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ORIGINAL PAPER

Punic amphorae found at Corinth: provenance analysis and implications for the study of long-distance salt fish trade in the Classical period

Leandro Fantuzzi[1,2] · Evangelia Kiriatzi[1] · Antonio M. Sáez Romero[3] · Noémi S. Müller[1] · Charles K. Williams II[4]

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Abstract
The Punic Amphora Building (PAB) at Corinth, Greece, excavated in the late 1970s and dated to the mid-5th century BC, provided a remarkable archaeological context for the study of trade connections between Classical Corinth and the Punic West, based on the finding of hundreds of Punic amphorae and associated fish remains. The first studies indicated that these amphorae were mostly imported from the Straits of Gibraltar region, although the exact area/s of provenance remained undetermined. The recent macroscopic restudy of these amphorae suggested the existence of several fabrics, most probably associated with different production sites in southern Spain and/or northern Morocco. In order to verify this hypothesis, a provenance analysis of this material was performed. A total of 178 amphorae from Corinth's PAB were analysed through a combination of thin section petrography and elemental analysis by WD-XRF. Further information was obtained from the analysis of reference materials from production areas, including amphorae from known Punic kiln sites in the western Mediterranean and associated potential raw materials for ceramic production. The results indicated that Punic *Gadir*, present-day Cádiz, was the main supplier of salt fish which was packaged in amphorae and shipped to Corinth in the fifth century BC, although other Punic sites, especially those located on the coast of present-day Málaga province, also participated in these commercial interactions. The results of this research are of particular importance for the study of long-distance trade networks between the eastern and the western Mediterranean in the Classical period.

Keywords Amphorae · Corinth · Punic archaeology · Classical period · Petrography · WD-XRF

Introduction

Archaeological excavations conducted between 1977 and 1979 at the Roman forum of Corinth uncovered a building from the mid-fifth century BC in which thousands of amphora fragments were found, including a surprisingly large number of Punic amphorae and associated fish remains (Williams II 1978, 1979, 1980; Fig. 1). These findings suggested the existence of a strong commercial link between Classical Corinth and Punic sites of the western Mediterranean. The fish remains were predominantly of tuna and gilthead sea bream (Zimmerman Munn 2003; Theodoropoulou and Sáez 2015). The finding of thousands of fish scales, in many cases as well-preserved rectangular scale packs, was remarkable and indicated the use of the amphorae as containers for transporting chunks of dry salted fish from the western Punic sites. The vast majority of the amphorae had a similar shape, initially assigned to the generic type Mañá-Pascual A4 (Zimmerman Munn 2003) and later ascribed mainly to type T-11213 according to the more detailed typology by Ramon (1995). However, the diversity of macroscopic fabrics suggested their possible relation to various production sites. Another Punic amphora type, initially called 'hole-mouthed jar' (Williams II 1979) or T-1451 (Ramon 1995), was also found but in minor amounts. It was these significant archaeological finds

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✉ Leandro Fantuzzi
leandro.fantuzzi@uca.es

1 Fitch Laboratory, British School at Athens, Athens, Greece
2 Universidad de Cádiz, Cádiz, Spain
3 Universidad de Sevilla, Seville, Spain
4 American School of Classical Studies at Athens, Athens, Greece

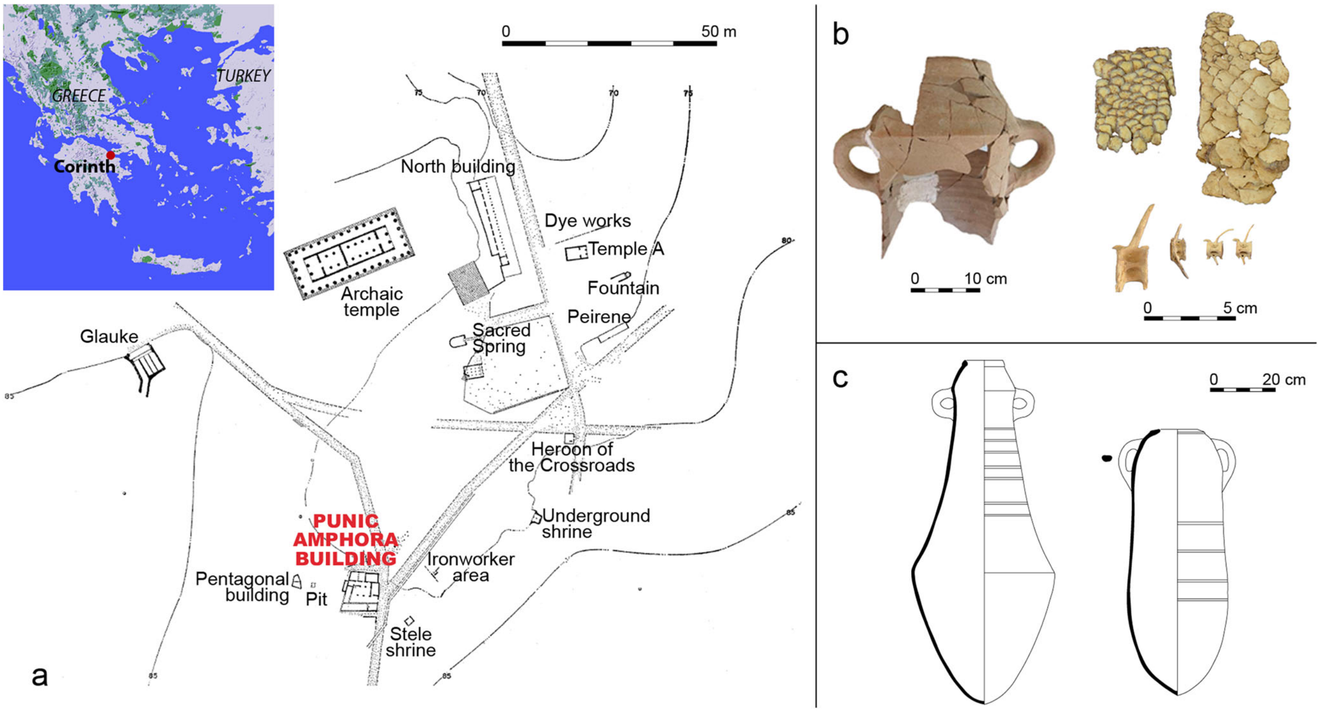


Fig. 1 **a** Classical Corinth in the mid-fifth century BC, and location of the Punic Amphora Building (based on Williams 1979). **b** Representative example of a western Punic amphora and tuna remains—scale packs and vertebrae—found at the PAB (photos of fish remains, Tatiana Theodoropoulou). **c** Illustrations of western Mediterranean amphora type T-11213 and central Mediterranean amphora type T-1451 (from Ramon 1995)

that led the excavators to name the complex as the 'Punic Amphora Building' (PAB). In addition to Punic amphorae, also large quantities of amphorae from the Aegean region, mostly from Chios and Mende, were found in the building, as were local Corinthian amphorae and lesser amounts of fine wares, cooking wares and other materials (Williams II 1978, 1979, 1980; Koehler 1981; Zimmerman Munn 2003). Two successive phases were reported for the PAB by the excavators: both amphorae and fish remains are scarce in the earlier one (c. 470–460 BC), but very common in the later one (c. 460–430s BC) which corresponds to the peak of the building's commercial activity (Williams II 1979; Zimmerman Munn 2003).

A first characterisation of 31 samples of Punic amphorae from Corinth's PAB (Maniatis et al. 1984) allowed for the identification of two compositional groups, with some technological differences between them. Their origin was associated with the wider region of the Straits of Gibraltar, either northern Morocco or southern Spain. The results of that project, a cutting-edge study for its time, based on a multi-technique analysis of the materials, suggested that all amphorae would come from a single or from neighbouring production sites (Maniatis et al. 1984). Their exact provenance was not determined, but a link with Kouass on the Atlantic coast of Morocco was tentatively suggested (Zimmerman Munn 1983, 2003) (Fig. 2), since this was the only Punic amphora kiln site known in the region at that time.

Over the last decades, however, our knowledge of Punic amphora production sites in the western Mediterranean has greatly increased. Concerning the fifth century BC, in addition to the early findings from Kouass (Ponsich 1967, 1968; Kbiri Alaoui 2007), there is now also unquestionable evidence of amphora production in other areas, mostly in southern Spain. In the Bay of Cádiz, for example, evidence of various contemporary workshops has been documented in the current city of San Fernando (De Frutos and Muñoz 1994, 1996; Ramon et al. 2007; Sáez 2008, 2010, 2011, 2014a; Sáez and Belizón 2017), which functioned, in Punic times, as a suburb of the city of *Gadir* (present-day Cádiz) specialising in pottery production (Sáez 2014b). Further direct evidence of amphora production in this period was found along the coast of Málaga province, especially at the site of Cerro del Villar close to the Punic city of *Malaka*, present-day Málaga (Aubet et al. 1999; Mora and Arancibia 2018), as well as at the kiln site of Los Algarrobeños in Vélez-Málaga (Martín and Recio 1994; Martín et al. 2006; Mateo 2015), close to Punic settlements (e.g. Cerro del Mar) and also to earlier Phoenician settlements and kiln sites. Apart from these areas, it is possible that other important Punic sites in southern Spain and northern Morocco could have produced transport amphorae for exporting fish products (Fig. 2), although for the fifth century BC, no other direct evidence has been documented so far (see discussion in Sáez 2011).

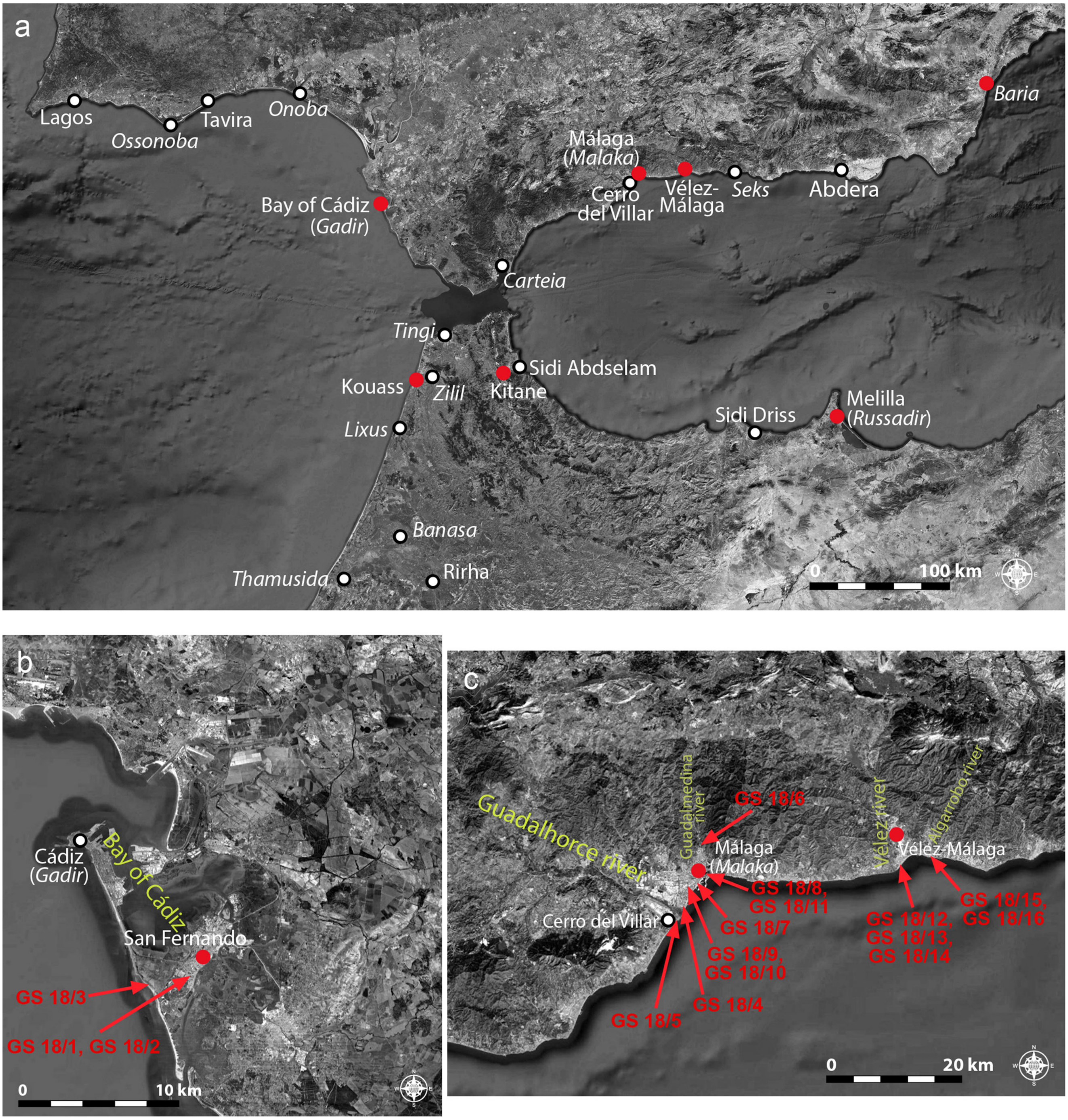


Fig. 2 **a** Location of main Punic sites in the Straits of Gibraltar region. In red, sites from where reference samples were taken for comparison. **b** Location of geological sampling points in the Bay of Cádiz. **c** Location of geological sampling points in the coast of Málaga province (Map data Google, SIO, NOAA, US Navy, NGA, GEBCO, Landsat/Copernicus)

In the light of these recent advances in the study of western Punic amphora production sites, a re-examination of the Punic amphorae from Corinth's PAB was carried out to consider again their provenance. This included, in a first step, a thorough macroscopic study of the amphora assemblage and the definition of macroscopic fabric groups, and, at a second stage, the combined petrographic and elemental analysis of a large number of amphorae representative of the various macroscopic groups. In order to investigate provenance more effectively, reference materials from production areas, including amphorae from known Punic kiln sites in the western Mediterranean, were also analysed, and data were compared with both the newly acquired and with published data from Punic amphora production sites in the wider region of the Straits of Gibraltar. The results of this new interdisciplinary study, presented in this paper, contribute significant new evidence for the organisation of salted fish trade in the Punic West and for commercial relations between Corinth and the western Mediterranean in the Classical period.

Macroscopic study and sampling

Based upon initial studies by Williams II (1979) and Maniatis et al. (1984), the macroscopic restudy of the Punic amphorae from PAB's context enabled the identification of a variety of macro-fabrics and forms. Most of the western Punic amphorae were classified as type T-11213, but other related types (T-11214, T-11215 and T-11216, see Ramon 1995) were also identified in the assemblage. In addition, a few amphorae were associated with the central Mediterranean type T-1451.

Six macroscopic fabric groups were defined (Fig. 3). Four of these (macro-groups 1 to 4) comprised western Punic amphorae, suggesting a possible relation to different production sites or areas. About two-thirds of the Punic amphora assemblage in Corinth's PAB (over an estimated total of 369 amphorae) are associated with macro-group 1. Macroscopic comparison with amphorae from western Punic sites indicated that this main group likely originates in the area of Cádiz/*Gadir*, whereas macro-group 3 seems related to the eastern coast of Andalusia. Concerning macro-groups 2 and 4, a provenance either in the eastern coast of Andalusia or in the Mediterranean or Atlantic coasts of northern Morocco was initially proposed. Two poorly represented macro-groups were possibly related to Punic products from Tunisia (macro-group 5) and western Sicily (macro-group 6), the former including samples of uncertain typology and the latter including amphorae of type T-1451.

The hypothesis formulated on the basis of this macroscopic restudy of the amphorae was that many western Punic sites—mainly Cádiz, but also others—may have been involved in the salted fish trade with Corinth and other Greek cities in the fifth century BC (similar significant finds have been attested also at Olympia and Athens; see Lawall 2006). Testing this hypothesis became the starting point of the new scientific research programme. A total of 178 Punic amphora samples from the PAB were selected. These included 24 of the 31 amphora samples analysed in the first study by Maniatis et al. (1984) (labelled CPA), selected in order to reassess them in the light of the new evidence, as well as 154 new samples from PAB's context (labelled PAB; see Supplementary Table 1). For this recent sampling, representative individuals of the six macro-groups were selected, ensuring that all observed internal variability was covered, although the number of samples taken for each group did not pretend to be representative of their frequencies in the archaeological context. The vast majority of the 178 amphora samples correspond to the main phase of activity of the building, dated to c. 460–430s BC, except for seven samples (PAB 18/43, PAB 18/44, PAB 18/149, PAB 18/157, CPA-8, CPA-30 and CPA-31) which come from a context related to the first phase (c. 470–460 BC), and two samples (CPA-1 and CPA-2) from a pit found a few metres west of the PAB and dated also to c. 460–440 BC (Williams II and Fisher 1976; Zimmerman Munn 2003). The sampling of the first phase was limited due to the low number of Punic amphorae found in this earlier context.

A set of 65 amphora samples of the same types, coming from Punic sites in southern Spain and northern Morocco, was also analysed as reference material for comparison (labelled WPS, for 'Western Punic Sites'; Supplementary Tab. 1). Most of these reference samples come from kiln sites with evidence of amphora production in the Punic period, including sites in the Bay of Cádiz (workshops in San Fernando), Málaga city and Velez-Málaga (Los Algarrobeños workshop) in southern Spain, and an individual sample from Kouass in Morocco (Fig. 2a). In addition, in order to explore other potential sources, a few samples were analysed from other Punic sites, which are considered possible production centres of amphorae in the fifth century BC (as suggested by macroscopic fabrics only but with no direct evidence so far for production). Such sites include Kitane (Morocco) and Melilla (Spain) in northern Rif, as well as Baria in southeastern Spain (Fig. 2; Supplementary Tab. 1). Potential raw materials for ceramic production, collected from areas surrounding the likely production zones, were analysed as well. These included 16 geological samples (labelled GS) of clays and sands from the areas of San Fernando in the Bay of Cádiz, the lower Guadalmedina and Guadalhorce rivers in Málaga, and the mouth of the rivers Velez and Algarrobo in the area of Velez-Málaga (Fig. 2b–c; Supplementary Tab. 1).

Analytical methods

The amphora samples were subjected to thin section petrographic analysis, combined with refiring tests, as well as elemental analysis by means of wavelength dispersive X-ray fluorescence (WD-XRF) spectroscopy.

Thin sections were prepared for all the samples included in this study, and were examined using a Zeiss Axio Scope.A1 polarising microscope, working with magnifications between × 12.5 and × 500. The ceramic fabrics were analysed and described following an adjusted version of the systems proposed by Whitbread (1989, 1995) and Quinn (2013).

The amphorae samples were also subjected to refiring tests. A chip from each sample was refired at 1000 °C in controlled oxidising conditions using a Nabertherm L5/5 furnace. Maximum temperature was achieved gradually over 2 h and soaking time was 1 h 30 min. The furnace was then turned off and the samples were left to cool overnight. The above

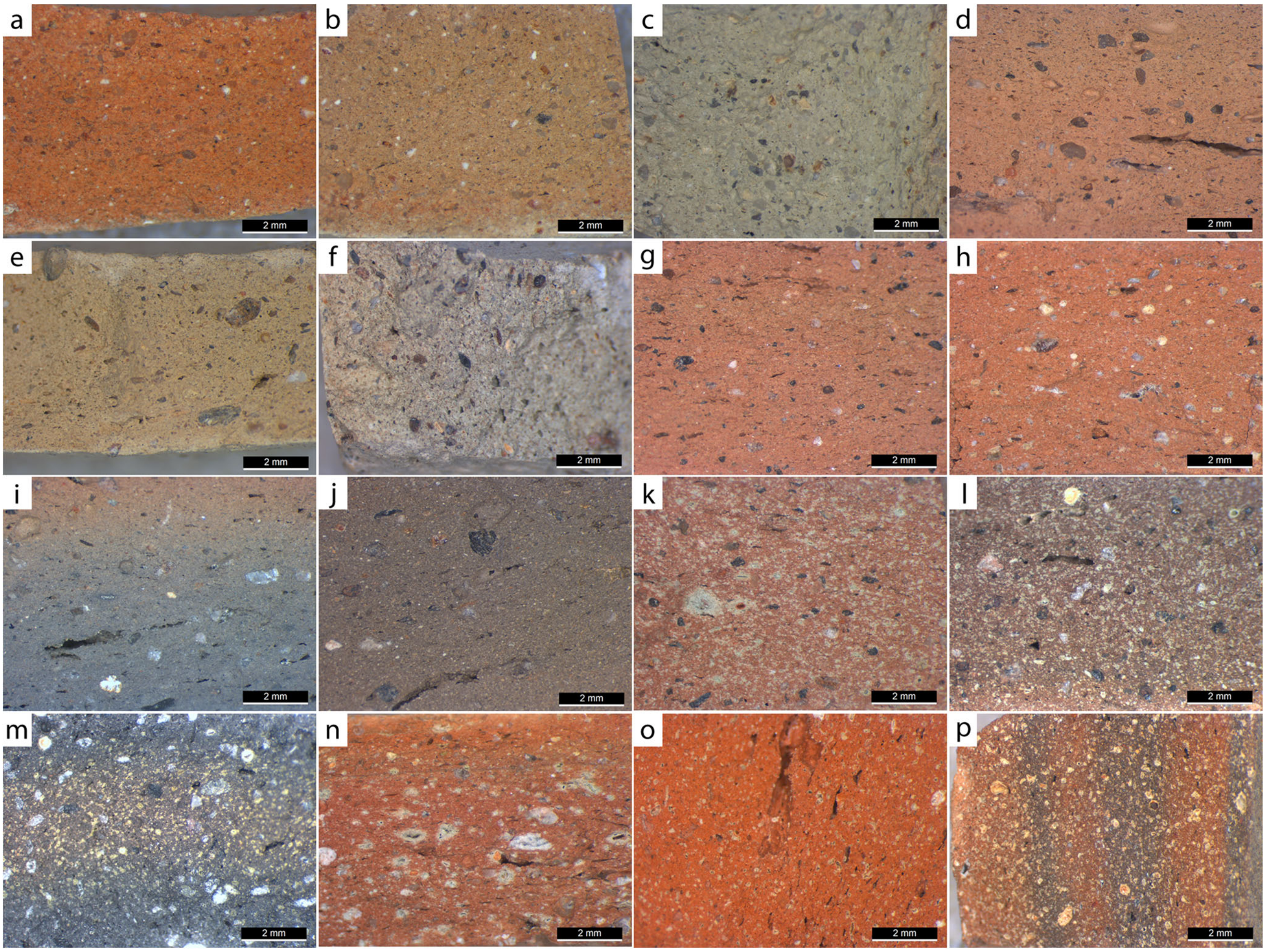


Fig. 3 Photographs of fresh breaks (× 12.5) representing the macroscopic fabric groups identified in the Punic amphora assemblage. (**a**–**c**) Macro-group 1, samples PAB 18/30, PAB 18/31 and PAB 18/38; (**d**–**f**) Macro-group 2, samples PAB 18/54, PAB 18/67 and PAB 18/63; (**g**–**j**) Macro-group 3, samples PAB 18/71, PAB 18/75, PAB 18/88 and PAB 18/90; (**k**–**m**) Macro-group 4, samples PAB 18/115, PAB 18/117 and PAB 18/132; (**n**) Macro-group 5, sample PAB 18/151; (**o**) Macro-group 6, samples PAB 18/152 and PAB 18/157

temperature was considered to be well above or roughly equal to the original firing temperatures of the pottery under study, based on the examination of the clay matrix optical activity in thin section. The refiring of all the amphora samples under the same conditions and at elevated temperature, presumably higher than those of their original firing, was intended to eliminate any colour variation caused by the original firing conditions or any other association with fire (related either to use or postdepositional conditions) and thereby provide an additional line of evidence for macroscopic groupings reflected in colour, in close integration with petrographic and elemental analysis (Whitbread 1995, 390–391; Kiriatzi et al. 2011, 70). Colours of fresh breaks were recorded using the Munsell Soil Color Charts (Munsell Color 1990).

Most of the amphora samples from Corinth's PAB were also examined through elemental analysis, except for few cases where not enough material was available for WD-XRF analysis (see Supplementary Tab. 1). As for the reference samples of amphorae from western Punic sites (WPS), the petrographic analysis provided the basis for assessing the validity of the samples (as not all of them identified as local products) and for selecting a representative sample subset, which was then analysed by WD-XRF (Supplementary Tab. 1). None of the samples from Los Algarrobeños workshop in Vélez-Málaga could be analysed by WD-XRF due to their small sample size.

The elemental analysis was performed using a BRUKER S8 TIGER 4KW WD-XRF spectrometer with Rh excitation source. Samples were measured as glass beads prepared from 1 g of ignited sample and 6 g of a mixture of lithium metaborate/lithium tetraborate with lithium bromide added as non-wetting agent. Twenty-six major, minor and trace elements were determined (Na, Mg, Al, Si, P, K, Ca, Ti, Fe, V, Cr, Mn, Co, Ni, Cu, Zn, Rb, Sr, Y, Zr, Ba, La, Ce, Nd, Pb, Th) using a custom calibration based on 43 certified reference materials (Georgakopoulou et al. 2017).

As regards geological samples of potential raw materials for ceramic production, experimental briquettes were prepared for each clay sample and fired at three different temperatures (700 °C, 900 °C and 1050 °C) in controlled oxidising conditions, for their subsequent petrographic and elemental analysis. Geological samples of sands were thin sectioned for petrographic analysis as well (overall methodology as in Kiriatzi et al. 2011).

Results and discussion

Petrographic analysis and refiring tests

Thin section analysis under the polarising microscope, combined with refiring tests, allowed for the identification of seven fabric groups (FG 1 to FG 7; Table 1). The best represented groups among the selected samples from Corinth's PAB were FG 1 (n = 68), FG 2 (n = 24) and FG 5 (n = 63).

Petro-group FG 1

This group comprised sedimentary fabrics composed of quartz, microfossils and calcite inclusions in a carbonate-rich clay matrix (Fig. 4). Inclusions showed bimodal grain size distribution, with a sandy coarse fraction (> 0.20 mm, predominantly medium sand) mainly composed of subrounded to rounded quartz, common to few alkali feldspar and carbonate inclusions (calcite and microfossils), rare micas and plagioclase, and very occasionally chert, garnet and fragments of mudstone or sandstone. Monocrystalline quartz, calcite and calcareous microfossils were also the main components of the fine fraction (0.20–0.01 mm). Microfossils included a great variability of foraminifera, in addition to minor amounts of echinoids and shell fragments. Occasional small bone fragments, some of them identifiable as fish (Horowitz and Potter 1971; Shahar and Dean 2013), were observed in several samples.

This group was relatively homogeneous in terms of petrographic composition and textural parameters. However, fabric variations were observed based on the colour and optical activity of the matrix under the microscope and the degree of decomposition of carbonate inclusions (Table 1; Fig. 4b–c), both of which are potentially associated with varied firing conditions. Similar variations were observed in the fabric colour and texture in the macroscopic examination of the same amphorae (Fig. 3a–c). After refiring, the samples became reddish yellow to very pale brown or pale yellow (Table 1). Samples which in thin section appeared to be higher-fired than others showed no significant changes of colour (pale yellow) after refiring, thus indicating that they had been initially fired at temperatures over 1000 °C. In fact, the additional experimental refiring of a lower-fired sample in FG 1 to a temperature of 1080 °C (CPA 5; Maniatis et al. 1984) resulted in a fabric very similar to the one observed in those high-fired samples (Fig. 4d–e), thus suggesting that colour variation after refiring was still due to the original firing conditions as the original firing temperature varied significantly.

Except for these differences, the general fabric characteristics were similar for all samples assigned to group FG 1. Variations in the mode of the coarse fraction and the abundance of fine quartz inclusions were found, but this variability was gradual and it was not possible to differentiate clear fabric sub-groups on this basis.

The fabrics in FG 1 showed strong resemblance to reference samples from kiln sites in San Fernando, Bay of Cádiz (Fig. 4f). The same fabric variations observed within FG 1 were also observed in fabrics from this area (no significant differences were found between samples from different workshops in San Fernando). A geological sample of sand (GS 18/3) from the same area also showed similar characteristics (e.g. dominance of subrounded to rounded quartz) to the coarse fraction that was observed in FG 1. The provenance of this petrographic group could therefore be associated with the Bay of Cádiz, an interpretation that is supported by comparison with previous petrographic studies on amphorae from this region (e.g. Cau 2007; Johnston 2015).

Petro-group FG 2

FG 2 was characterised by a bimodal distribution of the inclusions, with a coarse fraction (> 0.25 mm, predominantly medium and coarse sand) dominated by fragments of low-grade metamorphic rocks derived from pelites and psammites (mostly phyllite), and sedimentary rocks ranging from fine-grained argillaceous rocks to quartz sandstone (Fig. 5a). The coarse fraction also included monocrystalline and polycrystalline quartz, micritic lumps, occasional fragments of igneous rocks and chert, and very rarely serpentinite. The fine fraction was composed of quartz, micas (mostly muscovite), opaques/iron oxides, calcite (sparite and micrite) and calcareous microfossils (foraminifera mainly, but also ostracods and echinoids).

As in FG 1, internal fabric differences were observed in group FG 2 associated with gradual variations in the degree of decomposition of carbonate inclusions, as well as in the optical activity of the matrix, likely associated with differences in firing conditions. These appear to account for at least part of the macroscopic variability observed among samples of this group (Fig. 3d–f). The samples usually refired reddish yellow, sometimes with slightly pinker hues (Table 1), suggesting the use of a broadly similar type of clay base, although potentially with some variation. Samples that in thin section appeared to be higher-fired than others refired very pale brown to pale yellow, showing similar colours to those before refiring except for the disappearance of light grey zones

Table 1 Summary of the results obtained from the thin section petrographic analysis. For each fabric group, the macroscopic colours of the samples before and after refiring tests are given (using Munsell Soil Color Charts)

Petrographic fabric group	Samples	Macroscopic colour of fresh break	Macroscopic colour of fresh break after refiring tests
FG 1: Quartz, microfossils and calcite inclusions, calcareous matrix ($n = 68$)	PAB 18/1 to PAB 18/45, PAB 18/51, PAB 18/64, PAB 18/69, PAB 18/76, PAB 18/78, PAB 18/79, PAB 18/97, PAB 18/98, PAB 18/99, CPA-1, CPA-2, CPA-3, CPA-5, CPA-7, CPA-13, CPA-14, CPA-17 to CPA-21, CPA-26. Outlier: PAB 18/52	Reddish yellow (5YR 6/6, 7/6); very pale brown (10YR 7/3, 7/4, 8/4); light yellowish brown (10YR 6/4); light red (2.5YR 6/8); pale yellow (2.5Y 7/4, 8/4, 5Y 8/3)	Reddish yellow (7.5YR 7/6, 8/6); very pale brown (10YR 8/4); pale yellow (2.5Y 8/4, 5Y 8/3)
FG 2: Low-grade metamorphic and sedimentary rocks, accessory igneous rocks and serpentinite ($n = 24$)	PAB 18/46 to PAB 18/50, PAB 18/53 to PAB 18/63, PAB 18/65 to PAB 18/68, PAB 18/80, PAB 18/84, CPA-16, CPA-22	Reddish yellow (5YR 7/6, 7.5YR 7/6); light yellowish brown (10YR 6/4); very pale brown (10YR 7/3, 7/4); pale yellow (2.5Y 7/4, 5Y 7/3, 8/3) grading into light grey (2.5Y 7/2, 5Y 7/1)	Reddish yellow (5YR 6/6, 7/6); pink (7.5 YR 8/4); very pale brown (10YR 8/3, 8/4) to pale yellow (2.5Y 8/4)
FG 3: Rounded quartz, serpentinite, low-grade metamorphic and sedimentary rocks ($n = 5$)	PAB 18/88, PAB 18/89, PAB 18/91, CPA-8, CPA-11	Grey (7.5YR 5/0) grading into reddish yellow (5YR 6/6) towards the outer surface; light reddish brown (5YR 6/4), with light grey core (10YR 7/2)	Reddish yellow (5YR 6/6) to light reddish brown (5YR 6/4)
FG 4: Quartz-muscovite schist ($n = 6$)	PAB 18/73, PAB 18/75, PAB 18/81, PAB 18/93, PAB 18/103, PAB 18/122	Reddish yellow (5YR 6/6); reddish brown (5YR 5/4) to light reddish brown (5YR 6/4) in PAB 18/122	Light red (2.5YR 6/6); light reddish brown (5YR 6/4) in PAB 18/122
FG 5: Garnet-staurolite-quartz-mica schist ($n = 63$)	FG 5.1 ($n = 44$): PAB 18/71, PAB 18/72, PAB 18/74, PAB 18/77, PAB 18/82, PAB 18/86, PAB 18/87, PAB 18/90, PAB 18/92, PAB 18/100, PAB 18/101, PAB 18/102, PAB 18/104 to PAB 18/107, PAB 18/109 to PAB 18/112, PAB 18/115 to PAB 18/121, PAB 18/123, PAB 18/125 to PAB 18/129, PAB 18/134 to PAB 18/139, PAB 18/141, CPA-4, CPA-6, CPA-9, CPA-15. FG 5.2 ($n = 10$): PAB 18/113, PAB 18/114, PAB 18/124, PAB 18/130 to PAB 18/133, PAB 18/140, PAB 18/142, CPA-30. FG 5.3 ($n = 5$): PAB 18/70, PAB 18/83, PAB 18/85, PAB 18/94, PAB 18/95. Outliers: samples PAB 18/108, PAB 18/143, PAB 18/144, CPA-10	Reddish brown (5YR 5/3, 5/4), light reddish brown (5YR 6/4), brown (7.5YR 5/2, 5/4), light brown (7.5YR 6/4) or light yellowish brown (10YR 6/4), often grading into reddish yellow (5YR 6/6); sometimes with grey (7.5YR 5/0), very dark grey (7.5YR 3/0) or greyish brown (10YR 5/2) zones	Light red (2.5YR 6/6); reddish brown (5YR 5/4); light reddish brown (5YR 6/4); reddish yellow (5YR 6/6)
FG 6: Quartz and carbonates, fine fabrics ($n = 5$)	PAB 18/152, PAB 18/153, PAB 18/154, PAB 18/156, PAB 18/157	Red (2.5YR 5/8) or reddish brown (2.5YR 5/4), with dark grey (5YR 4/1) zones; rarely yellowish red (5YR 5/6) with brown core (7.5YR 5/4)	Red (2.5YR 5/6) to light red (2.5YR 6/6)
FG 7: Angular quartz, feldspars and micas, accessory metamorphic rocks ($n = 3$)	PAB 18/149, PAB 18/150, PAB 18/151	Reddish brown (2.5YR 5/4); outer wall: light yellowish brown (10YR 6/4) or reddish yellow (5YR 6/8)	Reddish brown (2.5YR 5/4)
Singleton: Angular quartz and alkali feldspar	PAB 18/96	Reddish yellow (5YR 6/6)	Red (2.5YR 5/6)
Singleton: Angular quartz and feldspars, accessory metamorphic rocks	PAB 18/145	Greyish brown (10YR 5/2) grading into reddish yellow (5YR 7/6) towards the outer surface	Reddish yellow (5YR 7/6)
Singleton: Subrounded-rounded quartz and carbonates, Fe-rich matrix	PAB 18/148	Dark reddish grey (5YR 4/2); core: reddish brown (5YR 5/3)	Reddish brown (2.5YR 5/4)
Singleton: Quartz, feldspars and carbonate inclusions, with sedimentary and low-grade metamorphic rocks, calcareous matrix	CPA-31	Very pale brown (10YR 8/4); core: light brownish grey (2.5Y 6/2)	Pink (7.5YR 8/4)

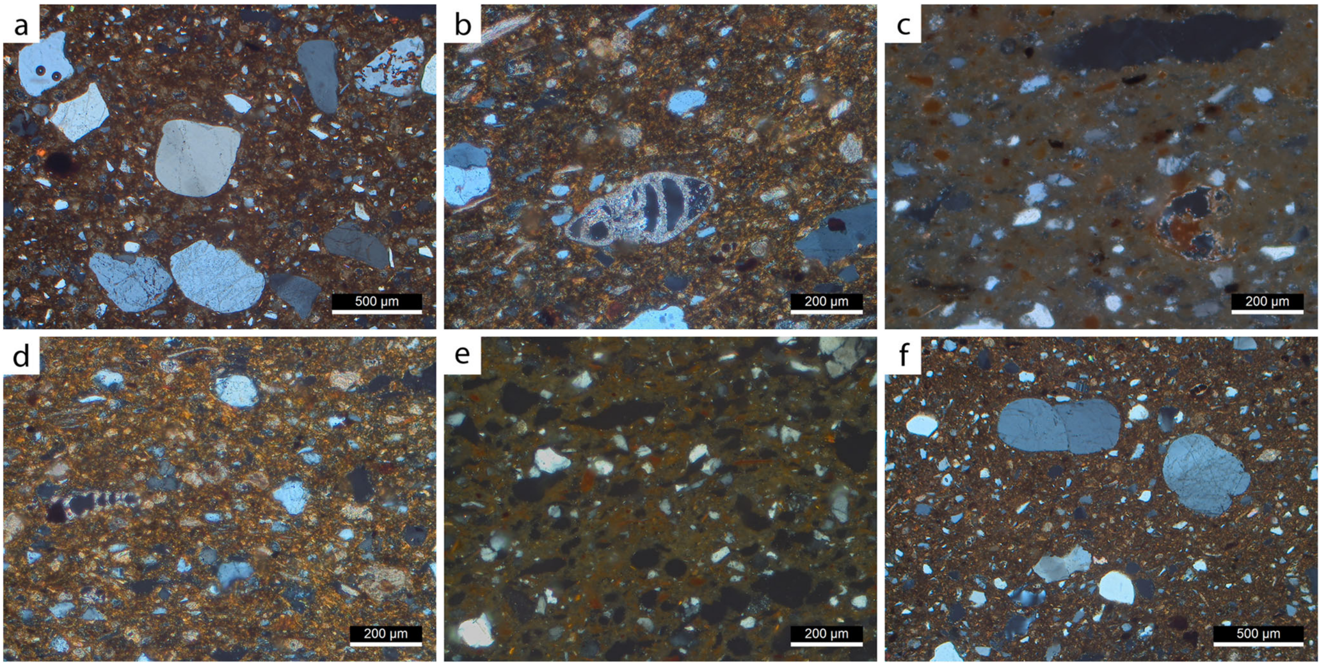


Fig. 4 Petrographic fabric group FG 1: photomicrographs of thin sections, taken under crossed polars. **a** Sample PAB 18/19, × 50. **b** Sample PAB 18/24, lower-fired fabric. **c** Sample PAB 18/69, higher-fired fabric. **d** Sample CPA-5, as-received state. **e** Sample CPA-5, after refiring at 1080 °C. **f** Sample WPS 18/10, from a kiln site in San Fernando, Bay of Cádiz

observed in a few samples; this would suggest that these amphorae were originally fired at temperatures often over 1000 °C and, in some cases, under variable reducing-oxidising conditions and/or different firing duration.

The predominance of low-grade metamorphics and sedimentary rocks in FG 2 suggests a provenance area close to outcrops of the Malaguide-Ghomaride complex of the Internal Betic-Rif Zone, located in the areas of Málaga in southern

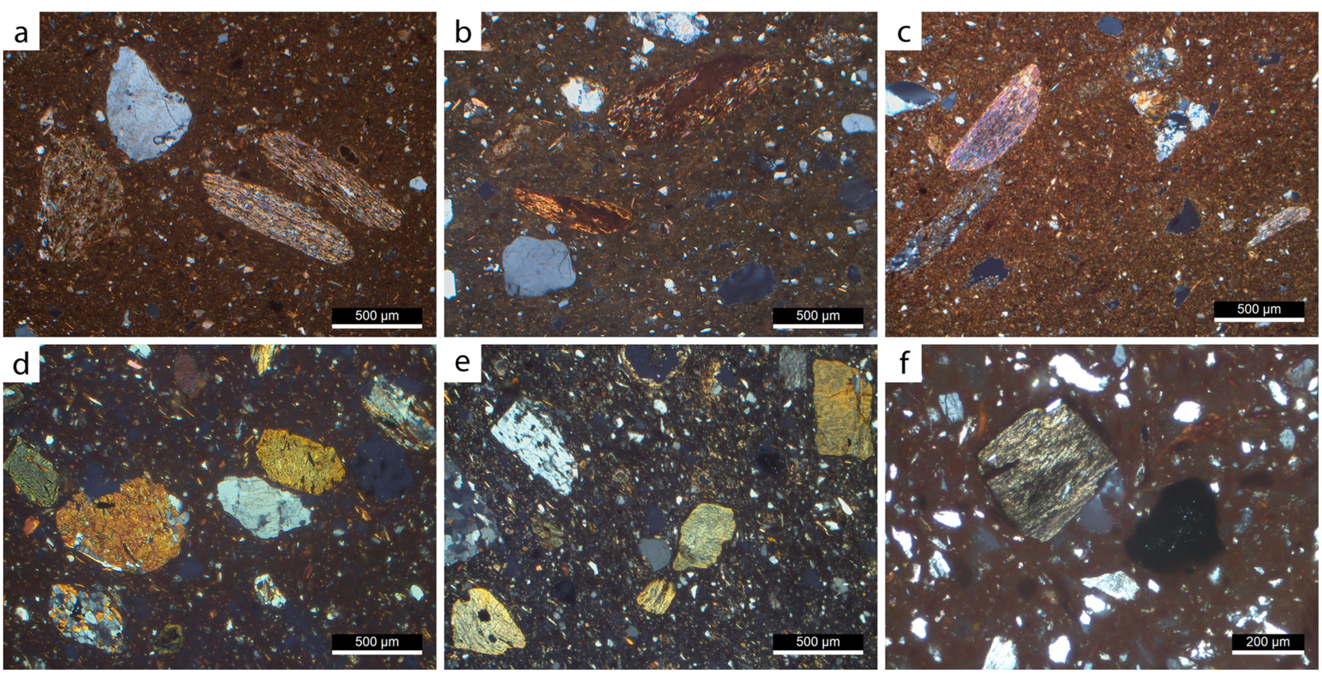


Fig. 5 Petrographic fabric groups FG 2 (**a**–**c**) and FG 5 (**d**–**f**): photomicrographs of thin sections, taken under crossed polars. **a** Sample PAB 18/47. **b** Sample WPS 18/25, from a kiln site in Málaga city. **c** Experimental briquette of a clay sample, GS 18/7, from the Guadalmedina basin in Málaga city, fired at 700 °C. **d** Sample PAB 18/109. **e** Sample WPS 18/62, from the kiln site of Algarrobeños in Vélez-Málaga. **f** Experimental briquette of a clay sample, GS 18/14, from the mouth of the Vélez river (area of Vélez-Málaga) fired at 1050 °C

Spain and/or Tetouan in northern Morocco (Didon et al. 1973; Fontboté 1983; Martín-Algarra 2004; Serrano and Guerra 2004; Chalouan et al. 2008). However, the concurrent presence of these rocks and accessory serpentinite in some samples points to Málaga as a more plausible hypothesis, since this lithological association is more likely to be found close to the city of Málaga, due to the contribution of the Ronda ultramafic complex in this area (Fontboté et al. 1972; Aldaya et al. 1980; Junta de Andalucía 1998; Serrano and Guerra 2004; Fantuzzi and Cau 2017). The same fabric as in FG 2 was observed in one of the reference samples from the Málaga suburban workshops (Fig. 5b). Rocks and inclusions similar to those recorded in the ceramic fabric were also observed in some of the geological samples of clays and sands analysed from Málaga (GS 18/6 to GS 18/10), in particular from the Guadalmedina river valley, and also in a mudbrick sample from a kiln site in Málaga city (GS 18/11) (Table 1, Fig. 5c). For these reasons, and considering also the archaeological evidence, the provenance of FG 2 is considered to be linked with the area of Málaga city.

Petro-group FG 5

The fabrics in this group were characterised by inclusions derived from medium-grade metamorphic rocks, in particular garnet-staurolite-quartz-mica schist (Fig. 5d). Grain size distribution of the inclusions was bimodal, with a coarse fraction (1.75–0.15 mm; mode 0.20–0.40 mm) mainly composed of polycrystalline quartz/quartzite, garnet, staurolite and metamorphic rock fragments derived from schist. The fine fraction (0.15–0.01 mm) contained dominant micas—both muscovite and biotite—and monocrystalline quartz, in addition to opaques/iron oxides and highly altered or decomposed carbonate inclusions, as suggested by reaction rims and ghosts of microfossils. Fabrics in this group were relatively heterogeneous in terms of relative frequencies of some types of inclusions, especially garnet and staurolite, although with gradual variations. By far, the most common fabrics (subgroup FG 5.1; $n = 44$) contained abundant garnet and staurolite; however, there were less represented fabrics which contained staurolite but no garnet (FG 5.2; $n = 10$), and vice versa (FG 5.3; $n = 5$). Moreover, other metamorphic minerals such as kyanite, which were present as accessory inclusions, were also observed in variable amounts. Despite this gradual variability, all samples assigned to FG 5 were very similar in textural parameters, with only slight variations in the abundance of coarse fraction. The clay matrix was relatively similar in these samples, with light brown to reddish brown colour in PPL and no optical activity. There were variations in the degree of development of carbonate reaction rims, which were consistent with textural variations observed in the macroscopic fabrics (Fig. 3 g, j–m). Variation in macroscopic colour related to core/margin differentiation or to gradual change in colour between the inner and outer surfaces was also common in the samples of this group; as expected, these zones of varied colour disappeared after refiring tests, when homogeneous reddish colours—in hues ranging from light red to reddish brown—were recorded (Table 1).

The provenance of group FG 5 should be located in an area with medium-grade metamorphic rocks. Comparison with the regional geology (Aldaya et al. 1980; Junta de Andalucía 1998; Fontboté 1983; Martín-Algarra 2004; Chalouan et al. 2008) showed that these are very common in the Mediterranean coast of Andalusia (particularly eastern Málaga and Granada) and, to a lesser extent, in the Rif region in northern Morocco. The existing evidence for Punic amphora kiln sites pointed to the area of Velez-Málaga as a strong possibility. In fact, the geology of this area is dominated by outcrops of garnet-staurolite mica schist (Aldaya et al. 1980; Elorza and García Dueñas 1981; Junta de Andalucía 1998). Similar fabrics were reported for Phoenician-Punic amphorae and other ceramics from Velez-Málaga by other authors in the past (Amadori and Fabbri 1998; Pringle 1998; Iliopoulos et al. 2009; Miguel 2014; Montana and Randazzo 2018). Comparison with reference samples from the kiln site of Algarrobeños in Velez-Málaga also supports this provenance hypothesis, since their fabrics were very similar to those in FG 5 (Fig. 5e). Furthermore, experimental briquettes of a geological clay sample from this area (GS 18/14) showed strong similarities with the amphora samples in terms of clay matrix and inclusion composition (Fig. 5f), although with a coarser texture (i.e. higher frequency of coarse sand inclusions); this suggests that a similar clay might have been used for manufacturing the amphorae in FG 5, possibly after a process of refining.

Other petro-groups

Apart from FG 1, FG 2 and FG 5, the other petrographic fabric groups identified in this study were poorly represented in the assemblage (Table 1).

FG 3 ($n = 5$) was characterised by a range of coarse inclusions similar to those recorded in FG 2 but with clearly different frequencies: in this case, a much higher amount of quartz (rounded to subrounded) and serpentinite inclusions was observed (Fig. 6a). The fine fraction was rich in mica, quartz and calcitic inclusions, but microfossils were rare, indicating that the raw clay used was probably different from the one used in FG 2. In wall sections, the samples in this group were bicoloured to the naked eye, usually grey grading into reddish yellow towards the outer surface (possibly indicating shorter firing or soaking time), although an homogeneous reddish yellow colour was recorded after refiring (Table 1). Apart from PAB amphorae samples, also reference samples from Málaga kiln sites (Fig. 6b) were assigned to FG 3. The regional geology points to the mouth of the Guadalhorce river as the most likely

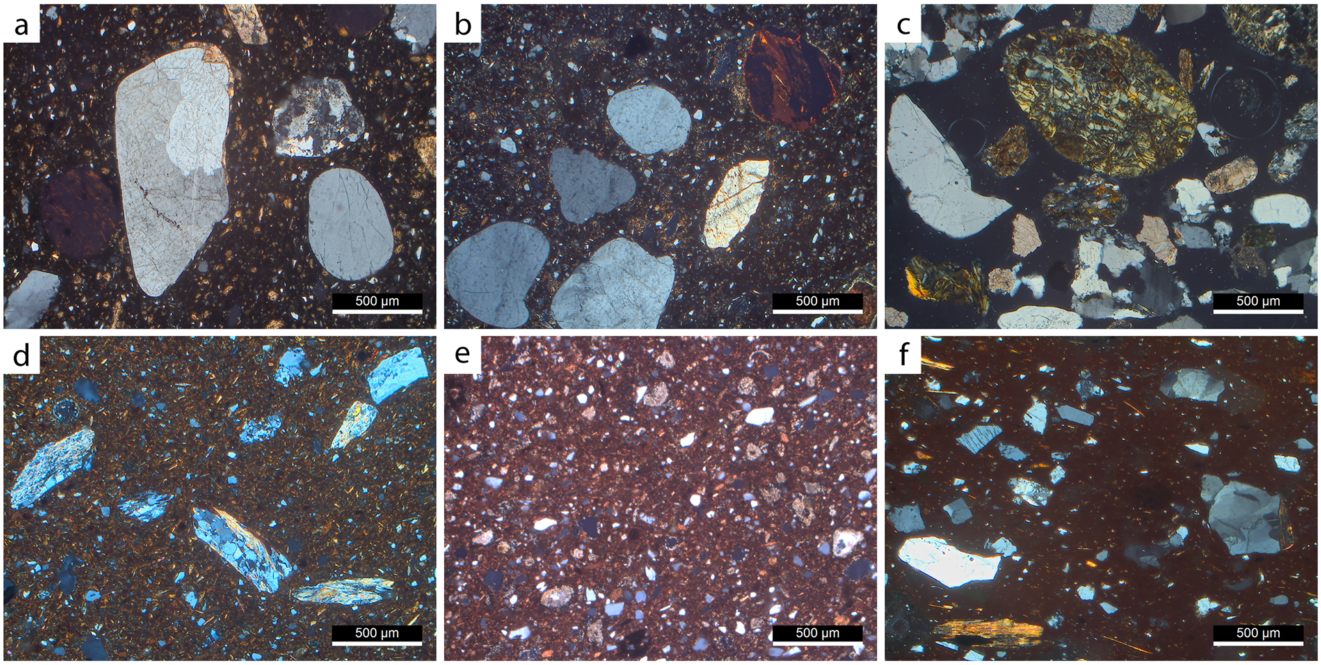


Fig. 6 Photomicrographs of thin sections taken under crossed polars, showing various petrographic fabric groups. **a**–**c** FG3: (**a**) sample PAB 18/91; (**b**) sample WPS 18/19, from a kiln site in Málaga city; (**c**) geological sample of sand, GS 18/4, from the mouth of the Guadalhorce river, western Málaga city. **d** FG 4, sample PAB 18/73. **e** FG 6, sample PAB 18/156. **f** FG 7, sample PAB 18/151

provenance area, an interpretation supported by the analysis of sand samples from this zone (Fig. 6c). Based on this evidence, as well as on other published petrographic studies (Cardell et al. 1999; Miguel 2014), a provenance in the area of Málaga, close to the mouth of Guadalhorce river (Málaga city? Cerro del Villar?), could be proposed for this group.

The samples assigned to FG 4 ($n = 6$) were characterised by a coarse fraction dominated by inclusions derived from quartz-mica schist (Fig. 6d). FG 4 shows some similarities with FG 5, but with nearly no medium-grade metamorphic minerals except for very rare garnet inclusions. The clay matrix was usually orange coloured in PPL, optically active to slightly active, except in sample PAB 18/122 in which the matrix was optically inactive, reddish brown to light brown in PPL. The samples in FG 4 refired light red to light reddish brown (Table 1), similar to samples assigned to FG 5. From a strictly geological point of view, based on the metamorphic composition of the inclusions, only a general provenance in the Mediterranean coast of Andalusia or northern Morocco could be proposed for FG 4, although the similarities with FG 5 suggested the possibility of a common provenance area for both.

Unlike groups FG 1 to FG 5, which were related to western Punic amphora types (T-11213 and related), FG 6 ($n = 5$) included samples of central Mediterranean amphorae of type T-1451. These were relatively fine-grained fabrics, composed of angular quartz and carbonate inclusions showing unimodal grain size distribution, predominantly in the range of very fine sand and coarse silt (Fig. 6e). Comparison with published reference fabrics from production sites of this type of amphorae indicated that the provenance of FG 6 must be located in western Sicily (Alaimo et al. 1997, 1998, 2002, 2003; Iliopoulos et al. 2002, 2009; Montana and Randazzo 2015, 2018), most likely in the area between Palermo and Solunto (see fabric SP-II in Montana and Randazzo 2015, 2018).

A few samples of amphora body sherds were related to another fabric (FG 7, $n = 3$) characterised by inclusions of angular quartz, feldspars, micas and accessory metamorphic rock fragments (Fig. 6f). At present, neither the petrographic composition nor the typological evidence enabled any provenance hypothesis concerning this fabric.

Finally, four amphora samples analysed were each associated with different fabrics (Table 1). For three of them, the combined petrographic and archaeological evidence suggested a general provenance in the Straits of Gibraltar region (PAB 18/96, PAB 18/145 and CPA-31). Conversely, the fabric in sample PAB 18/148—an amphora body sherd—composed of dominant coarse quartz (usually subrounded to rounded) and carbonate inclusions in a ferruginous matrix, pointed to a probable provenance in Tunisia, based on comparison with published reference fabrics for Punic amphorae and other ceramics (e.g. Amadori et al. 2002; Maraoui Telmini and Bouhlel 2011; Braekmans and Gupta 2018).

Elemental analysis

WD-XRF analysis was performed on a total of 158 Punic amphora samples from Corinth's PAB. The elemental data

(Supplementary Tab. 2) was first examined by calculating the compositional variation matrix or CVM (Aitchison 1986, 2005; Buxeda 1999). The obtained value for the total variation (vt = 1.09) was relatively high and indicated a polygenic population (Buxeda and Kilikoglou 2003; Buxeda et al. 2003), in agreement with the results of petrographic analysis. The highest variability, according to the CVM, was due to variations in CaO (τi = 5.09), Mn (τi = 4.12), P_2O_5 (τi = 3.72) and Pb (τi = 3.25). The high τi value for Pb was biased by the presence of a very high concentration in one sample (CPA-1), possibly as a result of contamination. This element, as well as P_2O_5, Na_2O and Cu, was excluded from the multivariate statistical treatment in order to avoid possible contamination problems.

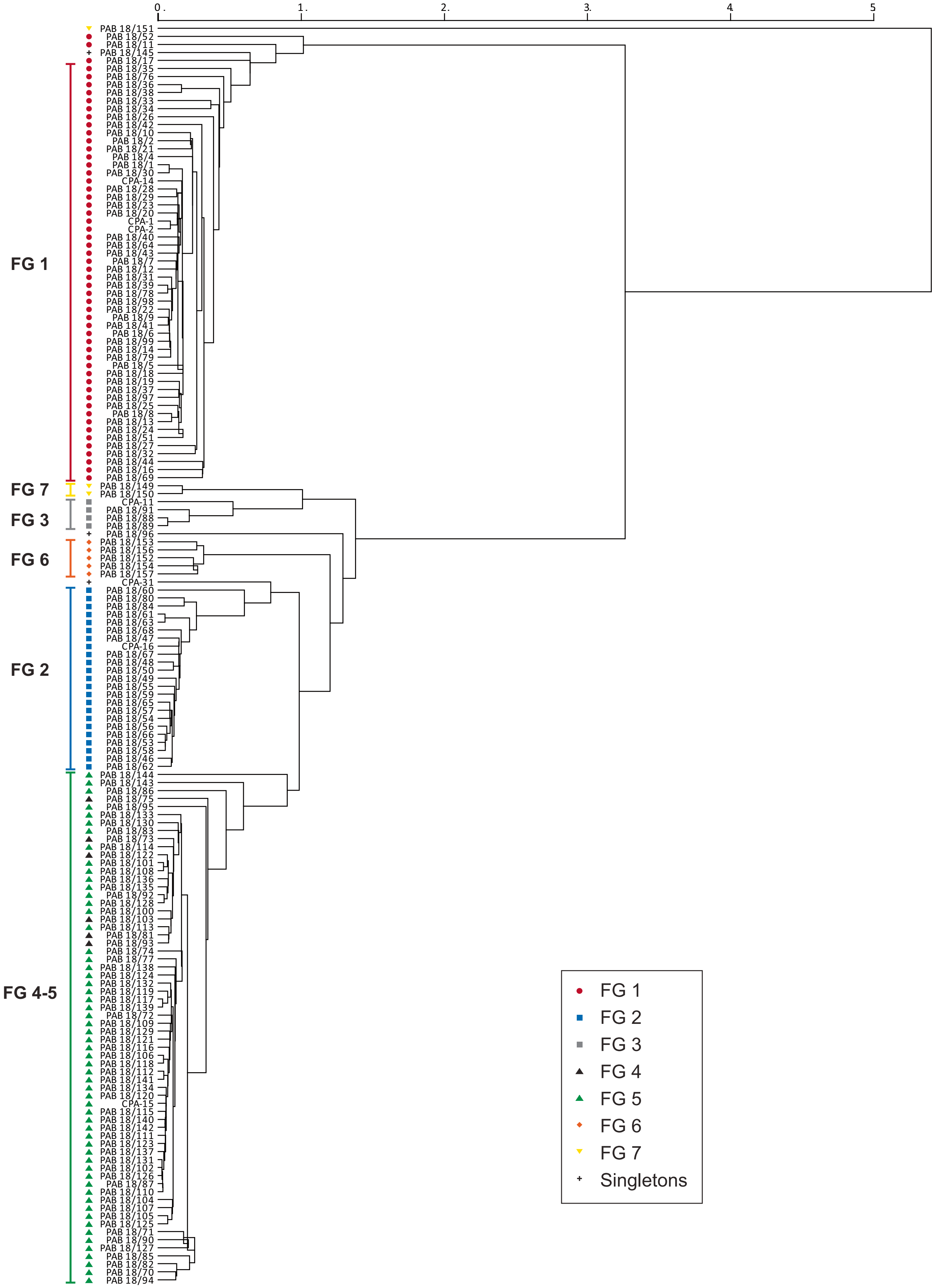
Cluster analysis (CA) of the elemental data revealed the presence of six main chemical groups in the Punic amphora assemblage (Fig. 7). These correlate well with the petro-groups, except for FG 4 and 5 which clustered together. In the latter case, the two petro-groups seem to form one compositional group, as was already suggested by certain similarities observed in thin sections. In fact, calculation of CVM for this chemical group resulted in a very low total variation (vt = 0.14) and supported its interpretation as a monogenic population. This is relevant for the understanding not only of the relation between FG 4 and 5, but also of the different subgroups identified in FG 5 (Table 1; FG 5.1 to 5.3), since they all can be considered as a single compositional group of the same provenance. The high frequency of aluminous metamorphic minerals such as garnet and staurolite in these samples could account for the high Zn content and may contribute to relatively high Al_2O_3 levels observed (Fig. 8a). Enriched Zn content in staurolite was reported for medium-grade schists of the Torrox unit close to Velez-Málaga (García-Casco and Torres-Roldán 1999, see also Tuisku et al. 1987); in fact, Zn concentrations were consistently higher in samples of FG 5.1 (rich in garnet and staurolite) and FG 5.2 (staurolite-rich) compared with those of FG 5.3 (garnet-rich) and FG 4 (lack of garnet and staurolite) (Fig. 8b). Except for this variation, which was gradual, no other significant differences in elemental composition were found between the petrographic subgroups within FG 4–5, thus suggesting a common provenance area for the whole group.

Very low total variation values—indicative of monogenic populations—were also obtained for all the other main chemical groups identified in CA (Fig. 7), associated with FG 1 (vt = 0.20), FG 2 (vt = 0.13), FG 3 (vt = 0.17) and FG 6 (vt = 0.19), although the two latter comprised only four and five samples, respectively. The chemical homogeneity of these main groups, whose average composition is given in Table 2, points to a common provenance for all the samples in each group, and provides further evidence that the various fabrics identified within some of them were mostly related to variations in firing conditions, as suggested by petrographic analysis (Table 1), rather than to the use of different raw materials for ceramic production. As for the small petro-group FG 7 (n = 3), two of its samples clustered together in CA while sample PAB 18/151 behaved as a loner (Fig. 7; Supplementary Tab. 2).

The low compositional variability for each group could be related to natural variations of the source raw materials, and this would account for slight textural variations observed in thin section, especially for FG 1. This large group was differentiated from other groups by lower percentages of Fe_2O_3, Al_2O_3 and MgO, and high CaO (Table 2; Fig. 9a–b); this is consistent with the carbonate-rich composition of the fabrics documented in the petrographic analysis for this group. Variations in CaO content within FG 1 might also be partially related to the presence of secondary calcite observed in some samples of this group; however, in most cases, the nature of these features—e.g. carbonate reaction rims—could be associated with a partly allochthonous origin (Cau et al. 2002), and, therefore, the CaO concentrations would not necessarily be affected; indeed, no direct relation was found between samples with secondary calcite and the relative amount of CaO within FG 1, and accordingly, refiring colours.

The elemental analysis also revealed that samples assigned to FG 3 and FG 7 had higher concentrations of Ni and Cr (as well as Co and MgO) compared with the rest of samples analysed (Fig. 9c). In the case of FG 3, this could be associated with the abundance of serpentinite in the fabric, thus suggesting the use of raw materials with contribution of ultramafic lithologies. The same enrichment in Ni and Cr was reported by other authors for Phoenician ceramics from sites located in the mouth of the Guadalhorce river, in particular Cerro del Villar (Behrendt and Mielke 2011; Behrendt et al. 2012; Miguel 2014); this supported the provenance hypothesis formulated after the petrographic analysis for FG 3.

Multivariate statistical analysis performed on the amphorae from Corinth's PAB and on reference samples—amphorae and experimental briquettes of geological clays—from western Punic kiln sites (Supplementary Tab. 2; Fig. 10) provided further support for the provenance hypothesis not only of FG 3 but also of other groups. The large group FG 1 clustered with reference samples from workshops in San Fernando (Bay of Cádiz), confirming that the latter could be considered as the provenance area for FG 1; a very low total variation value was obtained for this cluster (vt = 0.25). On the other hand, reference samples of amphorae from kiln sites in Málaga clustered with groups FG 3 and, in one case, FG 2, forming quite homogeneous chemical groups (vt = 0.23 and vt = 0.14, respectively); also, a clay sample (GS 18/7) from the lower Guadalmedina basin in Málaga city clustered with FG 2. This supported a provenance in Málaga for these two groups, as suggested by the petrographic analysis. Based on the combined chemical and petrographic evidence, FG 3 could be associated with the use of raw material sources from the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PAB 18/90
PAB 18/127
PAB 18/85
PAB 18/82
PAB 18/70
PAB 18/94
FG 1
FG 7
FG 3
FG 6
FG 2
FG 4-5
FG 1
FG 2
FG 3
FG 4
FG 5
FG 6
FG 7
Singletons

◀ **Fig. 7** Dendrogram from cluster analysis on the simple-log transformed elemental data for 157 Punic amphorae from Corinth's PAB that were analysed by WD-XRF. CA was performed using the centroid agglomerative method and the squared Eculidean distance, and it was based on the subcomposition Mg, Al, Si, K, Ca, Ti, Fe, V, Cr, Mn, Co, Ni, Zn, Rb, Sr, Y, Zr, Ba, La, Ce, Nd and Th. Correspondence with petrographic fabric groups (FG) is indicated for each sample and for the main clusters

mouth of the Guadalhorce river, whereas FG 2 was probably related to a source in the lower Guadalmedina basin (both rivers flow through the current city of Málaga). As for groups FG 4 and FG 5, the combined petrographic and elemental evidence pointed to a provenance in the area of Velez-Málaga, as discussed. Indeed, clay sample GS 18/14, collected from this area, clustered with FG 4–5 in CA (Fig. 10). Amphora reference samples from this area were not analysed chemically in this study, but comparison with published reference data from other authors strongly supported this hypothesis by showing similar bulk compositions and trends for specific elements (e.g. Al and Zn) to those found in FG 4–5 (Amadori and Fabbri 1998; Behrendt and Mielke 2011; Behrendt et al. 2012; Miguel 2014).

As concerns FG 6, comparison with existing compositional reference groups from Punic amphora production sites in western Sicily (Alaimo et al. 1997, 1998, 2002; Montana and Randazzo 2015, 2018) showed broad similarities which would support a provenance in this region as was already suggested by both thin section petrography and the typology of the amphorae. However, the available data has not permitted reliable attribution of FG 6 to the main production area of amphora type T-1451, located between Palermo and Solunto (Bechtold 2015). Four of the five samples assigned to FG 6—with the exception of PAB 18/154—were similar in major elemental composition to the reference groups established for these two sites (Alaimo et al. 2002; Montana and Randazzo 2018). However, with regard to trace elemental composition, the published reference data for Punic amphorae produced in the Classical period in Solunto/Palermo (Montana and Randazzo 2018: group SP-II) showed remarkable differences with the samples in FG 6, particularly much higher concentrations of Ni and Ba, and lower values for Zn, Ce and La, in the former. While it cannot be excluded, it seems unlikely that these significant compositional differences which appear in a number of elements are due to differences in analytical performance, instead they may be due to the use of different clay pastes—and possibly different source areas. For this reason, FG 6 cannot conclusively be attributed to the area of Palermo/Solunto at this point, even if the provenance of this group in the wider region of western Sicily is strongly supported by the obtained results.

Archaeological implications and conclusions

The scientific analysis of Punic amphorae from Corinth's PAB revealed the presence of well-defined compositional groups. The vast majority of the 178 amphora samples analysed in this study fell into one of the six groups defined on combined petrographic and chemical evidence; most samples were assigned to three of them (FG 1, FG 4–5 and FG 2), while only few samples fell into the other three groups (FG 3, FG 6 and FG 7).

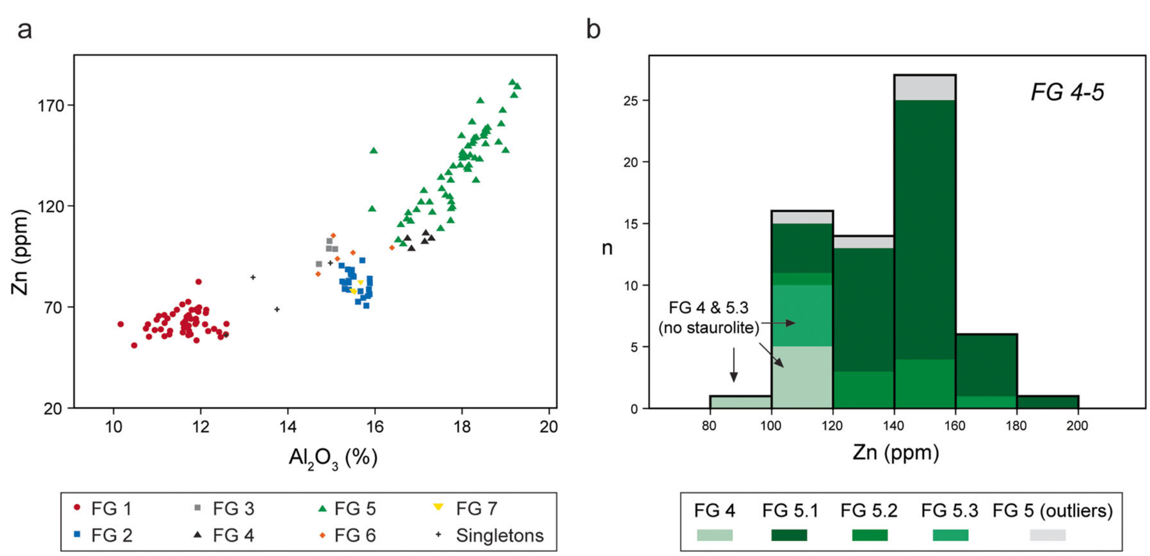

Fig. 8 **a** Binary variation diagram, using normalised data, of Al_2O_3 vs Zn for the amphorae analysed from Corinth's PAB; correspondence with petrographic fabric groups (FG) is indicated for each sample. **b** Histogram of Zn concentrations (from WD-XRF) for the amphorae included in compositional group FG 4–5; an indication of the petrographic fabrics, according to OM analysis, is given. A correlation is observed between lack of staurolite inclusions and lower Zn concentrations

Table 2 Mean normalised elemental composition (WD-XRF) of the Punic amphora groups identified in this study. Concentrations of major and minor oxides are in %; trace elements are in ppm. Relative standard deviation values for each element are given in parentheses

	FG 1		FG 2		FG 3		FG 4–5		FG 6	
	(*n* = 52)		(*n* = 23)		(*n* = 4)		(*n* = 64)		(*n* = 5)	
(%)										
Na_2O	0.89	(16)	0.65	(18)	0.85	(5)	0.89	(9)	0.92	(20)
MgO	2.17	(7)	2.59	(5)	2.94	(4)	2.71	(5)	2.03	(9)
Al_2O_3	11.65	(4)	15.56	(1)	14.92	(1)	17.83	(4)	15.35	(4)
SiO_2	63.90	(2)	59.85	(1)	62.77	(2)	60.10	(2)	63.83	(3)
P_2O_5	0.27	(23)	0.27	(33)	0.31	(12)	0.24	(32)	0.26	(17)
K_2O	2.70	(12)	3.16	(8)	2.60	(10)	2.85	(7)	2.15	(9)
CaO	13.06	(11)	10.98	(9)	8.39	(12)	7.11	(13)	8.14	(24)
TiO_2	0.66	(3)	0.77	(2)	0.80	(3)	0.86	(2)	0.83	(2)
Fe_2O_3	4.51	(5)	5.94	(2)	6.12	(2)	7.15	(6)	6.30	(3)
(ppm)										
V	81	(8)	115	(4)	119	(3)	129	(4)	119	(6)
Cr	83	(7)	103	(7)	202	(7)	112	(6)	102	(5)
Mn	359	(19)	589	(10)	1092	(2)	858	(17)	382	(8)
Co	22	(6)	28	(5)	34	(4)	31	(8)	26	(5)
Ni	37	(10)	56	(15)	126	(4)	56	(12)	44	(18)
Cu	54	(46)	54	(14)	55	(13)	57	(25)	43	(13)
Zn	63	(9)	82	(7)	98	(4)	137	(15)	97	(7)
Rb	94	(7)	123	(5)	91	(16)	120	(7)	86	(11)
Sr	351	(7)	340	(8)	248	(14)	251	(7)	281	(15)
Y	23	(5)	28	(4)	30	(7)	33	(8)	28	(1)
Zr	226	(14)	192	(3)	224	(9)	207	(4)	287	(4)
Ba	353	(10)	402	(20)	471	(2)	333	(9)	281	(12)
La	28	(14)	36	(9)	39	(7)	41	(7)	38	(6)
Ce	59	(10)	74	(6)	81	(4)	83	(5)	82	(4)
Nd	27	(9)	34	(10)	36	(6)	38	(7)	34	(4)
Pb	28	(78)	30	(30)	30	(7)	32	(26)	25	(22)
Th	9	(12)	12	(9)	11	(25)	13	(10)	11	(7)

Comparison between the macroscopic groups initially defined in the archaeological study of Corinth's PAB context and the compositional groups identified in this research showed a partial correspondence between them (Table 3). Compositional groups FG 1, FG 2 and FG 6 corresponded well with macro-groups 1, 2 and 6, respectively, and all the samples in macro-group 4 fell into the compositional group FG 4–5; however, amphorae in macro-group 3 were related to either FG 4–5 or FG 3 (and two singletons), while the small macro-group 5 was associated with a variety of fabrics (FG 7 and two singletons).

The most significant observation derived from this comparison is that the macro-group 1/FG 1, associated with a provenance in the Bay of Cádiz, was predominant in the Punic amphora assemblage from Corinth's PAB, representing about 67.5% of an estimated total of 369 amphorae in the archaeological context. The remaining western Punic amphorae, included in macro-groups 2 to 4/FG 2 to 5 (and singletons), correspond to about 28.2% of the Punic amphorae from the building. Most of these were related to macro-groups 3–4 (23.9%), equivalent to FG 4–5 (Velez-Málaga) and, in minor amount, FG 3 (Málaga), whereas macro-group 2/FG 2 (also with a highly probable provenance in Málaga) accounts for only 4.3% of the total assemblage. On the other hand, macro-groups 5 and 6, for which a central Mediterranean provenance was initially hypothesised, represent together about 4.3% of the Punic amphorae; the majority of these correspond to imports from western Sicily (macro-group 6/FG 6), whereas macro-group 5 comprised an indeterminate fabric (FG 7) and two singletons, including one probable Tunisian sample (Table 3).

Another interesting observation that can be made from the integration of macroscopic and chemical-petrographic analysis concerns the relation between the typological

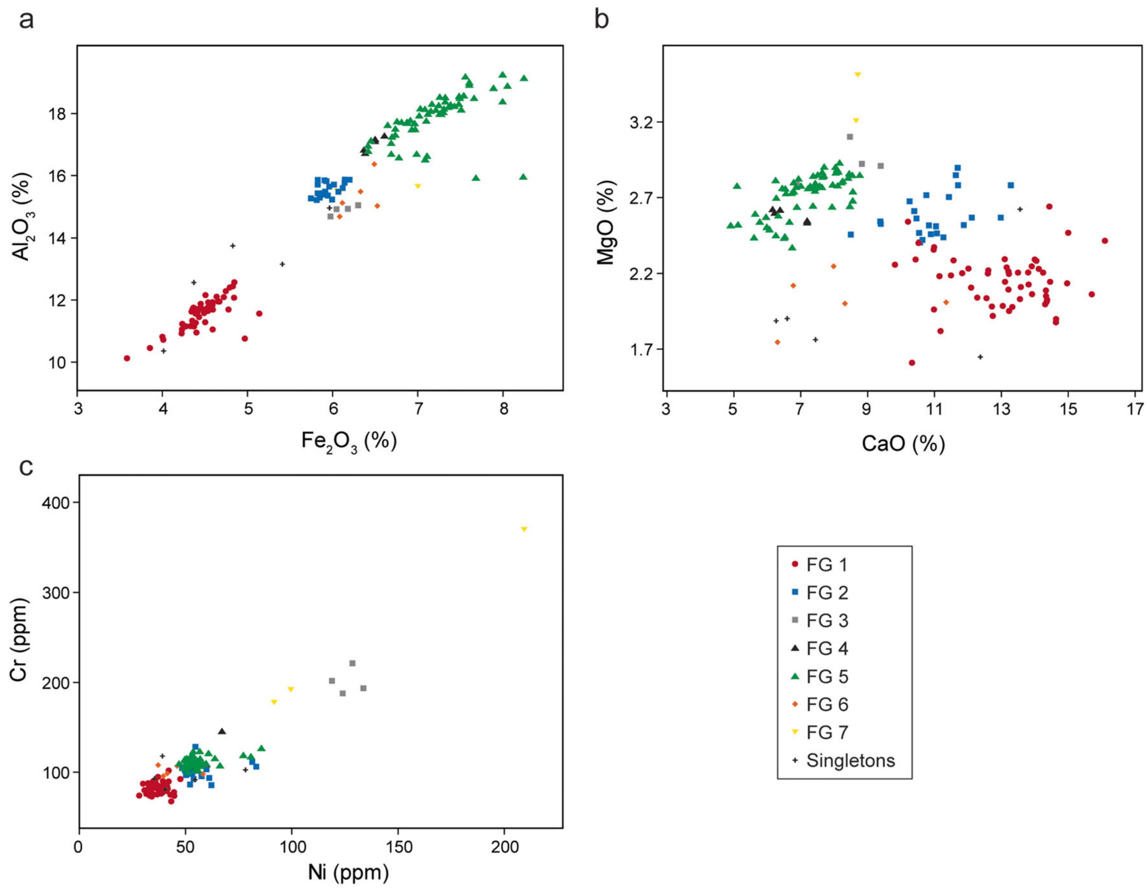

Fig. 9 Binary variation diagrams, using normalised data, of (**a**) Fe_2O_3 vs Al_2O_3, (**b**) CaO vs MgO; (**c**) Ni vs Cr, for the amphorae analysed from Corinth's PAB. Sample PAB 18/151, with very high MgO, was not considered in (**b**). Correspondence with petrographic fabric groups (FG) is indicated for each sample

characteristics of the amphorae and the compositional groups (Table 3). The large group FG 1 was associated with type T-11213 (based on typology by Ramon 1995), while FG 2 was related exclusively to type T-11216. For FG 3, no conclusions could be drawn since there was only one classifiable individual (as T-11213). Conversely, FG 4–5 was associated with more diversified types, including T-11213, T-11214 and T-11215. As expected, the western Sicilian group FG 6 comprised amphorae of a typical central Mediterranean Punic type, T-1451, whose main production area is located between Palermo and Solunto (Bechtold 2015). Therefore, the results of the analysis indicated that all the Punic amphorae of types T-11214 and T-11215 found in Corinth's PAB were produced in the area of Velez-Málaga; those of type T-11216 could be associated with a highly probable provenance in Málaga, while most of the amphorae of type T-11213 were imported from the area of Cádiz, although other amphorae of the same type came from the Andalusian coast between Málaga and Velez-Málaga (Fig. 11). This observation has significant implications, since it sheds new light into the production areas of each of these western Punic types and provides scientific evidence to support Ramon's (1995) suggestion that all these related amphora types would be various versions of the same model from different workshops. In any case, production of these amphorae was certainly not limited to the abovementioned sites, since it is highly probable that many other Punic sites on both sides of the Straits of Gibraltar manufactured similar forms of amphorae, especially the main type T-11213 (Ramon 1995; Sáez 2011). According to the results of this study, however, the Bay of Cádiz and—to a lesser extent—the coast of Málaga province were the main suppliers of salted fish packaged in amphorae and shipped to Corinth throughout the fifth century BC. This is also consistent with the existing direct evidence for amphora workshops, since the majority of the kiln sites documented so far for this period are located in these areas, as discussed in previous sections.

In summary, the results of this research enable a more accurate view of the maritime trade between Corinth and the Punic western Mediterranean in the fifth century BC, by modifying the initial hypothesis that all the Punic amphorae found in Corinth's PAB would have been produced in one single workshop or area (Maniatis et al. 1984), associated with Kouass in Morocco (Zimmerman Munn 2003). This previous

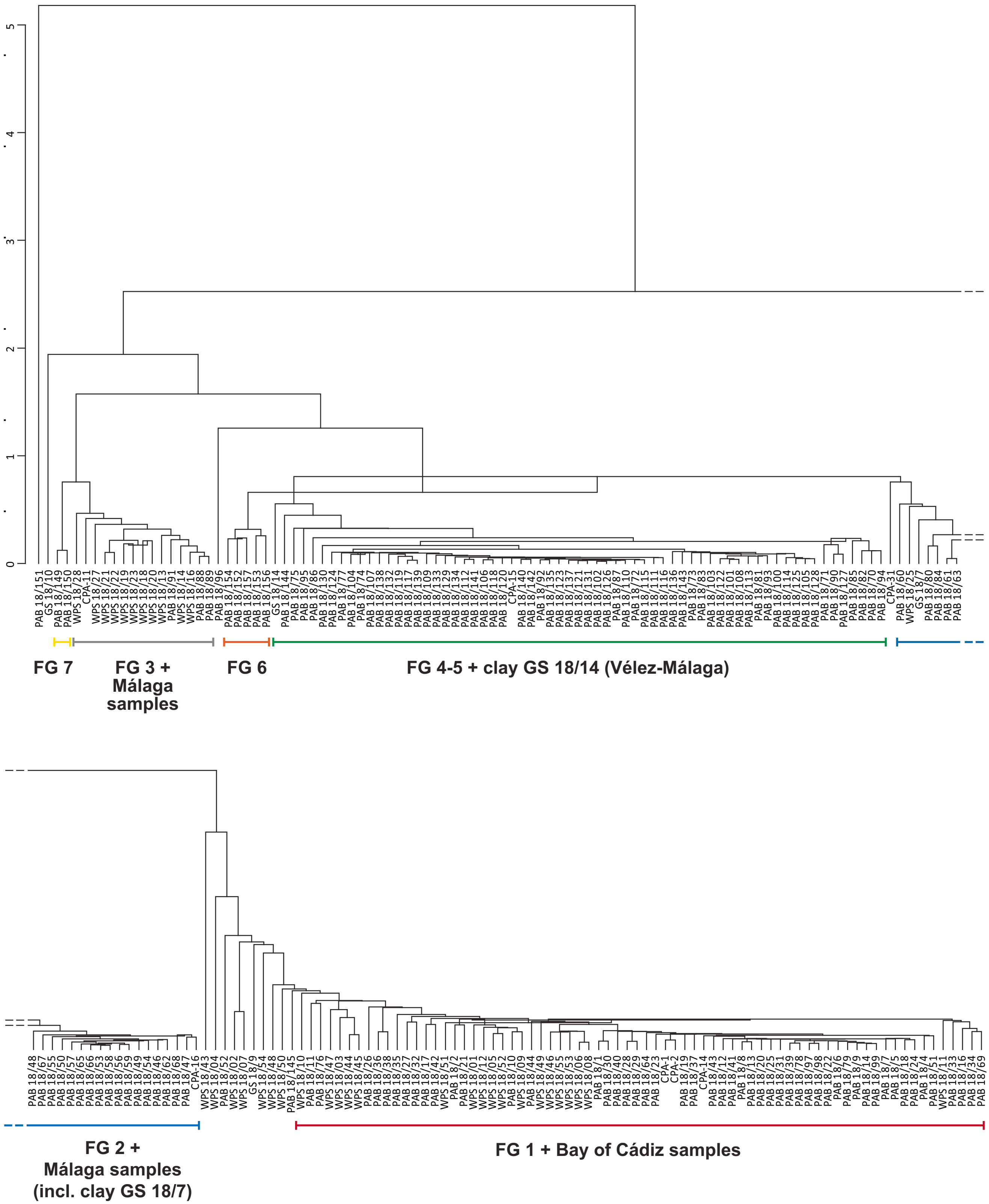

Fig. 10 Dendrogram from cluster analysis comparing the elemental composition (WD-XRF) of amphorae from Corinth's PAB and reference samples from western Punic sites, including amphorae from kiln sites as well as experimental briquettes of geological clays collected from areas near the production sites. CA was performed on the simple-log transformed subcomposition Mg, Al, Si, K, Ca, Ti, Fe, V, Cr, Ni, Zn, Rb, Sr, Y, Zr, Ba, La, Ce, Nd and Th, using the centroid agglomerative method and the squared Euclidean distance

model did not deny the central role of Cádiz/*Gadir* in the salted fish business, but suggested that the amphorae were manufactured in Kouass and then transported empty to Cádiz, on the other side of the Straits of Gibraltar, where they would be filled with fish and then be exported (see Zimmerman Munn 2003). The scientific analysis of amphorae in the present study, however, showed that the majority—but not all—of the transport amphorae were actually produced in the Bay of Cádiz, particularly in the kiln sites of San Fernando, a few kilometres south of Cádiz. This evidence reinforces the hypothesis that Punic *Gadir* was the main hub controlling the trade of salted fish from the Punic West to the Greek world and that the site also played a key role in the amphora production and export. This is consistent with other types of evidence which attest the predominant position of *Gadir* in this trade during the fifth century BC, including the excavation of several fish-processing facilities (Muñoz et al. 1988; Sáez 2014a, 2014b) as well as literary references to the dry salted fish from *Gadir* (*tarichos Gadeirikon*) in Classical Greek sources (López Castro 1997; Zimmerman Munn 2003; García Vargas and Ferrer Albelda 2006, 2012).

Nevertheless, even if about two-thirds of the Punic amphorae in Corinth's PAB were products from *Gadir*, the analytical results verified that a good part of the amphorae arriving at this building was manufactured in other Punic areas and sites, especially in the Mediterranean coast of Andalusia, in particular the area of Velez-Málaga and, to a lesser extent, Málaga. These non-Gadiritan products account for about one-third or less of Punic amphorae found at Corinth's PAB, and suggest that, despite the dominance of *Gadir*, other Punic port cities (e.g. *Malaka*) were also attempting to take part in the salted fish trade with Classical Corinth. As concerns the coast of northern Morocco, one should not discount the possibility that some of the scarcely represented fabrics in this study with unknown provenance (particularly a few singletons) could come from this area, but no clear evidence of amphora production has been found so far and this area did not seem to play a significant role in the production of the amphorae exported to Corinth.

The presence of a few central Mediterranean amphorae in Corinth's PAB, mostly from western Sicily, is probably a reflection of the trade routes between the Straits of Gibraltar and Greece, which must have included a port of call at one or more of the Punic sites on this island. Despite the close commercial links that existed between Sicily and Corinth from the Archaic to the Classical period (Zimmerman Munn 1983), the predominance of western Punic amphorae in PAB's assemblage may suggest a more direct relation between the Punic West—particularly *Gadir*—and Corinth as regards the trade of salted fish (Zimmerman Munn 2003). Nevertheless, it cannot be excluded that both western Punic and Sicilian Punic amphorae were loaded, all together, into composite cargoes at a Greek harbour in Sicily or Magna Graecia, and then transported eastwards, as has been suggested for example for Himera (Bechtold and Vassallo 2018). Like western Punic amphorae (T-11213 and related types), Sicilian Punic amphorae in Corinth's PAB, identified as type T-1451, may have been used for the transport of salted fish, although no direct evidence for their contents has yet been found (Bechtold 2015).

It is also important to note that the few Punic amphorae analysed from the first phase reported for the PAB (c. 470–460 BC) showed no significant differences in fabrics or provenance with the amphorae from the main phase (c. 460–430s BC). The former were assigned to FG 1 (PAB 18/43, PAB 18/44), FG 3 (CPA-8), FG 5 (CPA-30), FG 6 (PAB 18/157), FG 7 (PAB 18/149) and a singleton (CPA-31), thus coming from production sites in the Punic western Mediterranean—including samples from Cádiz, Málaga and Vélez-Málaga—and, in one case, western Sicily. For this first phase, the results suggest, therefore, the same trends in terms of amphora provenance as those found for the second phase, which comprises the bulk of the assemblage. From these observations, it seems plausible that the routes involved in the trade of salted fish were the

Table 3 Correspondence between compositional groups (based on thin section petrography and WD-XRF analysis) and macroscopic groups/typology for the Punic amphorae from Corinth's PAB, including the provenance proposed for each group after the analysis

Compositional (chemical-petrographic) group	Macroscopic group	Amphora type/s	Proposed provenance after analysis
FG 1	1	T-11213	Bay of Cádiz: San Fernando
FG 2	2	T-11216	Málaga most probably
FG 3	3	T-11213	Málaga
FG 4–5	3–4	T-11213, T-11214, T-11215	Vélez-Málaga
FG 6	6	T-1451	Western Sicily
FG 7	5	Indeterminate	Indeterminate
Singleton CPA-31	3?	T-11213	Mediterranean coast of Andalusia or N Morocco
Singleton PAB 18/96	3	T-11213	Straits of Gibraltar region
Singleton PAB 18/145	5	Indeterminate	Straits of Gibraltar region
Singleton PAB 18/148	5	Indeterminate	Tunisia most probably

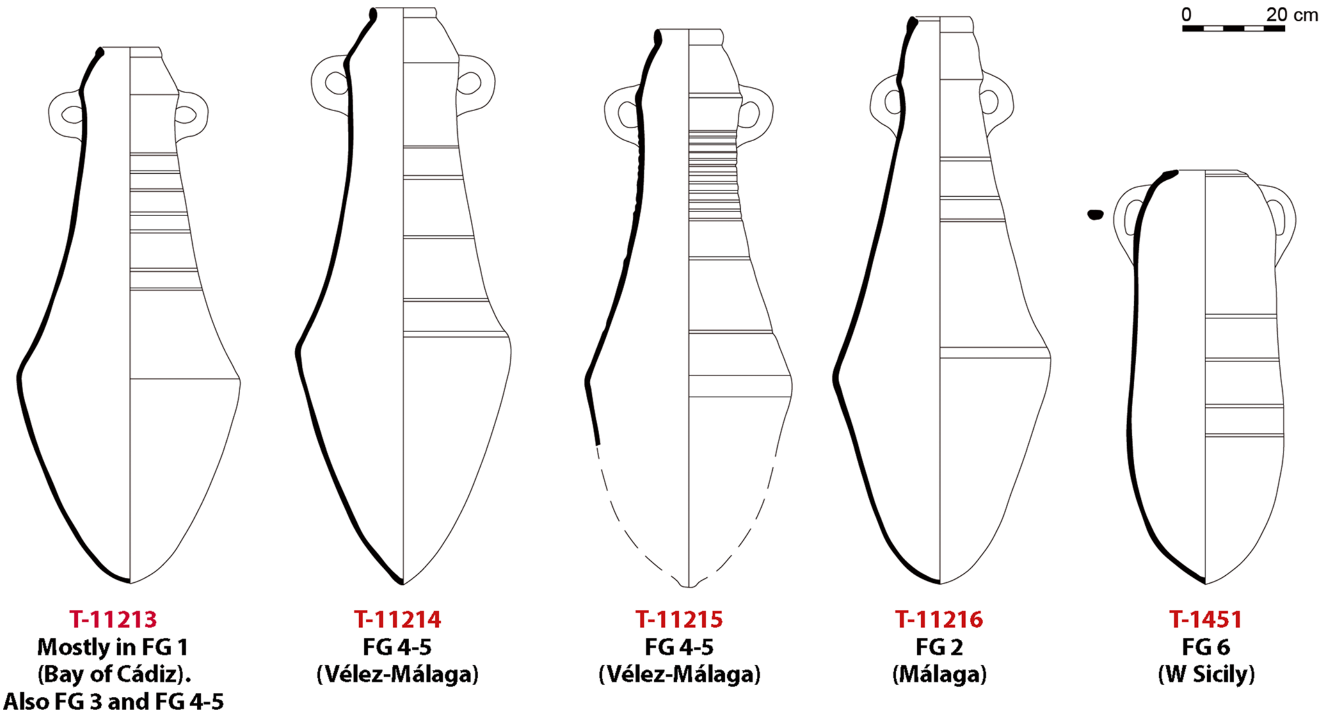

Fig. 11 Summary of the relation between amphora typology and compositional groups, based on the integrated macroscopic and chemical-petrographic analysis of the Punic amphorae from Corinth's PAB (illustrations based on Ramon 1995)

same during the entire lifespan of the PAB. In summary, scientific analysis has yielded new evidence for the provenance of the Punic amphorae found in Corinth's PAB and has shed new light on the commercial ties between Classical Corinth and the Punic West, particularly concerning the salted fish trade. The assemblage of Punic amphorae from the PAB is to this day the most complete of its type in the eastern Mediterranean; in the case of Greece—apart from Corinth—so far, only very few transport vessels of the same types have been found in Olympia and Athens (Ramon 1995; López Castro 1997; Lawall 2006). The assemblage of the PAB must therefore be considered a highly significant context for understanding the development of long-distance trade connections between the eastern and the western Mediterranean in the Classical period (Williams II 1995; Zimmerman Munn 2003). The results of the current study not only contribute new evidence for these relations, but, in addition, the data obtained from the scientific analysis of Punic amphorae in Corinth are also important for western Punic archaeology, since they provide relevant information on the production areas of amphorae for maritime trade of fish by-products, which was a key economic activity in the Punic West and a flourishing business for the western elites during the fifth century BC (Sáez 2018).

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