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RESEARCH

Multianalytical approach to the exceptional Late Roman shipwreck of Ses Fontanelles (Mallorca, Balearic Islands, Spain)

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Abstract
The paper presents the results of an interim analytical approach to the Late Roman shipwreck of Ses Fontanelles recently found in the island of Mallorca (Balearic Islands, Spain). The excellent state of preservation of the hull and the cargo, including amphorae with painted inscriptions (*tituli picti*), and its location in shallow waters offshore of one of the main touristic beaches of the island makes this a unique finding in the Mediterranean. A first season of excavations and study of the cargo triggered an analytical approach to solve some of the problems pose by archaeological research, mainly related to the possible origin of the vessel. The analytical strategy combines petrographic analysis for the study of the provenance of the amphorae, archaeozoology and residue analysis to identify their content, and analysis of the wood and plant remains to understand the use of vegetal resources in shipbuilding and in the stow of the cargo. The results of the combination of the petrographic analysis, the study of the ichthyofauna and the organic residue analysis suggest that the boat probably departed from the area of Cartagena in the southeastern part of the Iberian Peninsula, carrying a cargo of fish sauce (*liquaminis flos*), oil, and wine (probably also some olives preserved in grape derivatives), transported in three main types of amphorae. The analysis of the wood shows, as known in Roman shipbuilding, a clear selection of forest resources. The shipbuilders used pine for longitudinal parts of the hull, while for the small pieces related to the assemblage system (pegged, mortise and tenons) and subjected to a great stress they selected harder woods mainly Cupressaceae, *Olea europaea*, and *Laurus nobilis*. In addition, the study reveals that mainly branches of *Vitis vinifera,* but also other herbaceous plants were used as dunnage protecting the cargo during the journey. The results help to shed some light into different aspects of this unique vessel sunk in Mallorcan waters and contributes to show the benefit of applying archaeological sciences in maritime archaeology.

Keywords Petrographic analysis · Residue analysis · Archaeozoology · Amphora content · Wood · Shipbuilding · Maritime archaeology · Late Antiquity

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Introduction

The Balearic Islands lay not far from the eastern coast of the Iberian Peninsula placed in a strategic position within the navigation and trade routes of the western Mediterranean in Antiquity (e.g., Mascaró Pascarius 1971; Ruiz de Arbulo 1990; Izquierdo i Tugas 1996; Moreno Torres 2005; Guerrero Ayuso 2006). The islands as stepping-stones in these navigation routes were points of scale. Often, the boats experienced problems and sunk. This was the case of the shipwreck known as Ses Fontanelles. It was accidentally found in 2019 in one of the main touristic beaches (39º31′44.47’’N, 2º43′43.74’’E) not far from the city of Palma, the current capital of Mallorca, the largest island of the archipelago (Fig. 1). This prompted the authorities to undertake a rescue excavation in summer 2019 (Munar Llabrés et al. 2022). Soon they realized the exceptional state of preservation of the cargo and of the hull of the vessel. After a first evaluation and the excavation of a section of the shipwreck, corresponding to the bow, the rest of the remains were left in situ and covered again. After the rescue excavation, an interinstitutional project (ARQUEOMALLORNAUTA) was devised to study the materials already recovered, and to ensure the continuity of the excavation and the detailed study of the shipwreck.

The ship transported a relevant cargo of products packaged in amphorae around the fourth century of our era, a time for which commercial activities in the Western Mediterranean are still little known. This, together with the preservation of an impressive quantity of inscriptions depicted on the amphorae (*tituli picti*), makes this site a unique example in the Mediterranean and an excellent case for the study of commercial dynamics in Late Antiquity.

A first campaign of study of the materials recovered in the 2019 excavation helped to classify the ceramic findings and opened some major questions (Bernal-Casasola and Cau Ontiveros 2020a). To solve some of the main problems raised by the wreck and its cargo, an interim multi-proxy analytical targeted approach was designed based on a combination of methods and analytical techniques. The main aim was to use analytical techniques to help defining the cargo, and the vegetal resources that could help to better understand the origin of this ancient vessel sunk in Mallorcan waters during Late Antiquity. To understand the provenance of the different types

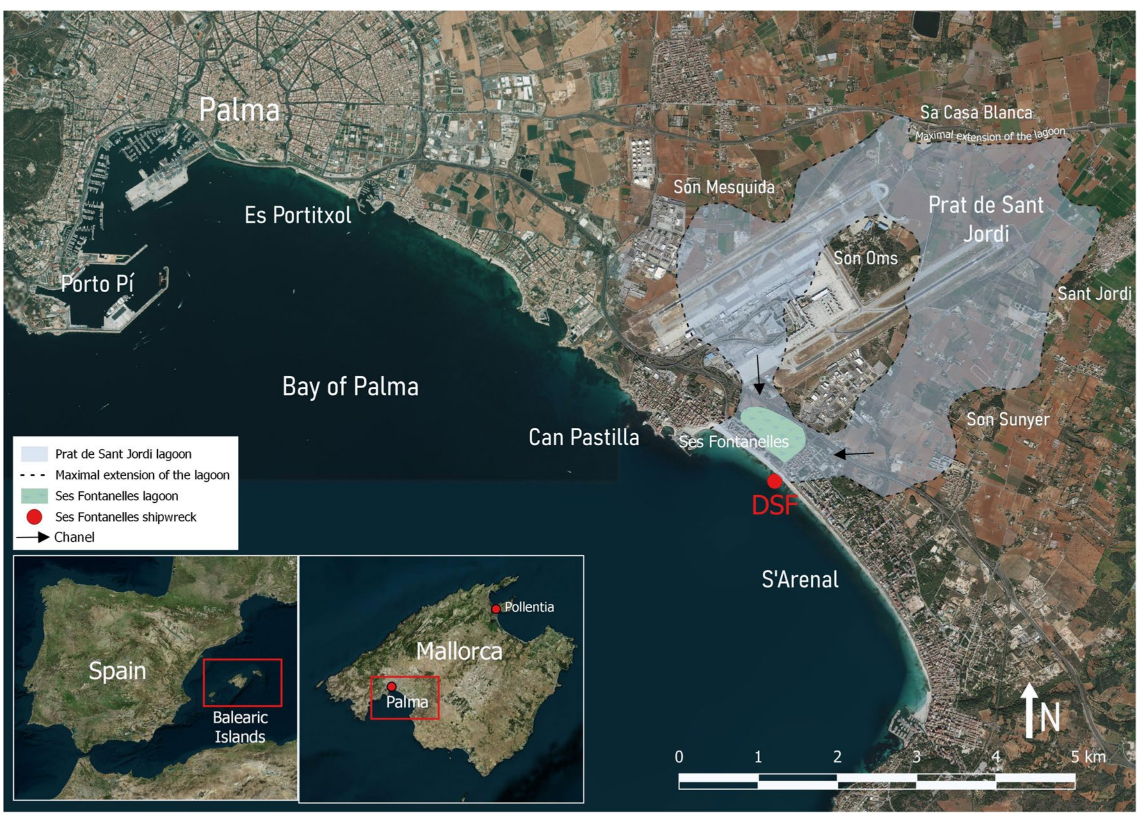


Fig. 1 Location of the Ses Fontanelles shipwreck in proximity to the homonymous area in Mallorca, after Munar Llabrés et al. 2022. The shaded grey area corresponds to the former lagoon of Pla o Prat de Catí, now named Ses Fontanelles, with the blue-shaded region indicating the visible remnants of this historical lagoon

of amphorae a selection was subjected to petrographic analysis. To identify the products contained in the amphorae, some of them (including some that were still sealed) were micro-excavated and the content studied employing an archaeozoological approach and organic residue analysis. Finally, a first set of wood remains from the hull, plants found between the cargo, and bark used as stoppers to seal the amphorae were also studied to understand the use of vegetal resources and to shed light into the species used in shipbuilding.

Overall, this contribution presents the first multianalytical results obtained from this important shipwreck and aims to highlight the beneficial relationship between inorganic and organic analysis, and between maritime archaeology and archaeological sciences. Certainly, over the last decades the application of archaeological sciences to the study of shipwrecks have largely contributed to maritime archaeology worldwide for a wide range of chronologies and geographical areas. An excellent multianalytical approach was undertaken, for instance, with a fifth century shipwreck in Santa Maria in Padovetere (Ferrara, Italy) focused on the environmental conditions and the study of shipbuilding techniques (Beltrame et al. 2019). Apart from the studies of conservation science, it is worth mentioning the advance in the use of geophysics and in general remote sensing techniques in the detection and monitoring of shipwrecks with spectacular results (e.g., Caratori Tontini et al. 2006; Bates et al. 2011; Grøn et al. 2015; Ødegård et al. 2016; Giachi et al. 2017; Pacheco-Ruiz et al. 2019; Ward and Ballard 2004). Archaeobotany in general has been essential for the study of the wood used in shipbuilding and providing important information on provenance and chronology of the boat construction (e.g., Colombini et al. 2003, 2007; Beltrame and Gaddi 2007; Capretti et al. 2008; Allevato et al. 2009; Deforce et al. 2014; Domínguez-Delmás et al. 2013; Liphschitz 2015, 2019; Traoré et al. 2016, 2018) with important contributions from radiocarbon dating (e.g., Lorentzen et al. 2014). These approaches have been combined, of course, with the analytical study of the myriad of materials that formed part of the cargoes or of the crew's belongings on board, notably including inorganic materials such as ceramics, glass objects, metals, stones, but also different organic materials and other substances (Colombini et al. 2003; Muller 2004; Lempiäinen-Avci et al. 2022). Also, archaeozoological studies have been contributing enormously in the study of shipwrecks, including full studies of the faunal remains oriented to dietary reconstruction (e.g., Hamilton-Dyer 1995), the identification of the content of the cargoes (e.g., Auriemma 2000; Barkai et al. 2013), or to singular applications like, for instance, the study of a mandibula of a mouse found in the Late Bronze Age Uluburun shipwreck that allowed to determine that the Canaanite port of Ugarit was probably one of the steps of the boat in its last journey (Cucchi 2008). All these studies and many others are excellent examples of the benefits of the application of archaeological sciences in maritime archaeology.

Our interim multianalytical approach to the shipwreck found in Mallorca aims to modestly contribute combining organic and inorganic analysis and generalizing the analytical studies, even in cases when the resources, and therefore the number of samples, are limited. This is just a first targeted step to solve archaeological questions waiting for a full excavation and a more developed strategy of application of archaeological sciences to this exceptional shipwreck.

The shipwreck and its cargo

The shipwreck lays just 65 m off the coast and just two meters depth in a very busy area of the coast, covering an area of approximately 12 m long by 5 m wide. The excellent state of preservation helps to reconstruct the composition and disposition of the cargo (Fig. 2). The hull was divided into horizontal sections by vertical bulkheads, which were used to organize the cargo inside the hold. It is also important to emphasize that the hull is very well preserved from bow to stern (approximate height of 1.5 m). The interim examination of the shipbuilding confirmed that the vessel belongs to the shell-first with mortise and tenons assemblage tradition, being a typical example of western Roman imperial naval architectural type (Pomey et al. 2012; Munar Llabrés et al. 2022).

The typological study of the amphorae recovered in the first season of excavations has allowed to classify 249 pieces with diagnostic attributes that fit into four main types (or groups of types) (Fig. 3) (Bernal-Casasola et al. 2020b). From a typological point of view, the Almagro 51c type amphorae are especially abundant, many of them exhibiting painted inscriptions (*tituli picti*) formed by a line with the names *Ausonius* et *Alunni*, and a second line allusive to the content: *Liq Flos,* restorable as *Liquaminis Flos* (*liquamen* flower), a liquid fish sauce appreciated in the Roman period (Soler i Nicolau et al. 2021) (Fig. 3, DSF-179, DSF-189). The shipwreck is a unique example since is one of the few cases around the Mediterranean where, thanks to an exceptional state of preservation, is possible to relate the information of the painted inscriptions with the paleocontent. The second group identified is represented by a new type of amphora that we have named Ses Fontanelles I, but that could be probably considered as an imitation of the oil amphorae type Dressel 23, commonly manufactured in the *Baetica* (southern Spain). A third group of containers are the flat-bottomed amphorae related to containers manufactured in the third and fourth centuries, especially in the eastern part of *Baetica,* where some workshops have been excavated (Bernal-Casasola 2019). These containers have been traditionally considered as for transporting wine based on their typology and on their prototype, the "Gaulish"

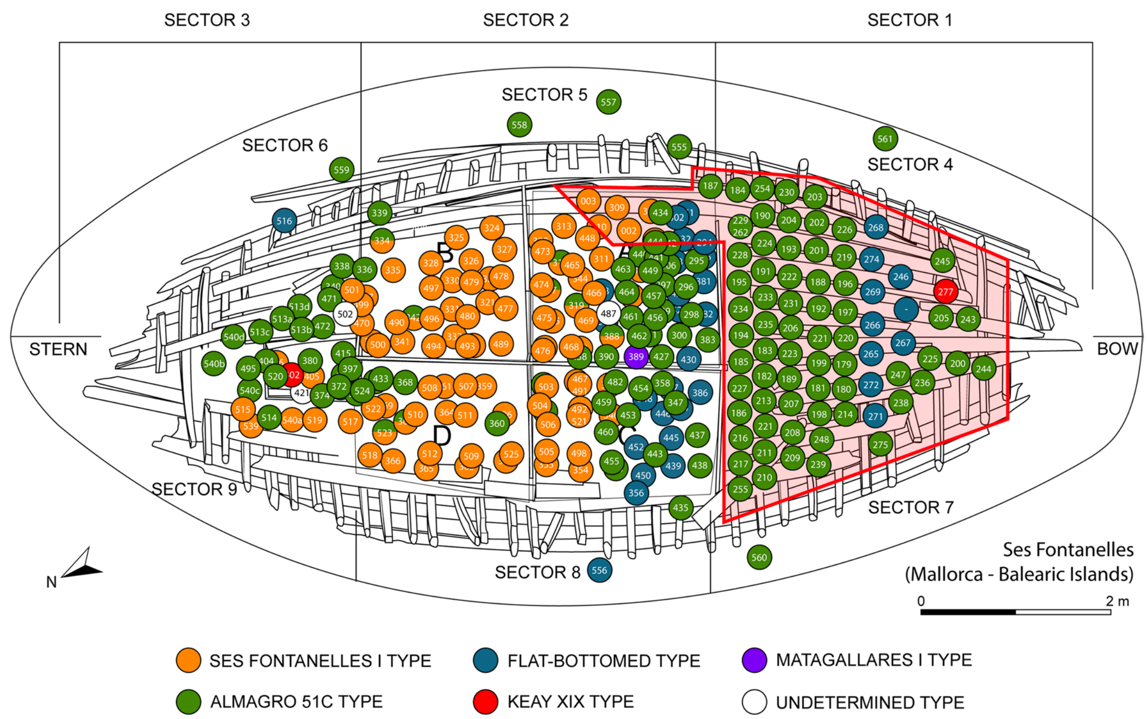


Fig. 2 Plan of the shipwreck with the positioning of the amphorae of the cargo documented during the excavation process

amphorae produced in the *Narbonensis*. However, in our case some of these amphorae contained solid residues including what it seems olives pits, indicating that perhaps some of them could contained preserved fruits. The amphorae repertoire is completed by type Keay XIX, but so far only three examples have been recovered. This might indicate that this type was possibly related to the crew than to the commercial cargo or that it was just represented by a few items. The cargo was organized at least in two tiers that covered the whole length and width of the ship. The amphorae were vertically arranged to maximize the limited space available (Munar Llabrés et al. 2022). Ses Fontanelles I type amphorae, which were larger and heavier, occupied the bottom tier of the center and the stern area (sectors 2 and 3). Smaller containers were mostly found near the bow (Sector 1) and the sides (Fig. 2). The amphorae were stooped with numerous quantities of what in the excavation seemed branches of vine shoots, but also other plants, as dunnage to protect the cargo during the journey (Frost 2011).

Methods and materials

Petrographic characterization of ceramics

All amphorae and sherds recovered in the first archaeological campaign were macroscopically examined. Of these materials, 25 complete or nearly complete amphorae were further examined with the help of a Dino-Lite digital microscope. In addition, ten selected samples were examined in the laboratory of ERAAUB/IAUB at the University of Barcelona using an Olympus SZH stereoscopic microscope equipped with a continuous zoom between 7.5X and 64X, with 1X and 2X oculars, working between 7.5 and 128 magnifications. Systematic photographs were taken at 10X and 30X on both polished and fresh fractured sections.

The ten selected samples were also analyzed by Optical Microscopy (MO) using thin sections, for petrographic and mineralogical characterization at ERAAUB/IAUB (Table 1). Preparations were made from a fragment of ceramic embedded in resin, downgraded with a Struers Discoplan TS cutter-rectifier, and manually lapped using a powder abrasive to a thickness of 30 µm, in which the quartz shows a grey-white first order interference color. The ceramic fabric observations were made with an Olympus BX41 polarizing microscope, equipped with 2x, 4x, 10 × and 20 × lenses and 10 × eyepieces, working between 20 and 200 magnifications. The petrographic descriptions of the fabrics were made following the system proposed by Whitbread (1989, 1995) and Quinn (2013). Grain sizes for inclusions in petrographic descriptions were defined using the American Geophysical Union (Udden-Wentworth scale) system. The following abbreviations are used in the description of the inclusions of each fabric or petrographic group: eq = equidimensional; el = elongated; a = angular; sa = subangular; r = rounded;

Fig. 3 Main types of amphorae documented at Ses Fontanelles shipwreck: DSF-179 and DSF-189, Almagro 51c with *tituli picti*; DSF-266, Flat-bottom amphora; DSF-002, Ses Fontanelles I type

sr = subrounded. All photomicrographs, both in binocular and under the polarizing microscope, were captured with a computer-controlled Olympus DP70 digital camera.

Archaeozoological approach: the study of the ichthyofauna in amphorae

Some of the sealed amphorae were selected to sample their contents. The materials recovered from the microexcavation of these amphorae were wet sieved through a series of sieves of progressively smaller mesh size (*i.e.*, 4 mm, 2 mm, 500 µm, 250 µm, 125 µm, 63 µm) and then air-dried. The only exception was the broken amphora DSF-231 that retained several bones embedded in the inner walls and its toe. Most of the identifiable fish bones were sorted through 500 µm mesh sieve, using a Dino-Lite handheld digital microscope for its triage at the laboratory of ARQUIB at the University of the Balearic Islands. Four of the six samples from Almagro 51c amphorae provided ichthyofauna remains: DSF-220, DSF-231, DSF-235 and DSF-257. The two samples from flat-bottomed amphorae (DSF-266 and DSF-272) were sterile in terms of fish remains (Table 1). To estimate the body size (total length—LT) of the fishes we followed the osteometric procedure indicated by Assis and Amaro (2006) for sardines. For the anchovies we built our own model from an extant reference population (n = 9) based on the length of the dentary (LD) as this was the predominant element. The following linear regression formula was used: LT = 8.95*LD- 0.18 (r^2 0.882) (Assis and Amaro 2006). Only left-sided dentaries were used to avoid the repetition of individuals. The measurements were done with a Dino-Lite Edge digital microscope and using Dino-Capture 2.0 software.

Organic residue analysis of some amphorae

Porous materials absorb liquid and semi-liquid substances that enter in contact with them. Almost 50 years of research

Table 1 Details of the amphorae analysed. ORA = Organic Residue Analysis

SAMPLE ID	Typology	Petrography	ORA LAB n./ Old sample n	Ictiofauna, Volume analysed/Diagnose	Comments
DSF-002	Ses Fontanelles I	Fabric 1	1/52	-	
DSF-003	Ses Fontanelles I	Fabric 1	-	-	
DSF-183	Almagro 51c	Fabric 1	-	-	With *titulus pictus*
DSF-185	Almagro 51c	Fabric 1	-	-	With *titulus pictus*
DSF-186	Almagro 51c	Fabric 1	-	-	With *titulus pictus*
DSF-195	Almagro 51c	Fabric 1	-	-	With *titulus pictus*
DSF-220	Almagro 51c		4/60	15 ml, Fertile	Dark sediment with sandy inclusions and multiple ichthyological inclusions
DSF-226	Almagro 51c		-	1200 ml, Sterile	Sandy, but with ichthyological remains?
DSF-231	Almagro 51c		-	Fertile	Toe of amphorae presenting several ichthyological remains attached both on the inner walls and in its basal part
DSF-235	Almagro 51c		-	212 ml, Fertile	Composed mainly of ichthyological remains and a little sand. Coming from the toe of the amphora
DSF-256	Almagro 51c		-	171 ml, Sterile	Sample composed exclusively of sand
DSF-257	Almagro 51c		-	15 ml Fertile	Coming from the internal bottom next to the toe
DSF-263	Almagro 51c	Fabric 1	-		
DSF-266	Flat-base amphora	Fabric 1	-	114 ml, Sterile	Composed exclusively of sand and fragmented and rolled shells, with fibers of *P. oceanica*. Post-depositional intrusions
DSF-267	Flat-base amphora		2/67	-	
DSF-270	Flat-base amphora	Fabric 1	-	-	
DSF-272	Flat-base amphora		5/76	5 ml, Sterile	Small resinous sample with sand remains
DSF-274	Flat-base amphora		3	-	
DSF277	Keay XIX	Fabric 2	-	-	

have shown that through chemical analysis it is possible to try to determine the original content of ceramic containers and especially amphorae (Briggs et al. 2022; Condamin et al. 1976; Evershed 1993, 2008; Garnier 2007; Garnier and Pecci 2021; Garnier et al. 2011; Guasch-Jané et al. 2004; Pecci et al. 2017, 2021; Regert 2011; Woodworth et al. 2015). For a first approach to the content, five samples were selected: one from an Almagro 51c amphora (DSF220) for which the *tituli picti* informed of the content being *liquaminis flos* (a liquid fish sauce), one from Ses Fontanelles I type (DSF002), and three from flat-bottomed amphorae (DSF267, DSF274, and DSF272) (Table 1).

Each ceramic sample was cleaned mechanically, and then it was sub-sampled in the laboratory used by the ERAAUB/IAUB, University of Barcelona, and analysed by the author using the infrastructure of the Scientific and Technological Centres (CCiTUB) of the University of Barcelona. The specimens were ground, and the powders were extracted by using three different extraction methods:

i. The alkaline extraction proposed by Pecci et al. (2020) was carried out on approximately 1 g of sample to identify fruit acids. Before extraction, 50 µl of internal standard (*n*-hexatriacontane) were added. The alkaline hydrolysis is carried out with 3 ml of KOH in water (1 M) (vortex followed by 2 h in an ultrasonic bath). After centrifugation and acidification, 2 ml of ethyl acetate (× 3) are added to the supernatant and mixed with a vortex. The extracts are dried under a nitrogen flow. Although 50 µl of internal standard were added in the preparation of the samples, this is not visible in extracts i of samples 2, 3 and 4.
ii. The total lipid extract was carried out following Charters et al. 1993, modified by Pecci et al. (2013a) using KOH in methanol. Before extraction, we added 20 µl of internal standard (*n*-hexatriacontane).
iii. A further alkaline extraction was carried out on the powder already extracted by extraction ii (3 ml of KOH in water were added to the powder, vortexed and sonicated for 2 h. After adding chloroform and mixing with a vortex, the supernatant was dried under a slow nitrogen flow (2 ml x 3 times) (Pecci et al. 2013a).

All the extracts were trimethylsilylated with 30 µl of N,O-bis(trimethylsilyl)trifluoroacetamide (BSTFA, Sigma-Aldrich) heating at 70 °C. 75 µl of hexane were added and the extracts analysed with gas chromatography coupled with mass spectrometry (GC–MS). It is important to stress that extract i must not be completely dried before adding the hexane. Analyses were carried out using a Thermo Scientific TS GC ultra chromatographer, equipped with a Restek silica capillary column Rtx®-1 of 60 m, 0.32 mm ID, 0.25 µm of thickness coupled to a Thermo Scientific ITQ 900 mass spectrometer operated in electronic ionization (70 eV). The mass range is *m/z* 40–650. A blank sample was analysed using the same solvents employed for the analysis of the archaeological samples.

Analysis of wood and plant remains

After the first excavation season and awaiting the full excavation of the shipwreck for an extensive sampling, 20 interim samples of wooden elements from various components of the hull were selected. The rest of samples up to a total of 101 specimens (Table 2), were selected from branches and herbaceous plants used as packaging placed between the amphorae to prevent their movement and breakage during the journey, and from bark used to seal the amphorae. A pinecone found within the cargo was also included.

The study of the cell structure of the wood was based on the observation of its three anatomical planes (transverse, longitudinal radial, and longitudinal transverse) using a reflected light microscope Olympus BX60, with 50x, 100x, 200 × and 500 × magnifications. In addition, a HITACHI S-3400N scanning electron microscope (SEM) has been used to obtain detail images at further magnifications. The taxonomic identification of wood remains is based on comparative analysis of the cellular anatomy of the woods of the different species. Wood anatomy atlases of European woods (Schweingruber 1990) and the reference collection of wood and coal of the ArqueoUIB Research Group (Universitat de les Illes Balears) have been used as comparative materials. The degree of accuracy of the taxonomic identification has varied in each case depending on the conservation of the wood and/or the difficulty of obtaining thin sections from the different anatomical planes.

Several bunches of herbaceous plants were also analyzed. In this case, as these are non-woody plant remains, their taxonomic identification is not based on the analysis of the type of cells and cell structures typical of woody tissue. A first approach to these materials has been carried out to characterize them both macroscopically and microscopically, and to provide a first insight, awaiting further analyses. A test was carried out with one of these samples ("T.A. 2"). The contents of the sample were dissed in water to identify the various elements. Two of the herbaceous plant elements present were selected to be observed in the optical microscope with transmitted light without any treatment or preparation (stains, etc.). Different elements of his anatomy could be observed in this way.

Table 2 Synthesis of the wood and plant remains studied

Material/Type of element	Number of samples
Mineral concretion	**2**
Concretion on stopper	2
Bark	**12**
Material inside amphora	1
Stopper of amphorae	11
Wood	**20**
Peg 1	1
Peg 2	1
Peg 3	1
Peg 4	1
Peg 5	1
Unknown fragment	3
Tenon 1	1
Tenon 2	1
Stanchion	1
Stringer	1
Pin 1	1
Pin 2	1
Pin 3	1
Pin 4	1
Pin 5	1
Pin 6	1
Rib 105	1
Wood	1
Herbaceous (dunnage)	**2**
Herbaceous	2
Pinecone	**1**
Pinecone	1
Vine's shoots (dunnage)	**62**
Vine's shoots	62
Branch	**2**
Branch attached to stopper	2
Total	**101**

Results

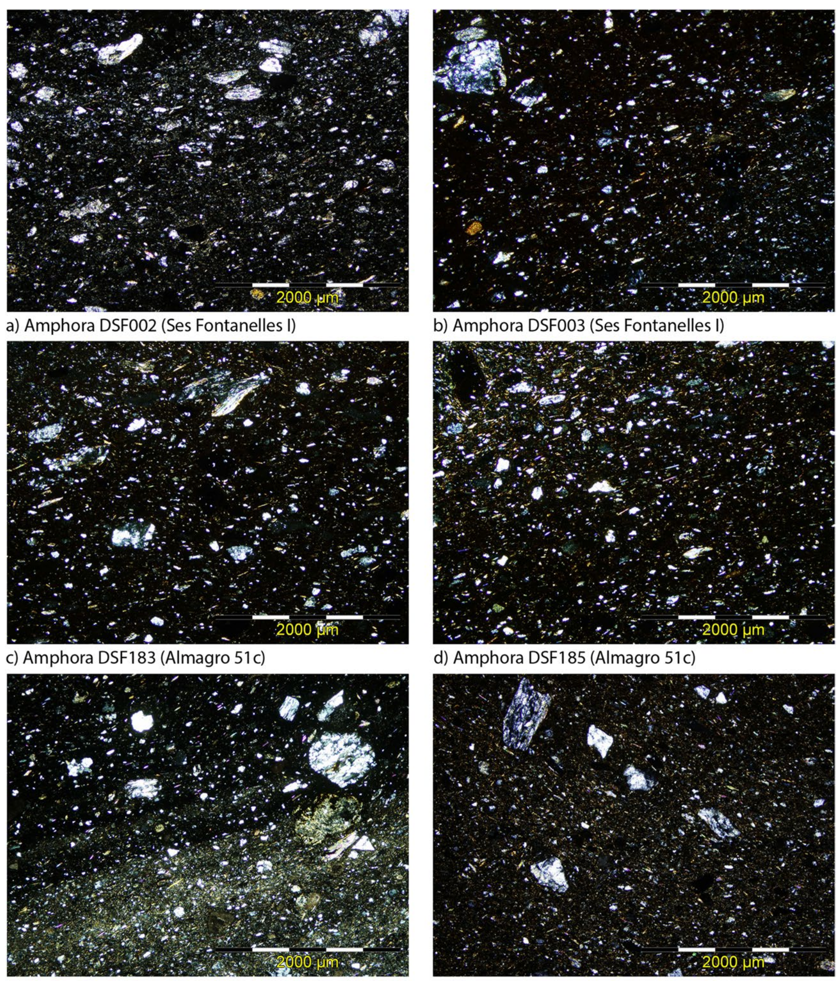
Petrographic characterization: approaching the provenance of the amphorae

From a macroscopic point of view, although ceramics certainly share similarities, especially in the abundant micaceous content, the fabrics are not entirely homogeneous, with a diversity of colors and textures that could perhaps indicate a multiplicity of products. Thin-section petrographic analysis on the selected amphorae enabled the identification of two fabric groups. A full petrographic description of these groups is available in the Supplementary materials, and the discussion here is orientated towards the provenance issue.

Petrographic Group 1 (Fig. 4) includes almost all the samples analyzed (nine out of 10), including the five samples of Almagro 51c amphorae, the two flat-bottomed amphorae, and the two amphorae of the type Ses Fontanelles I (Table 1). The strong similarities in fabric between these nine samples provides evidence of a provenance, most likely, in the same area for all of them. The percentage of coarse inclusions is variable, although never very high, and, in any case, there is a continuous variability between samples with very little coarse fraction and others where it is more common. Similarly, the relative frequencies of the different types of inclusions vary between individuals, although again gradually and always repeating the same range of main inclusions, especially micas (mainly muscovite), monocrystalline and polycrystalline quartz/quartzite, and fragments of metamorphic rocks likely derived from mica-schist, along with other components in minor amounts.

The typology of the amphorae ——especially in the case of Almagro 51c—— points to a provenance either in southern Spain or in Portugal. Comparison with regional geology helps to suggest various possible provenance areas in which there is an important contribution of metamorphic materials, such as the Mediterranean coast of southern Spain (particularly from Málaga to Cartagena), or the Guadalquivir Valley (Aldaya et al. 1972, 1980; Fontboté 1983; Junta de Andalucía 1998; Martín-Algarra 2004). Other areas such as the Atlantic coast of *Baetica* (e.g., Cadiz Bay), the bay of Algeciras, or southern and western *Lusitania* could instead be ruled out. In the latter area, corresponding to the lower valleys of the Sado and Tagus, although some rather micaceous fabrics of Late Roman amphorae have been reported (e.g., Mayet et al. 1996; Fantuzzi et al. 2015), the comparison with the samples from the wreck of Ses Fontanelles indicates that these are clearly different products, both in terms of clay matrix and texture and composition of the inclusions.

Fig. 4 Representative photomicrographs of the petrofabric Group 1 (under crossed Nicols)



a) Amphora DSF002 (Ses Fontanelles I)
b) Amphora DSF003 (Ses Fontanelles I)
c) Amphora DSF183 (Almagro 51c)
d) Amphora DSF185 (Almagro 51c)
e) Amphora DSF263 (Almagro 51c)
f) Amphora DSF270 (Flat-bottomed amphora)

In the case of areas with contribution of metamorphic rocks, it is mainly through comparison with reference materials and previously known fabrics that it is possible to obtain a first insight into the possible provenance based on the compositional compatibility. Thus, the fabrics observed in Petrographic Group 1 are clearly different from those defined in previous studies for the Guadalquivir Valley (e.g., Grubessi 1999; Grubessi and Conti 1999; Fantuzzi and Cau 2017, 2019), the coast of present-day Málaga province (e.g., Fantuzzi and Cau 2017; Fantuzzi et al. 2020), or the coast of Granada (e.g., Vigil de la Villa et al. 1998). Conversely, in the easternmost part of the southern Iberian Peninsula, particularly in the western zone of Cartagena, comparison with previously published studies reveals similarities between our Petrographic Group 1 and the fabrics described for El Mojón workshop (Berrocal 2012: 256–257), where a fine fabric containing predominant inclusions of quartz, muscovite, and fragments of metamorphic rocks rich in quartz and muscovite, as well as iron oxides, has been recorded. It should be noted that we have compared the samples of Petrographic Group 1 with thin sections of four amphorae from the workshops of El Mojón and Mazarrón in Cartagena, and while clear similarities are observed in both the main types of inclusions and textural parameters, some differences are also noticed, especially in the relative frequency of inclusions. In this regard, we should also mention that the samples used as comparison elements are mostly *spatheia,* with fabrics possibly more refined than in other amphora types. In addition, the frequencies of the different components in the amphorae from El Mojón are very variable (Berrocal 2012: 257), especially in the case of calcite, which might suggest the use of raw materials from various outcrops to produce the amphorae. For all the above, the relationship of the Petrographic Group 1 of Ses Fontanelles with the productions of El Mojón or, at least, of the Cartagena area is a very likely hypothesis, especially when comparing with the information previously published by other authors (Berrocal 2012). It is worth mentioning that the workshops in Cartagena (particularly El Mojón) and Granada (sites of Los Matagallares and Los Barreros, in Salobreña) are the only areas known to date in the Mediterranean coast of Spain with well-documented production of both Almagro 51c amphorae and flat-bottomed amphorae (Bernal-Casasola 1998, 2001; Berrocal 2012); in the case of Málaga, production of Almagro 51c amphorae is well documented, but not of flat-bottomed amphorae (Serrano 2004).

On the other hand, in the case of Petrographic Fabric 2 (Fig. 5), which includes only one of the samples analyzed (DSF-277), corresponding to a Keay XIX amphora, the fabric observed in thin section indicates a provenance in an area with a dominant metamorphic contribution, but different from the production area of Petrographic Group 1. The nature of the metamorphic rocks present in this fabric could be compatible with different areas with low to very low grade metamorphism associated with phyllite outcrops, as is the case ——especially—— of the bay of Málaga, in relation to the outcrops of the Maláguide Complex (Aldaya et al. 1980; Fontboté 1983; Junta de Andalucía 1998; Martín-Algarra 2004), and also from other more eastern areas of the southern part of Iberia related to the Alpujárride Complex, where phyllite outcrops can also be found, although in many cases along with other rocks related to a higher degree of metamorphism (Fontboté 1983; Junta de Andalucía 1998; Martín-Algarra 2004).

Comparison with the petrographic reference collection at ERAAUB, as well as with comparative materials found in different publications, shows partial similarities with amphorae fabrics between the Punic and Late Roman periods in the Málaga region, including amphorae of the same type Keay XIX (Fantuzzi and Cau 2017; Fantuzzi et al. 2020). It should be noted that the Málaga coast was, based on the archaeological evidence known to date, the main production area of Baetican Keay XIX amphorae –in addition to the

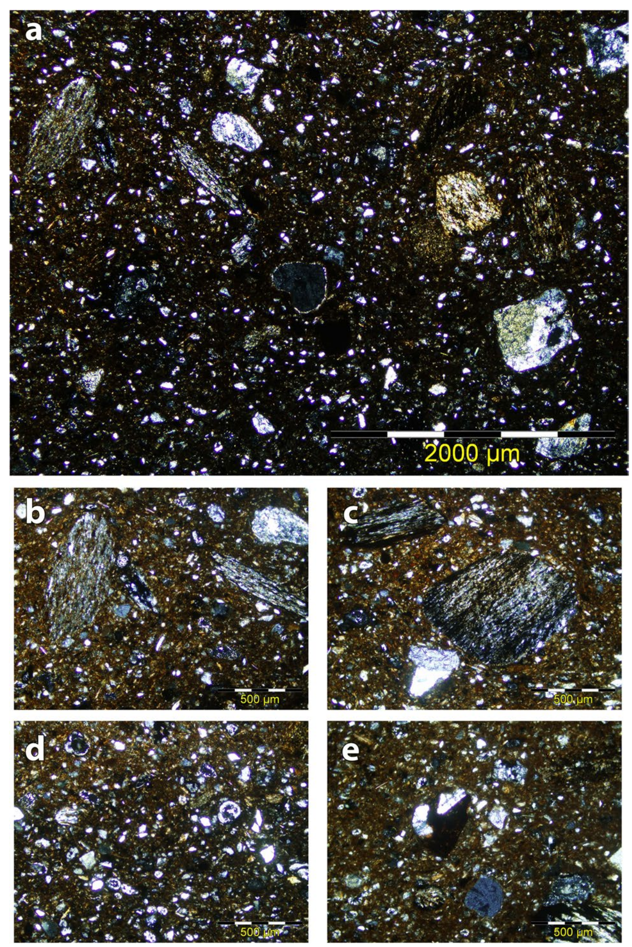


Fig. 5 Representative photomicrographs of the petrographic Fabric 2 (under crossed Nicols)

important production centers known in *Lusitania*– with various documented workshops (Bernal-Casasola 2001; Serrano 2004; García Vargas and Bernal-Casasola 2008). There are, however, some differences with the most typical fabrics of coastal Málaga, especially the lower frequency of sedimentary rock fragments (argillites, sandstones, and limestone) in sample DSF-277, as well as the absence of some inclusions (serpentinite and pyroxene) that are sometimes –but not always– found in accessory quantities in the products of Málaga due to the proximity of the ultra-mafic complex of the Ronda mountain range (Fantuzzi and Cau 2017; Fantuzzi et al. 2020). However, the characteristics of the metamorphic rocks found in the DSF-277 fabric, as well as the other types of inclusions observed –e.g., the fragments of igneous rocks present in an accessory quantity, identical to those documented in other Málaga products (Fantuzzi et al. 2020) suggest that the fabric of sample DS-F277 could correspond to a different variant within the products of the Málaga coast. It is important, in this sense, to note that the amphora DSF-277 corresponds to an atypical morphological variant of the Keay XIX type, different from that analyzed in previous petrographic studies (Fantuzzi and Cau 2017). For this formal variant we do not know possible workshops and there is no information concerning the chronological and geographical relationship with respect to the best-known variants of this type. The presence of a particular fabric could respond to various factors: either a variant of Keay XIX produced in another pottery workshop in the same region, or use of different clay sources at different chronological times of Keay XIX production.

In any case, it should also be noted that the comparison with reference materials and the geology of other production areas for Keay XIX amphorae ——like the cases of western and southern *Lusitania*, as well as the Baetican coast between Huelva and the bay of Algeciras, and the coast of Granada—— suggests that none of them could be proposed as provenance area for sample DSF-277. Something similar happens in El Mojón wokshop in Mazarrón Bay, in the Cartagena area, where amphorae like Keay XIX have also been attested (Berrocal 2012); in this case, the fabric of sample DSF-277 could be compatible from a strictly geological point of view, considering the presence of outcrops of phyllites and quartzites a few kilometers from the site (Espinosa Godoy et al. 1974). However, the products of this and other well-known workshops in the area are very different in terms of fabric both macroscopically and petrographically from the amphora DSF-277. In summary, the integration of the existing archaeological information on the manufacture of Keay XIX amphorae together with the analytical evidence obtained from this study (and in combination with previous studies), suggest as a most likely hypothesis a provenance around the Málaga coast for the amphora DSF-277 recovered at Ses Fontanelles shipwreck. In any case, both the lack of known workshops producing the morphological variant of Keay XIX to which this amphora is related to, and the differences mentioned above with respect to the most typical petrographic fabrics in Málaga amphorae, do not allow us for the moment to provide further details concerning its provenance.

The study of the ichthyofauna: which fish sauce?

All faunal remains recovered from the amphorae containing fish sauce reveals that the substance was derived almost exclusively from a single species: the European anchovy (*Engraulis encrasicolus*). The only exception was a hio-mandibular bone of sardine (*Sardine pilchardus*) identified in the sample DSF-231 (Fig. 6F). A selection of anatomical elements was used to estimate the minimum number of individuals (NMI) of each sample (Table 3). The anatomical representation of the anchovy is quite similar in all samples. The dentaries and other elements of the cranial region are predominant, with the rest of the appendicular skeleton appearing underrepresented, to a greater or lesser extent. Considering the dentaries as a reference for the minimum number of individuals (NMI), the percentage of representation of the vertebrae has been calculated by dividing the number of vertebrae observed by the expected number of vertebrae (e.g., the anchovy has 46–47 vertebrae, if 65 are observed, the estimated NMI will be equal to 2). The average percentage is 19%, ranging from a maximum of 33.3% (DSF-235) to a minimum of 7.1% (DSF-220). On the other hand, the number of vertebrae appears to be correlated to the estimated number of scales, since in those samples where there are with fewer vertebrae there are also fewer scales.

Although it is tempting to suggest that the content of the Almagro 51c amphorae was composed almost exclusively of anchovies' heads, the embedded content in the resin of the inner walls of the amphora DSF-231 (Fig. 7A) showed various articulated skeletons of anchovy (Fig. 7B, C and D; Table 3), with their ribs and vertebrae still in anatomical position. The cranial parts of these specimens were recovered at the lower wall and toe of the amphora probably because of the detachment of the heads during the micronization process. For this reason, we suggest that, despite the observed partial anatomical representation in most of the samples, the fish sauce was made of whole anchovies.

The sardine found in sample DSF-231 had a total length of 11.4 cm based on the dorsal length of the hiomandibular bone (CRD, Fig. 6F) and using the following linear regression: $LT = 32.89*CRD + 8.43$ (r^2 0.931); where LT was the total length and r^2 was the coefficient of determination (Assis and Amaro 2006). In the case of the anchovies (Fig. 8), the size range is between 7 and 12.5 cm ($n = 36$; $x = 8.7$; $CV = 13.5$), although the vast majority were individuals with sizes between 8 and 10 cm. Although there

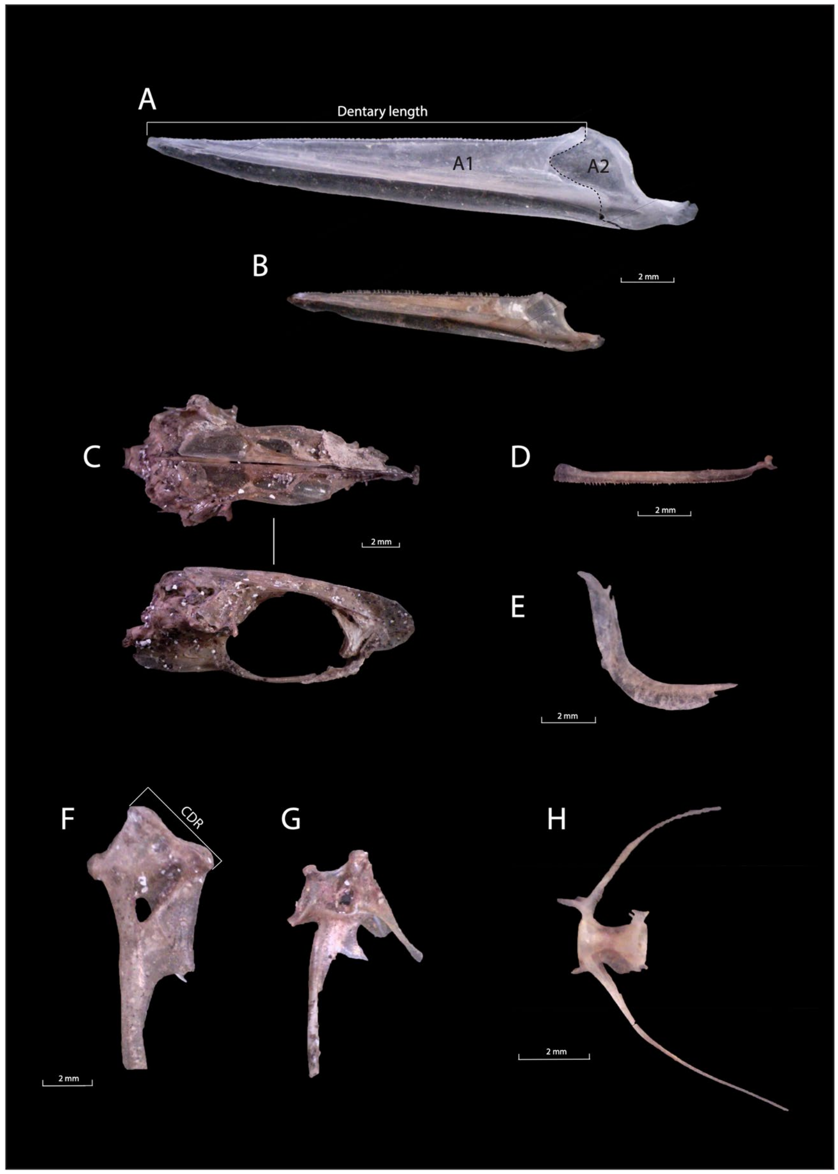


Fig. 6 Selection of osteological remains selected for taxonomic identification and quantification. **A** current left dentary of an extant anchovy (A1) and joint bone in anatomical connection (A2); **B** specimen of anchovy from Ses Fontanelles; **C** neurocraneum of anchovy, dorsal and lateral view; **D** anchovy maxillar; **E** cleithrum; **F** sardine hyomandibular bone (DSF-231) and measurement used for size inference (CRD); **G** anchovy's hyomandibular bone; **H** anchovy's vertebra

Table 3 Results of the ichthyofauna analysis, number of remains of anchovies identified. The sample marked with * only counts for the remains recovered at the bottom of the toe of the amphora (Fig. 7), and those bones attached to the walls of the amphora container have not been considered

Element	DSF-220	DSF-231*	DSF-235	DSF-257
Dental (right)	12	12	3	9
Dental (left)	14	15	3	8
Articular	2	2	0	2
Neurocranium	7	11	2	8
Maxillary	18	19	5	15
Cleitro	14	14	3	9
Hiomandibular	12	18	3	5
Vertebra	9	65	10	51
Scales	Few (< 25)	Present (c. 50–100)	Abundant (> 250)	Present (c. 50–100)

are no significant differences in the size of the individuals present in the four samples, the occurrence of some larger fishes is observed in the DSF-235 sample (Fig. 8, small box).

Organic residue analysis: further investigating the content of the amphorae

Almagro 51c

The amphorae DSF-220 (sample 4), Almagro 51c type, displays a painted inscription (*titulus pictus*) *Alunnii et Ausonii NN() liq(uaminis) f < l(o)s* informing of its content *liquaminis flos* (flower of *liquamen*, a fish sauce). All extracts are dominated by abundant dehydroabietic acid, followed by abietic acid, and methyl dehidroabietate. Extracts ii and iii also display 7-oxodehydroabietic acid,

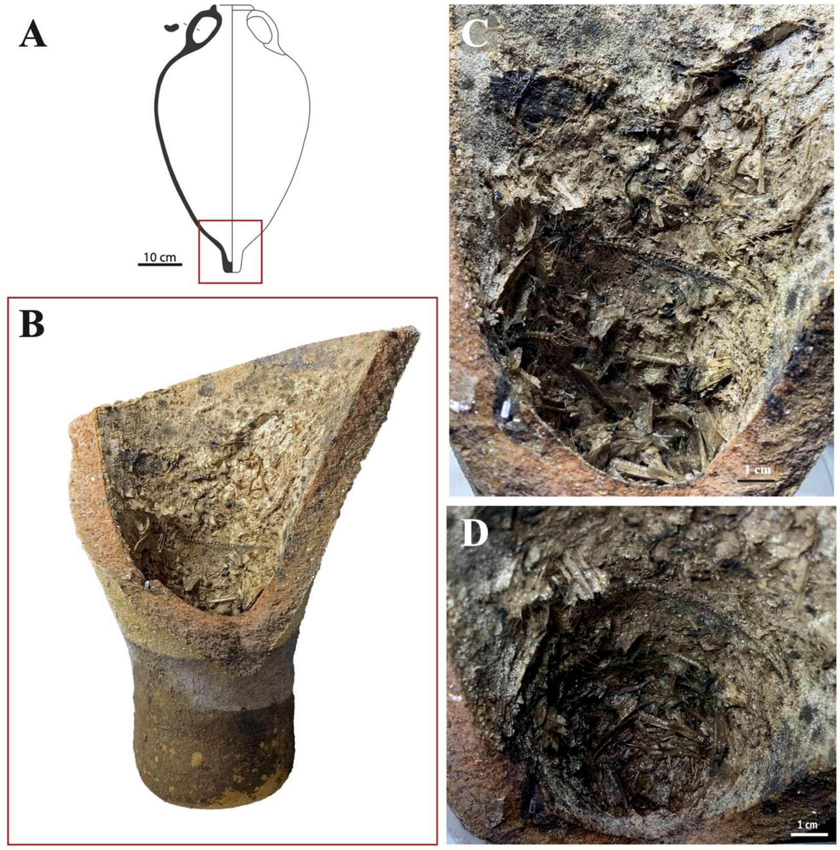


Fig. 7 Fish remains attached to the inner walls of the toe of an Almagro 51c amphora (DSF-231). **A** container typology and sampled section; **B** view of the toe of the amphorae; **C** several skeletons of anchovies attached to the walls and still in anatomical connection; **D** detail of the basal area of the toe where the sample studied was collected from

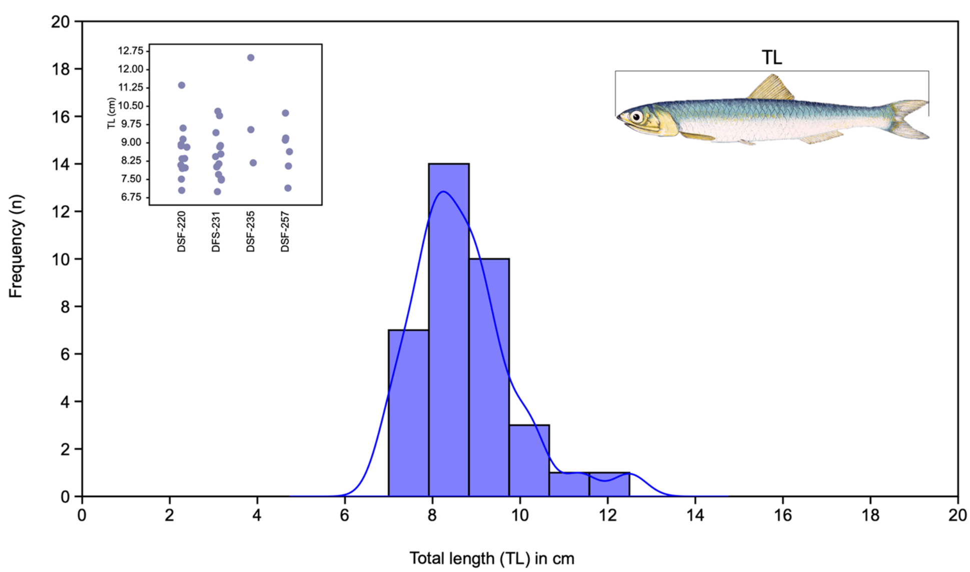


Fig. 8 Sizes of the anchovies identified in the samples. The small box at the top left separates cases by amphora sample ID

and retene. These are markers of Pinaceae products. Specifically, methyl dehydroabietate is the marker of pitch obtained burning the wood of Pinaceae trees, while retene is the marker of heating (Colombini et al. 2005).

Extract i displays tartaric, malic, and succinic acids. Although tartaric acid is not exclusive marker for grape (as it is present also in other fruits, such as tamarind), it is contained in this fruit and considering the context and period studied, the presence of these three acids likely indicates that the amphora contained grapes derivatives, probably wine or vinegar (Barnard et al. 2011; Garnier and Valamoti 2016; McGovern et al. 2017; Pecci et al. 2013b, 2020). Ratios of malic and tartaric acid have been proposed in the literature to identify products from grapes with greater certainty, after extraction under acidic conditions proposed by Garnier and Valamoti (2016). As the extraction method used in this study is different, such ratios cannot be used here with any certainty. However, given the context, the period studied here and the abundance of wine as amphorae content (Bernal-Casasola 2019; Bernal et al. 2021), the most likely hypothesis is that these acids come from grape-derived products.

As stated above, chromatograms are dominated by pitch residues (summing up more than 70% of the lipidic residue), that possibly do not allow to detect other compounds present in low concentrations. However, in all extracts, palmitic, and stearic acid are present. Cholesterol is also present in the sample, while β-sitosterol is absent. Although sterols could derive from post-depositional contamination (Hammann et al. 2018), this could also suggest an animal origin of the content of the amphora. In extract ii also $C_{20:0}$ and $C_{22:0}$ are present. These compounds are present in fish but are not exclusive markers of this product. Therefore, the results of the analyses indicate an animal origin of the content possibly mixed with wine, vinegar, or other wine derivative, or the use of these products to give flavour/preserve the fish products.

Ses Fontanelles I amphora type

In amphora DSF-002 Ses Fontanelles I type (sample 1), the oleic acid ($C_{18:1}$) is the most abundant fatty acid in extracts i (where in the methylated and silylated form sum up the 68% of the chromatogram area) and ii (Fig. 9A), followed by palmitic acid ($C_{16:0}$). In extracts i and iii $C_{9:0}$ is the most abundant among short chain fatty acids, and azelaic acid is the most abundant among dicarboxylic acids.

β- sitosterol is present in traces in extract i. In general, the profile of the three extracts is compatible with various plant oils, including olive oil. However, the analyses performed do not allow for the identification of TAGs, therefore we cannot fully confirm the presence of olive oil. Sample 1 is the only sample, among the five analyzed, in which tartaric acid is not identified. This datum reinforces the idea that this type of amphora was carrying a plant oil. Differently from the other analyzed amphorae, dehydroabietic acid is present only in traces and there are no markers of the production process of the resin/pitch (such as retene or methyl dehydroabietate markers respectively of heating resin or extracting pitch directly from the wood).

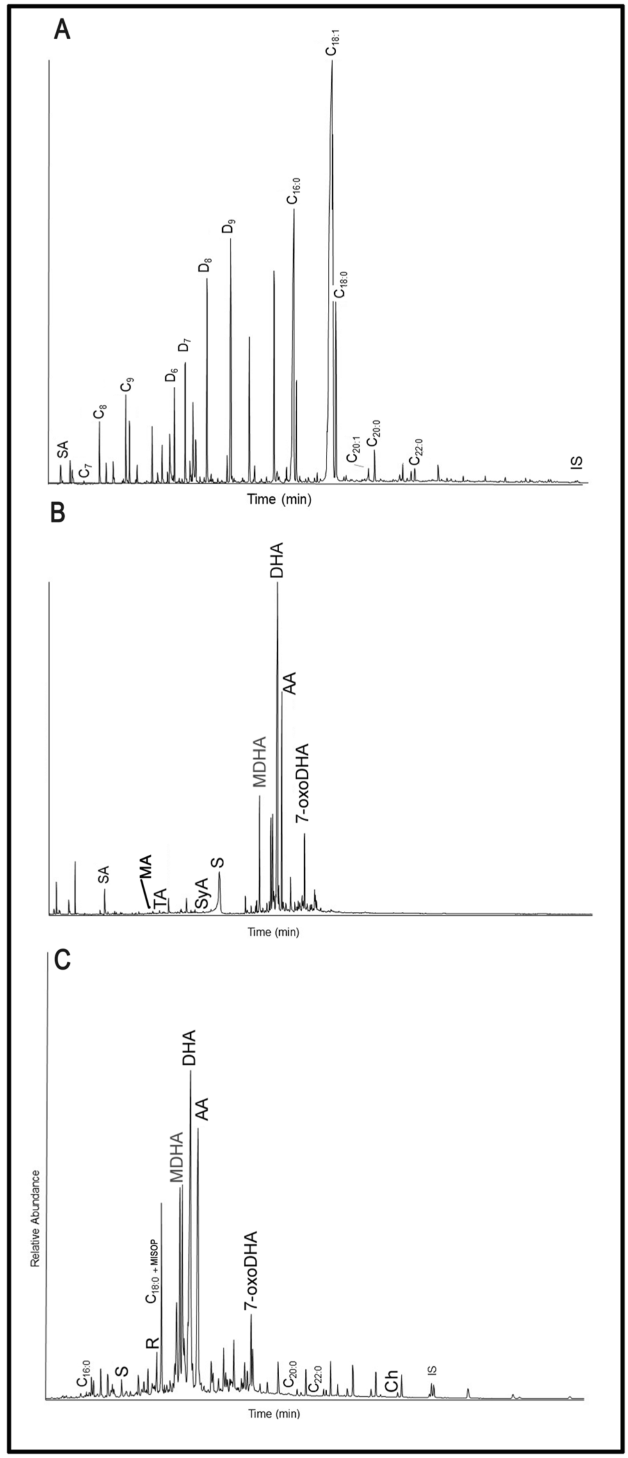


Fig. 9 **A** partial gas chromatogram of extract i of sample 1 (DSF-002). **B** partial chromatogram of extract i in sample 2 (DSF-267); **C** partial chromatogram of extract ii in sample 4 (DSF-220). $C_{n:0}$ are the fatty acids with a specific number (n) of carbons. DHA = dehydroabietic acid, AA = abietic acid, MDHA = methyl dehidroabietate, 7-oxoDHA = 7-oxodehydroabietic acid, MISOP = methylisopimarate, TA = tartaric acid, MA = Malic acid, SA = succinic acid, SyA = syringic acid, S = sulfur, R = retene, D_x = dicarboxylic acids with x carbon atoms. IS is the internal standard

The flat-bottomed amphorae

Three samples were recovered and analyzed from flat-bottomed amphorae. A few olive pits were preserved in amphora DSF-267.

The samples from amphora DSF-267 (sample 2), DSF-274 (sample 3) and DSF-272 (sample 5), are dominated by dehydroabietic acid followed by abietic acid. Methyl dehydroabietate and 7- oxodehydroabietic acid are also present (Fig. 9B). These are markers of pitch obtained when burning the wood of Pinaceae trees. In sample DSF-272 pitch is visible even to the necked eye.

Extract i of the three amphorae displayed tartaric, malic, and succinic acids. The proportion between tartaric and malic acid, which, as indicated above, is sometimes used to assess the presence of grape derivatives in archaeological samples (last Briggs et al. 2023), varies in the extracts of the three analysed amphorae (Table 4), suggesting that only in one case we could confirm the presence of grape derivative. However, as stated above, as the extraction method used in this study is different, such ratios cannot be used here. Moreover, previous experiments and ethnoarchaeological works have shown that using the alkaline method we have applied here, this proportion in wine residues changes depending on ageing, type of materials and contexts (Pecci et al. 2013b). This is also in agreement with the original archaeological hypothesis on the content of these amphorae.

Extract i of samples DSF-267 (sample 2) (Fig. 9B) and DSF-274 also displayed syringic acid. This acid is related to the presence of red wine (Guasch-Jané et al. 2004), however further analyses should be performed to confirm this hypothesis, as syringic acid could also derive from contamination.

Sulfur is present in extracts i and iii of the three amphorae.

Oleic acid ($C_{18:1}$) is present in extract ii of the amphorae, followed by palmitic acid ($C_{16:0}$), and stearic acid ($C_{18:0}$) (Fig. 9). β-sitosterol is present in traces in extract i. These data are compatible with a plant oil. However, these compounds are not abundant in the two amphorae. As mentioned above, olives were recovered in the bottom of the amphora DSF-267. In the case of modern mills, it is possible to identify the residues of the oil released by the storage of olives on the floor (Pecci et al. 2013a), therefore we thought we might identify residues compatible with oil, possibly produced by the storing of olives in the amphorae. However, the results suggest that likely, if olives were preserved as solids in a wine/vinegar medium (as extraction i suggests), they did not release abundant fats.

Wood and macroplant remains

Elements of the hull of the vessel

The results of the taxonomic identification of the 20 wood elements analyzed are expressed in Table 4. In short, four different taxa have been identified, three corresponding to conifers, Cupressaceae (cypress and juniper family), *Pinus* (indeterminate pine) and *Pinus t. pinea* (Stone pine type); and two to angiosperms, *Olea europaea* (olive tree) and *Laurus nobilis* (laurel) (Table 5).

For the small parts of the hull three different taxonomic categories have been identified: Cupressaceae, *Olea europaea*, and *Laurus nobilis* (Table 5). In the case of fragments belonging to the family Cupressaceae (Fig. 10A, B) anatomical elements have not been clearly observed to differentiate the genus *Cupressus* (cypress) and *Juniperus* (juniper). Similarly, in other cases it has not been possible to clearly differentiate between the two species of angiosperms identified, *Olea europaea* and *Laurus nobilis* (Fig. 10C, D). Among the larger elements that make up the hull of the boat only a single genus, *Pinus* sp, has been documented (Table 5). In two cases, it has been possible to differentiate that these corresponds to stone pine type *(Pinus* t. *pinea*) (Fig. 10E, F). In two other cases only the genus, *Pinus* sp, has been determined.

The analysis of the wooden elements of the hull of the boat shows in any case a clear distinction in the woods used for large parts and for those of smaller sizes that formed part of the hull assembly system (pegged, mortise, and tenons).

Table 4 Results of the GC–MS analyses displaying the presence of pitch, of tartaric, malic, and succinic acid, and the proportion between tartaric and malic acid. DHA = dehydroabietic acid, AA = abietic acid, MDHA = methyl dehidroabietate, 7-oxoDHA = 7-oxodehydroabietic acid, TA = tartaric acid, MA = Malic acid, SA = succinic acid, Syr = syringic acid

LAB n	SAMPLE ID	Typology	Resin/pitch	Presence of TA/MA/SA	TA/MA
1	DSF-002	Ses Fontanelles I	DHA in traces	-	-
2	DSF-267	Flat-base amphora	DHA, AA, MDHA, 7- oxoDHA	TA, MA, SA, Syr	1,3
3	DSF-274	Flat-base amphora	DHA, AA, MDHA, 7- oxoDHA	TA, SA, MA, Syr	0,3
4	DSF-220	Almagro 51C	DHA, AA, MDHA, 7-oxoDHA, retene	TA, MA, SA	0,2
5	DSF-272	Flat-base amphora	DHA, AA, MDHA, 7- oxoDHA	TA, MA, SA	0,2

Table 5 Result of taxonomic identification of recovered wood objects (excluding branches)

Element identified	Conifer indet	Cupressaceae	Indet	*Laurus nobilis*	*Laurus/Olea*	*Olea europaea*	*Pinus* sp.	*Pinus t. pinea*	Total
Peg 1		1							1
Peg 2		1							1
Peg 3	1								1
Peg 4	1								1
Peg 5		1							1
Unknown fragment			3						3
Tenon 1					1				1
Tenon 2					1				1
Stanchion							1		1
Stringer								1	1
Pin 1				1					1
Pin 2				1					1
Pin 3					1				1
Pin 4			1						1
Pin 5						1			1
Pin 6				1					1
Rib 105								1	1
Wood							1		1
Total	**2**	**3**	**4**	**3**	**3**	**1**	**2**	**2**	**20**

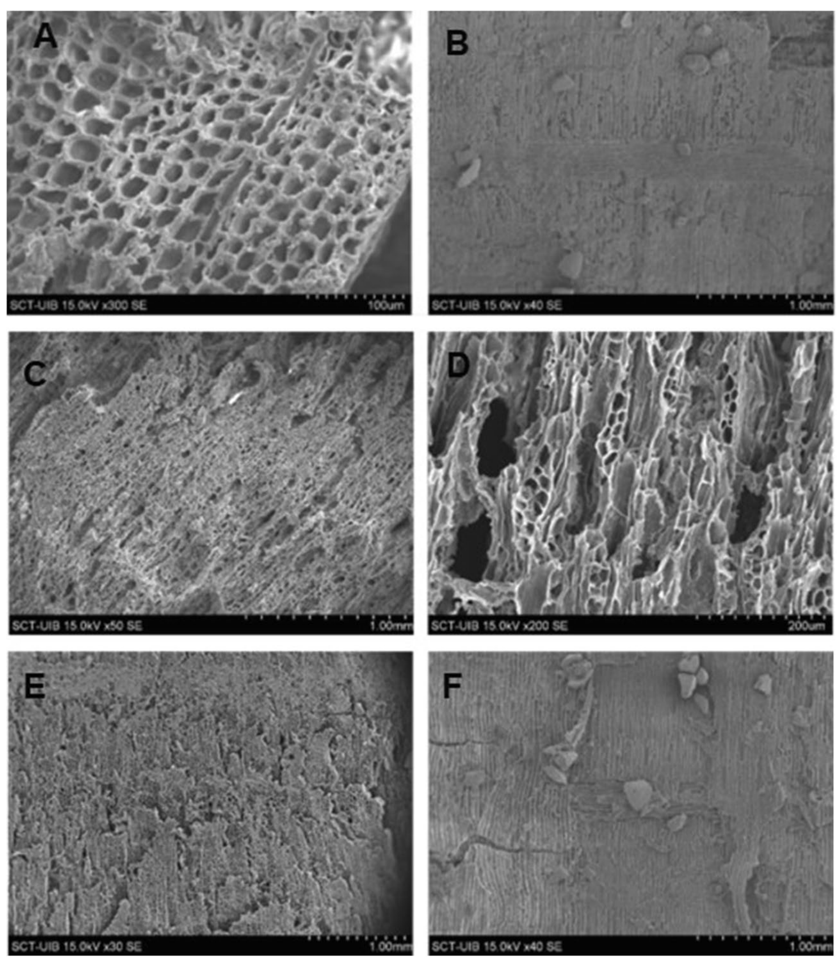


Fig. 10 SEM micrographs of the transverse plane (**A**) and longitudinal radial (**B**) of a wooden fragment of Cupressaceae. SEM micrographs of the transverse plane (**C**) and tangential longitudinal (**D**) of a fragment of *Olea europaea* wood. SEM micrographs of the transverse plane (**E**) and longitudinal radial (**F**) of a *Pinus t. pinea* wood fragment

Other plant remains

Several bunches of herbaceous plants interwoven with twigs, together with branches, were found between the amphorae as dunnage to protect the cargo during the journey. All branches were analyzed, together with some samples of the bunches of herbaceous plants and twigs and three fragments of wood of indeterminate shape and origin also found among the cargo (Table 6).

One of the small branches (sample DSF-40) belong to a plant in the Lamiaceae family (Fig. 11A, B, C). However, most of the branches (n = 61) were fragments of common grape vine (*Vitis vinifera*, Fig. 11D, E) placed between the amphorae transported by the boat to prevent their movement and collision. Two other herbaceous plants show the presence of paracytic stomata, in parallel to the axis of the leaf (Fig. 12A, B). Long cell structures and short cells could be observed in these samples, and some of the long ones presented anticlinal walls profusely undulated. The presence of tomentum was also observed (Fig. 12A, B). This consisted of trichomes of various sizes, apparently single-celled, and especially associated with cells of the nerviations, where they concentrate very densely. Some images show structures that are possibly silica (phytoliths, Fig. 12B). Thus, the observed material has a diversity of well-preserved cellular elements that could in principle be related to plants in the

Table 6 Results of the taxonomical identification of branches and unclassified wooden fragments

Element	Indeterminable	Lamiaceae	*Vitis vinifera*	Total
Branch (dunnage)		1	61	62
Indeterminate woody fragment	3			3
Branch attached to stopper	1			1
Total	**4**	**1**	**61**	**66**

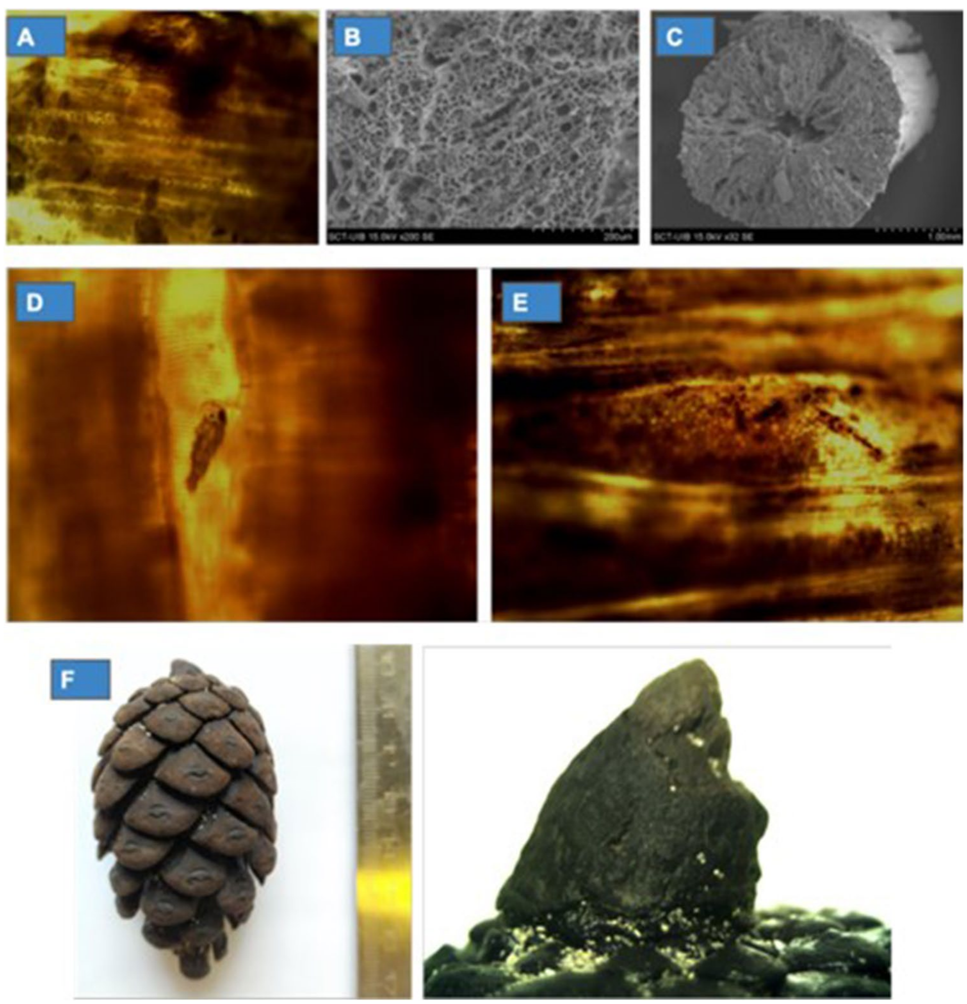


Fig. 11 Fragment of Lamiaceae branch: **A** longitudinal tangential plane seen under the optical microscope; **B** and **C** view of the transverse plane on the SEM; **D** and **E** images of the optical microscope of the longitudinal tangential plane of a *Vitis vinifera* fragment; **F** pinecone of *Pinus halepensis*: overview and detail of the curved peduncle

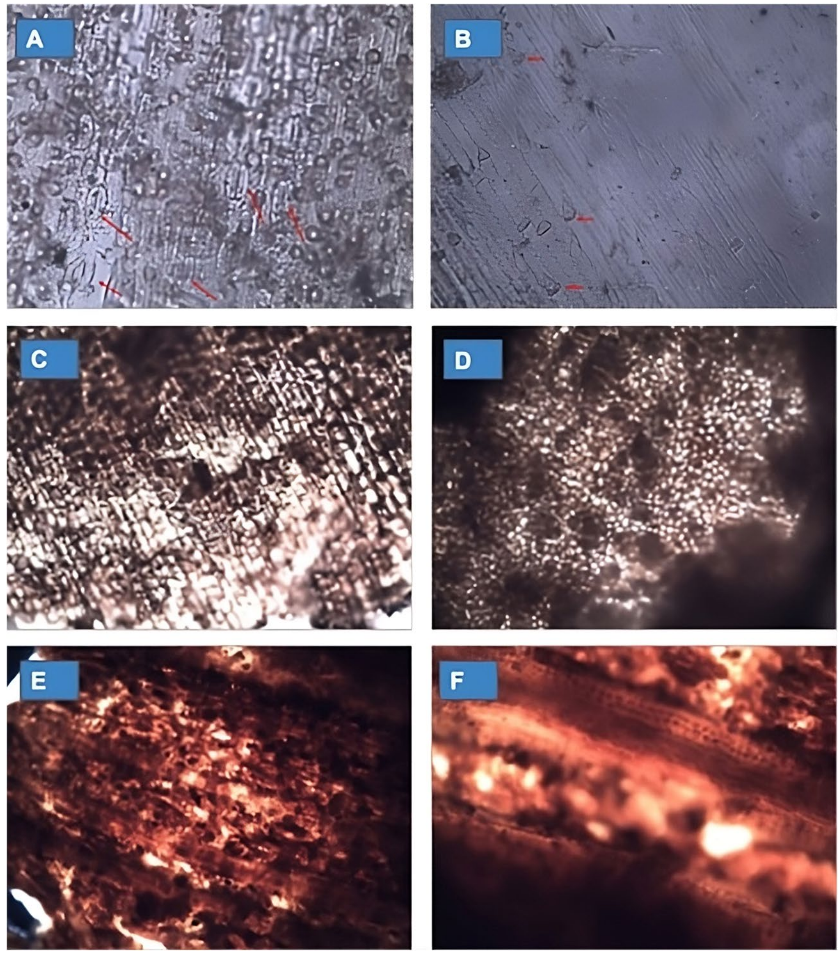


Fig. 12 **A** paracytic stomata (red arrows) from one of the samples analyzed in "T.A. 2"; **B** trichomes (red arrows) and phytoliths from one of the samples analyzed in "T.A. 2."; **C** to **F** photographs of the cell structure of the bark observed in the transmitted light optical microscope

grass family (*Poaceae*), but a confirmation using phytolith analysis is already planned.

In addition, tree bark stoppers used to seal the mouths of the amphorae were analyzed. In all cases, the different elements of the cell structure of tree bark could be observed (Fig. 12C to F). However, taxonomic identification beyond the determination of bark (cork) was not possible because of the taxonomic undefinition of this part of woody plants and by the conservation of the samples analyzed. However, due to the size of some of them, both in diameter and thickness, the cork pieces probably come from a tree species with a great development of this organ protecting the trunk. The most plausible hypothesis is that the cork oak *(Quercus suber),* a tree especially appreciated for its large cork production, was used to prepare the stoppers to seal the amphorae.

Finally, among the materials found on the boat a pinecone was identified according to the size and morphology of its components, mainly the peduncle (element that joins the pineapple to the branch) and the sheaths (Fig. 11F). In this case, the morphological elements indicate that it is an Aleppo pine pinecone (*Pinus halepensis*). It presents a patent peduncle, elongated, and curved, typical of this species. The seminiferous scales have slightly convex apophysis. Finally, the measurements of this pinecone (7.1 × 4 cm) fit quite well within the range of the pinecones of this pine species (6–12 × 3.5–4.5 cm) (Amaral Franco 1989).

Discussion

The multi-proxy approach to Ses Fontanelles shipwreck helps to a better archaeological interpretation of the boat and its cargo.

For the provenance of the amphorae cargo, the petrographic analysis provides additional and complementary evidence to the typological and macroscopic information. All amphorae of the Almagro 51c, Ses Fontanelles I, and flat-bottomed types are very similar to each other in terms of the petrographic fabric (Petrographic Group 1), indicating broadly the same provenance for all of them. The petrographic characteristics, in combination with the available archaeological evidence, point to the Cartagena area, in southeastern Iberian Peninsula, as a likely area of manufacture. On the other hand, for the only specimen of a variant of Keay XIX amphora a provenance in the current coast of Málaga may be proposed as the most likely hypothesis. Overall, it seems that the boat transported a cargo of products packaged in amphorae produced around Cartagena in southeastern Iberian Peninsula.

The archeozoological study reveals that the fish sauce transported in the Almagro 51c amphorae labeled as *liquaminis flos* was prepared using primarily small-medium-sized anchovies *(Engraulis encrasicolus*), despite the occasional presence of sardines. The documented taxonomic selection and homogeneity of sizes between 7 and 12.5 cm is in line with that observed in other areas of the western Mediterranean (García-Vargas et al. 2018), highlighting that these small pelagic species were the subject of an intense and widespread fishing for the preparation of salting products (Grainger 2021). From a historical and archaeological point of view, this practice can be contextualized in the renaissance of the production of fish salting during the Constantinian period with the generalization of new products based on small fish, such as sardine, wing, blotched picarel, or the same anchovy (Bernal-Casasola 2001; Bernal-Casasola et al. 2016, 2020a, b; García-Vargas et al. 2018). At the same time, the samples studied here represent one of the few cases in the Balearic Islands where the fish remains were preserved in primary position (paleocontent in amphorae).

The results of the organic residue analysis provide further information about the content of the amphorae. The Almagro 51c amphora analyzed (DSF-220), which has a painted inscription (*titulus pictus*) informing of its content *liquaminis flos*, displays residues that indicate the presence of animal products but cannot be surely attributed to fish at this stage of analysis. The results are however interesting because they indicate the use of resin or pitch to coat the vessel and the presence of tartaric and succinic acids, suggesting a grape derivative content, which could have been used as a condiment to the fish sauce or the result of a reuse of the vessel. A combination of products was likely also preserved in the flat-bottomed amphorae. In fact, in one of them, olives were preserved, and residues are compatible with wine or other grape derivatives. It has been suggested that sterols can be indicative of the content of the amphorae coming from waterlogged contexts (Garnier et al. 2011). However, we also know that sterols could derive from post-depositional contamination (Hammann et al. 2018). In any case, in this regard, it is interesting that we could identify cholesterol in the Almagro 51c type sample, and β-sitosterol in the Ses Fontanelles I amphora type DSF-002 (sample 1), which agrees with animal products in the first case and plant oil in the second. In general, it is interesting that from the data obtained from samples 2–5 it is possible that substances that are identified as solid residues were stored in grape derivatives. An alternative explanation could be the reuse of the amphorae, a practice that is more common than previously thought. If this would be the case, then wine/vinegar or other grape derivatives could have been absorbed during a first use of amphorae and then these would have been re-coated with pitch and used for a different content (olives, fish products). All these amphorae were coated with pitch, from Pinaceae, which was mostly visible also to the naked eye and could have been used as a waterproofing and/or preserving agent for the content of the amphorae. In some cases, it is possible to identify the production process of pitch extraction, which was heated and/or extracted by burning the wood. Sulfur, which is also present in all of them, could derive from contamination or could have been mixed to the pitch to waterproof the amphorae and/or preserve the content. Finally, Ses Fontanelles I amphora type DSF-002 (sample 1), only displayed residues compatible with a plant oil content. Differently from the other amphorae, only traces of resin, and no sulfur were identified in this amphora.

The study of the wood used in the shipbuilding has identified five different taxonomic categories: Cupressaceae, *Olea europaea*, *Laurus nobilis, Pinus* t. *pinea*, and *Pinus* sp. (Table 5). A selection of timber resources is clearly observed. For the construction of the large elements of the hull pine was used (Table 5), taking advantage of the wood of this tree that develops large trunks of straight growth, which, despite offering a wood of medium hardness and density, is especially optimal for the manufacture of these large elements which absorb water and expand transversely optimally for pegged, mortise, and tenon joints tightness'. In contrast, for the smaller elements of the hull assembly system (P, M & T) *Cupresaceae*, *Laurus nobilis* and *Olea europaea* woods were used (Table 5). The latter two species offer woods with a high density and fine grain, especially appreciated in cabinetry to make small elements and complex shapes. In the case of elements made of *Cupresaceae* wood, the genus or species used has not been more accurately determined. Considering the forest formations in which the identified taxa are developed, they could be Phoenician juniper (*Juniperus phoenicea*), a tree developing in coastal sand dune formation. However, we have not been able to be confirm this properly from the observation of the anatomy of the wood. In any case, the various species of the genus *Juniperus* also offer dense and fine grain woods specially indicated for the manufacture of this type of small objects. Furthermore, an association between taxon and object type is also documented considering the small elements of the assembly system (Table 5). For the manufacture of the pegs, only *Cupresaceae* wood has been documented, while only woods of *Laurus nobilis* and *Olea europaea* have been used for the tenons and treenails. The use of different woods is normal and has been widely attested in other ships similar chronology (e.g., Giachi et al. 2003, 2017;

Beltrame and Gaddi 2007; Allevato et al. 2009). The identified species correspond to thermo- or meso- Mediterranean vegetation, without documenting, for example, taxa of broad-leaved formations (e.g., oaks, deciduous *Quercus,* or beech, *Fagus sylvatica)* or alpine (such as fir, *Abies alba,* mountain pine, *Pinus mugo,* or Scots pine, *Pinus sylvestris).* Among the angiosperms identified, Olea *europaea* develops very extensively in all the low and middle lands of the circum-Mediterranean region, being in many cases the main tree component of open maquia formations or forming part of the undergrowth of other forest formations. *Laurus nobilis* (laurel) is also a taxon of clear development in the Mediterranean basin, although in this case the populations are more restricted to shady places and with greater humidity. For conifers, pine woods have been identified. When it was possible to differentiate the type, they correspond to Stone pine type *(Pinus* t. *pinea)*, so also discarding taxa typical of high mountain areas. Stone pine *(Pinus pinea)* is a species of lowlands and, although it grows in continental territories, develops significantly in coastal areas throughout the Mediterranean basin, also in sandy dunes. Among the 62 branches of woody plants analyzed used to secure the cargo (Table 6) most of them correspond to fragments of grape vine (*Vitis vinifera*), except for one corresponding to the *Lamiaceae* family. They were interwoven with herbaceous plants, and the analysis of few of them suggests that could be of the *Poaceae* family. They could be leaves and/or stems of common reed *(Phragmites* sp.), also a common coastal plant in the Mediterranean basin that was used in this case also to protect some of the amphorae during the journey. The use of vine shoots and other plants to secure the cargo was a common practice in ancient Mediterranean navigation, as witnessed in several shipwrecks such as Port Vendres (Liou 1974), Cap del Vol (Spain) (Nieto and Foerster 1980), Madrague de Giens, Dramont E (Santamaria 1995), Gran Ribaud F (Long et al. 2006), Ma ‘agan Mikhael B (Israel) (Cvikel 2020), or several of the shipwrecks found in Saintes-Maries-de-la-Mer (SM2, SM24, SM9) (e.g., Marlier 2018), just to cite a few examples. These plants were interpreted as for protecting the hull from the cargo but also to protect the cargo, as clearly demonstrated in the Madrague de Giens (Tchernia et al. 1978) and in Ses Fontanelles. Amphorae, sensible to friction and mechanical breakage, needed at least sometimes a proper packaging. Finally, the pinecone analyzed has been identified as *Pinus halepensis,* a taxon that develops in large areas of the Mediterranean basin and it is also especially present in coastal areas. In the Iberian Peninsula, it is one of the main coastal forest formations south of the Llobregat River, which does not contradict the main hypothesis of the origin. The presence of pinecones in shipwrecks is not rare. Sometimes it has been interpreted as dunnage, as in the case of Madrague de Giens or more recently in the Ma ‘agan Mikhael B shipwreck in Israel (Cohen and Cvikel 2018), but also as related to the sealing system of the amphorae.

Conclusions and future perspectives

Considering all the information obtained through the application of a multi-proxy approach to the exceptional shipwreck of Ses Fontanelles several conclusions concerning its origin can be drawn.

All the analytical data suggest that *Alunnius et Ausonius* prepared a trade enterprise fleeting, a merchant ship with a cargo composed mainly of fish sauce (*Liquaminis flos*), in Almagro 51c amphora, oil transported in Ses Fontanelles I amphorae (probably an imitation of Dressel 23 type), and grape derivates or fruits preserved in those substances in flat-bottomed amphorae. The analysis of the ichthyofauna has contributed to understand that this fish sauce was basically prepared with small *engraulidae* particularly anchovies but with presence of sardine. It is possible that also a, so far, invisible cargo occupied part of the space in the galley (Munar Llabrés et al. 2022). These products were carefully stowed in the hold of the merchant ship using vine shoots and herbaceous plants as dunnage for protection. Petrographic analysis of the amphorae suggests an origin for the cargo in southeastern Iberian Peninsula, and particularly in Cartagena or its surroundings. The study of the wood of the elements of the hull and branches and herbaceous plants recovered suggest species of a temperate region, mainly in coastal areas and in lowlands ruling out the use of species of mountainous vegetation, compatible with the area of southeastern Iberian Peninsula.

On the light of this first analytical approach, it is very likely that the vessel departed from some port of the area, perhaps from the main city of *Carthago Nova* or *Carthago Spartaria* (current Cartagena) in Late Antiquity. The boat probably departed from the city itself or a nearby port and sunk for reasons that we still do not know in the large bay of Palma in Majorcan waters.

On a more methodological basis, we hope that this interim study shows that even in cases where the resources, and therefore the sampling, are limited, a well-defined initial archaeological question and a precise selection of samples can help to obtain analytical results that help in the archaeological and historical interpretation of the Roman and Late Antique Mediterranean trading. Future perspectives include a major multidisciplinary an interinstitutional project to finish the excavation of the shipwreck, the full study of its cargo and the naval architecture, and the evaluation of the possibilities of the extraction of the hull for future display. All these will count with an integrated and extensive multianalytical approach that could serve to confirm or refute some of the initial hypothesis proposed here and certainly to shed light into this exceptional shipwreck found in Mallorca waters.

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Declarations

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