Reconstructing Production of Hellenistic Pottery and Maritime Trade Routes: Insights from a Hellenistic Shipwreck near Žirje, Croatia

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Abstract:

The discovery of a Hellenistic shipwreck dating back to the 4th century BCE off the coast of Žirje Island in Dalmatia, southern Croatia in 2015 has sparked a series of investigations aimed at determining the vessel's origin of departure and direction of travel. Our study aims to determine the departure port of this merchant ship through the archaeometric analysis of 40 tableware and kitchenware samples recovered from the ship's galley. To investigate their provenance, we employed various analytical techniques, including ceramic petrography and instrumental neutron activation analysis (INAA). Given that the samples were retrieved from the seabed and exposed to seawater for over two millennia, a series of scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS) and X-ray diffraction (XRD) analyses were conducted to assess post-depositional alterations in the microstructure. Operating under the assumption that the ship originated from a port in the vicinity due to its size, we conducted analyses on samples of raw clay collected on the island of Hvar, where the Greek colony of Pharos was established at the beginning of the 4th century BCE, engaging in local pottery production. Our study reveals that the tableware was produced in Pharos, whereas the origins of the kitchenware aboard the ship's galley remain undetermined, adding another variable to the reconstruction of the ship's departure and shedding light on the broader network of contacts within the Hellenistic trading system in Dalmatia. Furthermore, examination of the post-depositional context unveiled significant alterations in the ceramic microstructure, including the precipitation of secondary minerals such as calcite, gypsum, and pyrite, as well as chemical enrichments and depletions.

Keywords: Hellenistic shipwreck, trade, tableware, kitchenware, provenance, ceramic petrography, geochemistry

Statements and Declarations

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Introduction

Ceramic artefacts remain one of the most crucial forms of material evidence in the studies of the ancient Mediterranean world (Rotroff 2006: 138-141). While written documentary evidence from this period provides some key evidence regarding trade, the unique characteristics of the inorganic artefacts have proved to be useful in capturing past cultural interactions, and particularly insightful in untangling the intricate network of maritime trade in the ancient Mediterranean (Arnaud 2012). The containerisation of the Mediterranean world has long been documented, with increasing understandings of standardisation in long-range maritime transactions, resulting in more attention drawn towards the vessels used for the transportation of goods in the archaeological literature (Bevan 2014; Eiring and Lund 2002). The remains of trading vessels that sunk mid-voyage hold important information regarding past trading activities and the complexities of commercial exchange, especially when considering the number of recorded shipwrecks during the Hellenistic period (Gibbins 2001). Archaeologists have sought clarification of the ancient economies through the identification and interpretation of production locations of ceramic vessels via typological characteristics and archaeometric analysis (Peacock 1977; Whitbread 1995), attempting to reconstruct ancient trade networks in the Mediterranean.

The Hellenistic period saw a significant growth in the seaborne transport of goods in the Mediterranean, indirectly reflective of the economic transformations of the period (Davies 2006). In addition to official shipping channels, this region also saw innumerable smaller vessels engage in trading ventures, operating without fixed schedules and ports of call, otherwise termed as cabotage or tramping (Horden and Purcell 2000: 140), accounting for increased exchange and distribution of commodities. An important factor to consider for maritime trade during this period is inter-regional connectivity as a result of Greek colonisation (Dommelen, 2012). The establishment of Greek emporion, or 'ports-of-trade', is often discussed in literature regarding ancient economies due to their role as instruments of local and regional trade as well as long-distance trade (Demetriou 2011). Such polities dedicated to facilitating economic trade are also observed in the Adriatic, with nodes acting as intermediaries aiding connectivity in the wider trade network of the Mediterranean. The Adriatic has historically been an important interface for cultural and commercial exchange, especially following the expansion of the Hellenistic world. The beginning of the 4th century BCE saw the establishment of two Greek colonies on the Dalmatian islands, with Pharos on the island of Hvar and Issa on the island of Vis (Fig. 1), enabling an influx of trade in the Adriatic which resulted in cultural and economic changes (Slapšak and Stančič 1999; Šegvić et al 2012; Miše 2015: 61-65; Kirigin 2018)

With the discovery of a Hellenistic shipwreck off the coast of the island of Žirje, Croatia, a series of investigations have attempted to establish the origin of departure and direction of travel of the trading vessels (Radić Rossi et al 2020; Miliša et al 2022; Miše and Quinn 2022). These studies have focused on the detailed petrographic and chemical characterization and the sourcing of the raw materials used to manufacture the surviving cargo of transport amphorae, shedding new light on the commercial activities in this region. In addition to the more common amphorae recovered, abundant table and kitchenware were also recovered from the wreck site. This study will act as a continuation of the above investigations with the detailed analysis of other surviving ceramic artefacts from the ship's galley, contributing to the understanding of this trading vessel as well as the wider scope of maritime transactions in the Mediterranean. The present paper explores the results of detailed archaeometric analyses, including ceramic petrography, XRD analysis, SEM-EDS analysis and geochemical analysis via INAA, of a ceramic assemblage composed of 21 kitchenware and 19 tableware samples from the Žirje shipwreck. These analyses offer important insights regarding provenance, which consequently can be used as a proxy to aid the determination of the trading vessel's point of departure. The study sheds new light on the complex trade networks and economies of the ancient Mediterranean world, revealing valuable information regarding regional connectivity in the Adriatic.

Archaeological and Regional Context

The ceramic assemblage investigated for this study was recovered during 2015 – 2020 excavations of a shipwreck located off the coast of the island of Žirje, Croatia (Fig. 1). The merchant trading vessel sank mid-voyage, and with no evidence of a surviving hull upon surveying, it is characterised by the remaining cargo and other surviving ceramic materials (Radić Rossi et al 2022: 15-25). Results from initial surveying of the site concluded that the vessel likely capsized mid-voyage, resulting in the contents of the ship, including the cargo of 4th century BCE Corinthian type B amphorae, spilling out onto the seabed (Radić Rossi et al 2020). Approximately 130 transport amphorae and 70 ceramic vessels were recovered, some of which sustained damages incurred either during the sinking of the ship or through post-depositional processes on the seabed (Radić Rossi et al 2022: 17).

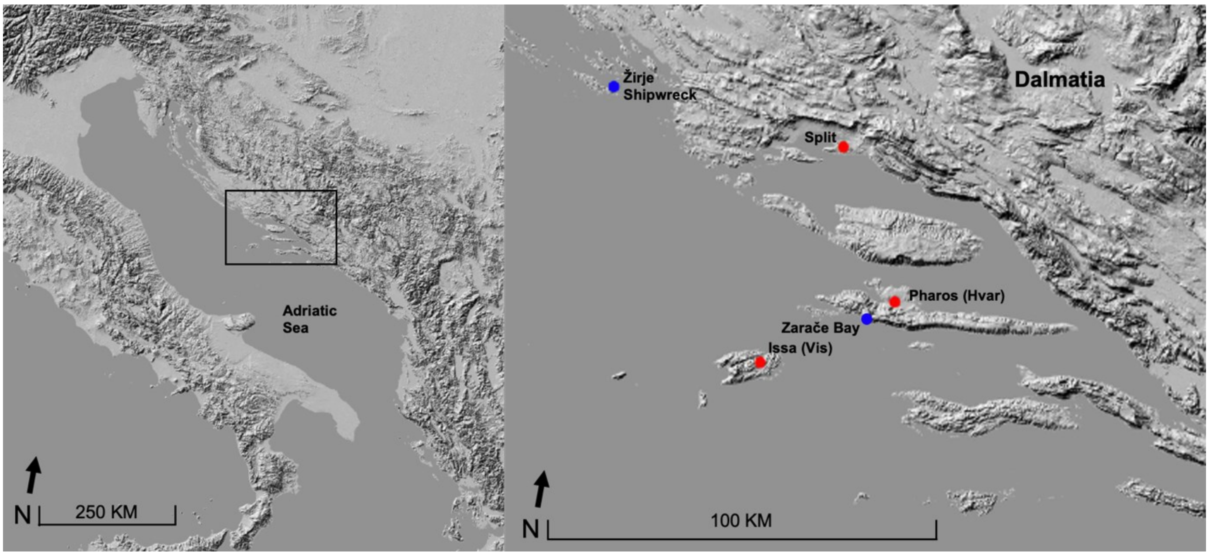


Fig. 1 Map of the Adriatic Sea in the Central Mediterranean region; Location of the Žirje shipwreck in relation to the Greek colonies of Issa on the island of Vis and Pharos on the island of Hvar (See Supplement 3 for coordinates)

Previous analysis of the transport amphorae from the Žirje shipwreck has revealed two distinct fabric groups. The production location of samples was determined through petrographic comparisons to the fabric classes of Corinthian type B amphorae established by Whitbread (1995), attributing the amphorae to production centers in Corfu and Corinth (Miše and Quinn 2022). Furthermore, comparative analyses of transport amphorae from terrestrial and marine contexts, including samples from the Žirje shipwreck, were conducted to identify the post-depositional alterations and the effects of seawater on the ceramic fabric as well as geochemical alterations (Miše et al 2021). The effects identified include geochemical changes to the ceramic composition in addition to surface and microstructural alterations of the ceramics (Miše 2022: 32-33; Miše et al 2021).

Two of the amphorae found at the site contained a sludge mixture of sand, clay, shellfish and calcified remains of sea organisms, with the clay suspected to be part of the original contents of the amphorae. One interpretation suggests that these amphorae were filled and used as ballasts on the ship, although, their presence could also possibly suggest that the raw materials within the amphorae were transported to an unknown workshop (Miliša and Rogošić 2022: 181). The transportation of raw clay by ships has been observed during the Hellenistic period in Egypt at production sites in Tell el-Timai (Hudson et al 2018), as well as production centres in Dalmatia, with raw materials from Zarače Bay on the island of Hvar transported to Issa and Pharos for the production of fine table wares (Miše et al 2020). The island of Hvar, specifically the region of Zarače Bay, is also a candidate for the source of the raw materials used to produce the ceramics from the Žirje shipwreck. The island is characterised by its karstic landscape that is predominantly composed of bedded limestone with layered limestone and dolomite further inland (Oštrić et al 2014), and Zarače Bay is characterised by the formation of Middle-Upper Eocene flysch identified from the reddish-brown mudstone with bioclastic limestone (Marnčić 1981). The use and transportation of the raw materials from these deposits have been observed during the Hellenistic period (Miše et al 2020), and therefore, can be used as a source of comparison for this investigation into the ceramics from the galley of the Žirje shipwreck and the raw clay found within the transport amphorae.

Materials and Methods

The ceramic assemblage investigated for this project is composed of 40 samples of kitchenware and tableware (Fig. 2 and 3) which were found alongside the 130 transport amphorae, likely belonging to the ship's cargo and galley. The ceramic assemblage analysed includes fragments from cooking pots of various sizes and forms including casserole dishes, cooking jugs and large bowls and jugs; tableware from the ship includes juglets, globular jugs (with double bar handles in a Heracles knot), drinking cups (skyphoi) and small bowls and plates (Table 1). The fragments of ceramic samples analysed (Fig. 3) exhibited varying levels of sustained damage and marine encrustation as a result of prolonged exposure to the marine environment. Some vessels also accumulated a dark layer of crusted algae on the ceramic surface in addition to other biological fouling, with the full extent of the post-depositional processes documented and discussed in Miliša et al (2022: 39-75).

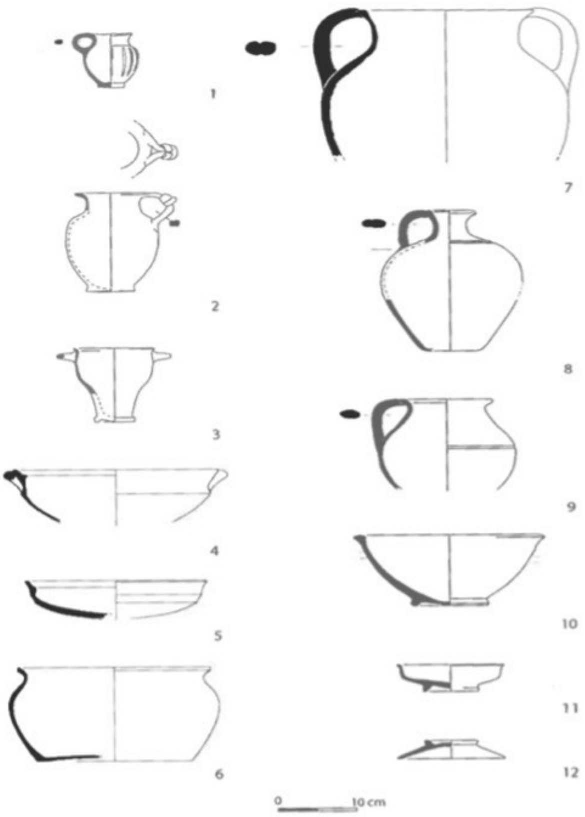


Fig. 2. Illustrations Pottery types recovered from the Žirje shipwreck 1) juglet, 2) globular jug with double bar handles in Heracles knot, 3) skyphos (drinking cup), 4 and 5) lopás (casserole dish), 6 and 7) caccábe (cooking pot), 8 and 9) large jugs, 10) large bowl, 11) small bowl, 12) lid/small plate (drawings by S. Čule, G. Stelo and L. Cavassa published in Milisša et al 2022, Fig. 182: 129)

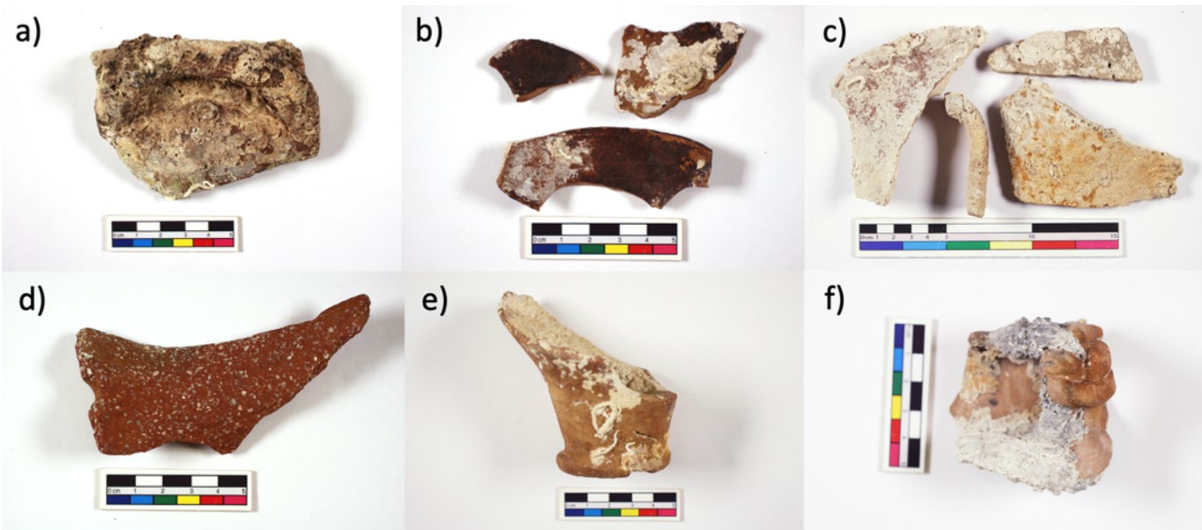


Fig. 3. Examples of fragments analysed in this study a) handle on rim from cooking jug, b) body sherds from small bowl with black slip, c) rim, body sherds and handle from large cooking vessel, d) rim of large cooking pot with large white angular inclusions, e) base of drinking cup, f) neck and handle of globular jug with Heracles knot

An integrated approach of microstructural, mineralogical and geochemical analysis of the vessels from the galley of the shipwreck was chosen for this study (Table 1). The samples were investigated using a combination of 1) thin section petrography via optical microscopy for microstructural analysis and identification of post-depositional alterations; 2) X-ray Diffraction (XRD) analysis for investigating alterations to the mineralogical composition which may not be detected through ceramic petrography ; 3) Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy mapping (SEM-EDS) for identifying post-depositional alterations to the chemical composition. The above analyses were conducted in the Wolfson Archaeological Science Laboratories at the Institute of Archaeology, University College London.

Ceramic thin sections of 38 collected samples were produced following descriptions detailed in Quinn (2022: 21-46). Detailed petrographic descriptions following the thin section description system outlined by Whitbread (1989) and modified by Quinn (2022) were produced for each thin section sample prior to grouping the samples based on their petrographic characteristics, with the identification of compositional patterning in the assemblage based on the type, appearance, size and distribution of inclusions and voids, as well as the optical characteristics of the surrounding matrix and textural components.

Due to prolonged exposure to the marine environment, post-depositional alterations in the microstructure of some samples were observed through ceramic petrography (as detailed in the Results section). To further investigate the possibility of mineralogical alterations in the most affected samples, additional XRD analysis was conducted on two selected samples (ZJ006 and ZJ009). From a cut surface of the samples, a spatula was used to scrape out the core of the sherds to produce the fine powder required for XRD analysis, with the intention of avoiding the outer surfaces with post-depositional alterations such as marine encrustation.

Similarly, we employed SEM-EDS to map the cross-sections of samples that exhibited microstructural alterations in thin section (ZJ006, ZJ009, ZJ016, ZJ017). SEM mapping was used to detect the distribution of chemical elements across the sample cross-sections, identifying areas most exposed to seawater. Additionally, point analyses and backscatter imaging were conducted to further examine chemical and microstructural changes in these regions. The results of the SEM-EDS analyses, along with the statistical analysis described below, were used to identify the elements altered by the marine environment.

The bulk geochemical composition of all collected samples was characterised via instrumental neutron activation analysis (INAA) at the University of Missouri Research Reactor (MURR). Due to the intake of seawater from the post-depositional environment, the sample surfaces were cleaned with a silicon carbide drill bit before being powdered for INAA analysis. The samples were exposed to a series of two irradiations and three gamma counts, resulting in a combined total of 33 short-lived and long-lived elements (Al, As, Ba, Ca, Ce, Co, Cr, Cs, Dy, Eu, Fe, Hf, K, La, Lu, Mn, Na, Nd, Ni, Rb, Sb, Sc, Sm, Sr, Ta, Tb, Ti, Th, U, V, Yb, Zn, and Zr) (Glascock et al 2004). Multiple methods of multivariate statistical analyses were employed for the investigation of the bulk geochemical data of a reduced list of 23 elements (La, Lu, Nd, Sm, Yb, Ce, Co, Cr, Eu, Fe, Hf, Ni, Sc, Ta, Tb, Th, Zn, Zr, Al, Dy, Mn, Ti, V), excluding those which have been identified to be enriched (As, Ca, Na, Sb, Sr and U) and depleted (Ba, Cs, K and Rb) as a result of exposure to the marine environment, as detailed in Miše et al (2021). Following preliminary exploratory descriptive statistical analysis, Principal

Component Analysis (PCA) was applied to identify compositional patterning, followed by Hierarchical Cluster Analysis (HCA) conducted to identify subgroups in the given elemental variables of the ceramics.

In addition to the ceramic vessels, two samples of raw clay found within two different transport amphorae from the ship were analysed, as well as two field samples of clay collected from deposits on the island of Hvar. One of the raw clay sample from amphorae from the shipwreck displayed a creamy white appearance, while the other exhibited a light olive-grey coloration. Both samples included a fair amount of small broken shells and debris which resulted in the friable consistency even after processing. Two raw clay samples were collected from the island of Hvar, where the Greek colony of Pharos was established at the beginning of the 4th century BCE. The clay was sourced from deposits in Zarače Bay, situated near the village of Milna on the southern coast of the island (Fig. 1). This sampling strategy was employed under the assumption that the workshop in Pharos, due to its proximity to the shipwreck and the small size of the vessel, was responsible for producing the vessels recovered from the Žirje shipwreck. This workshop used the clay from Zarače Bay to produce the same type of tableware, as highlighted in Mise et al. (2021). The results of the compositional analysis of all clay samples were compared with the composition of ceramic vessels to identify potential matches and determine the possible source of production of ceramics. A comparative study of thin sections and geochemical data was also conducted between the ceramics from the shipwreck, the 4 clay samples, and amphorae samples from the ship and from Pharos, previously analysed in (Miše et al 2021; Miše and Quinn 2022).

Results

Thin Section Petrography

The 38 ceramic thin sections examined under the polarising microscope revealed two dominant fabric groups, Fabric 1 and Fabric 2, as well as five unique samples which also represent separate fabrics (Table 1). The petrographic analysis of the sherds revealed that most of the samples exhibit some level of post-depositional alteration (Fig. 4 C and D), discussed in detail below in a separate chapter. Fabric 1, composed of 17 samples of kitchenware and 5 samples of tableware, is characterised by the presence of equant and elongate sub-angular quartz and chert inclusions in an iron-rich clay matrix (Fig. 4A). The poorly sorted fine sand – silt-sized inclusions range between 15-30% of the fabric composition and display a unimodal grain size distribution. Other notable inclusions present in all samples include biotite, muscovite, siltstone, opaque minerals, argillaceous inclusions and phyllite, with most samples exhibiting inclusions of microfossils identified as calcified foraminifera.

Fabric 2, composed of 12 tableware samples, is characterised by a fine calcite-rich matrix with minimal equant and elongate sub-angular silt-sized inclusions (Fig. 4B). Fine biotite and muscovite inclusions are the dominant inclusions with some alignment of biotite and muscovite mica parallel to the vessel walls. A small amount of foraminifera microfossils was also identified in a few samples. Four of the 12 tableware samples have evidence of brownish-black decorative slips with fine biotite and muscovite inclusions.

In the analysed assemblage, there are five samples with petrographically unique microstructures that do not match the two main fabric groups. Their detailed description and photomicrographs are presented in Supplement 1. Raw clays from Hvar (sample HV001in Fig. 4E) had an iron-rich clay matrix with fine monocrystalline quartz, biotite, muscovite and few calcified microfossils. The clay samples from the Žirje shipwreck (sample ZJ041 in Fig. 4F) are characterised by a calcite-rich matrix with fine monocrystalline quartz, biotite and an abundance of shells and microfossils which are likely the result of post-depositional processes.

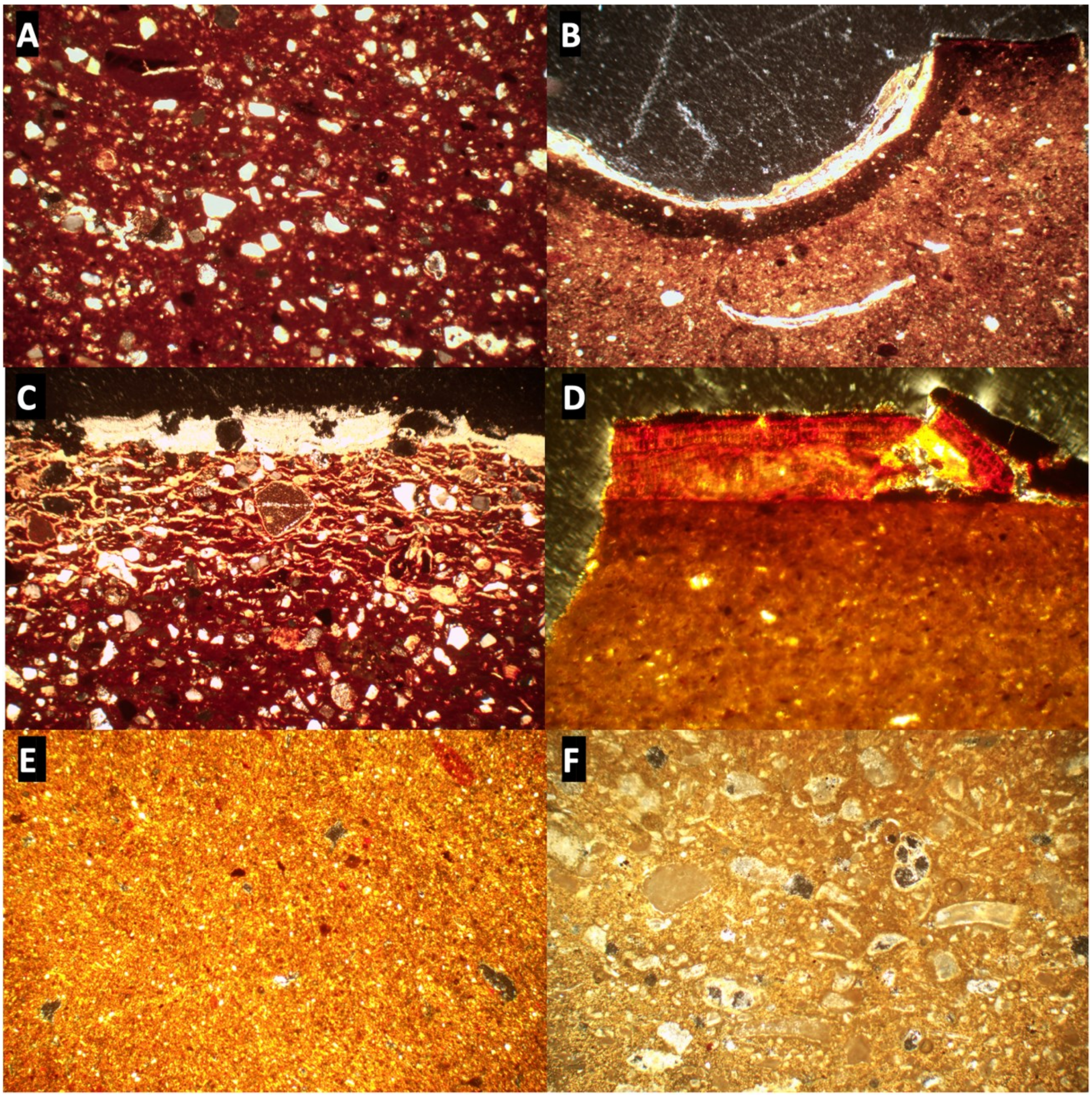


Fig. 4 Photomicrographs of petrographic fabrics identified in the 38 kitchen and tableware samples from the Žirje shipwreck in this study. **A** Fabric 1 (kitchenware and tableware), **B** Fabric 2 (tableware), **C** Post-depositional alteration on Fabric 1, **D** Post-depositional alteration on Fabric 2, **E** Clay from Hvar, **F** Clay from Žirje Shipwreck (all except 3D taken in XP at 50X, field of view= 3mm; 3D taken in XP at 100X, field of view= 1.5mm)

XRD

The results from the XRD analysis on kitchenware samples ZJ006 and ZJ009 confirmed the presence of the mineralogical components identified petrographically, with the same mineral phases represented in both analysed samples. The XRD diffractogram for sample ZJ006 is presented below (Fig. 5). Minerals identified and the corresponding 2-Theta values (deg.) for peaks are as follows: minerals related to the clay paste composition include quartz (20.86, 26.64, 36.55, 40.29, 42.45, 50.15, 67.67, 81.29), biotite (26.64), muscovite (27.91), and kaolinite (54.83). Minerals identified related to the firing technology of the ceramics includes gehlenite (29.77, 33.20, 59.94), diopside (35.09) and hematite (64.04). Minerals present which are likely the result of the post-depositional environment include calcite (39.45) and gypsum (11.62, 23.43).

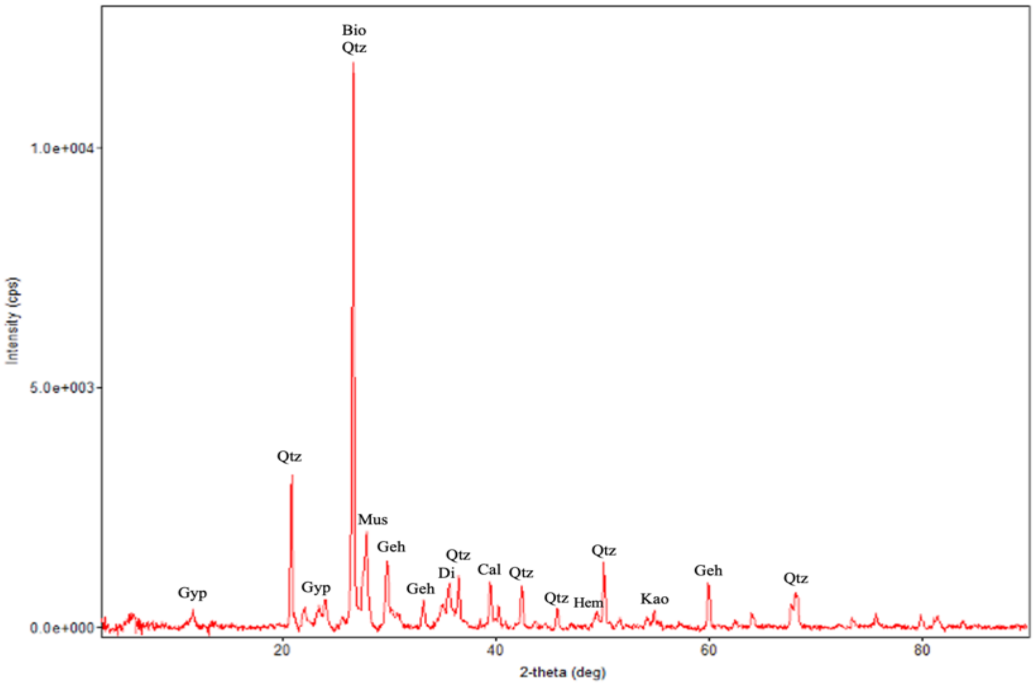


Fig. 5 XRD Diffractogram of kitchenware sample ZJ006 from Fabric 1, Gyp = Gypsum, Qtz = Quartz, Bio = Biotite, Mus = Muscovite, Geh = Gehlenite, Di = Diopside, Cal = Calcite, Hem = Hematite, Kao = Kaolinite

Post-Depositional Alteration

The characteristics of the ceramic sherds are reflective of the marine depositional environment and the investigation into the microstructural, mineralogical and chemical post-depositional alterations is paramount to the understanding and interpretation of the composition of the assemblage. Most of the samples examined exhibit some level of post-depositional alteration, with marine encrustation and other biological formations observed on the outer surfaces of the sherds to varying degrees (Fig. 4C and D). There are also significant alterations visible throughout the ceramic body, in the form of precipitated secondary phases within the voids, notably calcite and pyrite crystals which form during burial in marine environments (Cau Ontiveros et al 2002; Ferri et al 2019). Instances of precipitated gypsum are also often detected as a result of the marine environment (Maritan 2020), occurrences of which were identified along with calcite in the Žirje assemblage via XRD analysis (Fig. 5)

Elemental distribution maps (Fig. 6) were produced via SEM-EDS analysis to identify and illustrate compositional differences in the ceramic body that could indicate enrichment or depletion of specific elements by seawater. Significant enrichment of calcium was observed within voids and distributed within the matrix along the margins of the sherds, as well as areas of high iron and magnesium. Spot analysis of crystals deposited around the margins of voids in the fine tableware (Fig. 6B and 7A) confirmed these to be pyrite (Buxeda I Garrigos et al 2005), their formation resulting from the reduction of Fe to Fe^{2+} in alkaline conditions beneath marine sediments (Ferri et al 2019). The results of the investigation into the effects of the post-depositional environment on the assemblage has revealed that the seawater may permeate across both finer and coarser wares when submerged, and the presence of decorative slips and marine encrustation, in this case, do not act as a sufficient barrier to prevent the intake of seawater and dissolved minerals. Furthermore, the alterations as a result of the water are mostly concentrated around the margins of the sample which are most susceptible to the uptake and circulation of mobile cations from the seawater (Maritan 2020).

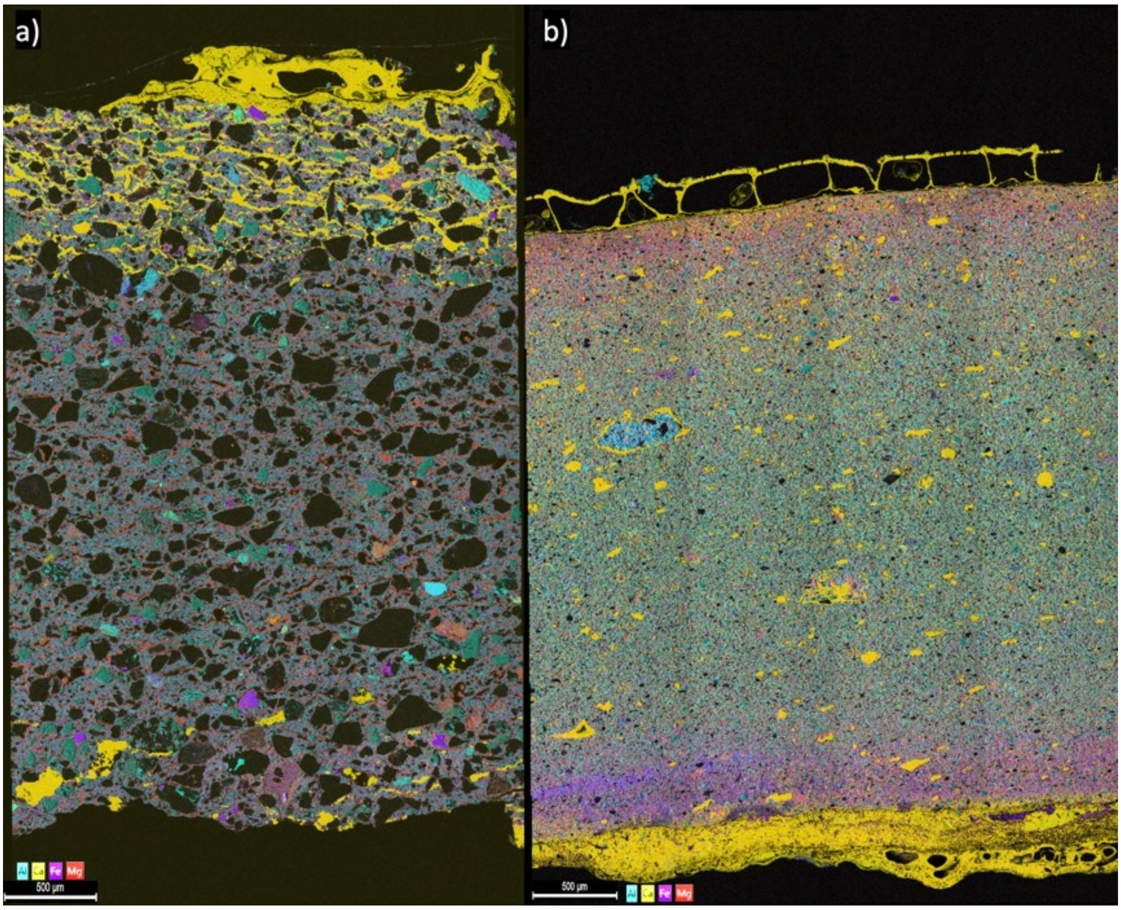
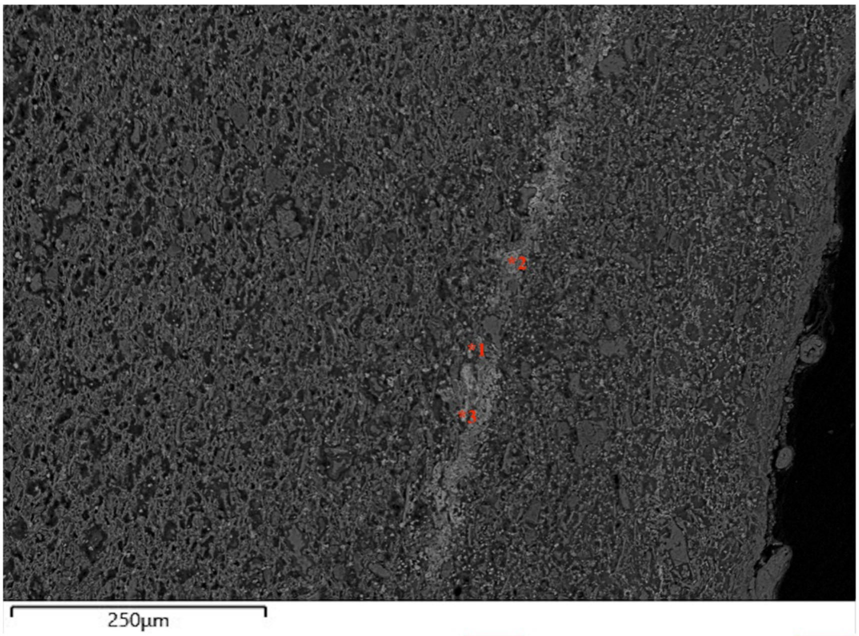


Fig. 6 SEM-EDS elemental distribution maps of **A** ZJ009 kitchenware sample and **B** ZJ016 tableware sample. Colour legend for elemental maps (Cyan= Al, Yellow= Ca, Purple= Fe, Red=Mg)

A



B

Wt%	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	V	Fe
Point 1	38.32	0.23	4.78	4.88	9.19	0.31	5.52	0.60	2.78	0.34	0.08	32.97
Point 2	26.20	0.30	3.29	3.84	3.48	0.46	6.73	0.16	1.86	0.17	0.16	52.97
Point 3	38.83	0.17	4.91	4.98	9.43	0.28	5.99	0.44	2.74	0.27	0.10	31.85

Fig. 7. **A** SEM Backscattered electron image of sample ZJ016, highlighting the iron-rich minerals along the margin of the sample with notations of the locations of point measurements which were taken for elemental compositional analysis, **B** corresponding values of SEM EDS point analysis highlighting the sulphur and iron content

Geochemical Characterisation and Classification

Due to the marine burial environment of the analysed sherds from Žirje and the post-depositional alteration seen in thin section, it was decided to disregard the values for the elements As, Ca, Na, Sb, Sr, U, Ba, Cs, K and Rb as these are susceptible to enrichment or depletion by seawater (Mise et al. 2021). The values for the remaining 23 elements (La, Lu, Nd, Sm, Yb, Ce, Co, Cr, Eu, Fe, Hf, Ni, Sc, Ta, Tb, Th, Zn, Zr, Al, Dy, Mn, Ti, V) (Supplement 2) were retained for the purpose of statistical exploration via univariate, bivariate and multivariate methods (Quinn 2022: 365-380). Principal component analysis conducted on the standardised and log-10 transformed elemental values of the 40 kitchenware and tableware samples is illustrated below (Fig. 8), with Principal Component 1 representing 60% of the total variance and Principal Component 2 representing 23% of the total variance, explaining a total of 83% of the total variance represented in the data. The score plot reveals two well-defined chemical groups which correspond to the two main petrographic fabrics identified in the assemblage, with the outliers mostly identified to be the petrographically unique samples. Sherds belonging to Fabric 1 form a somewhat dispersed group characterised by higher Al, Ti and Th values with sherds from Fabric 2 exhibiting higher Ni, Co and Sc relative to the other samples. Hierarchical cluster analysis was applied to understand the patterning of the chemical groups identified. The dendrogram (Fig. 9) was produced using Euclidean distance and Wards linkage and cut where the rate of agglomeration was reduced, resulting in 3 main clusters. The same compositional groups were detected with the first cluster representing Fabric 2 (Chemical Group 2) and the larger cluster with 2 sub-clusters reflecting Fabric Group 1 and the petrographically unique samples (Chemical Group 1). However, it seems that this division is not solely based on the type of ware, as both subgroups contain a mix of tableware and kitchenware samples (Table 1).

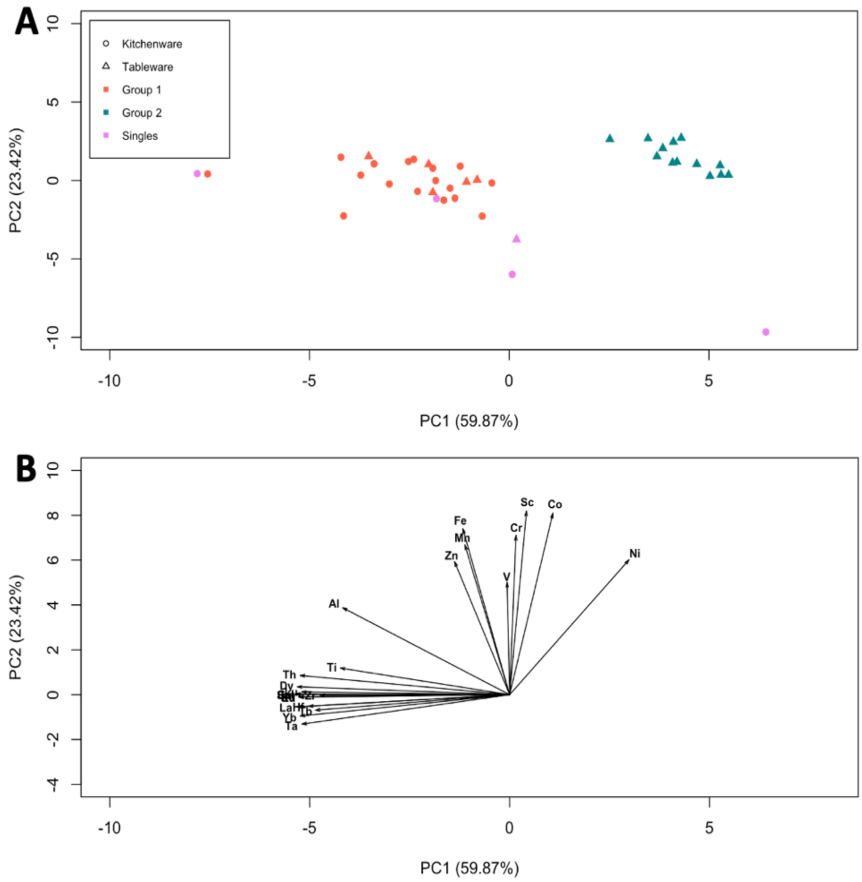


Fig. 8 PCA plots for Log-Transformed INAA data for the ceramic assemblage from Žirje, **A** score plot labelled by ware type and petrographic groups **B** Loadings for score plot

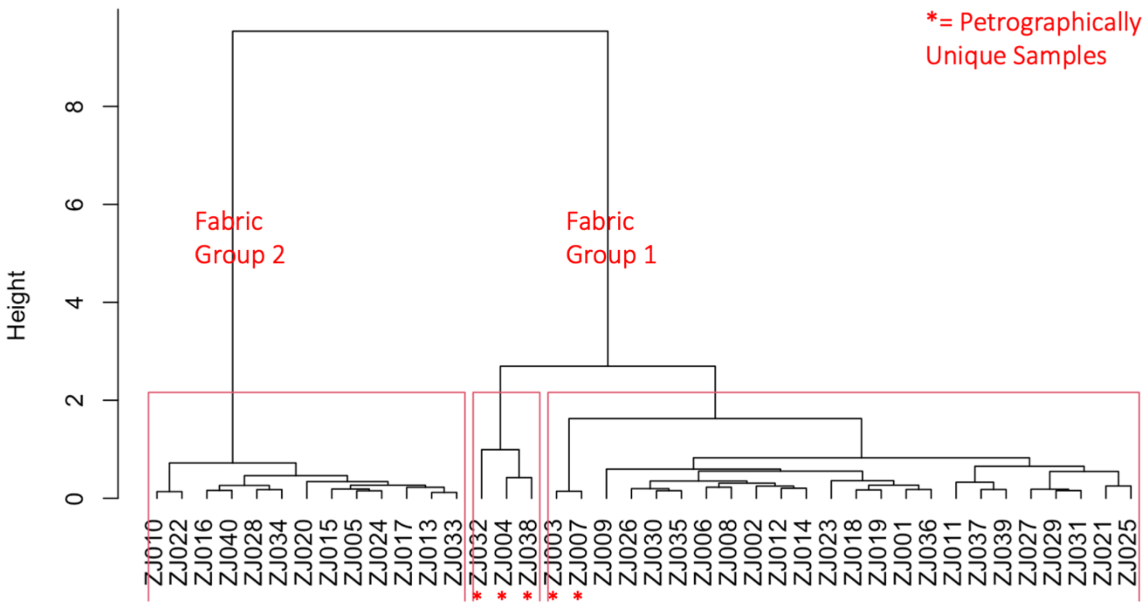


Fig. 9 Hierarchical agglomerative cluster (Ward Linkage, Euclidean distance) dendrogram for the geochemical composition of ceramics from Žirje, highlighting petrographically unique samples (ZJ003, ZJ004, ZJ007, ZJ032 and ZJ038) which are classified as chemical group 1

Table 1. Summary of samples analysed, detailing the analytical methods used and the corresponding groups from petrographic (Fabric Group) and INAA analysis (Chemical Group)

Sample ID	Type of ware	Shape	Ceramic petrography	SEM-EDS	XRD	INAA	Fabric Group	Chemical Group
ZJ001	kitchenware	Bowl	x			x	Fabric Group 1	Chemical Group 1
ZJ002	kitchenware	Casserole	x			x	Fabric Group 1	Chemical Group 1
ZJ003	kitchenware	Bowl	x			x	Single 1	Chemical Group 1
ZJ004	kitchenware	Bowl	x			x	Single 2	Chemical Group 1
ZJ005	tableware	Cup	x			x	Fabric Group 2	Chemical Group 2
ZJ006	kitchenware	Bowl	x	x	x	x	Fabric Group 1	Chemical Group 1
ZJ007	kitchenware	Casserole	x			x	Fabric Group 1	Chemical Group 1
ZJ008	kitchenware	Bowl	x			x	Fabric Group 1	Chemical Group 1
ZJ009	kitchenware	Casserole	x	x	x	x	Fabric Group 1	Chemical Group 1
ZJ010	tableware	Cup	x			x	Fabric Group 2	Chemical Group 2
ZJ011	tableware	Cup	x			x	Fabric Group 1	Chemical Group 1
ZJ012	kitchenware	Casserole	x			x	Fabric Group 1	Chemical Group 1
ZJ013	tableware	Jug	x			x	Fabric Group 2	Chemical Group 2
ZJ014	kitchenware	Casserole	x			x	Fabric Group 1	Chemical Group 1

ZJ015	tableware	Cup (Skyphos)	x			x	Fabric Group 2	Chemical Group 2
ZJ016	tableware	Small Bowl	x	x		x	Fabric Group 2	Chemical Group 1
ZJ017	tableware	Jug	x	x		x	Fabric Group 2	Chemical Group 2
ZJ018	tableware	Cup	x			x	Fabric Group 1	Chemical Group 1
ZJ019	kitchenware	Bowl	x			x	Fabric Group 1	Chemical Group 1
ZJ020	tableware	Jug with Heracles Knot	x			x	Fabric Group 2	Chemical Group 2
ZJ021	kitchenware	Large Bowl	x			x	Fabric Group 1	Chemical Group 1
ZJ022	tableware	Large Jug	x			x	Fabric Group 2	Chemical Group 2
ZJ023	kitchenware	Bowl	x			x	Fabric Group 1	Chemical Group 1
ZJ024	tableware	Cup (Skyphos)	-			x	Fabric Group 2	Chemical Group 2
ZJ025	tableware	Cup	x			x	Fabric Group 1	Chemical Group 1
ZJ026	tableware	Cup	x			x	Fabric Group 1	Chemical Group 1
ZJ027	kitchenware	Bowl	x			x	Single 3	Chemical Group 1
ZJ028	tableware	Cup	x			x	Fabric Group 2	Chemical Group 2
ZJ029	tableware	Cup	x			x	Fabric Group 1	Chemical Group 1

ZJ030	kitchenware	Bowl	x			x	Fabric Group 1	Chemical Group 1
ZJ031	kitchenware	Bowl	-			x	Fabric Group 1	Chemical Group 1
ZJ032	kitchenware	Casserole	x			x	Single 4	Chemical Group 1
ZJ033	tableware	Jug	x			x	Fabric Group 2	Chemical Group 2
ZJ034	tableware	Jug	x			x	Fabric Group 2	Chemical Group 2
ZJ035	kitchenware	Bowl	x			x	Fabric Group 1	Chemical Group 1
ZJ036	kitchenware	Bowl	x			x	Fabric Group 1	Chemical Group 1
ZJ037	kitchenware	Bowl	x			x	Fabric Group 1	Chemical Group 1
ZJ038	tableware	Bowl	x			x	Single 5	Chemical Group 1
ZJ039	kitchenware	Bowl	x			x	Fabric Group 1	Chemical Group 1
ZJ040	tableware	Jug	x			x	Fabric Group 2	Chemical Group 2
ZJ041	clay from ship 1	Greenish Clay	x			x		Chemical Group 3
ZJ042	clay from ship 2	White Clay	-			x		Chemical Group 3
HV001	geological clay Hvar	Greenish Clay	x			x		Chemical Group 2
HV002	geological clay Hvar	Greenish Clay	x			x		Chemical Group 2

Discussion

The results of our investigation into the mineralogical composition of the ceramics via petrographic analysis can contribute towards our understanding of the raw materials used to produce the Hellenistic tableware and kitchenware and aid in reconstructing their production process. The petrographic analysis of the samples from Fabric 1 revealed no indications of tempering. The mix of sedimentary and metamorphic inclusions in the samples suggests that the original raw material source is sedimentary in nature. Coupled with the presence of foraminifera microfossils distributed in the clay paste, the raw material source could be suggested to be a marine sedimentary deposit (Quinn and Day, 2007). The fine tableware in Fabric 2 has minimal inclusions, with the ceramic matrix likely being calcareous due to the significant amount of fine micritic calcite distributed throughout. The dominant inclusions also suggest that the raw material source is likely a marine sedimentary deposit, often times found along the coast. The difference in clay paste recipes between the two dominant fabric groups results in a difference in textures and performance characteristics for the vessels. As tableware are often associated with finer textures and kitchenware having coarser textures (Sillar and Tite 2000), these qualities affect the mechanical and thermal performance characteristics of the vessels produced and explain the choice of using distinct recipes for vessels with separate purposes. Considering that Fabric 1, consisting of predominantly kitchenware items, reflects a clay paste recipe with larger inclusions and Fabric 2, consisting of only fine tableware samples, exhibiting minimal inclusions, the difference in raw materials observed can be considered an intentional choice by the potters. Therefore, it can be suggested that the significant difference observed between the two dominant fabric groups can be partially related to the technological choice of the producers and the performance requirements of the vessels produced (van der Leeuw 1993). While the mechanical and thermal properties of ceramics have been extensively studied (Kilikoglou et al 1998; Vekinis and Kilikolou 1998), the differences between Hellenistic fine and kitchenware remain underexplored and are not within the scope of the present study.

Observations regarding the appearance of the clay matrix were used to investigate the ceramic pyrotechnology used in the production of these vessels, including the firing temperature and the firing atmosphere. The matrix of all samples (except ZJ003, ZJ027, ZJ032, and ZJ038) analysed exhibit relatively low optical activity, indicative of the sintering of clay minerals as a result of a higher firing temperature (Gliozzo 2020; Quinn, 2022). Furthermore, the colour and inhomogeneities observed in the iron-rich clay matrix can also be indicative of the firing atmosphere. The red appearance of Fabric 1 suggests a predominantly oxidising firing atmosphere, however, the layering observed in many samples, mostly with darker cores, is indicative of areas with poor oxidation as a result of the firing environment (Quinn 2022: 277) It should be noted, however, that the post-depositional alterations are also likely to alter the appearance of the ceramic cross-section. SEM mapping of cross-sections of the kitchenware (Fig. 6a) and tableware (Fig. 6b) reveals that post-depositional alterations predominantly occur along the margins of the samples, where they are more exposed to seawater. Additionally, SEM mapping indicates that the decorative slip on tableware does not effectively prevent the influx of seawater into the samples. This is evident in sample ZJ016 where the accumulation of calcium, as a result of dissolvement and precipitation, is more pronounced along the margins, alongside the formation of pyrite (Fig. 7A and B.)

Upon establishing geochemical groups for the ceramic assemblage, the data for the raw clay samples were introduced to identify any compositional similarities among ceramics from the ship's galley, clays retrieved from the transport amphorae at the shipwreck, and raw clay sourced from Zarače Bay on the island of Hvar (Fig. 10A). Score plots reveal significant compositional differences between the clay contained within the transport amphorae recovered from the shipwreck (Fig. 10) and vessels from the ship's galley. This disparity indicates that the clay found within the amphorae was not used in the production of the vessel recovered from the shipwreck, and it is unlikely to match the clay collected from the Zarače Bay deposit. Based on their compositional differences, we can assume that the clay used in the transport amphorae was likely employed as ballast on the ship, rather than for pottery production.

However, clay samples collected from Zarače Bay on the island of Hvar appear to share compositional similarities with tableware samples from Fabric/Chemical Group 2. Petrographic similarities are also evident (Fig. 4B and E), despite differences in coloration within the matrix. These variations likely stem from different firing environments of the vessels in ancient kilns and clay briquettes in modern electrical kilns.

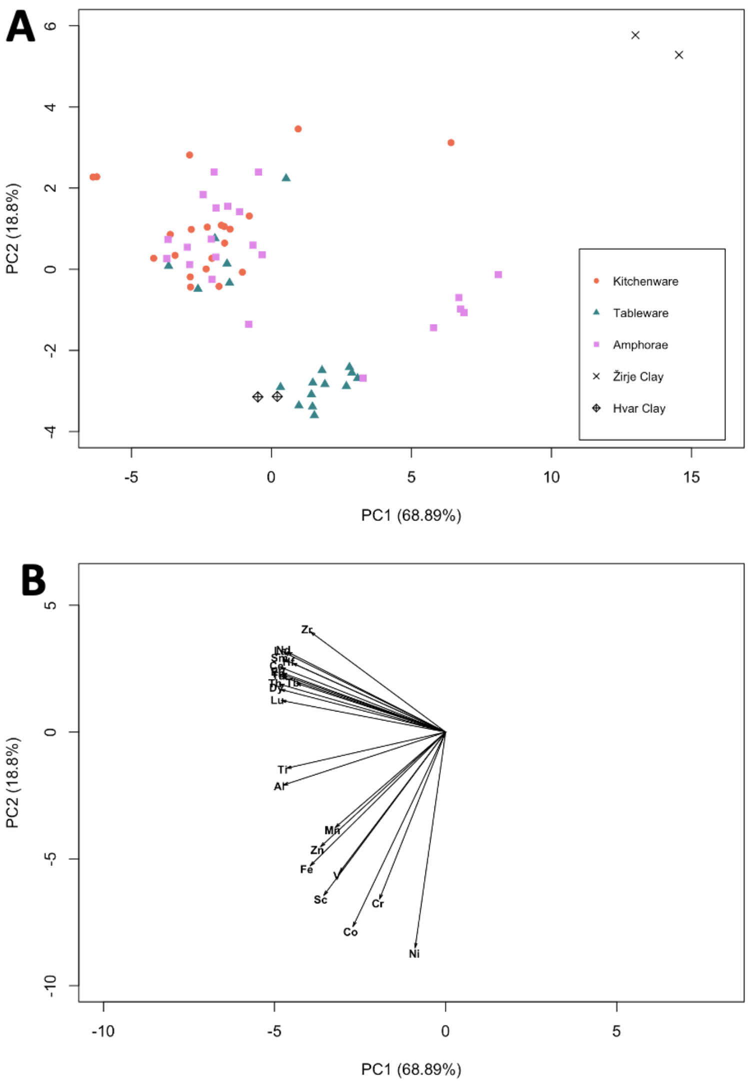


Fig. 10 PCA plots for Log-Transformed INAA data **A** score plot of kitchenware, tableware, amphorae and clay samples from Žirje Shipwreck and raw clay from Hvar, **B** Loadings for score plot

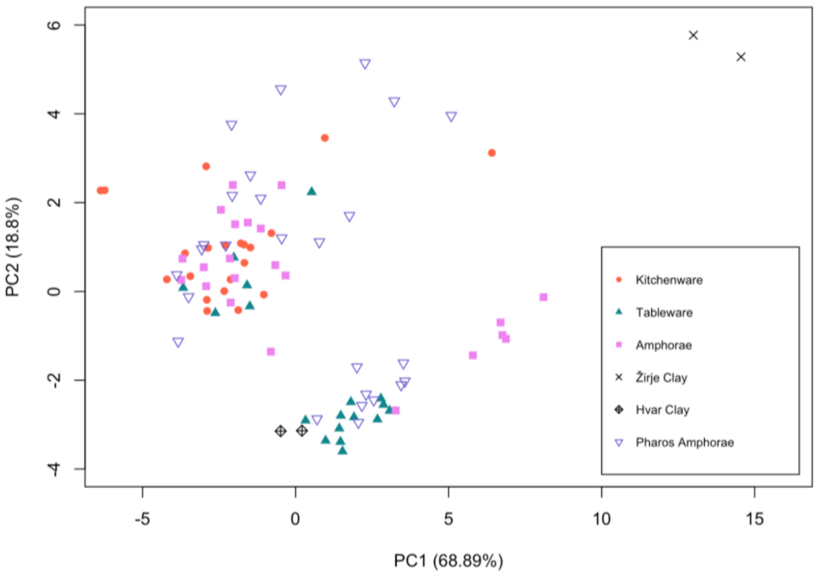


Fig. 11 PCA score plot for Log-Transformed INAA data of kitchenware, tableware, amphorae and clay samples from the Žirje Shipwreck with amphorae samples from Pharos projected onto the plot.

Petrographic and geochemical comparisons were made with previously analysed transport amphorae from the same shipwreck (Miše et al 2021) as well as amphorae from Pharos (Miše and Quinn 2022; Miše et al 2019), expanding the area investigated for provenance determination. Petrographic and geochemical similarities were observed between the ceramic samples from Fabric 1 and many of the amphorae samples from Žirje (Fig. 10A), previously classified as 'Fabric Group 3' (Miše and Quinn 2022). Petrographic similarities observed include patterning seen in the type, appearance and size of dominant inclusions such as mono and polycrystalline quartz, biotite and chert in an iron-rich clay matrix. This would suggest that these samples were likely to have been produced using a closely related raw material source, therefore suggesting the possibility of these vessels being produced in workshops in the same location or region. Similarly, many transport amphorae samples recovered in Pharos, also classified as 'Fabric Group 3' (Miše and Quinn 2022), share significant similarities with the samples from Fabric 1, with similarities also observed geochemically, illustrated by the somewhat dispersed cluster in Fig. 11. The Corinthian type B transport amphorae from fabric 'Group 3' is characterised by the largely homogenous dark red clay paste, suggested to correspond with the Corinthian type B Fabric Class 3 of Whitbread's classification of Greek transport amphorae (Whitbread 1995). These have been attributed to production locations in either Corinth or Corfu, however, it is noted that further differentiation may be difficult without field sampling of relevant geological deposits (Miše and Quinn 2022). It is also important to note that there are some outliers among the transport amphorae and kitchenware samples from the Žirje shipwreck, with the variations observed supporting the previous suggestion of a mixed cargo where vessels were likely produced in different locations.

Fig. 11 also reveals a correlation between some transport amphorae samples from Pharos, identified as Corinthian type B, and the tableware samples from Fabric 2 found on the shipwreck. Both of these groups align with the local clay sourced from Zarače Bay on the island of Hvar. Furthermore, Fig. 11 also demonstrates that one amphora sample from the Žirje shipwreck appears to share significant compositional similarities to these groups, reinforcing the suggestion that the trading vessel was travelling with a mixed cargo from various workshops. The correlation observed compositionally between these groups suggests that some of the amphorae samples from Pharos, the tableware and the one amphora from the Žirje shipwreck could have potentially been crafted using similar raw materials from Zarače Bay. In contrast, majority of the transport amphorae recovered from the Žirje shipwreck do not match with clays from Zarače Bay, leaving their source of origin undetermined, although there is potential for future investigations, perhaps in Corinth and Corfu, as previously suggested (Miše and Quinn, 2022).

Maritime Trade in the Hellenistic Dalmatia and the role of Pharos

Utilizing integrated analytical methodologies on ceramic artefacts recovered from shipwrecks has emerged as an indispensable approach in reconstructing the dynamics of ancient Mediterranean trade networks (e. g. Miše and Quinn 2022). By integrating earlier compositional analysis of transport amphorae recovered from the Žirje shipwreck with analyses of kitchen and tableware recovered from the ship's galley, we may begin to try and understand the journey of this merchant vessel before it sunk mid-voyage. The analyses seem to suggest that a large part of the tableware which match with the composition of the clay from Zarače bay on the southern side of the island of Hvar, were produced locally. Given that the clay deposits in Zarače Bay were used to produce tableware in two neighboring pottery workshops—Issa on the island of Vis and Pharos on the island of Hvar—due to their similar composition (Miše et al., 2020), the exact origin of the tableware found in the Žirje shipwreck remains uncertain. However, considering that Pharos emerged as a prominent trading hub in the 4th and 3rd centuries BCE, as evidenced by the heterogeneity of amphorae assemblages in Pharos (Miše and Quinn, 2022), it is reasonable to postulate that the ship that sank near the island of Žirje likely departed from Pharos. Further support for this conclusion can be drawn from the small size of the ship (Radić Rossi et al 2020): while it is plausible that this vessel was involved in long-distance trade, and it may have carried amphorae produced in places like Corfu or Corinth, it is more likely that it loaded its cargo in Pharos before heading toward northern Dalmatia, where it ultimately met its end near the waters of Žirje.

Presuming the tableware were owned by the ship's crew, it's plausible to speculate that the crew either procured these artefacts locally in Dalmatia or the crew came from the same town. Interestingly, the kitchenware onboard does not seem to have originated in the Dalmatian Hellenistic workshop, as their composition do not match the local clay. Similarly, the cargo, comprising of transport amphorae, was also not locally sourced; its provenance likely lies beyond Dalmatia (Miše et al 2020). Previous analysis of the transport amphorae, reinforced by the current study, demonstrates that the merchant vessel that sank near the island of Žirje carried a mixed cargo of amphorae from diverse workshops, most of which likely did not originate from Pharos. However, through cross-referencing INAA data from the previous study of transport amphorae from Pharos with INAA data of raw clay samples from Zarače Bay, a close match between Corinthian type B amphorae and a specific sample (SGP17 in Miše and Quinn 2022) identified as Corinthian type A' with Zarače clay is observed. This confirmation solidifies Pharos as a possible production centre for Corinthian-type amphorae.

Additional examination of the transport amphorae, tableware, and kitchenware retrieved from the Žirje shipwreck provides valuable insights into trading patterns in Dalmatia during the Hellenistic period of the 4th century BCE. Analysis reveals that while the transport amphorae aboard the merchant vessel were produced in various workshops, they were not of local origin, similar to the kitchenware. Based on these findings, coupled with observations of the above-mentioned vessel's relatively diminutive size, we hypothesize that the ship's point of departure was likely in Pharos. This hypothesis is grounded in the significance of Pharos as a prominent Greek city at that time, engaged in amphorae and tableware production, and fostering inter-regional trade connections (Jeličić Radonić and Rauter Plančić 1996; Miše 2005). Pharos may have served a dual role as both a producer of amphorae and an intermediary in the trading network. The mixed cargo found on the Greek merchant vessel is consistent with historical documentation of such practices dating back to the 7th and 6th centuries BCE (Hodos 2020:120)

While the tableware aboard the ship traces back to Pharos, the kitchenware does not, sparking curiosity regarding its connection to the ship's crew. Notably, following Hodos's proposition that kitchenware constituted a permanent assemblage of ships for use in the galley (Hodos 2020: 116), the Žirje shipwreck suggests a diverse crew, perhaps including individuals from Pharos, other Greek cities in the vicinity, such as Issa, or possibly indigenous personnel working for Greek merchants. This implies trade interactions among local communities, supporting the postulation that the ship, after its departure from Pharos, met its demise while engaged in transporting goods to northern Dalmatian Iron Age communities.

The results of our investigation of the kitchenware and tableware from the Žirje shipwreck, along with the comparison to previous studies conducted in the region, support the hypothesis suggesting Pharos' involvement in the production of Greek fine wares and transport amphorae (Miše et al 2019; Kirigin, 2006), as well as the utilization of local resources along the southern coast of Hvar for pottery production during the Hellenistic period in Pharos (Miše et al 2020). Consequently, the association between tableware from the Žirje shipwreck and the pottery workshop on Pharos implies a connection between merchant trading vessels and Pharos, thus strengthening the possibility of Pharos serving as a departure point for the ship.

Conclusion

This investigation into the ceramic assemblage of kitchenware and tableware from the galley of the Žirje shipwreck has unveiled two distinct petrographic and geochemical groups, indicating different sources of raw materials. The samples also display varying degrees of mineralogical and chemical alteration due to the post-depositional marine environment, enabling detailed analyses of these transformations.

Comparing our findings with previous studies on transport amphorae from Pharos and local clay from Hvar suggests that the amphorae likely originated outside of Dalmatia, possibly in Corinth and/or Corfu, due to similar fabric characteristics noted by Miše and Quinn (2022). In contrast, the tableware from the ship’s galley likely came from Dalmatia, specifically Pharos.

Considering the Žirje ship's small size and its probable limited trade within the Adriatic (Radić et al., 2020), the diverse origins of the transport amphorae and ceramic assemblage suggest the ship was likely engaged in cabotage or tramping (Horden and Purcell, 2000: 140), collecting goods from various ports. Pharos emerges as one of the important trading hubs.

Therefore, it is plausible that the merchant ship loaded amphorae cargo in Pharos before sailing north and sinking near the Žirje Islands.

The results of this study, compared with previous analyses, suggest that Pharos served a dual role as both an intermediary contributing to Mediterranean maritime connectivity and as a production center. Ultimately, the detailed archaeometric analysis of the transport amphorae, kitchenware, and tableware from the Žirje shipwreck provides valuable insights into life aboard a Hellenistic merchant vessel.

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Author Contribution

IRR-provided material for analysis and archaeological background. Material preparation, data collection, and analysis were performed by VH. VH wrote the main manuscript with contributions by MM and edits by PSQ and IRR. All authors reviewed the manuscript.

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Reconstructing Production of Hellenistic Pottery and Maritime Trade Routes: Insights from a Hellenistic Shipwreck near Žirje, Croatia

Victoria Hawkins[5] , Maja Miše[6], Patrick Sean Quinn[7], Irena Radić Rossi [8]

Supplement 1

Descriptions of Petrographically Unique Samples

With detailed petrographic analysis of the assemblage analysed, 5 samples are determined to be petrographically unique from the 2 dominant fabric groups and are described and pictured below.

ZJ003 is characterised by a larger proportion of inclusions with a weakly bimodal grain size distribution. Notable inclusions include quartz, chert, biotite and muscovite in a reddish orange optically active groundmass. The optical activity of the clay paste could potentially be attributed to a lower firing temperature prior to the sintering of clay minerals (<850°C), although the higher proportion of fine biotite and muscovite inclusions in the matrix also contributed to the 'optically active' appearance. Post-depositional alterations identified in the sample consists of a small amount of secondary calcite in a few of the voids.

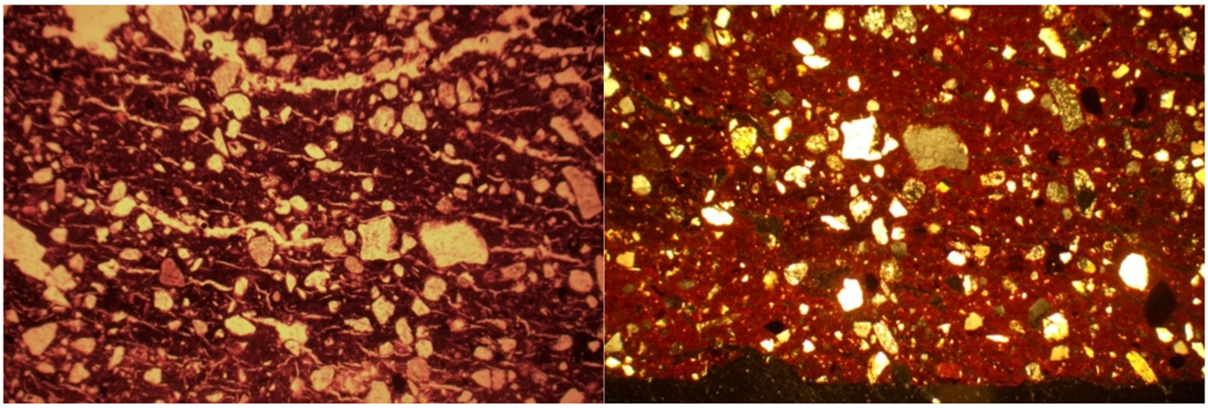

Figure 1. Photomicrographs of ZJ003 in PPL (left) and in XP (left) (taken at 50X, field of view = 3 mm)

ZJ004 is characterised by the angular quartz inclusions, some with undulatory extinction, in addition to the micritic and biomicritic limestone inclusions within a reddish brown, iron-rich clay matrix. Other inclusions of note includes chert including fibrous chalcedony, argillaceous inclusions in the form of clay pellets. The formation of clay pellets is the result of incomplete rehydration of clay minerals during working and forming. An inclusion of calcareous sandstone is also present and likely reflects the source of the sand temper. Post-depositional alterations includes some secondary calcite in the voids, redistributed calcite in matrix and a small amount of marine encrustation on the sample surface.

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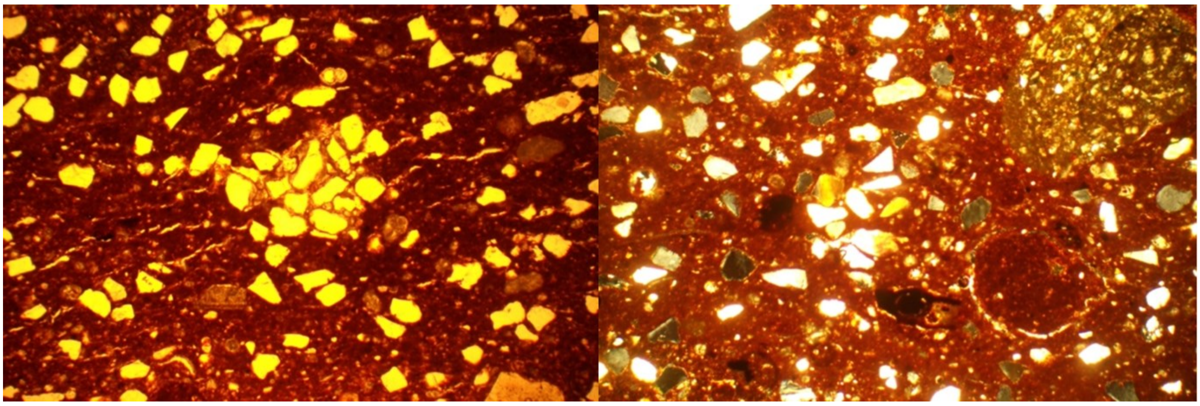

Figure 2. Photomicrographs of ZJ004 in PPL (left), and in XP (right) (taken at 50X, field of view = 3 mm)

ZJ007 is characterised by the mottling seen in the matrix of the sample, with streaks of dark brown/black clay paste in the main dark reddish brown clay paste. This is likely the result of a high iron content and the incomplete oxidation of the sample when firing. Inclusions of quartz, chert, and biotite were observed along with textural features such as clay pellets from clay working. The voids visible across the sample are mostly channels and vughs which are aligned parallel to the vessel walls, indicative of wheel forming. Some secondary calcite is visible in a small number of the voids with marine encrustation limited to some outer areas of the sample.

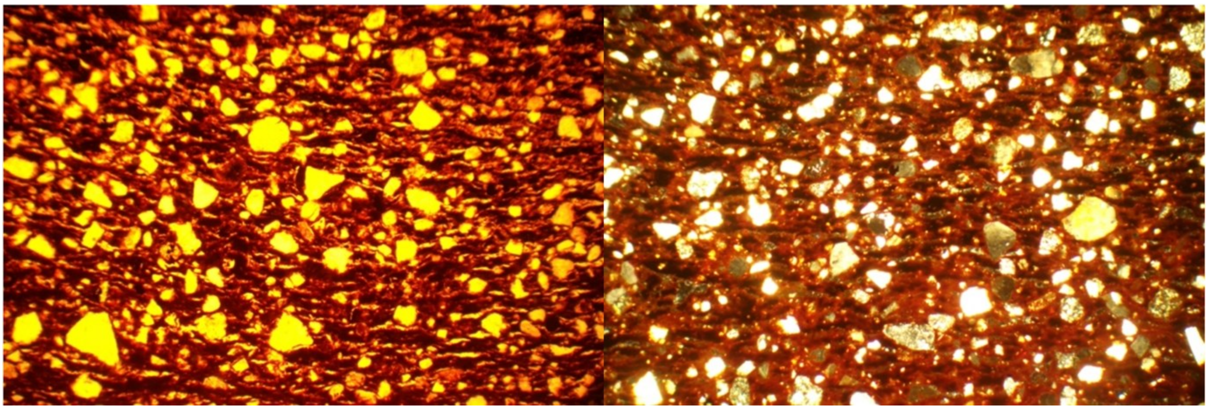

Figure 3. Photomicrographs of ZJ007 in PPL (left), and in XP (right) (taken at 50X, field of view = 3 mm)

ZJ032 is characterised by the large, angular calcite inclusions in a bright orangey to red, iron-rich optically active matrix. The size and nature of the calcite inclusions suggest that it crushed calcite was intentionally added for tempering, the only sample in the whole assemblage to demonstrate this. The components of the fine fraction includes mostly biotite and quartz inclusions, and given their size, they are likely derived from the original raw material source. It is uncertain if the clay processing involved refinement of the clay or if the original raw material contained only some, silt-size inclusions. Post depositional alterations observed in the sample includes the precipitation of secondary calcite within voids, redistributed calcite throughout the sample, with focus around voids and the margins of the sample.

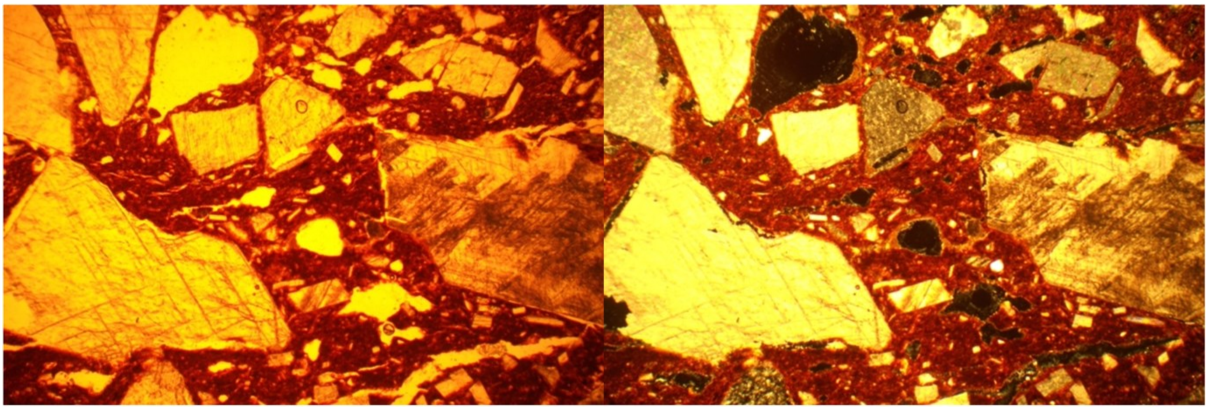

Figure 39. Photomicrographs of ZJ032 in PPL (left),and in XP (right) (taken at 50X, field of view = 3 mm)

ZJ038 is characterised by the inclusions of quartz, biotite, degraded calcite and fine muscovite inclusions in a reddish brown matrix. The matrix is optically active and shows some evidence of layering, with a lighter margin of yellowy brown around the dominant reddish brown clay matrix. Voids includes vughs and vesicles which are randomly aligned and oriented.
Post-depositional alterations includes some secondary calcite in voids, redistributed calcite in the clay matrix across sample with no presence of marine encrustation.

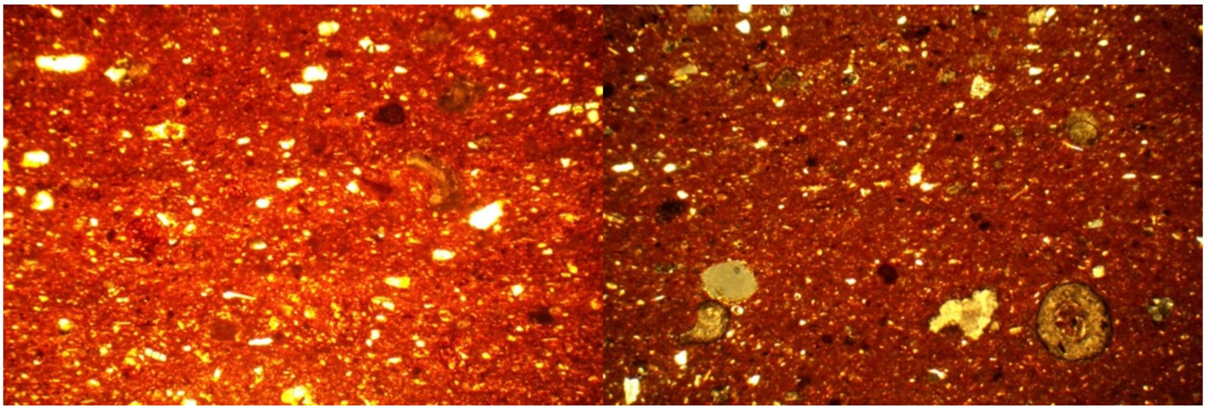

Figure 38. Photomicrographs of ZJ038 in PPL (left), and in XP (right) (taken at 50X, field of view = 3 mm)

Reconstructing Production of Hellenistic Pottery and Maritime Trade Routes: Insights from a Hellenistic Shipwreck near Žirje, Croatia

Victoria Hawkins[9] , Maja Miše[10], Patrick Sean Quinn[11], Irena Radić Rossi [12]

Supplement 2

The results of the INAA geochemical compositions of all samples analysed classified according to type, site and fabric group. All measurements are in ppm.

Table 1A: INAA geochemical composition of analysed samples

Sample	Type	Site	Fabric Group	As	La	Lu	Nd	Sm	U	Yb	Ce	Co	Cr	Cs	Eu	Fe	Hf	Ni
ZJ001	Kitchenware	Zirje	Group 1	29.57	41.74	0.49	36.85	7.45	2.23	3.58	81.40	29.47	330.99	2.81	1.43	49838	7.32	150.58
ZJ002	Kitchenware	Zirje	Group 1	25.23	46.70	0.49	42.79	8.08	2.23	3.68	90.21	27.20	300.71	5.08	1.62	49162	7.96	141.65
ZJ003	Kitchenware	Zirje	Loner 1	66.85	68.87	0.68	59.19	11.91	5.69	4.23	126.99	24.81	257.91	7.01	2.38	57217	9.15	125.40
ZJ004	Kitchenware	Zirje	Loner 2	58.17	34.94	0.43	32.05	6.56	3.03	3.00	66.98	15.93	122.73	1.76	1.50	44209	5.10	100.14
ZJ005	Tablware	Zirje	Group 2	148.28	26.33	0.39	22.05	5.21	3.53	2.29	54.36	33.89	324.93	2.27	1.08	54654	3.35	263.85
ZJ006	Kitchenware	Zirje	Group 1	33.35	41.16	0.43	34.63	7.01	2.71	3.18	77.65	23.15	288.35	4.41	1.35	41556	8.08	146.05
ZJ007	Kitchenware	Zirje	Group 1	28.22	66.84	0.60	58.35	11.58	2.89	4.71	120.58	23.31	263.53	6.81	2.33	54483	9.81	121.78
ZJ008	Kitchenware	Zirje	Group 1	53.16	42.02	0.44	35.66	7.42	4.98	3.13	81.34	27.90	291.82	5.12	1.43	45307	8.11	124.66
ZJ009	Kitchenware	Zirje	Group 1	49.84	47.57	0.51	45.75	8.15	2.70	3.75	95.45	20.59	274.33	1.65	1.55	49642	9.65	93.15
ZJ010	Tableware	Zirje	Group 2	115.99	23.72	0.34	24.16	4.60	3.04	2.03	48.64	32.16	291.10	1.11	0.92	53525	3.07	178.93
ZJ011	Tableware	Zirje	Group 1	63.66	50.17	0.50	43.57	8.75	3.65	3.66	90.81	27.47	257.30	7.98	1.76	55363	5.85	134.59
ZJ012	Kitchenware	Zirje	Group 1	27.19	41.99	0.43	39.62	7.27	1.84	3.33	79.14	24.96	277.05	1.74	1.49	47012	6.96	160.97
ZJ013	Tableware	Zirje	Group 2	68.27	26.63	0.35	26.69	5.08	2.87	2.27	54.11	33.35	322.29	3.95	1.09	53539	3.37	252.25
ZJ014	Kitchenware	Zirje	Group 1	70.17	39.21	0.47	34.90	7.03	2.87	3.12	77.03	27.51	274.29	2.63	1.37	52990	7.18	141.31

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ZJ015	Tableware	Zirje	Group 2	96.81	25.05	0.33	23.88	4.85	2.74	2.33	51.02	36.48	310.23	0.61	1.02	61528	3.30	246.63
ZJ016	Tableware	Zirje	Group 2	100.70	25.78	0.35	24.66	4.97	3.15	2.25	51.81	32.78	305.12	1.16	1.03	53600	3.27	197.02
ZJ017	Tableware	Zirje	Group 2	97.43	25.56	0.33	23.69	4.97	3.81	2.15	51.99	29.54	302.13	2.82	1.02	48894	3.20	249.48
ZJ018	Tableware	Zirje	Group 1	25.25	40.31	0.49	36.96	6.97	2.54	3.11	78.98	32.79	337.48	3.81	1.44	48647	8.80	198.43
ZJ019	Kitchenware	Zirje	Group 1	89.34	40.94	0.46	38.55	7.58	6.88	2.81	83.58	28.11	359.79	5.01	1.47	49070	7.89	199.50
ZJ020	Tableware	Zirje	Group 2	93.23	27.65	0.34	30.71	6.00	12.79	2.28	58.52	35.33	334.19	3.78	1.16	53572	3.43	231.04
ZJ021	Kitchenware	Zirje	Group 1	37.82	38.61	0.42	34.79	6.83	2.63	2.80	75.02	24.18	274.36	5.96	1.36	48054	5.43	163.71
ZJ022	Tableware	Zirje	Group 2	83.76	24.19	0.34	24.35	4.67	2.99	2.08	49.21	31.24	298.19	0.94	1.00	49924	3.10	180.19
ZJ023	Kitchenware	Zirje	Group 1	75.73	44.52	0.50	40.11	7.94	3.75	3.55	85.07	30.70	336.11	3.99	1.54	56830	10.05	126.30
ZJ024	Tableware	Zirje	Group 2	46.94	26.11	0.38	22.59	5.07	2.89	2.27	53.61	35.59	320.23	0.55	1.06	53835	3.39	259.81
ZJ025	Tableware	Zirje	Group 1	53.12	38.64	0.48	35.83	6.85	3.26	2.80	74.26	25.92	302.38	5.20	1.36	49267	6.78	227.02
ZJ026	Tableware	Zirje	Group 1	50.04	40.53	0.43	38.40	7.11	3.44	3.10	79.70	27.39	285.94	5.69	1.44	49894	6.95	163.59
ZJ027	Kitchenware	Zirje	Loner 3	51.79	43.41	0.48	36.26	7.55	2.98	3.22	81.94	22.21	215.17	5.75	1.53	48176	6.09	140.29
ZJ028	Tableware	Zirje	Group 2	48.13	23.96	0.31	22.46	4.56	1.51	2.30	48.39	28.21	292.37	1.26	0.95	52214	3.04	213.95
ZJ029	Tableware	Zirje	Group 1	46.64	44.26	0.43	38.74	7.87	2.93	3.32	84.65	24.17	221.04	6.02	1.57	49320	6.03	182.21
ZJ030	Kitchenware	Zirje	Group 1	52.94	38.30	0.44	35.50	6.79	2.38	3.20	74.86	31.10	314.93	3.38	1.34	54865	7.34	148.06
ZJ031	Kitchenware	Zirje	Group 1	49.01	44.89	0.46	40.85	7.94	2.61	3.44	85.49	26.51	233.10	5.86	1.63	52142	6.55	144.64
ZJ032	Kitchenware	Zirje	Loner 4	6.17	24.96	0.32	21.49	4.34	1.19	2.20	44.55	10.85	150.46	3.43	0.92	24023	2.95	101.57
ZJ033	Tableware	Zirje	Group 2	39.29	26.28	0.37	27.19	5.04	2.51	2.27	53.78	30.51	312.13	1.62	1.08	51208	3.26	284.06
ZJ034	Tableware	Zirje	Group 2	32.89	24.98	0.33	24.07	4.78	2.39	2.02	50.98	34.22	299.94	1.55	0.99	49604	3.14	223.66
ZJ035	Kitchenware	Zirje	Group 1	13.90	43.01	0.46	37.94	7.40	2.54	3.22	82.87	27.20	311.02	2.30	1.51	50555	6.98	151.16
ZJ036	Kitchenware	Zirje	Group 1	30.85	41.46	0.46	37.45	7.28	4.40	3.10	80.90	26.48	336.18	5.15	1.44	46394	7.84	142.12
ZJ037	Kitchenware	Zirje	Group 1	43.53	51.32	0.50	46.23	9.05	3.30	3.54	97.13	29.09	272.35	5.25	1.89	55185	7.14	164.14
ZJ038	Tableware	Zirje	Loner 5	36.04	33.28	0.38	30.86	6.42	6.62	2.95	66.90	19.59	143.46	6.60	1.23	41807	4.16	89.32
ZJ039	Kitchenware	Zirje	Group 1	24.61	49.11	0.50	41.15	8.48	3.35	3.77	94.74	26.70	264.77	7.44	1.74	50864	7.57	145.60
ZJ040	Tableware	Zirje	Group 2	34.66	25.34	0.33	22.94	4.83	2.55	2.14	51.09	33.75	300.74	1.55	1.01	49620	3.25	201.96

ZJ041	Clay from ship 1	Zirje		7.90	17.20	0.19	19.30	3.73	8.67	1.27	31.86	8.85	86.95	2.19	0.68	15912	1.28	64.33
ZJ042	Clay from ship 2	Zirje		7.49	14.80	0.18	15.18	2.89	2.11	1.19	26.54	10.97	78.97	1.61	0.59	14297	1.18	42.37
HV001	Geological clay 1	Hvar		9.05	28.82	0.40	25.31	5.49	2.39	2.52	58.06	34.95	371.80	7.97	1.20	54788	3.62	240.41
HV002	Geological clay 2	Hvar		6.49	28.01	0.38	27.23	5.36	1.54	2.63	58.01	33.95	350.73	8.23	1.14	53830	3.45	253.71

Table 1B: Continued INAA geochemical composition of analysed samples																	
Sample	**Type**	**Site**	**Fabric Group**	**Rb**	**Sb**	**Sc**	**Sr**	**Ta**	**Tb**	**Th**	**Zn**	**Zr**	**Al**	**Ba**	**Ca**	**Dy**	**K**
ZJ001	Kitchenware	Zirje	Group 1	63.13	1.90	17.54	148.02	1.31	1.09	14.14	133.56	197.89	80859	294.86	56386	5.93	16673.00
ZJ002	Kitchenware	Zirje	Group 1	76.49	1.57	16.52	184.96	1.35	0.97	15.68	108.91	192.79	81612	209.67	45095	5.66	13741.00
ZJ003	Kitchenware	Zirje	Loner 1	86.70	3.58	16.43	21.26	1.86	1.32	20.20	129.42	224.16	105110	249.57	4083	8.29	16489.00
ZJ004	Kitchenware	Zirje	Loner 2	46.80	0.95	12.82	251.01	1.29	0.87	8.32	106.86	154.40	59960	179.30	63510	5.60	11169.00
ZJ005	Tableware	Zirje	Group 2	53.08	2.10	19.23	252.64	0.83	0.69	9.50	134.41	111.62	75187	204.77	90331	4.30	15565.00
ZJ006	Kitchenware	Zirje	Group 1	77.96	1.45	13.47	249.89	1.15	0.89	12.92	95.75	186.24	68217	242.12	35843	5.44	15276.00
ZJ007	Kitchenware	Zirje	Group 1	81.42	2.55	16.39	107.16	1.81	1.28	19.71	128.12	252.20	100610	139.09	29018	8.12	11933.00
ZJ008	Kitchenware	Zirje	Group 1	74.12	1.78	15.09	204.67	1.33	0.91	14.13	107.75	217.62	68981	214.70	45566	5.50	14327.00
ZJ009	Kitchenware	Zirje	Group 1	34.92	2.41	14.32	80.54	1.47	1.03	16.68	102.22	226.03	85059	194.12	11036	6.27	9637.20
ZJ010	Tableware	Zirje	Group 2	26.87	1.25	16.42	386.78	0.71	0.56	8.23	102.90	53.58	66147	136.59	86227	3.99	10968.00
ZJ011	Tableware	Zirje	Group 1	114.31	2.26	18.75	256.68	1.51	1.07	16.13	137.91	109.93	96047	297.48	57483	6.51	18220.00
ZJ012	Kitchenware	Zirje	Group 1	41.81	1.20	16.20	266.44	1.31	0.90	13.47	105.00	155.22	79105	202.75	60003	5.85	14011.00
ZJ013	Tableware	Zirje	Group 2	76.02	1.01	19.04	601.48	0.81	0.62	9.33	123.57	84.99	77921	287.95	94031	4.11	19213.00
ZJ014	Kitchenware	Zirje	Group 1	54.98	2.41	15.78	145.84	1.23	1.10	13.82	119.67	185.39	75790	150.17	38166	5.62	10021.00
ZJ015	Tableware	Zirje	Group 2	23.23	1.12	18.03	160.17	0.70	0.64	8.72	126.63	104.35	73208	152.03	90619	4.27	9781.80
ZJ016	Tableware	Zirje	Group 2	27.16	0.94	17.39	172.61	0.78	0.65	8.63	108.70	108.38	67508	142.51	61025	4.40	11967.00
ZJ017	Tableware	Zirje	Group 2	62.86	1.45	18.10	535.27	0.76	0.63	8.62	109.43	99.26	71352	334.28	108600	4.18	18436.00

ZJ018	Tableware	Zirje	Group 1	68.52	1.37	16.77	198.47	1.35	1.14	13.46	107.68	202.15	76436	319.38	54217	5.64	17801.00
ZJ019	Kitchenware	Zirje	Group 1	81.43	7.59	17.02	141.24	1.33	1.21	14.67	133.78	213.15	76440	306.77	42432	6.06	20287.00
ZJ020	Tableware	Zirje	Group 2	69.13	2.49	19.43	522.17	0.90	0.63	9.44	131.97	139.20	76228	264.95	97807	4.44	17019.00
ZJ021	Kitchenware	Zirje	Group 1	89.04	1.13	17.33	312.37	1.10	1.13	12.77	116.77	108.65	77500	279.54	84775	5.46	18579.00
ZJ022	Tableware	Zirje	Group 2	31.02	1.30	16.69	345.72	0.81	0.64	8.32	114.90	53.16	62848	199.93	87157	3.83	12761.00
ZJ023	Kitchenware	Zirje	Group 1	66.36	2.81	16.63	70.83	1.37	0.97	15.83	136.61	253.16	77032	202.25	30102	6.01	14630.00
ZJ024	Tableware	Zirje	Group 2	18.88	1.04	18.40	256.52	0.79	0.61	8.83	145.57	92.97	69515	177.50	90994	4.33	9532.90
ZJ025	Tableware	Zirje	Group 1	87.35	1.04	16.43	145.66	1.21	1.33	12.73	115.89	130.76	71115	235.15	31229	5.42	21048.00
ZJ026	Tableware	Zirje	Group 1	91.23	0.93	17.05	137.28	1.29	0.81	13.41	119.75	157.13	73013	241.44	25242	5.64	20825.00
ZJ027	Kitchenware	Zirje	Loner 3	83.08	1.48	15.24	290.26	1.32	0.93	13.96	115.62	152.79	81404	275.68	43246	5.95	17372.00
ZJ028	Tableware	Zirje	Group 2	36.95	0.75	17.04	270.36	0.80	0.63	8.28	112.80	76.58	65521	130.34	101480	3.95	11167.00
ZJ029	Tableware	Zirje	Group 1	88.76	1.61	15.28	156.20	1.35	0.90	14.11	125.43	172.46	78299	199.61	46413	5.99	15059.00
ZJ030	Kitchenware	Zirje	Group 1	55.69	1.43	16.42	220.12	1.32	0.85	13.07	130.06	153.62	78106	225.62	51947	5.78	14167.00
ZJ031	Kitchenware	Zirje	Group 1	86.95	1.53	15.84	143.02	1.29	0.99	14.74	116.66	186.89	82961	229.84	38978	5.92	16992.00
ZJ032	Kitchenware	Zirje	Loner 4	42.40	0.58	10.25	108.51	0.77	0.59	7.11	85.03	69.84	50712	61.01	230890	3.38	3403.10
ZJ033	Tableware	Zirje	Group 2	40.71	0.59	18.55	303.89	0.86	0.61	8.93	121.12	87.78	75853	239.33	90912	4.40	14087.00
ZJ034	Tableware	Zirje	Group 2	47.22	0.59	17.80	375.37	0.80	0.53	8.60	110.63	72.88	67277	169.46	100390	3.93	14135.00
ZJ035	Kitchenware	Zirje	Group 1	53.71	1.15	18.15	221.57	1.25	0.84	13.96	120.65	168.96	82034	266.67	63188	6.12	16934.00
ZJ036	Kitchenware	Zirje	Group 1	85.30	1.43	16.54	186.71	1.24	1.17	13.87	114.11	150.37	75161	285.26	64991	5.73	15464.00
ZJ037	Kitchenware	Zirje	Group 1	73.73	2.00	17.85	228.84	1.53	1.12	16.69	126.07	167.70	92910	296.61	53055	6.64	16719.00
ZJ038	Tableware	Zirje	Loner 5	117.55	2.23	14.97	350.13	1.48	1.06	11.30	123.73	113.34	77410	383.06	71441	5.01	21486.00
ZJ039	Kitchenware	Zirje	Group 1	96.38	1.72	16.59	185.31	1.46	1.31	15.20	120.54	203.24	85324	323.86	51415	6.25	14351.00
ZJ040	Tableware	Zirje	Group 2	46.69	0.75	17.92	495.86	0.83	0.56	8.58	120.76	102.59	73547	226.25	97177	3.99	11589.00
ZJ041	Clay from ship 1	Zirje		35.50	0.77	6.54	3324.00	0.39	0.38	4.70	58.97	79.79	30535	89.96	393820	2.81	6626.70
ZJ042	Clay from ship 2	Zirje		32.36	0.37	6.04	3180.60	0.33	0.40	4.00	64.71	50.65	24220	96.83	415620	2.26	4400.00

HV001	Geological clay 1	Hvar		138.46	0.71	20.92	340.67	1.07	1.48	9.83	131.44	87.50	79996	296.82	78511	4.56	22486.00
HV002	Geological clay 2	Hvar		134.36	0.63	20.50	302.42	0.82	1.02	9.60	120.64	90.33	74818	335.52	87891	4.64	25418.00

Table 1C: Continued INAA geochemical composition of analysed samples							
Sample	**Type**	**Site**	**Fabric Group**	**Mn**	**Na**	**Ti**	**V**
ZJ001	Kitchenware	Zirje	Group 1	964.65	6954.7	5026.8	144.91
ZJ002	Kitchenware	Zirje	Group 1	1056.30	5630.0	4747.2	109.36
ZJ003	Kitchenware	Zirje	Loner 1	849.12	4341.9	5696.2	137.43
ZJ004	Kitchenware	Zirje	Loner 2	419.27	2249.1	4777.1	98.03
ZJ005	Tableware	Zirje	Group 2	936.53	4051.0	4001.1	154.00
ZJ006	Kitchenware	Zirje	Group 1	988.40	5972.4	3890.1	120.78
ZJ007	Kitchenware	Zirje	Group 1	1045.60	3034.1	5490.9	142.81
ZJ008	Kitchenware	Zirje	Group 1	776.64	6095.8	4751.1	135.05
ZJ009	Kitchenware	Zirje	Group 1	1045.10	4927.1	5135.0	82.90
ZJ010	Tableware	Zirje	Group 2	819.64	3227.5	3840.6	152.23
ZJ011	Tableware	Zirje	Group 1	930.15	5176.4	4446.1	171.25
ZJ012	Kitchenware	Zirje	Group 1	987.64	5570.8	3903.1	89.53
ZJ013	Tableware	Zirje	Group 2	855.79	4898.0	3892.5	139.92
ZJ014	Kitchenware	Zirje	Group 1	879.54	4249.0	4229.7	103.77
ZJ015	Tableware	Zirje	Group 2	931.80	2508.8	3779.3	172.96
ZJ016	Tableware	Zirje	Group 2	1074.10	3190.7	3805.4	138.94
ZJ017	Tableware	Zirje	Group 2	860.36	4583.8	4841.8	161.74
ZJ018	Tableware	Zirje	Group 1	1107.90	7120.6	5224.8	145.13
ZJ019	Kitchenware	Zirje	Group 1	964.08	6568.6	5393.3	141.31
ZJ020	Tableware	Zirje	Group 2	901.47	4775.3	4775.1	156.62
ZJ021	Kitchenware	Zirje	Group 1	917.46	5800.5	4378.7	125.13

ZJ022	Tableware	Zirje	Group 2	905.84	3010.3	3439.5	138.53
ZJ023	Kitchenware	Zirje	Group 1	807.22	5062.9	5287.5	147.01
ZJ024	Tableware	Zirje	Group 2	1000.90	2746.3	3564.7	129.64
ZJ025	Tableware	Zirje	Group 1	744.68	6181.0	4529.6	143.33
ZJ026	Tableware	Zirje	Group 1	706.80	6550.4	4426.7	139.33
ZJ027	Kitchenware	Zirje	Loner 3	811.86	4587.6	4174.2	155.51
ZJ028	Tableware	Zirje	Group 2	895.54	2711.1	4122.4	113.02
ZJ029	Tableware	Zirje	Group 1	684.39	4225.5	4594.3	148.07
ZJ030	Kitchenware	Zirje	Group 1	926.30	5499.2	4527.9	130.61
ZJ031	Kitchenware	Zirje	Group 1	667.85	4260.5	4055.0	147.00
ZJ032	Kitchenware	Zirje	Loner 4	325.46	1342.4	3409.9	109.89
ZJ033	Tableware	Zirje	Group 2	898.96	3900.9	4149.6	119.27
ZJ034	Tableware	Zirje	Group 2	961.12	3798.4	3448.3	128.56
ZJ035	Kitchenware	Zirje	Group 1	1016.80	7024.6	4540.2	127.19
ZJ036	Kitchenware	Zirje	Group 1	928.42	7315.2	4851.1	142.32
ZJ037	Kitchenware	Zirje	Group 1	1015.20	5253.7	5089.4	154.63
ZJ038	Tableware	Zirje	Loner 5	747.63	8765.2	3879.9	86.94
ZJ039	Kitchenware	Zirje	Group 1	1008.00	5060.0	4458.7	153.38
ZJ040	Tableware	Zirje	Group 2	963.54	3564.1	3349.3	116.32
ZJ041	Clay from ship 1	Zirje		321.85	8196.0	1371.0	52.64
ZJ042	Clay from ship 2	Zirje		500.30	3772.7	1385.7	45.72
HV001	Geological clay 1	Hvar		1016.20	8356.6	4673.6	151.75
HV002	Geological clay 2	Hvar		1079.40	8227.8	4418.0	151.29

Reconstructing Production of Hellenistic Pottery and Maritime Trade Routes: Insights from a Hellenistic Shipwreck near Žirje, Croatia

Victoria Hawkins[13] , Maja Miše[14], Patrick Sean Quinn[15], Irena Radić Rossi [16]

Supplement 3
DMS Coordinates for Sites Mentioned

Coordinates for a point on the eastern coast of Žirje Island, Croatia near to the location of the shipwreck. Exact coordinates for the shipwreck site cannot be provided due to the risk to the heritage site:
43°39'24.482''N, 15°42'11.685''E

Coordinates for the raw clay sourced from deposits in Zarače Bay on the island of Hvar:
43°09'01.40''N, 16°30'47.26''E.

Coordinates for modern town of Stari Grad where the Greek colony of Pharos was established on the island of Hvar:
43°10'58.48''N, 16°36'22.806''E

Coordinates in the town of Issa where the Greek colony was established on the island of Vis:
43° 3'36.8424''N, 16° 10' 52.5216''E

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