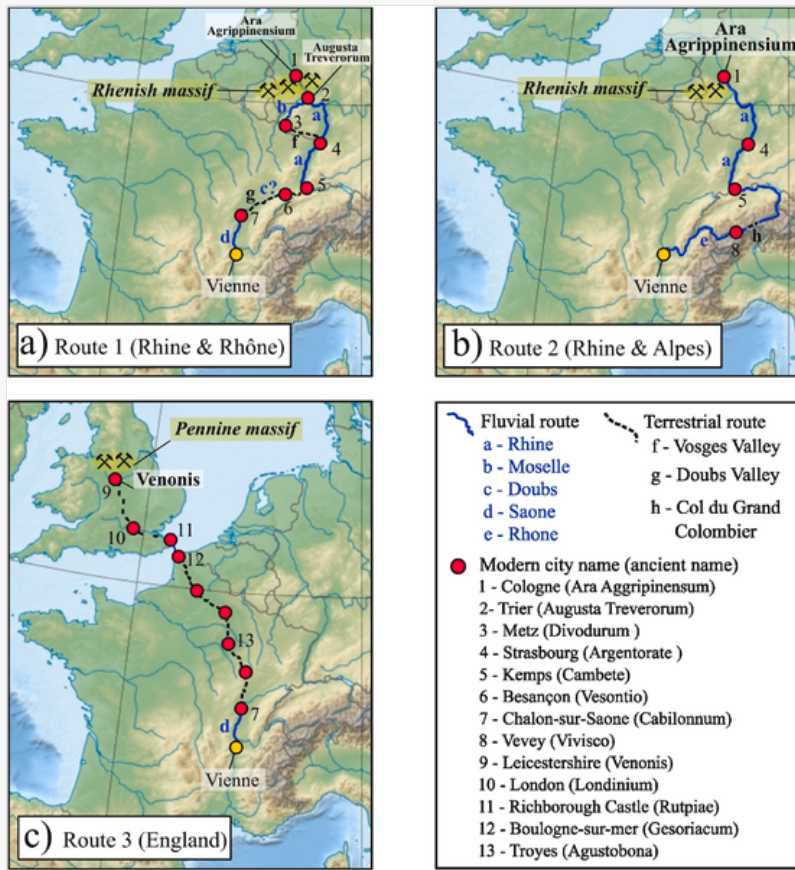
Within the Roman empire, Pb ingots were transported through a vast and well-established network of land, fluvial, and maritime trade routes (Domergue and Rico, 2014b). Among the network of Roman roads in Gaul, the *Viae Agrippae*, built in the 1st century BCE, radiated from the strategic Roman settlement of Lyon (*Lugdunum*) to the Atlantic Ocean, the Mediterranean, and the Rhine region (Purcell, 1990). Because imperial roads (e.g., *Viae Agrippae*) were mainly designed for military and administrative purposes, fluvial transport was often preferred to support heavy transport (Duval, 1989). As the upstream river travel was constraining, it is likely that overland routes, located mainly on towpaths, were often preferred, whereas river traffic was probably favored for the downstream navigation (Franconi, 2014). Moreover, the transport of Pb ingots does not entail volume constraints but does require sufficient animal towing power.

Based on the main mapped strategic routes (i.e., *Tabula Peutingeriana*) of the Roman Empire (Miller, 1916), using the ORBIS Geospatial Network Model of the Roman World (Scheidel and Meeks, 2012), we identified the most relevant and reliable routes for connecting a chosen mining district to Vienne. Three routes are tested from a) the Rhenish Massif, b) the Alpes, and c) England, identified as the main probable sources of Pb for Vienne (Fig. 6).

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alt-text: Fig. 6


Fig. 6



Three most probable routes of conveyance of Pb ingots to Vienne from the Rhenish Massif via the Rhine (a) or the Alpes (b) and from England (c), using the ORBIS Geospatial Network Model of the Roman World (Scheidel and Meeks, 2012).

From the Rhenish massif mining district to Lyon, a Roman network of forts and cities (i.e., Neuss, Bonn, Mainz, Strasbourg, Basel) was established along the Rhine, linked by direct routes that served mainly for military and administrative purposes but also as supply routes in Gaul (Dalgaard et al., 2022; Franconi, 2014). The first possible route (Fig. 6a) passes through or along the Rhine River from Cologne to Kems, or alternatively along the Moselle River, followed by an overland route to the Rhine in the Vosges valley between Metz and Strasbourg, and continued by the Doubs River to Chalon-sur-Saone, and by the Saone and Rhône River to Vienne (i.e., Route 1 in Table 1). An alternative route through the Alpes (Fig. 6b) follows the same path as route 1 until Kems, but then continues overland to Vevey through the Alpes and rejoins Vienne through or along the Rhone River (i.e., Route 2 in Table 1). This later route segment corresponds to the route between Wallis and Vienne (i.e., route 4 in Table 1). The comparison of routes 1 and 2 shows that when upstream river travel by towpath is chosen, the cost is identical (26 denarii, Table 1) for the two routes, but Route 1 is the fastest route to Vienne (44 vs 46 days, Table 1).

Table 1

 The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To view the actual presentation of the table, please click on the [Preview](#) located at the top of the page.

Q6 Estimation of the distance, time, and cost per kg. of Pb of the three probable routes connecting the Rhenish Massif to Vienne using the ORBIS Geospatial Network Model of the Roman World (Scheidel and Meeks, 2012). The mean daily travel speeds established by the model are 20 km/day by donkey or wagon, 65 km/day for downriver travel, and 15 km/day for upriver travel. Freight charges for road and river transport are set according to the Tetrarchic price Edict of 301 CE (Roueché, 1989). For route 1, an alternative (*) via the Moselle River is proposed, and information is presented as numbers in parenthesis.

	Route 1: Rhine (via Moselle)*		Route 2: Alpes		Route 3: Britannia	Route 4: Wallis
	Fluvial/terrestrial	Terrestrial only	Fluvial/terrestrial	Terrestrial only	Maritime/terrestrial	Terrestrial only
Distance (Km)	1025 (983)	911 (873)	968	923	1412	320
Time (days)	46 (41)	44 (42)	55	46	49	16
Cost per Kg. of goods by donkey (denarii)	10 (13)	26 (25)	16	26	26	9
Cost per Kg. of goods by wagon (denarii)	11 (15)	32 (29)	19	32	30	11

When the combination of fluvial and terrestrial routes is considered, route 1 is the fastest (46 days) and the cheapest itinerary (10–11 denarii, Table 1), all modes of transport considered. Marked volumes of traffic on the Rhine River have been reported since the first century CE (Ellmers, 1978; Ollive et al., 2006, 2008), and flat-bottomed Roman Barges with load capacities estimated between 65 and 110 tons have been excavated throughout the Rhine basin (Bockius, 2003; Vos et al., 2011). In the continuity of the Rhine, the Saone/Rhône Rivers were also major routes for Roman inland water shipping (Christol and Fiches, 1999; Lonchambon et al., 2009). Consistently, the large number of Pb ingots retrieved in the Mediterranean Sea (see section 3.2.2) support the fluvial transport at least for the Saone/Rhône part of the routes. Hence, roads and rivers were surely used to complement each other.

From the Pennines mining district to Vienne, the route (Fig. 6c) passes through England from Venonis to the port of Richborough, followed by a maritime navigation to Boulogne-sur-Mer, and a terrestrial route to Vienne via Troyes (i.e., Route 3 in Table 1). In comparison to route one from the Rhenish massif, the transport of Pb from the Pennines shows similar travel duration but a higher cost of transport (Table 1) when the combination of fluvial and terrestrial routes is considered.

4 Conclusion


The study of the Pb isotopic signatures of Roman pipes and artifacts from Vienne suggests that most of the lead used by the manufacturers at Vienne was of distant origin. The most probable source is attributed to the mines in the Rhenish massif, but one cannot exclude a contribution from mines in Roman Britain. Surprisingly, local and regional mines appear to be secondary in the composition of Viennese Pb products.

This certainly reflects the economic market for Pb during Imperial Rome, where, as today, Pb manufacturers in Vienne bought raw materials at the best price, according to the existing market, and made stocks according to metal prices and dependence on supply and demand. One also has to consider that Pb production and export from the Rhenish massif were managed by the state. Hence, supply costs were probably not a major obstacle in the centralized economy of the Roman Empire, and transport from Gallia Belgica seems realistic. The presence of local signatures on a small number of objects also reveals that, in some cases, local mines were probably used when Pb prices rose or for smaller production runs.

Future archaeological discoveries of new artifacts, together with the study of other artifacts, and new historical information, will certainly complete this picture, refine the chronology, and identify importation routes for this metal, which was central to the development of Roman Gaul.

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Appendix A Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2025.109227>.

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Highlights

- Intense manufacturing of lead (Pb) artifacts in Vienne during the Roman period.
 - Artifacts exhibit narrow range of Pb isotope compositions.
 - Only few artifacts exhibit Pb isotope signature consistent with local Pb ores.
 - Isotope modeling attributes Pb ore sourcing to Rhenish or Pennines mines.
 - Pb ores were probably shipped by Romans down the Rhine River to Vienne.
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Appendix A Supplementary data

The following is the Supplementary data to this article:

 [Multimedia Component 1](#)

Multimedia component 1

alt-text: Multimedia component 1

Queries and Answers

Q1

Query: Please check that the affiliations link the authors with their correct departments, institutions, and locations, and correct if necessary.

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