



UNIVERSITAT^{DE}
BARCELONA



**MÀSTER D'ESTUDIS
AVANÇATS EN ARQUEOLOGIA**
UNIVERSITAT DE BARCELONA

**A MATERIAL CHARACTERIZATION OF IBERIAN, PUNIC, AND ROMAN
AMPHORAE FROM THE DEPOSITS OF THE IBERIAN TOWN OF
KISSA/CASSIS (VILAR DE VALLS, TARRAGONA)**

Final Master's Thesis 2026

Advisors: Jaume Buxeda i Garrigós, Judith Peix i Visiedo

Berta Soler i Gumà

Màster d'Estudis Avançats en Arqueologia

Abstract

The 29 ceramic amphorae, studied in this project were recovered in the Iberian settlement of Vilar in Valls, Tarragonés, Catalonia, Spain. These ceramics, dated to the late 3rd century BCE, belong to a historical period related to interactions between Iberian, Roman, and Carthaginian peoples, and the eventual emergence of the Second Punic War (218 BCE). This research aims to better the understanding of trade at this time, by identifying the provenance of these ceramics as well as traces of manufacturing techniques such as estimated firing temperatures (EFT). For this purpose, the reconstructed amphorae have been digitalized, and samples chemically and mineralogically characterized by wavelength-dispersive X-ray fluorescence (WD-XRF) and Powder X-ray diffraction (PXRD), respectively, as well as observed under stereomicroscopy. Results confirm known distribution patterns of imported wares, and the evidence of similar technical traditions in different workshops. Finally, the contrast with the database enables us to relate some of the individuals analyzed in this study to some others from the same area, namely the workshop of Fontscaldes and workshops in Pontons, Alt Penedès.

Keywords

Provenance, WD-XRF, PXRD, Technology, EFT, Second Punic War, Iberian

Resum

Les 29 àmfors de ceràmica estudiades en aquest projecte es van recuperar al jaciment ibèric del Vilar, a Valls, Tarragonès, Catalunya, Espanya. Aquestes ceràmiques, datades a finals del segle III aC, pertanyen a un període històric relacionat amb les interaccions entre els pobles íbers, romans i cartaginesos, i l'eventual aparició de la Segona Guerra Púnica (218 aC). Aquesta investigació pretén millorar la comprensió del comerç en aquest moment, identificant la provinença d'aquestes ceràmiques, així com traces de tècniques de fabricació per estimar les temperatures de cocció equivalents (TCE). Per a aquest propòsit, les àmfors reconstruïdes s'han digitalitzat i les mostres s'han caracteritzat químicament i mineralògicament mitjançant fluorescència de raigs X de dispersió de longitud d'ona (WD-XRF) i difracció de raigs X en pols (PXRD), respectivament, així com estudiades sota estereomicroscòpia. Els resultats confirmen els patrons de distribució coneguts de les mercaderies importades i l'evidència de tradicions tècniques similars en diferents tallers. Finalment, el contrast amb la base de dades ens permet relacionar alguns dels individus analitzats en aquest estudi amb alguns altres de la zona, concretament el taller de Fontscaldes i els tallers de Pontons, a l'Alt Penedès.

Paraules Clau

Provenencia, WD-XRF, PXRD, Tecnologia, EFT, Segona Guerra Púnica, Iberic

Index

1. Introduction.....	1
2. Archaeological Context.....	2
3. Materials	7
4. Methods	9
4.1. Photogrammetric Digitalization.....	9
4.2. Stereomicroscopic Observations	11
4.3. Wavelength-Dispersive X-ray Fluorescence (WD-XRF).....	11
4.4. Powder X-ray Diffraction (PXRD)	13
5. Results.....	14
5.1. Photogrammetric Digitalization.....	14
5.2. Stereomicroscopic Observations	18
5.3. WD-XRF.....	25
5.4. PXRD.....	39
6. Discussion.....	54
6.1. Iberian.....	54
6.2. Punic.....	56
6.3. Greco – Italic.....	58
7. Conclusions	58
Bibliography	61
Annex	68

1. Introduction

The study is based on the reconstructed remains of twenty-nine amphorae that were recovered in a single deposit within the site at Villar de Valls (Alt Camp, Tarragona, Catalonia) by PROMAC, a unit within the GRACPE research group, at the University of Barcelona.

The archaeological context that has been deduced from other materials at the site, such as coinage, lines up with recorded battle at Kissa/Cassis in 218 BCE. It has been thought that the destruction found at the site was caused by the passing through of Hannibal's army on their way northward (Noguera and Menéndez, 2022). This is corroborated by the site's condition, as well as ballistic projectiles, ashes, and burnt beams the amphora sherds were mixed into. The site was most likely abandoned immediately after its destruction, and such the remains were left in situ until archaeological interventions were commenced. The team in the 2022 season revealed and reconstructed most of the amphorae to near completion. Most of the amphorae are of Iberian typology but also included a few examples of Greco-Italic and Punic wares as well. The project is intended to reveal further information on the provenance and use of these wares, as well as the context of the 'warehouse' they were found in.

The objective of this project is to further characterize the context and material makeup of the amphorae found at the site of Villar de Valls. Specifically, using archaeometric techniques, we will be able to learn about the pieces as well as compare the results to the previous understanding about the amphora throughout the ancient world in order to establish trade routes and understand the patterns of commerce between Vilar and contemporaneous sites. The goals we hope to achieve through these methods are as follows:

1. Maintain as much information (in terms of morphometry, texture, color, and fractures) as possible for further study once the objects themselves have been returned to the corresponding museum and destroyed for analytical purposes. To achieve this, digital 3D modelling using photogrammetry will be used.
2. Study the provenance of the amphorae in order to reconstruct patterns of

commerce throughout the Mediterranean in the late 3rd century BCE. This will be achieved using wavelength dispersive X-ray Fluorescence (WD-XRF) and comparisons with established chemical data.

3. Establish relationships between the data set, using chemical data as well as macroscopic techniques.

4. Study the technological process of firing the ceramics and define the equivalent firing temperature (EFT), allowing for insight into production, through powder X-ray Diffraction (PXRD).

5. Align results within the context of Iberian archaeology to better develop the current understanding of the site and specifically its role in commercial tradeways throughout northwestern Iberia prior to the Second Punic War (218 BCE).

2. Archaeological Context

First and foremost, this project is centered around the archaeological site of Vilar de Valls, the potential location of the Iberian town of Kissa/Cassis. This complex is located in the Catalan town of Valls (Alt Camp), 20 km north of Tarragona and 4 km south of the well-known Iberian ceramic workshop of Fontscaldes (Figure 1a) (Fabra i Salvat and Burguete, 1986). The site lies on an Upper Miocene formation of poorly rounded conglomerates, set in a red detritic matrix with red clay interlayers. These were formed due to a river system established, receiving intense sediment loads from a steep cliff to the southwest (Mont-roig-Reus) (Otina Hermoso and Vergès Bosch, 2004, pg. 6). Despite finds being spread out in various locations within Vall's, this project study will focus on a ceramic deposit found in 2022-2023 in the remains of the building found close to the railway and by warehouses (Figure 1b) (Noguera and Menéndez, 2022, 2023). As well as the Iberian remains such as this, Valls is also home to the ruins of a Roman fort and a Carthaginian camp, which will play an important role in contextualizing the material recovered and the dating of the town's destruction later.

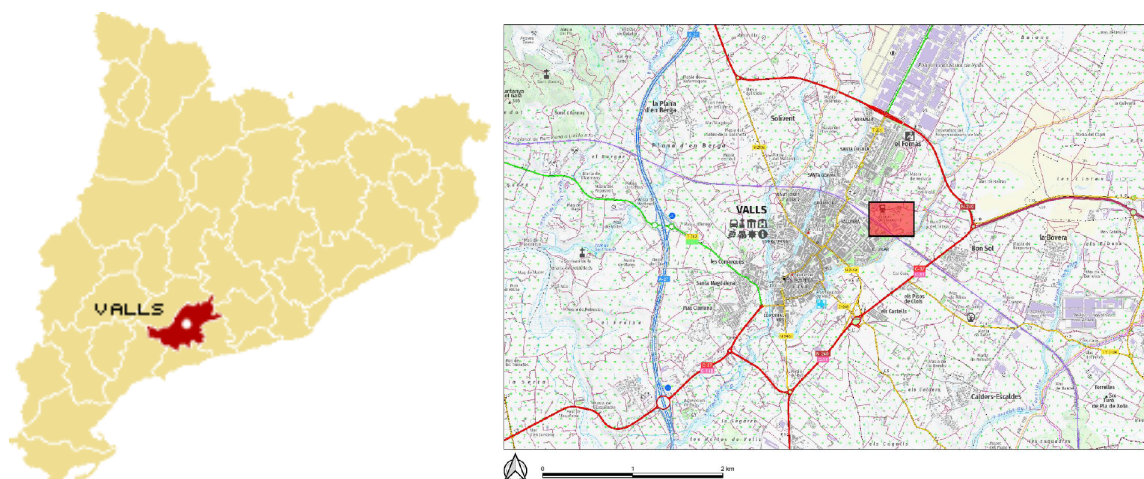


Figure 1. a) Location of Valls within Catalunya, Spain (Valls, n.d.). b) Location of site within Valls (Noguera and Menéndez, 2022, 2023)

The Iberians were one of the various populations that occupied the Iberian Peninsula beginning around the second half of the 6th c BCE, and whose various periods lasted until the turn of the millennium. As explained by Santacana (2005a), the first, Early Iberian Period, is dated approximately from 550–400 BCE, and is characterized by a lower number of sites, the appearance of widespread related language and an increase in thrown ceramics. The High Period from 400–200 BCE shows the formation of more formal States and a large demographic growth through urban centers becoming larger and more numerous, as well as indicating increased grain storage capabilities. The last period is based around the Roman conquest following the Second Punic War in 218 BCE, and assimilation into Latin culture until about the year 25 BCE.

The Iberians, though considered a group of populations, stretching from Western Andalusia to southern France along the western Mediterranean coast, were divided into many communities, such as Cessetania, which was located in the modern states of Tarragona, Penedes, and Garraf, which encompasses the archaeological site of Vilar (Santacana, 2005b). This population, due to its contact with Phoenician trading, adopted technologies such as metallurgy, ceramic throwing, and wine making, and they were of the earliest Iberians to establish metal coinage just before 218 BCE (Belarte et al., 2024). The Second Punic War, the establishment and subsequent importance of the Roman port town of Tarraco (modern day Tarragona), and the

suppression of uprisings, resulted in the absorption and assimilation of nearby indigenous populations (Belarte et al., 2024).

Found and partially destroyed during construction first of the railway Vilanova - Valls in the late 19th c CE, and then of a municipal football field in the 1920s, there are many periods of the site's history that are lacking appropriate documentation (Fabra i Salvat and Burguete, 1986). Despite initial efforts by Josep Colomines and Josep de C. Serra Rafols from the Institute of Catalan Studies, to preserve the material, disinterest led to the cessation of official archaeological activity (Serra Rafols, 1930). Clandestine activity by locals during the following years attempted to keep the town alive, as construction and black-market activity continued to destroy the site.

Eventually, The Commission of Archaeology of the Institute of Vallenc Studies launched the resumption of archaeological intervention of the area in 1983, and excavations since then have allowed for the study of different aspects of the material culture of this site (Otiña Hermoso and Vergès Bosch, 2004). During these past 50 years, there have been continued efforts to excavate the site, resulting in the eventual discovery of the deposit studied in this project. Despite these efforts, the progress has been heavily dependent on the ongoing expansion and construction of the town, with finds such as those in 2008 and 2019 being possible only due to reforms to the nearby school and the demolition of warehouses (Noguera and Menéndez, 2022). Between the University of Barcelona and private companies like SOT Archaeological Prospection, finds in the last 10 years have reshaped our understanding of the site, and cemented our understanding of its chronology and destruction (Menéndez and Noguera, 2024).

Since 2021, the Research Group on the Archaeology of the Complexity and the Processes of social Evolution (GRACPE per its initials in Catalan) of the University of Barcelona, specifically the Protohistory, Ancient Mediterranean, and Colonizacions (PROMAC) team have spearheaded the efforts to excavate, describe, and analyze this site. They function under the project: "El canvi cultural a la Cessetània Oriental durant la Protohistòria i l'època romano republicana" (CLT009/18/00031).

The town boasted a potent defense system, including a moat whose excavated remains measure 14 m wide and 4 m deep. This moat presumably was hundreds of meters long, connecting the Catllar and Titit ravines that flank the town, which would shut out access from its northern end (Noguera, 2025). Alongside the moat, an 8 m thick defensive wall surrounded the settlement, constructed two stone layers, the exterior of which measured 1.20 m and the interior of which measured 0.80 m, which were filled with a 6 m thick layer of clay. This would give the wall a plasticity that would give the town strong defenses against projectiles from siege engines (Menéndez and Noguera, 2024). Within the town walls, alongside two cobbled streets measuring more than 5 m across, an area of simple connected warehouses and a neighborhood of large, complexly built houses were identified. As of 2023, three neighborhoods were identified, with a total area of 2500 m² (Menéndez and Noguera, 2024).

During the 2022 campaign, two of the warehouses directly alongside the outer defense wall were excavated. The intervention area included an area of 9.20 by 4.7 meters, of about a meter of stratigraphic potency, corresponding to zone 1 (Figure 2). These buildings were presumably destroyed by a fire, which had collapsed the adobe structure, as well as the reed and clay covered wooden ceiling (Noguera and Menéndez, 2022, 2023). The fire hardened much of the clay construction material, which completely covered the remains of up to 19 amphorae, most of which were Iberian in typology, but some of which were Italic and Punic (Noguera and Menéndez, 2022).

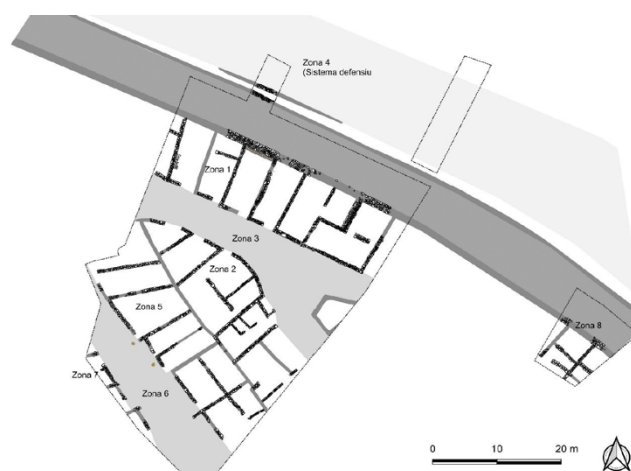


Figure 2. Archaeological map of the Intervention area. Zones marked, with Zone 1 in the northern area (Noguera and Menéndez 2022, 2023)

The 2023 campaign continued this intervention, revealing the remaining amphorae for this study, identified using diagnostic rim fragments and reconstruction as 23 of Iberian origin, as well as 2 Italic and 4 Punic. These amphorae were nearly all fragmented and mixed with layers of ash and burnt beams, but the incredible preservation, including an entirely whole specimen, point to the speed and intensity of the destruction. It also shows the complete abandonment of these houses after the event, which has been long identified (Fabra i Salvat and Burguete, 1986). Alongside these amphorae, other fragments of local and imported dishware were found that point to a site chronology of the end of the 3rd c BCE, but the 2023 campaign also found evidence of occupation as far back as at least the 5th c BCE (Menéndez and Noguera, 2024). Furthermore, eight rounded stones were found within the collapse (Figure 3). These stones, based on their form, weight and stratigraphical location, were determined to belong to ballistic projectiles shot from torsion-powered artillery, which were only in the hands of Carthaginian tacticians until late in the Second Punic War (Menéndez and Noguera, 2024). Putting this together with a significant presence of Carthaginian coinage around the site, peaking at the left shore of the Catllar ravine, it seems probable that this site was destroyed by Hannibal Barca's troops as they passed the area in 218 BCE during the Second Punic War.



Figure 3. Ballistic projectiles found alongside ceramic fragments, including those studied in this project (Noguera and Menéndez, 2022, 2023)

Hannibal's troops, prior to famously crossing the Alps in a frontal assault on Rome, made their way up the Iberian territory. This territory, at the time, was mostly controlled by the Carthaginian up until the Ebro River, with strong trade influence up and down the coast (Lopez Castro, 2019). Despite the growing presence of Roman military outposts in the north, Hannibal Barca began to push upwards into this territory. With

the help of certain Iberian locals, and against the pushback from others, they eventually began to move into lands that garnered them attention from the Romans, and the Second Punic War was underway (de Lile, 2019). As battles were fought towards the north, skirmishes went either way. The local settlements, due to their supplies and advantageous positions, were thrown into the middle, sometimes as allies and often as collateral damage (Lopez Castro, 2019).

Due to historical fonts and the seeming importance of this site, some scholars have pointed out the possibility of the settlement being the Iberian town by the battle of Kissa/Cissis, as mentioned by Polybius (III, 76) and Livius (XXI, 60) (Noguera and Menéndez, 2022). They write that after the Romans landed in Emporion (present day Empuries), and conquered their way south, they encountered a formidable Carthaginian army and fought a battle close to the town of Kissa or Cassis, respectively. Livius claims the town was plundered by the victorious Romans, but the loot was poor, which may indicate the partial destruction of the town by the Carthaginian army camping outside its walls. After this, the rest of the site would be attacked by the Romans and after a few years, completely abandoned as the first Iberian rebellions got underway.

3. Materials

A total of 29 amphorae were archaeometrically characterized in this study (Table 1). These amphorae were found during the 2022–2023 excavation season in two rooms making up Zone 1 from the site, specifically Stratigraphic unit 1022 and 1024. 23 of these amphorae have been typologically classified as Iberian Sanmartí 2B. Three categories of Punic Amphora were identified: two are found to be Ebussitan Punic T.8.1.3.1, one as T.8.2.1.1 Punic from around the Strait of Gibraltar, and one Central Mediterranean Mañà C. Lastly, two Greco Italic amphora were identified, one as a Lyding-Will B and one as a Lyding-Will C. After sampling, these reconstructed amphorae were packaged and brought to the museum at Valls, Tarragona.

ID	Ceramic Class	Shape	Type
VV0032	Ebussitan Punic amphora	amphora	T.8.1.3.1
VV0033	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0034	Central Mediterranean Punic amphora	amphora	Tomorrow C
VV0035	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0036	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0037	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0038	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0039	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0040	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0041	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0042	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0043	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0044	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0045	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0046	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0047	Italic Amphora	amphora	Lyding-Will B
VV0048	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0049	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0050	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0051	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0052	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0053	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0054	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0055	Italic Amphora	amphora	Lyding-Will C
VV0056	Punic amphora of the Strait Circle	amphora	T.8.2.1.1
VV0057	Ebussitan Punic amphora	amphora	T.8.1.3.1
VV0058	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0059	Oxidized Iberian pottery	amphora	2B Sanmartí
VV0060	Oxidized Iberian pottery	amphora	2B Sanmartí

Table 1. Individual Sample list, with Class, Shape, and Type

The 17 amphora which were deemed complete enough to be photographed from all angles (able to be handled without disassembling and placed upside down in a tripod stand) were used for Photogrammetric digitalization. Twenty-eight amphorae (all but one: VV0060 was not sampled as it was 100 % complete in situ) were used for chemical and mineralogical analysis after being prepared in the following way: Between 15 and 20 g of each individual were used in the preparation of powdered samples. In most cases, existing fractures were exploited for the selection of these individuals. When necessary, a water-cooled diamond table saw and diamond Dremel bits were utilized to achieve the appropriate amount (Figure 4). An even superficial layer of each surface was removed using Dremel sanding bits in order to limit contamination from postdepositional processes and potential exterior finishes and internal coatings such as paint, tar, etc. The fragment was then pulverized then using a tungsten cell mill (Spex Mixer model 8000D) with ball bearings in order to homogenize the sample (Figure 5).



Figure 4. Dremel used to remove sample from VV005, estimating approximately 20 g to ensure sufficient material for all analyses (Soler i Gumà, 2025)



Figure 5. SPEX SamplePrep tungsten ball bearing mill loaded with samples VV0034 and VV0036 (Soler i Gumà, 2025)

4. Methods

4.1 Photogrammetry

For detailed digitalization of the reconstructed amphora, Close Range Structure from Motion Photogrammetry was used, in conjunction with Agisoft Metashape Software,

to create 3D computer models which retained color, texture, and relative size of each artifact. In order to standardize the process, a Canon EOS 850D camera with a Canon EF 50 mm 1: 1.4 lens was used on a fixed tripod, along with two lights that followed the angle of the camera to reduce shadows and create smooth lighting conditions that reveal the textures of each piece. This was further achieved by setting each piece in front of a black cloth backdrop. Each amphora was set in a tripod stand that was sunken into a dirt base upon a rotating table (Figure 6). This allowed each piece to be rotated about the same axis easily and then turned upside down in the same position to reveal the inferior portion. A series of photographs with overlapping points were taken from three angles - straight on, $\frac{3}{4}$ angle, and from nearly vertical. These three angles were achieved by raising the tripod and adjusting the angle of the camera, trying to keep each angle as consistent as possible. They were taken for both the superior and inferior parts of the amphora, at approximately 15-20 pictures per angle. The pieces were turned by hand about 15-18° for each photograph (Figure 6). A blank picture of the backdrop with the artifact's tag was used to ensure clear differentiation and identification of each series of pictures.



Figure 6. Process of turning each specimen for the documentation of its inferior portion (Soler i Guma, 2025)

The photographs were uploaded into a computer with the Agisoft Metashape software and separated by amphora. Each series of photographs was uploaded into a new project and first aligned and a point cloud created. Any sections that were unable to align properly were rephotographed, with care taken to ensure that proper overlap

between points was achieved. From here, the mesh was created and cleaned up to ensure that only the amphora itself was represented. After the mesh, the model and its texture were synthesized at high quality. Final touch ups, especially focusing on missing sections and the mouth of the piece, were made to make sure the models were easy to read and smooth.

4.2 Stereomicroscopic Observations

Each of the 28 samples used for the previous analyses had an extra small fragment saved in order to observe them under an Olympus microscope Olympus SZX10, in conjunction with the program Cell. Each fragment was given a fresh fracture with pliers in order to reveal the fabric with as little alteration from postdepositional processes as possible. These fragments were set onto a dish with sand to keep them stable as they were studied under the microscope. Each piece was characterized by the following parameters: matrix color, texture, porosity, and inclusions. In this section it is also considered whether the color is consistent throughout the fragment or if there are differences between the core and outer layers of the fabric. Inclusions were characterized due to their frequency (proportion compared to the matrix), their size, the frequency of each size, and the roundness of each grain from rough to smooth. These were determined according to Orton et al. (1993) and Rye (1981). Any inclusions which appeared to be diagnostic were noted. Pictures of various levels of magnification (10X, 20X) were taken for each sample, especially focusing on these with particularly characteristic inclusions, using the previously mentioned program. When necessary, in order to capture details or the coloration of thicker samples, 50X or 6.3X magnification was utilized.

4.3 Wavelength - Dispersive X-Ray Fluorescence (WD-XRF)

The chemical composition of the samples was determined using wavelength-dispersive X-ray fluorescence (WD-XRF) upon the pre-powdered and homogenized samples, which were first dried in a stove at 105 °C for at least 24 h. In order to determine the major and minor elements, two duplicated 30 mm glass disks were prepared by weighing 0.3 g of sample and mixing with 5.7 g of lithium tetraborate with lithium iodine as a flux and anti-adherent. Each part was weighed in a well calibrated

laboratory scale to at most a 0.0005 margin of error. Each mixture was homogenized first by hand in a platinum (95 % Pt - 5 % Au) crucible, and introduced into a Malvern Analytical Claisse LeNeo fusion machine at a temperature of 1125 °C. This resulted in a fused glass disks after pouring into the standard 30 mm mold for WD-XRF (Figure 7).



Figure 7. Glass disk during cooling stage after being poured from crucible at 1125°C. These disks will measure the major and minor elements

For the trace elements, 6 g of specimen were utilized to create pressed pellets with a grain size of < 80 μm . This was mixed with 2 ml of a solution made up of 20 % synthetic n-butyl metacrylate (Elvacite 2044) in acetone by mass. The mixture was homogenized by hand in an agate mortar until dry and returned to a powdered state. A base of boric acid (H_3BO_3) is set into a 40 mm aluminum receptacle with the sample on top, and it is subjected to 200 kN of pressure for 60 s in a Herzog press.

Once prepared, the quantification of elements is done using an PANalytical AxiosmAX-Advanced Spectrometer, with Rhodium as the x-ray source, calibrated with 56 standards (International Geological Standards). Interferences were taken into account, and the matrix effects were corrected using the PANalytical Pro-Trace software for the trace elements. The concentration of Na_2O , MgO , Al_2O_3 , SiO_2 , P_2O_5 , K_2O , CaO , TiO_2 , V, Cr, MnO, Fe_2O_3 , Co, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Mo, Sn, Ba, Ce, W, Pb and Th. At the same time, Loss on Ignition (LOI) was calculated based on the calcination of 0.3 g of each sample dried for 4 h at 950 °C in a Heraeus model M-110 Muffle Furnace (Figure 8). It used a heating curve of 3.4 °C / min and free cooling. The results from major and minor elements are expressed by the concentration of oxides in

percentage of mass (wt %), while the trace elements are expressed as elemental concentrations in ppm or mg/kg. The sum of concentrations from the major, minor, and trace elements, as well as the Loss on Ignition are within the range of (98 - 102 %).



Figure 8. Approximately 0.3 g of each specimen in clay crucibles before loss on ignition test (Soler i Guma, 2026)

Statistical treatment of the results was achieved with programs created in R (R Core Team, 2025). All individuals were analyzed at the laboratories at the Centres

Científics i Tecnològics de la Universitat de Barcelona (CCiTUB). Precision and accuracy have been established by comparing the results with the Montana Soil Standard (SRM 2711) from the National Institute of Standards and Technology (NIST). The raw data results can be found in the annex (Annex 1, Table 1).

4.4 Powder X-Ray Diffraction (PXRD)

Samples were analyzed based on the powder method of X-Ray Diffraction for their mineralogical characterization. Preparation was based on 0.5 - 1 g of the pre-prepared powdered and homogenized samples. The samples were fixed on a cylindrical specimen holder (PW1811/27 or PW1811/16) with a standard diameter of either 27 or 16 mm and a thickness of 2.5 mm using manual pressure and a frosted glass. These were loaded into a 240 mm radius Bragg-Bretano PANalytics X'Pert PRO MPD Alpha-1. This uses the K-alpha radiation from Cu ($\lambda = 1.5418$), with a Ge (111)

focalized primary monochromator, and a working power of 45 kW, 40 mA. The Diffractometer has a divergence window that varies to achieve an irradiated length that is parallel to the 10 mm X-Ray beam with a mask in the incident beam. This regulates the length radiated on the sample in the axial direction to 12 mm, and it has an X'Celerator detector with an active length of 3.347°. The measurements were made between 5 and 80 ° with a step size of 0.026° and a count of 50 s. Results were then analyzed in conjunction with the initial groups defined from the WD-XRF results.

5. Results

5.1 Photogrammetric Digitalization

Due to limitations in time and materials for the construction of stands for the reconstructed amphorae, we were unable to perform photogrammetric digitalization of all 29 amphorae examined in this project. In order to use the existing turn table and amphora tripod, specimens needed to be nearly complete with a rim capable of bearing significant weight. This resulted in a final cohort for photographing of 17 amphorae including 16 of Iberian Sanmartí B typology, and one of Italic C (Figures 9-15). Photographs were taken prior to sampling for other methods in order to document as much as possible of each specimen. The following are a selection of stills from the final results, with all 3D renders available open access on the ARQUB SketchFab (<https://sketchfab.com/arqub>).



Figure 9. From left to right: VV0039, VV0050, VV0048. These specimens show banding patterns, characteristic of being made on a thrower's wheel



Figure 10. From left to right: VV0042, VV0053, and VV0038. These amphorae are characterized by their strong red and orange coloration on the pivot. This may be from being in the ground as the fire struck, cooling the pivot as the rest overheated



Figure 11. From left to right: VV0051, VV0041, and VV0027. These amphorae are characterized by their strong fire affectation patterns, as well as the banding pattern



Figure 12. VV0043 and VV0049 showing scaling affectation postdepositionally alongside banding pattern present. This is likely from the heat of the fire impacting the structural integrity of the ceramic and resulting in external layers flaking off



Figure 13. In Photogrammetric 3D modelling with fragmented pieces such as VV0045 , shadows impact coloration and texture. Using a combination of Normal Textured (left) and Tiled Textured (right) Models in Metashape, we can get a better picture of the true shape



Figure 14. Amphora VV0060 found complete in situ in Stratigraphic layer 1024 (left), and digitized (right) (Noguera I Menéndez, 2022, 2023)

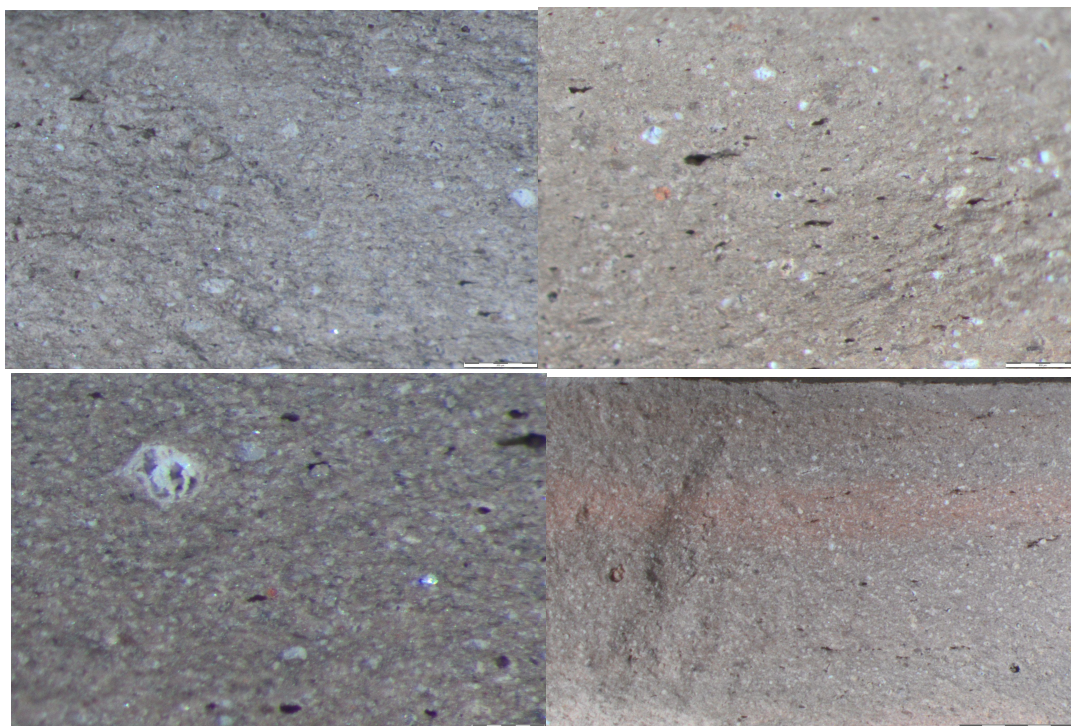


Figure 15. VV0055, an Italic Lyding-Will type C amphora, is the only non-Iberian specimen from the deposit that was complete enough to be digitized

5.2 Stereomicroscopic observations

Through the use of stereoscope microscopy, each of the 28 amphorae (VV0060 was not sampled as it was 100 % complete in situ) were given a fresh fracture and analyzed under an Olympus SZ stereomicroscope using the Cell software, according to Orton et al. (1993) and Rye (1981). Several paste types were identified, grouped as follows:

VIB001: Individuals VV0035, VV0036, VV0040, VV0045, VV0051, VV0054 (Iberian). Very fine grey paste indicating reduction of iron with beige core sometimes present (commonly referred to as sandwich paste in Iberian Archaeology) (Rye, 1981). Very low inclusions that are moderately sorted throughout the paste. Medium to low porosity, in mostly channels (Figure 16b, 16f). White and grey subround inclusions that are mostly under 0.2 mm, a few at around 0.4 mm (Figure 16b, 16c). Brown subround inclusions at approximately 0.3 mm (Figure 16a, 16d). Very small shining minerals that are identified possibly as micas dispersed throughout (Figure 16c, 16d). Individual VV038 seems fire altered, due to darker grey coloration (Figure 16f).



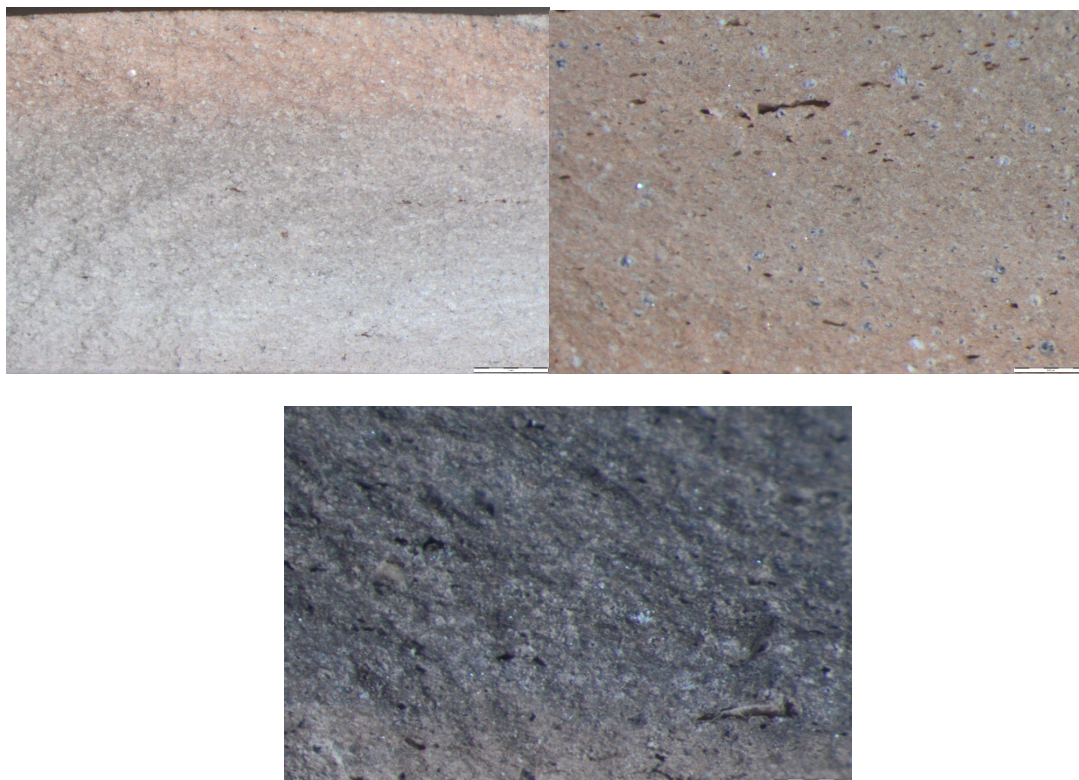


Figure 16. a) Individual VV0035 at 20x (upper left). b) Individual VV0036 at 20x (upper right). c) Individual VV0040 at 50x (upper middle left). d) Individual VV0045 at 10x (upper middle right). e) Individual VV0051 at 10x (lower middle left). f) Individual VV0054 at 20x (lower middle right). g) Individual VV0038 at 20x (bottom)

VIB002: Individuals VV0033, VV0039, VV0041, VV0043, VV0044, VV0049, VV0050, VV0058, VV0059 (Iberian). Fine grey and beige-orange pastes with cores indicating reduction of iron present (Rye, 1981). They present medium low inclusions that are moderately sorted and medium low porosity in vesicle morphology. Most inclusions are grey and white and seem to be located around pores, indicating possible calcite growths (17a, 17b, 17g, 17h). Some sorting of the patterning to these growth's coloration present in individual VV0059 (17d). Other inclusions are up to ~0.2 mm and include subround red and dark brown inclusions (17c, 17d, 17e). Two individuals presented brown banding, with one also presenting red banding (17f, 17i).

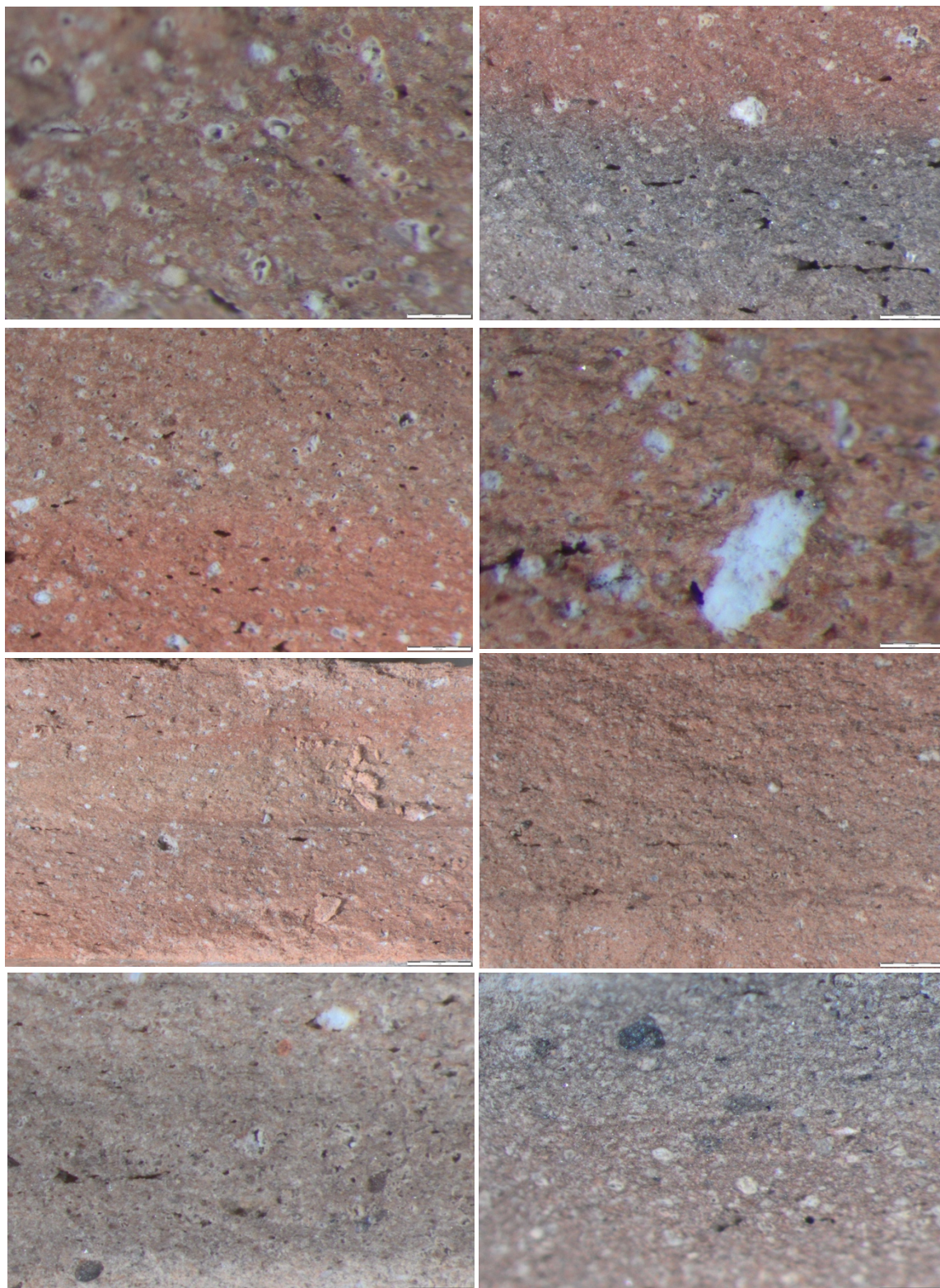




Figure 17. a) Individual VV0049 at 20x (upper left). b) Individual VV0050 at 50x (upper right). c) Individual VV0058 at 20x (upper middle left). d) Individual VV0059 at 10x (upper middle right). e) Individual VV0039 at 20x (middle left). f) Individual VV0041 at 10x (middle right). g) Individual VV0033 at 20x (lower middle left) h) Individual VV0044 at 50x (lower middle right). i) Individual VV0043 at 10x (lower left)

VIB003: Individual VV052 (Iberian) - Coarse paste, with four layers of coloration. A very fine dark grey exterior, a layer of orange, a thick grey core, and a very fine orange interior, indicating reduction of iron (Rye, 1981). The inclusions are moderately sorted, and are higher in number. These include: ~0.78 mm subround opaque black, ~0.35 mm angular opaque white (possibly calcites), and very small subround opaque beige inclusions throughout. Medium porosity, which are flat vesicles in morphology (Figure 18).

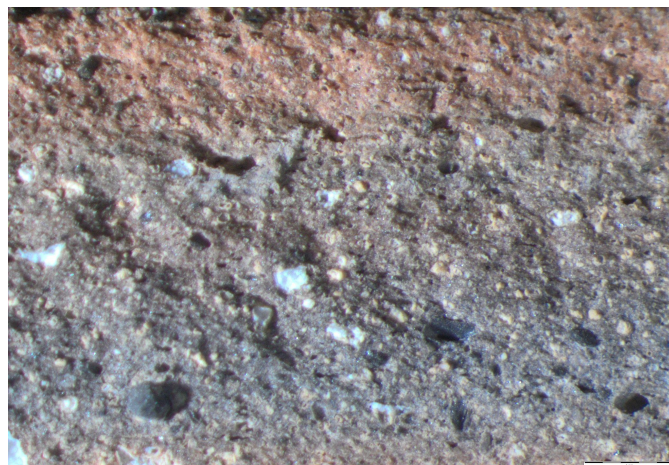


Figure 18. Individual VV0052 at 10x

VIB004: Individual VV053, VV046 (Iberian) - Medium fine paste, with a beige and orange coloration. Medium porosity with extended vesicles making up the majority (Figure 19a, b). The inclusions are moderately sorted, and are high in number and generally larger than in other groups. These include: opaque subround white inclusions with black coloration, around 0.7 mm (4a). Small subround black, red, and beige inclusions throughout (Figure 19a, b). 0.46 mm orange and white opaque inclusions (Figure 19a, b). 0.75 mm red opaque subangular inclusion (Figure 19a). Smaller dark red inclusions extended in morphology (Figure 19a, b). Dark grey/brown opaque inclusions at 0.8 mm (Figure 19a, b). Individual VV046 presents lighter beige banding throughout paste (Figure 19b).



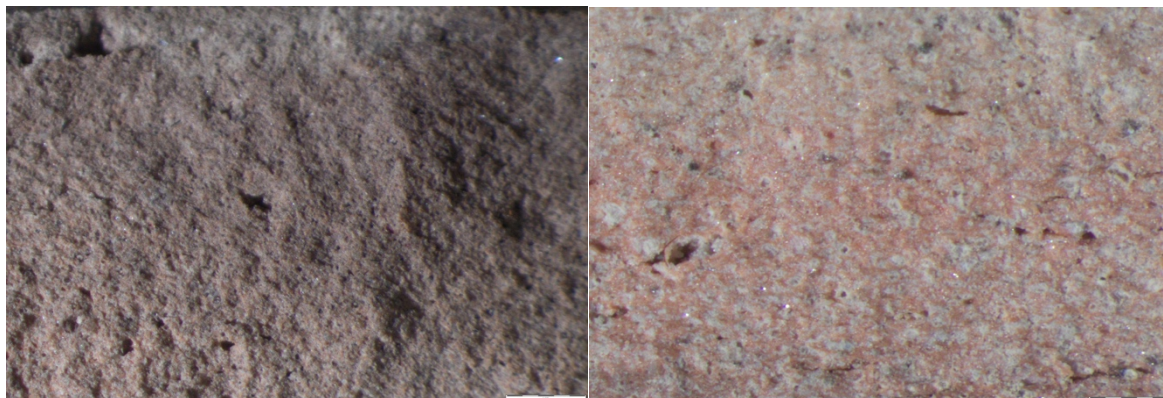
Figure 19. a) Individual VV0053 at 10x (left). B) Individual VV0046 at 20x (right)

VIB005. Individual VV048 (Iberian) - Fine paste in 5 even layers (Figure 20). From exterior to interior: Brown, grey-brown, orange-brown, blue-grey, light orange-brown, with a final thin layer of light beige. This could indicate a 'double – core' from iron reduction in two phases (Rye, 1981). Low porosity and medium inclusions that are well sorted. Inclusions are generally subround, opaque and around 0.3 mm, including black, white, beige, and red. Larger black and tan subangular inclusions around 0.5 mm present. A large 1 mm crystalline inclusion within a vacuole is present, with orange spots. Very small shining minerals, potentially micas, found throughout the paste.



Figure 20. Individual VV0048 at 10x

VPE: Individuals VV032, VV037, VV042, VV057 (Punic T.8.1.3.1, Iberian) - Very fine beige paste with very low inclusions that are moderate in sorting. Medium porosity mostly vesicles in morphology, some flatter in shape (Figure 21b, 21c). Small grey subround inclusions ~ 0.15 - 0.5 mm (Figure 21a, 21b, 21c), elongated subangular red opaque inclusions ~0.3 mm (21b, 21c), and potential very small shining micas throughout (Figure 21a, 21b, 21d). Possibly calcite - like formations around pores (Figure 21b, 21c, close look in Figure 21d).



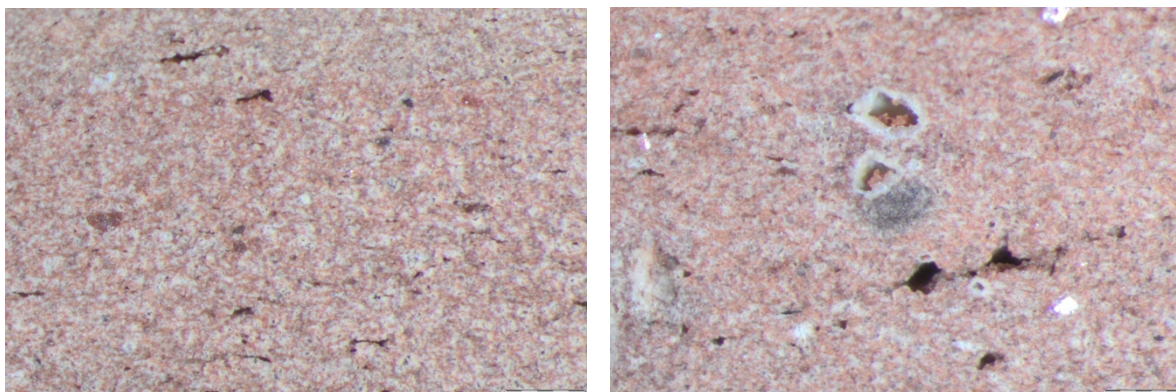


Figure 21. a) Individual VV0032 at 10x (upper left). b) Individual VV0037 at 20x (upper right) c) Individual VV0042 at 20x (lower left). d) Individual VV0057 at 20x (lower right)

VIT: Individuals VV047, VV055 (Italic B, Italic C) - Coarse orange paste with a thin light beige sandwich present. Moderate high in number of inclusions and sorting, of the following morphologies. Black opaque subangular inclusions around 0.50 mm (22a), brilliant black of around the same size and form (Figure 22b), translucent white angular inclusion, potentially quartz (Figure 22a, b), and very small subround black and white inclusions throughout (Figure 22a, b). This paste has a high porosity which are mostly vesicles and channels (Figure 22a, b). Possible band of beige clay visible in matrix (Figure 22a, b).

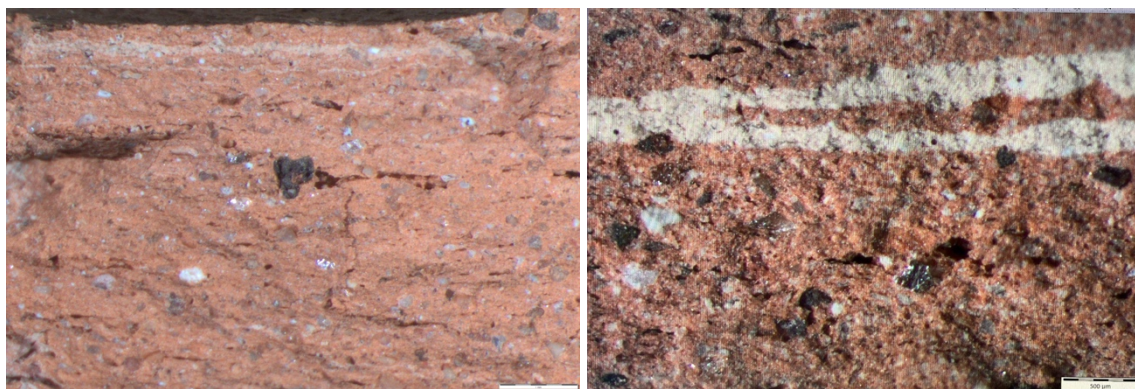


Figure 22. Individual VV0055 at 10x (left). Individual VV0047 at 20x (right)

VPC: VV034 (Punic Mañà C) - Coarse red/orange paste with a beige exterior. High inclusions that are medium to well sorted. These include many subround ~0.15 mm white quartz-like inclusions, angular grey opaque inclusions around 0.3 mm, elongated

angular opaque red inclusions measuring about 0.5 mm, and round opaque red inclusions at around 0.3 mm (Figure 23).

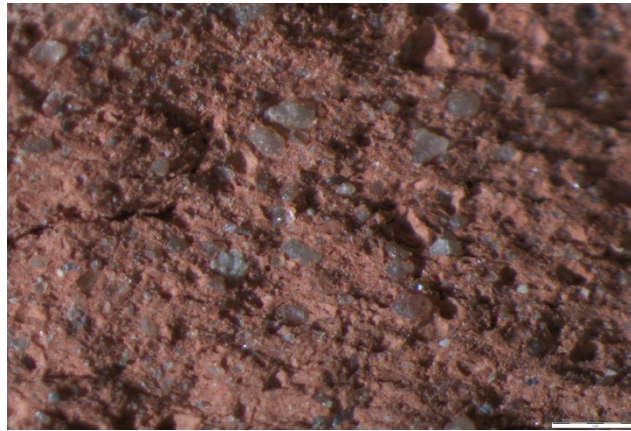


Figure 23. Individual VV0034 at 10x

VPC: Individual VV056 (Punic T.8.2.1) - Beige, fine paste, with a fine grey sandwich layering, with moderately sorted inclusions (Figure 24). Moderate inclusions of three types around 0.54 mm: Rounded opaque red-brown, subround dark grey opaque, angular translucent white (likely quartz, but further analysis required). Small opaque red-brown elongated angular and small shiny inclusions also present. Low porosity in mostly small vesicles shapes, with a few larger vughs present.



Figure 24. Individual VV0056 at 10x

5.3 Wavelength – Dispersive X-Ray Fluorescence (WD-XRF)

The results of the chemical characterization of the 28 samples (Annex 1, Table 1) were given as a chemical composition by percentage, expressed in major (shown as oxides = >1 %), minor (0.01 % - 1 %), and trace (<0.01 %) elements. To explore the dataset,

they were first treated statistically to be interpretable and comparable to previously defined reference groups that could help pinpoint the potential provenance of each specimen. To clean the data prior to treatment, certain elements were excluded if they identified as having the potential to falsely impact the variability. The following elements were excluded: Co and W due to possible contamination from the use of Tungsten Carbide cells as well as ball bearings during the milling process; Mo and Sn were excluded due to analytical imprecisions, as both were lower than their regression limits. Finally, Pb and Cu were excluded due the anomalous values detected in several individuals (Annex 1, Table 1).

First, the variation matrix determines the covariance structure of the data, giving us a total variation (tv) of 1.96 (Annex 1, Table 2), which indicates a polygenic group, meaning they are unlikely to come from one production center, or have the same origin (Buxeda i Garrigós and Kilikoglou, 2003). The information entropy, or Shannon index, quantifies how evenly the chemical differences are related to the retained components. The compositional evenness graph reveals that the elements that introduce more variability are Sr, CaO, MgO, and Na₂O ($\tau.j < 0.3$, *i.e.*, tv accounts for less than 30 % of the trace of the variance–covariance matrix after an alr transformation using any of these elements as a divisor), and, to a lesser extent, Pb, P₂O₅, K₂O ($0.3 < \tau.j < 0.5$) (Figure 25). All these indicators show that even if the chemical variability is linked to a few elements, the composition varies significantly in all retained components (the information entropy has a value of 3.79 Sh, *i.e.*, 81.57% of the maximum attainable), meaning that many elements are introducing significant variability in the analysis. Regarding Sr, the high variability is likely due to the extreme values only present in some individuals (such as VV0037 with 1002 mg/kg, VV0040 with 942 mg/kg, VV0051 with 1302 mg/kg, and VV0053 with 1757 mg/kg) that can arise from contamination. Because of this, for the remainder of the analysis, Sr will be added to the removed elements, the updated compositional evenness graph shows the stark decrease in tv after its removal (Figure 26).

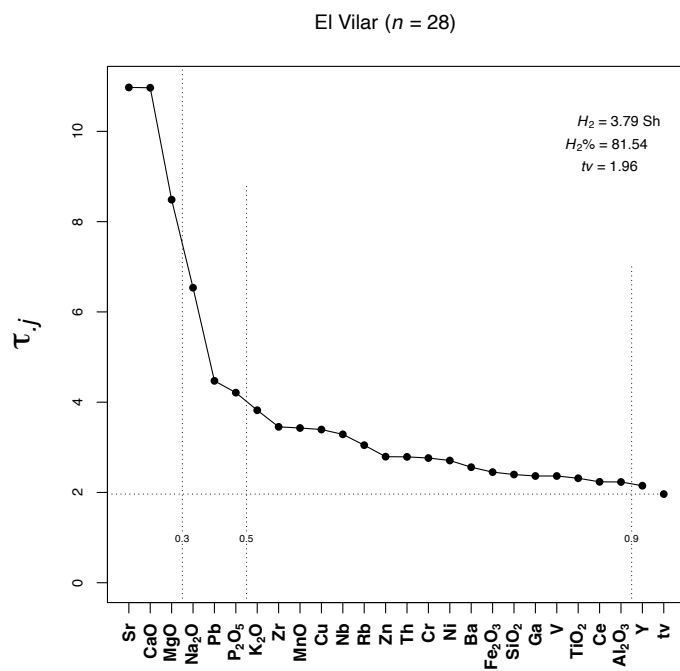


Figure 25. Compositional evenness graph. H^2 : information entropy (in Shannons, Sh); $H^2\%$: percentage of the maximum possible attainable tv = total variance

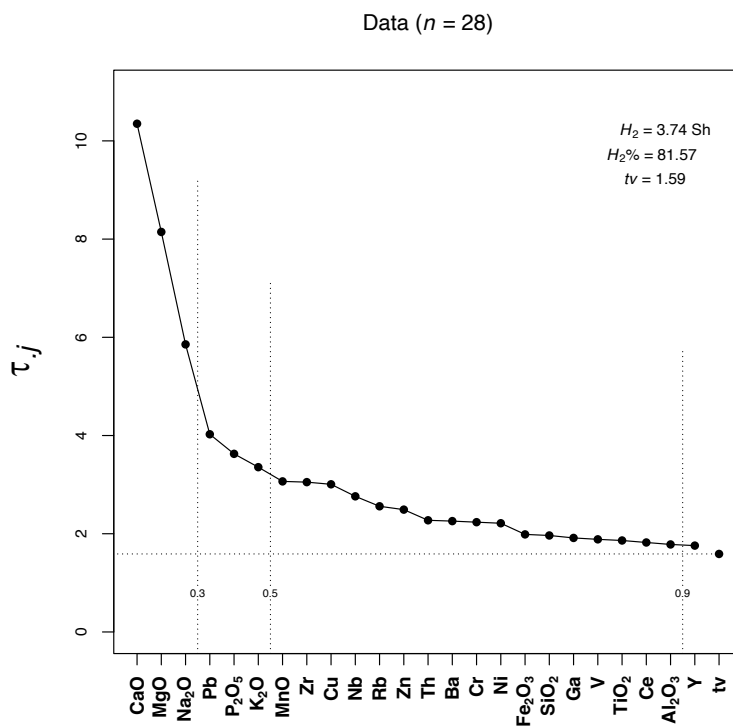


Figure 26. Compositional evenness graph removing Strontium, showing decrease in variance from prior

The chemical makeup of each sample, expressed in elemental concentrations, corresponds to a projective space $d+1$ -dimensional within the simplex $\mathbb{S}^d$, where each projective point is represented by homogeneous coordinates with a constant k

$$(k \in \mathbb{R}_+), C(w) = x = [x_1, \dots, x_d, x_{d+1}] \mid x_i \geq 0, (i = 1, \dots, d, d+1), x_1 + \dots + x_d + x_{d+1} = k,$$

(in this case, $k=100$). The vector space of these projective points corresponds to the positive orthant $\mathbb{R}^{d+1}$ (Aitchison and Greenacre, 2002; Barceló-Vidal, *et al.* 2001; Buxeda i Garrigós, 2008). Therefore, for the statistical treatment of this data, each were transformed into log- ratios (Aitchison, 1986; Buxeda i Garrigós, 1999), using the clr transformation in centered logratios, based on:

$$x \in \mathbb{S}^d \rightarrow z = \ln\left(\frac{x}{g(x)}\right) \in \mathbb{H} \subset \mathbb{R}^{d+1},$$

Where $\mathbb{S}^d$ is the d -dimensional simplex, and $g(x)$ the geometrical mean of all the $d+1$ components of x , and $\mathbb{H} \subset \mathbb{R}^{d+1}$ a hyperplane vector subspace of $\mathbb{R}^{d+1}$ (Aitchison, 1986; Buxeda i Garrigós, 2018; Buxeda i Garrigós, 1999; Egozcue and Pawlowsky-Glahn, 2011). The statistical treatment of the chemical data was carried out using R software (R Core Team, 2025).

Several graphs were produced using the treated data. First, the results are analyzed using only the samples from this study, using the euclidean distance and the centroid agglomerative algorithm in order to complete the groupings. The results of the statistical treatment are summarized in the dendrogram resulting from the cluster analysis using the squared Euclidean distance and the centroid algorithm, on the clr transformed subcomposition MgO, Al₂O₃, SiO₂, CaO, TiO₂, V, Cr, MnO, Fe₂O₃, Ni, Zn, Zr and Ba (Figure 27). This graph shows a structure divided into seven preliminary chemical groups, plus ten ungrouped individuals, from which three general tendencies can be identified: Iberian Amphorae which are low calcareous (CaO ~ 2.2 %) and have elevated MgO (MgO ~ 5.8 %) are grouped on the left and are marked in green and yellow. In the middle, they are also Iberian amphorae, but are calcareous (CaO ~ 6.8 %), and are high in MgO (MgO ~ 7.0 %), and consist of the orange, teal, blue, purple, and red groups. On the right are those that are slightly more calcaraeous (CaO ~ 9.2

%) with less MgO (MgO ~ 2.1 %), which include all of the imported typologies as well as one Iberian specimen – VV0046.

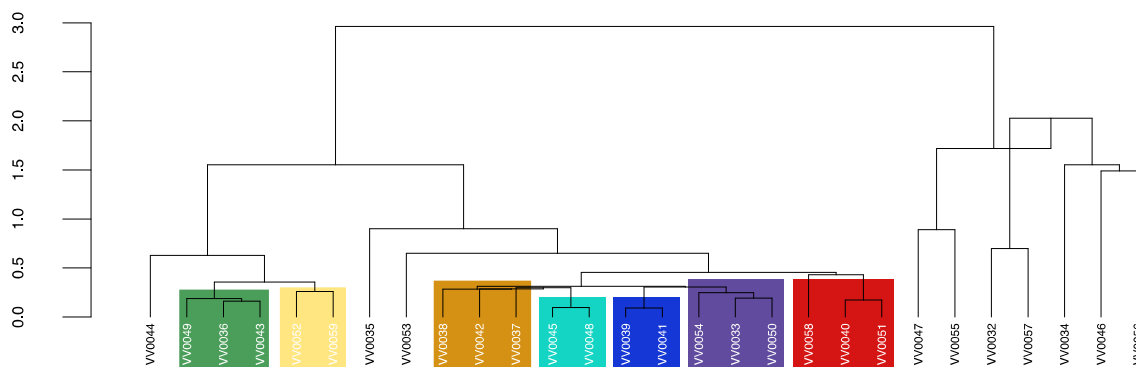


Figure 27. Dendrogram resulting from the cluster analysis of the 28 individuals analyzed using squared Euclidean distance and the centroid agglomerative method on the subcomposition MgO, Al₂O₃, SiO₂, CaO, TiO₂, V, Cr, MnO, Fe₂O₃ (as total Fe), Ni, Zn, Zr and Ba, after clr transformation

To further investigate these groups, as well as the still ungrouped individuals, we compared these results with individuals from the ARQUB (GRACPE) research unit database, first of Iberian typologies, which contains ceràmics from what is now Catalonia, País Valencià and Illes Balears. The resulting dendrograms made it possible to identify specimens with similar elemental compositions, either among themselves or in relation to previously defined reference groups, thereby defining distinct Chemical Groups (CGs). These results are fully comparable with the same elements determined for each sample ($n = 643$):

Alorda Park (Calafell) ($n = 63$), Bassa del Mas (Santa Magdalena de Polpis) ($n = 2$), Bastida de les Alcusses (Moixent) ($n = 8$), peci de la Cala Sant Vicenç (Pollença) ($n = 19$), Camp de les Lloses (Tona) ($n = 17$), Can Bartomeu (Cabrera de Mar) ($n = 18$), Castellet de Banyoles (Tivissa) ($n = 14$), Castellet de Bernabé (Llíria) ($n = 8$), Castellons (Flix) ($n = 15$), Puntal dels Llops (Olcou) ($n = 7$), Estinclells (Verdú) ($n = 4$), Fonts dels Igols/ Font de Mas Pollina (Pontons) ($n = 31$), Fontscaldes (Valls) ($n = 40$), Hortes de Cal Pons (Pontons) ($n = 49$), Illeta dels Banyets (el Campello) ($n = 4$), Lleida (Lleida) ($n = 3$), Isona (Isona) ($n = 14$), La Muela de Arriba (Requena) ($n = 2$), La Solivella (Alcalà de Xivert) ($n = 4$), La vinya d'en Pau / Vinya de Torelletes (Vilafranca del Penedès) ($n = 17$), Los Villares (Caudete de las Fuentes) ($n = 4$), Mas Castellar (Pontons) ($n = 21$), Morálaga (Sinarcas) ($n = 5$), Necròpolis del Puig de la Nau (Benicarló) ($n = 6$), Puig de

la Nau (Benicarló) ($n = 1$), Puig Castellar (Santa Coloma de Gramenet) ($n = 22$), Puig de la Misericòrdia (Vinaròs) ($n = 4$), Riera de Sant Simó (Mataró) ($n = 8$), Riera de Vista Alegre (Mataró) ($n = 58$), Santuari de Sa Punta des Patró (Sta Margalida, Mallorca) ($n = 7$), Sebes (Flix) ($n = 15$), Taller d'Andújar (Andújar) ($n = 4$), Taller del Campello (el Campello) ($n = 42$), Torre de Foios/Castellet del Mas de Magdalena (Llucena) ($n = 1$), Tossal de Sant Miquel (Llíria) ($n = 4$), Trapucó (Maó, Menorca) ($n = 86$), Turó del Vent (Llinars del Vallès) ($n = 12$), Turó dels Dos Pins (Cabrera de Mar) ($n = 8$), peci de Binissafúller (Sant Lluís, Menorca) ($n = 7$). (Tsantini, E., 2018, Tsantini et al., 2005, Tanstini et al., 2005b, Freixas et al., 2025, Buxeda i Garrigós and Madrid i Fernàndez, 2004, Buxeda i Garrigós and Madrid i Fernàndez, 2014, Buxeda i Garrigós et al., 2014)

The results of the Iberian data set are visualized in the dendrogram resulting from the cluster analysis using the squared Euclidean distance and the centroid algorithm, on the clr transformed subcomposition MgO, Al_2O_3 , SiO_2 , CaO, TiO_2 , V, Y, K_2O , Cr, MnO, Fe_2O_3 (as total Fe), Ni, Zn, Zr, V, Ga, and Ba, after clr transformation (Figure 28). This graph shows the structure of the database, from which six groups were defined that include our dataset, alongside the locations of the remaining nine individuals. The groups extracted here were generally following the same trends as the previous (Figure 27), except for in two cases. VV0040 separates from the group and is considered a loner. Similarly, VV0059 is plot in CGFNC01a. This is most likely due to the removal of some elements when dealing with the larger dataset. In order to compare results with previously published works, only the elements that coincide can be compared. Because of this, slightly different elements are analyzed for compatibility, in this case, Th was removed as well as those previously mentioned.

Six groups were identified from the data. Three new chemical groups were defined in the scope of this study: CGDVV01, CGDVV02, and CGDVV03. Consecutively, three groups were made up of previously defined groups in Peix et al. (2026), to which individuals from Vilar have been added. These six groups are generally split into four that group closely together on the left hand side, identified with the labels CGDVV02, CGFNC01a, CGFNC01b, and CGFNC01c (Figure 28) The first group, CGDVV02, does not adjoin completely, and is composed of Iberian individuals only from this site. The following three of these are composed of Iberian individuals as well, but in addition

line up with productions from Fonstcaldes, a known production center nearby. These form generally the same trends of three separate groups within the Fontscaldes production, which were identified in Peix et al. (2026). Next, relatively nearby within the Iberian dendrogram, is group CGDVV03, which includes two Iberian individuals from this study as well as three individuals found at the Font dels Igols production in Pontons, approximately 35 km away. Lastly, far to the right of the graph, is group CGDVV01, which is made up of four Iberian individuals from the site. All the remaining samples were determined to be un-grouped, though the two Italic samples were loosely related, as were the two Ebussitan samples.

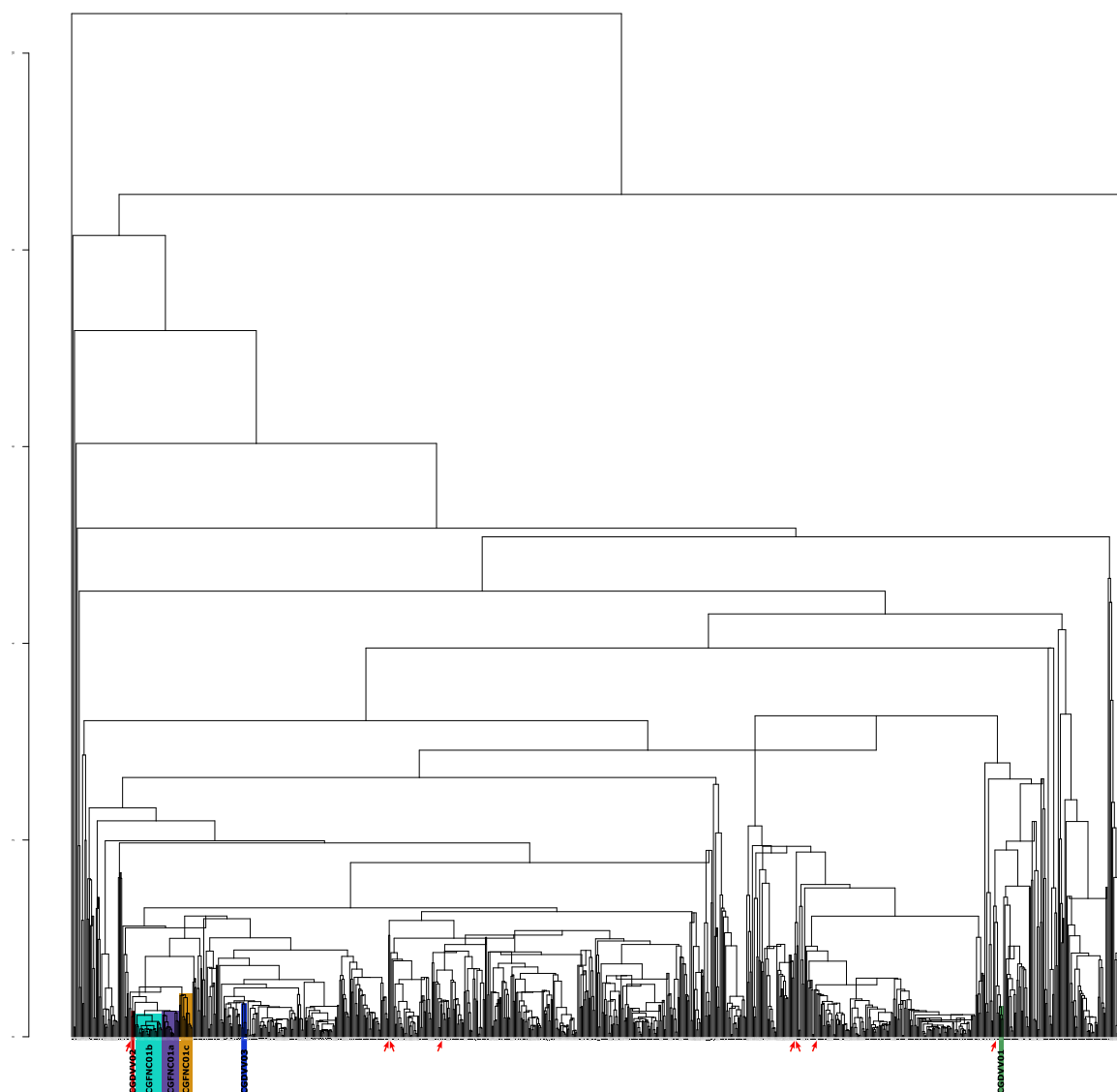


Figure 28. Dendrogram resulting from the cluster analysis of the 22 Iberian individuals analyzed in the study compared to the previously defined RGs using squared Euclidean distance and the centroid agglomerative method on the subcomposition MgO, Al₂O₃, SiO₂, CaO, TiO₂, V, Y, K₂O, Cr, MnO, Fe₂O₃ (as total Fe), Ni, Zn, Zr, Ve, Ga, and Ba, after clr transformation. In Red: CGDVV02, in Teal: CGFNC01b, in Purple: CGFNC01a, in Orange: CGFNC01c, in Blue: CGDVV03, in Green: CGDVV01. Individuals not grouped marked with yellow arrows

The statistical treatment was repeated with the Punic individuals compared with relevant typologies from the ARQUB (GRACPE) data bank for works in progress or already published. These results are fully comparable with the same elements determined for each sample ($n = 643$):

- **Phoenician and first Iron Age** ceramics from several sites **in the present-day Catalonia ($n = 344$)**: El Calvari ($n = 26$), Aldovesta ($n = 27$), La Ferradura ($n = 27$), Barranc de Gàfols ($n = 25$), Sant Jaume ($n = 78$), Turó de la Font de la Canya ($n = 75$), Coll del Moro ($n = 5$), Vilanera ($n = 17$), Timba de Santa Bàrbara ($n = 27$), Mas d'en Gual ($n = 1$), Cova de la Font Major ($n = 5$), Puig Roig del Roget ($n = 5$), Sant Martí d'Empúries ($n = 23$), and Turó del Calvari ($n = 4$).
- **Phoenician and Punic** ceramics from sites **outside the present-day Catalonia ($n = 196$)**: Camposoto workshop in Cadiz Bay ($n = 5$), two sites in Eivissa (Ses Figueretes workshop, $n = 63$; Puig des Molins, $n = 20$), several sites on the Algerian coast ($n = 7$) (Clovis, El Djalía, Quiza, Hodjadj), Lebanon ($n = 101$) (Tyre), and Kach Kouch (Oued Laou) (Morocco) ($n = 21$).
- **First Iron Age** ceramics on the **eastern coast of the Iberian peninsula ($n = 103$)**: La Fonteta ($n = 36$) (del Pino et al., 2024), Penya Negra ($n = 10$) (del Pino et al., 2022), and Castellar de Librilla ($n = 57$) (Cutillas-Victoria et al., 2021).

The analysis was then repeated with the addition of relevant published datasets, mainly by WD-XRF, but with different sets of trace elements or even only with major and minor elements ($n = 589$):

- **Alaimo et al., 1998 (Phoenician and Punic ceramics, $n = 43$)**: Motya (Sicily) ($n = 16$), Soluntum (Sicily) ($n = 27$)
- **Cardell et al., 1999 (Phoenician ceramics, $n = 16$)**: Cerro del Villar (Málaga)
- **Vendrell, 2000 (Grey monochrome ceramics, $n = 23$)**: Sant Martí d'Empúries (present-day Catalonia)

- **Montana et al., 2009 (Archaic-Hellenistic tableware, $n = 34$):** Soluntum (Sicily)
- **Fabbri et al., 2014 (Punic shell-shaped lamps, $n = 11$):** Puig des Molins (Eivissa)
- **Amadori et al., 2017 (Phoenician and Punic ceramics, $n = 102$):** Carthage ($n = 32$), Mount Sirai (Sardinia) ($n = 10$), Pithecusa ($n = 4$), Othoca (Sardinia) ($n = 9$), Sulci (Sardinia) ($n = 15$), Tharros (Sardinia) ($n = 12$), and Toscanos (Vélez-Málaga) ($n = 20$).
- **Fantuzzi et al., 2020 (Phoenician ceramics, $n = 195$):** ceramics from the Corinth's Punic Amphora Building ($n = 158$), San Fernando (Cadiz Bay) ($n = 25$), and Málaga ($n = 12$).
- **García et al., 2021 (Regional and Phoenician tradition ceramics, $n = 14$):** Lisbon.
- **Taccola et al., 2023 (Phoenician and Punic amphorae, $n = 38$):** Pisa.
- **Fantuzzi et al., 2024 (Punic Kuass Ware, $n = 25$):** from Málaga ($n = 20$) and San Fernando (Cadiz Bay) ($n = 5$)
- **Cutillas et al., 2024 (Punic amphorae, $n = 37$):** Cartagena.
- **Orsingher et al., 2025 (Phoenician oil bottles, $n = 51$):** Motya (Sicily)

The results from Comparison 2 are visualized in Figure 29, showing only one sample fit neatly into a previously identified group – VV0056. Typologically from the Punic controlled Strait of Gibraltar area, it aligned with the well-known productions there, specifically the Juan XXIII site in Malaga. It also grouped in with amphorae found in Corinth's Amphora building, which have been previously identified to have been produced in the late 3rd c BCE in Malaga (Fantuzzi et al., 2024). The two Ebussitan samples were not found to be closely related to each other or any specific production on the island, but they do loosely group with these productions. Lastly, the Center – Mediterranean amphora was completely unrelated to anything in the database. Because of this, no Chemical Groups were identified from these results. Similarly, the Italic samples did not align with each other or other known production centers, though this could be due to the smaller sample size utilized.

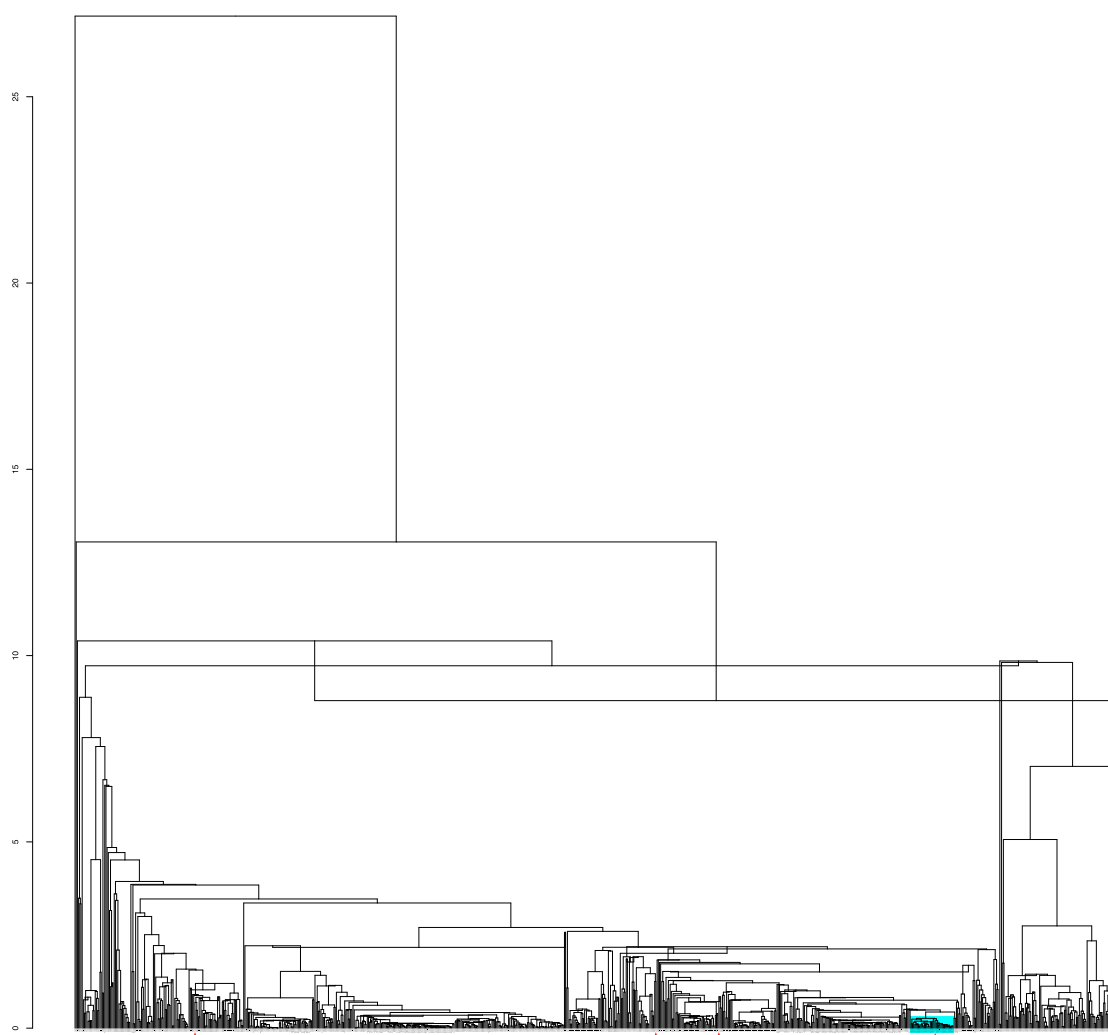


Figure 29. Dendrogram resulting from the cluster analysis of the 4 Punic individuals analyzed in the study compared to the previously defined RGs using squared Euclidean distance and the centroid agglomerative method on the subcomposition MgO, K₂O, Al₂O₃, SiO₂, CaO, TiO₂, V, Cr, MnO, Fe₂O₃ (as total Fe), Ni, Zn, Sr, Ce, Th, Rb, Zr and Ba, after clr transformation. Vilar individuals marked with red arrows, Corinth Amphora building and Malaga production centers in teal

After sorting the raw data according to the defined CGs, the following elemental compositions were identified as being characteristic to the group's formation. The means and standard deviations can be found in Table 2. CGDVV01 (VV0049, VV0043, VV0036, VV0044) is low calcareous (CaO = 1.92 ± 0.44), with an elevated MgO of 5.32 ± 0.09 as well as an elevated Al₂O of 20.54 ± 0.39 . CGDVV02 (VV0035, VV0051, VV0058) is border calcareous (CaO = 4.62 ± 0.27), with a high MgO content of 7.77 ± 0.04 . CGDVV03 (VV0039, VV0041) is characterized as calcareous (CaO = 7.87 ± 0.85), with an elevated MgO of 5.38 ± 0.33 . CGFNC01a (VV0033, VV0050, VV0054, VV0059)

is the least calcareous of the Fontscaldes CGs, having a CaO makeup of 5.11 ± 1.51 . It also has a high MgO content of 6.17 ± 0.51 . CGFNC01b (VV0045, VV0048) has a CaO of 6.87 ± 0.73 , and a high MgO of 7.75 ± 0.04 . The most calcareous of the groups is CGFNC01c (VV0038, VV0042, VV0037, VV0053), at CaO = 8.83 ± 1.61 , and it has a magnesium content of 7.08 ± 0.5 .

Of those which did not appear to form chemical groups, the following characteristics were established. Of three Iberian individuals: VV0040 is calcareous (Ca = 5.66 %) and has very high MgO (MgO = 8.96 %), VV0046 is calcareous (CaO = 6.38 %) with low MgO (MgO = 1.88 %), and VV0052 is low calcareous (CaO = 2.45 %) with high MgO (MgO = 7.33 %). Of the Greco Italic individuals: VV0047 is calcareous (CaO = 9.51 %), MgO (MgO = 3.43 %), with elevated Na₂O (Na₂O = 1.77 %), and has elevated Nb (Nb = 28 mg/kg). VV0055 is calcareous (CaO = 10.81 %), has low MgO (MgO = 1.91 %), Elevated Na₂O (Na₂O = 1.45 %), and elevated Nb (Nb = 35 mg/kg). Of the Punic individuals, (VV0056) aligned with production centers in Malaga (as it was a loner, it was not given a chemical group), and is characterized by being calcareous (CaO = 12.28 %) with MgO (MgO = 2.66 %). The two Ebussitan samples were similar, but not enough to reveal a single provenance. VV0032 is calcareous (CaO = 6.29 %) with low MgO (MgO = 1.97 %), and VV0057 is calcareous (CaO = 9.22 %) with low MgO (MgO = 1.41 %). Lastly, the Central Mediterranean amphora VV0034 is calcareous (CaO = 9.83 %), has low MgO (MgO = 1.47 %), elevated SiO₂ (SiO₂ = 62.50 %), low potassium (K₂O = 1.59 %), and low Rb (Rb = 73 mg/kg).

	CGDVV01		CGDVV02		CGDVV03		CGFNC01a		CGFNC01b		CGFNC01c	
	$\bar{X}$	s	$\bar{X}$	s	$\bar{X}$	s	$\bar{X}$	s	$\bar{X}$	s	$\bar{X}$	s
Na ₂ O	0.44	0.09	0.58	0.34	0.51	0.03	0.43	0.09	0.34	0.03	0.46	0.11
MgO	5.32	0.53	7.72	0.96	5.28	0.33	6.17	0.51	7.75	0.04	7.08	0.50
Al ₂ O ₃	20.54	0.39	17.36	0.12	18.09	0.56	18.72	0.37	17.57	0.39	16.60	0.52
SiO ₂	56.83	1.49	57.67	0.51	55.03	0.38	56.25	1.21	55.01	0.22	54.96	2.12
K ₂ O	6.03	0.21	5.27	0.15	5.32	0.08	5.44	0.12	5.30	0.14	5.09	0.28
CaO	1.92	0.44	4.62	0.27	7.87	0.85	5.11	1.51	6.87	0.73	8.93	1.61
TiO ₂	0.90	0.10	0.83	0.00	0.81	0.01	0.82	0.02	0.81	0.01	0.79	0.02
V	122	8	96	5	107	1	110	7	98	4	90	4
Cr	80	10	59	3	70	5	72	8	70	5	60	8
MnO	0.06	0.00	0.07	0.01	0.09	0.00	0.07	0.01	0.07	0.00	0.08	0.01
Fe ₂ O ₃	7.81	0.60	5.76	0.23	6.85	0.22	6.83	0.43	6.13	0.17	5.86	0.34
Ni	40	2	28	2	34	3	38	4	32	3	29	2
Zn	115	9	133	32	111	8	110	7	122	4	135	14
Ga	27	1	23	0	23	1	26	1	23	1	22	1
Rb	220	7	177	5	183	11	213	14	186	4	172	7
Y	28	1	31	1	28	1	28	1	28	1	30	2
Zr	159	14	222	10	166	9	176	21	180	6	204	30
Nb	17	1	15	1	15	0	16	0	15	0	15	1

Ba	616	29	620	116	655	34	608	17	557	19	725	157
Ce	74	5	79	1	80	1	82	3	76	9	78	3
Th	14	1	14	2	14	1	14	1	15	0	14	1

	VV0032	VV0034	VV0040	VV0046	VV0047	VV0052	VV0055	VV0056	VV0057
Na ₂ O	0.57	0.26	0.40	0.72	1.77	0.37	1.45	0.51	0.74
MgO	1.97	1.47	8.96	1.88	3.43	7.33	1.91	2.66	1.41
Al ₂ O ₃	17.65	11.75	17.89	16.69	16.88	18.88	16.48	15.18	16.99
SiO ₂	62.50	69.00	55.16	63.82	58.37	57.28	60.57	59.35	62.43
K ₂ O	5.16	1.59	4.76	3.52	3.15	5.79	2.78	3.03	3.13
CaO	6.29	9.83	5.66	6.38	9.51	2.45	10.81	12.28	9.22
TiO ₂	0.95	0.74	0.85	0.90	0.79	0.83	0.71	0.83	0.96
V	92	94	107	109	104	101	92	106	97
Cr	69	80	61	69	75	75	67	92	67
MnO	0.03	0.07	0.06	0.08	0.12	0.07	0.06	0.07	0.03
Fe ₂ O ₃	4.73	5.15	6.09	5.84	5.85	6.85	5.09	5.96	4.96
Ni	24	21	32	30	32	35	26	39	23
Zn	84	76	201	149	92	114	84	86	81
Ga	24	16	23	20	19	24	19	19	22
Rb	205	73	162	129	145	213	161	127	166
Y	32	23	30	33	31	30	27	28	33
Zr	279	263	200	243	248	204	296	194	291
Nb	18	19	15	16	28	15	35	17	21
Ba	528	517	762	713	495	742	448	435	424
Ce	80	71	77	89	102	85	99	77	89
Th	18	9	12	14	20	14	23	13	19

Table 2. Means ($\bar{X}$) and standard deviations (s) of normalised values within chemical groups. Normalised values of lone individuals below. Major and minor elements, expressed as oxides, in mass fraction percentage (w %). Trace elements expressed as w mg/kg

The chemical groups, together with the non-grouped individuals represented as outliers, were analyzed through a Principal Component Analysis. The two first principal components in the covariance form a biplot and explain more than 70 % of the variance (VE = 72.40 %) (Figure 30). The first principal component explains most of the variance (VE = 51.20 %) and shows the relative values of MgO, K₂O and MnO on the left-hand side and Na₂O, and CaO on the right-hand side. These components are the most involved in group formation, which was visualized earlier in the compositional evenness graph (Figure 25, 26). Along this first principal component, the biplots show a clear division between chemical group CGDVV01 on the left, CGDVV02, CGDVV03, CGFNC01a, CGFNC01b, and CGFNC01c in the middle, and most outliers on the right. The main differences creating these structures is the relationship between the MgO and CaO content. The general tendency of the groups is to have relatively high values for both of these and therefore are close to the center. The outliers which have very low MgO but are also highly calcareous shift to the right, and chemical group CGDVV01 demonstrates very low values for both.

The second principal component (VE = 21.20 %) is mainly determined by the influence of CaO and MgO together against Na₂O. From the top, group CGDVV01 similarly to before demonstrates very low values for both CaO and MgO, but additionally has lower values of Na₂O than some of the outliers. Most of the groupings fall into the area that indicates a strong presence of both CaO and MgO with little impact from Na₂O. Finally, it is important to notice the significantly higher concentrations of Na₂O in the outlier groups, which places them generally along that vector.

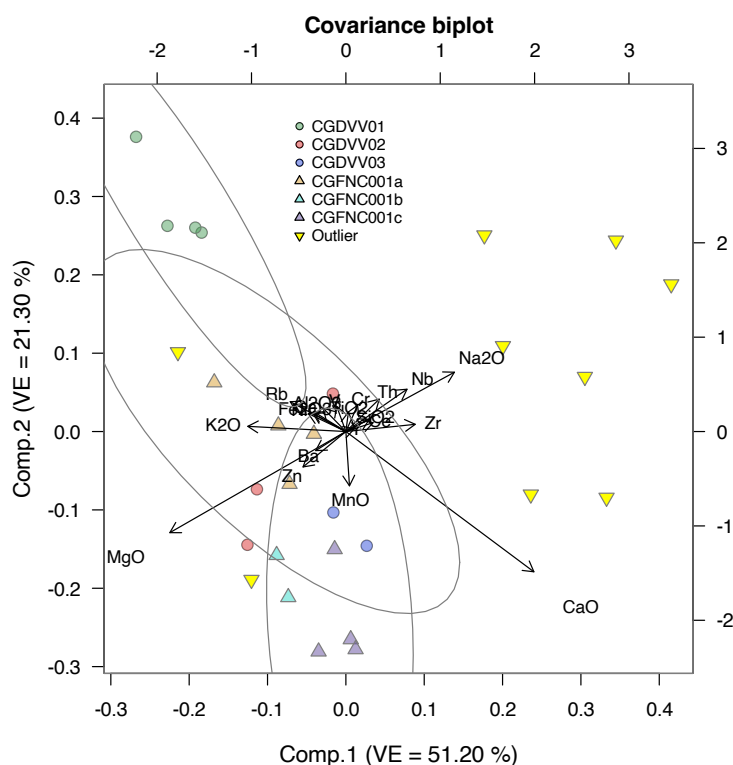


Figure 30. Principal Component Analysis by chemical groups. The x-axis represents principal component 1 (PC1), and the y-axis principal component 2 (PC2). VE = variance explained

Generally speaking, in this biplot we see that there is little separation between CGDVV02 and CGFNC01a. There also seems to be a lot of mixing between CGDVV03 and CGFNC01c. Because of this, we continued to analyze the other Biplots created between the Principal Components, to find which one explained their eventual separation. Since these groups are generally high in MgO, we removed the outliers that were poor in MgO in order to clear up the biplots and allow the variance between groups to be clearly interpretable. In the covariance plot for Components 2 and 3, which correspond to 23.71 % of the total variance, we can see the separation of these

groups (Figure 31). CGVV03 goes to the far left, outside of the ellipse that corresponds to CGFNC01c. This is likely due to CGVV03 having significantly less MgO. CGDVV02 also moves away from CGFNC01a, though in this case less homogeneously. This is due to the general trend of the group having a higher MgO than CGFNC01a, but also having one sample with a higher Na₂O than the rest. Overall, the PCA analysis confirm the dendrogram trend of these groups to join together.

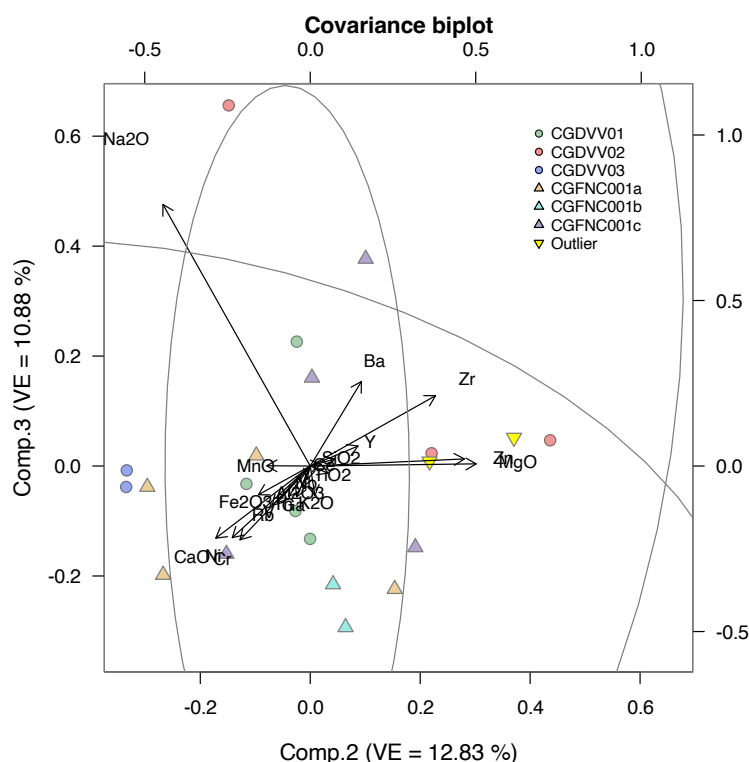


Figure 31. Principal Component Analysis by chemical groups, after removing MgO - poor outliers. The x-axis represents principal component 1 (PC1), and the y-axis principal component 2 (PC2). VE = variance explained

4.4 Powder X-Ray Diffraction (PXRD)

Chemical results also allow us to categorize each individual from low calcareous to calcareous through placement on ternary plots, according to each's chemical composition of (CaO - Al₂O₃ - SiO₂ and CaO - MgO - SiO₂ systems) (Figure 32a, b). These ternary plots also include the location of the chemical composition of certain minerals (Wo, An, Mul, Gh, and Wo, Di, En, Ak, Mtc, and Fo, respectively). These minerals form thermodynamic equivalence triangles within the plot, which indicate the expected minerals that would form from a magma made from a given composition. For

ceramics, based on the location within the plots, they can give a starting point in identifying the minerals that would be present in the sample if they reached a high enough temperature.

Within the first plot, individuals that are included in the quartz–wollastonite–anorthite thermodynamic triangle are classified as significantly calcareous. Those included in the quartz – anorthite – mullite triangle are slightly less calcareous and have a higher proportion of Al_2O_3 . This distribution reflects specific technological choices and helps to identify differentiation between low-calcareous ($\text{CaO} < (5-6) \%$), calcareous, ($\text{CaO} > (5-6) \%$), and highly calcareous ($\text{CaO} > (15-26) \%$) compositions. This indicates the proportional presence of calcium carbonate (CaCO_3) in the original mixture, which decomposes into CaO during firing according to the following reaction:



This reaction starts at approximately 700 °C, but it is usually completed, in ceramics, at approximately 800 °C. Part of the resulting CaO remains within the ceramic matrix, where it reacts to form high-temperature phases such as calcium silicates and calcium–aluminium silicates (anorthite, gehlenite) or calcium–magnesium silicates (diopside) (Gliozzo, 2020, Maniatis and Tite, 1981; Picon, 1973).

Since MgO content has been shown in our data to have a more significant role in grouping than Al_2O_3 , the second plot (Figure 32b) gives us a picture that more accurately reflects our previous findings. The results are split between the Qz-Wo-Di and Qz-Di-En/Fo thermodynamic triangles. Enstatite and Forsterite are composed with high quantities of Mg. Wollastonite does not contain MgO. As we can see, the outliers and some of CGFNC01c, which have less MgO, tend towards the left of the CaO-MgO-SiO₂ system. In the other hand, the other groups fan out towards the right.

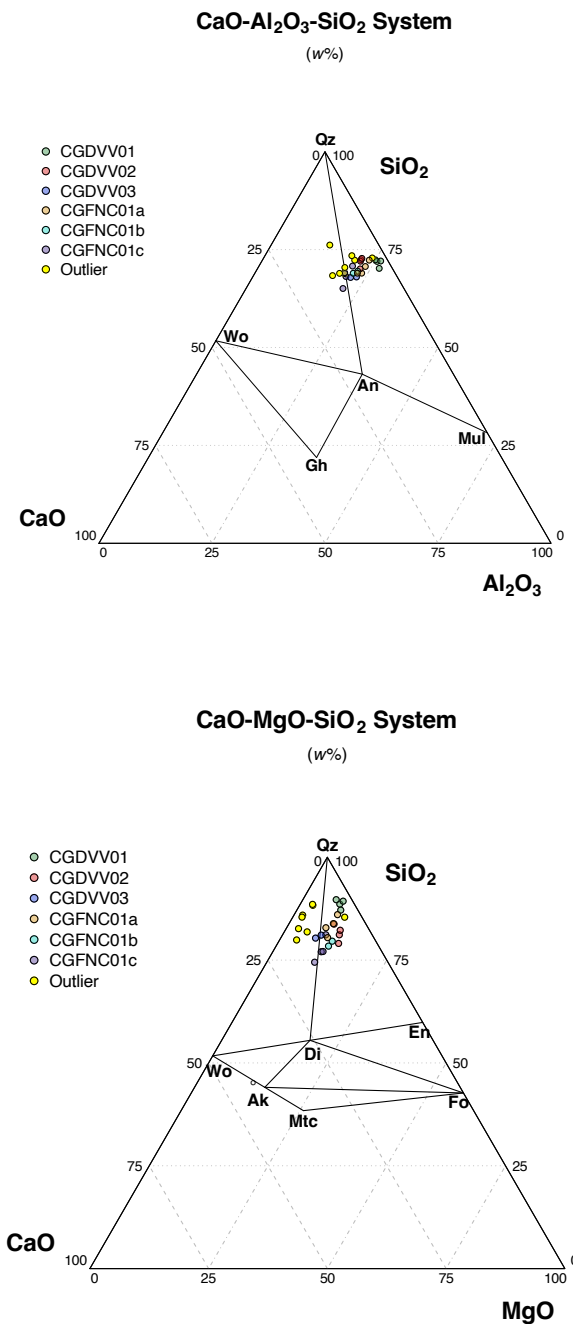


Figure 32. a) SiO₂ - CaO - Al₂O₃ system, b) SiO₂ - CaO - MgO system

The diffractograms were interpreted keeping these tendencies in mind. Their mineralogical makeup was identified using established mineralogical patterns. The minerals that were identified were classified according to Maggetti (1981) into three categories, firstly primary minerals that originated from the raw materials used and have not been altered by firing or post depositional processes; firing minerals, which are formed when the firing process causes the transformation of primary phases into

new minerals; and secondary minerals, which are formed after the firing process, usually occurring due to crystallization or mineral transformation from contact with external solutions after deposition. Thus, the chemical composition, mineralogical composition, firing process, and burial conditions will impact the presence or absence of certain crystalline phases. Through these phases, we can estimate the Equivalent Firing Temperatures, which were defined by Roberts as the temperature that if applied during a similar amount of time to the original firing, would result in an equivalent degree of sintering as the piece being studied (Roberts, 1963). It has also been defined as the temperature which would achieve an equivalent effect to the observed piece after 1 h (Picon, 1973). Due to the complex interactions between factors that cannot always be identified accurately, such as maximum temperature, and heating and cooling times, TCEs are not an exact representation of actual firing temperatures. Despite this, they allow a clearer picture to help guide our understanding of technological practices. Within one chemical (WD-XRF) group, these phases allow samples to be organized into fabrics, which correspond to similarly fired specimens, by temperature range (Table 3):

- Low-fired (<800-850 °C): only primary phases are present; no clear firing phases are formed.
- Well-fired (800/850-950/1000 °C): illite-muscovite can still be observed alongside clear firing phases (e.g. gehlenite, plagioclase, spinel, and pyroxene).
- Overfired (1000-1100 °C): further changes in mineralogical phases. Illite-muscovite has totally decomposed, and, in some cases, new firing phases are observed (like spinel and hercynite).

RG/PRCU and fabric	CaO w %	MgO w %	Mineral	Individuals	EFT (°C)
CGDVV01 (LC; MM)	1.92 ± 0.44	5.32 ± 0.53			
F1			Ill, Qz, Afs, Pl (?), Cal, Dol (?)	VV0036	< 800/850
F2			Ill, Qz, Afs, Pl (?), Cal, Px, Hem	VV0043, VV0049	VV0044, 800-850 / 900-950
CGDVV02 (LC; HM)	4.62 ± 0.27	7.72 ± 0.96			
F1			Ill, Qz, Afs, Pl, Cal, Px, Hem (?), Fo (?)	VV0035, VV0051	VV0058, < 950/1000

CGDVV03 (C; MM)	7.87 ± 0.85	5.28 ± 0.33			
F1			Ill, Qz, Afs, Pl, Cal, Px, Hem, Fo (?)	VV0041, VV0039	< 950/1000
CGFNC01a (BC; HM)	5.11 ± 1.51	6.17 ± 0.51			
F1			Ill, Qz, Afs, Pl (?), Cal, Px	VV0059, VV0054	VV0050, < 950/1000
F2			Ill, Qz, Afs, Pl (?), Cal, Px, Hem	VV0033	< 950/1000
CGFNC01b (C; HM)	6.87 ± 0.73	7.75 ± 0.04			
F1			Ill, Qz, Afs, Cal, Px, Hem (?), Fo	VV0058	< 950/1000
F2			Qz, Afs, Pl (?), Cal, Px, Hem (?), Fo	VV0048	> 950/1000
CGFNC01c (C; HM)	8.93 ± 1.61	7.08 ± 0.50			
F1			Ill, Qz, Afs, Pl, Cal, Px, Hem (?)	VV0053, VV0038	< 900/950
F2			Ill, Qz, Afs, Pl, Cal, Px, Fo, Hem (?)	VV0042	900/950 – 950/1000
F3			Qz, Afs, Pl, Cal, Px, Fo, Hem	VV0037	> 950/1000
Loners					
VV0052 (LC; HM)	2.45	7.33	Ill, Qz, Afs, Pl(?), Px, Fo(?), Hc(?)	VV0052	< 950/1000
VV0040 (BC; HM)	5.66	8.96	Ill, Qz, Afs, Cal, Px	VV0040	< 950/1000
VV0046 (BC; M)	6.38	1.88	Ill, Qz, Afs, Pl, Hem, Cal, Px	VV0046	< 950/1000
VV0047 (C; M) (Italic)	9.51	3.43	Ill, Qz, Afs, Pl, Hem, Cal, Px	VV0047	< 950/1000
VV0055 (C; M) (Italic)	10.81	1.91	Ill, Qz, Afs, Pl, Hem, Cal, Px, Gh	VV0055	800/850 – 950/1000
VV0034 (C; M) (Punic)	9.83	1.47	Ill, Qz, Afs, Hem, Cal	VV0034	< 800/850
VV0056 (C; M) (Punic)	12.28	2.66	Ill, Qz, Afs, Pl, Hem, Cal, Px	VV0056	< 950/1000
VV0032 (BC; M) (Ebussitan)	6.29	1.97	Ill, Qz, Afs, Pl, Hem, Cal, Px, Gh, Spl	VV0032	900/950 – 950/1000
VV0057 (C; M) (Ebussitan)	9.22	1.41	Ill, Qz, Afs, Pl, Hem, Cal, Px, Gh	VV0057	800/850 – 950/1000

Table 3. Mineralogical results of the studied reference groups. LC: low calcareous; BC: border calcareous; C: calcareous; M: magnesium; MM: medium magnesium; HM: high magnesium CG: Chemical group, ID: ceramic individuals, EFT: equivalent firing temperature (°C), * indicates absence of the illite–muscovite at 10 Å. Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Ill = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Qz = quartz; Abbreviations follow Warr (2021)

Of the chemical groups, CGDVV01 is made up of two Fabrics, the first of which has an EFT below 800/850 °C (Figure 33a). It is characterized by the presence of illite – muscovite (Ill) and Alkali Feldspapr (Afs) as primary phases. There is no development of firing phase minerals, and thus its EFT must be below the range of their development.

Fabric 2 has an EFT of 800/850 – 900/950 °C (Figure 33b). This fabric also presents primary phases of Ill and Afs, alongside plagioclase (Pl). This fabric has developed

pyroxenes (Px) and hematite (Hem), indicating firing phases and a higher EFT. Due to the high MgO content, these Px are probably a mixture of diopside (Di) and Enstatite (En), but as the diffractogram patterns vary their precise identification is complex.

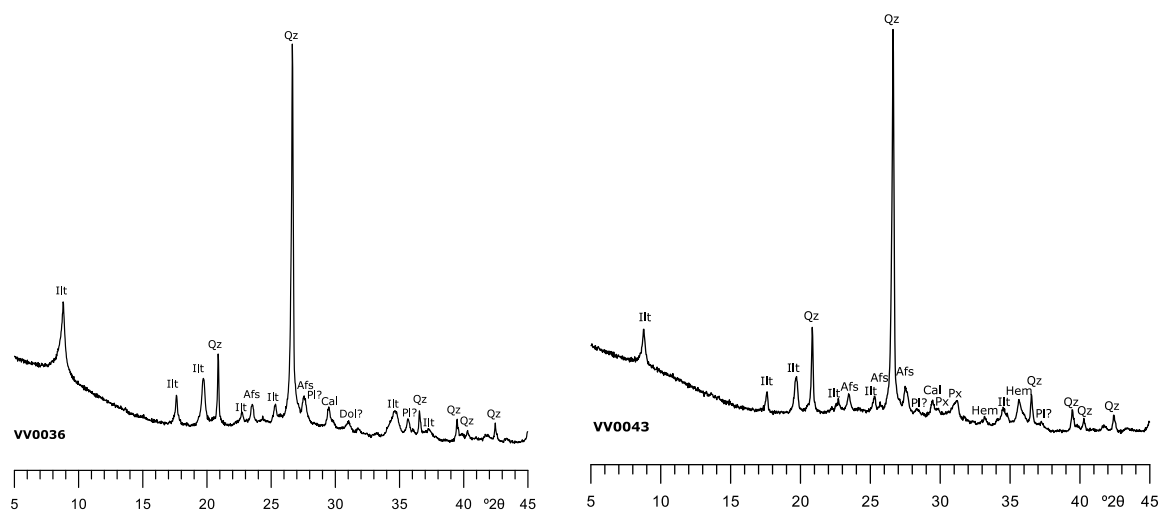


Figure 33. CGDVV01 Fabrics 1 and 2 representatives labeled. Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Illt = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Qz = quartz; Abbreviations follow Warr (2021). a) VV0036 (Fabric 1) b) VV0043 (Fabric 2)

CGDVV02 appears to be composed of one fabric with an EFT of < 950/1000 °C (Figure 34). It is characterized by the presence of Illt, Pl, and Afs as primary phases. The development of Px and potentially Hem and forsterite (Fo), Therefore, the range is established by the lack of decomposition of the Illt.

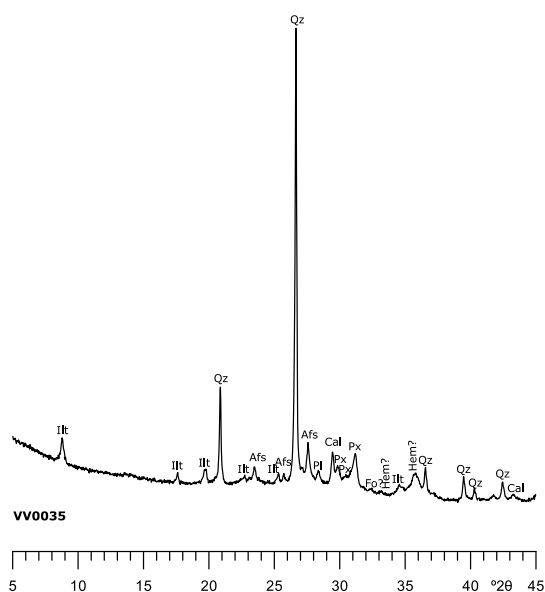


Figure 34. CGDVV02 Fabric 1 representative labeled (VV0035). Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Ill = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Qz = quartz; Abbreviations follow Warr (2021)

CGDVV03 also has one fabric with an EFT of < 950/1000 °C (Figure 35). It is characterized by the presence of Ill, Pl, and Afs as primary phases. The development of Px and potentially Hem and forsterite (Fo), suggest high temperatures. Therefore, the range is established by the lack of complete decomposition of the Ill, though the near disappearance of the 10 Å peak suggests higher temperatures as well.

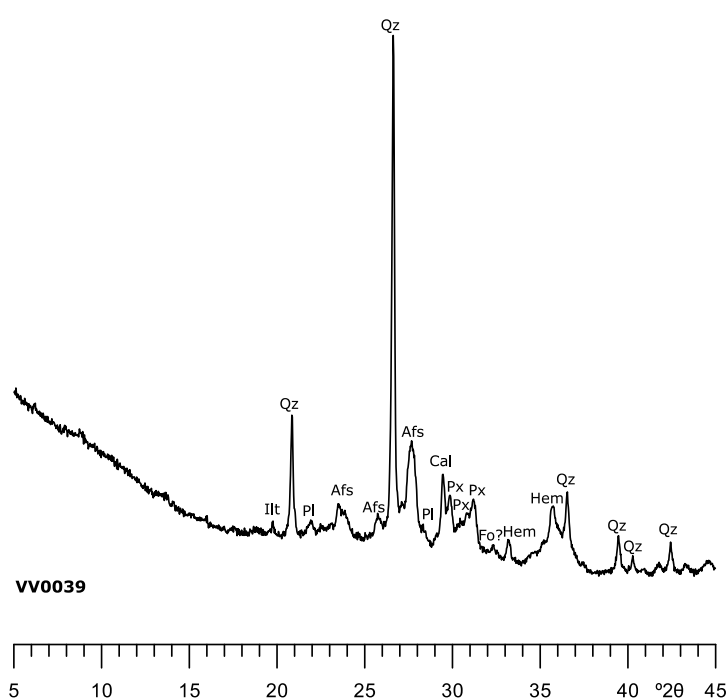


Figure 35. CGDVV03 Fabric 1 representative labeled (VV0039). Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Ill = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Qz = quartz; Abbreviations follow Warr (2021)

CGFNC01a is made of two fabrics, the first of which EFT of < 950/1000 °C (Figure 36a). It is characterized by the presence of Ill and Afs as primary phases. The development of Px and Fo typically indicate firing phases, but the strong peaks of Ill set the main range.

The second fabric has an EFT of < 950/1000 °C as well (Figure 36b). It is characterized by the presence of Ill, possibly Pl, and Afs as primary phases. The development of Px and Fo, as well as possibly Hem, indicate firing phases. This, alongside the reduced

intensity in the Illt suggest a slightly higher temperature than fabric one, but it is difficult to confirm this due to the complexity in interpreting if Hem was present as a primary phase.

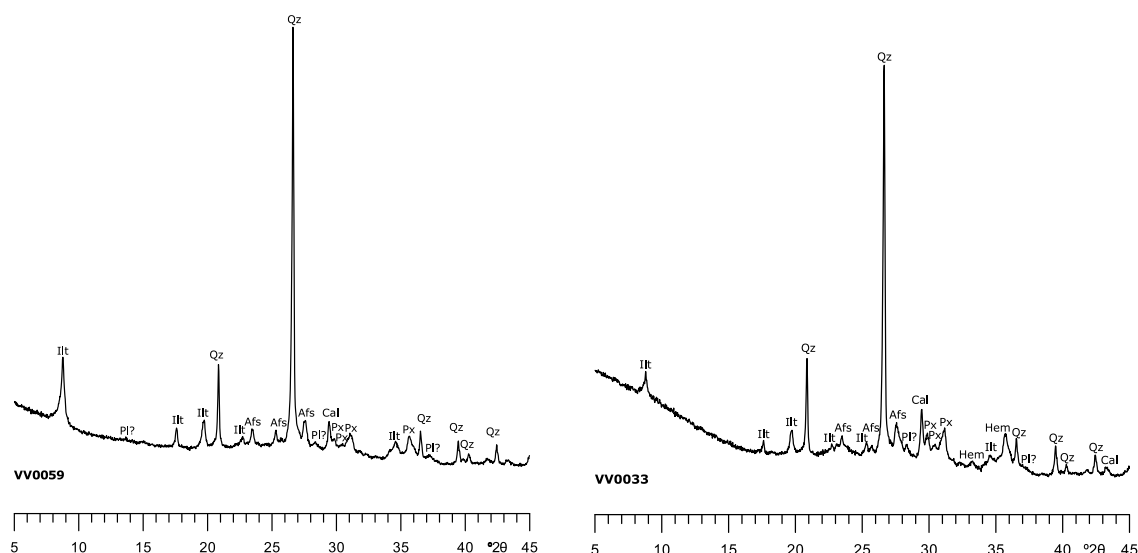


Figure 36. CGFNC01a Fabric 1 and 2 representatives labeled. Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Illt = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Qz = quartz; Abbreviations follow Warr (2021). a) VV0059 (Fabric 1) b) VV0033 (Fabric 2)

CGFNC01b is made up of two fabrics, the first of which has an EFT of below 950/1000 °C (Figure 37a). It is characterized by the presence of Illt, Pl, and Afs as primary phases. The development of Px, Fo, and possibly Hem typically indicate firing phases, but it is difficult to interpret whether they could be primary phases. Due to this, the range is established based on the presence of Illt.

The second fabric has a higher EFT over 950/1000 °C (Figure 37b). It is characterized by the presence of Pl, and Afs as primary phases. The development of Px, Fo, and possibly Hem typically indicate firing phases, but it is difficult to interpret whether they could be primary phases. In this fabric the Illt has completely decomposed, resulting in the establishment of the EFT above the temperature this occurs.

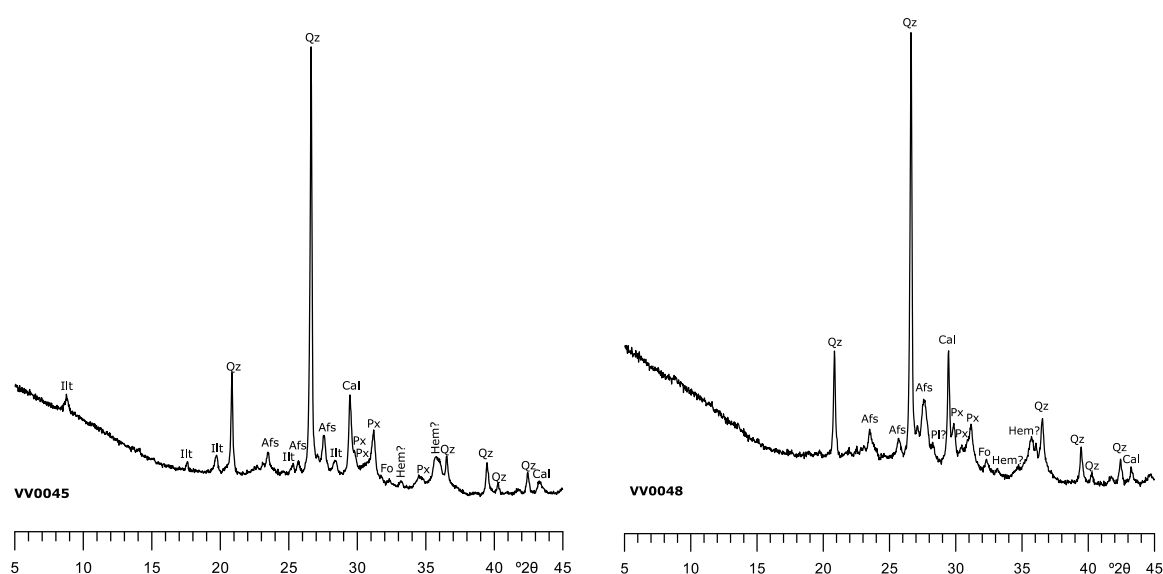


Figure 37. CGFNC01b Fabric 1 and 2 representatives labeled. Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Ilt = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Qz = quartz; Abbreviations follow Warr (2021). a) VV0045 (Fabric 1) b) VV0048 (Fabric 2)

CGFNC01c is characterized by three fabrics, the first of which has an EFT of < 950/1000 °C (Figure 38a). It is characterized by the presence of Ilt, Pl, and Afs as primary phases. The development of Px and possibly Hem typically indicate firing phases, but it is difficult to interpret whether they could be primary phases. Due to this, the range is established based on the presence of Ilt.

The second fabric has an EFT in the range of 900/950–950/1000 °C (Figure 38b). It is characterized by the presence of Ilt, Pl and Afs as primary phases. The development of Px, Fo, and Hem typically indicate firing phases, but it is difficult to interpret whether some could be primary phases. Due to the presence of Illite and development of Fo, the range thins in margin.

The last fabric has an EFT of > 950/1000 °C (Figure 38c). It is characterized by the presence of Pl and Afs as primary phases. The development of Px, Fo, and possibly Hem typically indicate firing phases the complete decomposition of Ilt indicates high temperatures were achieved, and the EFT reflects the temperature needed for this decomposition.

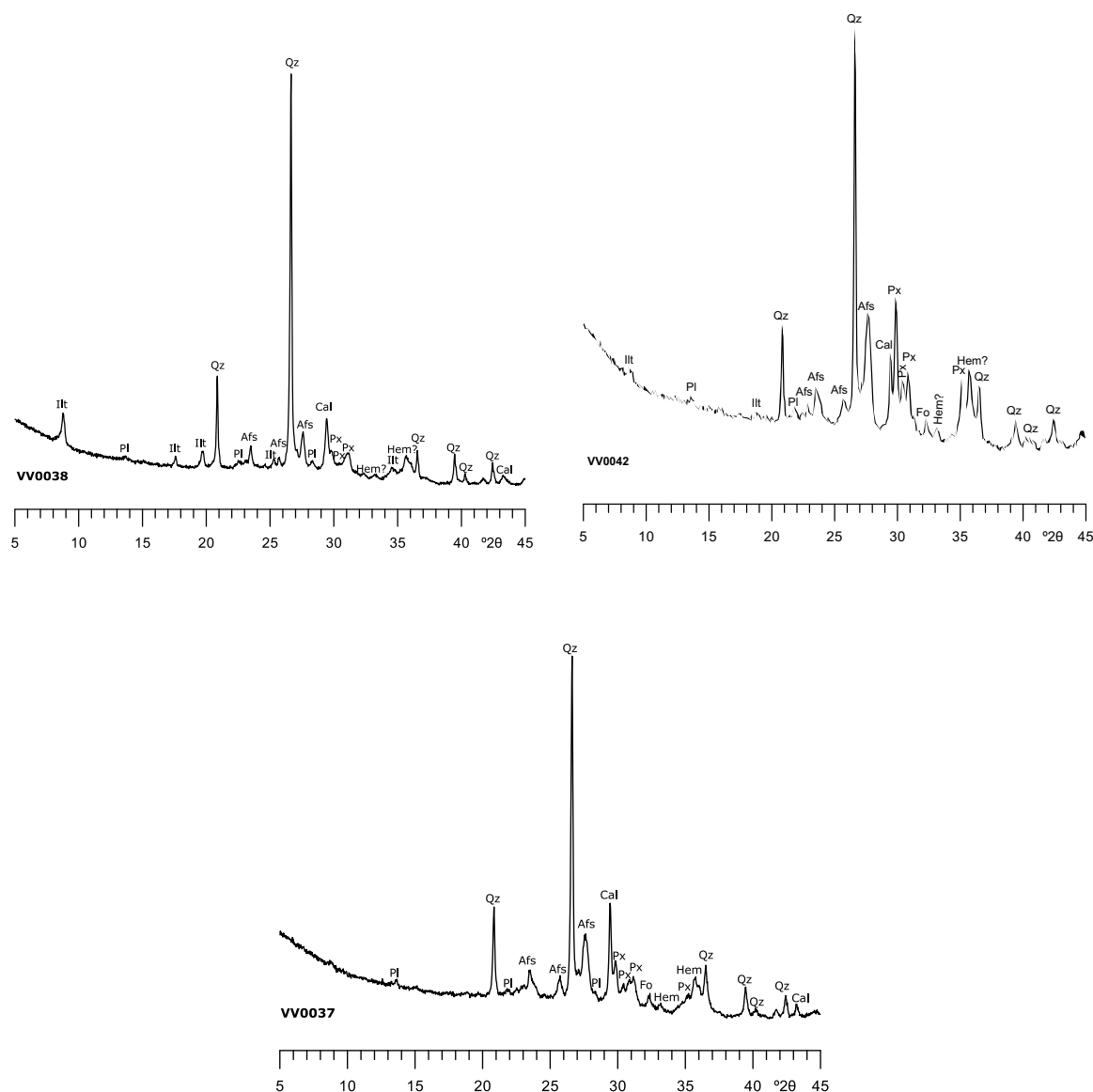


Figure 38. CGFNC01c representatives of Fabrics 1, 2, and 3 labeled. Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Illt = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Qz = quartz; Abbreviations follow Warr (2021). a) VV0038 (Fabric 1) b) VV0042 (Fabric 2) c) VV0037 (Fabric 3)

Of the Iberian loners, VV0052 has an EFT of < 950/1000 °C. (Figure 39). It is characterized by the presence of Illt, Afs, and probably Pl as primary phases, and has the development of Px as a firing phase, and probably hercynite (Hc), which is a characteristic mineral from oxygen poor reduction environments. The presence of these phases, alongside potentially Fo, suggest high firing temperatures.

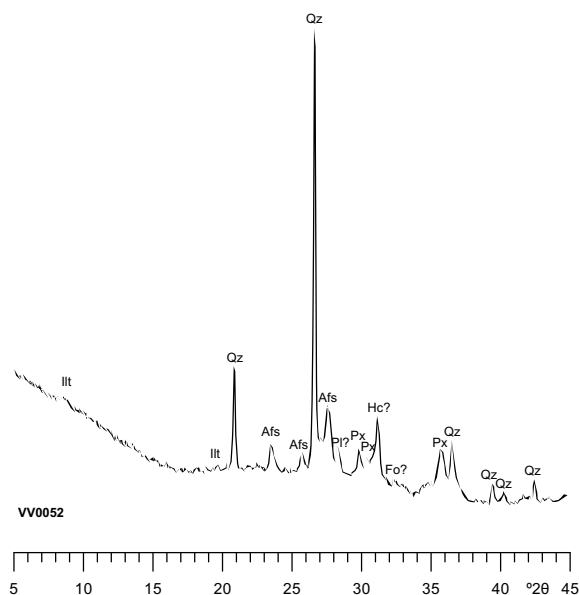


Figure 39. Iberian VV0052 diffractogram labeled. Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Ill = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Qz = quartz; Abbreviations follow Warr (2021)

VV0040 similarly has an approximate VV0052 has an EFT of < 950/1000 °C. (Figure 40). It is characterized by the presence of Ill and Afs as primary phases. The development of Px indicate potential firing phases

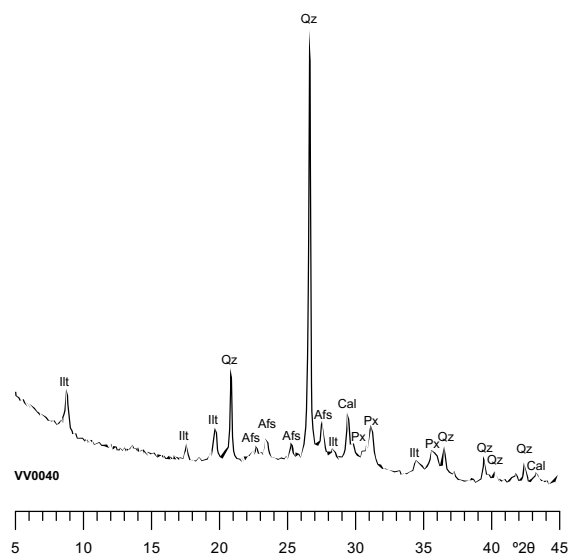


Figure 40. Iberian VV0040 diffractogram labeled. Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Ill = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Qz = quartz; Abbreviations follow Warr (2021)

VV0046 has an EFT of < 950/1000 °C (Figure 41). It is characterized by the presence of Illt, Afs, and Pl and has the development of Px and Hem, probably as firing phases. The presence of these phases, alongside the lack of intensity from Illt, could suggest higher firing temperatures. The range is established based on the lack of complete decomposition from the Illt.

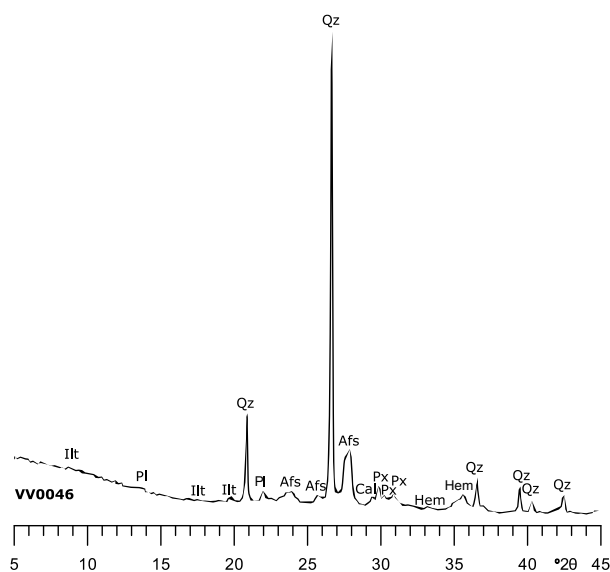


Figure 41. Iberian VV0046 diffractogram labeled. Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Illt = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Qz = quartz; Abbreviations follow Warr (2021)

VV0047 has an EFT of < 950/1000 °C (Figure 42). It is characterized by the presence of Illt, Afs, Pl, and Hem and has the development of Px as firing phases.

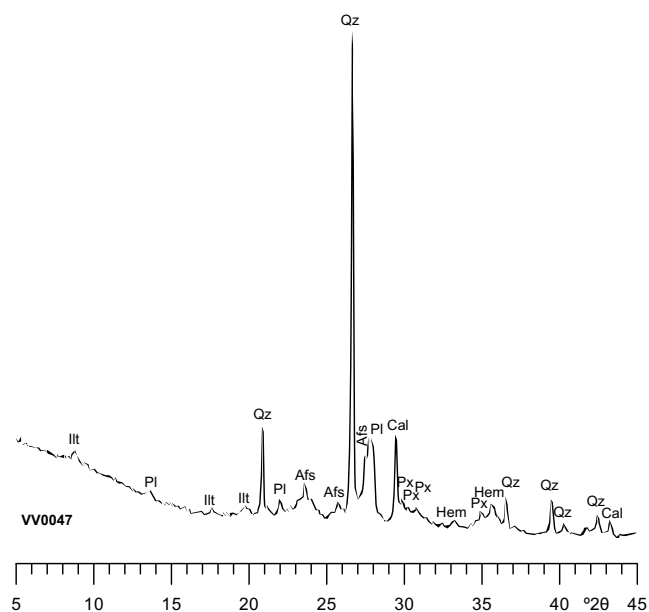


Figure 42. Italic VV0047 diffractogram labeled. Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Illt = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Qz = quartz; Abbreviations follow Warr (2021)

Italic individual VV0055 has a EFT of 800/850–950/1000 °C (Figure 43). It is characterized by the presence of Illt, Afs, and Pl as primary phases, and has the development of Px, Gh, and Hem as firing phases. The presence of these phases, especially Gh, establish the EFT range as Gh has developed but not decomposed yet.

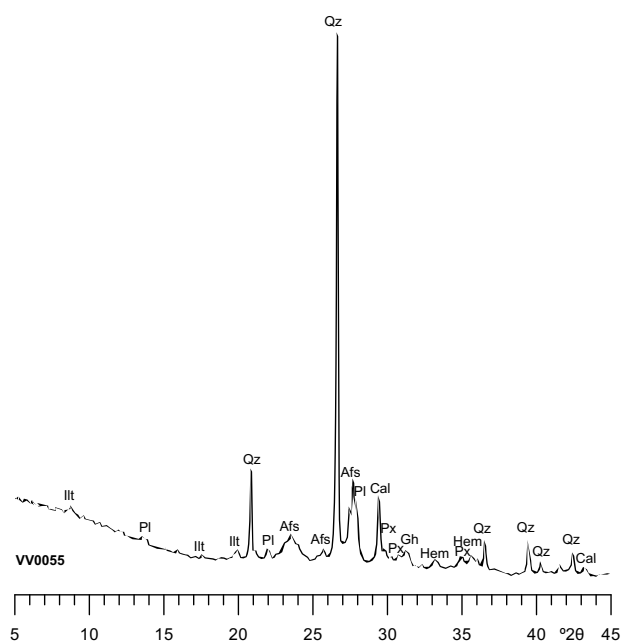


Figure 43. Italic VV0055 diffractogram labeled. Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Ilt = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Qz = quartz; Abbreviations follow Warr (2021)

The Punic individual from Malaga, VV0056 has an EFT of < 950/1000 °C (Figure 44). It is characterized by the presence of Ilt, Afs, and Pl as primary phases, and has the development of Px and Hem as firing phases. The presence of these phases could suggest higher firing temperatures, but it cannot be ensured in loners, so the range is established based on the lack of complete decomposition from the Ilt.

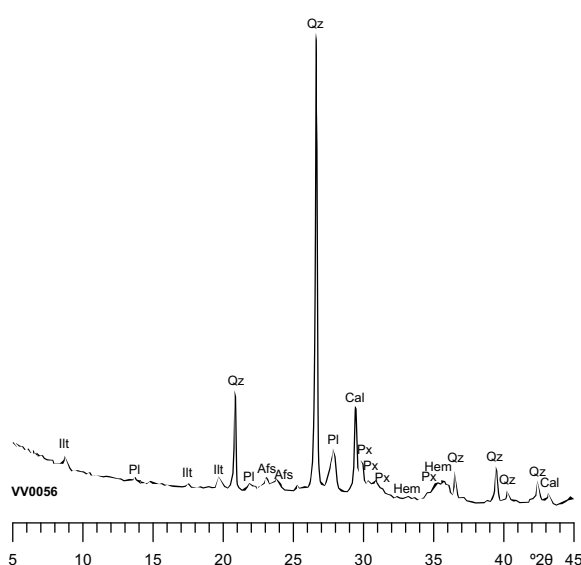


Figure 44. Punic VV0056 diffractogram labeled. Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Ilt = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Qz = quartz; Abbreviations follow Warr (2021)

The Punic Ebussitan sample VV0032, has an EFT of 900/950 – 950/1000 °C (Figure 45). It is characterized by the presence of Ilt, Afs, and Pl as primary phases, and has the development of Px, Hem, Gh and Spinel (Spl) as firing phases. Spl is typically a mineral developed in low calcareous ceramics, and Gh is typically found developed in calcareous ceramics. As this piece is border calcareous, it presents development of both of these mineral phases. The temperatures that these minerals appear and decompose allow for the EFT to be established with a very small range.

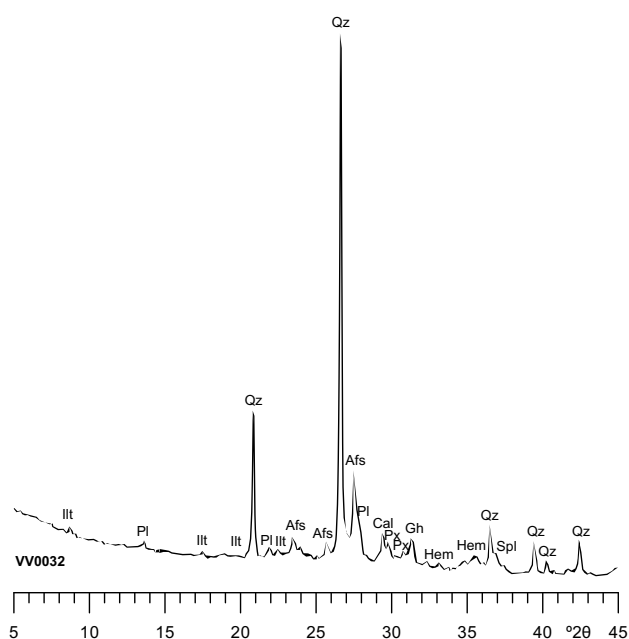


Figure 45. Punic VV0032 diffractogram labeled. Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Ilt = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Spl = Spinel; Qz = quartz; Abbreviations follow Warr (2021)

The Punic Ebussitan sample VV0057, has an EFT of 800/850 – 950/1000 °C (Figure 46). It is characterized by the presence of Ilt, Afs, and Pl as primary phases, and has the development of Px, Hem, and Gh as firing phases. The temperatures that these minerals appear and decompose allow for the EFT to be as well-fired.

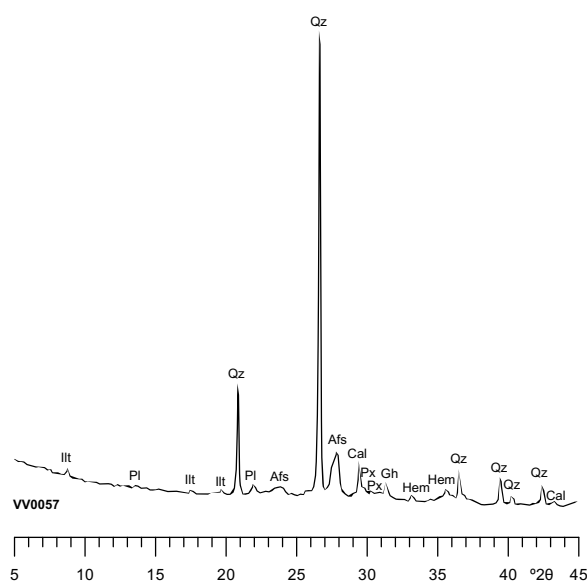


Figure 46. Punic VV0057 diffractogram labeled. Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Illt = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Qz = quartz; Abbreviations follow Warr (2021)

Lastly, the Central Mediterranean example VV0034 has a low EFT of < 800 – 850 °C (Figure 48). It is characterized by the presence of Illt and Afs as primary phases, and has Hem, which usually indicates a firing phase. In this case, since there is no decomposition of the calcite, the Hem must be primary and the EFT is low. Since it displays very non-intense peaks of Illt, and has very little potassium (K₂O), it may not be an illite – muscovite clay base.

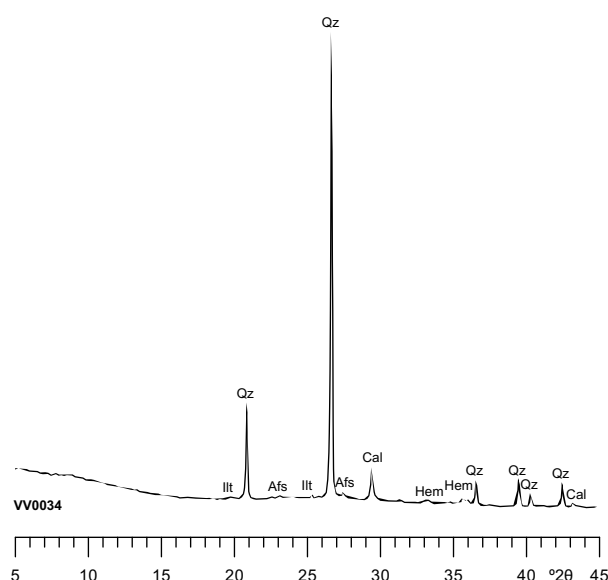


Figure 48. Punic VV0034 diffractogram labeled. Mineral abbreviations used are: Afs = alkali feldspar; Cal = calcite; Cen: Clinoenstatite; Gh = gehlenite; Fo: Forsterite; Hem = hematite; Hc = Hercynite; Illt = illite (illite–muscovite); Pl = plagioclase; Px = pyroxene; Qz = quartz; Abbreviations follow Warr (2021)

6. Discussion

6.1 Iberian

All the Iberian amphorae studied were classified as Sanmartí 2B typology, though these are known to be produced in a variety of workshops and kilns. Three chemical groups named for this site containing 9 amphorae were defined: CGDVV01, CGDVV02, and CGDVV03. CGDVV01 is characterized by being low calcareous with an elevated aluminum and magnesium content. CGDVV02, even if still low calcareous, has a

slightly higher concentration of calcium, with a high magnesium content. CGDVV03 corresponds to a calcareous paste and also has an elevated magnesium content. The two individuals in CGDVV03 were identified to be of close chemical relation to a group from Pontons (Alt Penedès, Catalonia). This was a known production area with many different identified kilns (Cardona i Colell, 2018). These amphorae likely originated from this area, which is about 20-35 km away from Vilar. However, it is challenging to accurately identify which of these sites the amphorae came from, though they align best with those from Font dels Ígols, due to the geographic similarities between production centers in the area. The equivalent firing temperatures that have been estimated from the diffraction mineralogy results for these two amphorae are below 950-1000 °C.

Next, 10 amphorae were identified to be chemically and statistically related to three previous groups defined from Fontscaldes, a production center only 3 km from Vilar (Peix, 2026). These are characterized from a to c from least to most calcareous. CGFNC01a is border calcareous and exhibits an elevated magnesium. CGFNC01b is calcareous, with a very high magnesium content. CGFNC01c is the most calcareous, with a high magnesium. Despite this close compositional relationship, Fontscaldes has been established, since its appearance in the literature, to have begun producing ceramics nearly a hundred years after the destruction of Vilar, between the mid 2nd and early 1st centuries BCE (Cardona Colell, 2021). As the imported ceramics line up with the already established late 3rd c BCE dating for Vilar, there is too significant a discrepancy between them to confirm this production site as the provenance for these pieces.

Archaeometry provenance functions under the incertitude area of provenance or non-resolution space and the conjunction areas: even when samples align very closely with known production centers, there is still a degree of uncertainty and a different unknown production center in the same geographical area could produce chemically indiscernible results (Buxeda and Madrid, 2017). Because of this, it is possible that the amphorae at this deposit were not necessarily produced in the later Fontscaldes workshop. Despite this circumstance, the significant years of rigorous archaeological

interventions into the area call into doubt the possibility of a large-scale production center that has not yet been identified.

To date, three individuals (VV0040, VV0046, and VV0052), when compared with other Iberian amphorae from the database, were not identified as related to any known production center. These amphorae varied significantly from the rest of those found at the site. These amphorae emphasize the importance of creating databases whenever production centers are identified. Without these databases, it is very difficult to accurately pinpoint their provenance.

At the least, they show the variety of ceramics that were being produced in distinct Iberian contexts, which were then used throughout the area of their reach and beyond. As amphorae from southern Spain has been established using Organic Residue Analysis to contain mostly beer, with occasional wine, all of the amphorae found help understand the habits of those who lived in Vilar (Sanmartí et al., 1998). The general trend of high magnesium is not particularly common, which could be due to minerals such as magnesite in the primary materials. Because of this, these levels may point to particular technological decisions that are unique to these areas of production.

6.2 *Punic*

Based on typology from the archaeological excavation and reconstruction, three types of amphorae were identified within the Punic samples. Two of them were identified as Ebussitan T.8.1.3.1, one was identified as Central Mediterranean Mañà C, and one was identified as T.8.2.1, from the area of the Strait of Gibraltar. Our investigative work has found that the pastes from the Mañà C and T.8.2.1, at macroscopic level, do not resemble any of the other amphora found, nor do they resemble each other. The Ebussitan individuals generally strayed from the Iberian pastes as well, though a few fine Iberian samples were similar. These findings give an initial outlook into the geographic contexts in which the different typologies were produced.

After chemical analysis and comparison to the Punic database, the two Ebussitan amphorae have been identified as most likely from distinct production centers. However, both chemically align broadly with other Ebussitan samples analyzed in the past studies (Figure 29). Since we found that the amphorae do not closely align to any

specific production center, we are not able to provide a more concrete estimation. Despite this, since Iberian trade with Ebusitan Phoenicians was common, it is not a great surprise that these amphorae were present (Tsantini et al., 2005). This is especially reasonable when the Phoenician presence in the area was reaching its peak prior to the Second Punic War with Rome.

Next, the central Mediterranean amphora does not chemically or macroscopically display similarities to any of the other amphorae previously analyzed that can be found in the database, and therefore we are unable to confirm where this amphora was made from its chemical composition. It strays greatly from the rest of the samples in chemical and mineralogical makeup, and even indicates the possibility of not being made from the same illite – muscovite clay base as the rest. It also has a very low EFT of < 800/850, indicating a potential difference in firing techniques as opposed to the other Punic samples which had higher EFTs (Table 3).

Lastly, the amphora that was identified as from the Strait of Gibraltar aligns very closely with chemical compositions from known workshops such as Juan XXIII in Malaga (Fantuzzi et al. 2024). Specifically, these production centers are known to have produced amphorae that traveled as far as Corinth (Fantuzzi et al., 2020). Amphorae from this area were an important piece in the Punic trade system, and therefore a variety of typologies are not uncommon to find in Iberian sites such as Vilar (Albelda et al., 2022). The chemical group that most closely aligned with these production centers also generally contained pieces that have been dated to approximately the same timeframe as Vilar, in the late 3rd c BCE, further confirming the scope of Phoenician trade routes all throughout the Western Iberian Peninsula at the time. Before the Second Punic War, trading posts from the Carthaginians were found throughout the Iberian Peninsula. Amphorae were a common trade piece, usually used to store wine, salt fish, and garum. The specific production centers in Malaga are typically linked to salt fish, and the breadth of its reach indicates its importance in Mediterranean commerce (Fantuzzi et al., 2020). Unfortunately, similarly to the Italic amphorae, organic residue analysis has not been performed to identify what these specific specimens contained.

6.3 *Greco-Italic*

The two Italic amphorae have not been able to be linked to any specific production center using the current available resources, likely due to limitations in the breadth of Greco-Italic references available within the database. However, as expected, when compared to the other amphorae from the same deposit, they show a more similar composition to each other than those of different typologies. Even then, we have determined them to be chemically distinct enough from each other that they are unlikely to come from the same production.

Through ocular microscopy, we have established an initial corroboration, as the pastes are very similar, both being coarse ware and having large black inclusions. This could indicate volcanic rocks that are common in finds from Italic production centers in the south of Italy (Carratoni, 2016). Italic amphorae of Type C have been found throughout the Mediterranean, including Empùries in Catalonia and Minorca on the Balearic Islands, as they are of the most common type of Greco-Italic amphora found (Lyding Will, 1982). Type B is less commonly found and likely represents a short-lived transitional phase in the late 3rd c BCE (Lyding Will, 1982). These types of imported amphora are mostly identified as containing wine or garum, important trade pieces throughout the Mediterranean (Bernal - Casasola, 2015). Unfortunately, organic and residue analysis of these two amphorae has not been done yet, but this could be a further venture in order to understand the trade patterns of Vilar. Through this systematic approach, we can confirm that the amphorae we are discussing are not examples of local productions mimicking Italic forms. Thus, Italic origins of these amphorae can be confirmed, although the precise origin of the production centers remain unknown.

7. Conclusions

As evidenced throughout this project, Vilar was an important example of contact with surrounding Iberian production centers, as well the Carthaginian and Roman trade systems (Figure 42). Prior to its destruction, it served as a storage location for a large number of amphorae of distinct provenances and typologies.

Using chemical and mineralogical techniques, several of the Iberian specimens were established to display similar compositional and technological characteristics to

those produced in the nearby workshop in Fontscaldes. Due the lack of agreement between the dating of these sites, further research will have to be conducted in order to fully understand whether these dates need be reexamined or if there could be an unknown production center nearby.

One group of Iberian amphorae indicated a provenance near Pontons, in the Alt Penedès. As this area is known to have a large quantity of kilns, and is approximately 30 km from Valls, it helps us understand the trading patterns of these communities. The rest of the Iberian amphoras that grouped together were unique to this site and did not fit into Reference Groups from known production centers. Nevertheless, they shared the high magnesium contents that, to present, are typical characteristics of the products from Fontscaldes and the Alt Penedès.

The imported wares were generally also unmatched, though they present the great variety of typologies and the important reach of the Carthaginians at the time. In particular, the only individual that was able to have its provenance established likely came from a production center in Malaga whose wares have been found as widespread as Corinth, Greece. Despite the building tensions prior to the Second Punic War, which would result in the eventual destruction and abandonment of Vilar, the trade systems and therefore daily lives of people from all three cultures were evidently linked. Finally, even if we cannot establish a clear relationship to specific production centers, the two Ebussitan amphorae are, most probably, related to two different production centers located in this Island of Ebussus, deepen in our knowledge of the relationship between Vilar and the western Punic world.

Through the digitalization of these amphoras, we have been able to accurately reproduce the colors, textures, and fractures of the reconstructed pieces in order to allow for further study beyond its return to Valls. This, alongside the characterization created throughout this project, will allow for further studies with an ever – expanding cohort of comparison reference groups from within and outside the research group. Its chemical and mineralogical data have allowed for the establishment of provenance for many Iberian wares, and has allowed us to further unravel their roles in the daily lives of those in Iberian Catalonia. The characterization of imported wares further

establishes the relationships between ancient communities throughout the 3rd century BCE.

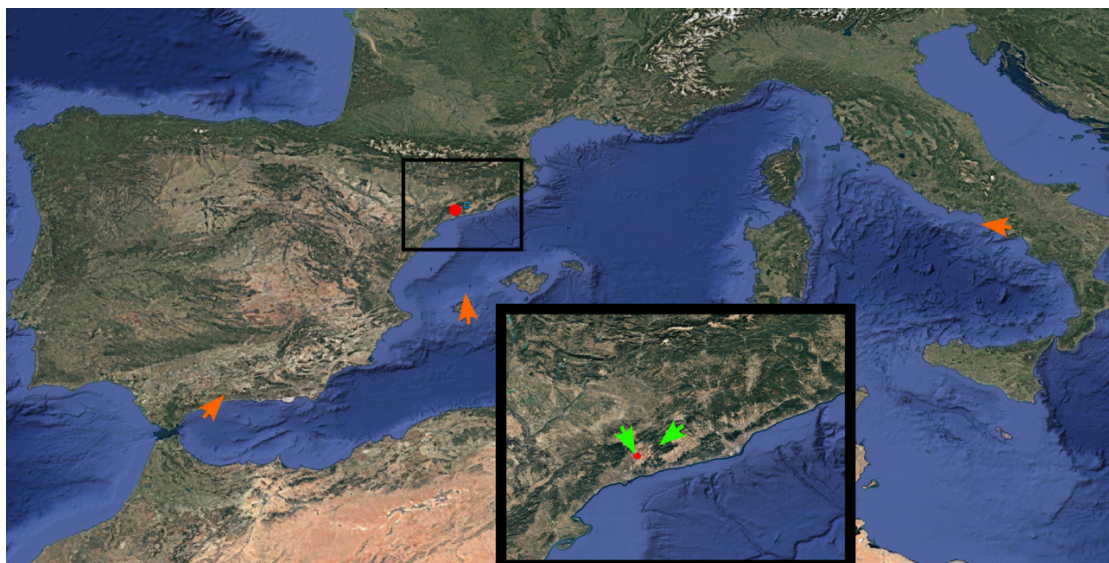


Figure 49. Map of production centers (green arrows, Fonstcaldes and Pontons) and import locations (orange arrows, Malaga, Ibiza, Naples) to Vilar (red) (via Google Maps, QGIS)

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Annex 1. Tables

Table 1. WD-XRF results on the individuals studied. Major and minor elements, expressed as oxides, and loss on ignition (LOI) are in mass fraction percentage (w %). Trace elements are in w mg/kg

	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	K ₂ O	CaO	TiO ₂	V	Cr	MnO	Fe ₂ O ₃	Co	Ni	Cu	Zn	Ga	Rb	Sr	Y	Zr	Nb	Mo	Sn	Ba	Ce	W	Pb	Th	LOI
VV0032	0.39	1.92	17.25	61.07	0.13	5.04	6.15	0.93	90	67	0.03	4.62	16	23	19	82	23	200	128	31	273	18	0	7	516	78	85	18	18	2.61
VV0033	0.39	5.34	18.35	53.59	0.14	5.24	5.74	0.80	110	76	0.07	7.12	20	38	29	105	25	206	331	28	175	16	0	4	592	76	26	18	13	3.17
VV0034	0.18	1.42	11.36	66.68	0.10	1.54	9.50	0.72	91	77	0.07	4.98	17	20	13	73	15	71	308	22	254	18	1	1	500	69	67	16	9	4.07
VV0035	0.36	6.42	17.04	56.57	0.18	4.96	4.55	0.80	97	60	0.06	5.78	16	29	30	107	22	177	543	30	216	15	0	4	699	76	24	19	14	3.13
VV0036	0.30	5.21	19.69	55.55	0.16	5.96	1.93	0.82	114	75	0.05	6.90	20	42	40	110	26	211	185	26	152	16	0	4	577	66	8	21	14	3.58
VV0037	0.31	6.85	15.64	51.80	0.20	5.08	8.59	0.76	87	60	0.07	5.30	16	27	31	138	21	169	1002	30	206	14	0	3	727	72	57	27	13	5.41
VV0038	0.38	6.04	15.75	53.89	0.16	4.83	6.48	0.76	84	49	0.07	5.74	16	25	21	108	20	158	420	28	191	14	1	3	638	71	16	30	14	6.21
VV0039	0.51	5.31	17.80	52.72	0.26	5.18	7.00	0.78	104	71	0.09	6.74	19	35	29	112	23	184	242	27	153	14	0	4	654	78	45	21	14	3.84
VV0040	0.22	8.45	16.88	52.03	0.16	4.49	5.34	0.80	101	58	0.06	5.74	15	30	37	190	22	153	942	28	189	14	0	2	719	73	8	33	11	5.56
VV0041	0.45	4.73	16.57	51.80	0.26	4.93	7.94	0.75	99	63	0.09	6.27	19	30	26	98	21	165	292	27	161	14	0	3	591	75	19	22	13	6.79
VV0042	0.43	6.86	16.70	50.69	0.20	5.00	10.51	0.74	91	67	0.07	6.03	18	31	28	132	21	172	302	27	158	14	0	2	525	75	32	34	14	3.47
VV0043	0.35	4.45	19.60	56.86	0.18	5.73	2.09	0.85	116	70	0.06	7.38	19	37	22	100	25	212	283	28	174	16	0	3	642	78	35	26	14	2.93
VV0044	0.35	5.37	20.15	55.22	0.32	6.06	1.25	0.82	114	74	0.06	7.72	21	37	30	121	26	224	189	27	139	16	0	4	594	71	18	24	13	2.99
VV0045	0.34	7.41	17.00	52.55	0.15	4.96	6.06	0.78	96	63	0.07	5.96	17	32	29	118	22	179	307	27	168	14	0	3	518	78	26	31	14	5.47
VV0046	0.70	1.84	16.34	62.47	0.28	3.45	6.24	0.88	107	68	0.08	5.72	18	29	22	146	20	126	174	32	238	16	0	3	698	87	65	68	14	2.48
VV0047	1.67	3.24	15.93	55.08	0.19	2.97	8.97	0.75	98	71	0.11	5.52	17	30	44	87	18	137	336	29	234	26	0	3	467	96	27	35	19	5.60
VV0048	0.30	7.35	16.46	52.19	0.16	5.14	7.03	0.76	91	69	0.07	5.72	20	29	29	113	21	174	355	28	175	14	0	3	543	66	54	24	14	4.94
VV0049	0.47	5.66	20.45	53.39	0.38	5.67	2.21	1.02	131	93	0.06	8.32	20	40	31	116	26	209	183	28	155	18	0	4	583	74	39	16	14	2.50
VV0050	0.44	6.04	18.10	54.26	0.14	5.20	4.40	0.77	95	63	0.07	6.45	18	33	30	97	24	198	396	28	182	15	0	5	604	80	15	18	15	4.32
VV0051	0.35	8.11	16.70	55.12	0.14	5.15	4.69	0.80	94	55	0.06	5.30	15	26	30	163	22	167	1302	30	224	14	0	3	627	77	27	25	12	4.01
VV0052	0.36	7.19	18.53	56.22	0.16	5.68	2.40	0.81	99	74	0.07	6.72	20	34	28	112	24	209	730	29	200	15	0	5	728	83	59	54	14	2.20
VV0053	0.37	7.02	14.72	51.38	0.15	4.35	8.25	0.72	79	50	0.08	5.12	15	25	30	133	19	152	1757	29	215	13	0	3	844	76	18	24	11	8.17
VV0054	0.42	5.84	19.84	53.80	0.18	5.81	4.52	0.80	108	75	0.05	6.92	20	41	40	107	26	220	260	26	137	15	0	3	560	80	31	19	13	2.14
VV0055	1.38	1.82	15.70	57.71	0.11	2.65	10.30	0.68	88	64	0.06	4.85	15	25	16	80	18	153	318	26	282	33	1	2	427	94	42	37	22	5.16
VV0056	0.48	2.50	14.27	55.78	0.16	2.85	11.54	0.78	100	86	0.07	5.60	18	37	31	81	18	119	280	26	182	16	0	2	409	72	29	26	12	6.49
VV0057	0.71	1.36	16.35	60.08	0.08	3.01	8.87	0.92	93	64	0.03	4.77	15	22	14	78	21	160	190	32	280	20	0	6	408	86	41	26	18	3.65
VV0058	0.38	7.79	16.56	55.33	0.16	5.14	4.15	0.79	87	55	0.07	5.60	17	27	27	115	22	169	332	31	204	15	0	2	472	77	20	26	14	4.77
VV0059	0.29	5.96	18.38	56.25	0.19	5.46	3.16	0.82	109	63	0.06	6.76	17	34	28	115	24	195	301	28	182	16	0	5	586	79	18	24	14	3.00

Table 2. Compositional variation matrix. Completar què són cada símbol (vt...)

	Fe2O3	Al2O3	MnO	P2O5	TiO2	MgO	CaO	Na2O	K2O	SiO2	Ba	Rb	Th
Fe2O3	0	0.0097	0.0757	0.0675	0.0210	0.2621	0.4846	0.2457	0.0632	0.0325	0.0394	0.0376	0.0600
Al2O3	0.0097	0	0.0987	0.0880	0.0102	0.2718	0.4534	0.2069	0.0503	0.0230	0.0367	0.0190	0.0310
MnO	0.0757	0.0987	0	0.1052	0.1048	0.2865	0.3501	0.2511	0.1801	0.0896	0.0789	0.1611	0.1282
P2O5	0.0675	0.0880	0.1052	0	0.1034	0.2965	0.6058	0.3037	0.1111	0.1316	0.0977	0.1188	0.1558
TiO2	0.0210	0.0102	0.1048	0.1034	0	0.3359	0.3907	0.2029	0.0879	0.0084	0.0398	0.0487	0.0326
MgO	0.2621	0.2718	0.2865	0.2965	0.3359	0	0.8812	0.7069	0.1456	0.3760	0.2355	0.2276	0.4060
CaO	0.4846	0.4534	0.3501	0.6058	0.3907	0.8812	0	0.3985	0.6557	0.3396	0.4369	0.5595	0.3528
Na2O	0.2457	0.2069	0.2511	0.3037	0.2029	0.7069	0.3985	0	0.3708	0.1889	0.2666	0.2596	0.1199
K2O	0.0632	0.0503	0.1801	0.1111	0.0879	0.1456	0.6557	0.3708	0	0.1253	0.0745	0.0208	0.1238
SiO2	0.0325	0.0230	0.0896	0.1316	0.0084	0.3760	0.3396	0.1889	0.1253	0	0.0444	0.0750	0.0322
Ba	0.0394	0.0367	0.0789	0.0977	0.0398	0.2355	0.4369	0.2666	0.0745	0.0444	0	0.0674	0.0909
Rb	0.0376	0.0190	0.1611	0.1188	0.0487	0.2276	0.5595	0.2596	0.0208	0.0750	0.0674	0	0.0589
Th	0.0600	0.0310	0.1282	0.1558	0.0326	0.4060	0.3528	0.1199	0.1238	0.0322	0.0909	0.0589	0
Nb	0.0768	0.0589	0.1293	0.1869	0.0477	0.5019	0.3379	0.1108	0.2049	0.0323	0.1167	0.1153	0.0231
Pb	0.1510	0.1306	0.1404	0.2074	0.1270	0.4540	0.4091	0.2352	0.2331	0.1149	0.1332	0.1919	0.1158
Zr	0.1118	0.0814	0.1472	0.2354	0.0494	0.5001	0.2737	0.1619	0.2187	0.0291	0.0922	0.1489	0.0486
Y	0.0320	0.0141	0.0890	0.1143	0.0069	0.3126	0.3479	0.1800	0.0861	0.0103	0.0330	0.0500	0.0256
Sr	0.4639	0.4502	0.3622	0.5843	0.4523	0.3404	0.6171	0.6808	0.4662	0.4326	0.3021	0.4883	0.5150
Ce	0.0364	0.0212	0.0772	0.1283	0.0151	0.3591	0.3202	0.1448	0.1201	0.0094	0.0484	0.0644	0.0175
Ga	0.0118	0.0026	0.1112	0.0961	0.0133	0.2560	0.4699	0.2383	0.0425	0.0282	0.0363	0.0153	0.0437
V	0.0077	0.0089	0.0875	0.0831	0.0090	0.3212	0.4327	0.2118	0.0870	0.0167	0.0437	0.0467	0.0445
Zn	0.0567	0.0483	0.0957	0.0992	0.0548	0.1926	0.4491	0.3024	0.0745	0.0679	0.0278	0.0794	0.1098
Cu	0.0691	0.0695	0.0936	0.1058	0.0951	0.1707	0.5100	0.2838	0.0834	0.1147	0.0838	0.0809	0.1299
Ni	0.0113	0.0195	0.0884	0.0788	0.0381	0.2587	0.4959	0.2513	0.0663	0.0529	0.0609	0.0378	0.0718
Cr	0.0233	0.0281	0.0965	0.1066	0.0200	0.3870	0.3941	0.2141	0.1301	0.0219	0.0727	0.0746	0.0515
τj	2.4508	2.2321	3.4280	4.2113	2.3149	8.4861	10.9663	6.5365	3.8219	2.3973	2.5594	3.0474	2.7888
tv/τj	0.8014	0.8799	0.5729	0.4664	0.8484	0.2314	0.1791	0.3005	0.5139	0.8193	0.7674	0.6445	0.7042
rντ	0.9824	0.9903	0.9649	0.9529	0.9907	0.5993	0.5872	0.8164	0.8607	0.9672	0.9578	0.9474	0.9337
	Nb	Pb	Zr	Y	Sr	Ce	Ga	V	Zn	Cu	Ni	Cr	
Fe2O3	0.0768	0.1510	0.1118	0.0320	0.4639	0.0364	0.0118	0.0077	0.0567	0.0691	0.0113	0.0233	
Al2O3	0.0589	0.1306	0.0814	0.0141	0.4502	0.0212	0.0026	0.0089	0.0483	0.0695	0.0195	0.0281	
MnO	0.1293	0.1404	0.1472	0.0890	0.3622	0.0772	0.1112	0.0875	0.0957	0.0936	0.0884	0.0965	
P2O5	0.1869	0.2074	0.2354	0.1143	0.5843	0.1283	0.0961	0.0831	0.0992	0.1058	0.0788	0.1066	
TiO2	0.0477	0.1270	0.0494	0.0069	0.4523	0.0151	0.0133	0.0090	0.0548	0.0951	0.0381	0.0200	
MgO	0.5019	0.4540	0.5001	0.3126	0.3404	0.3591	0.2560	0.3212	0.1926	0.1707	0.2587	0.3870	
CaO	0.3379	0.4091	0.2737	0.3479	0.6171	0.3202	0.4699	0.4327	0.4491	0.5100	0.4959	0.3941	
Na2O	0.1108	0.2352	0.1619	0.1800	0.6808	0.1448	0.2383	0.2118	0.3024	0.2838	0.2513	0.2141	
K2O	0.2049	0.2331	0.2187	0.0861	0.4662	0.1201	0.0425	0.0870	0.0745	0.0834	0.0663	0.1301	
SiO2	0.0323	0.1149	0.0291	0.0103	0.4326	0.0094	0.0282	0.0167	0.0679	0.1147	0.0529	0.0219	
Ba	0.1167	0.1332	0.0922	0.0330	0.3021	0.0484	0.0363	0.0437	0.0278	0.0838	0.0609	0.0727	
Rb	0.1153	0.1919	0.1489	0.0500	0.4883	0.0644	0.0153	0.0467	0.0794	0.0809	0.0378	0.0746	
Th	0.0231	0.1158	0.0486	0.0256	0.5150	0.0175	0.0437	0.0445	0.1098	0.1299	0.0718	0.0515	
Nb	0	0.1365	0.0389	0.0486	0.5256	0.0251	0.0751	0.0507	0.1418	0.1642	0.0930	0.0453	
Pb	0.1365	0	0.1209	0.1022	0.4468	0.0934	0.1520	0.1383	0.1164	0.2038	0.1641	0.1546	
Zr	0.0389	0.1209	0	0.0371	0.4026	0.0323	0.0938	0.0800	0.1208	0.2009	0.1451	0.0824	
Y	0.0486	0.1022	0.0371	0	0.3907	0.0090	0.0190	0.0212	0.0449	0.0885	0.0494	0.0368	
Sr	0.5256	0.4468	0.4026	0.3907	0	0.4135	0.4501	0.4785	0.3015	0.3877	0.4944	0.5270	
Ce	0.0251	0.0934	0.0323	0.0090	0.4135	0	0.0296	0.0218	0.0665	0.1004	0.0508	0.0311	
Ga	0.0751	0.1520	0.0938	0.0190	0.4501	0.0296	0	0.0117	0.0484	0.0685	0.0192	0.0320	
V	0.0507	0.1383	0.0800	0.0212	0.4785	0.0218	0.0117	0	0.0584	0.0766	0.0161	0.0110	
Zn	0.1418	0.1164	0.1208	0.0449	0.3015	0.0665	0.0484	0.0584	0	0.0696	0.0707	0.0954	
Cu	0.1642	0.2038	0.2009	0.0885	0.3877	0.1004	0.0685	0.0766	0.0696	0	0.0456	0.0985	
Ni	0.0930	0.1641	0.1451	0.0494	0.4944	0.0508	0.0192	0.0161	0.0707	0.0456	0	0.0279	
Cr	0.0453	0.1546	0.0824	0.0368	0.5270	0.0311	0.0320	0.0110	0.0954	0.0985	0.0279	0	
τj	3.2873	4.4724	3.4533	2.1491	10.9737	2.2354	2.3648	2.3647	2.7926	3.3944	2.7080	2.7625	
tv/τj	0.5974	0.4391	0.5687	0.9139	0.1790	0.8786	0.8305	0.8306	0.7033	0.5786	0.7252	0.7109	
rντ	0.8825	0.9434	0.8206	0.9891	0.3671	0.9603	0.9828	0.9934	0.9172	0.8943	0.9718	0.9775	
tv	1.9640												