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## Multivariate statistical study of lead isotopic data: proposal of a protocol for provenance determination

Céline Tomczyk, Kévin Costa, Bruno Desachy, Patrice Brun, Christophe Petit

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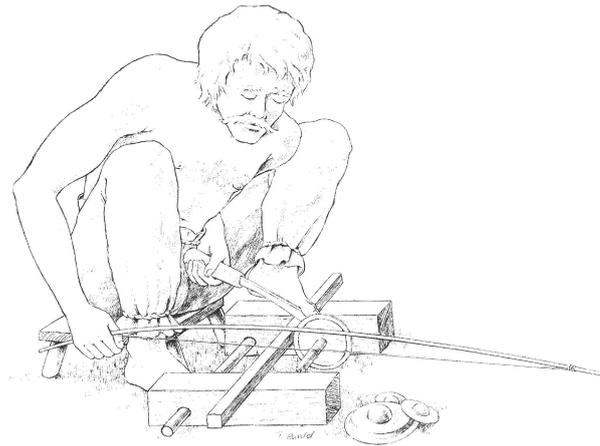
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73



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## Preface

The International Conference „Archaeometallurgy in Europe”, held at Miskolc in Hungary from the 19<sup>th</sup> to the 21<sup>st</sup> of June 2019 is by now a well-known and fully established international scientific meeting, at which scholars with different backgrounds can present their research on ancient metal finds, metal analysis, ancient mining, the reconstruction of various kinds of production processes, ancient technologies and every topic that belongs to metals and their transformation from ore to objects.

Our meeting at Miskolc was the fifth of a series that begun in Milan in 2003, followed in 2007 by the conference in Aquileia, both in Italy. The third was held at Bochum, in Germany, in 2011 and the fourth at Madrid, Spain, in 2015. The special aim of our 2019 conference was that of emphasizing and strengthening the interdisciplinary character and the various activities in the field of archaeometallurgy and widening the focus towards Eastern Europe.

The papers we present in this volume use scientifically collected data that allow the re-examination of aspects of archaeology and offer a view of antiquity based on materials science, supplemented by archaeological, literary and stylistic evidence, i.e. the methods by which human activities have been reconstructed in the past.

The presentation of research, availability of information, discussion and confrontation is an important side of this conference. Publishing new data and research in this frame - although in some cases only in short form - is important. The volumes of the conference „Archaeometallurgy in Europe” have been planned as a window on the world of archaeometallurgy, as general information for students, scholars and in general for anyone interested in these topics and, finally, as a tangible historical memory of the kind of studies carried out at this time. We all know that

research can be dated, just like the ancient objects we are studying. For these reasons and more, even though we received a good number of submissions, it is a pity that some interesting papers presented at Miskolc were not delivered for publication in this volume. Apparently, as it transpired at the conference, some of the authors decided to publish in a journal with impact factor. Nevertheless, a shorter or different version could have been submitted for publication in this volume as well, in particular as we know that the collection of papers, the peer-reviewing, corrections and the printing process normally take a couple of years. These volumes play an important role for our scholarly community, because they also represent an occasion for valuable corrections and discussion on weak points during the peer-reviewing stage, which is always carried out by two specialists in the field of the topic, while most journals with impact factor simply use their own reviewers, who do not know a thing about ancient metallurgy. The result is that the papers published in some journals are often less than mediocre.

We hope that the next volumes of this series will collect a larger number of papers presented at the conference, and we will be able to demonstrate once again that the frame within which archaeology can be studied is - and will be in the future - greatly enhanced by archaeometallurgical research.

We are very grateful to all reviewers and especially to the English native speakers who took the time to check the language of the papers in this volume.

To all of you a heartfelt thank you!

The editors

## **Previous Standing Committee of the AiE:**

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Susan LA NIECE (UK)  
Barbara ARMBRUSTER (France)  
Vasiliki KASSIANIDOU (Cyprus)

At the meeting of the Standing Committee that took place during the conference, Béla TÖRÖK (Hungary), Jiří HOŠEK (Czech Republic) and Miljana RADIVOJEVIĆ (UK) were nominated for membership of the Standing Committee and accepted, and an Advisory Committee without voting right was established.

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Miskolc City Transportation Company  
and

The Historical Metallurgy Society

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# **Multivariate statistical study of lead isotopic data: proposal of a protocol for provenance determination**

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## **Abstract**

Provenance studies using lead isotopes have two main limitations: the effects of overlaps (some mining regions have signatures that are too close to one another to be clearly discerned) and the difficulty of identifying whether an artifact is derived from a mixture of ores from different sources. These limitations are related to the fact that two-dimensional observation does not allow the full extent of variation in isotope ratios to be observed. This work presents a multivariate statistical treatment: the application of a AHC (Agglomerative Hierarchical Clustering analysis) using the 5 isotope ratios commonly used by archaeologists and geologists.

This statistical treatment was tested on two case studies, selected because the origins of the artifacts are well known. It is a question of testing that the statistical treatment creates classes consistent with the contexts of mineralization and links the artifacts to an expected origin (nearby mines in the case of protohistoric copper slags from the Alps, Cypriot rather than Sardinian mining areas in the case of oxhide ingots).

In each case, the clustering creates statistical classes corresponding to the mineralized units. The observation of subclasses allows precision at the mining district scale in the case of the Alps but also erases the effects of overlaps between Cyprus and Sardinia. Artefacts that cannot be assigned to a statistical class are potentially derived from a mining zone not included in the database or from mixture of sources. However, in order to confirm this, it seems essential to build a database of the isotopic signatures of the main European copper deposits.



# Multivariate statistical study of lead isotopic data: proposal of a protocol for provenance determination

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## **Introduction: Studies of provenance, limitations of two- and three-dimensional approaches**

The number of lead isotope analyses is increasing considerably but, despite this, as mentioned by Artioli et al. (2020) no methodological approaches currently allow an efficient interpretation of the origins.

However, the methodologies used in provenance studies have evolved considerably since the 1980s. Archaeologists first compared the signatures of minerals and artifacts by simple binary reading on two separate graphs:  $^{208}\text{Pb}/^{206}\text{Pb}$  vs  $^{207}\text{Pb}/^{206}\text{Pb}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  vs  $^{207}\text{Pb}/^{206}\text{Pb}$  (Stos-Gale and Gale 2009). It was not before the early 1990s that this graphical reading was made easier by the drawing of 95%

confidence ellipsoids underlining the signature of the various mining districts.

During the 2000s, these ellipsoids are beginning to be plotted using the Euclidean distance, which is statistically more accurate. At the same time Baxter (1999) had the idea of applying Kernel densities to sharpen the contours and test whether different normal populations could be extracted in the mining districts. However, this idea was not conclusive: the regional variations were too complex to show using this method.

Research work initiated since the middle of 2010 by the Padua laboratory team proposes source tracing work in which Euclidean distances are plotted in 3D (Artioli et al. 2014) which makes it possible to appreciate the variations of 3 ratios on the same graph.

Even more recently, the use of Th/U/Pb relationships, model age and a AHC (Agglomerative Hierarchical Cluster) to create consistent statistical groupings of ore deposit has recently been proposed by Albarède et al. (2020) in the case of the Aegean rim.

Multidimensional models could therefore greatly improve the interpretation of lead isotopic provenance studies. The latter being, in spite of several decades of existence, even today still essentially limited to graphic interpretations, involving a degree of subjectivity in the interpretation of the proximity of samples. Thus, provenance studies using lead isotopes are sometimes unable to make a clear-cut decision on certain origins and therefore currently has two main limitations (Baron and Coustures 2018):

(i) The difficulty of distinguishing regions with very similar signatures. This phenomenon is regularly referred to as signature overlaps. In this case, it is impossible to precisely define the origin of an artifact: two or more possible regions of origin are then proposed. Graphic reading so limits the number of comparison data used (a selection of mining regions incremented in the graphs is made, otherwise the graph becomes unreadable).

(ii) The complexity of determining whether or not an artifact's signature corresponds to a mixture of minerals (which can occur at different stages of an object's conception: from the manufacture of the ingot to the recycling of old objects to shape new ones). To resolve this issue, recent studies (still in their inception

stages) also propose statistical treatments: Longman et al. (2018) and Bray and Pollard (2012).

The aim of this study is to test a methodology based on a multidimensional statistical analysis, in order to try to reduce if not eliminate these problems of subjectivity and overlaps and to highlight cases of potential source mixing. This method uses all five commonly used lead isotope ratios, treated via AHC (Agglomerative Hierarchical Cluster).

In order to test the proposed statistical model, we wanted to test the provenance of reduction slags from the Neolithic and Bronze Age. This choice is motivated by the fact that the slags have, at this period, an assumed local origin. Indeed, as developed by O'Brien, 2015 (229-233) in the Neolithic as well as in the Bronze Age, pyrometallurgical activity (smelting and not melting) is commonly carried out in the immediate vicinity of mines: ranging from only a few metres to a maximum distance of 10 km (the most common distance seems to be of the order of 1 to 2 km). Slag is often used as ore data for isotope studies, as its origin is assumed to be local (Sayre et al. 1992; Begemann et al. 2003; Ling et al. 2019; or also the Oxalid database (in which, for example Skouries/A. Ioannis slag heap is classified in the ore category)). This fact is debatable because slag can be the result of mixtures of minerals from different mines but also because its signature can be affected by the addition of a possible flux. We will therefore consider them as semi-finished products, whose source ore is theoretically located at a short distance from the workshop where the reduction slag was smelted. Slags are therefore of particular interest because, while their source can be assumed, a possible mixture of sources from several local deposits cannot be ruled out.

We selected a study area in view of the large amount of published isotope signature data for both ores and slags: the Neolithic and Bronze Age reduction slags of the Italian Alps. The lead isotope ratios of the slag are compared with the signatures of the entire Alps. The slag-based case study allows us to determine whether ore deposits with isotopic signatures that are theoretically close because they are of the same age (but of different metallogeny) can be isolated statistically. The fineness of statistical

divisions and the affiliations of slag to ore deposits statistical groups will be tested.

A second case study will be presented. It concerns the origin of the oxhide ingots found in Sardinia whose Cypriot origin can be questioned. Here it is a subject of testing the effect of signature overlaps. The lead isotopic signature from the mines in Sardinia and Cyprus are considered to be very close. Our aim is then to define whether an AHC can differentiate the ores of the two islands.

## Methodology: details of statistical processing

### Isotope ratios considered

There are 4 lead isotopes:  $^{204}\text{Pb}$  is a non-radiogenic isotope which has a low relative abundance (1.4%) (and which measurement can interfere with the measurement of  $^{204}\text{Hg}$ ) hence the fact, as previously mentioned, that historically, archaeological provenance studies use ratios that are therefore not normalized to  $^{204}\text{Pb}$  but to  $^{206}\text{Pb}$ .

There are three other lead isotopes (which are radiogenic) resulting from the decay of uranium:  $^{206}\text{Pb}$  and  $^{207}\text{Pb}$  (resulting from the disintegration of the  $^{238}\text{U}$  and  $^{235}\text{U}$  respectively) and  $^{208}\text{Pb}$  from the decay of  $^{232}\text{Th}$  (a chemical element that behaves differently from uranium). The quantity of thorium varies greatly from one rock to another: the physico-chemical behaviour of thorium is complex. Thorium is therefore used to distinguish metallogenic contexts. Thus, lead isotopes do not just

measure a deposit closure age via lead isotopy (it is possible to calculate the age of mineralization via lead isotopes, let us quote Stacey and Kramers (1975) or Cumming and Richards (1975)) they also provide with  $^{208}\text{Pb}$ , information about the geological contexts of formation (Faure 1986; Marcoux 1986).

Lead isotopes are used in the form of isotope ratios. Of the 6 possible ratios are used in provenance studies:  $^{208}\text{Pb}/^{206}\text{Pb}$ ,  $^{207}\text{Pb}/^{206}\text{Pb}$ ,  $^{206}\text{Pb}/^{204}\text{Pb}$  (most classically used in archaeology) but also  $^{208}\text{Pb}/^{204}\text{Pb}$ , and  $^{207}\text{Pb}/^{204}\text{Pb}$  (mainly used in studies conducted by geologists, although archaeologists are increasingly beginning to use ratios standardized on  $^{204}\text{Pb}$ ). Also, both  $^{207}\text{Pb}$  and  $^{208}\text{Pb}$  resulting from the decay of uranium, their ratio is of little interest. Moreover, the statistical tests we were able to conduct (Pearson coefficient and positioning in a circle of correlations) show that this ratio behaves almost identically to the normalized ratios on the  $^{206}\text{Pb}$ . This very similar behaviour may justify its non-use.

The choice of the use of the different isotope ratios can be statistically questioned. Considering the set of lead isotope signature data on ores available in the Oxalid database (Stos-Gale and Gale 2009) (more than 1,500 signatures), the calculation of Pearson's correlation coefficients (allowing to investigate the relationship between quantitative variables) emphasizes that normalization to  $^{204}\text{Pb}$  is more discriminating (Tab. 1).

	Variables	$^{208}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	
	$^{208}\text{Pb}/^{206}\text{Pb}$	1	0.944	-0.904	-0.106	-0.523	ARCHAEOLOGICAL RATIOS
	$^{207}\text{Pb}/^{206}\text{Pb}$	0.944	1	-0.975	-0.200	-0.697	
GEOLOGICAL RATIOS	$^{206}\text{Pb}/^{204}\text{Pb}$	-0.904	-0.975	1	0.390	0.778	
	$^{207}\text{Pb}/^{204}\text{Pb}$	-0.106	-0.200	0.390	1	0.685	
	$^{208}\text{Pb}/^{204}\text{Pb}$	-0.523	-0.697	0.778	0.685	1	

Table 1: Pearson correlation coefficients for the whole Oxalid database: the normalized isotope ratios over  $^{204}\text{Pb}$  have a value closer to zero: they are more discriminating. The closest value to independence at  $^{206}\text{Pb}/^{204}\text{Pb}$  is  $^{207}\text{Pb}/^{204}\text{Pb}$ .

Nevertheless, the ratios normalized on  $^{206}\text{Pb}$  do not have a Pearson correlation coefficient of 1, so they will still contribute to a multivariate statistical treatment based on Pearson correlation coefficients: they will add additional precision to it. Thus, rather than running a statistical model on the 3 most discriminating ratios, we have chosen to use each of the 5 ratios.

We therefore propose a very simple idea: to take into account all 5 commonly used lead isotope ratios and to apply a multivariate statistical treatment to them: an AHC.

### **Creation of population groups: use of an AHC**

We have chosen to use statistical processing by AHC (Agglomerative Hierarchical Classification). AHC partitions the data by separating them into different classes. These classes can be based on the similarity or dissimilarity of the samples. The created classes are then partitioned into subclasses. These successive groupings produce a binary classification tree called a dendrogram. A partition is considered good when individuals of the same class are close (low intra-class variability) and when individuals of 2 different classes are far apart (high inter-class variability).

The signatures have been classified according to their similarity. We parameterize the AHC with a Pearson correlation coefficient index of similarity and a mean link type aggregation. We used an automatic truncation according to a principle of maximum inertia. AHC can be performed directly on isotope ratios. However, due to the large amount of data processed, we recommend to first normalize the data, then perform a Component Analysis on the normalized data and then perform AHC on the coordinates of the Component Analysis. The results of the AHC obtained with or without the Component Analysis are nevertheless very close.

The classes provided by clustering thus correspond here to a division based solely on lead isotopic signatures similarities: ores with close isotopic signatures are grouped together in the same statistical class.

The use of AHC avoids the need to consider possible outliers: these are isolated in unique classes and do not disturb the model. Moreover, the similarity thresholds are directly readable on the dendrogram, which allows a look at the quality of the statistical groupings, i.e. the groups of provenance created.

Nevertheless, the ability of AHC to create groupings with similar values requires caution when tracing sources: if new ore data is added, the classes may vary somewhat. This is true for ores, but also for objects: if all slags from the same site are injected into the model, they may all be distributed in the same statistical (sub)class consisting only of slags. The origins are therefore tested one by one to avoid this phenomenon. The class and, above all, the subclass in which the artifact is inserted then allows us to define its origin.

### **Case studies: contribution and limitations of the proposed model to source tracking studies**

#### **Copper slags from the Neolithic and Bronze Age of the Italian Alps - ability to distinguish between large ore bodies?**

This study area was selected because there is an extensive bibliography of mineral signature data for the Alps and Tuscany. In addition, these data relate mainly to copper deposits, which is not the case in many other regions where the analyses concern deposits where copper is not in the predominant metal compared to lead. Moreover, the geological contexts and copper deposits are generally very well described in the various source publications used. 27 slag signatures (which we have numbered from 1 to 27) were thus compared with 389 isotopic signatures from ores, corresponding to all the data collected in the Alps (Fig. 1).

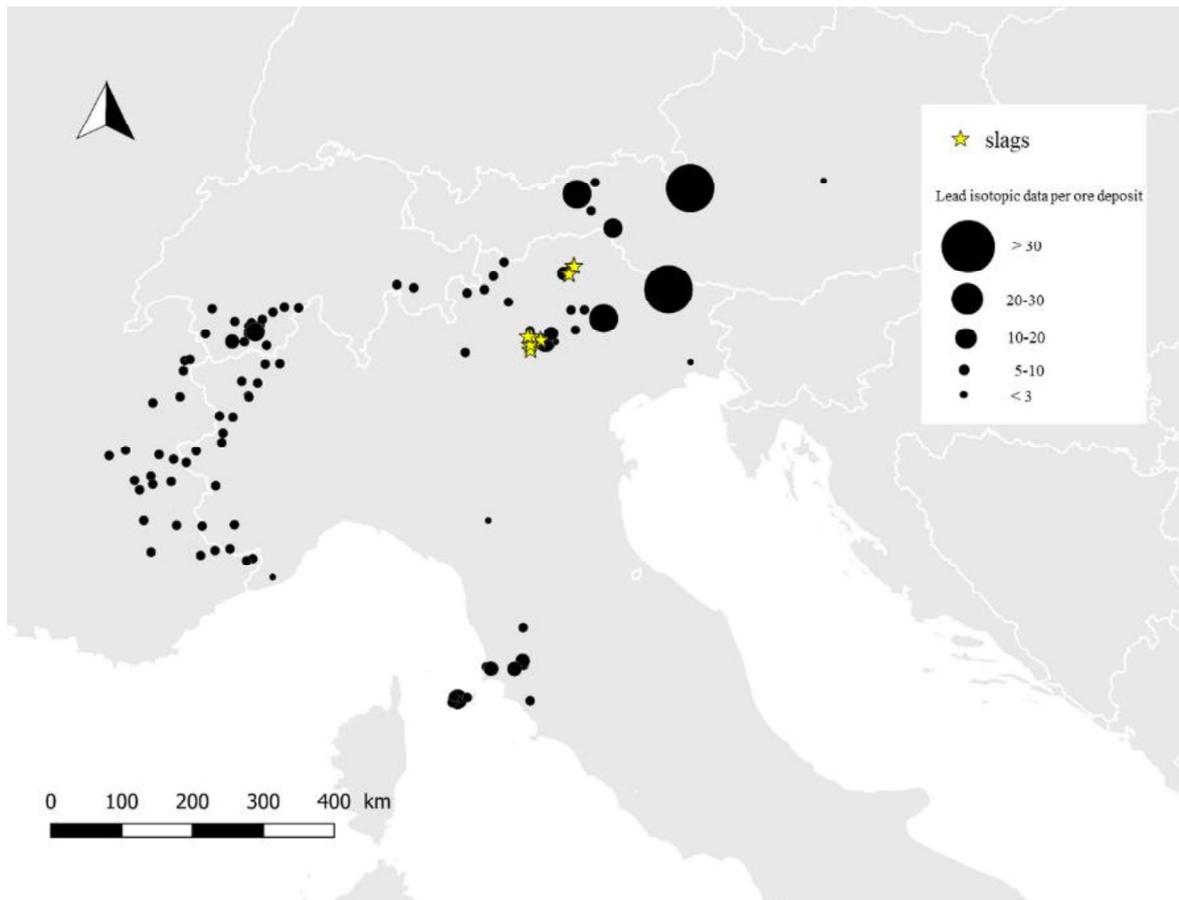


Fig. 1: Location map: in black lead isotopic analyses carried out on ores, stars: reduction slag whose origin is being sought to be defined.

The source data used is for slag: Addis 2013; Artioli et al. 2015 and for ore deposits: Oxalid database; Marcoux 1986; Cattin 2008; Chiarantini et al. 2018; Giunti 2011; Nimis et al. 2012; Artioli et al. 2016; Pernicka et al. 2016.

By observing the correlation circle of the Component Analysis, it is possible to visualize the contribution of each ratio to the statistical model (Fig. 2). The correlation circle has the same aspect as the general structure (Tab. 1).  $^{206}\text{Pb}/^{204}\text{Pb}$  and  $^{207}\text{Pb}/^{204}\text{Pb}$  have a correlation close to independence.  $^{206}\text{Pb}/^{204}\text{Pb}$  is strongly anti-correlated with the ratios normalized on  $^{206}\text{Pb}$ , which corresponds to a very open angle. The ratios normalized on  $^{206}\text{Pb}$  are then the extremes of the model. Between these extremes forming the main opposition, the archaeological information lies in the position of the variables in relation to each other either:

- the close association of the ratios  $^{208}\text{Pb}/^{206}\text{Pb}$  and  $^{207}\text{Pb}/^{206}\text{Pb}$  corresponds to a closed angle, i.e. to high cosine values and therefore high correlation coefficients;

- the less marked association of the ratios  $^{208}\text{Pb}/^{204}\text{Pb}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$ , which is nevertheless opposed to the pole of the two ratios normalized on  $^{206}\text{Pb}$ ;

- finally, the relative indifference of the  $^{207}\text{Pb}/^{204}\text{Pb}$  ratio to the main opposition, in weak correlation, close to independence, with the extremes,  $^{206}\text{Pb}/^{204}\text{Pb}$  in particular.

This perception of the system of oppositions and associations integrating all the variables provides an overall view and nuances that are more difficult to obtain by examining the variables two by two using a simple bivariate correlation coefficient.

The archaeological information therefore lies in the fine variations in the position of the variables in relation to each other (and not in the two-by-two relations). Precision depends on a few points of correlation coefficient (i.e. a few angular degrees in Component Analysis). Correlations must therefore necessarily be multiple.

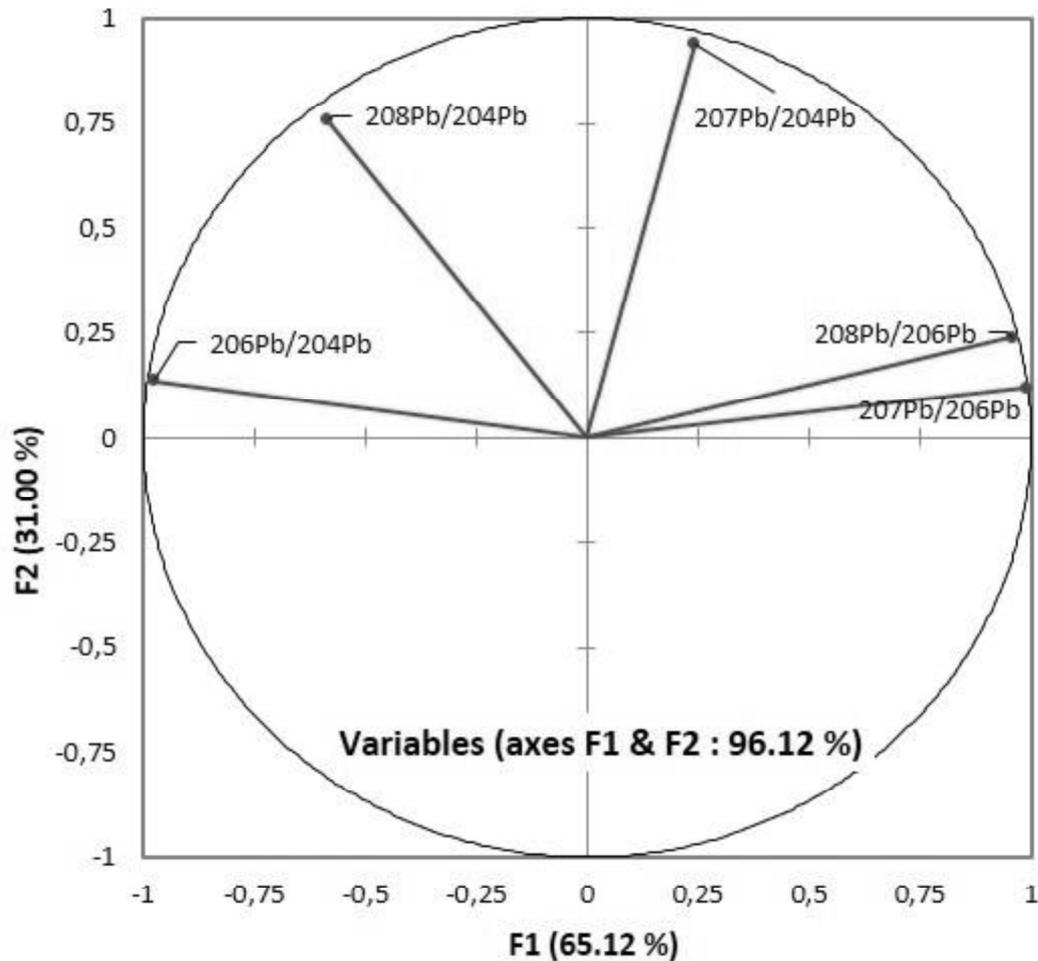


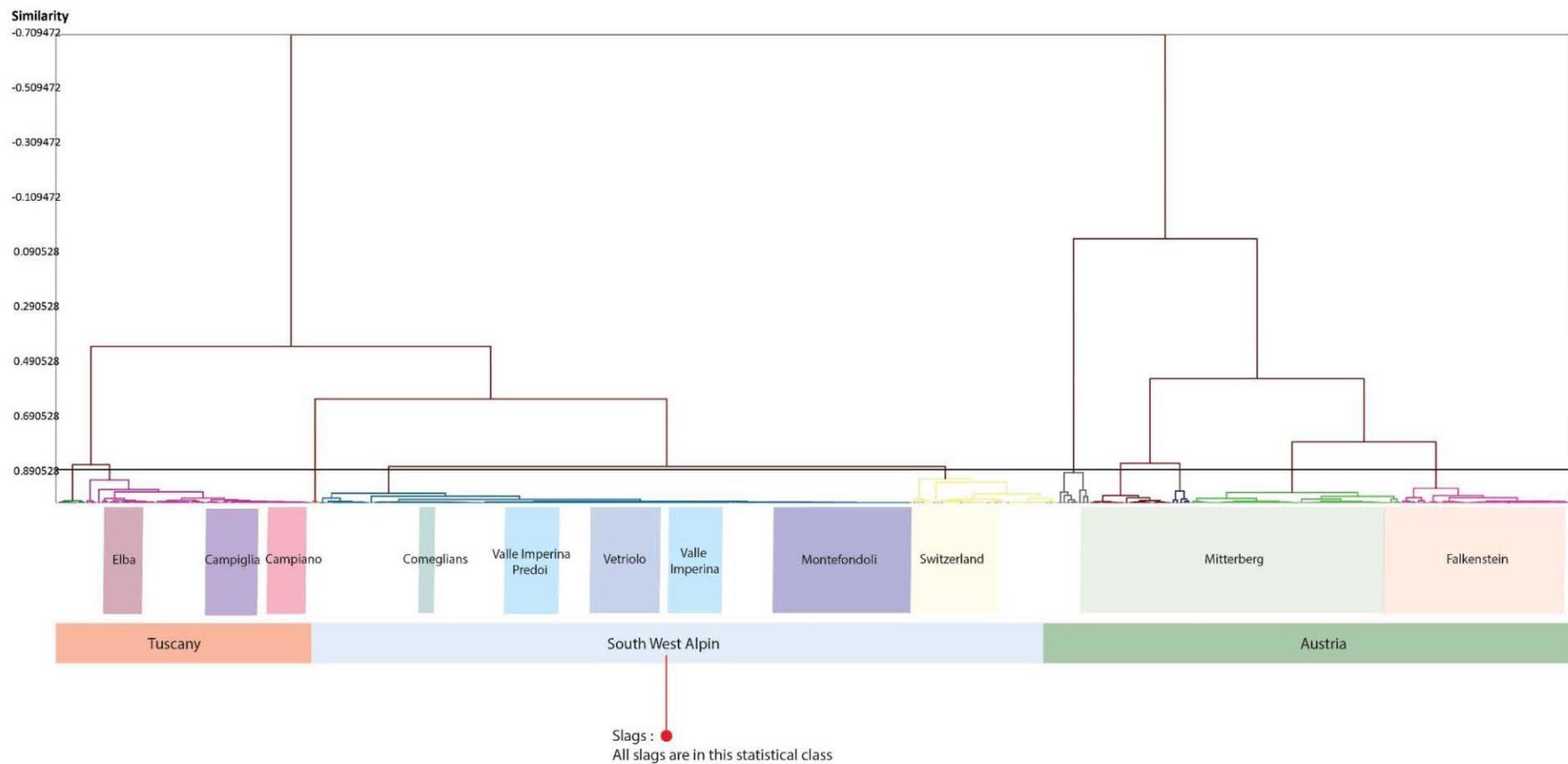
Fig. 2: Circle of correlations obtained from the Component Analysis performed on all 389 lead isotopic signatures collected in the scientific literature for the Alps and Tuscany.

AHC allows a perspective on different scales. First of all, it can be seen that the Western Alps are statistically very clearly separated from the Eastern Alps (Austrian Tyrol) and Tuscany: each region is individualized in large statistical classes. All the slags show signatures corresponding to the Western Alps (Fig. 3). This first result is consistent with the location of the reduction sites.

A second clustering can then be carried out on this large class corresponding to the Western Alps in order to specify the allocations of the different copper slags. Most slags have clear affiliations and can be linked to large mining areas. A precision on the scale of the type of deposit but also on the scale of the mining district is then possible (Fig. 4). Nevertheless, in the case of 4 of them (slags 2, 6, 22 and 23) only

the type of deposit can be clearly defined (VMS (Volcanogenic massive sulfide) for slag 6, AATV (Alto Adige, Trentino, Veneto) for the others). If one considers that the local repository is sufficiently well documented and that all the variability of the isotopic signatures of the deposits is referenced in the source database, these slags could be interpreted as coming from mixtures of sources. Indeed, they are isolated in poorly defined subclasses.

Finally, as previously mentioned, the dendrogram resulting from the AHC reveals similarity thresholds between the different constituents of the same class. It is thus possible to judge the precision of the slag allocations in the different statistical classes and subclasses of the AHC (Fig. 5).



**Fig. 3: Dendrogram obtained for the whole of the Alps.**  
 For details, the readers can look at the file under the link : <https://halshs.archives-ouvertes.fr/view/index/docid/3192963>

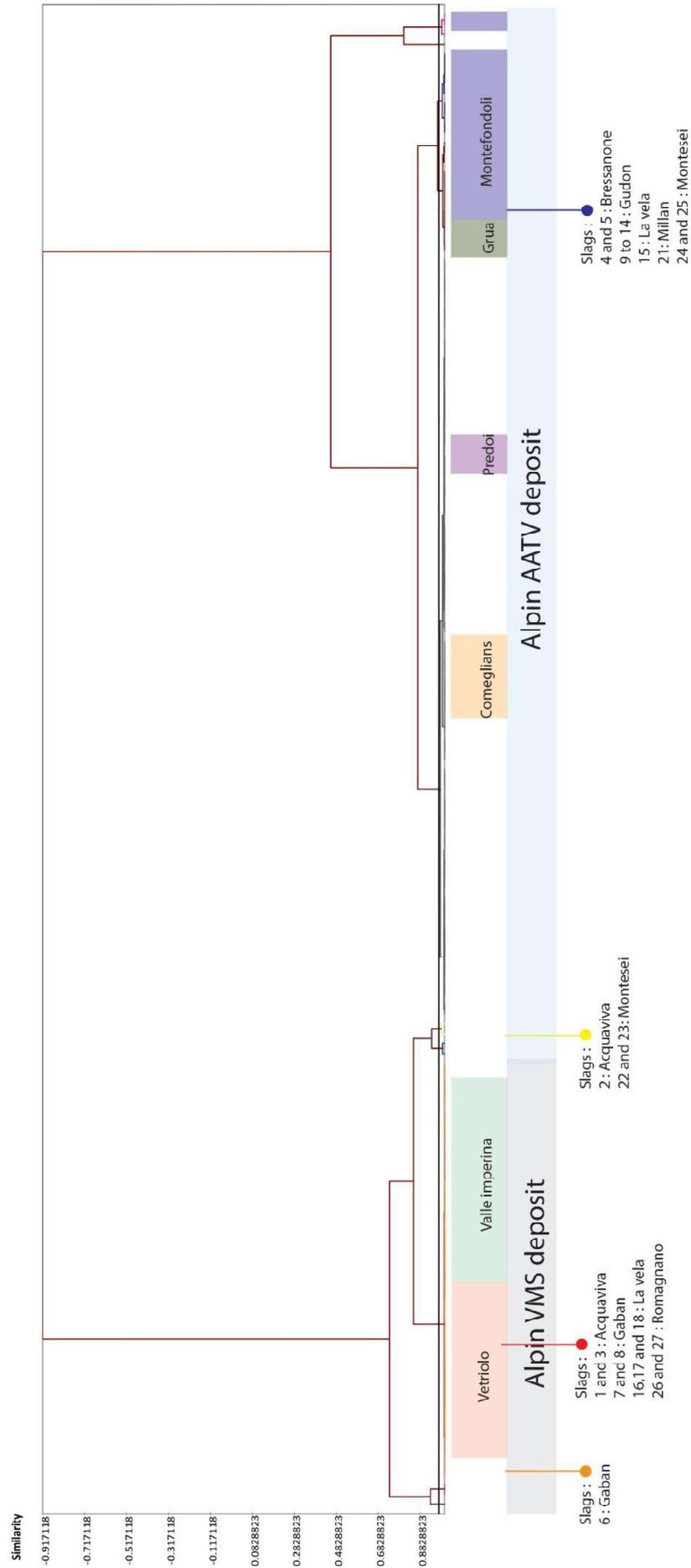


Fig. 4: Dendrogram resulting of the AHC carried out in the Western Alps.  
 For details, the readers can look at the file under the link : <https://halshs.archives-ouvertes.fr/view/index/docid/3192963>

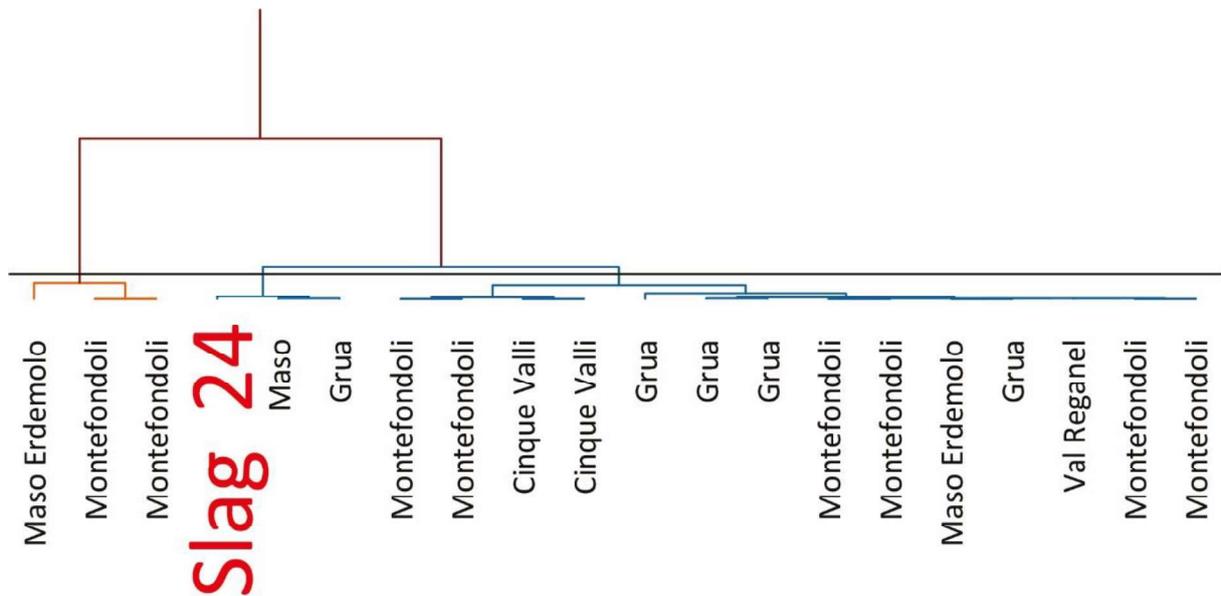


Fig. 5: Example of slag number 24: 97% similarity with the class and 99.5% similarity with the subclass.

In this first case study, the statistical classes and sub-classes proposed by the clustering prove to be perfectly consistent with the archaeological and geological contexts: the slags are affiliated to nearby copper mines. A precision on the scale of the mining district appears possible. Indeed, even for the slags, whose origin remains unclear because several sources of production seem to be possible, the possible mines are concentrated in restricted areas around the workshops (Fig. 6):

possible sources of slag 22, poorly defined by AHC).

The results are much more accurate than conventional provenance tracing methods (by binary reading and Euclidean distances in two- or three-dimensional approaches): a much wider range of potential source mines is obtained using AHC (Fig. 6).

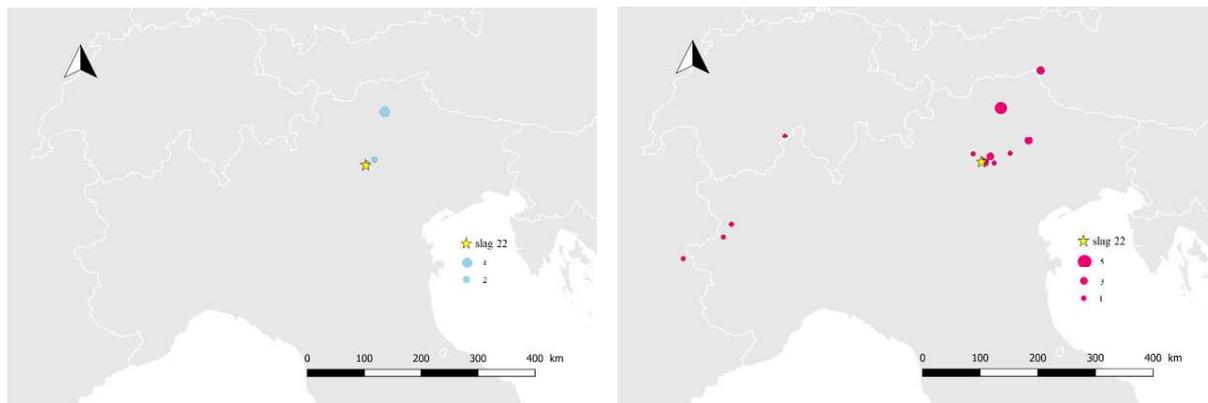


Fig. 6: Possible sources for slag 22 from Montesei obtained: on the left (in blue) via the multivariate statistical treatment presented and on the right (in red) by Euclidean distances.

### Oxhide ingots from Sardinia/Cyprus – signature overlaps

The results obtained from the study of slag indicate that AHC allows the isotope signatures of ores to be separated with great precision. Geological contexts and more, mines are

becoming individualized. We therefore wanted to test whether the proposed statistical processing method can reduce the signature overlap effects observed in the case of binary diagrams. For this purpose, we tested, in this second case study, the origin of oxhide ingots found in Sardinia (dated from the Bronze Age).

The production of oxhide ingots is proven in Cyprus but many such ingots have been discovered in Sardinia and the island has copper deposits. The question of the origin of these ingots was then widely debated (Stos-Gale et al. 1997; Kassianidou 2001; Pinarelli 2004; Stos-Gale 2011; Kassianidou 2013). This difficulty in obtaining a clear result is linked to the fact that Cyprus and Sardinia present a significant overlap in the isotopic signatures of the ores, making it impossible, by graphic reading, to clearly determine the origin of these ingots. Budd et al. (1995) describe this overlap as impossible to overcome with two-dimensional diagrams.

We therefore compared 124 signatures of oxhide ingots found in Sardinia (from Oxalid database) to 265 signatures of minerals from Cyprus and 250 signatures of minerals from Sardinia (also from Oxalid database). Other analyses of ingots were carried out by Lo Schiavo et al. (2009), Begemann et al. (2001) and Montero Ruiz et al. (2018) but were not used in this work.

The circle of correlations derived from the Component Analysis also shows here a significant contribution of taking into account the ratios normalised on  $^{204}\text{Pb}$  and  $^{206}\text{Pb}$ . Here again, the precision of the statistical model is based on few angular degrees (Fig. 7).

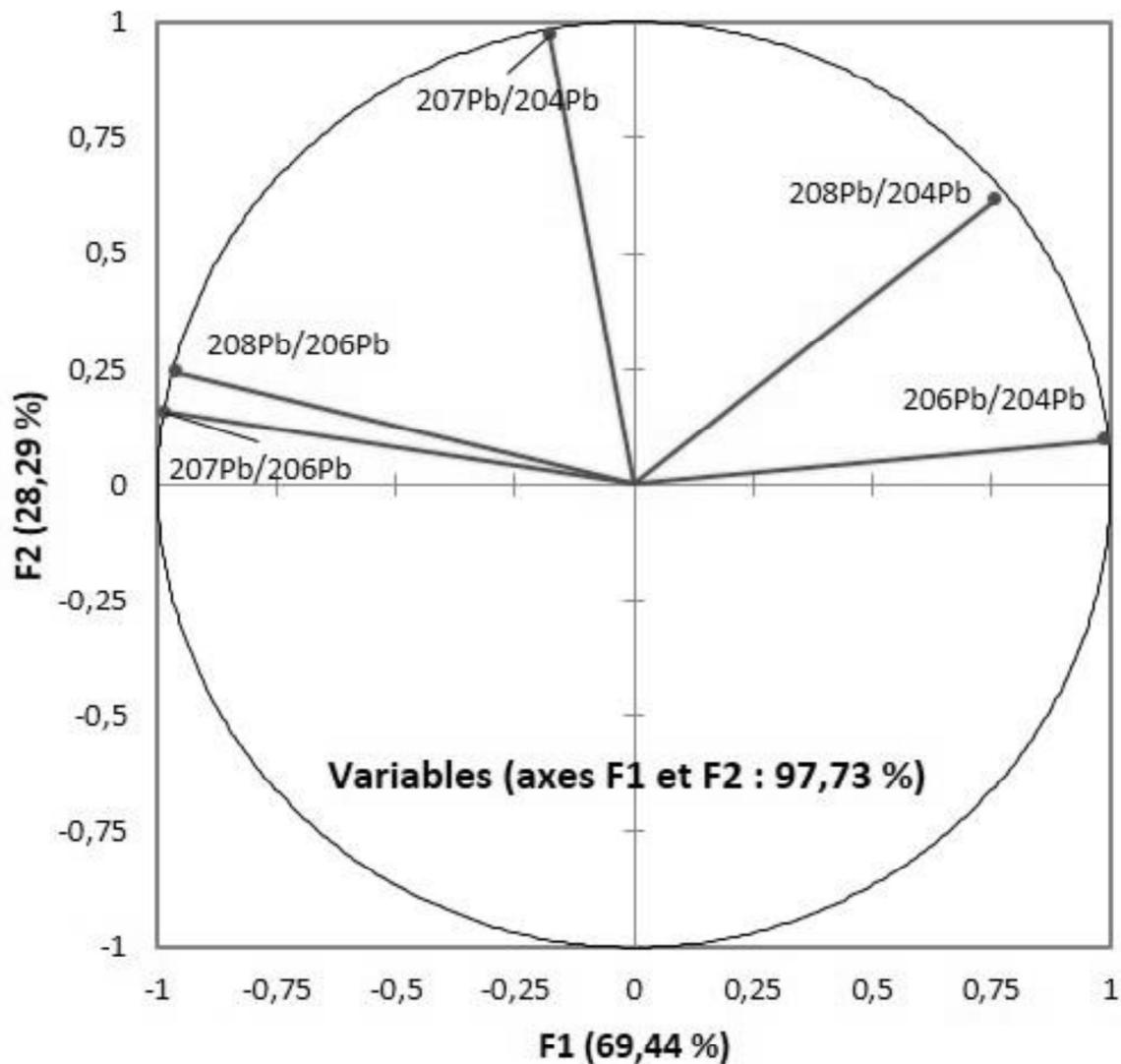


Fig. 7: Circle of correlations obtained for the Component Analysis performed on all 515 isotopic signatures from the Oxalid database for Cyprus and Sardinia.

If this is not the case by reading binary graphs, in AHC, the Cypriot and Sardinian deposits are perfectly individualized. The different Cypriot copper districts are also individualized (Fig. 8). In addition, no geological context is specified in the Oxalid database, but the clustering allows the Sardinian deposits to be divided into three main distinct classes (which can be subdivided into subclasses).

It would then be more than interesting to check, mine by mine, whether the divisions of the AHC correspond to a geological reality but, without precise details concerning the sampled zone, it is impossible to carry out this work.

The AHC establish that the vast majority of the ingots here are clearly of Cypriot origin and, more precisely, from the districts of Solea and Larnaca. 4 of the ingots could be of Sardinian origin but one of them is isolated in a subclass (on the left of the graph): it does not correspond to any analysed deposit. This lack of similarity can be interpreted in two ways: the artifact was made from copper from different ore deposits (mixture of sources) or, the source of the ore used is not given in the database (it could come from other sources including the Middle East).

This result is relevant, however, it underlines that the search for a place of production must take into account as many copper-bearing regions as possible. It therefore seems essential to build up a solid database of lead isotope analyses carried out on ores on a European scale (including the analysis of ores from known production sites). Only once the most complete sampling possible has been obtained will it be possible to say that an artifact not affiliated with any region could be from a mixture of sources (not very problematic in the case of semi-finished products, that are potentially few subject to mixing of sources, but that may not be the case for finished products).

The application of a multivariate statistical treatment for provenance studies therefore seems promising. However, it will have to be supported by a database of all major European (or even Western Asia/Middle East depending on the study area) copper mineralization.

## Conclusion

By taking into account five isotope ratios and not three, it is possible to propose precise statistical models using multivariate statistics, in this case an AHC.

The statistical discrimination is consistent with the geological data: in the case of databases for which information on the type of deposit is available, each type of deposit is individualized in a statistical class. Mines also tend to isolate themselves into subclasses (if no geological information is available, it is unfortunately not possible to take a critical approach of the created groups).

The limitations mentioned for tracing production sources can be circumvented through the use of AHC. In the case of Sardinian and Cypriot deposits, the effects of overlaps observed with just 3 isotope ratios taken into account are erased. Objects that stand alone in subclasses or are associated with heterogeneous classes can come from mixtures of sources or from mines not referenced in the database used for the model.

Thus, the proposed statistical treatment appears to be precise and consistent in the study of the origin of semi-finished products (in the case of the Alps, all slag is assigned to mines close to the workshops, ingots are correctly assigned to Cyprus even though 3 of them could be Sardinian). Finally, in contrast to a simple graphical reading, it is possible to estimate the accuracy of the assignments via the intra-class and intra-sub-class similarity thresholds.

If this is a statistical processing trial, the results appear promising and application to finished products seems possible within large regions but also on a larger scale. It is a possible solution to reduce the effects of signature overlaps present in binary diagrams.

Multivariate statistical processing can also efficiently identify artifacts whose signatures do not correlate with any mining areas. Moreover, it seems essential to check that most of the copper-bearing zones of the studied area have been analysed by lead isotopy. Otherwise, artifacts that do not show a clear assignment will remain in this vagueness: are they from a mixture of sources or from an area not included in the database?

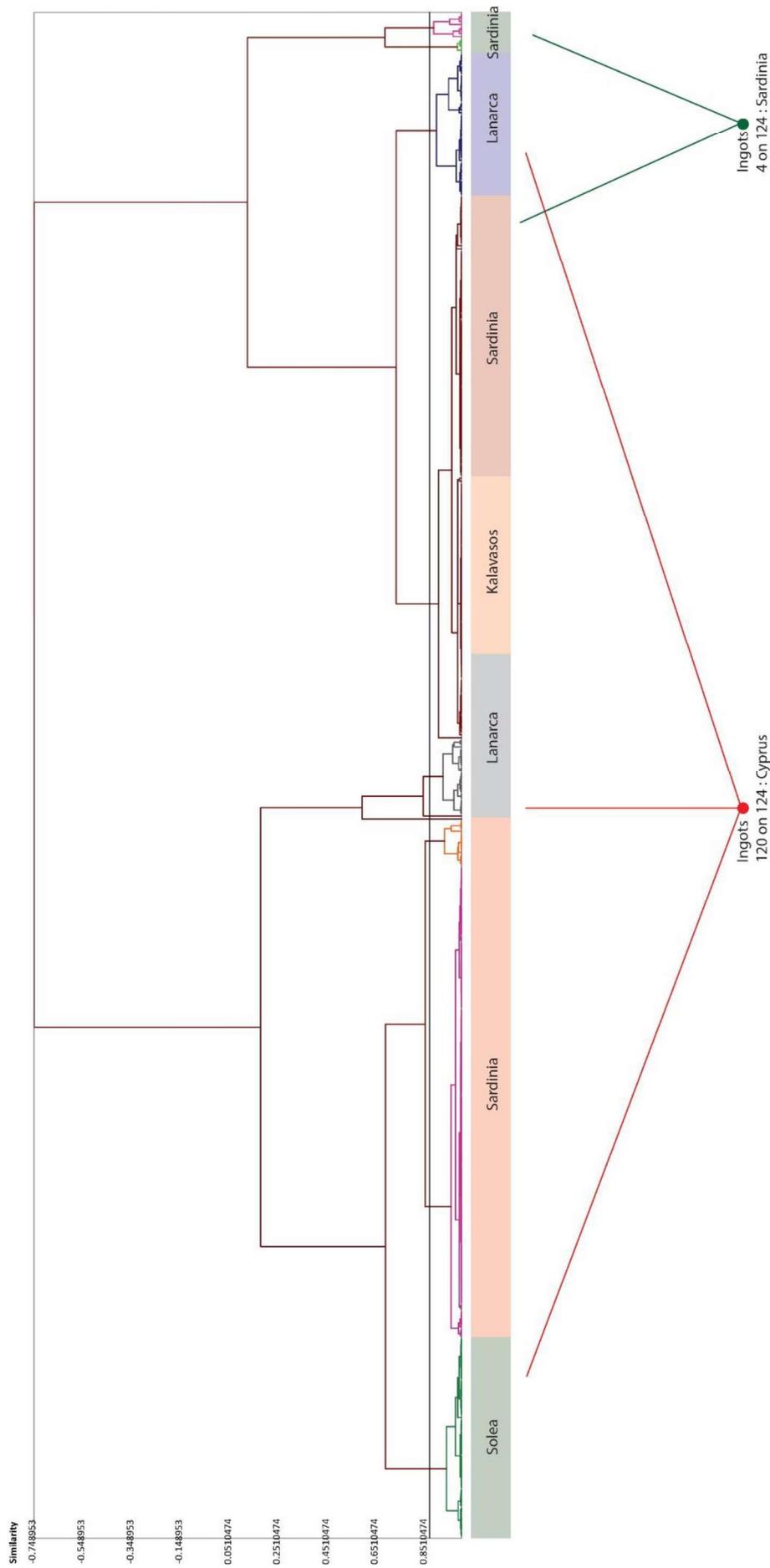


Fig. 8: Dendrogram obtained from AHC and allocation of oxide ingots found in Sardinia.  
 For details, the readers can look at the file under the link : <https://halshs.archives-ouvertes.fr/view/index/docid/3192963>

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