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The transport amphorae of Gela: a multidisciplinary study on provenance and technological aspects

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ABSTRACT

Mineralogical, petrographic and chemical analyses were performed on thirty-eight samples of transport amphorae found at Gela, an important Greek colony on the southern coast of Sicily. Based on macroscopic observation, the amphorae, which are datable between the second half of the 6th and the end of the 5th century B.C., were supposed to be local because of similarities to the common wares from the same site. Therefore, in order to verify the provenance of the samples, they were compared to a reference group of locally made ceramics (kiln spacers, kiln wasters, common wares, ancient mud bricks, modern bricks) and twelve samples of local clayey sediments. The results of the analyses have allowed the assignment of all the amphorae to Gela, with the exclusion of five samples, maybe produced in neighbouring sites, and to determine for the first time the archaeometric characteristics of the Geloan medium-coarse ceramics. The aim of our research has also been to investigate some technological aspects of this production, as the location of the clay sources, the methods of clay preparation, and, in particular, the causes of the typical whitening effect on the surface of the vessels.

1. Introduction

Gela, founded in the early 7th century B.C. by Rhodian and Cretan colonists on the southern coast of Sicily, was an important and rich *polis*, thanks to its wide agricultural hinterland (the well known "*campi geloi*", whose fertility is mentioned in the literary sources) and its optimal geographical location, both in the middle of a wide gulf and close to the mouth of a river, formerly navigable, connecting the coast to the inland.

The archaeological excavations, conducted throughout the 20th century, discovered numerous ceramic wares, many imported - evidence of lively economic and cultural contacts - and a larger number ascribed to the local craftsmen. Remains of ancient workshops have also been discovered in peripheral areas of the town: two archaic kilns (7th–6th century B.C.) excavated in via Dalmazia (Adamesteanu, 1956) and in via Bonanno (De Miro and Fiorentini, 1983), producing fine wares; a kiln dating back to the classical age (second half of the 5th century) near the old station (called *Stazione Vecchia*), probably producing terracotta figurines (Spagnolo, 1991); and a hellenistic kiln dump (second half of the 4th – early 3th century B.C.), close to the S. Giacomo's church (Adamesteanu, 1954), producing fine and red-figure wares.

Therefore, in the archaeological studies so far carried out, scholars have repeatedly stated the vitality of Gela in the clay manufacture: from the production of vessels (Orlandini, 1957, 1960) to the creation and production of several coroplastic types (Orlandini, 1956; Sguaitamatti, 1984; Spagnolo, 2000; Uhlenbrock, 1988) and architectural terracottas (Bernabò Brea and Carta, 1949–51). The identification of local products, however, has always been founded on traditional methods, namely observation with the naked eye: only in a few cases scholars have referred to some macroscopic peculiar features of the clay fabric, such as colour or presence of inclusions (Adamesteanu, 1956; Orlandini, 1954; Uhlenbrock, 1988).

Nowadays, the definition of the characteristics of ceramic products by scientific methods is absolutely necessary in order to recognize and to localize each production site as well as to obtain a reliable historical reconstruction of work methods and technological knowledge of ancient communities. Furthermore, the archaeometric identification of the production sites of transport amphorae is particularly important, because the jars are specifically connected to land resources and represent the main type-fossil of the ancient trade of commodities.

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So, the aim of this study is twofold, concerning aspects of both provenance and technology: firstly, to verify the attribution to local workshops of a large group of transport amphorae found in Gela, datable from the second half of the 6th to the end of the 5th century B.C.; and furthermore to determine, through analyses on these jars, the main technological characteristics of the Geloan medium-coarse ceramics.

After a preliminary examination, the group of jars were generically ascribed to the "family" of the western-Greek amphorae. Nevertheless, the macroscopic observation of the clay paste, quite similar to the supposed local medium-coarse ware, soon gave us grounds to believe it might be a specific Geloan production, so far unknown (Spagnolo, 1995).

The amphorae belong to the main archaic and classical western-Greek types: the so-called "Ionian-Massalian", "pseudo-Chian" and "Corinthian-Corcyrean" types. The problems related to these ceramic shapes came up recently and are still being debated (Gassner, 2003; Santos Retolaza, 2008; Sourisseau, 2000; Spagnolo, 2002). The western-Greek colonies produced very similar jars, evidently descending from common "models", that is why currently the different production centres cannot be easily distinguished at first sight. Recently, some provenance studies on this subject have been conducted: among these, the investigations of amphorae from Marseilles (Sourisseau, 1998), Locri (Barra Bagnasco et al., 2001), Velia (Gassner, 2003; Sauer and Gassner, 2008) and, regarding Sicily, of amphorae from the Strait area and the southern coast of the island (Barone, 2002; Barone et al., 2002, 2004, 2009, 2011a).

2. Geological framework

From the geological point of view Gela is located in the foredeep of the Sicilian segment of the Appenninic – Maghrebian orogen. This basin has been developed since the Late Miocene and was filled by quaternary clayey sediments. The structural arrangement of the area is made more complex by the wedge of the frontal thrusts of the Gela nappe, in which numerous formations were involved in the late orogenetic phases (Grasso, 2001). As result of this geological structure, different sedimentary terrains crop out in the Gela district. The sequence starts with the Lower Miocenic variegated clays, unconformabled overlaid by the Tortonian – Langhian clays and the sands of the Terravecchia and Licata Formations. The Late Miocene is characterised by the Messinian evaporitic sequence (Ogniben, 1969) (diatomites and bituminous briny clays, bituminous limestones, gypsum, gypsiferous marls and gypsarenites and salts, from the bottom to the top). The end of the evaporitic crisis is marked by Pliocene white marls of the Trubi Formation. Both the Messinian evaporites and the Trubi Formation are repeatedly interrupted by interposed gravity mass flows (Argille Brecciate). During the Medium-Late Pliocene and Pleistocene the sedimentation is dominated by calcarenites, sands and clay testifying to some transgressive–regressive circles. Finally, the younger sedimentation is represented by Quaternary marine and fluvial alluvium.

In particular, in the area of the ancient *polis*, on which the modern town has been developed (Fig. 1), the terrains are mainly formed by sands and clays belonging to the Mt. St. Giorgio marly clays Formation and to the Caltagirone Sands Formation, both belonging to Selinuntian (Lower Pleistocene) (Di Grande and Giandinoto, 2002).

3. Investigated materials

The thirty-eight amphora samples selected for this study (Table 1) were found in *contrada Molino a Vento* (the acropolis of the Greek city) and in different areas on the northern side of the Gela hill.

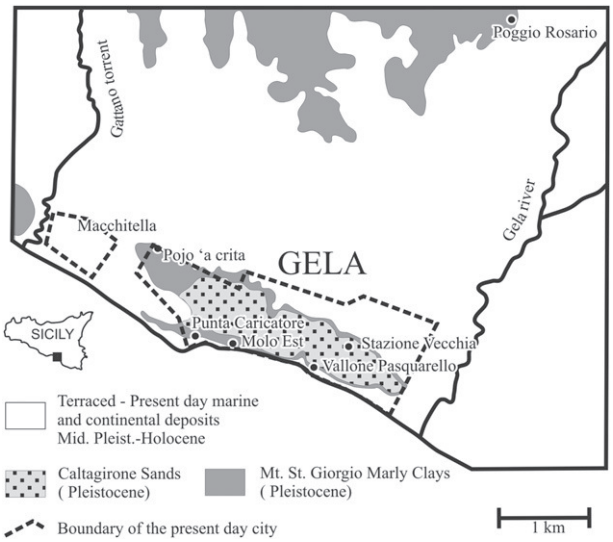

Fig. 1. Geological sketch map of the Gela area with the sampling location of the clayey sediments.

As previously mentioned, they belong to the main archaic and classical western-Greek types. The so-called "Ionian-Massalian" type, here conventionally named *I Form*, datable from the second half of the 6th to the early 5th century B.C., is characterized by a thick, almond-shaped rim (obtained by folding up the wall of the neck such as to produce an empty space inside) with a ridge at the base, a short cylindrical or slightly swollen neck, a turnip-shaped body and a small, truncated cone-shaped toe (Fig. 2a–b). Probably developed from the *I Form* during the first half of the 5th century B.C., the so-called "pseudo-Chian" type (or MGS II type in Van der Mersch [1994]), here conventionally named *II Form*, has a high, echinus-shaped rim, underlined by a ridge, a tall swollen neck, a tapering belly and a hemispherical knob toe (Fig. 2c). Finally, the so-called "Corinthian-Corcyrean" type (or MGS I type in Van der Mersch [1994]), here conventionally named *III Form*, certainly modelled after the Corinthian Type B (Koehler, 1979, 1981) approximately in the second quarter of the 5th century B.C., is documented by some fragments of characteristic flaring rims and conical cap toes (Fig. 2d,e).

Our jars are very similar to many amphorae from various sites in Sicily and Magna Graecia; nevertheless, they show some peculiar characteristics, such as the wider hollow inside the thickness of the *I Form* rims. Worth of note is also the presence of differently sized jars, corresponding to different capacities.

In regard to the clay paste, with the naked eye the vessels look homogeneous: they mostly show a hard, rather depurated and porous paste, pink (7.5 YR 7/4) to red (2.5 YR 5/8), with numerous white fine inclusions and voids. However, one of the most peculiar features is the light-coloured surface (usually 10 YR 8/3 or 2.5Y 8/3), which is common also to tiles, wares and terracotta figurines from Gela. As for the figurines, Orlandini (1954) first pointed out this peculiarity and explained it as a slip, observing its frequency even in modern local clay products. Later, Uhlenbrock (1988) noted that the chromatic effect does not concern only the surface of the artefacts but a more or less thick superficial layer, both inner and outer, and rightly identified it as a whitening of the ceramic body. More recently, this feature has been also observed in the medieval glazed pottery from Gela and Agrigento (Cuomo Di Caprio, 1991, 2007; Cuomo Di Caprio and Fiorilla, 1992) and in late Roman pottery from Northern Africa (Bonifay, 2004).

In the preliminary macroscopic classification of the pastes of our amphorae, we have noticed some differences connected with the

Table 1
List of the examined samples (amphorae, reference materials, clayey sediments, laboratory tests).

	Sample	Form	Provenance	Colour	Analyses
Amphorae	Gela 23	I	Via Scerra	5 YR 6/6; surf. 10 YR 8/3	OM, XRD, XRF
	Gela 24	I	Molino a Vento	5 YR 6/6; surf. 10 YR 8/3	OM, XRD, XRF
	Gela 25	I	Molino a Vento	5 YR 7/6; surf. 2.5Y 8/3	OM, XRF
	Gela 26	I	Molino a Vento	5 YR 7/6; surf.-core 2.5Y 8/3	OM, XRD, XRF
	Gela 27	II	Molino a Vento	2.5Y 7/3; sup. 5Y 7/3	OM, XRD
	Gela 28	II	Molino a Vento	7.5 YR 7/4; surf. 10 YR 8/3	XRF
	Gela 29	I	Molino a Vento	2.5 YR 6/8; surf. 2.5Y 8/3	XRF
	Gela 30	I	Molino a Vento	2.5 YR 6/8; surf. 2.5Y 8/3	OM, XRD, XRF
	Gela 31	I	Molino a Vento	2.5 YR 6/8; surf. 2.5Y 8/3	XRF
	Gela 32	I	Molino a Vento	2.5 YR 6/8; surf. 10 YR 8/3	XRF
	Gela 33	I	Molino a Vento	2.5YR8/2; surf.-core 5YR7/6	XRF
	Gela 34	II	Molino a Vento	5 YR 6/6; surf. 2.5Y 8/3	OM, XRD, XRF
	Gela 35	II	Molino a Vento	2.5 YR 6/8; surf. 2.5Y 8/3	OM, XRF
	Gela 36	II	Molino a Vento	2.5 YR 5/6; surf. 10 YR 8/3	OM, XRD, XRF
	Gela 37	I	Molino a Vento	5 YR 6/4; surf. 10 YR 8/2	OM, XRD, XRF
	Gela 38	I	Molino a Vento	10 YR 7/4; surf. 2.5Y 8/3	OM, XRD, XRF
	Gela 39	I	Molino a Vento	2.5 YR 6/8; surf. 2.5Y 8/3	OM, XRD, XRF
	Gela 40	I	Molino a Vento	2.5 YR 5/8; surf. 7.5 YR 7/4	OM, XRD, XRF
	Gela 41	I	Molino a Vento	2.5 YR 6/8; surf. 7.5 YR 7/4	OM, XRD, XRF
	Gela 42	II	Molino a Vento	5 YR 5/6; surf. 2.5Y 8/2	OM, XRD
	Gela 43	II	Molino a Vento	2.5 YR 6/8	XRF
	Gela 44	I	Molino a Vento	2.5 YR 6/8; surf. 10 YR 8/3	OM, XRF
	Gela 45	III	Molino a Vento	2.5 YR 5/8; surf. 10 YR 8/2	OM, XRD
	Gela 46	III	Molino a Vento	2.5 YR 5/8; surf. 10 YR 8/2	OM, XRD
	Gela 75	I	Molino a Vento	5 YR 7/6; surf. 2.5Y 8/3	OM, XRD, XRF
	Gela 76	I	Via Tucidide	2.5 YR 6/8; surf. 2.5Y 8/3	OM, XRD, XRF
	Gela 77	II	Molino a Vento	2.5 YR 5/8; surf. 2.5Y 8/3	OM, XRD, XRF
	Gela 78	I	Molino a Vento	2.5 YR 5/6; surf. 5 YR 7/4	OM, XRD, XRF
	Gela 98	I	Molino a Vento	7.5 YR 6/3; surf. 2.5Y 8/2	XRF
	Gela 99	II	Molino a Vento	10 YR 8/4; surf. 2.5Y 8/3	OM, XRF
	Gela 100	II	Molino a Vento	7.5 YR 7/6; surface 5Y 8/2	XRF
	Gela 101	II	Molino a Vento	7.5 YR 7/6; surf.-core 2.5Y 8/2	OM, XRF
	Gela 102	II	Molino a Vento	2.5 YR 6/6; surf. 2.5Y 8/2	OM, XRF
	Gela 103	II	Molino a Vento	5 YR 6/6; surf. 2.5Y 8/3	XRF
	Gela 104	II	Molino a Vento	2.5 YR 5/8; surf. 10 YR 8/3	OM, XRF
	Gela 105	III	Molino a Vento	2.5 YR 5/6; surf. 10 YR 8/3	OM, XRF
	Gela 106	III	Molino a Vento	5 YR 6/6; surf. 10 YR 8/3	XRF
	Gela 107	III	Molino a Vento	2.5 YR 5/6; surf. 2.5Y 8/2	XRF
Local ceramics (reference materials)	Gela 108	kiln spacer	Molino a Vento	5 YR 5/4; surf. 10 YR 8/3	OM, XRD, XRF
	Gela 109	kiln spacer	S. Giacomo	5Y 7/3	OM, XRD, XRF
	Gela 110	kiln spacer	Stazione Vecchia	5 YR 7/6; surf. 2.5 YR 8/3	OM, XRD, XRF
	Gela 111	basin	Stazione Vecchia	2.5 YR 5/8; surf. 10 YR 8/2	OM, XRD, XRF
	Gela 112	basin	Stazione Vecchia	10 YR 7/4; surf. 2.5Y 8/3	OM, XRD, XRF
	Gela 113	loom weight	Stazione Vecchia	2.5 YR 5/8; surf. 10 YR 8/3	OM, XRD, XRF
	Gela 114	kiln waster	Stazione Vecchia	5Y 5/2	OM, XRD, XRF
Modern bricks (reference materials)	GE1M			5 YR 7/6; surf. 2.5Y 8/3	OM, XRD, XRF
	GE2M			5 YR 7/6; surf. 2.5Y 8/3	OM, XRD, XRF
	GE3M			5 YR 7/6; surf. 2.5Y 8/3	OM, XRD, XRF
	GE4M			5 YR 7/6; surf. 2.5Y 8/3	OM, XRD, XRF
	GE5M			5 YR 6/6	OM, XRD, XRF
	GE6M			2.5Y 8/4	OM, XRD, XRF
Mud bricks (reference materials)	GBL5		Bosco Littorio		XRD, XRF
	GBL6		Bosco Littorio		XRD, XRF
	GBL7		Bosco Littorio		XRD, XRF
	GBL8		Bosco Littorio		XRD, XRF
Clayey sediments	GE3A		Porto Rifugio, near Molo Est		XRD, XRF
	GE4A		Poggio Rosario		XRD, XRF
	GE5A		Punta Caricatore		XRD, XRF
	GE6A		Pojo 'a Crita		XRD, XRF
	GE7A		Poggio Rosario		XRD, XRF
	GE8A		Stazione Vecchia		XRD, XRF
	GE9A		Pojo 'a Crita		XRD, XRF
	GE10A		Pojo 'a Crita		XRF, granulometry
	GE11A		Pojo 'a Crita		XRF, granulometry
	GE12A		Vallone Pasqualello		XRF, granulometry
	GE14A		Pojo 'a Crita		XRF
	GE15A		Pojo 'a Crita		XRF
Test tiles	GE11A-T		Pojo 'a Crita		OM
	GE12A-T		Vallone Pasqualello		OM
	GE11A-S		Pojo 'a Crita + sandy sediments		OM
	GE12A-S		Vallone Pasqualello + sandy sediments		OM
Clayey sediments fired at different temperatures (550°, 750° and 900°)	GE7A-T		Poggio Rosario		XRD
	GE9A-T		Pojo 'a Crita		XRD

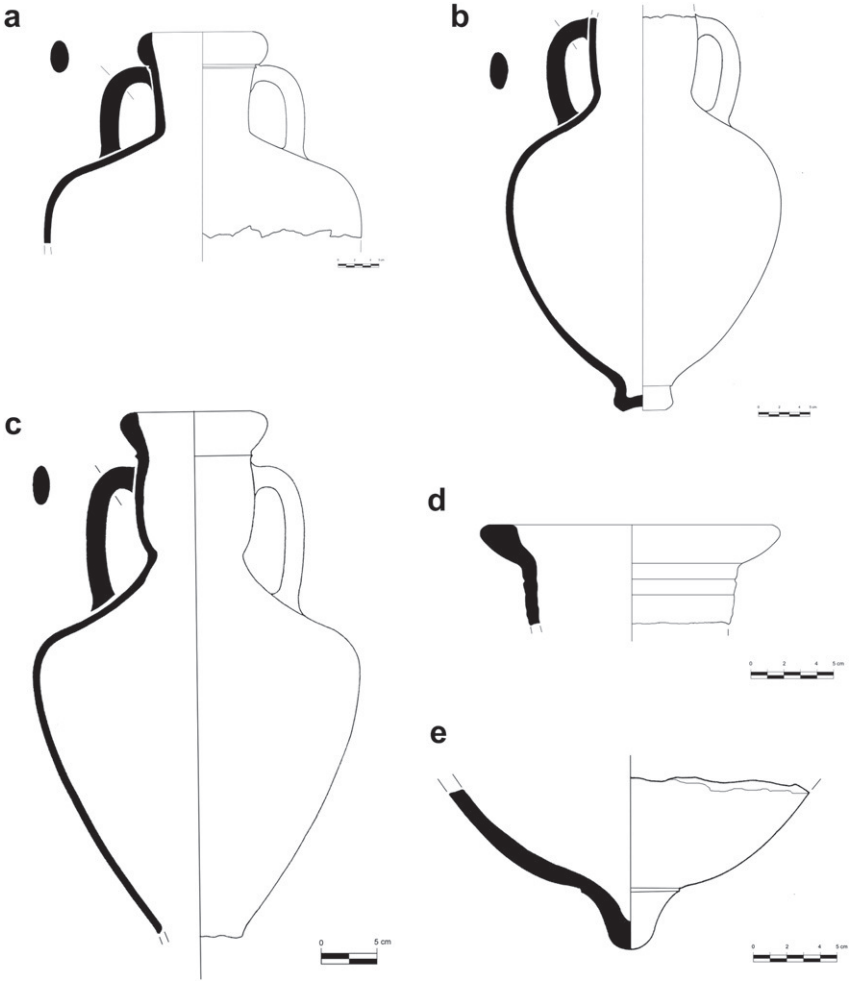

Fig. 2. a) *I Form* amphora (Gela 24); b) *I Form* amphora (Gela 37); c) *II Form* amphora (Gela 104); d-e) *III Form* amphorae fragments.

whitening effect: the more porous pastes usually have a thicker whitened superficial layer and a light pink core (Fig. 3A); on the contrary, the more compact pastes have a thin whitened superficial layer and a red core (Fig. 3B). In a few cases, the more porous pastes even have a whitened core, resembling a sandwich. Finally, some amphorae have not whitening effect (Fig. 3C).

In order to verify the attribution of our amphorae to the local production, we have compared them with a control group of certain local provenance (Gela 108-114): two kiln spacers, a kiln waster, two common ware fragments and a loom weight from the ancient craftsmen's quarters (near the *Stazione Vecchia* and the S. Giacomo's church), and a kiln spacer from the acropolis.

Furthermore, we have examined six samples of modern bricks (GE1M - GE6M), produced at the present time from local raw clays (clay pits in *contrada Spinasanta-Priolo*, 8 km to the east of Gela), and four samples of mud bricks (GBL5-8) from archaic buildings discovered in 1985 at Bosco Littorio (at the foot of the acropolis).

Finally, twelve samples of clayey sediments have been taken in different places of the town area (Table 1, Fig. 1), which is quite rich of outcropping clays. With the purpose of identifying the ancient clay sources, first of all we have chosen the places next to the ancient craftsmen's quarters and then the more recently employed supplies: the *Vallone Pasqualello* (GE12A), contiguous to Via Dalmazia (the above-mentioned archaic kiln site); the area of the *Stazione Vecchia* (GE8A); the coast near *Punta Caricatore - Porto Rifugio* (GE3A, GE5A) and the *Pojo 'a Crita*, (i.e. *Clay Knoll*) (GE6A, GE9A, GE10A, GE11A, GE14A, GE15A), both until recently used as clay pits. Only the GE4A and GE7A samples have been taken from a small hill at 4 km to the north of the modern town (*Poggio Rosario*).

In order to understand the technological process of the amphorae production, some laboratory tests of ceramic pastes were also made. In particular, a likely use of sandy temper in the manufacture was investigated by making four test tiles: two tests (GE11A-T, GE12A-T) formed from only clayey sediments (GE11A and GE12A, respectively); the others (GE11A-S and GE12A-S) mixed from the same clays with the addition of local sandy sediments. Furthermore, the firing process was tested by means of fired at different temperatures (i.e. 550°, 750° and 900 °C) two laboratory tests (GE7A-T and GE9A-T) made from the GE7A and the GE9A clayey sediments.

4. Methods of analysis

Mineralogical, petrographic, and geochemical analyses were performed by means of X-ray diffraction (XRD), optical microscopy (OM), and x-ray fluorescence (XRF), respectively. In the case of very small samples, we chose the methods of analysis on the basis of their typology and dimensions (Table 1).

The samples were analysed in the laboratory of the Department of Geological Sciences at the University of Catania. X-ray diffraction (XRD) patterns were obtained using a SIEMENS D5000, with Cu-kα radiation and Ni-filter. Randomly oriented powders were scanned from 2° to 45° 2θ, with a 0.02° 2θ step size and a count time of 2s

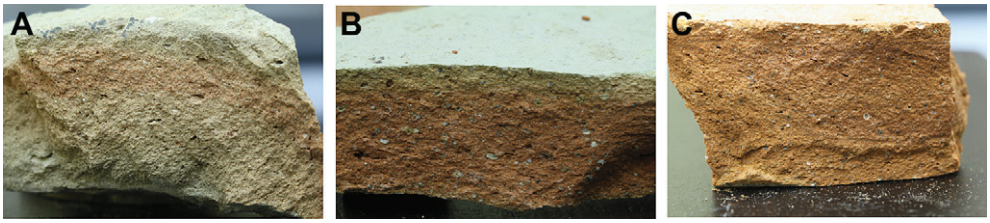

Fig. 3. Macro photograph of some representative samples showing the colour variation along the section: A) Gela 103 sample, with a thick whitened layer and a light pink core; B) Gela 76 sample, with a thin whitened superficial layer and a red core; C) Gela 40 sample, without whitening.

per step. The tube current and the voltage were 30 mA and 40 kV, respectively. Chemical analyses of major and trace elements were performed by X-ray fluorescence (XRF) spectrometry (PHILIPS PW 2404/00) on powder-pressed pellets; total loss on ignition (LOI) was gravimetrically estimated after overnight heating at 950 °C. A quantitative analysis was carried out using a calibration line based on 45 international rocks standards. The limits of detection (LOD) were: SiO_2 = 1 wt%, TiO_2 = 0.01 wt%, Al_2O_3 = 0.1 wt%, Fe_2O_3 = 0.05 wt%, MnO = 0.01 wt%, MgO = 0.02 wt%, CaO = 0.05 wt %, Na_2O = 0.01 wt%, K_2O = 0.05 wt%, P_2O_5 = 0.01 wt%, V = 10 ppm, Cr = 5 ppm, Co = 2 ppm, Ni = 5 ppm, Zn = 15 ppm, Rb = 5 ppm, Sr = 10 ppm, *Y* = 3 pm, Zr = 20 ppm, Nb = 2 ppm, Ba = 30 ppm, La = 5 ppm, Ce = 10 ppm, Th = 3 ppm. The precision was monitored by routinely running a well-investigated in-house standard (obsidian). The average relative standard deviations (RSD) were less than 5%. Finally, the accuracy was evaluated using an international standard that is compositionally similar to the analysed samples. The accuracy was good for major elements (<3%), except MnO, and for trace elements (≤5%). The petrographic analyses were performed following the scheme proposed by Whitbread (1995), in which a detailed characterisation of microstructure, groundmass and inclusions has been reported.

5. Results

5.1. Petrographic analyses

All the analysed amphorae show similar petrographic features and can be attributed to the same fabric (*sensu* Whitbread [1995]) with dominant quartz and common feldspars. A complete description of this fabric is reported in Appendix A. The ceramics are characterized by the presence of inclusions essentially consisting of very fine sand (0.06–0.125 mm). The spatial distribution of inclusions is quite uniform with good sorting and a packing ranging between 5% and 20%. The inclusions are represented by dominant polycrystalline and monocrystalline quartz, common feldspars (plagioclases and K-feldspars) and rare fragments of metamorphic rocks (fine grained schist). These latter, even if do not outcrop in the southern-central Sicily, are occasionally present in the sandy silty fraction of almost all the eastern Sicilian sediments due to the terrigenous contributions from the metamorphic basement cropping out in the north-east of the island.

The groundmass is generally heterogeneous with a colour varying from yellow-greenish beige, reddish brown or greyish. Numerous remains of calcareous microfossils or their moulds, filled with recrystallized microcrystalline calcite, are observable too, especially in the Gela 99 sample. On the basis of the abundance of mica laths in the groundmass, two sub-fabrics can be identified:

i) with fossiliferous and scarcely micaceous groundmass, samples Gela 23, 24, 37, 38, 39, 41, 44, 75 and 76 (*I Form*), Gela 27, 34, 35, 36, 42, 102 and 104 (*II Form*), Gela 105 (*III Form*);
ii) with fossiliferous groundmass, samples Gela 25, 26, 30, 40 and 78 (*I Form*); Gela 77, 99 and 101 (*II Form*); Gela 45 and 46 (*III Form*) (Fig. 4).

The ceramic reference materials show petrographic characters which are remarkably consistent with those of the amphorae, with the exception of some modern bricks that are richer in coarse inclusions. In particular, samples Gela 108, 110, 111, 113 and GE3M, GE4M, GE5M, show a fossiliferous and micaceous groundmass, while Gela 109, 112, 114 and GE1M, GE2M, GE6M, belong to the sub-fabric with fossiliferous and scarcely micaceous groundmass.

From the comparison between the petrographic features of the amphorae and the test tiles, it appears evident that the ancient ceramics are very similar to the tests obtained from the locally outcroppings clayey sediments without addition of sand. This observation permits to establish that the amphorae were produced using local clay as it is, and that the differences in the silty-sandy inclusions abundance are due to the variability in the granulometric distribution of the sediments in the area of Gela, ranging, also in the same outcrop, from clayey silt to silty clay, with a maximum sandy fraction of 20%.

5.2. Chemical analyses

The chemical compositions of the analysed amphorae and the reference materials are reported in Table 2.

All the samples are similar in the major elements composition and, in particular, they have CaO≥6%. Worth of note is the presence of very high Na_2O abundances in two clayey sediments (GEA6A and GEA7A), attributable to halite (as XRD analyses testify), likely due to a salt water aquifer. For this reason the two samples are excluded from the following chemical elaborations.

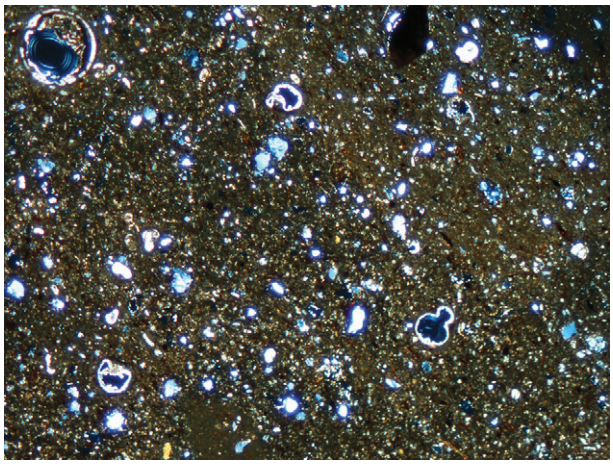

Fig. 4. Microphotograph (cross polars) of the Gela 99 sample.

Table 2
(a) Concentrations of major elements (wt%) and trace elements (ppm), obtained by XRF analysis of the transport amphorae. (b) Concentrations of major elements (wt%) and trace elements (ppm), obtained by XRF analysis of the reference materials.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Sr	V	Cr	Co	Ni	Zn	Rb	Y	Zr	Nb	Ba	La	Ce	Pb	Th
a)																									
Gela 23	61.25	0.68	13.56	5.34	0.07	2.14	13.64	0.80	2.31	0.20	506.6	78.5	85.2	24.6	41.9	72.4	74.9	23.9	185.1	9.1	436.4	38.4	71.8	17.3	9.9
Gela 24	63.49	0.68	12.98	5.20	0.07	1.96	12.38	0.80	2.03	0.40	472.1	57.4	81.4	22.9	38.2	67.7	73.4	27.5	287.1	11.4	925.3	35.6	84.5	16.1	9.9
Gela 25	60.88	0.71	14.12	5.43	0.06	2.32	13.29	0.90	2.07	0.23	446.5	84.8	86.6	21.8	46.1	70.9	67.3	15.4	215.0	5.4	393.0	35.9	67.8	10.4	10.8
Gela 26	57.28	0.77	15.05	6.14	0.06	2.75	14.30	1.26	2.13	0.28	579.1	90.1	100.7	27.6	49.7	73.9	68.5	24.9	206.6	11.4	249.9	43.4	93.8	10.7	15.4
Gela 28	60.55	0.73	13.62	5.69	0.06	2.63	13.37	0.95	2.17	0.23	535.9	62.3	89.8	24.0	42.0	71.7	82.6	26.0	255.3	11.4	281.8	41.0	75.4	20.4	9.3
Gela 29	60.06	0.74	14.55	5.49	0.06	1.97	13.72	0.83	2.36	0.22	633.2	84.7	89.3	26.9	41.2	64.4	81.0	25.0	217.8	11.3	469.7	34.2	81.1	18.7	10.5
Gela 30	60.86	0.74	14.29	5.26	0.06	1.89	13.76	0.61	2.28	0.26	573.4	73.3	82.6	24.9	39.6	69.5	52.4	15.6	180.0	5.6	1569.0	32.8	78.9	16.4	4.3
Gela 31	60.17	0.71	13.80	5.43	0.07	2.20	14.20	0.93	2.20	0.29	514.8	69.3	83.7	21.8	45.7	74.8	70.1	15.9	199.6	6.2	342.3	39.3	64.4	14.3	10.4
Gela 32	61.45	0.71	13.69	5.40	0.07	1.81	13.77	0.56	2.22	0.33	519.6	63.6	71.0	21.1	40.1	70.2	53.2	16.5	184.4	7.2	2017.1	31.1	55.2	15.9	10.3
Gela 33	60.75	0.73	14.35	5.88	0.07	2.18	12.73	0.88	2.15	0.29	535.9	79.0	93.8	26.0	43.7	68.7	74.6	24.9	196.1	8.5	662.6	37.0	79.9	14.5	5.7
Gela 34	59.45	0.72	13.81	5.56	0.06	2.70	13.79	1.08	2.57	0.25	458.2	60.0	85.9	24.6	48.5	67.7	67.3	15.0	198.7	5.7	258.1	35.4	72.9	11.1	11.9
Gela 35	61.54	0.87	15.40	6.47	0.06	2.55	9.77	1.03	2.12	0.21	483.6	62.3	101.4	27.0	47.6	66.9	63.4	17.6	216.6	8.0	1122.0	29.4	86.1	15.5	13.3
Gela 36	60.76	0.71	13.14	5.30	0.05	2.17	14.54	0.85	2.28	0.21	398.0	59.9	83.3	22.8	39.4	62.8	62.6	16.1	218.5	5.7	353.4	30.2	69.8	16.2	6.6
Gela 37	61.57	0.66	12.80	5.13	0.07	1.92	14.64	0.98	1.94	0.30	548.8	65.5	79.2	23.6	41.6	66.5	45.3	14.3	191.7	3.5	2130.1	28.9	70.8	18.6	7.5
Gela 38	61.39	0.66	13.47	4.98	0.06	2.27	13.75	0.95	2.11	0.37	368.1	60.4	72.5	17.0	42.6	55.0	46.9	10.5	154.2	1.0	368.2	33.4	79.8	17.1	0.0
Gela 39	59.73	0.67	13.13	5.46	0.08	2.67	14.77	1.02	2.18	0.29	515.9	70.0	76.6	24.7	42.5	73.1	64.8	15.2	147.8	6.2	420.2	35.9	69.4	15.8	3.6
Gela 40	60.76	0.69	13.23	5.19	0.07	3.23	13.52	0.70	2.17	0.45	483.9	70.6	69.3	22.0	40.4	67.2	52.5	13.7	162.2	4.3	694.3	31.3	72.7	15.1	6.4
Gela 41	61.06	0.75	13.53	5.78	0.08	3.80	12.06	0.71	1.99	0.24	413.8	63.7	72.4	23.5	47.0	70.1	34.7	8.1	116.2	0.0	379.9	32.1	69.6	12.4	0.0
Gela 43	61.53	0.82	14.88	6.06	0.07	2.15	11.39	0.78	2.08	0.24	324.0	78.9	86.1	24.8	42.9	66.2	45.4	9.6	149.9	0.0	1053.1	33.2	66.0	12.2	0.0
Gela 44	60.68	0.71	13.43	5.59	0.08	2.84	13.66	0.77	1.94	0.31	435.0	71.5	83.6	23.8	47.9	69.7	54.1	13.9	173.1	3.6	738.2	37.6	74.5	14.8	10.6
Gela 75	61.22	0.65	12.77	5.22	0.07	1.88	15.13	0.80	2.01	0.25	564.4	60.7	83.4	23.6	40.6	61.9	72.7	23.7	204.8	9.3	523.0	34.8	59.9	14.7	9.2
Gela 76	59.20	0.71	13.69	5.85	0.08	2.29	14.63	0.93	2.26	0.38	784.0	74.6	87.2	25.9	42.1	72.4	78.2	25.4	232.3	11.3	374.5	36.7	63.7	18.3	11.2
Gela 77	60.09	0.73	14.28	5.72	0.08	2.21	13.27	0.94	2.37	0.30	543.3	73.3	84.7	28.5	42.0	76.0	80.5	25.7	263.8	13.4	505.6	39.9	90.1	19.5	12.3
Gela 78	59.37	0.86	17.94	7.61	0.09	2.93	6.33	1.24	3.47	0.16	156.0	95.7	137.3	43.8	95.0	94.2	130.9	25.4	142.6	5.5	423.4	44.0	88.0	19.2	13.2
Gela 98	61.35	0.76	14.98	6.07	0.07	2.23	11.15	0.93	2.17	0.28	376.7	85.1	100.7	26.0	48.6	64.9	64.6	13.6	170.4	3.4	612.6	42.1	89.9	12.7	7.4
Gela 99	57.29	0.70	15.74	6.09	0.14	2.88	13.32	1.11	2.48	0.23	471.7	77.5	112.3	34.6	68.8	79.7	76.7	12.9	97.1	0.9	461.4	33.3	76.6	9.5	3.5
Gela 100	58.43	0.71	13.67	5.75	0.07	3.09	15.16	1.52	1.28	0.31	552.2	76.8	95.2	28.0	48.6	75.3	29.0	27.3	213.0	10.7	339.1	36.9	104.0	5.6	10.8
Gela 101	59.80	0.70	13.91	5.63	0.07	2.89	13.71	1.19	1.88	0.23	486.6	79.1	90.5	24.8	49.0	67.5	54.2	16.8	184.2	6.3	369.6	31.3	79.2	9.0	8.7
Gela 102	61.55	0.77	14.61	5.55	0.08	2.06	12.23	0.75	2.22	0.19	406.8	59.5	86.5	22.3	47.9	65.6	62.7	14.3	178.4	4.8	762.7	37.0	82.8	15.5	12.4
Gela 103	58.98	0.69	13.15	5.33	0.06	2.44	15.92	0.88	2.30	0.25	613.0	61.7	85.7	24.9	43.8	65.1	70.9	25.1	256.3	8.6	439.5	35.0	61.2	17.0	9.0
Gela 105	58.58	0.75	13.94	6.09	0.07	3.59	13.57	1.02	2.07	0.31	685.9	74.6	82.3	25.1	45.4	78.9	64.1	15.7	184.1	4.6	411.4	34.1	73.6	17.6	4.4
Gela 106	60.60	0.78	14.79	5.77	0.08	2.17	12.81	0.59	2.20	0.22	480.7	74.0	90.1	24.2	48.3	74.8	58.2	13.2	166.7	3.5	863.4	33.1	74.8	16.1	8.5
Gela 107	60.79	0.79	14.91	5.69	0.08	2.39	12.46	0.48	2.21	0.20	513.9	63.7	65.7	25.8	42.3	70.7	48.7	13.7	163.6	5.3	1708.4	35.9	66.3	14.9	8.8
b)																									
GE1M	60.82	0.61	12.23	5.01	0.07	2.40	15.60	1.21	1.84	0.20	427.4	70.5	79.0	25.0	38.9	70.2	68.3	32.8	266.7	14.3	344.6	35.1	72.2	7.4	10.6
GE2M	62.29	0.63	12.49	5.31	0.06	2.33	13.54	1.19	1.95	0.20	390.7	74.3	84.0	23.4	40.2	66.4	65.1	32.6	278.2	14.5	285.8	35.6	89.6	4.0	11.4
GE3M	58.48	0.70	14.02	5.68	0.07	2.84	14.83	1.16	2.00	0.21	416.0	89.0	95.2	25.4	48.8	74.6	70.4	31.3	242.1	10.6	409.7	36.8	85.5	5.4	11.1
GE4M	59.10	0.67	13.64	5.50	0.07	2.78	14.68	1.27	2.08	0.20	419.4	84.7	88.7	27.6	45.6	76.8	75.9	31.6	255.1	14.4	316.1	37.0	74.2	6.0	11.5
GE5M	60.23	0.68	13.43	5.10	0.07	2.53	14.57	1.08	2.11	0.19	394.2	74.8	81.3	24.8	44.1	68.7	65.3	17.6	194.7	6.6	1643.0	32.1	63.7	15.3	10.3
GE6M	62.24	0.59	12.10	4.67	0.07	2.87	14.27	0.91	2.08	0.21	422.2	66.3	77.1	24.5	36.9	69.0	80.5	32.6	261.1	13.1	320.5	31.6	47.9	9.4	9.3
GE3A	61.06	0.53	12.22	4.18	0.06	1.61	18.09	0.50	1.57	0.19	511.4	51.4	57.8	18.3	25.3	52.0	49.3	20.7	170.5	11.3	380.4	25.3	48.4	17.5	4.0
GE4A	57.64	0.80	15.98	5.48	0.06	2.61	14.42	0.61	2.18	0.22	407.3	80.3	83.2	27.1	28.0	56.0	74.5	25.3	198.5	17.3	215.9	30.5	69.8	13.8	7.8
GE5A	57.82	0.64	13.03	4.80	0.07	2.76	16.99	1.97	1.69	0.22	377.0	59.3	67.2	22.1	27.3	103.0	50.1	24.3	229.6	15.7	283.6	27.2	46.8	6.0	8.5
GE6A	26.68	0.51	5.52	3.79	0.06	1.40	10.43	50.87	0.76	0.00	289.7	35.4	34.9	13.5	14.4	38.2	48.3	18.5	193.3	12.6	97.6	17.4	38.9	10.0	5.2
GE7A	38.43	0.62	10.09	4.29	0.05	1.79	12.81	30.34	1.51	0.06	361.5	54.0	58.5	17.5	17.0	45.7	64.8	19.2	136.2	14.7	133.9	27.3	42.4	0.0	7.1
GE8A	64.06	0.32	7.38	2.55	0.08	0.83	22.53	0.62	1.27	0.35	466.2	32.1	34.4	14.8	20.6	36.3	35.0	17.6	196.8	8.0	280.7	13.8	38.2	24.5	4.0
GE9A	58.70	0.66	13.74	5.10	0.08	2.25	16.85	0.50	1.90	0.21	566.3	64.1	70.0	24.1	25.7	52.7	61.4	24.3	246.1	14.2	279.8	28.9	59.2	14.5	4.8
GE11A	62.43	0.66	12.55	4.70	0.07	1.83	15.18	0.58	1.82	0.18	346.6	64.2	66.2	22.8	29.4	51.4	59.6	21.2	255.1	9.8	213.9	29.1	49.7	14.0	7.6
GE12A	57.53	0.77	15.96	5.33	0.07	2.05	15.37	0.37	2.37	0.18	434.6	79.3	84.2	24.1	35.1	59.2	73.2	19.2	129.6	9.9	186.0	33.3	72.3	15.0	7.0
GE14A	59.10	0.92	17.96	6.00	0.06	1.85	10.84	0.36	2.76	0.16	316.5	66.0	91.5	18.8	31.1	50.9	71.4	17.0	115.9	11.4	200.9	30.7	70.7	17.1	7.5
GE15A	59.01	0.85	16.83	5.00	0.08	1.78	13.37	0.36	2.59	0.14	215.6	51.7	68.9	13.2	36.0	35.0	44.8	6.7	73.3	3.1	158.6	31.5	43.4	11.0	8.9

GBL5	62.18	0.88	15.55	6.53	0.06	2.57	9.87	1.04	2.14	0.22	318.0	25.8	33.5	13.5	17.6	24.2	34.4	20.2	275.5	5.1	372.2	12.1	45.2	12.6	3.3
GBL6	61.28	0.72	13.26	5.34	0.05	2.19	14.66	0.86	2.30	0.21	289.4	29.0	36.9	11.1	26.4	27.8	31.9	18.3	235.6	3.1	297.5	19.7	56.0	13.4	6.3
GBL7	62.18	0.67	12.93	5.18	0.07	1.94	14.78	0.99	1.96	0.30	313.1	28.7	39.4	14.4	24.6	36.2	34.3	18.5	250.1	4.9	513.4	17.1	31.8	11.7	5.6
GBL8	61.97	0.66	13.60	5.03	0.06	2.29	13.88	0.95	2.13	0.38	310.1	23.5	33.0	11.8	17.0	25.4	31.4	18.2	441.3	6.2	862.2	22.3	39.4	9.3	3.9
Gela 104	59.73	0.67	13.29	4.99	0.07	1.96	15.82	0.95	2.28	0.23	626.0	67.0	71.0	16.9	38.5	46.6	62.6	20.1	191.6	7.1	303.1	31.2	58.5	16.3	7.8
Gela 108	62.13	0.77	14.67	5.84	0.09	1.80	11.33	0.99	2.16	0.23	421.5	62.1	75.9	25.1	37.9	51.7	61.8	22.5	228.0	9.2	601.1	31.9	73.2	21.4	10.1
Gela 109	60.36	0.74	14.78	5.89	0.07	2.25	12.32	1.00	2.37	0.22	403.3	73.8	86.9	21.6	44.4	65.3	64.1	22.2	203.9	9.8	319.9	34.0	86.1	17.2	14.3
Gela 110	60.84	0.64	12.22	5.10	0.08	1.67	16.39	1.14	1.68	0.25	513.3	43.6	63.7	15.7	38.9	44.1	28.3	22.0	214.3	6.1	605.6	25.4	57.8	7.4	7.9
Gela 112	59.58	0.74	14.56	5.94	0.07	2.38	13.50	0.88	2.09	0.26	513.0	73.8	87.3	20.5	41.4	61.3	61.1	24.1	204.4	10.6	312.3	36.7	66.2	10.0	6.3
Gela 113	60.15	0.70	13.83	5.59	0.07	1.94	14.28	0.85	2.20	0.39	748.2	55.7	72.9	17.5	33.6	48.8	62.1	24.9	212.1	10.8	594.1	33.0	59.7	15.9	8.6
Gela 114	64.28	0.74	12.98	5.75	0.09	1.07	10.96	1.39	2.55	0.20	398.8	55.7	74.8	22.2	36.7	61.0	50.3	20.3	254.6	8.7	484.9	33.7	80.3	12.5	8.6
Gela 111	60.08	0.66	13.41	5.11	0.07	2.00	15.27	0.91	2.19	0.30	512.2	63.8	67.4	19.1	38.7	49.4	59.9	14.5	182.4	6.9	451.0	23.9	71.1	17.3	10.7

In order to eliminate the constant sum problem of compositional data, we used the Aitchison approach (Aitchison, 1986) widely used in the archaeometric study (Aitchison et al., 2002; Buxeda i Garrigós, 1999; Barone et al., 2005, 2011b). In order to highlight the presence of compositional groups among the amphorae or between these and the reference materials, multivariate cluster analyses were performed on trace elements, firstly transformed into center logarithmic ratios (clr) (Aitchison, 1986) according to:

$$x \in \mathbb{S}^d \rightarrow y = \ln(x_d/g_D) \in \mathbb{R}^d$$

where x is a compositional vector with D parts, g_D is the geometric mean, $\mathbb{S}^d$ is a *d*-dimensional simplex (d = D-1), y is log-transformed composition and $\mathbb{R}^d$ is real space with d dimension. The use of the crl transformed data for cluster analysis is possible since they maintain the characters of Euclidean geometry (Martin-Fernandez et al., 1999).

The structure of the dendrogram (Fig. 5) highlights a main cluster formed by both amphorae and reference materials with low linkage distance. Only the amphorae Gela 38, 41, 43, 78 and 99 are separated from the main cluster: the chemical differences between them and the remaining samples may be due to a different local clay source, but it can not be excluded their importation from close production sites in which the raw materials have similar compositional features. For this reason, these five samples have been excluded from the following discussion, focused on the individuation and characterisation of the Geloan amphorae production.

The chemical homogeneity of the main cluster samples is testified by the low total variance separately calculated for both major and trace elements (vt = 0.331 and 1.784, respectively). The data reported in Table 3 are relative to the variation array calculated after additive logarithmic ratios (alr) transformation (Aitchison, 1986) according to:

$$x \in \mathbb{S}^d \rightarrow y = \ln(x_d/x_D) \in \mathbb{R}^d$$

where x is a compositional vector with D parts, $\mathbb{S}^d$ is a *d*-dimensional simplex (d = D-1), y is log-transformed composition and $\mathbb{R}^d$ is real space with d dimension.

Variances (τ_i) for each element and their percentages (vt/τ_i), with respect to the total variance "vt", are also reported in Table 4. The elements that mainly contribute to the variation are Na_2O for the major elements, and Ba, Nb, Th, Pb and Y for trace elements.

The comparison between the chemical composition of the main group of amphorae and the reference materials has been carried out by means of principal components analysis, whose results are illustrated in the biplot (Fig. 6) constructed using arl transformation of major and trace elements. Even if the explained variance for the first two principal components is low, the diagram permits to observe some chemical variability among the amphorae, principally due to Ba, that can be indicative of a post-burial alteration (Mommsen, 2004; Schwedt et al., 2004). Worth of note is that the variation field of the amphorae is largely overlaid to that of the raw materials and of the reference ceramics.

6. The problem of the light-coloured surface

As evidenced in the macroscopic description of our samples and as reported in the archaeological literature, the ceramics from Gela often show a light-coloured surface, which appears as a peculiar characteristic since the archaic age and is documented in modern local products as well. As mentioned above, the whitened amphorae can be subdivided into two groups with: i) a thick

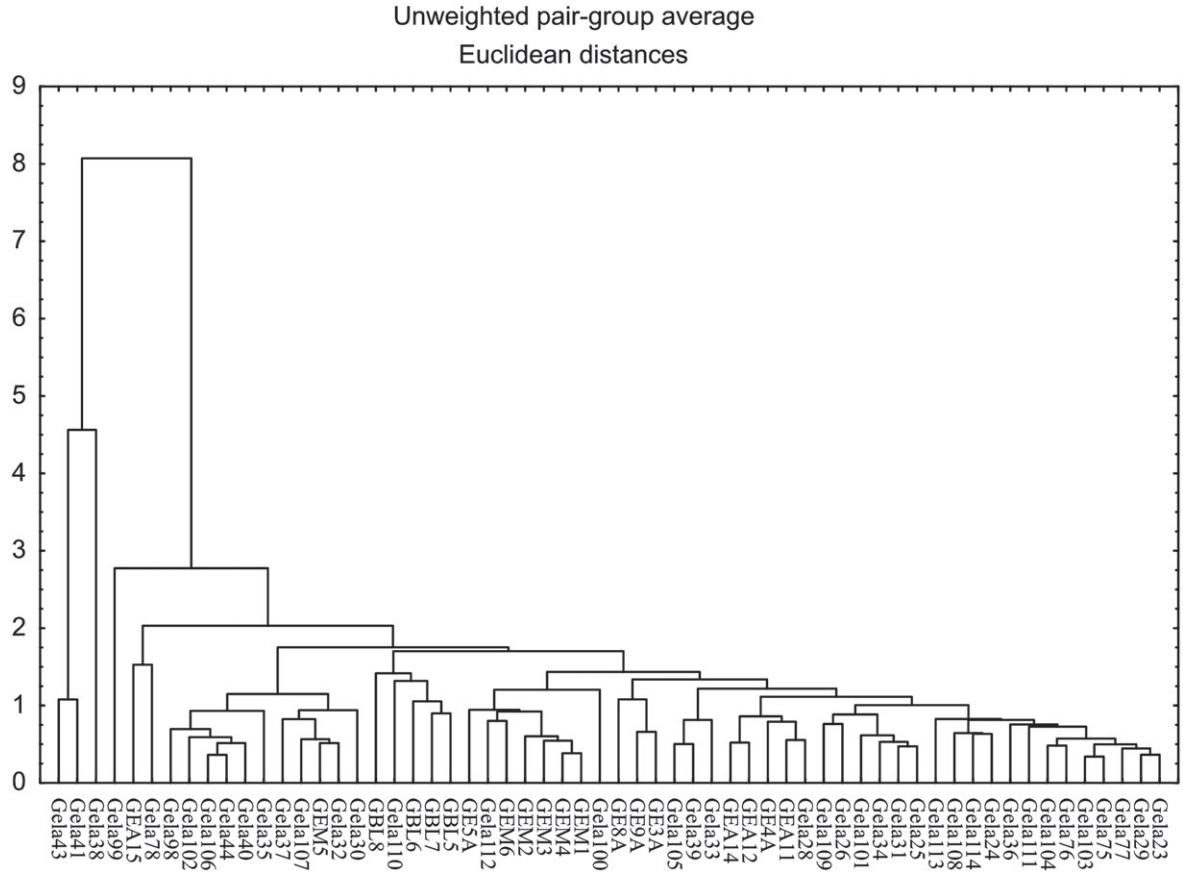

Fig. 5. Cluster analysis of the examined amphorae and reference materials using trace elements previously clr transformed.

whitened superficial layer and a light pink core (Fig. 3A); ii) a thin whitened superficial layer and a red core (Fig. 3B).

From the mineralogical point of view, the XRD analysis shows that the more whitened samples have, on average, higher diopside and anorthite abundances in comparison with the reddish ones, which are characterized by the presence of hematite and sometimes of calcite. These differences are also recognizable in the same sample, between the light outer layer and the reddish inner portion, as evidenced by the quantitative analysis, obtained by means of the Rietweld method using the Maud software (Luterotti et al., 1999), carried out on the representative Gela 77 sample (external layer: Cc = 0%, Di = 31.6%, Hm = 0.86%, Geh = 1.41%; inner portion: Cc = 9.27%, Di = 6.15%, Hm = 3.92%, Geh = 6.51%).

Concerning the causes of the whitening effect, as yet different hypotheses have been made. Uhlenbrock (1988) first attributed the light-coloured surface of many archaic terracotta figurines from Gela to the use of salt intentionally added to the clay paste, a well documented technique in the modern Sicilian handicraft (Hampe and Winter, 1965). Successively, this aspect was investigated in some archaeometric studies on medieval glazed pottery from Gela and Agrigento (Cuomo Di Caprio, 1991; Cuomo Di Caprio and Fiorilla, 1992), according to which the whitening effect, apart from the salt admixture, should be also due to the characteristics of the local raw materials (large amounts of calcite and iron oxides) and to a high firing temperature in a reducing atmosphere. Later, but referring to late Roman pottery from Northern Africa, Bonifay (2004), simply ascribed the effect to the use of sea water in clay preparation.

With the aim of discovering the causes of the colour variations on our samples, we investigated the firing behaviour of two

Table 3
Variation array of major elements calculated after additive logarithmic ratios (*alr*) transformation (Aitchison, 1986).

Variation Array	Vt	0.331								
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
SiO_2		0.004	0.003	0.005	0.011	0.036	0.012	0.067	0.014	0.048
TiO_2	4.426		0.001	0.002	0.016	0.032	0.022	0.067	0.016	0.061
Al_2O_3	1.469	−2.956		0.002	0.014	0.033	0.019	0.065	0.015	0.058
Fe_2O_3	2.381	−2.045	0.912		0.014	0.026	0.019	0.054	0.019	0.053
MnO	6.784	2.358	5.314	4.403		0.043	0.022	0.085	0.030	0.048
MgO	3.242	−1.184	1.772	0.861	−3.542		0.039	0.049	0.060	0.061
CaO	1.498	−2.928	0.029	−0.883	−5.286	−1.744		0.062	0.028	0.048
Na_2O	4.245	−0.181	2.776	1.864	−2.539	1.003	2.747		0.102	0.093
K_2O	3.344	−1.082	1.874	0.963	−3.440	0.102	1.846	−0.901		0.073
P_2O_5	5.419	0.993	3.950	3.038	−1.365	2.177	3.921	1.174	2.075	
$vt/\tau_{.i}$	0.020	0.022	0.021	0.019	0.028	0.038	0.027	0.064	0.036	0.054

Table 4
Variation array of trace elements calculated after additive logarithmic ratios (*alr*) transformation (Aitchison, 1986).

Variation Array	Vt = 1.784													
	Sr	V	Cr	Co	Ni	Zn	Rb	Y	Zr	Nb	Ba	La	Ce	Pb	Th
Sr		0.034	0.037	0.022	0.038	0.022	0.064	0.054	0.037	0.135	0.421	0.036	0.055	0.079	0.158
V	1.994		0.016	0.014	0.015	0.014	0.065	0.083	0.051	0.189	0.435	0.018	0.023	0.112	0.143
Cr	1.803	−0.190		0.009	0.007	0.015	0.050	0.063	0.026	0.164	0.441	0.014	0.013	0.102	0.110
Co	3.047	1.054	1.244		0.009	0.008	0.055	0.059	0.027	0.153	0.401	0.012	0.013	0.087	0.123
Ni	2.464	0.471	0.661	−0.583		0.008	0.063	0.089	0.038	0.200	0.414	0.012	0.018	0.106	0.110
Zn	2.005	0.012	0.202	−1.042	−0.459		0.055	0.074	0.031	0.173	0.392	0.010	0.022	0.081	0.129
Rb	2.109	0.116	0.306	−0.938	−0.355	0.104		0.079	0.045	0.152	0.520	0.043	0.082	0.052	0.153
Y	3.331	1.337	1.528	0.284	0.867	1.326	1.222		0.033	0.038	0.572	0.063	0.075	0.145	0.136
Zr	0.952	−1.041	−0.851	−2.095	−1.512	−1.053	−1.157	−2.379		0.105	0.456	0.031	0.040	0.088	0.098
Nb	4.334	2.340	2.530	1.286	1.870	2.329	2.224	1.003	3.382		0.741	0.158	0.175	0.246	0.187
Ba	−0.121	−2.114	−1.924	−3.168	−2.585	−2.126	−2.230	−3.452	−1.073	−4.455		0.450	0.426	0.344	0.571
La	2.683	0.689	0.880	−0.364	0.219	0.678	0.573	−0.648	1.731	−1.651	2.804		0.023	0.091	0.114
Ce	1.933	−0.061	0.130	−1.114	−0.531	−0.072	−0.176	−1.398	0.981	−2.401	2.054	−0.750		0.125	0.127
Pb	3.563	1.570	1.760	0.516	1.099	1.558	1.454	0.232	2.611	−0.771	3.684	0.880	1.630		0.238
Th	4.075	2.082	2.272	1.028	1.611	2.070	1.966	0.744	3.123	−0.259	4.196	1.392	2.142	0.512	
$vt/\tau_{.i}$	0.080	0.081	0.071	0.066	0.075	0.069	0.099	0.104	0.074	0.188	0.439	0.072	0.081	0.126	0.160

different clayey sediments, GE7A and GE9A. They are characterized by a considerable abundance of clay minerals (smectite, illite, kaolinite), quartz, calcite (fewer in GE7A) and minor amounts of feldspars. Furthermore the GE7A sample, as mentioned above, has abundant NaCl, that is absent, on the contrary, in the GE9A sample.

Two laboratory-made paste tests of the raw materials were fired at 550°, 750° and 900 °C for 12 h. The GE7A-T and the GE9A-T colours changed with the increase of temperature: i) at 550 °C, GE7A-T showed a light pink colour (7.5 YR 7/4), that turned to light yellowish pink (7.5 YR 8/2) on the surface, while GE9A-T presented a homogeneous reddish brown colour (5 YR 4/6); ii) at 750 °C, GE7A-T was light pink (5 YR 7/4) in the core and light yellow (10 YR 8/3) on the surface, whereas GE9A-T maintained the reddish brown colour (5 YR 4/6); iii) at 900 °C, the GE7A-T sample was yellowish pink (7.5 YR 8/6) and very pale yellow (2.5Y 8/3) in the core and on the surface, respectively, on the contrary GE9A-T was dark red (2.5 YR 4/8).

The quantitative mineralogical composition of the two sets of the sample tests is reported in Table 5. In the GE7A-T sample calcite disappears starting from 750 °C, when the formation of diopside and anorthite begins. Worth of note is the low abundance of hematite already at 550 °C. On the contrary, in the GE9A-T sample the formation of Ca-silicates begins at a higher temperature and the hematite is more abundant.

The firing induced mineralogical transformation of the two samples was also investigated by means of combined thermo-gravimetric (TG)/differential scanning calorimetry (DSC) analysis, that on the whole confirmed the different behaviour of the halite bearing sample. In particular, the decarbonatation of calcite has the apex at 725 °C in the GE7A and at 800 °C in the GE9A. In the same way, the newly-formed Ca-silicates appear at 750 °C and 850 °C in the GE7A and in the GE9A, respectively (Fig. 7).

Furthermore the TG curve of the NaCl bearing GE7A sample shows a loss of mass at 500°–525 °C, probably due to the formation and volatilization of the Cl-compound, developed during the firing process. The formation of these chlorides is confirmed by the presence, revealed by XRD analysis, of $FeCl_3$ as sublimates on the floor and on the inner walls of the modern kilns producing Geloan traditional bricks and tiles.

These results permit to explain the whitening effect as principally due to the formation of volatile iron chlorides (Abbott, 2008) and, consequently, to the decrease of the hematite abundance in the ceramics. In this context, the reducing atmosphere during high firing temperatures is significant because it restricts the stability field of Fe_2O_3. On the contrary, the role of the calcite and the formation of diopside at lower temperature in the presence of NaCl assume less importance than hypothesized in previous researches (Cuomo Di Caprio, 2007).

7. Archaeological considerations and conclusions

The quite homogeneous petrographic and chemical features of our amphorae show a good agreement with the data obtained from the reference materials (common ware, kiln spacers and kiln

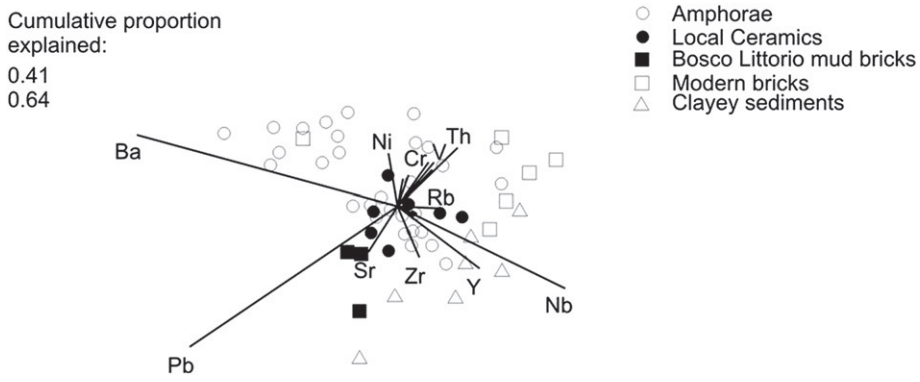

Fig. 6. Biplots constructed using major and trace *crl* transformations.

Table 5
Quantitative analysis, obtained by means of the Rietweld method using the Maud software, carried out on GE7A-T, GE9A-T and Gela 77 samples. Qz = quartz; Ab = albite; Or = orthoclase; Cc = calcite; Dol = dolomite; An = anorthite; Di = diopside; Wo = wollastonite; Hm = hematite; Geh = gehlenite; Ms = muscovite; Il = illite; Hal = halite.

	Qz	Ab	Or	Cc	Dol	An	Di	Wo	Hm	Geh	Ms/Il	Hal
GE7A 550°	31.4	8.46	11.91	12.22	3.02	0.0	0.0	0.0	2.3	0.0	26.3	4.4
GE7A 750°	35.4	2.01	0.0	1.76	0.49	17.1	28.3	5.3	2.2	2.0	5.5	0.0
GE7A 900°	16.2	0.0	4.30	0.0	0.0	23.95	48.0	7.5	0.0	0.0	0.0	0.0
GE9A 550°	52.1	4.0	3.1	10.9	0.0	0.0	0.0	0.0	3.4	0.0	26.5	0.0
GE9A 750°	54.3	4.3	3.4	5.2	0.0	0.0	0.2	0.0	3.5	0.0	22.7	0.0
GE9A 900°	39.0	0.0	6.03	0.0	0.0	29.5	4.9	2.13	5.0	13.5	0.0	0.0
Gela 77 (surf.)	45.2	0.0	0.0	0.0	0.0	20.9	31.6	0.0	0.9	1.4	0.0	0.0
Gela 77 (core)	38.6	6.9	0.0	9.3	0.0	21.6	6.1	0.0	3.9	6.5	7.0	0.0

wasters; modern bricks; archaic mud bricks; local clayey sediments). On the whole both petrographic and chemical data strongly point to assigning to Gela the production of most of the studied amphorae. Only the provenance of five samples (Gela 38, 41, 43, 78, 99) is in doubt, since their chemical composition and petrographic characters do not explain if they have been locally produced using different raw materials, or they have been imported from neighboring sites, whose localization can be the subject of future research. It is important to stress the historical value of the assignment to Gela of a rich and lasting amphora production. This may support the hypothesis that the territory owned many natural resources and produced goods (oil, wine, honey or something else) not only for local needs but probably for export too.

Another remarkable piece of information which emerges from our study is that the chronology of the amphorae coincides with the period of greatest prosperity of the Greek *polis*, from the second half of the 6th century B.C. until the destruction of the city in 405 B.C. by the Carthaginians, whereas after the reconstruction (338 B.C.) the Geloans, as far as we know, did not ever produce transport jars.

As regards to the technological aspects, the amphorae and, in general, the medium-coarse ware of Gela, were likely produced with locally outcropping clayey sediments. The clay sources were probably located very close to the ancient town, as in recent times. The use of intentionally added temper seems excluded by the comparative petrographic analysis of the amphorae and the laboratory paste tests, and by the evidence of the local modern ceramic production. The slight differences between the samples concerning the grain size and the abundance of the inclusions and the amount of mica may be attributable to the variability of the local clayey sediments.

The clay manufacturing of the amphorae seems to be careful enough for this ceramic class and a good firing technology is also testified by the high quality of the artefacts. However, in this case, the formation of Ca-silicates is not indicative of the high firing temperature since, as showed by the TG and DSC analysis, the presence of NaCl reduces the temperature necessary for the formations of these minerals.

But the very typical feature of the Geloan ware is the light-coloured surface that we explain as the result of several coexisting factors: the use of calcareous clay; the presence of salt in the raw materials or the addition of sea water in clay preparation (maybe especially helpful to avoid a too rapid drying process before firing, as the modern craftsmen of Gela affirm); the skilful firing behavior, which allowed the attainment of high temperatures in reducing atmosphere; and a quite efficient natural fuel that does not produce smoke. Today the favorite fuel is the olive husk, because of its high calorific value, but in the antiquity wheat straw, that is efficient too, could be much more easily found, being Gela, according to the historians, one of the ancient world's leading cereals producers.

We can hypothesize that at the beginning the whitening effect was obtained unintentionally, because of the characteristics of the raw materials. But the results probably were not aesthetically satisfactory: the color of the surface was likely not uniform and showed many spots. This soon gave rise to the necessity of controlling the chromatic effect and then the experience in the firing behavior became important.

Considering the evidence of the Geloan amphorae, the whitening technique dates back to the 6th century at least, but from common wares and terracotta figurines of the early phase of the sanctuary of Bitalemi (Uhlenbrock, 1988) we can argue that it was probably known at Gela since the second half of the 7th century B.C. As for our specimens, the slight differences among them in the appearance of the surface do not coincide exactly with the chronological differences; nevertheless, the *Form II* amphorae usually

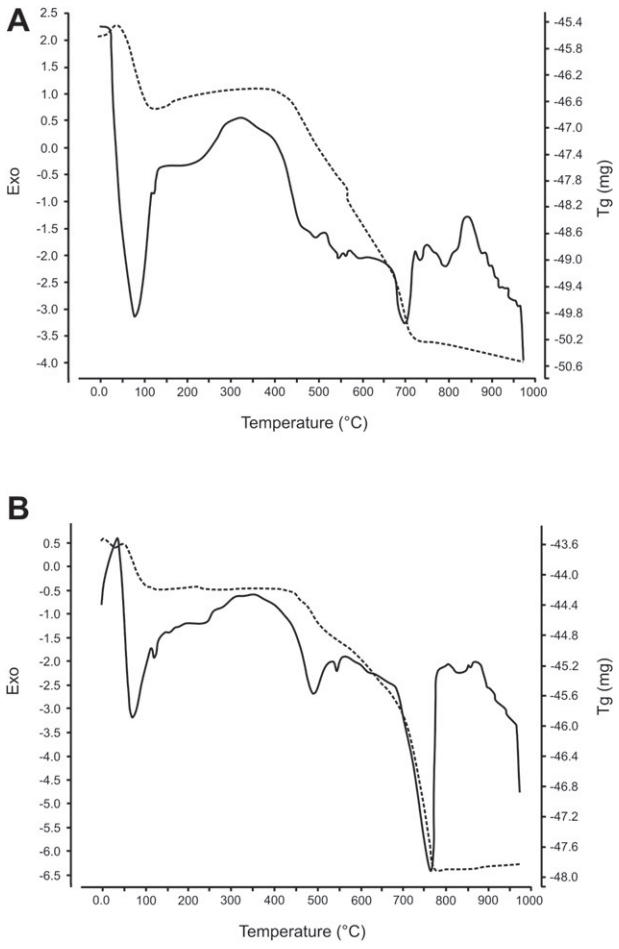

Fig. 7. TG and DSC analysis of the studied clay sediments. A) GE7A sample; B) GE9A sample.

show a more homogeneous and smoother light-coloured surface than the others. Therefore, we can hypothesize that it was a certain technological progress, but we should always consider the personal abilities of the craftsmen and the efficiency of every single kiln.

As for the reasons why the light-coloured surface was so requested, according to Bonifay (2004), it is more porous; therefore, the contents of the vessels keep cooler. But the porosity is not a useful property for transport amphorae, in the case of liquid contents. We think that the whitened surface was probably more appreciated because it proved to be harder, stronger and resistant to splintering, as the modern craftsmen of Gela also affirm.

It is highly likely that this knowledge was conveyed from Gela to the neighboring more recently founded colonies (like Agrigento, which has very similar raw materials) and later, also touching the coast of Northern Africa, it has been handed down to the Middle Ages and present times.

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Appendix

A) Transport amphorae

Fabric with dominant quartz and common feldspars.

Fossiliferous and micaceous groundmass: Gela 23, 24, 37, 38, 39, 41, 44, 75 and 76 (*I Form*); Gela 27, 34, 35, 36, 42, 102 and 104 (*II Form*); Gela 105 (*III Form*).

Fossiliferous and scarcely micaceous groundmass: Gela 25, 26, 30, 40 and 78 (*I Form*); Gela 77, 99 and 101 (*II Form*); Gela 45 and 46 (*III Form*).

I. Microstructure

a) Vughy microstructure: common vughs and vesicles (from 5% to 30%); b) spatial distribution: from single space to open; c) preferential orientation: present mainly in linear vughs or absent.

II. Groundmass

a) Normally heterogeneous; b) micromass optically active or subordinately scarcely B-fabric: banded or mottled; c) colour: (PPL) yellow-greenish beige, reddish brown or greyish; d) c:f from 5:95 to 20:80.

III. Inclusions

a) Grain size distribution: prevalently bimodal or polymodal; b) coarse inclusions – dominant: polycrystalline and monocrystalline quartz; c) fine inclusions – common: quartz; scarce: feldspar and fragments of metamorphic rocks.

B) Reference materials

Fabric with dominant quartz and common feldspars.

Fossiliferous and micaceous groundmass: Gela 108, Gela110, Gela 111 and Gela 113; GE3M, GE4M and GE5M.

Fossiliferous and scarcely micaceous groundmass: Gela 109, Gela 112 and Gela 114; GE1M, GE2M and GE6M.

I. Microstructure

a) Vughy microstructure: common vughs and vesicles (from 5% to 30%); b) spatial distribution: from single to double space; c) preferential orientation: present mainly in linear vughs or absent.

II. Groundmass

b) Normally heterogeneous (except the Gela 108, 109 and 114 samples, that have a homogeneous groundmass); b) micromass optically active or subordinately scarcely B-fabric: banded or mottled; c) colour: (PPL) greenish grey, reddish brown or greyish; d) c:f from 15:85 to 20:80.

III. Inclusions

a) Grain size distribution: prevalently bimodal or polymodal; b) coarse inclusions – dominant: polycrystalline and monocrystalline quartz; scarce: feldspars c) fine inclusions – common: quartz; scarce: feldspar, fragments of metamorphic rocks and chert.

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