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Ceramic production and trade in Eivissa (Balearic Islands, Spain) during Vandal rule: An integrated analytical study

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ABSTRACT

An assemblage of ceramics discovered at the Es Castell site in the island of Eivissa, Spain, represents a significant archaeological context dating back to the period when the Balearic Islands were under the rule of the Vandal Kingdom of Carthage. Through archaeometric analysis, new evidence has emerged regarding the production and trade of ceramics on the island during this era. The pottery selection examined includes common wares, amphorae, and cooking wares. Utilizing techniques such as WD X-ray fluorescence, X-ray diffraction, and optical microscopy through thin-section analysis, a comprehensive chemical, mineralogical, and petrographic characterization was conducted.

The results reveal that common wares, along with certain types of amphorae, were locally manufactured on the island, potentially in multiple production centers. Conversely, cooking wares and other amphorae were imported to Eivissa, as evidenced by their fabric composition, which does not align with the geological properties of the island and is also found in other archaeological contexts across the western Mediterranean.

1. Introduction and aims of the study

During the extensive temporal span recognized as Late Antiquity (Brown, 1971), the Mediterranean region underwent a profound transformation. This era, extending approximately from the reforms of Diocletian in the 3rd century CE to the coronation of Charlemagne in 800, stands as a pivotal phase of History. It witnessed a multifaceted alteration in the socio-cultural landscape, shaping the trajectory from the Roman world to the emerging medieval Mediterranean.

The Balearic Islands, located off the western coast of the Iberian Peninsula, including the three major islands of Mallorca, Menorca and Eivissa, were in a strategic position within the trade routes of the western Mediterranean, and particularly those linking north Africa with Galia and the Italian Peninsula with the Iberian Peninsula. This is the reason why the islands were traditionally overtaken by the different forces dominating the Mediterranean. Historically, since the 4th century CE the Balearic Islands functioned as an independent province within the Roman Western Empire. However, they shifted hands over time, coming under Vandal control in AD 455 and subsequently falling under Byzantine rule in AD 543. Notably, the Balearics witnessed a transformative transmutation, culminating in the Islamic conquest of the early tenth century, signifying a distinct departure from prior traditions. In this ever-evolving context, the Balearic Islands offer a unique laboratory for comprehending the multifaceted transformations that occurred during this extended historical epoch.

The island of Eivissa, along with the entirety of the Balearic Islands, bore witness to profound political, social, and economic changes during a pivotal era in its history. Among the most noteworthy occurrences was the annexation of these islands by the Vandal Kingdom of Carthage in AD 455. The Vandal foray into the western Mediterranean marked a momentous turning point in the fifth century (Courtois, 1955), as they encroached upon the Roman Empire's borders. Their westward

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expansion, beginning around AD 409, saw them firmly establish a presence in Baetica (southern Iberia). The Hidacio Chronicle recounts Vandal incursions in 425, impacting cities like Cartagena, Seville, and even the Balearic Islands. In 426, under the leadership of Geiseric, the Vandals crossed the Strait of Gibraltar, extending their dominion into North Africa. By 433, they had successfully captured Carthage, securing a strategically vital position for controlling the western Mediterranean. In 455, following a plundering campaign targeting Rome in the aftermath of Valentinian III's demise, the Balearics came under Vandal rule. The Vandal conquest of the Balearics marked a significant turning point, separating the islands from the destiny of the Iberian Peninsula under Visigothic rule. This circumstance likely contributed to the subsequent Byzantine control of the Balearics, with Muslim occupation becoming effective only two centuries after the occupation of mainland Iberia (Amengual, 2005: 92).

Despite the scarcity of written sources from the Vandal period (e.g., Amengual, 1988, 1991; Amengual and Cau Ontiveros, 2005), accounts from Victor de Vita offer insight into the Synod of Carthage in 484. This synod, convened with the aim of condemning Catholic bishops, saw Vandal king Huneric summoning bishops Macarius of Menorca, Helias of Mallorca, and Opilio of Ibiza. This historical episode highlights the enduring organization of Christianity during this time. Furthermore, the islands' close ties with Sardinia throughout Late Antiquity become evident. It is a recurring pattern that during this period, the Balearic archipelago maintained stronger connections with North Africa and the central Mediterranean than with the Iberian Peninsula. Despite the negative historical perspective regarding the Vandals, pottery studies reveal a period marked by thriving Mediterranean trade, with Africa and particularly Carthage playing a vital role not only as exporters of goods but also as redistributors of other commodities (e.g., Fulford, 1980; Reynolds, 1993, 2003, 2010a, 2010b, 2016) using the previous fleet and renovating the port as one of the main infraestructures (i.e. Merrils, 2004,2017).

The downfall of the Vandal kingdom can be attributed, among other factors, to a critical error—their decision to involve the Byzantine Empire in their internal affairs. This provided the opportune moment for Justinian, driven by his expansionist ambitions, to initiate the conquest of North Africa. In a swift and decisive campaign, Belisarius captured Carthage in the year 533. By December of the same year, following his triumph at the Battle of Tricamaro, he issued the order to seize all Vandal-held territories, including the Balearic Islands. The task of overseeing the archipelago was entrusted to Apolinarius, in recognition of his exceptional service during the war, particularly in the Battle of Tricamaro. Consequently, it can be reasonably assumed that in AD 534, Ibiza, Mallorca, and Menorca were incorporated into Byzantine dominion, marking the end of the 80-year Vandal rule in the Balearics. This significant turn of events reshaped the geopolitical landscape of the region.

Archaeological evidence from the Vandal period remains somewhat limited, but significant findings have shed light on this era. Some ceramic assemblages have been dated to the Vandal period. In Mallorca, in the city of *Palma*, a ceramic deposit dated to the third quarter of the 5th century (c. AD 450–475) (Cau et al., 2014). This deposit reveals the presence of imports, with African Red Slip wares and African amphorae dominating, accompanied by Eastern Mediterranean materials. Regional products from Eivissa were also identified, along with minor contributions from other regions. There are also ceramic materials that can be dated to the Vandal period in several sitse across the Balearics. This is, for example, the case of the Roman city of Pollentia (Alcúdia, Mallorca) (e.g., Arribas et al., 1973, 1978; Martin, 1983; Gumà and Riera, 1997), the early Christian basilica of Fornells (Menorca) (Buxeda et al., 1997), Son Peretó (Manacor, Mallorca) (e.g., Riera Rullan and Cau, 2013, 2022), Son Sard (Son Servera, Mallorca) (Riera Rullan et al., 2015) or the ancient city of Sanisera (Sanitja, Menorca) (Valente and Contreras, 2013).

It is noteworthy that the creation of certain garbage dumps, dating back to the mid-5th century, has been tentatively associated with potential destructions caused by the Vandals. One example is the cistern of ses Païsses de Cala d'Hort in Eivissa, where a cistern was filled with debris. One of the layers, containing materials from the 5th century, has been interpreted as the result of cleaning and discarding debris from a rural settlement due to Vandal-induced destruction (Ramon, 1986: 32). Another cistern, utilized as a dumping ground, was discovered at the rural site of Sa Mesquida (Santa Ponça, Calvià, Mallorca) (Cau, 2003; Orfila, 1988, 1989; Orfila and Cau, 1994; Orfila and Merino, 1989; Marimón Ribas et al., 2005). While there is no direct correlation with Vandal actions in this case, it remains a possibility since the majority of the materials are also dated to the mid-5th century.

Nevertheless, one of the best ceramic assemblages for the Vandal period in the Balearics come from the island of Eivissa and it was found at the site known as Es Castell, situated in the upper part of the ancient city of *Ebussus* (Fig. 1a). At this location, archaeological excavations have revealed deposits securely dated to this historical period (Ramon and Cau, 1997; Ramon, 2008). Es Castell has provided valuable insights into the island's history, revealing a prolonged sequence of occupation extending from the Phoenician era in the 6th century BCE to the Late Medieval settlement. Within this site, specific contexts associated with the Vandal period were uncovered on the northern side of Tower II (located in sector C.200), positioned adjacent to the main entrance of the castle (Fig. 1b-c). Of particular significance is stratigraphical unit 1205, identified as a rubbish dump dating from AD 475–525. This unit yielded an extensive quantity of pottery fragments and faunal remains. These archaeological findings offer a tangible connection to the Vandal period, shedding light on the material culture, daily life, and habits of the people who inhabited this region during that time. Such evidence is crucial for constructing a more comprehensive understanding of the Vandal period and its impact on the Balearic Islands.

The ceramic assemblage from this site comprised over 300 vessels, albeit somewhat fragmented. This collection included a mix of both imported and locally produced artifacts. Among the imported materials, fine wares held a predominant presence, with notable examples being African Red Slip wares and Gaulish 'dérivées-des-sigillées paléochrétiennes' or DS.P. Furthermore, a smaller quantity of imported cooking wares, amphorae, jars, and lamps were also identified within the assemblage. Conversely, most of the assemblage, comprising over half of the collection, is believed to consist of locally produced items. These primarily encompass common wares but also include a limited number of amphorae. This diversity in ceramic materials provides valuable insights into the trade networks, cultural interactions, and local production methods of the Vandal period in the Balearic Islands, contributing to our understanding of the region's historical and economic dynamics during this era.

Landscape studies conducted in various areas of Mallorca have suggested that around the mid to end of the 5th century, a significant reorganization of rural occupation occurred. This shift, which may have coincided with Vandal dominion but might not have been a direct consequence of it, could likely be marked by the end of the villa system as the primary model for rural exploitation (Mas-Florit, 2021; Mas and Cau, 2007; Mas-Florit and Cau, 2011, 2013, 2019). While direct Vandal-related findings in the region are scarce, these changes in landscape and rural organization could respond to internal processes with limited influence from the Vandal conquest itself.

Nevertheless, there is no doubt that the Balearics were integrated into the commercial networks of the period, andceramics serve as a crucial indicator for exploring these trade relationships. The study of these ceramics provides valuable insights into the trade patterns of the time and the role of the Balearics in these commercial interactions. This contributes significantly to our understanding of the historical and economic dynamics of the island during the Vandal period.

To further investigate the ceramic assemblage of Es Castell (Eivissa), a selection of vessels was sampled for an analytical study, employing a comprehensive approach encompassing petrographic, mineralogical,

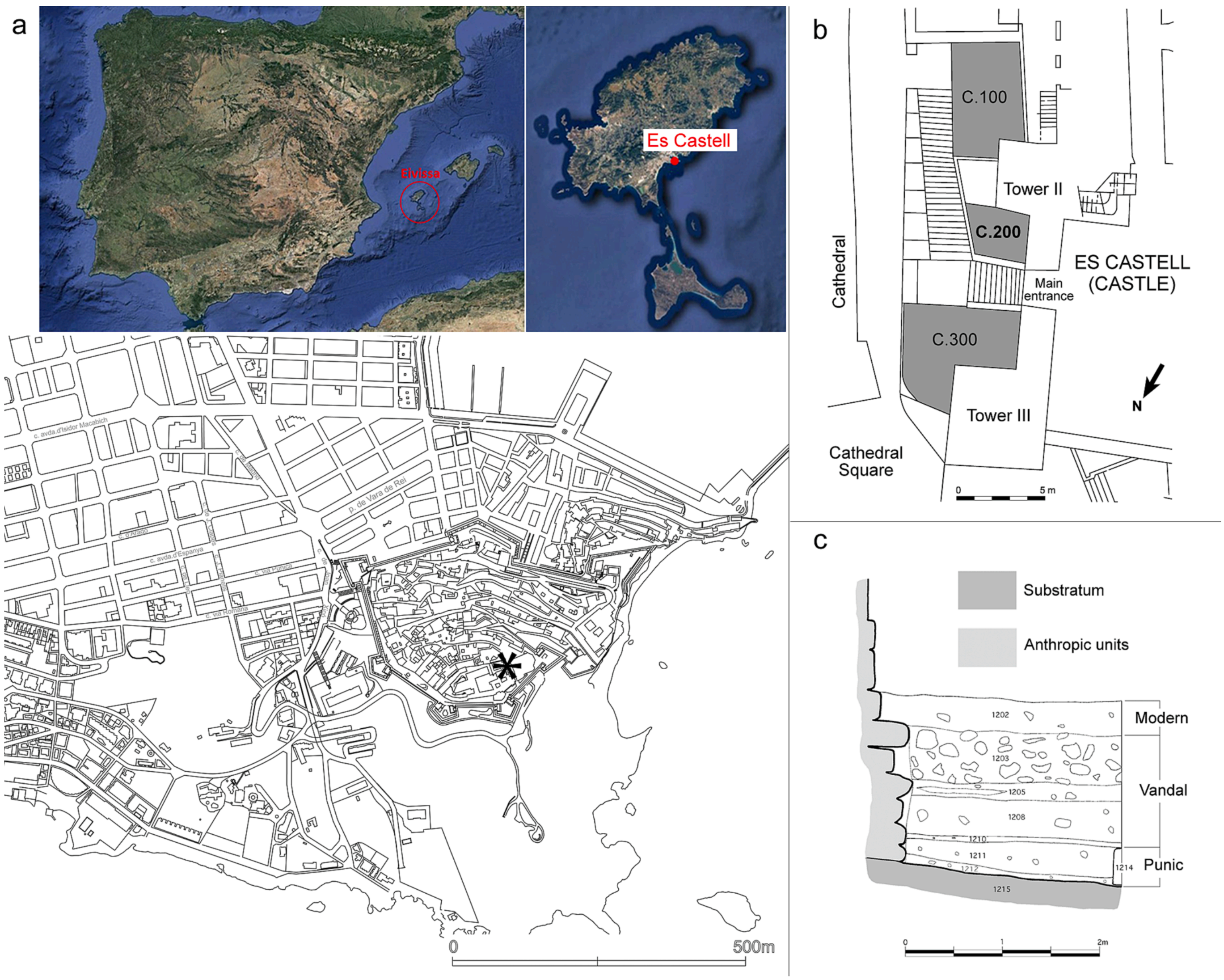

Fig. 1. (a) Location of Es Castell within the context of Eivissa and the Balearic Islands. (b) Plan of the site, with an indication of the sector C.200 where the Vandal context was excavated. (c) Section of sector C.200, with the stratigraphic sequence showing the Vandal layers.

and chemical analyses. The primary focus was on the ceramics presumed to be locally produced, aiming to characterize their composition, evaluate hypotheses regarding their provenance, and determine their compositional and technological variability. Additionally, imported cooking wares and amphorae were also subjected to analysis, with the objective of gaining insights into their composition and, consequently, investigating their provenance and technological characteristics.

Through this study, the ultimate objective is to enhance our understanding of pottery production and consumption in Eivissa during Late Antiquity, particularly during the period of Vandal rule over the island. By delving into these aspects, this research aims to shed light on the intricacies of the local ceramic industry and provide valuable insights into the broader socio-economic dynamics of the region during that historical period.

2. Analytical sampling

For the analysis, a total of 51 pottery samples were carefully chosen (Table 1). The selection criteria included diagnostic vessels, well-classified from a typological point of view, representing all the macroscopic groups defined for all the ceramic classes considered, and that could give at least 15 g of sample (weight required for the combination of analytical techniques to be applied). Most of these samples were obtained from the SU (stratigraphic unit) 1205, which is of particular significance. A few additional samples were also collected from other stratigraphical units, namely 1203 and 1209, which are likewise attributed to the Vandal period (Fig. 1c), based on the archaeological examination conducted by Ramon and Cau (1997).

Out of the selected samples, the majority (32) represent common wares that are presumed to have a local origin based on their macroscopic fabric and form. From a macroscopic point of view, most of the common wares corresponds to what are known as 'Ebusitan' products (see Ramon, 1986, 2008; Buxeda et al., 2005), this is to say ceramics likely produced in the island of Eivissa. These common wares encompass a variety of ceramic types, including jars (such as types RE-0206, RE-0501, and others), small bowls (RE-0807, RE-0808, and RE-0809), large bowls (types RE-0806 and RE-0816/RE-0817), spouting bowls (RE-0901 and RE-0902), and other forms (detailed in Table 1) (for further information on the RE- typology, refer to Ramon, 1986, 2008). Furthermore, some potential local amphorae were examined (types RE-0101, RE-0102, and others), alongside a few undetermined amphorae (ESC-01, ESC-03, ESC-48, ESC-52) that appear to be of imported origin based on their macroscopic characteristics.

The potential local products, including common wares and amphorae, account for nearly 60 % of the entire ceramic assemblage recovered from the site (Ramon and Cau, 1997). Therefore, it is crucial

Table 1
List of the samples analyzed, with their typological information.

Sample	Inv. number	Class/type	Sample	Inv. number	Class/type
ESC-01	C205-1	Amphora: indeterminate rim	ESC-27	C205-158	Common ware: large bowl RE-0817
ESC-02	C205-3	Amphora: simile Keay 19 (local imitation?)	ESC-28	C205-160	Common ware: large bowl RE-0806b
ESC-03	C205-10	Amphora: indeterminate spike	ESC-29	C205-163	Common ware: large bowl RE-0816 or RE-0817
ESC-04	C205-15	Common ware: jar RE-0206	ESC-30	C205-169	Common ware: bowl RE-0809?
ESC-05	C205-18	Common ware: jar RE-0501	ESC-31	C205-171	Common ware: bowl RE-indet.
ESC-06	C205-20	Common ware: jar RE-0206	ESC-32	C205-173	Common ware: bowl RE-0809?
ESC-07	C205-23	Common ware: jar RE-0206a	ESC-33	C205-175	Common ware: bowl RE-0817
ESC-08	C205-33	Amphora or small jar RE-0102	ESC-34	C205-176	Common ware: bowl RE-0817
ESC-09	C205-53	Common ware: jar RE-indet.	ESC-35	C205-180	Common ware: bowl RE-0817
ESC-10	C205-57	Amphora: RE-0101a	ESC-36	C205-219	Cooking ware: indeterminate cooking pot
ESC-11	C205-114	Common ware: spouting bowl RE-0901c	ESC-37	C205-221	Cooking ware: casserole (Cau, 2003 Fabric 3.2/3.3?)
ESC-12	C205-115	Common ware: spouting bowl RE-0901	ESC-38	C205-222	Cooking ware: casserole (Cau, 2003 Fabric 3.2/3.3?)
ESC-13	C205-116	Common ware: spouting bowl RE-0901a	ESC-39	C205-224	Cooking ware: casserole (Cau, 2003 Fabric 3.2/3.3?)
ESC-14	C205-119	Common ware: spouting bowl RE-0902 or variant	ESC-40	C205-226	Cooking ware: casserole (Cau, 2003 Fabric 3.2/3.3?)
ESC-15	C205-130	Common ware: small bowl RE-0809	ESC-41	C205-228	Cooking ware: casserole (Cau, 2003 Fabric 3.2/3.3?)
ESC-16	C205-131	Common ware: small bowl RE-0809	ESC-42	C205-231	Cooking ware: casserole (Cau, 2003 Fabric 3.2/3.3?)
ESC-17	C205-132	Common ware: small bowl RE-0809	ESC-43	C205-232	Cooking ware: casserole (Cau, 2003 Fabric 3.2/3.3?)
ESC-18	C205-134	Common ware: small bowl RE-0808	ESC-44	C205-234	Cooking ware: casserole (Cau, 2003 Fabric 3.2/3.3?)
ESC-19	C205-135	Common ware: small bowl RE-0808	ESC-45	C205-235	Cooking ware: casserole (Cau, 2003 Fabric 3.2/3.3?)
ESC-20	C205-139	Common ware: small bowl RE-0807	ESC-46	C205-237	Cooking ware: lid Hayes 196 (African)
ESC-21	C205-149	Common ware: large bowl RE-0806?	ESC-48	C203-3	Amphora: indeterminate spike
ESC-22	C205-150	Common ware: large bowl RE-0816 or RE-0817	ESC-49	C203-5	Amphora: RE-indet.
ESC-23	C205-151	Common ware: large bowl RE-0816 or RE-0817	ESC-50	C203-19	Common ware: bowl RE-indet.
ESC-24	C205-152	Common ware: large bowl RE-0817	ESC-51	C205-79	Common ware: jar RE-indet.
ESC-25	C205-153	Common ware: large bowl RE-0806b	ESC-52	C209-1	Amphora: indeterminate rim
ESC-26	C205-159	Common ware: large bowl RE-0816 or RE-0817			

to characterize these materials to explore whether they can be linked to specific production centers or at least to production areas within the island in broader sense, thus providing insights into the pottery manufacturing process on the island. Conversely, the analysis of indeterminate imported amphorae primarily aims to identify the possible regions of their production. The archaeological study (Ramon and Cau, 1997) documented a few Tunisian amphorae, but determining the provenance of the remaining indeterminate examples could contribute to investigating the origins of products transported in amphorae from other regions. By examining the chemical, mineralogical, and petrographic characteristics of these amphorae, valuable information can be obtained regarding their likely sources, contributing to a deeper understanding of trade and exchange patterns during the Vandal period in Eivissa.

In addition to the aforementioned materials, an additional set of 11 cooking wares was subjected to analysis (refer to online Table 1). The cooking ware assemblage discovered at Es Castell was predominantly characterized by handmade or slow wheel-made pottery, with a notable presence of short casseroles exhibiting a fabric containing abundant inclusions of mica, in particular biotite (appearing as abundant 'golden particles' in macroscopic observations as the main distinctive feature) (Ramon and Cau, 1997). Upon macroscopic examination, nine of these cooking wares bear resemblance to a fabric previously observed (and analytically characterized) in fifth-century contexts from the Balearic Islands (Cau, 2003, 2007: fabric 3.2/3.3), as well as in Alicante and Murcia (Reynolds, 1993, 2010a, 2010b: HMW8). The precise provenance of this fabric is currently undetermined, but it is believed to have been imported to the Balearic Islands. Previous analytical studies have demonstrated that fabrics that visually may appear similar can, in fact, be distinct products (e.g., Beltrán, 2005; Buxeda and Cau, 2004, 2005). Consequently, several cooking wares from Es Castell exhibiting a fabric rich in biotite were included in this analytical study to determine their potential association with any of the known fabrics mentioned above and to further explore their compositional variability.

The cooking wares discovered in SU 1205 that do not exhibit the aforementioned macroscopic fabric are quite limited in number. They comprise other handmade or slow wheel-made pottery, as well as wheel-made African cooking pots (Ramon and Cau, 1997). Two examples of these cooking wares were also included in the analytical study (refer to online Table 1).

The aim of the analysis is to delve deeper into the composition and properties of these cooking wares, providing insights into their potential provenance and production technology. By examining their chemical, mineralogical, and petrographic properties, this analysis aims also to explore possible variations within the biotite-rich fabrics already defined in other sites of the Balearics.

3. Methods

All the selected ceramic samples underwent comprehensive examination utilizing various techniques. Wavelength dispersive X-ray fluorescence (WD-XRF) spectroscopy enabled the chemical characterization of the samples. X-ray diffraction (XRD) analysis was conducted to determine the mineralogical composition of the samples. In addition, the samples underwent optical microscopy (OM) examination through thin section analysis. This petrographic-mineralogical study involved the preparation of thin sections of the ceramics, which were then examined under a microscope, helping in the identification of microstructural features, minerals, and rock fragments. By employing these three analytical techniques (WD-XRF, XRD, and OM), a comprehensive understanding of the chemical, mineralogical, and petrographic properties of the ceramic samples was obtained, enabling a detailed and thorough examination of their composition and characteristics.

The WD-XRF chemical analysis was carried out using a Phillips PW 2400 spectrometer with a Rh excitation source. Pulverized and

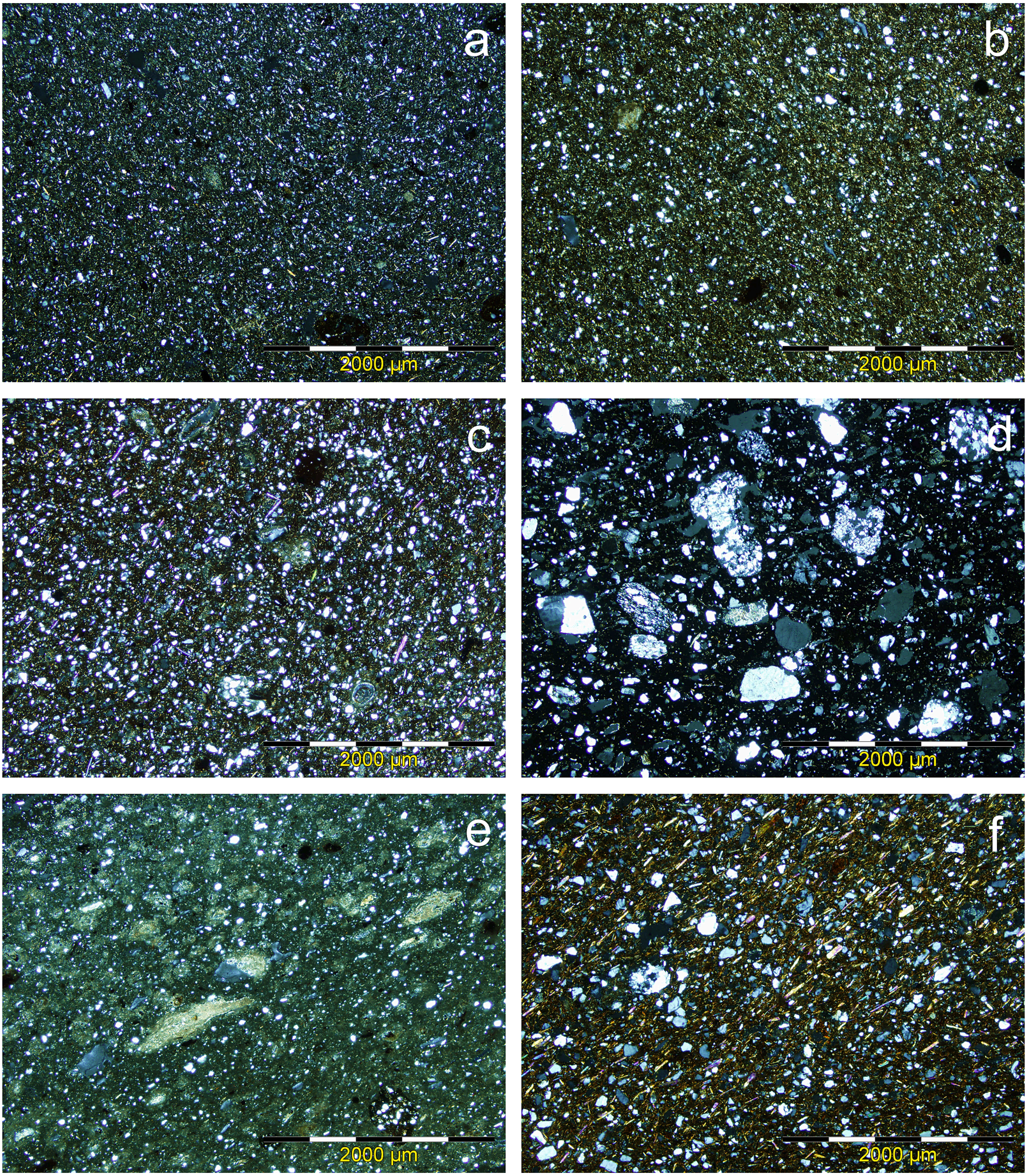

Fig. 2. Photomicrographs of thin sections of common wares and amphorae, taken in crossed polars at 40x. (a–c) Fine quartz and muscovite fabric group (a, ESC-24; b, ESC-34; c, ESC-12). (d) Acidic metamorphic and sedimentary fabric group (ESC-01). (e) Very calcareous fabric with fine quartz and muscovite (ESC-04). (f) Muscovite-rich fabric (ESC-48).

homogenized specimens were dried at 100 °C for 24 h. Major and minor elements were determined by preparing duplicates of fused beads using 0.3 g of specimen in an alkaline fusion with lithium tetraborate (1/20 solution). Trace elements and Na_2O were determined through pressed powder pellets, made from 5 g of specimen mixed with Elvacite agglutinating, placed over boric acid in an aluminum capsule and pressed during 60 s at 200 kN. A total of 25 major, minor and trace elements were determined. A calibration line based on 60 International Geological Standards was used for quantifying the elemental concentrations. The loss on ignition (LOI) was determined by firing 0.3 g of dried specimen, at 950 °C for 3 h. The obtained chemical data were transformed into additive log-ratios (alr) (Aitchison, 1986; Buxeda, 1999) and subjected to multivariate statistical treatment using the software S-PLUS 2000.

The mineralogical analysis through XRD was performed using a Siemens D-500 diffractometer, working with Cu-Kα radiation (λ = 1.5406 Å), and a graphite monochromator in the diffracted beam, at 1.2 kW (40 kV, 30 mA). Spectra were taken from 4 to 70°2θ, at 1°2θ/min (step-size 0.05°2θ; step-time 3 s). The crystalline phases were examined using the software High Score Plus by PANalytical, including the Joint Committee of Powder Diffraction Standards data bank. The mineral phases recorded through XRD allow for an estimation of equivalent firing temperatures (EFT) (Roberts, 1963; Maggetti, 1982; Murad and Wagner, 1996; Cultrone et al., 2001; Buxeda and Cau, 2004; Maggetti et al., 2011).

The petrographic-mineralogical analysis of thin sections by means of OM was carried out using an Olympus BX41 polarizing microscope, working with a magnification between 20X and 200X. The fabrics were analyzed and classified following the methodology by Whitbread (1989, 1995) and Quinn (2013).

4. Results

4.1. Common wares and amphorae

The OM petrographic analysis for the 40 samples of common wares and amphorae allows for the differentiation of two main fabric groups.

Most of these ceramics (35), including common wares and amphorae, can be grouped into a 'fine quartz and muscovite' fabric group (Fig. 2a-c), formed by fine grained fabrics with no added temper. These are characterized by fine quartz and micas, particularly muscovite, in addition to a variable frequency of fine carbonate inclusions (calcite and few microfossils), which are always present, though in varying quantities. The fine fraction of silt and very fine sand is predominant in all cases, with some samples showing a slightly coarser texture than others due to a higher frequency of very fine sand (Fig. 2a-c). Coarse inclusions are rare, and consist of iron nodules, clay pellets, limestone, calcareous fossils and quartzarenite; their presence is occasional, and no subfabrics can be clearly differentiated based on these inclusions. The clay matrix shows a brown, light brown or orange-brown color in PPL; it does not display optical activity except in very few cases (ESC-35 and, especially, ESC-49). Fine mesovoids are seen, but porosity is usually low. The characteristics of this fabric group points to the use of a calcareous and micaceous clayey raw material; no clear evidence of clay mixing is found.

XRD analysis for this 'fine quartz and muscovite' fabric group indicates that the equivalent firing temperature (EFT) for these ceramics is usually between 850 °C and 950 °C, as suggested by the presence of firing phases such as gehlenite and diopside (Table 2). There are very few samples that were low fired (EFT ≤ 800/850 °C) or high fired (EFT ≥ 950/1000 °C). The XRD mineralogical composition is typical of calcareous ceramics, except in a few specimens with lower CaO percentages (4–5 %) in which it is possible to find spinel as a firing phase (Table 2). In one individual, ESC-06, peaks of analcime are seen, indicating a post depositional alteration/contamination process which is characteristic of high-fired calcareous materials (Buxeda et al., 2002; Schwedt et al., 2006).

Table 2
Mineralogical composition and equivalent firing temperature (EFT) of the common wares and amphorae, based on XRD results. The samples are organized by fabric, according to the OM petrographic analysis.

Petrographic fabric	EFT (°C)	Minerals (XRD)	Individuals
Fine quartz and muscovite fabric group	≤800/850	Quartz, illite-muscovite, calcite, plagioclase, alkali feldspar	ESC-49
	850–900	Quartz, illite-muscovite, plagioclase, gehlenite, calcite, alkali feldspar, hematite (-)	ESC-02, 11, 12, 13, 15, 17, 18, 22, 23, 24, 25, 30, 32, 33, 35, 50, 51
	900–950	Quartz, illite-muscovite, plagioclase, gehlenite, pyroxene, calcite, alkali feldspar, hematite (-)	ESC-05, 08, 09, 10, 14, 16, 19, 28, 29, 31, 34
	900–950	Quartz, illite-muscovite, plagioclase, gehlenite, pyroxene, alkali feldspar, hematite (-)	ESC-27
	≥950/1000	Quartz, plagioclase, pyroxene, gehlenite, calcite, alkali feldspar	ESC-20
	≥950/1000	Quartz, plagioclase, pyroxene, gehlenite, alkali feldspar, spinel, hematite	ESC-07, 21, 26
	>1000	Quartz, plagioclase, pyroxene, gehlenite, calcite, alkali feldspar, analcime, hematite	ESC-06
Acidic metamorphic and sedimentary fabric group	850–900	Quartz, plagioclase, calcite, gehlenite, alkali feldspar, illite-muscovite, hematite	ESC-03
	900–950	Quartz, plagioclase, gehlenite, pyroxene, calcite, alkali feldspar, illite-muscovite (-), hematite (-)	ESC-01
	≥950/1000	Quartz, plagioclase, pyroxene, gehlenite (-), calcite, alkali feldspar, hematite	ESC-52
Very calcareous fabric with fine quartz and muscovite	~950/1000	Quartz, plagioclase, gehlenite, pyroxene, alkali feldspar, hematite (-), illite-muscovite (-)	ESC-04
Muscovite-rich fabric	≤800/850	Quartz, illite-muscovite, plagioclase, alkali feldspar, calcite	ESC-48

The second fabric group identified in the petrographic analysis ('acidic metamorphic and sedimentary') is represented by three specimens only (ESC-01, ESC-03 and ESC-52), which correspond to imported amphorae. They show a similar fabric in thin section (Fig. 2d), with an abundant coarse fraction, moderately sorted, composed of medium to coarse sand grains of quartz (subangular to rounded), acidic metamorphic rock fragments —derived from quartzite and quartz-mica schist, also few metagranite— and quartzarenite. Other common inclusions are alkali feldspar, limestone, calcareous fossils, and mudstone, as well as few plagioclase (rarely zoned) and occasional volcanic rock fragments derived from basalt or andesite, colorless clinopyroxene, and orthopyroxene. The fine fraction, mostly silt to very fine sand, comprises abundant quartz, micas —muscovite and biotite— and calcareous microfossils including foraminifera mainly, but also rare algae. The matrix shows a reddish brown to brown color in PPL, optically inactive (ESC-01, ESC-52) or with very low optical activity (ESC-03). Voids are frequent, including mesovughs, mesovesicles, and macrovughs. The

XRD patterns for this fabric group reveal a different mineralogical association in each sample, related to variations in the EFT, which is always above 850 °C, as suggested by the presence of firing phases in all the cases (Table 2).

Apart from these two well-defined fabric groups, there are two samples (jar ESC-04 and amphora ESC-48) that show individual fabrics in thin section and should be therefore considered as loners, meaning products that are represented just by one single specimen in the analysed sample. ESC-04, seems related to the first fabric group, since it is a fine fabric with quartz and muscovite inclusions, but it is differentiated by a much higher frequency of carbonate inclusions, which are dominant in the fabric, as well as a different clay matrix, with a yellowish-cream color in PPL (Fig. 2e). The inclusions are highly altered by the firing and the formation of secondary calcite, although remains of marine microfossils, including ostracods and foraminifera, can be identified. Coarse carbonate inclusions are relatively common, although evidence of tempering is not clear, since they seem more likely to be natural inclusions in the clayey raw material used, which must be associated with a marly clay. The EFT of this sample was relatively high, around 950/1000 °C, with an almost complete decomposition of phyllosilicates (Table 2).

As for the other petrographic loner, ESC-48, it shows a muscovite-rich fabric in thin section (Fig. 2f), with a fine-grained texture —inclusions ranging from silt to fine sand—, and no added temper. It is formed by predominant fine micas, mostly muscovite, and quartz. It is differentiated from the first fabric group by a much higher predominance of micas, a coarser texture (fine sand is more abundant in this fabric), and an accessory metamorphic contribution, as rare quartzite fragments can be found. Rare micritic calcite and occasional plagioclase and alkali feldspar are also present. The matrix shows an orange to brown color in PPL, and optical activity in XP. The absence of firing phases in XRD indicates relatively low firing temperatures (Table 2).

The normalized chemical data for the common wares and amphorae analyzed through WD-XRF (Table 3) reveal a calcareous composition (CaO > 5 %) for almost all the samples, but usually with CaO not higher than 15 %. According to these data, the two fabric groups defined from the petrographic analysis show clear differences in chemical composition. The samples with 'acidic metamorphic and sedimentary' fabrics (ESC-01, ESC-03 and ESC-52) are characterized by a lower content in Al_2O_3, K_2O, Rb, and Zr, and higher SiO_2, than the samples in the 'fine quartz and muscovite' fabric group. This can be especially associated with the higher abundance of quartz and acidic rock fragments in the former, and the higher micaceous content in the latter.

The petrographic loners ESC-04 and ESC-48 are also differentiated in chemical terms. ESC-04 shows much higher concentrations of CaO and Sr, in agreement with the high frequency of carbonate inclusions observed in thin section. ESC-48, on the other hand, is characterized by high K_2O and Rb, probably related to the abundance of muscovite in the fabric, in addition to clear differences in other elements in comparison with the rest of the data set, such as high concentrations of MgO, Na_2O, Pb, Y, and Ni, and low of Zr (Table 3).

Multivariate statistical treatment of the WD-XRF compositional data helps to better explore these chemical variations in the data set. A cluster analysis (Fig. 3) was performed on the alr transformed subcomposition Fe_2O_3, Al_2O_3, MnO, TiO_2, MgO, CaO, Na_2O, K_2O, SiO_2, Ba, Rb, Th, Zr, Y, Sr, Ce, Ga, V, Zn, Cu, Ni, and Cr, using Nb as divisor (P_2O_5 and Pb were left out from the analysis to avoid possible contamination problems). The samples with 'acidic metamorphic and sedimentary' fabrics are included in a well-defined chemical group in the cluster tree.

Almost all the samples in the 'fine quartz and muscovite' fabric group form a large cluster in the dendrogram, divided into two related clusters A and B (Fig. 3). The main difference between these clusters is seen in the bivariate diagram CaO vs SiO_2 (Fig. 4), with cluster A showing a higher calcareous composition and lower SiO_2% than cluster B. Even though the petrographic analysis reveals a gradual textural variability in this fabric group regarding the relative abundance of silt and very fine sand inclusions, it is observed that the samples in cluster B tend to contain a higher frequency of very fine sand inclusions of quartz than the samples in cluster A, where silty inclusions predominate. This can account for the observed differences in SiO_2%.

Further details on the chemical variability within this large cluster can be obtained through calculation of the compositional variation matrix (Aitchison, 1986, 1992; Buxeda, 1999; Buxeda and Kilikoglou, 2003). The obtained total variation value ($vt = 0.40$) is slightly higher than the usual accepted values for monogenic groups (Buxeda and Kilikoglou, 2003), so it might indicate the existence of two or more related compositional groups. According to the variation matrix, most of this variability is introduced by CaO ($\tau_{.CaO} = 3.44$). This is consistent with the differences observed in the bivariate and multivariate statistical treatment (Fig. 3 and Fig. 4).

The cluster analysis, in any case, suggests the existence of three chemical groups (QM-1 to QM-3) with higher compositional homogeneity (Fig. 3); their normalized chemical compositions are given in Table 4 online. A principal component analysis, based on the same alr transformed subcomposition as the cluster analysis, helps to better illustrate the differences between these groups (Fig. 5). The group QM-1, included in cluster A (Fig. 3), is mainly differentiated by higher CaO and Sr, and lower SiO_2, than the other two groups. All the samples in QM-1 are characterized, in thin section, by a finer texture than QM-2 and QM-3, due to a lower frequency of very fine sand inclusions of quartz (Fig. 2a). On the other hand, groups QM-2 and QM-3 can be distinguished from each other based on their concentrations of Fe_2O_3, Al_2O_3, TiO_2, Na_2O, and Cu (Tables 3-4; Fig. 5). In thin section, all the samples in group QM-3 present a distinctive fabric, with an even higher abundance of very fine sand quartz and muscovite inclusions (Fig. 2c) than the samples in group QM-2 (Fig. 2b). There is no other singularity in these fabrics that can be clearly associated with the aforementioned chemical differences between QM-2 and QM-3.

In summary, the chemical and petrographic evidence indicates that the variability found within the 'fine quartz and muscovite' fabric group may be explained by the presence of three chemical groups (QM-1 to QM-3), which tend to show differences in fabric as well. The calculation of the variation matrix for each of these groups yields low total variation values ($vt_{QM1} = 0.16$; $vt_{QM2} = 0.16$; $vt_{QM3} = 0.09$), supporting their interpretation as monogenic populations (Buxeda and Kilikoglou, 2003). In any case, the differentiation between these three groups is not always straightforward, especially in thin section where their boundaries are somewhat diffuse.

The sample ESC-06 behaves as a chemical outlier of the group QM-1 (Fig. 3 and Fig. 5). The presence of secondary analcime in this individual (as indicated by its XRD patterns) clearly affected the concentrations of Na_2O, K_2O and Rb (Table 3), because of a post-depositional alteration and contamination process (Buxeda et al., 2002; Schwedt et al., 2006).

4.2. Cooking wares

Nine of the cooking wares analyzed in this study correspond to a biotite-rich fabric to the naked eye. The thin section analysis reveals the same petrographic fabric for all these samples ('granodiorite/tonalite' fabric: Fig. 6a-b). It is characterized by an abundant and poorly sorted coarse fraction (0.20–3.50 mm, but usually below 1.00 mm), perhaps added as temper (although the evidence is not obvious), composed of plutonic rock fragments derived from granodiorite or tonalite, and large biotite flakes. Coarse inclusions of plagioclase, quartz and, to a lesser degree, alkali feldspar are frequent; these seem to derive from the same plutonic rocks. Accessory amphibole and epidote can be found in a few samples. The fine fraction (0.01–0.20 mm) is composed of abundant quartz and a lower frequency of other components, mainly biotite, plagioclase, and alkali feldspar. It is a porous fabric, with abundant elongated voids, in addition to frequent mesovughs and mesovesicles. The clay matrix is heterogeneous, with a darkened (reduced) core and lighter (oxidized) walls, the latter showing an orange-brown color in

Table 3
Normalized chemical results (WD-XRF) of the 40 common wares and amphorae. Concentrations of major and minor oxides are in %, other minor and trace elements are in ppm.

	Fe_2O_3	Al_2O_3	MnO	P_2O_5	TiO_2	MgO	CaO	Na_2O	K_2O	SiO_2	Ba	Rb	Th	Nb	Pb	Zr	Y	Sr	Ce	Ga	V	Zn	Cu	Ni	Cr
Fine quartz and muscovite fabric group																									
ESC-02	5.89	19.16	0.03	0.30	0.88	1.71	12.18	1.06	3.44	55.21	399	154	19	20	33	207	27	246	80	21	90	97	26	36	87
ESC-05	5.00	17.23	0.03	0.26	0.82	1.53	5.73	1.25	3.59	64.41	442	145	19	19	30	227	27	195	81	19	85	97	15	27	80
ESC-06	6.26	19.46	0.03	0.32	0.89	1.83	12.39	1.46	2.56	54.66	304	140	18	19	25	206	28	271	75	19	91	100	24	35	91
ESC-07	6.27	20.34	0.02	0.16	0.99	1.66	4.01	0.84	3.30	62.25	459	145	17	20	37	224	30	173	78	23	117	97	21	30	99
ESC-08	4.89	15.99	0.03	0.32	0.79	1.69	14.30	0.79	4.58	56.47	364	158	18	17	21	214	25	213	80	18	71	73	15	25	72
ESC-09	4.69	16.45	0.03	0.25	0.77	1.69	12.19	0.92	3.42	59.42	421	140	16	17	29	212	25	295	75	18	85	106	11	26	75
ESC-10	6.08	19.81	0.03	0.24	0.93	1.71	7.40	0.85	3.41	59.38	426	162	17	20	30	218	29	219	76	23	108	102	25	32	93
ESC-11	5.90	19.28	0.03	0.32	0.93	1.68	9.03	0.97	3.52	58.20	347	155	19	20	31	212	28	266	85	21	104	100	21	34	89
ESC-12	4.75	16.63	0.03	0.27	0.87	1.53	6.29	1.13	3.76	64.59	414	142	18	17	26	235	26	177	75	18	90	88	15	26	81
ESC-13	6.02	18.22	0.04	0.29	0.90	1.43	6.97	0.75	3.42	61.81	436	160	20	21	28	239	28	149	84	20	97	96	17	29	85
ESC-14	5.90	19.40	0.03	0.42	0.93	1.71	9.07	1.40	3.73	57.26	391	164	19	20	33	208	31	268	89	21	102	95	30	35	87
ESC-15	6.10	19.41	0.03	0.32	0.94	1.64	8.30	1.04	3.59	58.48	422	151	18	19	28	211	27	226	77	21	110	98	22	31	87
ESC-16	6.13	19.51	0.03	0.43	0.97	1.89	9.62	0.96	3.53	56.78	361	153	17	19	36	202	28	258	70	21	107	89	25	31	92
ESC-17	5.02	16.87	0.03	0.36	0.86	1.74	11.42	1.17	3.50	58.88	437	152	18	18	29	207	26	286	77	18	91	97	20	27	76
ESC-18	5.72	18.84	0.03	0.39	0.97	1.81	11.02	0.83	3.50	56.74	376	149	16	18	31	203	28	295	76	19	106	90	25	29	86
ESC-19	5.76	18.26	0.04	0.50	0.95	1.97	13.57	1.11	3.42	54.25	365	156	16	19	34	214	32	342	83	20	84	103	26	35	85
ESC-20	5.10	16.68	0.03	0.26	0.82	1.38	8.95	1.02	3.60	62.01	422	156	17	17	23	228	26	196	80	20	91	104	13	29	77
ESC-21	5.20	18.47	0.03	0.27	0.90	1.98	3.89	0.73	5.33	63.07	469	177	21	20	28	223	29	105	85	21	98	79	19	29	85
ESC-22	6.19	19.16	0.02	0.24	0.97	1.73	5.44	0.84	3.44	61.82	436	148	17	20	28	225	29	214	83	21	110	94	27	29	92
ESC-23	4.87	18.94	0.03	0.27	0.93	1.80	11.13	0.93	3.52	57.42	399	154	18	19	28	207	28	265	92	21	95	104	19	33	83
ESC-24	5.50	17.49	0.03	0.28	0.82	1.83	12.51	0.87	3.54	56.96	390	160	18	18	33	202	27	279	78	19	88	104	19	29	76
ESC-25	5.88	18.42	0.04	0.27	0.91	2.01	12.39	0.77	3.50	55.65	380	161	18	19	34	212	31	256	89	20	94	99	25	34	81
ESC-26	6.44	20.09	0.03	0.20	0.94	1.60	4.57	0.88	3.52	61.57	460	160	19	20	31	224	29	185	84	23	110	97	24	32	97
ESC-27	5.82	18.72	0.04	0.35	0.89	1.85	11.72	1.22	3.27	55.95	412	152	17	20	25	218	32	328	90	21	99	98	26	36	84
ESC-28	5.56	17.87	0.02	0.34	0.95	1.66	7.49	0.99	3.28	61.68	429	144	19	19	38	222	27	239	82	20	96	93	26	27	84
ESC-29	5.28	17.08	0.03	0.27	0.84	1.74	13.28	1.09	3.22	57.03	370	144	16	19	27	205	26	278	75	19	84	89	16	30	79
ESC-30	5.87	18.71	0.04	0.34	0.88	1.80	10.39	0.89	3.68	57.24	421	167	19	19	34	213	32	302	81	21	92	105	29	36	83
ESC-31	4.80	16.82	0.03	0.29	0.87	1.39	5.84	1.07	3.84	64.90	446	147	17	19	29	238	27	177	86	18	93	94	17	25	78
ESC-32	6.03	19.18	0.03	0.43	0.88	1.71	12.39	0.82	3.55	54.84	239	140	16	17	31	184	25	245	54	17	94	89	17	27	86
ESC-33	5.70	17.84	0.04	0.40	0.85	1.69	12.48	0.86	3.53	56.44	407	158	18	19	34	218	31	294	85	20	96	95	25	33	80
ESC-34	6.10	19.82	0.02	0.30	0.94	1.78	7.38	0.73	3.46	59.31	428	154	18	20	28	208	26	235	82	22	104	102	26	30	93
ESC-35	6.10	19.64	0.02	0.40	0.97	1.60	5.55	0.64	3.49	61.44	438	150	18	20	30	219	29	201	77	22	109	95	20	28	93
ESC-49	4.75	15.43	0.02	0.21	0.73	1.80	16.59	0.91	3.28	56.15	339	143	17	17	24	174	21	265	67	17	82	90	17	26	73
ESC-50	5.72	16.79	0.05	0.29	0.79	2.98	17.80	0.92	3.32	51.18	379	133	15	18	34	198	29	401	78	18	96	92	22	31	79
ESC-51	5.50	18.30	0.02	0.26	0.92	1.93	5.50	0.94	3.72	62.76	414	150	18	19	31	213	28	226	79	20	104	97	24	27	87
Acidic metamorphic and sedimentary fabric group																									
ESC-01	5.30	13.23	0.08	0.25	0.67	2.15	8.63	1.19	2.19	66.15	417	85	11	16	22	166	19	229	60	14	102	87	20	31	99
ESC-03	5.38	13.00	0.05	0.28	0.75	1.92	8.32	0.92	2.19	67.05	434	82	12	16	22	160	19	202	48	15	103	80	22	29	100
ESC-52	5.36	12.86	0.08	0.33	0.67	2.06	7.28	1.05	2.13	68.03	448	83	12	16	20	170	18	213	58	14	98	91	25	32	104
Very calcareous fabric with fine quartz and muscovite																									
ESC-04	4.96	17.06	0.03	0.50	0.71	1.85	21.58	1.20	3.03	48.91	389	141	14	16	18	178	25	423	72	20	76	108	23	36	76
Muscovite-rich fabric																									
ESC-48	5.85	18.26	0.06	0.29	0.75	3.11	5.10	1.49	4.66	60.25	516	197	25	21	140	169	42	163	81	23	77	77	23	75	110

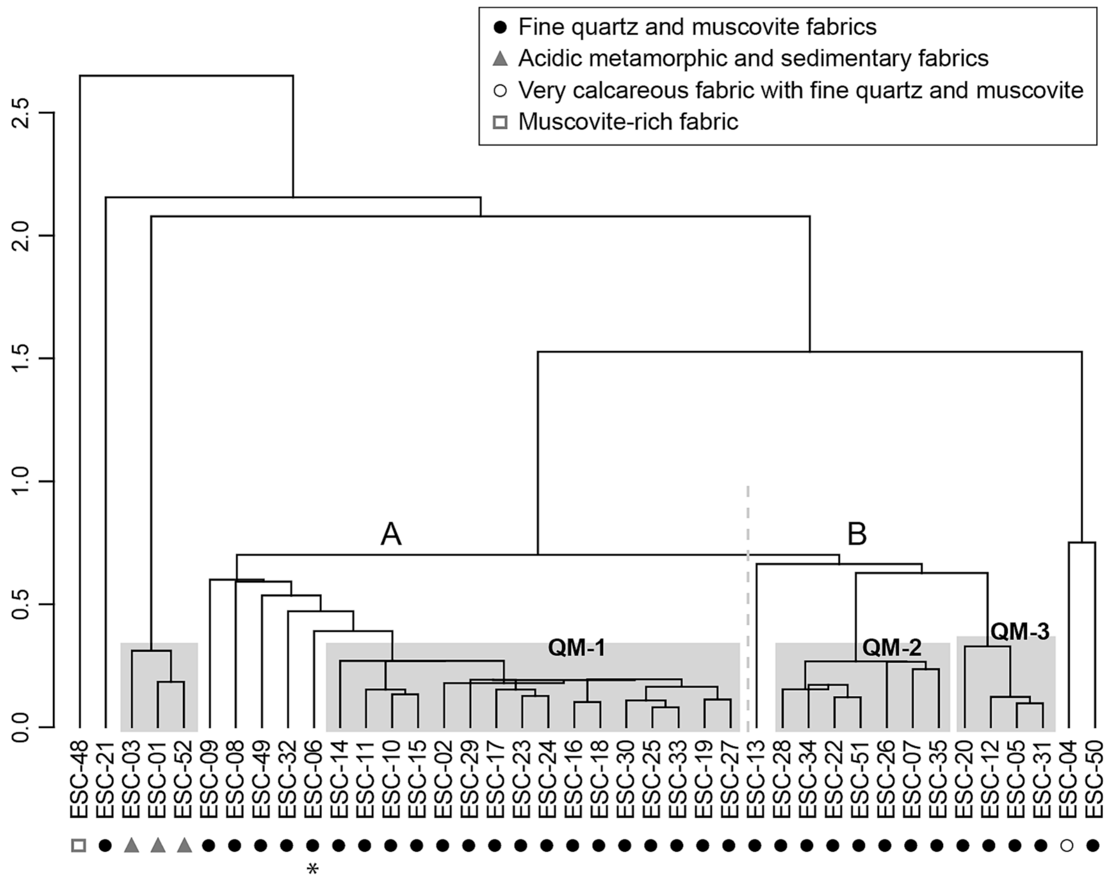

Fig. 3. Dendrogram resulting from cluster analysis on 40 common ware and amphora samples, based on the subcomposition Fe_2O_3, Al_2O_3, MnO, TiO_2, MgO, CaO, Na_2O, K_2O, SiO_2, Ba, Rb, Th, Zr, Y, Sr, Ce, Ga, V, Zn, Cu, Ni and Cr, using Nb as divisor in the log-ratio transformation of the data. The analysis was performed using the centroid agglomerative method and the squared Euclidean distance. QM indicates chemical groups related to the fine quartz and muscovite fabric group. Individuals affected by postedepositional crystallization of analcime are marked with an asterisk (*).

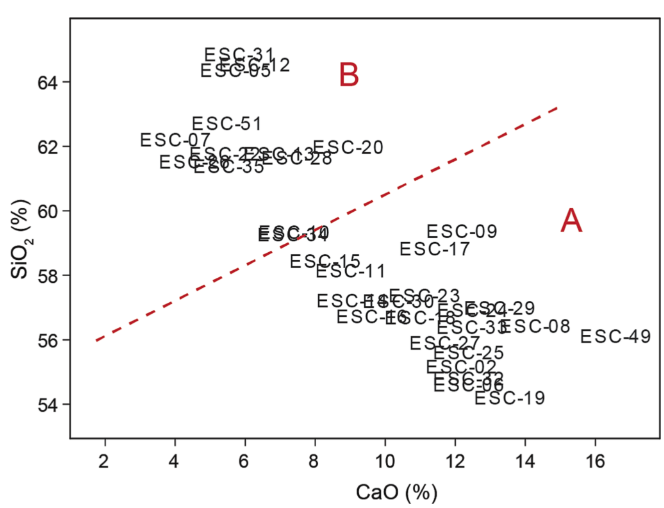

Fig. 4. Binary diagram (using normalized data) of CaO vs SiO_2, for the samples of clusters A and B defined from the cluster analysis.

PPL. The optical activity of the matrix in XP suggests relatively low firing temperatures, in agreement with the XRD patterns for these samples, characterized by the absence of firing phases (Table 5). All the individuals in this group show similar XRD patterns, with intense reflections of quartz and plagioclase, in addition to illite-muscovite and alkali feldspar.

Apart from the samples in the 'granodiorite/tonalite' fabric, two

Table 4
Mean chemical composition of groups QM-1, QM-2, and QM-3. Mean (m) and standard deviation (sd) values are presented for each element.

	QM-1 (n = 16)		QM-2 (n = 7)		QM-3 (n = 4)	
	m	sd	m	sd	m	sd
(%)						
Fe_2O_3	5.71	0.37	6.02	0.36	4.91	0.17
Al_2O_3	18.61	0.89	19.32	0.93	16.84	0.27
MnO	0.03	0.01	0.02	0.00	0.03	0.00
P_2O_5	0.34	0.07	0.27	0.08	0.27	0.02
TiO_2	0.90	0.05	0.95	0.02	0.85	0.03
MgO	1.79	0.10	1.71	0.12	1.46	0.09
CaO	10.97	1.83	5.70	1.31	6.70	1.52
Na_2O	1.00	0.17	0.84	0.12	1.12	0.10
K_2O	3.49	0.13	3.46	0.15	3.70	0.12
SiO_2	56.99	1.35	61.55	1.09	63.98	1.33
(ppm)						
Ba	394	26	438	17	431	16
Rb	156	6	150	6	148	6
Th	18	1	18	1	18	1
Nb	19	1	19	0	18	1
Pb	31	3	32	4	27	3
Zr	210	5	219	6	232	5
Y	29	2	28	1	26	1
Sr	275	33	210	25	186	11
Ce	81	6	81	3	80	5
Ga	20	1	21	1	19	1
V	97	9	107	7	89	4
Zn	98	5	96	3	96	7
Cu	24	4	24	3	15	1
Ni	33	3	29	2	27	2
Cr	84	5	92	5	79	2

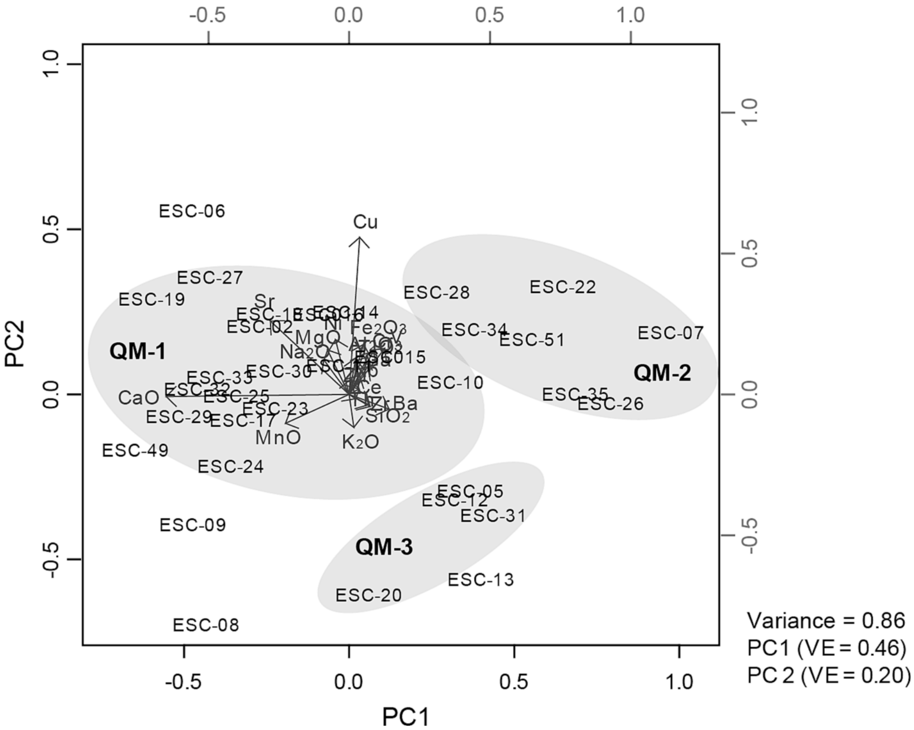

Fig. 5. PCA of the alr-transformed chemical data for the 33 common wares and amphorae included in the clusters A and B in Fig. 3; the analysis was performed on the covariance matrix. Plot of the two first principal components (PC1-PC2), based on the alr transformed subcomposition Fe_2O_3, Al_2O_3, MnO, TiO_2, MgO, CaO, Na_2O, K_2O, SiO_2, Ba, Th, Nb, Zr, Y, Sr, Ce, Ga, V, Zn, Cu, Ni and Cr (Rb is used as divisor). Chemical groups (QM-1 to QM-3) are indicated.

other cooking wares analyzed show singular fabrics in thin section.

The sample ESC-46 (Fig. 6c) presents a fabric with coarse rounded quartz inclusions (fine to medium sand, well sorted) and iron nodules, in an iron-rich clay matrix, which is optically inactive in XP. The fine fraction is relatively scarce, composed of dominant quartz, along with altered carbonate inclusions, as well as accessory micas and plagioclase. The bimodal distribution of the inclusions might suggest tempering. The XRD patterns reveals a complete decomposition of phyllosilicates and intense peaks of plagioclase and hematite, from which a high EFT ($\geq$950/1000 °C) can be estimated (Table 5).

On the other hand, the sample ESC-36 (Fig. 6d) is characterized in thin section by coarse sand inclusions of angular quartz and feldspars (alkaline, and less frequently plagioclase), in addition to plutonic rock fragments composed of these minerals, suggesting derivation from granite. Accessory components include very rare clinopyroxene and basic-intermediate volcanic rock fragments. This coarse fraction is not very abundant; however, the clear bimodal distribution indicates that it was added as temper. The fine fraction, composed of silt to very fine sand, is abundant and comprises dominant quartz, along with common micas (muscovite mainly) and alkali feldspar. A brown colored, optically active clay matrix is observed. It is a very porous fabric, due mainly to the presence of abundant fine elongated voids with a parallel orientation. The absence of firing phases in XRD indicates a low firing temperature (Table 5).

The normalized chemical composition of the cooking wares, obtained through WD-XRF analysis, is given in Table 6. Unlike the common wares and amphorae, all the cooking wares analyzed show the use of low calcareous clay pastes, with CaO percentages always below 5 %, indicating different technological choices between the classes of pottery regarding the characteristics of the raw materials used for their manufacture. Nevertheless, despite this broad similarity regarding their low-calcareous composition, which is common for cooking wares, the chemical data reveal compositional variability within this class. Each of the fabrics defined under thin section is characterized by a well differentiated chemical composition (Table 6).

All the samples in the 'granodiorite/tonalite' fabric group present a similar chemical composition, with high concentrations of Na_2O, Al_2O_3, K_2O, Pb, and Zn. A bivariate diagram Na_2O vs Zn (Fig. 7) allows for a clear differentiation between this group of samples and the other cooking wares analyzed. The content of Zn is always high (115–229 ppm). Concentrations of Pb also tend to be relatively high in these samples, with sample ESC-45 displaying the highest concentrations of both Pb and Zn (Table 6). It has not been possible to associate this high Pb with any specific mineral inclusion in thin section analysis.

As for the other cooking wares analyzed, sample ESC-46 ('rounded quartz' fabric) is characterized by comparatively higher concentrations of SiO_2 and lower of Al_2O_3, Na_2O, K_2O, and Rb (Table 6). This must be related to the higher predominance of quartz over feldspars and phyllosilicates compared to the other fabrics, as indicated by the petrographic analysis. Conversely, sample ESC-36 ('angular quartz and feldspars' fabric) shows a higher content in Al_2O_3, K_2O, Rb, and Ba than the previous individual (Table 6); this can be associated with the higher frequency of alkali feldspar and, in general, a petrographic composition derived from granitic rocks.

5. Discussion

The analytical characterization of common wares and amphorae from Vandal contexts in Es Castell reveals that most of the samples identified as local products exhibit relatively consistent compositional and technical characteristics, albeit with some variability. These samples were typically made from a calcareous clay with a high content of muscovite and quartz inclusions. No additional tempering materials were used, resulting in fine-grained fabrics with textural variations. Notably, there are discernible differences in the relative proportion of calcareous and siliceous components, with CaO percentages ranging from 5 % to 15 % in most cases, and SiO_2 percentages usually falling between 54 % and 64 %. It is worth mentioning that only a small number of specimens display a more distinct composition, such as ESC-04, ESC-21, and ESC-50 (refer to Fig. 3; Table 2-3 online).

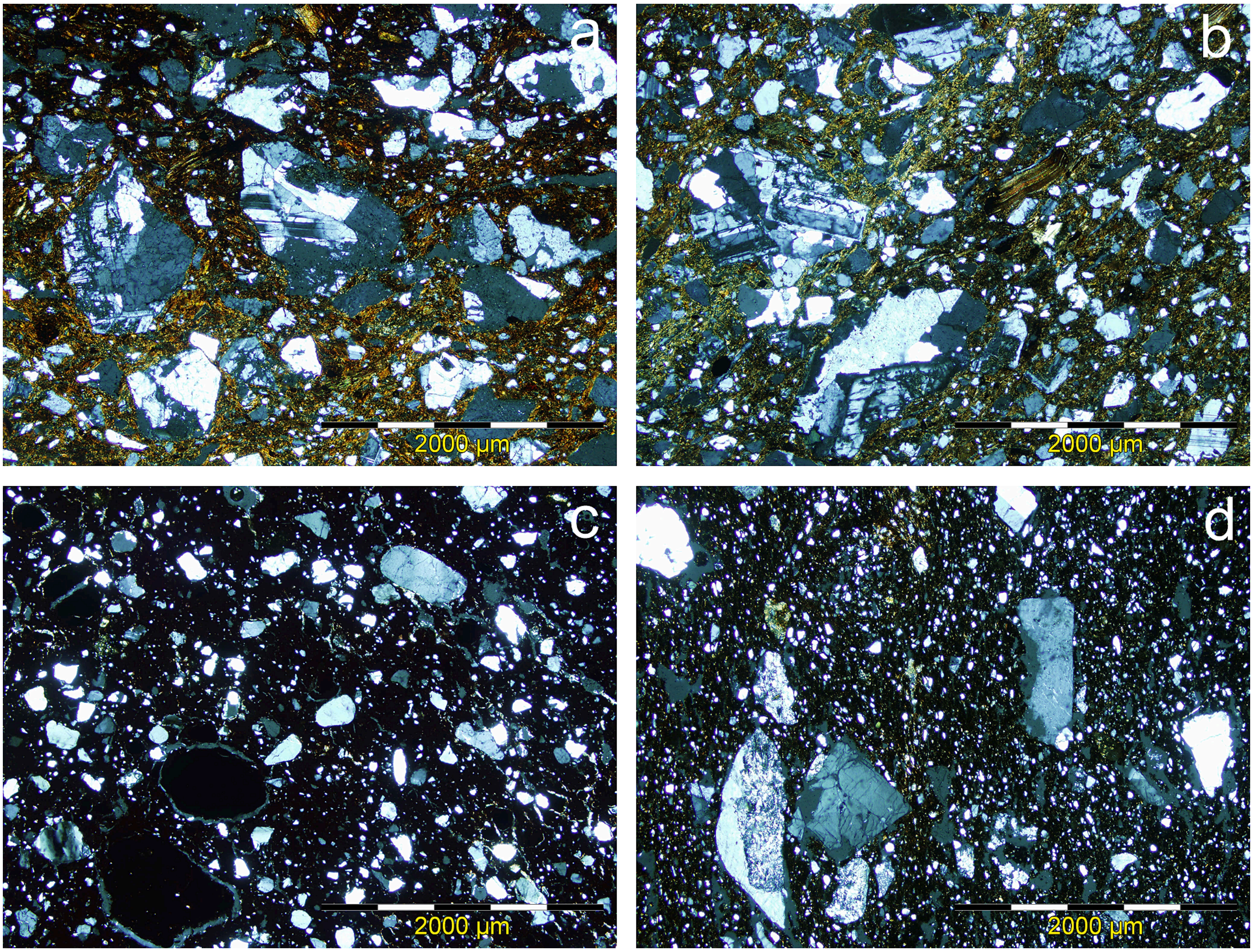

Fig. 6. Photomicrographs of thin sections of cooking wares, taken in crossed polars at 40x. (a-b) Granodiorite/tonalite fabric (a, ESC-39; b, ESC-43). (c) Rounded quartz and iron nodules fabric (ESC-46). (d) Angular quartz and feldspars fabric (ESC-36).

Table 5
Mineralogical composition and equivalent firing temperature (EFT) of the cooking wares, based on XRD results. The samples are organized by fabric, according to the OM petrographic analysis.

Petrographic fabric	EFT (°C)	Minerals (XRD)	Individuals
Granodiorite/ tonalite	<900/ 950	Quartz, plagioclase, alkali feldspar, illite-muscovite	ESC-37, 38, 39, 40, 41, 42, 43, 44, 45
Rounded quartz and iron nodules	≥950/ 1000	Quartz, plagioclase, hematite, alkali feldspar	ESC-46
Angular quartz and feldspars	<900/ 950	Quartz, illite-muscovite, plagioclase, alkali feldspar	ESC-36

Despite the observed variability, it is plausible to propose that all these samples were produced in Eivissa. The petrographic composition of their fabrics aligns with the geological formations found on the island, which consist of sedimentary calcareous deposits (such as limestones, marls, and others) from different geological periods, as well as Quaternary deposits like eolianites, conglomerates, and clays (Rangheard, 1971; IGME, 1972). Although no kiln products dating back to the Late Antiquity period have been characterised on the island, the chemical and petrographic characteristics of the specimens from Es Castell, along with their range of variability, closely resemble those of the 'Ebusitan' products. This term refers to common wares and amphorae found primarily in consumption sites on the Balearic Islands and with a provenance in Eivissa, as documented by studies conducted on other Late Antique materials by Buxeda et al. (1997, 1998, 2005) and Cau et al. (1997, 2004, 2019), and with compositions that are similar to those obtained for earlier Ebusitan amphorae (Buxeda and Cau, 1997). Moreover, it is important to consider the archaeological context, as the typological repertoire discovered in Es Castell for most of the common wares corresponds to what it has been described as 'Ebusitan products' in other Late Antique contexts (see Ramon, 1986, 2008; Buxeda et al., 2005).

Within the ceramic assemblage of Es Castell, three distinct chemical groups (labelled as QM-1, QM-2 and QM-3) can be identified. These groups are believed to represent local products and are remarkably consistent in terms of their chemical composition. Additionally, a few outliers and loners are also present. The thin section analysis of each chemical group reveals some differences, suggesting the use of different clayey raw materials and/or pottery manufacturing recipes. This observation could potentially indicate the existence of multiple production centers on the island. An interesting finding from the analysis is that each group encompasses a wide range of ceramic forms, while certain forms are found in more than one group (refer to Fig. 8).

In summary, the interpretation of the results suggests that during the Vandal period in Eivissa, a diverse range of ceramics, including different forms of common wares and amphorae, were produced using broadly similar raw materials and paste recipes. These ceramics were likely manufactured either in a single production center using different paste

Table 6
Normalized chemical results (WD-XRF) of the 11 cooking wares analyzed. Concentrations of major and minor oxides are in %, other minor and trace elements are in ppm.

	Fe_2O_3	Al_2O_3	MnO	P_2O_5	TiO_2	MgO	CaO	Na_2O	K_2O	SiO_2	Ba	Rb	Th	Nb	Pb	Zr	Y	Sr	Ce	Ga	V	Zn	Cu	Ni	Cr
Granodiorite/tonalite																									
ESC-37	6.15	19.77	0.06	0.34	0.68	1.81	3.23	1.44	3.01	63.38	304	141	13	13	58	129	16	189	48	22	101	194	21	16	84
ESC-38	4.79	18.83	0.04	0.36	0.54	2.19	2.73	1.89	3.56	64.94	276	148	13	12	64	96	16	207	46	21	90	161	16	10	80
ESC-39	6.08	20.14	0.04	0.19	0.68	2.04	2.44	1.92	3.10	63.23	301	140	13	12	79	97	16	166	53	23	110	177	33	17	96
ESC-40	6.18	20.20	0.04	0.22	0.58	1.94	2.78	1.64	3.14	63.16	285	139	14	13	77	93	16	162	48	22	105	175	20	16	94
ESC-41	5.62	17.97	0.04	0.23	0.56	1.95	3.22	1.81	3.37	65.12	269	138	12	12	40	117	18	188	41	19	100	115	21	14	84
ESC-42	5.38	18.62	0.04	0.18	0.60	1.73	2.04	1.72	3.26	66.33	225	139	15	13	46	129	17	159	54	21	92	134	23	13	87
ESC-43	5.12	19.32	0.03	0.33	0.56	2.18	2.68	1.90	3.23	64.53	263	138	13	11	42	99	15	223	41	21	93	116	14	13	85
ESC-44	4.94	19.19	0.04	0.17	0.58	2.05	2.78	1.98	3.45	64.69	218	147	13	12	51	97	16	187	41	20	89	175	27	11	85
ESC-45	4.96	19.51	0.03	0.23	0.62	2.09	2.76	1.87	3.25	64.56	203	140	13	11	119	97	14	183	42	21	92	229	30	12	83
Angular quartz and feldspars																									
ESC-36	6.95	18.33	0.05	0.18	0.78	1.55	1.70	0.70	3.68	65.92	417	138	19	19	33	276	26	114	84	20	122	67	12	32	99
Rounded quartz and iron nodules																									
ESC-46	6.32	14.96	0.04	0.22	0.84	1.83	4.91	0.41	2.25	68.08	311	81	13	21	19	235	23	164	73	16	106	94	11	24	105

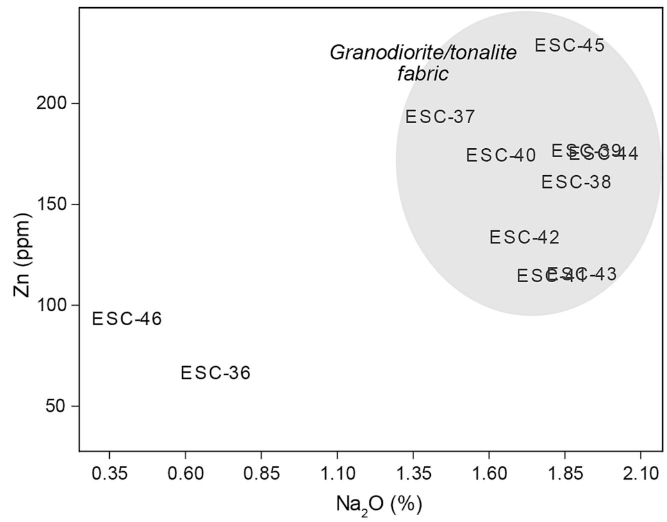

Fig. 7. Binary diagram (using normalized data) of Na_2O vs Zn, for the cooking wares analyzed.

recipes or in smaller, nearby production centers that concurrently produced a comparable range of forms using similar but slightly different raw materials.

Apart from the amphorae found within the "fine quartz and muscovite" fabric group, which can be interpreted as locally produced in Eivissa, a few other amphorae were subjected to analytical study. The results of the analysis indicate that these amphorae are of imported origin.

Three of these amphorae (ESC-01, ESC-03, ESC-52) (Fig. 8) belong to the 'acidic metamorphic and sedimentary' fabric group, characterized by a consistent chemical composition (as depicted in Fig. 3). The analysis reveals the use of a calcareous clay containing marine microfossils, enriched with quartz and micas, and the addition of a temper that exhibits some heterogeneity in composition. The temper primarily consists of fragments of acidic metamorphic and sedimentary rocks, with a minor contribution of basic igneous material. The chemical and petrographic composition of these amphorae matches that of amphorae found in Tarragona (Fantuzzi, 2015) classified as Keay 25Y. A similar fabric has also been identified in some Keay 1B amphorae (Peacock and Williams, 1986: 172; Capelli and Bonifay, 2007; Lemaître et al., 2011; Fantuzzi and Cau, 2018a), although there are slight differences in chemical composition (Fantuzzi, 2015). The Keay 1B amphorae, dated to the late 3rd to 4th centuries AD, have been suggested to originate from Algeria (Capelli and Bonifay, 2007). The samples found in Es Castell and Tarragona may share a common provenance area with the Algerian amphorae. However, due to significant gaps in knowledge regarding Algerian amphora workshops and the lack of analytical and archaeological information (see Capelli and Bonifay, 2007; Fantuzzi, 2015), it is challenging to confirm this hypothesis. Therefore, other possible provenance hypotheses should not be disregarded.

Another amphora analyzed from Es Castell, identified as ESC-48, exhibits a distinct fabric and chemical composition compared to the rest of the ceramic assemblage. Technologically, it is characterized by a clay with a high micaceous (muscovite-rich) content, abundant fine quartz, and the absence of added tempering materials. Previous research by Ramon and Cau (1997) suggested a possible provenance in the eastern Mediterranean for this amphora. However, currently, clear similarities to known petrographic-chemical groups of Late Antique amphorae from the eastern Mediterranean (e.g., Fantuzzi, 2015; Fantuzzi et al., 2015, 2016; Fantuzzi and Cau, 2018b) or other regions have not been identified. As a result, the provenance of ESC-48 remains unknown at present.

Concerning cooking wares, the samples exhibiting visible abundant

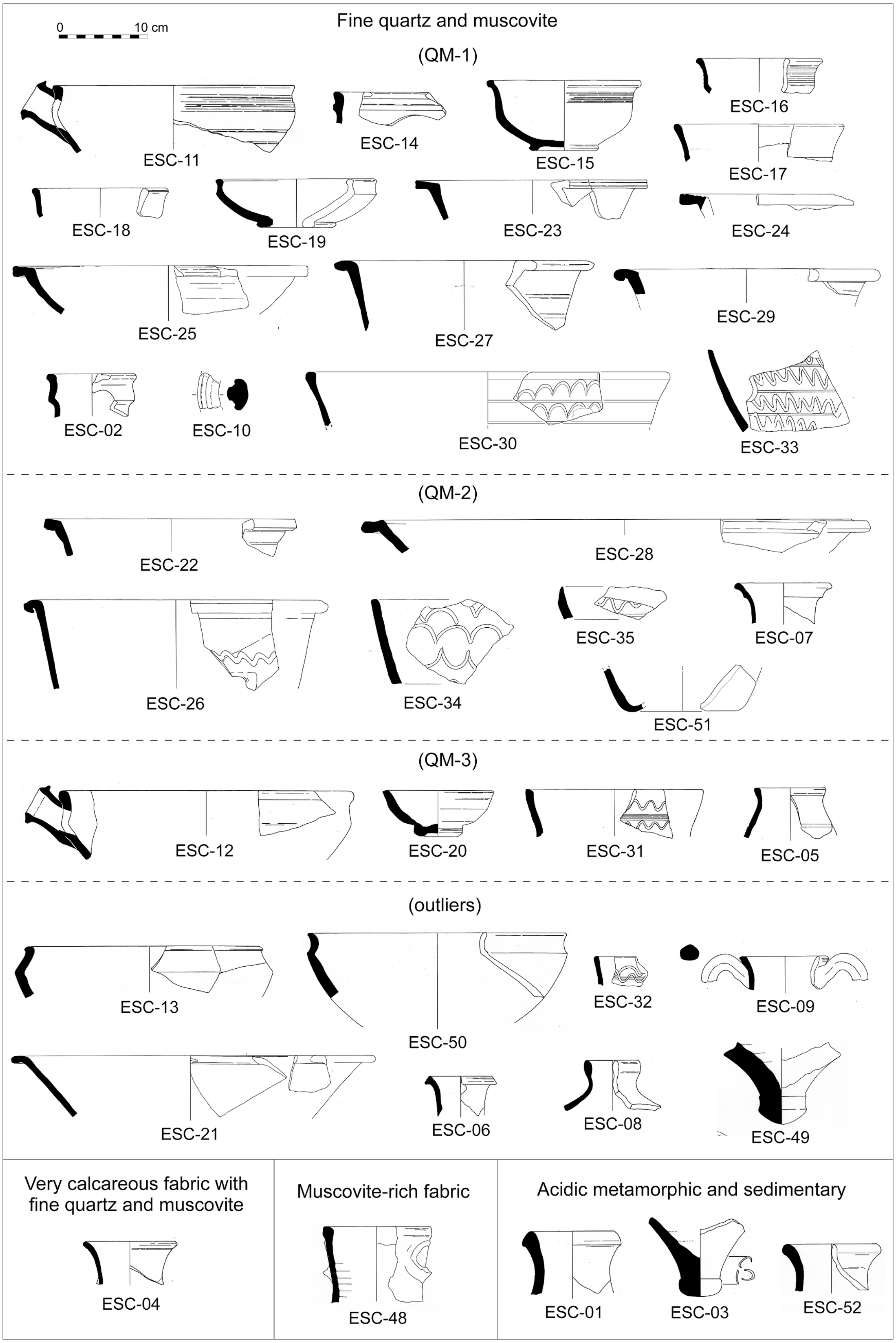

Fig. 8. Common wares and amphorae from Es Castell, organized by petrographic fabric and chemical groups (drawings from Ramon and Cau, 1997).

mica share a highly homogeneous petrographic, mineralogical, and chemical composition, referred to as the 'granodiorite/tonalite' fabric. This fabric corresponds to Fabric 3.2/3.3 as defined by Cau (2003) based on other ceramic contexts from the Balearic Islands. The provenance of this allochthonous fabric remains uncertain. Reynolds (1993, 2010a) has suggested Murcia as a potential area of origin, but other regions in the western or central Mediterranean with plutonic formations (granodioritic to tonalitic) should also be considered (Cau, 2007; Macias and Cau, 2012).

The ceramic forms documented in the assemblage of Es Castell primarily consist of short casseroles (as shown in Fig. 9), which can be associated with Form 2 of Cau's Fabric 3.2/3.3 and Form 2 of Reynolds' Handmade Ware (HMW) 8. Although this fabric is more typical of the 5th century, Reynolds (1985, 1993) notes that his Form 2 is still prevalent in early 6th-century contexts in Benalúa. The evidence from Es Castell, where similar forms are documented and the analytical results confirm the fabric's identity as Cau Fabric 3.2/3.3 and Reynolds HMW 8, supports the notion that the trade of these products remained significant during the late 5th to early 6th centuries.

In comparison to the dominant granodioritic/tonalitic fabric found in the cooking ware assemblage of Es Castell (Ramon and Cau, 1997), the other cooking wares analyzed exhibit completely different petrographic fabrics and chemical compositions. For example, a lid of type Hayes 196 (ESC-46) displays a fabric with coarse rounded quartz and iron nodules, which aligns with the Tunisian provenance suggested by typological data. On the other hand, a cooking pot (ESC-36) showcases a fabric with a less abundant non-plastics, consisting of inclusions derived from granite, along with a minor contribution of basic-intermediate volcanic material. The comparison with the ERAAUB's analytical database for Late Roman Cooking Wares in the Mediterranean (Cau, 1994, 1996, 1999, 2003, 2007; Buxeda et al., 1997, 2005; Cau et al., 1997, 2002; Buxeda and Cau, 2004; Macias and Cau, 2012) does not provide any clear indication of its provenance. In summary, while the dominant cooking wares in Es Castell display a granodioritic/tonalitic fabric, the remaining analyzed cooking wares show distinct fabrics and chemical compositions. Despite the lack of a clear provenance for some of these wares, their technological features and petrographic compositions indicate that they were not produced locally in Eivissa or regionally in the Balearics.

During the Vandal period, it is evident that pottery-making remained a significant activity on the island, rooted in the long-established tradition of Ebussus as a ceramic producer. This region maintained a robust ceramic industry. In addition to this thriving local ceramic production, the presence of imported materials underscores the island's integration into the broader dynamics of Mediterranean trade. Imported ceramics, including fine wares, cooking wares, and some amphorae from external sources, further highlight the Balearics' participation in these trade networks. This provides compelling evidence of the island's continued involvement in Mediterranean trade during the Vandal period. This trade activity played a vital role in shaping the island's economic and cultural connections with the wider Mediterranean world during this historical epoch.

6. Conclusions

The archaeological context of Es Castell is particularly significant since it is currently the main ceramic assemblage properly published that can be dated to the Vandal period in Eivissa. Whilst the first archaeological analysis of this assemblage suggested that around 60 % of the materials, specifically common wares, and some amphorae, would correspond to local products (Ramon and Cau, 1997), the present analytical study has proved that these ceramics can in fact be considered to have been produced in Eivissa, and that more than one production site could have coexisted. The ceramic products exhibited remarkable similarities in terms of technical aspects such as the selection of raw materials (with most samples composed of calcareous clays rich in quartz and muscovite), preparation of clay paste, and firing conditions. They also shared a similar typological repertoire, although slight variations in raw materials were observed. To gain a more comprehensive understanding of pottery production in Eivissa during Late Antiquity, it would be beneficial to analytically characterize ceramic products in production centers that could appear in the future, as this is crucial for establishing proper reference groups. Nevertheless, the identification of chemical-petrographic groups within consumption sites like Es Castell provides robust evidence of the diversity and variability of ceramics produced on the island during the Vandal occupation. It is important to highlight that

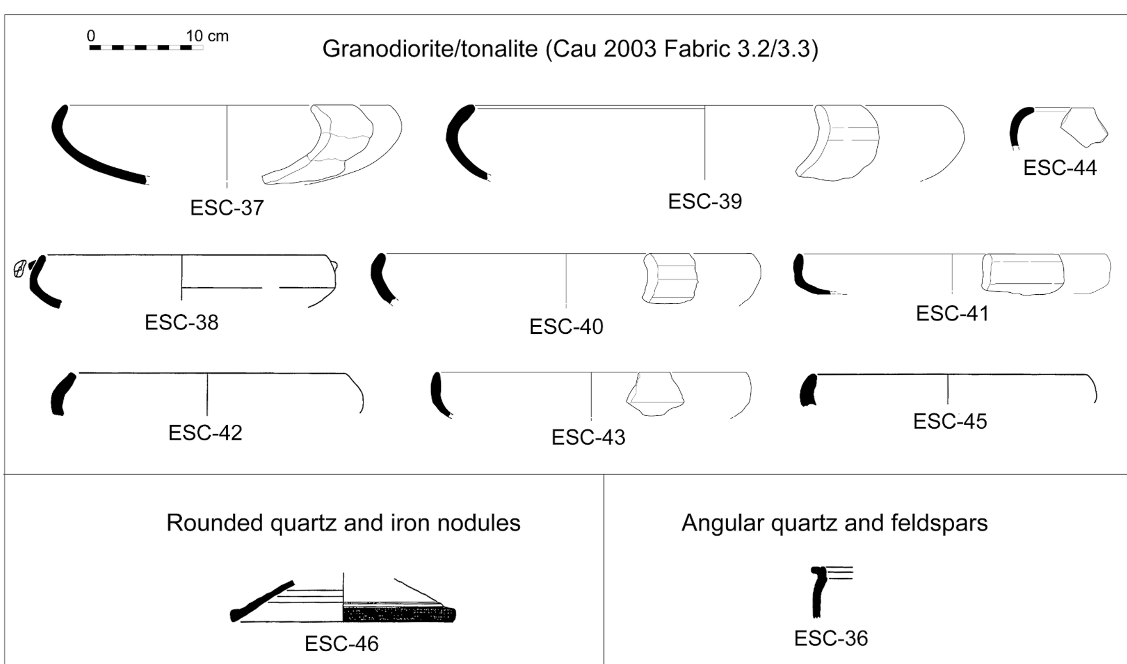

Fig. 9. Cooking wares from Es Castell, organized by petrographic fabric (drawings from Ramon and Cau, 1997).

this pottery tradition is rooted in the Punic period and that it was a constant all throughout the history of Eivissa in Antiquity. Therefore, the Vandal dominion did not imply any cease of the pottery-making activities on the island, and the production of common wares for daily used and amphorae for the transport and commercialization of the surplus continued.

The distribution and consumption of pottery on the island of Eivissa during the Vandal period encompassed not only locally produced ceramics but also imported materials. In Es Castell, the imported ceramics primarily consisted of fine wares, particularly from Tunisia, as previously identified in the archaeological analysis (Ramon and Cau, 1997). However, other imported products were also present. Among them were cooking wares, specifically handmade or slow wheel-made short casseroles, which exhibit a relatively homogeneous fabric and chemical composition. The precise provenance of these imported cooking wares remains undetermined. This fabric, which corresponds to Cau Fabric 3.2/3.3 or Reynolds HMW 8, has been documented in various contexts across the Balearic Islands, predominantly from the 5th century. Therefore, its presence at Es Castell suggests that its trade continued until the late 5th to early 6th centuries. Other types of imported cooking wares were poorly represented in the ceramic assemblage of Es Castell (Ramon and Cau, 1997). These included a Tunisian lid of type Hayes 196 (ESC-46) and an indeterminate cooking pot (ESC-36), which have been characterized through this study.

Furthermore, a limited number of imported amphorae were discovered at Es Castell, with the majority originating from Tunisia, as indicated by the typological examination conducted in the previous study (Ramon and Cau, 1997). The present analysis revealed two distinct fabrics among the indeterminate amphorae, the provenance of which remains uncertain, although Algeria is a plausible hypothesis for the more prevalent fabric in the assemblage. Other amphorae discovered at Es Castell were identified as local products from Eivissa, and in some cases, they were produced in the same production centers that manufactured common wares.

In summary, the analysis of the pottery assemblage from Es Castell provides valuable new insights into the local and imported ceramics that were in circulation on the island of Eivissa during the period of Vandal rule. This research sheds light on the ceramic materials and their origins, potentially revealing trade and cultural connections.

Furthermore, future analytical and archaeological studies that expand the scope to include other ceramic contexts from the Balearic Islands will be crucial in building a more comprehensive understanding of pottery production, distribution, and consumption patterns during Late Antiquity in this region. These broader investigations will help to paint a more detailed picture of the historical and economic dynamics at play in the Balearic Islands during that era.

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CRediT authorship contribution statement

Miguel Ángel Cau-Ontiveros: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing, Supervision, Project administration, Funding acquisition for the analytical work. **Leandro Fantuzzi:** Methodology, Formal analysis, Investigation, Writing. **Evanthia Tsantini:** Methodology, Formal analysis, Investigation, Writing. **Joan Ramon Torres:** Methodology, Investigation, Writing, Funding acquisition for the archaeological excavation.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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