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ORIGINAL PAPER

Reconstructing change in firing technology during the Final Neolithic–Early Bronze Age transition in Phaistos, Crete. Just the tip of the iceberg?

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Abstract
Changes in firing practice have been suggested as representing a revolution in ceramic technology at the beginning of the Bronze Age in Crete. The introduction of kiln structures has been held responsible for such a change, perhaps by newcomers to the island, along with other innovative technologies. However, these hypotheses were often based on limited analytical data and mostly on macroscopic examination. This paper re-examines the suggestion of a transformation in firing technology at the beginning of the Bronze Age by presenting analyses of the rich ceramic assemblage from the site of Phaistos in South-Central Crete, which offers a rare, good stratigraphic sequence from the end of the Final Neolithic into the Early Bronze Age. Here, firing technology is reconstructed by macroscopic examination of colour across vessel breaks, by SEM examination and FT-IR analysis. This allows the reconstruction of temperature ranges and firing rates over the phases considered and a re-assessment of changes in firing technology, revealing a more multi-faceted pattern of change. Finally, changes in firing procedure are contextualised in the overall ceramic operational sequence, revealing a complex, stepped picture of change in ceramic production over the transition from the Final Neolithic.

Keywords Firing · Technology · Ceramics · SEM · FT-IR

Introduction

Firing causes mineralogical and microstructural modification of clay bodies, which results in changes in characteristics such as porosity, resistance to physical and thermal stress, colour and hardness, all of which are key elements for the potter (cf. Rice 1987, pp. 80–109) as well as for the consumer. The type of raw material used, the kind of firing structure, temperature, atmosphere and duration of firing all influence such microstructural and mineralogical changes. While the reconstruction of ancient pyro-technology is a complex procedure, on account of the large number of variables involved, it remains important within archaeological science, because of its implications for our understanding of innovation and technological practice. As Tite (1995) has pointed out, of all the steps of the ceramic manufacturing sequence, firing reconstruction offers the archaeological scientist the allure of producing numerical results in the form of temperatures. The estimation of firing temperature, or better of 'equivalent firing temperature' (T_{eq}, cf. Robert 1963), was considered in the past literature the sole purpose of ceramic investigations and was often disconnected from its archaeological significance (cf. Perrinet and Courtois 1983; Edwards and Segnit 1984; Kaiser and Lucius 1989). At times, estimated firing temperatures were also used by archaeologists to distinguish between the use of 'kilns' and 'open-firing' as a way to measure technological advancement

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of past societies. Such simplistic approaches led to a reaction based on ethnography. Gosselain (1992) suggested that, rather than firing temperature, the differences in the duration and in the temperature rate are the only variables that allow firing structures to be distinguished, which may not be accessible to archaeologists. Indeed, Livingstone Smith (2001) suggested that there are no thermal parameters which allow us to clearly distinguish between different firing structures. More importantly, he argues that "firing technologies may be characterized by a number of socially significant facets and cannot be reduced to 'open' and 'kiln' categories without a considerable loss of technical and cultural information" (2001, p. 999). Gosselain and Livingston Smith are undoubtedly correct to point out that estimating firing temperature cannot be considered an isolated core of a study of ancient firing technology and that instead it should form part of broader research into ancient technology, related to a specific archaeological question (cf. also Tite 1995). Indeed, archaeological practice has already moved beyond the pure estimation of firing temperature in ceramics studies. The specific questions considered include, for example, understanding the way in which temper can affect ceramic properties (Hein et al. 2008) or the manipulation of firing parameters according to the surface final effect to produced (Wilson and Day 1994). In this paper, firing technology is investigated to further an understanding of the presence or absence of technological patterns in the Neolithic–Bronze Age transition in Crete and to assess the hypothesis of radical change in ceramic technology.

Archaeological background

The Neolithic and Bronze Age in the Aegean have been often approached with contrasting ideas and assumptions of their economic and social structures, settlement patterns and technological advances. Neolithic communities, often thought of as self-sufficient and egalitarian, were thought to give way to more complex and specialised Bronze Age societies (for discussion cf. Tomkins 2004, 2014). While the radical changes between the Neolithic and the Early Bronze Age in Crete (=EBA, referred in the literature on the island as Early Minoan, EM, Table 1) to some were caused by the migration of people to Crete (cf. Weinberg 1965; Muhly 1973; Warren 1974; Treuil 1983; Hood 1990a, b), still others argued for autochthonous development of social and political structures (Renfrew 1972, pp. 474–475; Vagnetti 1972; Vagnetti and Belli 1978; Branigan 1988, p. 197). However, in both cases, the ideas were often based on evidence from poorly stratified sites, on confused chronologies and on differences in theoretical approaches (cf. Tomkins 2007, pp. 13–18; Schoep and Tomkins 2012; Nowicki 2014, pp. 5–9; Tomkins 2014).

Since the early excavations (Evans 1921), the materials found at Knossos deeply influenced discussion on the Neolithic–Early Bronze Age transition. The striking differences in shape, surface finish and decoration of the Neolithic ceramics from those of the EBA at Knossos were taken to indicate an equally radical social change (Evans 1921, pp. 35–62; Hood 1990a, pp. 372–373; Hood and Cadogan 2011, pp. 281–286). Burnished and incised vessels characteristic of the Neolithic phase were abruptly substituted in EBA by jugs with long spouted neck and rounded base with a characteristic dark pattern-painted decoration on a light background, lidded pyxides and bottles with incised decoration, large storage jars (*pithoi*) and chalices with pattern burnished decoration (Evans 1921, pp. 35–38 and 58–62). The later publication of the Neolithic assemblages from Phaistos (Vagnetti 1972) and Nerokourou (Vagnetti et al. 1989) made it clear for the first time that the latest part of the Neolithic could not be considered merely a transitional ceramic style that could be labelled in different ways according to the scholars' preferences. Rather, it had to be considered a phase with its own characteristics distinguishing it from the previous and following phases in terms of material culture, settlement strategies, architectural features and engagement with other Aegean areas (cf. Vagnetti and Belli 1978, p. 161).

Since the 1970s, the latest phase of the Neolithic has been reconsidered, thanks to focused excavation campaigns, reviews of stratigraphy and detailed study of the pottery deposits. Systematic work has been carried out by other scholars at Knossos and Phaistos (for Phaistos cf. Di Tonto 2006; Todaro 2005, 2010, 2013; for Knossos cf. Wilson and Day 1994; Wilson and Day 2000; Tomkins 2007; Wilson 2007). Intensive survey and new excavations have extended our knowledge of the Neolithic in the rest of Crete (Haggis 2005; Hayden 2003; Papadatos 2008, 2012; Watrous et al. 2004). In recent years, this fieldwork has been supplemented by analysis of Final Neolithic (FN) and EM I pottery (Table 1;

Table 1 Chronology of the phases discussed in the text, according to the archaeological phasing system generally adopted for Crete (Schoep et al. 2012; Todaro 2013; Tomkins 2007)

Cretan Final Neolithic and Bronze Age phases	Approximate dates BC	Phaistos phases
Final Neolithic (FN) III	ca. 3600–3300	I
Final Neolithic (FN) IV	ca. 3300–3100/3000	II
Early Minoan (EM) IA	ca. 3100/3000–2900	III
Early Minoan (EM) IB	ca. 2900–2650	IV

cf. Wilson and Day 1994; Day et al. 1998, 2005, 2012; Nodarou 2011, 2012; Papadatos et al., in press) and this has revealed a complex and multifaceted picture.

However, Betancourt (2008) has presented a review of pottery production in Crete at the beginning EBA, which advocates the idea of a 'ceramic manufacture revolution', linked to the arrival of people from outside Crete bringing new technologies. He has specified a number of changes: (1) the selection and manipulation of calcareous pastes, producing lighter coloured pottery; (2) the introduction of the up-draught kiln, which allowed better control of kiln atmosphere and the achievement of consistent, high temperatures of firing; and (3) the introduction of new painting technology, which allowed the creation of the dark-on-light style. According to Betancourt, while Neolithic ceramics were porous, coarse and low fired, those of the EBA were less porous and harder and thus more suitable to store and transport perishable goods, such as milk and cheese (2008, p. 99). He argued that the knowledge of the manipulation of such products was brought into Crete from the Near East, with the 'secondary products revolution' (Sherratt 1981,1983), with other advanced technologies, such as pyrotechnology and ceramic manufacturing techniques (Betancourt 2008, pp. 96–103). Betancourt's technological reconstruction is supported by only limited evidence. Even if he acknowledges the presence of variability in Cretan ceramic fabrics, shape and surface treatment (2008, pp. 28–83), his pan-Cretan reconstruction regarding the Final Neolithic–Early Bronze Age (=FN-EBA) transition is based mainly on the analytical study of Aphrodite's Kephali in East Crete (Betancourt et al. 2013).

The recent project on pottery from Phaistos in south-central Crete (Fig. 1; Mentesana 2014, 2016; Mentesana et al. 2016) has focused on the technological reconstruction of ceramics from the latest phased of Neolithic to the earlier phases of Early Bronze Age (=FN-EBA), in order to assess this hypothetical change in ceramic technology. Compared to other sites in Crete, the FN III-EBA transition at Phaistos has a rather complete stratigraphic sequence and has benefited from a detailed consideration of phasing by Todaro (2010, 2013). The variety of wares available from these phases, from fine to coarse, allows us to discuss variation in technological choices used for ceramic manufacture both synchronically and diachronically. Taking its lead from Betancourt (2008) proposed technological revolution, this paper will investigate one aspect of the ceramic *chaîne opératoire* considered a key issue by the advocates of the technological revolution: firing.

Materials and methods

Materials

The ceramic material analysed belongs to the first four phases at Phaistos, as defined by Todaro (2010, 2013) and corresponds to FN III, IV, EM IA and EM IB of Tomkins' chronological system for Crete (2007; Table 1). In calendar years, this time lapse includes the end of the fourth and the beginning of the third millennium (ca. 3600–2650 BC; cf. Tomkins 2007). Three hundred four ceramic samples were chosen from the most reliable stratigraphic contexts at the site (cf. Mentesana 2016). Samples were selected on the basis of previous typological work (cf. Vagnetti 1972; Di Tonto 2003, 2006; Todaro 2010, 2013) and they represent the ceramic variability encountered at the site during the four phases (Table 2 and Fig. 2). They are divided according to the ware system adopted for the ceramic studies in the island (cf. Wilson 1985; Wilson and Day 1994) which include shape and surface treatment as briefly described in Table 2. During FN III, ceramics were manufactured in a restricted number of

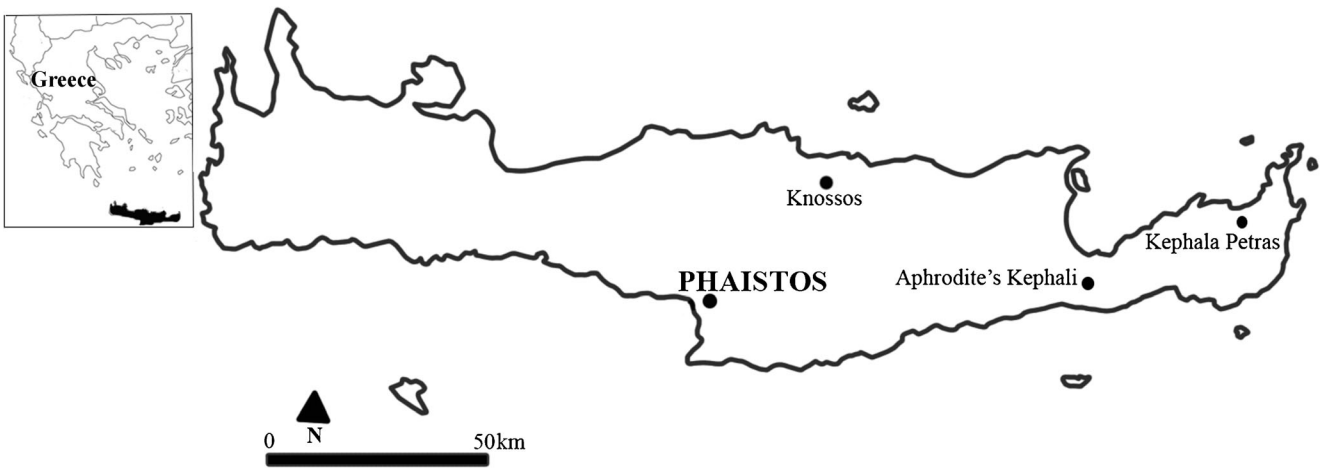


Fig. 1 Map of Crete with the sites mentioned in the text

Table 2 Wares present in the FN III-EM IB at Phaistos

Ware	Phase of occurrence	Surface treatment	Shapes	Example
Burnished ware (B)	FN III-FN IV	Homogeneously burnished on the inside and outside surface; colour varies from black to brown; can be also incised, jabbed, corrugated or encrusted with a red and white substance	Hemispherical bowl with off-set rim and V-shaped spout, carinated bowl with off-set rim, flaring bowl, jug/jar with V-shaped beak, collared jar, bottle	Fig. 2a
Scribble burnished ware (ScrB)	FN III-FN IV	Unevenly burnished which creates a 'scribble' effect	Bowl, collared jar	Fig. 2b
Red Slipped and Mottled ware (RS/M)	FN IV-EM IA	Thick red slip with irregular black spots	Flaring bowl hemispherical bowl, V-spouted bowl, jug/jar with a tall cylindrical neck	Fig. 2c
Burnished and Granulated ware (B/Gra)	FN IV	Small-medium sand grains mixed with a red substance are applied on the body of collared jar while the neck is burnished	Collared jar	Fig. 2d
Orange buff ware (O/Buff)	FN IV-EM IA	Smoothed with pairing marks	Bowl	Fig. 2e
Brown Slipped and Polished ware (BrS/Po)	EM IA	Slipped and polished with pairing marks	Bowl with everted rim, ring-footed bowl, globular jar, collared jar, deep bowl, fenestrated stand, scoop	Fig. 2f
Red Burnished ware (RBW)	EM IB	Red burnished surface, sometimes with a 'scribble' effect	Chalice	Fig. 2g
Dark Grey Pattern Burnished ware (DGPB)	EM IA-EM IB	Burnished on the inside and outside surface following geometrical patterns (EM IB) or with a 'scribble' effect; colour varies from black to light grey	Ring-footed bowl, chalice	Fig. 2h
Coarse ware	FN III-EM IB	Variety of surface treatments (wiping, wiping and washing and burnishing), usually combined in the same pot	Deep bowl	Fig. 2i
Dark-on-light ware (DOL)	EM IA-EM IB	Paint grading from dark-brown to purple to orange is applied following geometrical pattern on a cream colour slip or directly on the body	Jug, wide-mouthed juglet with horizontal spout/beak, collared jar	Fig. 2j
Wiped and Washed ware (W&W)	EM IB	Orange to red wash applied on a cream colour slip or directly on the body	Jar	Fig. 2k
Light-on-dark ware (LOD)	EM IB	Cream colour paint is applied following geometrical pattern on a red slip	Pyxis	Fig. 2l
Pithos Ware (PW)	EM IB	Wiped surface, usually pinkish in colour	Large container	Fig. 2m
Cooking Pot ware (CPW)	EM IA-EM IB	Wiped and/or scored dark red surface, often slipped on the interior	Deep bowl, baking plate	Fig. 2n

main shapes (deep bowls, deep bowl on a cylindrical foot, V-shaped spouted jug and jug/jars, usually of globular body and long cylindrical neck) and most of these shapes have a black burnished surface (B or ScrB). In FN IV, the same shapes are present but with a varied surface treatment, such as black burnished (B or ScrB), red slipped and mottled (RS/M) or burnished and granulated (B/Gra). The shape repertoire of EM IA is difficult to define as the material is very fragmentary and it seems to be characterised by the mixing of new and old features in terms of both shape and surface treatment (Todaro 2013, 171): bowls with everted rims similar to those of FN IV are found beside typical feature of the following EM IB phase, such as pedestal bowls, globular jars/jugs, cooking pots and lidded pyxides. Few vessels show a red slipped and mottled surface as in FN IV, while dark-on-light painted (DOL) and dark burnished (DGPB) surfaces make their first appearance at the site. The brown slipped vessels (BrS/Po) are the most abundant ware in EM IA. The EM IB is instead defined by very distinctive shapes, such as chalices, ring-footed bowls, large jars, juglet, cooking pots and large storage jars (*pithoi)*. The link between the surface treatment and the shape is marked in this phase, as observed in other EM I assemblages, such as at several sites from west Crete (Nodarou 2011), at Kephala Petras (Papadatos 2012) or at Knossos (Wilson and Day 1999): for example, chalices show a dark burnished surface, juglets and jars are always painted in dark-on-light background, and cooking pots have a typical scored surface. Therefore, while it can be acknowledged that changes occurred during these phases, it is crucial to

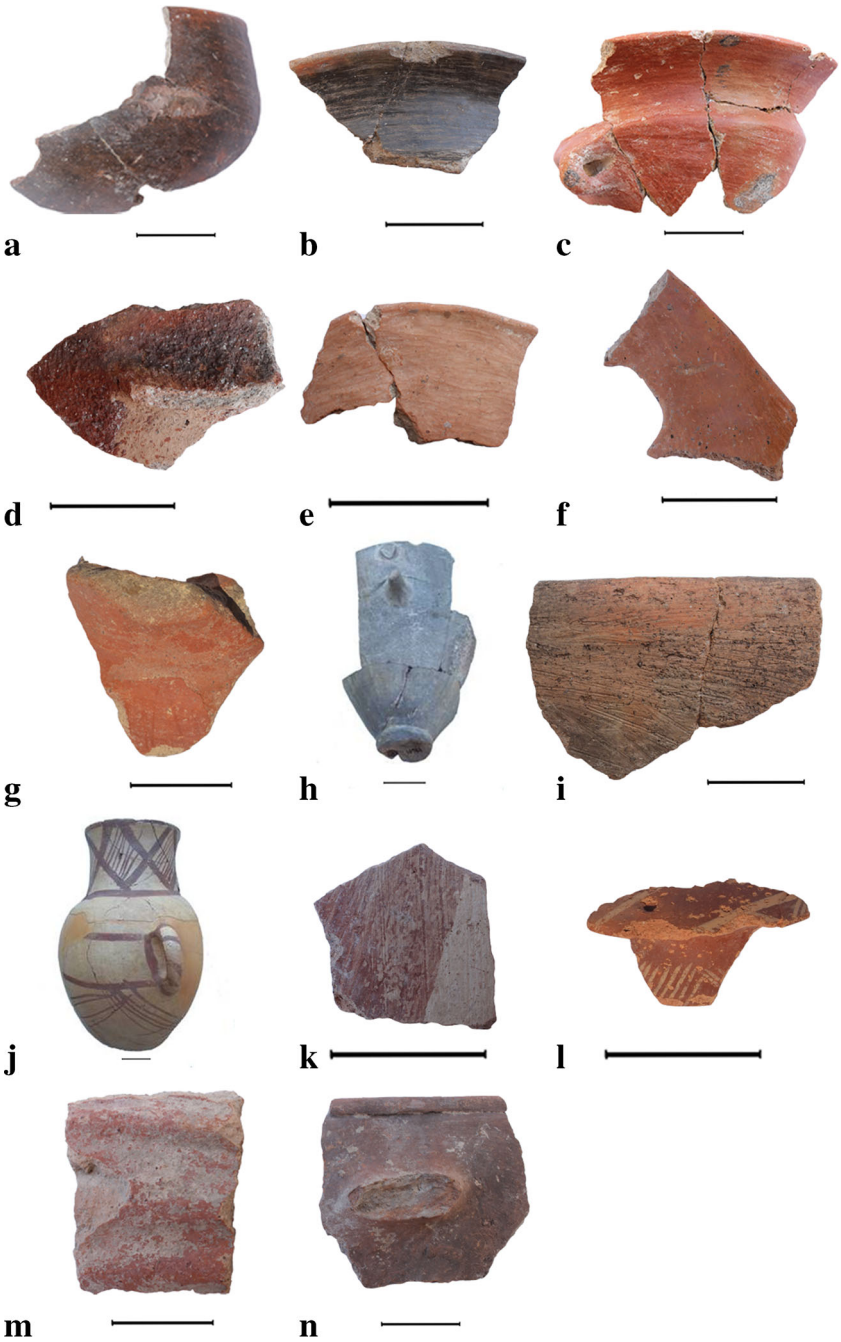


Fig. 2 Example of wares sampled from phases I to IV at Phaistos. **a** Burnished (B) bowl. **b** Scribble burnished (ScrB) bowl. **c** Red slipped and mottled (RS/M) bowl. **d** Burnished and granulated (B/Gra) handle of a jar. **e** Orange Buff (O/Buff) bowl. **f** Brown slipped and polished (BrS/Po) handle. **g** Red burnished (RBW) chalice. **h** Dark grey pattern burnished (DGPB) chalice. **i** Coarse (Coarse) deep bowl. **j** Dark-on-Light (DOL) jar. **k** Wiped and washed (W&W) jar. **l** Light-on-dark (LOD) pyxis. **m** Pithos (PW). **n** Cooking pot (CPW). Bar = 5 cm. (Photos courtesy of the Italian School of Archaeology in Athens)

understand whether it was a matter of a single 'technological revolution' as described by some literature based on firing procedures.

Methods

The integration of different analytical techniques and macroscopic observation is required for a better understanding of the firing process. All the 304 samples were prepared as thin sections with standard procedures and analysed under a polarised light microscope. Petrographic description was made according to the system developed by Whitbread (1989). Estimation of firing procedures was made by scanning electron microscopy coupled with energy dispersive spectroscopy (SEM-EDAX) and Fourier transform infrared spectroscopy (FT-IR), in addition to macroscopic observation of the colour developed by both body and surface during firing. This last feature was recorded for all the sampled ceramics from which 58 were selected for further analytical investigation (Table 3). Samples were chosen in order to represent the variability encountered in the main fabric and ware groups.

Table 3 Ware examined by FTIR and SEM by phase

Phase	Ware	FTIR	SEM
FN III			
	B	8	3
	Coarse	3	1
	ScrB	2	1
FN IV			
	B	1	
	B/Gra	1	3
	Coarse	2	1
	RS/M	3	3
	ScrB	4	3
FN IV-EM IA			
	O/Buff		1
EM IA			
	BrS/Po	1	5
	Coarse		1
	CPW		1
	DGPB	1	
	W&W	1	1
EM IA-B			
	Coarse		1
EM IB			
	CPW	1	2
	DGPB	2	2
	DOL		8
	LOD		1
	PW		1
	RBW		1
	W&W		2
Total		30	42

For ware abbreviations, cf. Fig. 1

While acknowledging the limitation of such estimates, macroscopic examination of colour variation in the pot section and surface can be used to suggest the atmosphere developed during or in the last stage of the firing. Four definitions were chosen to define the materials from Phaistos based on macroscopic observations. Oxidising (O) and Reducing (R) atmosphere are used for those samples which show evidence of exposure to a constant atmosphere, respectively, abundant in oxygen or abundant in carbon monoxide. This usually results in a light colour in O atmosphere and dark colour in R atmosphere, evenly developed from core to margins. Ceramics, however, often show intermediate stages. Commonly, dark-coloured core and light-coloured margins are encountered or light-coloured core and dark-coloured margins. In the first case, it can be argued that the ceramics were exposed to an oxidising atmosphere in the last phase of the firing (defined as partly oxidised: Partly O) with the following concurring cases: (1) after a reducing phase or/and (2) the ceramic paste contains abundant organic material. In both cases, firing was not maintained for long enough to allow a complete oxidation of the paste. When accompanied by evidence of variably developed microstructure across the vessel section and of micro-bloating, it can be suggested that firing was of short duration, perhaps with a corresponding steep temperature gradient (Buxeda et al. 2003, p. 273; Tomkins 2001, p. 304). In the second case, samples are defined as fired in a partly reducing atmosphere (Partly R), in which reduction occurred at the end of the firing, but was not maintained for long enough to obtain a homogeneous colour across the section, as would be the case in a fully reducing atmosphere firing.

SEM examination was performed on 42 vessels, in fresh fracture (Tite et al. 1982) to observe microstructural changes and estimate firing temperature in terms of T_{eq} (Tite and Maniatis 1975; Kilikoglou, in Wilson and Day 1994; Day and Kilikoglou 2001). EDAX analysis was used to obtain a semi-quantitative estimation of the chemical composition of different areas of the ceramic sample. The nomenclature used here for relative composition of the paste is low calcareous (< 6% CaO), calcareous (> 6% CaO) or high calcareous (> 10% CaO) paste, on the basis of CaO content. For FT-IR analyses, 30 samples were chosen, of which 14 were compared to the results obtained by SEM. FTIR samples were prepared using the potassium bromide pellet method (Berna et al. 2007) and FTIR spectra were collected in the range of 4000–400 cm^{-1}. Van der Marel and Beutelspacher (1976) have been adopted as reference for band identification and the results interpreted following the literature on ceramics (Maniatis et al. 1982, 2002; Shoval 1988, 2003; Shoval and Beck 2005; Maritan et al. 2006; Berna et al. 2007; Papadopoulou and Maniatis 2013).

Results

Thin-section petrography

Petrographic results are presented briefly in order to note features that may have been influenced by firing (cf. Mentesana 2014; Mentesana 2016; Mentesana et al. 2016). The samples from Phaistos have been divided into 9 main fabrics and 26 loners on the basis of their petrographic features. Colour names are used to easily identify each fabric, and they are not related to the vessel colour. With the exception of the Green fabric, all the main fabrics are local, that means that the raw materials used for the vessels manufacture can be found in the vicinity of the site in a radius of 10 km. The production location of the pottery can be considered 'broadly' near Phaistos or at the site itself. Examination of pottery from Phaistos has suggested a possible shift in the location of ceramic production between the four phases (Mentesana et al.

2016; Mentesana 2016), but there is no clear evidence of ceramic production at the site or nearby prior to EM II (Todaro 2012). Petrographic groups are described as follow (Table 4):

Blue fabric (Fig. 3a) is a major fabric at the site, mainly used to manufacture pottery in FN III, but continued, in a few examples, up to EM IB. The paste is densely packed with quartz, feldspars and mica, plus a varied coarse fraction, mainly fragments of metaquartzite, silt/sandstones, bioclastic limestone and basalt; organics are occasionally present. The coarse vessels are manufactured by the addition of a coarser fraction of the same mineralogy. FN III samples present high internal variability in terms of mineralogy compared to samples from the subsequent phases. The possibility that this is due to raw material intra-source variability or/and to the exploitation of different sources cannot be excluded.

Yellow fabric (Fig. 3b) is a broad fabric used from FN III and its frequency increases throughout FN IV-EM IA to become one of the main fabrics in EM IB. It is composed of an orange/red-firing clay mixed with a wide range of rounded to well-rounded aplastic inclusions, mainly low-medium grade metamorphic, sedimentary and basic igneous rock fragments. The size distribution of the coarse fraction and the mineralogical differences between the coarse and the fine fraction (absence of fragments of basic igneous and low-medium grade metamorphic rocks in the fine fraction) suggest the use of temper. While the packing, sorting and size of the aplastic inclusions vary over time and within single phases, leading to the formation of several subgroups, this is a consistent recipe over time. This fabric offers a strong match with later material from Ayia Triadha (Belfiore et al. 2007) and Kommos (Day and Kilikoglou 2001; Day et al. 2011).

Violet fabric (Fig. 3c) is found in some samples from FN III and EM IA, mainly in EM IB. This fabric is composed of a densely packed fine fraction of mica, quartz, feldspar and more rarely amphibole and epidote with organics occasionally present. A coarse fraction occurs only rarely, as larger inclusions of mainly low-grade metamorphic rocks, chert, siltstones and quartzite as well as very rarely altered basalt. Some samples from Knossos for which a provenance from the Mesara was suggested match this fabric (Wilson and Day 1999, p. 39).

Green fabric (Fig. 3d) occurs in samples of FNIV and EM IA. Densely packed with well-sorted inclusions of limestone and sandstone, this fabric finds a broad comparison with the Early Neolithic fabrics identified at Knossos (Fabrics 1b and 2a, Tomkins 2001).

Orange fabric (Fig. 3e) includes samples belonging to EM IA but mainly to EM IB. The fabric comprises a very fine orange-firing clay with larger sub-angular inclusions of mixed mineralogy, ranging from phyllite/schist to siltstones and sandstones, to basalt degrading to serpentinite, as well as rare granodiorite. The coarse fraction appears to be added by the potter by the absence of the metamorphic, sedimentary and igneous rock fragments in the fine fraction. This fabric is characterised by fine red clay pellets and striations, which represent the best microscopic evidence of clay mixing.

Pink fabric (Fig. 3f) first appears in EM IA but seems to have been in use mainly in EM IB. It is characterised by a red/orange clay densely packed with quartz, feldspar, muscovite, biotite, epidote and amphibole, while the

Table 4 Fabric occurrence per phase and ware

Fabric	Phase	Ware	Example
Blue: orange/brown clay densely packed with quartz and sand--size inclusions	FN III-IV, EM IA[a]-B[a]	B, ScrB, B/Gra[a], CPW, DGPB[a], RBW, Coarse	Fig. 3a
Yellow: orange/red-firing fine to very fine clay with sand-size inclusions	FN III[a]-IV, EM IA-B	B[a], ScrB[a], B/Gra, RS/M, O/Buff, BrS/Po, DOL, W&W, LOD, PW, Coarse	Fig. 3b
Violet: fine clay with well-sorted quartz, mica and metamorphic rocks	FN III, EM IA-B	B, DGPB	Fig. 3c
Green: yellow-firing clay with limestone and microfossils	FN IV-EMIA	O/Buff[a], BrS/Po[a]	Fig. 3d
Orange: orange-firing very fine clay(s) plus sand-size inclusions	EM IA-B	Coarse, DOL[a], W&W[a]	Fig. 3e
Pink: orange-firing clay densely packed with metamorphic and igneous rocks	EM IA-B	Coarse, CPW	Fig. 3f
Purple: fine red-firing clay packed with biotite, quartz, hematite and sand-size inclusions	EM IA-B	Coarse, ScrB[a], BrS/Po[a]	Fig. 3g
Brown: very fine yellow-firing clay with sedimentary and metamorphic rocks	EM IB	DOL	Fig. 3h
Red: red-firing clay with low-medium grade metamorphic rocks	EM IB	CPW, DOL[a]	Fig. 3i

[a] Minor occurrence relative to the sampled material of the same phase

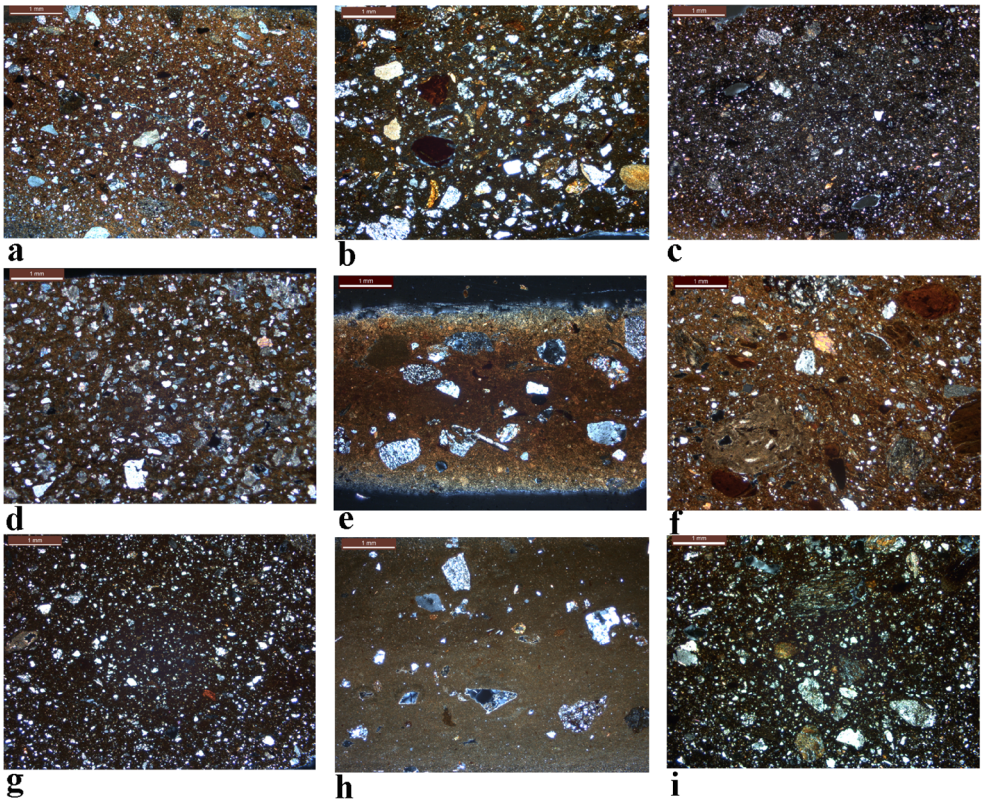


Fig. 3 Photomicrographs (XP) of the main fabrics from Phaistos. **a** Blue fabric (PHA 12/1). **b** Yellow fabric (PHA 12/241). **c** Violet fabric (PHA 12/91). **d** Green fabric (PHA 12/207). **e** Orange fabric (PHA 12/277). **f** Pink fabric (PHA 12/264). **g** Purple fabric (PHA 12/278). **h** Brown fabric (PHA 12/288). **i** Red fabric (PHA 12/267)

coarse fraction is composed of a wider range of metamorphic rocks (quartzite, metamorphosed limestone, amphibolite and gneiss, biotite schist, sillimanite-schist to chlorite phyllite), quartz sandstones/siltstones, calcite and plagioclase feldspars; rare altered basalt and shell fragment; and more frequent granodiorite and slate.

Purple fabric (Fig. 3g) is well attested in EM IA-B phases. The fabric is composed of a red-firing clay packed with a well-sorted fine fraction of mica, quartz and feldspar; larger inclusions of mixed mineralogy reflecting the mineralogy of the fine fraction occur rarely. The fabric presents some internal variability in terms of manipulation of the raw materials as some samples show signs of clay mixing. This fabric broadly matches with a group of LM IIIB short-necked amphorae from Kommos (Day et al. 2011).

Brown fabric (Fig. 3h) samples from this fabric belong exclusively to EM IB. Vessels are characterised by a yellow-firing, very fine clay containing some microfossils; a well-sorted and well-rounded coarse fraction of mixed nature (mainly quartz siltstones, lithic greywacke, metaquartzite, phyllite, biotite schist and gneiss) seems to have been added to the base clay. This fabric matches well some samples from the Kommos (Day and Kilikoglou 2001, Group 1, p. 116).

Red fabric (Fig. 3i) samples belong exclusively to EM IB and mainly to CPW. They are characterised by a coarse groundmass, densely packed with quartz, mica and amphibole and a coarse fraction of mainly medium-grade metamorphic rocks coupled with altered basic igneous rocks. The fabric has a close petrographic match to some of the wasters found in the Kommos kiln (Day and Kilikoglou 2001, Group 6, p. 117). This fabric includes also a DOL jar, which, however, shows evidence of possible clay mixing and it has been subgrouped for this reason.

Macroscopic examination

FN III samples present two patterns in terms of colour variations (Table 5). Some show a uniform dark grey or brown section (Fig. 4a) and usually a brown surface which suggests exposure to a constant atmosphere, which is identified as O. Some other samples show a striking colour variation between core and surface, from dark grey core to sharp red margins (Fig. 4b). These features point to the presence of organic compounds in the paste and/or a drastic change of atmosphere during firing from reducing to oxidising. This is defined as Partly O, as it was not constantly maintained to allow full oxidation. In some cases, especially in vessels belonging to the B and ScrB, the surface is consistently black to dark brown, meaning that the atmosphere was reducing in the last stage of the firing and not maintained for long enough to allow

Table 5 Summary of the recorded colours in section for samples analysed with SEM and FTIR grouped by phase

Sample		Phase	Ware	Fabric	Colour of the core	Colour of the rims	Surface colour	Atmosphere
PHA 12/	1	FN III	B	Blue	Brown	Bbrown	Black	O-Partly R
PHA 12/	5	FN III	B	Blue	Dark grey	Orange/dark grey	Black	Partly O-Partly R
PHA 12/	6	FN III	B	Blue	Light brown	Light brown	Dark brown	O-Partly R
PHA 12/	25	FN III	Coarse	Blue	Dark grey	Orange	Brown	Partly O
PHA 12/	35	FN III	ScrB	Blue	Brown	Brown	Brown	O-Partly R
PHA 12/	38	FN III	B	Blue	Light brown	Light brown	Light brown	O
PHA 12/	39	FN III	B	Blue	Light brown	Light brown	Light/dark brown	O-Partly R
PHA 12/	42	FN III	B	Violet	Dark grey	Orange	Black	Partly O-Partly R
PHA 12/	46	FN III	Coarse	Blue	Brown	Orange	Orange	Partly O
PHA 12/	51	FN III	B	Blue	Brown	Brown	Black	R
PHA 12/	57	FN III	B	Violet	Dark grey	Orange	Black	Partly O-Partly R
PHA 12/	87	FN III	ScrB	Yellow	Dark grey	Orange	Orange	Partly O
PHA 12/	90	FN III	Coarse	Blue	Brown	Brown	Black	R
PHA 12/	91	FN III	B	Violet	Dark grey	Orange	Black	Partly O-Partly R
PHA 12/	101	FN IV	ScrB	Blue	Dark grey	Orange	Black	Partly O-Partly R
PHA 12/	107	FN IV	ScrB	Blue	Grey	Grey/black	Black	R
PHA 12/	110	FN IV	ScrB	Yellow	Dark grey	Orange	Black	Partly O-Partly R
PHA 12/	111	FN IV	B	Blue	Dark grey	Orange	Black	Partly O-Partly R
PHA 12/	112	FN IV	ScrB	Blue	Dark grey	Orange	Black	Partly O-Partly R
PHA 12/	119	FN IV	RS/M	Yellow	Dark grey	Orange	Red/black (mottling)	Partly O
PHA 12/	125	FN IV	RS/M	Yellow	Dark grey	Orange	Red/black (mottling)	Partly O
PHA 12/	128	FN IV	RS/M	Yellow	Dark grey	Orange	Red/black (mottling)	Partly O
PHA 12/	132	FN IV	RS/M	Yellow	Dark grey	Brown	Red/black (mottling)	O
PHA 12/	135	FN IV-EM IA	O/Buff	Yellow	Grey	Orange	Red	Partly O
PHA 12/	138	FN IV	Coarse	Yellow	Dark grey	Orange	Red/black (mottling)	Partly O
PHA 12/	144	FN IV	Coarse	Yellow	Dark grey	Orange	Orange	Partly O
PHA 12/	161	FN IV	Coarse	Yellow	Grey	Orange	Orange	Partly O
PHA 12/	168	FN IV	B/Gra	Yellow	Grey	Orange	Red	Partly O
PHA 12/	170	FN IV	B/Gra	Yellow	Light orange	Light orange	Red	O
PHA 12/	173	FN IV	B/Gra	Blue	Orange	Orange	Orange	O
PHA 12/	182	EM IA	W&W	Pink	Brown	Brown	Brown	O
PHA 12/	186	EM IA	BrS/Po	Yellow	Light brown	Light brown	Orange	O
PHA 12/	187	EM IA	DGPB	Violet	Brown	Grey	Dark grey	R
PHA 12/	188	EM IA	BrS/Po	Blue	Orange	Orange	Orange	O
PHA 12/	206	EM IA	BrS/Po	Yellow	Light brown	Light brown	Orange	O
PHA 12	207	EM IA	BrS/Po	Green	Light brown	Orange	Light brown	O
PHA 12/	210	EM IA	CPW	Blue	Red	Red	Red	O
PHA 12/	220	EM IA	Coarse	Orange	Light red	Light red	Light red	O
PHA 12/	222	EM IA-B	Coarse	Purple	Dark red	Dark red	Dark red	O
PHA 12/	225	EM IA	BrS/Po	Yellow	Light brown	Light brown	Orange	O
PHA 12/	214	EM IB	CPW	Red	Dark red	Dark red	Dark red	O
PHA 12/	241	EM IB	DOL	Yellow	Light brown	Light brown	White-red painted	O
PHA 12/	242	EM IB	DOL	Yellow	Light brown	Light brown	White-red painted	O
PHA 12/	250	EM IB	W&W	Yellow	Orange	Orange	Orange	O
PHA 12/	258	EM IB	DOL	Yellow	Light brown	Light brown	White-red painted	O
PHA 12/	264	EM IB	CPW	Pink	Brown	Brown	Brown	O
PHA 12/	267	EM IB	CPW	Red	Red	Red	Red	O
PHA 12/	276	EM IB	PW	Yellow	Yellow	Yellow	Yellow	O
PHA 12/	277	EM IB	DOL	Orange	Orange	Orange	White-red painted	O

Table 5 (continued)

Sample		Phase	Ware	Fabric	Colour of the core	Colour of the rims	Surface colour	Atmosphere
PHA 12/	278	EM IB	DOL	Purple	Dark red	Dark red	White-red painted	O
PHA 12/	282	EM IB	DOL	Yellow	Light orange	Light orange	White-red painted	O
PHA 12/	284	EM IB	W&W	Purple	Dark red	Orange/dark red	Dark red	O
PHA 12	288	EM IB	DOL	Brown	Light brown	Light brown	White-red painted	O
PHA 12	289	EM IB	DOL	Red	Light brown	Light brown	White-red painted	O
PHA 12/	293	EM IB	DGPB	Violet	Brown	Grey	Dark grey	R
PHA 12/	295	EM IB	DGPB	Violet	Grey	Grey/black	Black	R
PHA 13/	5	EM IB	LOD	Yellow	Orange	Orange	Red-white painted	O
PHA 13/	11	EM IB	RBW	Blue	Grey	Orange	Orange	Partly O

a complete reduction of the vessel. In these cases, a Parly R label is added to identify the change in atmosphere at the final stage (Fig. 4a-b).

Many of the samples from FN IV show the same variability (Table 5), but there is a higher proportion of samples showing striking variation in colour across the break (Fig. 4c). Those samples that have a black burnished surface (B and ScrB ware) can be considered, as in the previous phase, exposed to a Partly O-Partly R atmosphere. Those samples that show the same colour variations between core and margins but with a light-coloured surface (RS/M, B/Gra, Coarse and O/Buff ware) are considered exposed to a Partly O atmosphere. On the other hand, in the same phase, a few vessels belonging to the RS/M and B/Gra show a homogeneous orange colour in section and light-coloured surfaces and are identified as being fired in an O atmosphere (Fig. 4d). RS/M is also characterised by black mottled areas, which, however, would have required a specific procedure, not adopted here, to be investigated. The literature reports several methods to produce this effect, none of which can be excluded (Noble 1960; Farnsworth and Simmons 1963; Betancourt et al. 1979).

In EM IA and mainly in EM IB, the majority of vessels show a homogeneous light brown/orange colour through the section and on the surface (Table 5). Petrography suggests that organics are less frequent as in the previous phases and some fabrics seem to be more calcareous than others (such as the Yellow fabric, see Section 3.2), both factors which may promote a lighter body colour. However, most of the samples

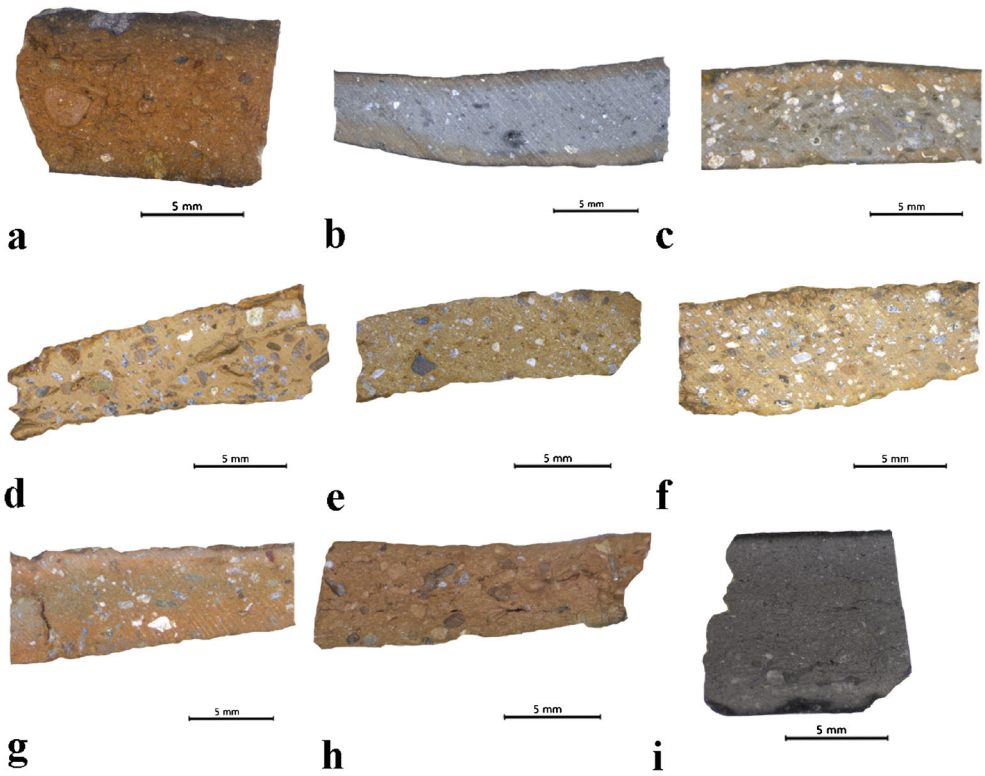


Fig. 4 Fresh cut ceramic samples from Phaistos. **a** PHA 12/1 (B), Blue fabric. **b** PHA 12/42 (B), Violet fabric. **c** PHA 12/112 (ScrB), Blue fabric. **d** PHA 12/170 (B/Gra), Yellow fabric. **e** PHA 12/188 (BrS/Po), Blue fabric. **f** PHA 12/206 (BrS/Po), Yellow fabric. **g** PHA 12/267 (CPW), Red fabric. **h** PHA 12/277 (DOL), Orange fabric. **i** PHA 12/295 (DGPB), Violet fabric

(Fig. 4e–h), regardless of fabric and ware, seem to be fired in a constantly maintained oxidising atmosphere, which allows the development of homogeneous colour through the section. Those vessels belonging to DGPB were fired in a R atmosphere, but they still show a homogeneously developed dark colour through section (Fig. 4i).

SEM-EDAX examination

Microstructures developed during firing, paste and surface composition are discussed here by phase and fabric, summarised in Table 6. Discussion of surface treatment is limited here to those carried out before firing and affected by temperature and atmosphere during firing (i.e. slipping, painting and burnishing), which can aid the reconstruction of firing practice.

Samples examined from FN III-IV belong to three different fabrics: Blue, Violet and Yellow. The samples of the Blue fabric show typical non-vitrified (NV) microstructure (Fig. 5a) in a low calcareous iron-rich paste. Samples from the Violet fabric were made also in a low calcareous paste, but microstructural differences between the core and the margins of the vessel, in the range of NV to initial vitrification/vitrification (IV/V) microstructure, can be observed (Fig. 5b, c). Yellow fabric samples were produced with a low calcareous paste which is higher in magnesium and develops a characteristic microporous microstructure probably due to its composition (Fig. 5d, e; cf. Maniatis et al. 1988, p. 270). Such samples also show micro-bloating in the core, which could suggest a fast-firing procedure (Fig. 5d, e; cf. Buxeda et al. 2003, p. 273; Tomkins 2001, p. 304). Sample 12/170 represents an exception amongst the Yellow fabric, being a high calcareous body, though the Yellow fabric does show high variability, either through source variability or inconsistent mixing.

In terms of surface treatment, the examination of B and ScrB suggests that burnishing was performed directly on the body and did not involve the application of a slip: the surface raw material is the same as the body with higher concentrations of potassium and more rarely of aluminium, which is due to the alignment and compaction of fine clay particles by burnishing (cf. Kilikoglou and Maniatis 1993, p. 439; Kilikoglou, in Wilson and Day 1994, pp. 70–73). The microstructure of the vessel surface is flat and more compact compared to the body and it shows NV or IV stages (Fig. 6a). O/Buff vessels do not have such a flat, compact surface and the surface is of similar composition of the body. RS/M vessels have a thick layer on top of the body, which is higher in iron and lower in magnesium and calcium compared to the body (Fig. 6b). Amongst the RS/M vessels, only sample 12/132 shows no chemical and microstructural difference between the body and the surface. The surface layer looks to be a well-flattened portion of the body, which being high in iron and low in calcium paste, suggesting the vessel was slipped (Fig. 6c). This vessel seems to be an exception amongst the others. B/Gra vessels are produced by applying a surface material different to that of the body: EDAX analysis shows a layer with raised iron and potassium and lower in calcium and magnesium compared. The roughness of the surface may be due to tempering with sand-size aplastic inclusions, resulting in the characteristic granulated appearance. The microstructure developed by the surface layer is typical of low calcareous clay (Fig. 6d).

The examination of EM IA-B samples reveals a picture of continuity and change. In addition, new fabric groups (Brown, Green, Orange, Pink, Purple and Red) appear and in the EM IB are linked with the production of specific wares (e.g. the Red and Pink fabric were used mainly for cooking pots; the Purple, Brown and Orange fabric for DOL and W&W; cf. Mentesana et al. 2016).

Samples belonging to the Blue and Violet fabric (CPW, DGPB, RBW, BrS/Po) show NV to IV microstructure (Fig. 4f), manufactured in a low calcareous paste and burnished directly on the body, without application of a slip, as was the case in previous phases (Fig. 6e). This is particularly significant in the case of samples 12/188 which as BrS/Po might have been expected to be slipped. However, the surface is a continuum with the body from the microstructural and chemical examination (Fig. 6f).

Samples from the Yellow fabric indicate a change in firing temperatures and the use of a more calcareous paste compared to the previous phases. Specifically, EM IA samples show NV to IV microstructure (Fig. 5g) as did the samples from the Blue and Violet fabric. In contrast, in EM IB, microstructures range from IV to total vitrification (TV) (Fig. 5h). In terms of surface treatment, the Yellow fabric was still used to manufacture mainly slipped and slipped and painted ware. The slip of BrS/Po is highly varied in our samples, but, compared to the body, all the slips are lower in calcium and higher in iron. The slips are thinly applied compared to the RS/M and subsequently burnished, producing a well-flattened layer (Fig. 6g). Despite the fact that macroscopically most of the samples seemed slipped with a creamy white substance and painted with a red substance afterwards, the samples analysed of DOL and W&W do not show any slip layer distinguishable from the body: the paint layer seems to have been applied directly on the body. Figure 6g shows the surface of sample 12/242: the top layer is composed of a material lower in calcium and magnesium and higher in iron and potassium, which has a dense V microstructure; this layer is applied directly on the body. LOD presents the opposite colour contrast on the surface: cream-white pattern on a red background. Sample 13/5 is examined from the surface down in order to better identify the different layers: the red slip is composed of a material high in iron and low in calcium, while the creamy white paint is similar in composition to the body, but contains higher

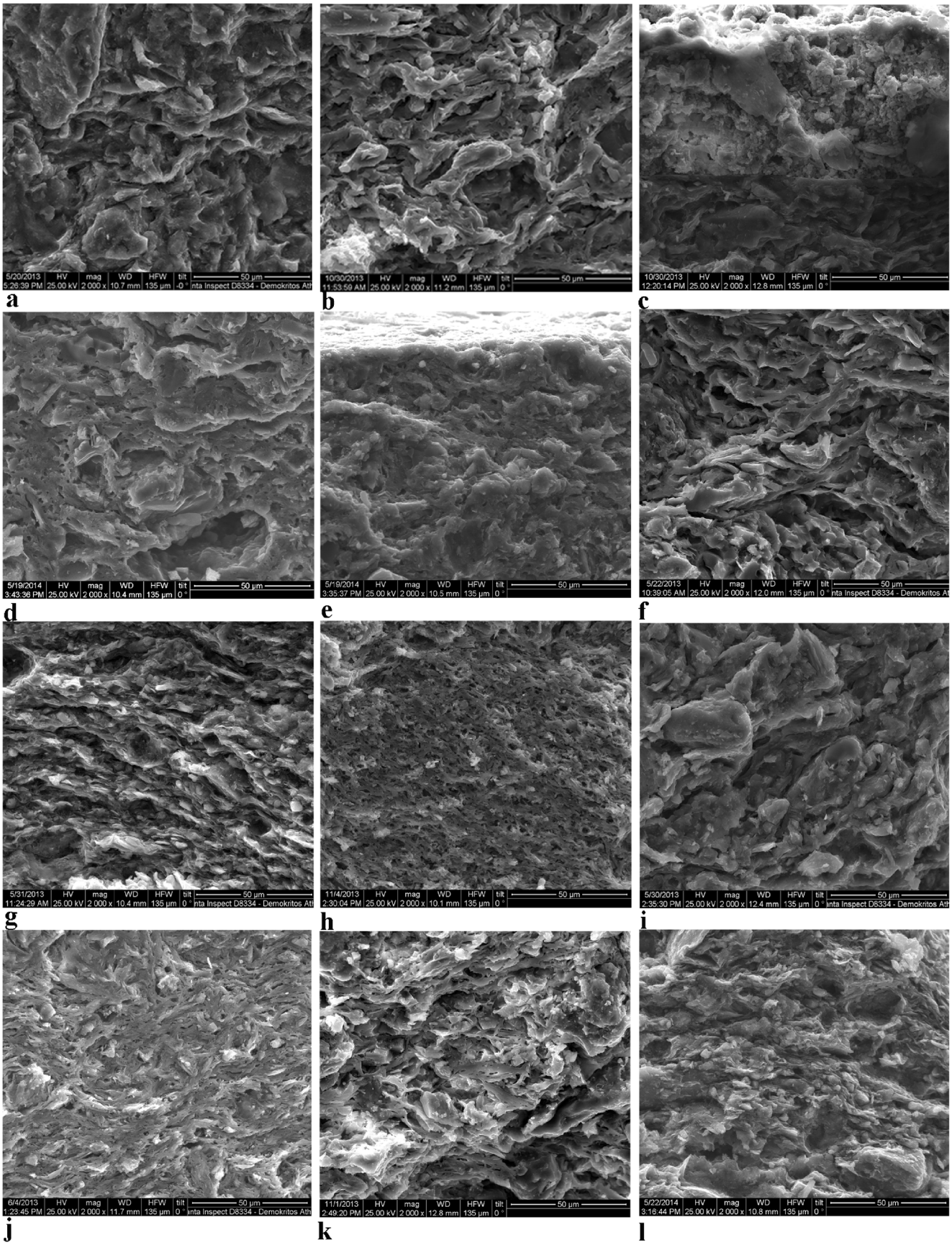
Table 6 Summary of SEM-EDAX examination

Sample		Phase	Ware	Fabric	Body microstructure	Body composition	Surface composition	Surface microstructure	Atmosphere	T_{eq}
PHA 12/	1	FN III	B	Blue	NV	low-calc.	Alike	NV	O-Partly R	800
PHA 12/	38	FN III	B	Blue	NV	low-calc.	Alike	NV	O	800
PHA 12/	87	FN III	ScrB	Yellow	V	low-calc.	Alike	IV	Partly O	850–950
PHA 12/	90	FN III	Coarse	Blue	NV	low-calc.	Alike	–	R	800
PHA 12/	91	FN III	B	Violet	IV/V	low-calc.	Alike	NV	Partly O-Partly R	800–950
PHA 12/	101	FN IV	ScrB	Blue	IV/V	low-calc.	Alike	–	Partly O-Partly R	800–950
PHA 12/	107	FN IV	ScrB	Blue	IV/V	low-calc.	Alike	–	R	800–900
PHA 12/	112	FN IV	ScrB	Blue	IV/V	low-calc.	Alike	NV	Partly O-Partly R	800–950
PHA 12/	119	FN IV	RS/M	Yellow	NV/IV$_c$	low-calc.	Iron-rich, calcium-poor slip	NV	Partly O	850
PHA 12/	128	FN IV	RS/M	Yellow	IV$_c$	low-calc.	Iron-rich, calcium-poor slip	IV	Partly O	800–850
PHA 12/	132	FN IV	RS/M	Yellow	NV	low-calc.	Alike	NV	O	800
PHA 12/	135	FN IV-EM IA	O/Buff	Yellow	IV/V$_c$	low-calc.	Alike	IV	Partly O	800–950
PHA 13/	161	FN IV	Coarse	Yellow	NV/IV	low-calc.	Iron-rich slip	IV	Partly O	850
PHA 12/	168	FN IV	B/Gra	Yellow	IV$_c$	low-calc.	Iron-rich, calcium-poor material	NV	Partly O	800–850
PHA 12/	170	FN IV	B/Gra	Yellow	V$_c$	high-calc.	Iron-rich, calcium-poor material	V	O	850–1050
PHA 12/	173	FN IV	B/Gra	Blue	NV	low-calc.	–	–	O	800
PHA 12/	182	EM IA	W&W	Pink	NV	calc.	Calcium-poor paint	NV	O	800
PHA 12/	186	EM IA	BrS/Po	Yellow	NV	calc.	Iron-rich, calcium-poor material	NV	O	800
PHA 12/	188	EM IA	BrS/Po	Blue	NV	low-calc.	Alike	NV	O	800
PHA 12/	206	EM IA	BrS/Po	Yellow	NV	calc.	Iron-rich, calcium-poor material	NV	O	800
PHA 12	207	EM IA	BrS/Po	Green	NV	high-calc.	Iron-rich, calcium-poor material	NV	O	800
PHA 12/	210	EM IA	CPW	Blue	NV	low-calc.	Alike	–	O	800
PHA 12/	220	EM IA	Coarse	Orange	V$_c$	calc.	Alike	V	O	850–1050
PHA 12/	222	EM IA-B	Coarse	Purple	IV$_c$	low-calc.	Alike	–	O	800–850
PHA 12/	225	EM IA	BrS/Po	Yellow	IV$_c$	calc.	Iron-rich, calcium-poor material	V	O	850–1050
PHA 12/	214	EM IB	CPW	Red	NV	low-calc.	Alike	–	O	800
PHA 12/	241	EM IB	DOL	Yellow	V$_c$	high-calc.	Iron-rich, calcium-poor paint	V	O	850–1050
PHA 12/	242	EM IB	DOL	Yellow	V$_c$	high-calc.	Iron-rich, calcium-poor paint	TV	O	950–1050
PHA 12/	250	EM IB	W&W	Yellow	V$_c$	high-calc.	–	–	O	850–1050
PHA 12/	258	EM IB	DOL	Yellow	TV$_c$	high-calc.	–	–	O	1050–1150
PHA 12/	267	EM IB	CPW	Red	NV	low-calc.	Alike	–	O	800
PHA 12/	276	EM IB	PW	Yellow	V$_c$	calc.	Alike	–	O	850–1050
PHA 12/	277	EM IB	DOL	Orange	IV	low-calc.	–	NV	O	800–850
PHA 12/	278	EM IB	DOL	Purple	V$_c$	low-calc.	–	V	O	850–950
PHA 12/	282	EM IB	DOL	Yellow	V$_c$	calc.	Iron-rich, calcium-poor paint?	–	O	850–1050
PHA 12/	284	EM IB	W&W	Purple	V$_c$	calc.	Calcium-poor paint	V	O	850–1050
PHA 12/	288	EM IB	DOL	Brown	V$_c$	high-calc.	Iron-poor slip and iron-rich, calcium-poor paint	TV	O	950–1050
PHA 12/	289	EM IB	DOL	Red	V	high-calc.	Iron-poor slip and iron-rich, calcium-poor paint	V	O	850–1050
PHA 12/	293	EM IB	DGPB	Violet	NV	low-calc.	Alike	NV	R	800
PHA 12/	295	EM IB	DGPB	Violet	IV	low-calc.	Alike	IV	R	750–800
PHA 13/	5	EM IB	LOD	Yellow	IV$_c$	calc.	Calcium-poor, iron-rich slip and iron-poor, calcium-rich paint	–	O	800–850
PHA 13/	11	EM IB	RBW	Blue	NV	low-calc.	Alike	NV	Partly O	800

low-calc. CaO < 6%, *calc. CaO* > 6%, *high-calc.* CaO > 10%, *NV* non-vitrified, *IV* initial vitrification, *V* extensive vitrification, *TV* total vitrification, *c* microstructure typical of a calcareous paste, – non-available data

calcium compared to the slip. No information on microstructure could be retrieved.

Greater variability is observed in other fabrics. The Green fabric sample, 12/207 (BrS/Po), has a high-calcareous paste and shows NV microstructure. The surface is slipped with an iron-rich, low calcium material, as are other samples from the same ware (Fig. 6h). The Red fabric includes sample 12/214 (CPW), which has a low calcareous paste, with NV


a
b
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◀ **Fig. 5** Secondary electron micrographs of some ceramic samples examined from Phaistos. **a** PHA 12/1 (B), NV microstructure. **b**, **c** PHA 12/91 (B), IV microstructure at the section core (b), NV microstructure at the section margin visible under the layer of superficial decoration (**c**). **d**, **e** PHA 12/135 (O/Buff), V microstructure and micro-bloating at the section core (d), IV microstructure at the section margin (**e**). **f** PHA 12/295 (DGPB), IV microstructure. **g** PHA 12/206 (DGPB), NV microstructure. **h** PHA 12/282 (DOL), V microstructure. **i** PHA 12/267 (CPW), NV microstructure. **j** PHA 12/220 (Coarse), V microstructure. **k** PHA 12/278 (DOL), IV-V microstructure. **l** PHA 12/182 (W&W), NV microstructure

microstructure (Fig. 5i), and 12/289 (DOL) which is made in a high-calcareous paste and higher fired. Petrography already suggested differences between these samples (see Section 3.1). In contrast to the other DOL samples, 12/289 shows two distinct layers on top of the body: the first composed of a material similar to the body but higher in calcium and potassium and lower in silica, which can be identified as the cream-white slip; the second layer, a red paint, is lower in calcium and magnesium and higher in iron. The two layers differ also in microstructure, the slip has a typical microsctructure of calcareous materials, while the paint shows a dense microstructure (Fig. 6j). Similarly, the DOL sample from the Brown fabric shows two thin layers of different composition (an iron-rich paint on a calcium-rich slip) but has a high calcareous paste with V microstructure (Fig. 6k). The two samples of the Orange fabric display IV to V microstructure, but, while similar in thin section, they show the use of low calcareous and calcareous paste, respectively (Fig. 5j). Samples from the Purple fabric are relatively high fired, all showing V microstructure, in a low calcareous paste, high in iron and magnesium, which shows a microstructure with clay filaments leaving mainly elongated pores (Fig. 5k). Sample 12/284, on the other hand, has higher calcium and magnesium, and a not dissimilar microstructure, but with larger spherical pores. The sample from Pink fabric, 12/182 (W&W), is made with a calcareous paste and shows NV microstructure (Fig. 5l). The surface treatment of DOL and W&W in the Orange, Purple and Pink fabrics seems to have been produced by applying an iron-rich paint directly to the body, as in the Yellow fabric samples. For example, in samples 12/182 and 12/284 (Fig. 6l), a thin layer was identified, with lower calcium and magnesium compared to the body. This layer seems applied directly on the vessel body, without the application of a light-coloured slip as background.

FT-IR examination

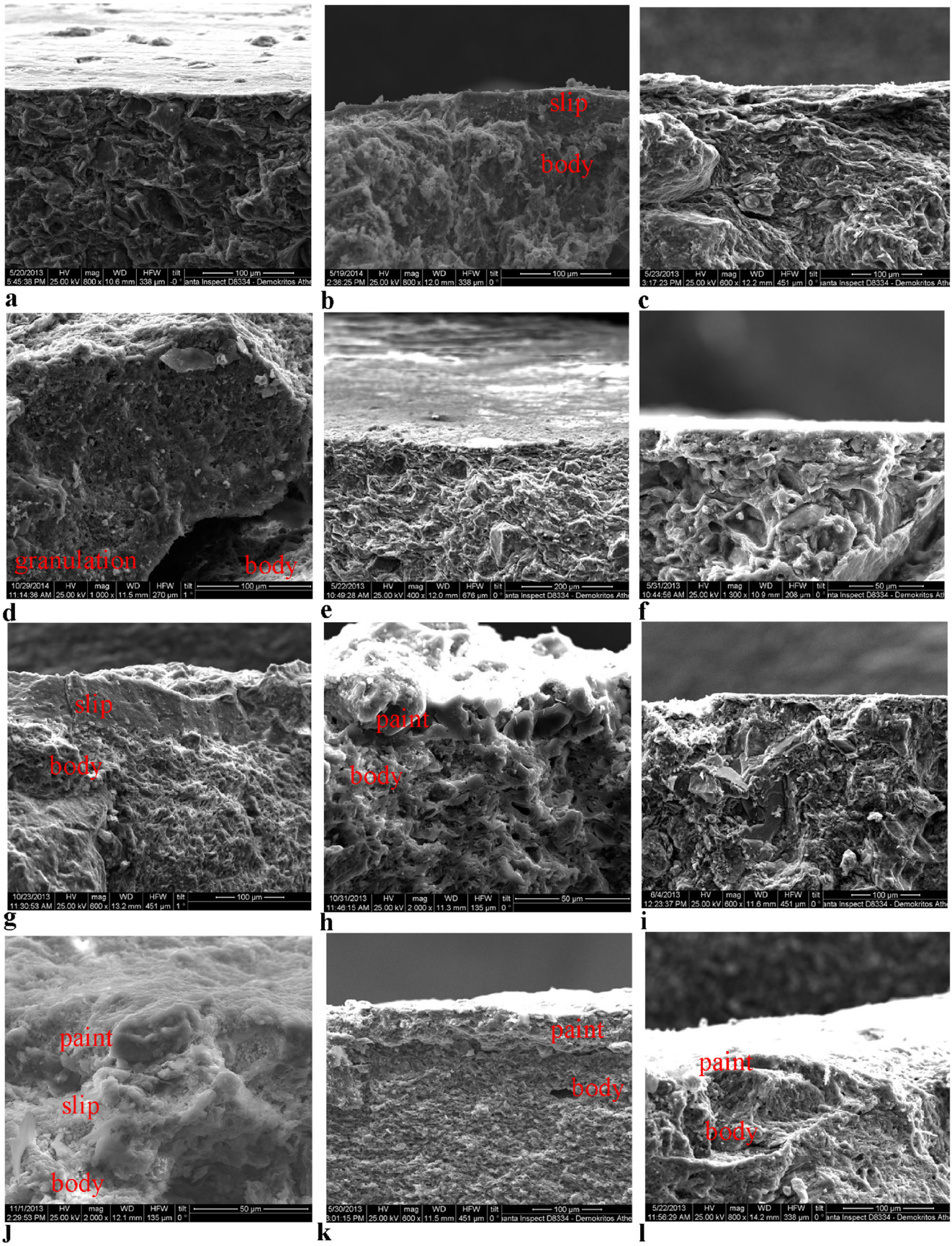
The shift in the main bands of FT-IR spectra is caused by a change in the crystalline and amorphous phases in the sample due to temperature increase (cf. Weiner 2010, pp. 300–306). The bands considered related to firing temperature increase are the main SiO stretching band shifting between 1029 and 1086 cm^{-1}; the SiO and AlO deformation bands shifting between 472 and 460 cm^{-1} and between 527 and 554 cm^{-1}; the presence of the OH stretching band (around 3620 cm^{-1}) which disappears around 600 °C; and the presence of the CO_3 band (1430/876 cm^{-1}) which, depending on amount and size of calcitic inclusions (Shoval et al. 1993), disappears around 700–750 °C. Figure 7 shows some of the FT-IR spectra according to fabric, while Table 7 presents the results for each sample.

Blue fabric Most samples from FN III show a narrow shift of the SiO stretching band from 1030 to a maximum of 1035 cm^{-1}, a SiO, AlO deformation band around 520–527 cm^{-1} and an OH stretching band around 3620 cm^{-1} (Fig. 7:a). Amongst these samples, 12/35, 12/51 and 12/90 show lower wavenumbers for the SiO, AlO deformation bands, while all the others show wavenumber around 474–471 cm^{-1}. Few other samples from FN III and all those from FN IV show higher wavenumbers for the SiO stretching band with two major peaks at around 1030/1080 cm^{-1} and the SiO, AlO bands around 460 cm^{-1} (Fig. 7b). Those might have a peak around 554 cm^{-1}. In contrast, samples from EM IA show the same band shifts of FN III samples. The presence of a CO_3 band at 1427/876 cm^{-1} in some samples is due to the presence of calcitic inclusions in the paste, which occasionally occurs in this fabric, and to a firing temperature below the calcite decomposition.

Violet fabric The FN III samples and sample 12/295 from EM IB show a rather broad SiO stretching band and mainly with two peaks around the 1030/1080 cm^{-1} wavenumber, low wavenumber of the SiO, AlO deformation bands around 460 cm^{-1} and some a shoulder around 554 cm^{-1} (Fig. 7c). In contrast, 12/187 (EM IA) and 12/293 (EM IB) show lower wavenumber for the SiO stretching band, higher for the SiO, AlO deformation bands a band around 527 cm^{-1} and the characteristic OH band (Fig. 7d). Only 12/57 show the presence of a CO_3 band.

Yellow fabric The FT-IR spectra of these samples show a SiO stretching band splitting into two main peaks around 1040 and 1080 cm^{-1} (Fig. 7e). Amongst the other samples, 12/87 show the highest wavenumber at 1088 cm^{-1} (Fig. 7f). The SiO, AlO def. band is shown at around 460 cm^{-1} and sometime as a doublet and most of the samples show a peak at 554 cm^{-1}. None of the samples show an OH stretching band. All the samples show the CO_3 band[1], less defined in samples 12/87 and 138. SEM-EDAX and petrographic examination have shown that this fabric has a higher calcium content in the micromass and more calcitic inclusions when compared to the previous fabrics.

Pink fabric The two samples from the Pink fabric show the SiO band at around 1033 cm^{-1}. Sample 12/264 shows also an


a
b
slip
body
c
d
granulation
body
e
f
g
slip
body
h
paint
body
i
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body
l
paint
body

◀ **Fig. 6** Secondary electron micrographs of the surface of some ceramic samples examined from Phaistos. **a** PHA 12/1 (B). **b** PHA 12/119 (RS/M). **c** PHA 12/132 (RS/M). **d** PHA 12/170 (B/Gra). **e** PHA 12/295 (DGPB). **f** PHA 12/188 (BrS/Po). **g** PHA 12/225 (BrS/Po). **h** PHA 12/242 (DOL). **i** PHA 12/207 (BrS/Po). **j** PHA 12/289 (DOL). **k** PHA 12/288 (DOL). **l** PHA 12/284 (W&W)

OH stretching band shoulder at 3620 cm^{-1} and a SiO, AlO def. band at 470 and 527 cm^{-1} (Fig. 7g). Sample 12/182 shows a shift for the same bands that can allow a distinction between the two samples (Fig. 7h). Both have a large CO_3 peak at 1427/876 cm^{-1} and a small at 712 cm^{-1} as the previous fabric group. At least for 12/182, SEM-EDAX analysis confirmed that the paste is calcareous.

Other characteristic bands observed in all the samples are those in the wavenumber range of 797–778 and 694 cm^{-1} which are due to the quartz contents; an OH deformation band at 1630 cm^{-1} which comes from the absorbed atmospheric water; the doublet at 2921 and 2853 cm^{-1} which is due to the presence of organic matter. The major part of the samples shows a peak around 648 cm^{-1} probably related to the chlorite minerals group or to post-depositional contamination and few other (12/128, 138, 187) peaks linked with the feldspars group around 722–727 cm^{-1}.

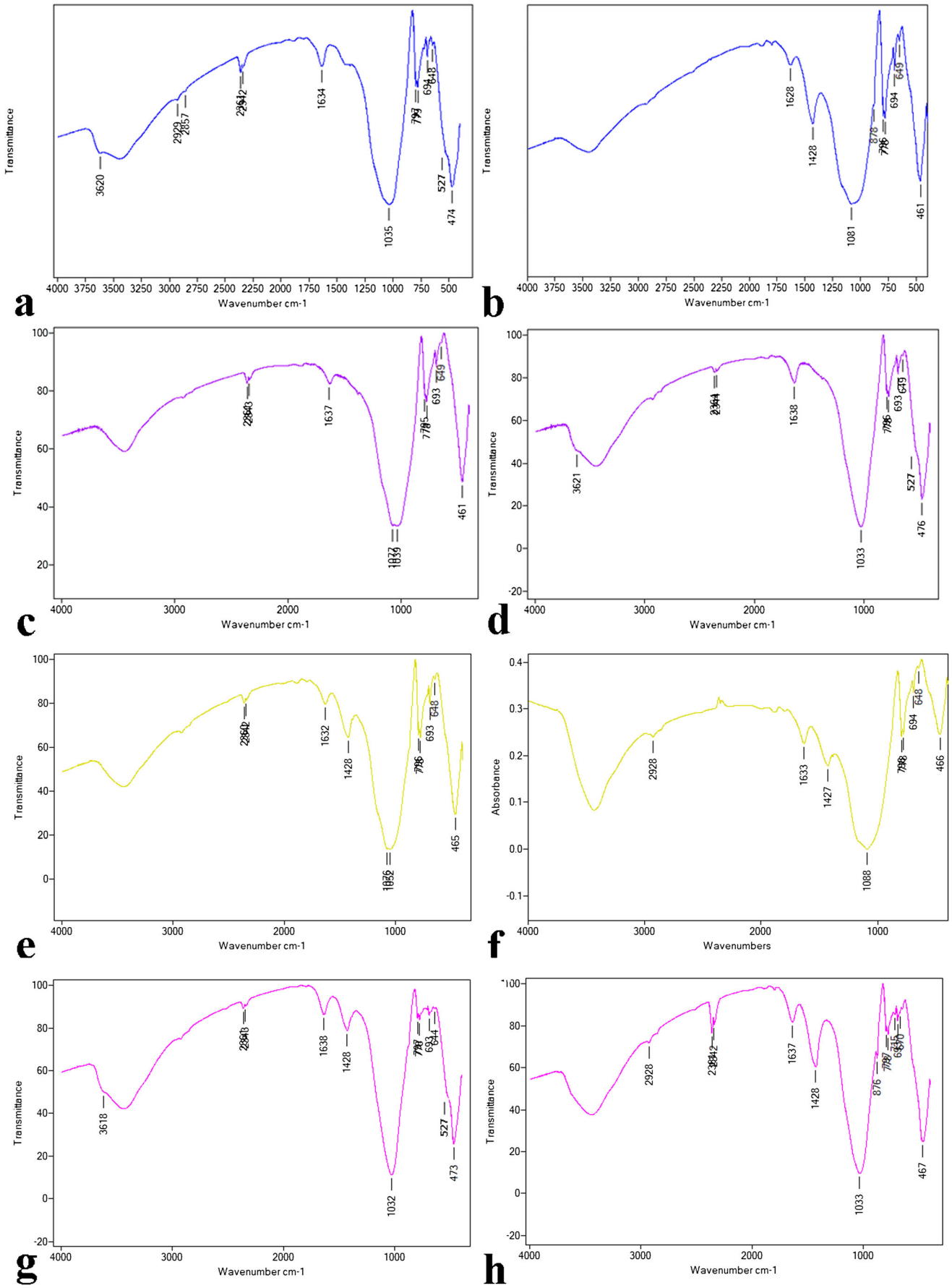
Discussion

The combination of analytical techniques and macroscopic examination is often used to assess firing in terms of firing temperature ranges and atmosphere. However, the works of Gosselain (1992) and Livingstone Smith (2001) suggest that the heating rate (i.e. the rate of temperature development up to the maximum temperature) and the soaking time (i.e. time of exposure to the maximum temperature) are the only variables that allow a distinction between different firing structures The recent experimental work by Thér (2014) supports this view: one-space firing (vessel in contact with the fuel, such as in pit fire or bonfire) develops fast heating rates and short soaking times, which can result in significant difference in temperature of core and margins of the vessel. On the contrary, two-space firing (vessels and fuel are separated, such as in two-chamber kiln) has a slow heating gradient and longer soaking times, allowing the development of microstructural and mineralogical changes along the vessel walls. Leaving aside for now the distinction between different structures, some of these features were observed during the examination of the material from Phaistos and allow us to discuss firing procedures beyond the definition of equivalent firing temperature, considering as much as we can also the atmosphere, heating rate and soaking time developed during firing (cf. Table 8). In terms of the temperature range, the microstructural, chemical and mineralogical changes observed allow us to group samples into:

- *Very low fired*: Vessels in this range show a nNV microstructure, the presence of molecular vibrations for crystalline water and specific amorphous phases. In specific, the samples show the SiO str. band below or around 1035 cm^{-1} and the OH stretching band at around 3620 cm^{-1}; the SiO, AlO def. band can be around 470 and at 527 cm^{-1}, but some samples do show other wavenumbers (cf. 12/90).
- *Low fired*: Compared to the previous range, vessels show the same NV microstructure but a change in the molecular vibrations of the amorphous phases: they lose the OH stretching band and the SiO, AlO deformation band shifts at 554 cm^{-1}.
- *Medium fired*: Vessels in this range show a change of the microstructure to IV and a change of the amorphous and crystalline phases, which suggests they were fired at a higher temperature than the *low fired* range vessels. The samples show the SiO str. band splits into two peaks, in the range of 1045 and 1078 cm^{-1} as result of changes in the clay crystalline structure upon heating (cf. Berna et al. 2007; Shoval and Becks 2005). The SiO, AlO def. band shifts at wavenumbers around 460 and at 554 cm^{-1}, but the samples show marked variation. The CO_3 band may be still present depending on the size and distribution of calcitic inclusions.
- *High fired*: vessels in this range show a V to TV microstructure and a further change in the molecular vibrations of the crystalline phases by showing the SiO str. narrowing around 1080 cm^{-1} and SiO, AlO def. band at 554 cm^{-1} disappears and in those samples characterised by calcitic inclusions the CO_3 band is reduced or disappears.

These changes may be correlated to ranges of temperature by comparing them with the published comparative material (cf. Section 2.2): a temperature of maximum 600 °C, 700 °C, 800 °C and between 800 and 1150 °C can be estimated respectively for the *very low fired*, *low fired*, *medium fired* and *high fired group*. However, the temperature range has to be considered as a broad estimate, as the comparative data are very different from those used for the pottery from Phaistos.

More importantly, microstructural variation when coupled with the examination of colour across the vessel section is helpful in estimating firing heating rates and soaking times. Those vessels which show consistently developed microstructure and colour from the core to the margins suggest they were exposed to slow heating gradient and longer soaking times. When these conditions occur, the vessel is discussed in terms of *slow firing*. In contrast, some vessels show variability in the


a
Transmittance
3620
2929
2857
1634
1035
527
474
Wavenumber cm-1
b
Transmittance
1628
1428
1081
694
649
461
Wavenumber cm-1
c
Transmittance
1637
693
649
461
Wavenumber cm-1
d
Transmittance
3621
1638
1033
693
527
476
Wavenumber cm-1
e
Transmittance
1632
1428
693
648
465
Wavenumber cm-1
f
Absorbance
2928
1633
1427
1088
694
648
466
Wavenumbers
g
Transmittance
3618
1638
1428
1032
527
473
Wavenumber cm-1
h
Transmittance
2928
1637
1428
1033
467
Wavenumber cm-1

◀ **Fig. 7** Some examples of the FTIR spectra by fabric. Blue fabric = **a** PHA 12/1. **b** PHA 12/112. Violet fabric = **c** PHA 12/295. **d** PHA 12/293. Yellow fabric = **e** PHA 12/119. **f** PHA 12/87. Pink fabric = **g** PHA 12/264. **h** PHA 12/182

microstructure, often with micro-bloating, and variation in the colour developed from the core to the margins, suggesting they were exposed to variable firing conditions in a short amount of time, which can be the result of fast heating rates and short soaking times. *Fast firing* procedures are considered responsible for such results. Only vessels analysed with SEM can be included in these two groups, as they rely on observation of micro-bloating and microstructure. However, some comments can be made regarding other samples as colour variation can be an indication of fast or slow firing. For example, the B ware of FN III shows sharp colour changes through the section from black core to red margins to a black surface. In this case, it can be argued that the vessel was exposed to a Partly O-Partly R atmosphere but with short soaking time which did not allow the full reduction of the vessel along the section. The carbon deposition technique or smudging is known in the literature to produce similar results (Rice 1987, p. 335). The macroscopic examination of colour differences on vessel body and surface, coupled with their examination with SEM-EDAX, shows potters' choices in firing procedure towards the achievement of desired vessels appearance by manipulating surface treatment and firing atmosphere accordingly.

The definition of these interpretative parameters is crucial in the interpretation of changes in firing procedure

Table 7 Principal vibrations in FTIR spectra of samples from Phaistos and correspondence with SEM results

Sample		Phase	Ware	Fabric	Si-O str.	Si-O, AlO def.		OH	CO_3	SEM
PHA 12/	1	FN III	B	Blue	1035	527 (sh)	474	3620		NV
PHA 12/	5	FN III	B	Blue	1080/1040		464			
PHA 12/	6	FN III	B	Blue	1035		473	3620		
PHA 12/	25	FN III	Coarse	Blue	1080/1040		464		1426	
PHA 12/	35	FN III	ScrB	Blue	1032		466	3620	1426/876	
PHA 12/	39	FN III	B	Blue	1030	520 (sh)	471	3621 (sh)	1426/876	
PHA 12/	42	FN III	B	Violet	1079/1018		463			
PHA 12/	46	FN III	Coarse	Blue	1073/1039	555 (sh)	475/461			
PHA 12/	51	FN III	B	Blue	1035	527 (sh)	474/464 (b)	3620		
PHA 12/	57	FN III	B	Violet	1075/1039	554 (sh)	463/475		1422	
PHA 12/	87	FN III	ScrB	Yellow	1088		466		1427	V
PHA 12/	90	FN III	Coarse	Blue	1033		464	3619		NV
PHA 12/	91	FN III	B	Violet	1031 (b)		464			IV/V
PHA 12/	101	FN IV	ScrB	Blue	1079/1045	554 (sh)	463–478		1423	IV/V
PHA 12/	107	FN IV	ScrB	Blue	1080 (b)		462		1425/878	IV/V
PHA 12/	110	FN IV	ScrB	Yellow	1078/1040	554	475/463		1421	
PHA 12/	111	FN IV	B	Blue	1080 (b)		463		1421	
PHA 12/	112	FN IV	ScrB	Blue	1081 (b)		461		1428/878	IV/V
PHA 12/	119	FN IV	RS/M	Yellow	1078/1052		465		1428	NV/IV
PHA 12/	125	FN IV	RS/M	Yellow	1078/1040	553	481/465		1429/876	
PHA 12/	128	FN IV	RS/M	Yellow	1042 (b)	554 (sh)	461		1426	IV
PHA 12/	138	FN IV	Coarse	Yellow	1079/1044	556	464		1422	
PHA 12/	144	FN IV	Coarse	Yellow	1077/1036	554 (sh)	469/476		1428/876	
PHA 12/	173	EM IA	B/Gra	Blue	1036	556	471		1428	NV
PHA 12/	182	EM IA	W&W	Pink	1033		467		1428/876	NV
PHA 12/	187	EM IA	DGPB	Violet	1022	530 (sh)	475	3629		
PHA 12/	188	EM IA	BrS/Po	Blue	1037		470	3630 (sh)	1423	NV
PHA 12/	264	EM IB	CPW	Pink	1032	527 (sh)	473	3618 (sh)	1428	
PHA 12/	293	EM IB	DGPB	Violet	1033	527 (sh)	476	3621		NV
PHA 12/	295	EM IB	DGPB	Violet	1077/1039 (b)		461			IV

Samples are arranged according to phase

b broad peak, *sh* shoulder

Table 8 Interpreted temperature ranges and firing rate for each sample examined

Sample		Phase	Fabric	Ware	Atmosphere	Temperature range	Firing rate
PHA 12/	1	FN III	BLUE	B	O-Partly R	Very low	Fast
PHA 12/	5	FN III	BLUE	B	Partly O-Partly R	Medium	Fast?
PHA 12/	6	FN III	BLUE	B	O-Partly R	Very low	Fast?
PHA 12/	25	FN III	BLUE	Coarse	Partly O	Medium	Slow?
PHA 12/	35	FN III	BLUE	ScrB	O-Partly R	Very low	Fast?
PHA 12/	38	FN III	BLUE	B	O	Low	Slow
PHA 12/	39	FN III	BLUE	B	O-Partly R	Very low	Fast?
PHA 12/	42	FN III	VIOLET	B	Partly O-Partly R	Low	Fast?
PHA 12/	46	FN III	BLUE	Coarse	Partly O	Low	Slow?
PHA 12/	51	FN III	BLUE	B	R	Very low	Slow?
PHA 12/	57	FN III	VIOLET	B	Partly O-Partly R	Medium	Fast?
PHA 12/	87	FN III	YELLOW	ScrB	Partly O	High	Fast
PHA 12/	90	FN III	BLUE	Coarse	R	Very low	Slow
PHA 12/	91	FN III	VIOLET	B	Partly O-Partly R	Medium	Fast
PHA 12/	101	FN IV	BLUE	ScrB	Partly O-Partly R	Medium	Fast
PHA 12/	107	FN IV	BLUE	ScrB	R	Medium	Fast
PHA 12/	110	FN IV	YELLOW	ScrB	Partly O-Partly R	Low-medium	Fast?
PHA 12/	111	FN IV	BLUE	B	Partly O-Partly R	Medium-high	Fast?
PHA 12/	112	FN IV	BLUE	ScrB	Partly O-Partly R	Medium-high	Fast
PHA 12/	119	FN IV	YELLOW	RS/M	Partly O	Medium	Fast
PHA 12/	125	FN IV	YELLOW	RS/M	Partly O	Medium	Fast?
PHA 12/	128	FN IV	YELLOW	RS/M	Partly O	Medium	Fast
PHA 12/	132	FN IV	YELLOW	RS/M	O	Low	Slow
PHA 12/	135	FN IV-EM IA	YELLOW	O/Buff	Partly O	Medium	Fast
PHA 12/	138	FN IV	YELLOW	Coarse	Partly O	Medium	Fast?
PHA 12/	144	FN IV	YELLOW	Coarse	Partly O	Medium	Fast?
PHA 12/	161	FN IV	YELLOW	Coarse	Partly O	Low	Fast
PHA 12/	168	FN IV	YELLOW	B/Gra	Partly O	Medium	Fast
PHA 12/	170	FN IV	YELLOW	B/Gra	O	High	Slow
PHA 12/	173	FN IV	BLUE	B/Gra	O	Low	Slow
PHA 12/	182	EM IA	PINK	W&W	O	Low	Slow
PHA 12/	186	EM IA	YELLOW	BrS/Po	O	Low	Slow
PHA 12/	187	EM IA	VIOLET	DGPB	R	Very low	Slow?
PHA 12/	188	EM IA	BLUE	BrS/Po	O	Very low	Slow
PHA 12/	206	EM IA	YELLOW	BrS/Po	O	Low	Slow
PHA 12	207	EM IA	GREEN	BrS/Po	O	Low	Slow
PHA 12/	210	EM IA	BLUE	CPW	O	Low	Slow
PHA 12/	220	EM IA	ORANGE	Coarse	O	High	Slow
PHA 12/	222	EM IA-B	PURPLE	Coarse	O	Medium	Slow
PHA 12/	225	EM IA	YELLOW	BrS/Po	O	Medium	Slow
PHA 12/	214	EM IB	RED	CPW	O	Low	Slow
PHA 12/	241	EM IB	YELLOW	DOL	O	High	Slow
PHA 12/	242	EM IB	YELLOW	DOL	O	High	Slow
PHA 12/	250	EM IB	YELLOW	W&W	O	High	Slow
PHA 12/	258	EM IB	YELLOW	DOL	O	High	Slow
PHA 12/	264	EM IB	PINK	CPW	O	Very low	Slow?
PHA 12/	267	EM IB	RED	CPW	O	Low	Slow
PHA 12/	276	EM IB	YELLOW	PW	O	High	Slow
PHA 12/	277	EM IB	ORANGE	DOL	O	Medium	Slow

Table 8 (continued)

Sample		Phase	Fabric	Ware	Atmosphere	Temperature range	Firing rate
PHA 12/	278	EM IB	PURPLE	DOL	O	High	Slow
PHA 12/	282	EM IB	YELLOW	DOL	O	High	Slow
PHA 12/	284	EM IB	PURPLE	W&W	O	High	Slow
PHA 12	288	EM IB	BROWN	DOL	O	High	Slow
PHA 12	289	EM IB	RED	DOL	O	High	Slow
PHA 12/	293	EM IB	VIOLET	DGPB	R	Very low	Slow
PHA 12/	295	EM IB	VIOLET	DGPB	R	Medium	Slow
PHA 13/	5	EM IB	YELLOW	LOD	O	Medium	Slow
PHA 13/	11	EM IB	BLUE	RBW	Partly O	Low	Fast?

? interpretation based only on macroscopic assessment

over the FN III-EM IB at Phaistos (Table 8 and Fig. 8). In terms of firing temperature range, this study shows that in FN III the majority of the vessels belong to the *very low* to *low fired* range and only a few samples to the *medium to high fired* range. In FN IV, the vessels belong to the *medium fired* range increases compared to the previous phase, but vessels still share the characteristics of the *low fired* range. In EM IA, most of the samples analysed belong to the *low fired* range, as in FN III. All the ranges, from *very low* to *high fired*, are represented in EM IB but, in contrast to the previous phases, this is clearly linked with fabric and ware. CPW, DGPB and RBW belong to the *low fired* range, which occurs in the Blue, Violet, Red and Pink fabrics. DOL, LOD, W&W and PW are fired in the *medium/high fired* range and those belong to the Yellow, Purple, Brown and Orange fabrics.

In terms of the firing rate, in FN III-IV, the majority of the vessels analysed show evidence of being subjected to firing in variable conditions, indicated as *fast firing*. In sharp contrast, samples from EM IA-B show features

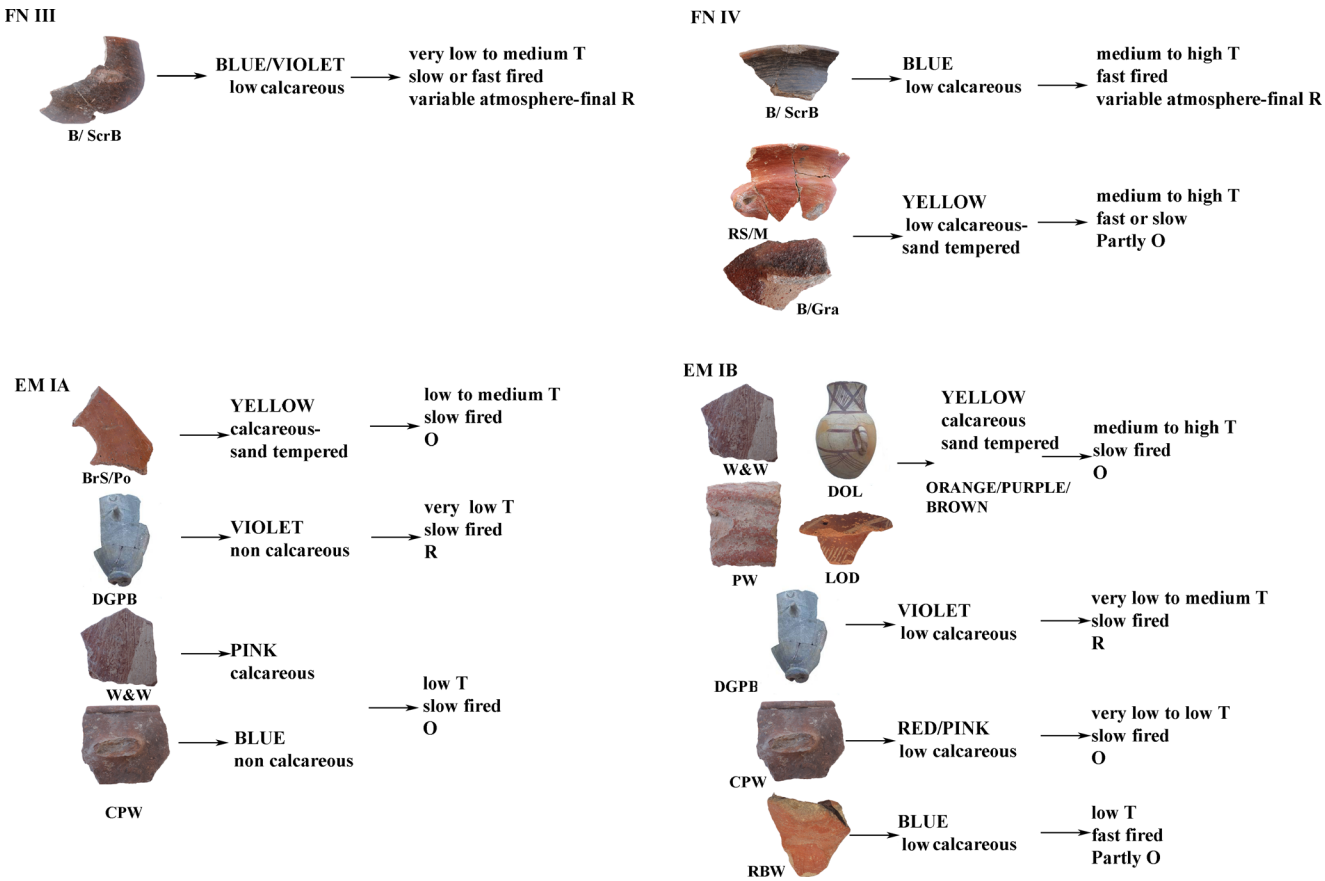


Fig. 8 Major trends observed in raw material choices and firing in the ceramics from Phaistos in the FN III-EM IB phases

suggesting that vessels were exposed to a rather constant firing atmosphere, long enough to allow the development of homogeneous colour and microstructural characteristics through the vessel's cross-section, interpreted as *slow firing*. This change from fast to slow firing procedures over the phases considered was observed in all the sampled materials.

The examination of the material from Phaistos shows that potters manipulated the firing atmosphere (reducing or oxidising) on the basis of the desired final effect. The black/brown surfaces of B, ScrB and DGPB are obtained by simply burnishing the vessel and changing the atmosphere to reducing at the end of the firing. The light brown surface of O/Buff is obtained by smoothing the surface and by firing in an oxidising atmosphere. In contrast, the similarly light brown BrS/Po were slipped with an iron rich material, burnished and then fired in an oxidising atmosphere. For the slipped or painted wares, such as the RS/M, B/Gra, DOL and LOD, an iron-rich or calcium-rich material was applied pre-firing, according to the desired effect and then vessels fired in an oxidising atmosphere (Mentesana et al. 2016).

In conclusion, do these results confirm or refute the adoption of different firing structures over time, i.e. switching between an open firing and a kiln firing, as suggested by Betancourt (2008)? With regard to the material from Phaistos, the pattern observed between phases indicates that firing procedures did change in terms of potters' control over the firing conditions towards the beginning of the EM IA in terms of temperature rate. It can be argued that this corresponds to a technical change and to the introduction of an equipment which allowed better control of the firing, such as a 'kiln' or a form of double-space firing (Thér 2014).

However, the study of the material from Phaistos has a more meaningful outcome than solely considering 'open' or 'kiln' firing: by EM IA, potters working at or near Phaistos had acquired and transmitted the different skills needed to perform a controlled firing. The use of any equipment or tools requires knowledge and skills which come with transmission and practice (Bourdieu 1977, 1984; van der Leeuw 1984). The equipment to perform a controlled firing might have been present and used in Crete before the EBA, but it is at that point in time that potters managed to use it in a different way. As this change involved the entire assemblage found at Phaistos, rather than one set of vessels, it can be argued that the transmission of knowledge and its practice involved the entire potters' community. Adopting the concept developed by Lave and Wenger (1991) and Wenger (1998), the potters can be seen as a *community of practice* where individuals engage in social learning and produce materials that reflect this shared activity and experience. Novelties, like the use of a new equipment, can be rejected or integrated into the set of shared knowledge and became a common practice for the entire community. A similar process might have taken place in the case of firing procedures at Phaistos during the FN-EBA transition.

Conclusion

The detailed study of firing technology on FN-EM I ceramic material from Phaistos provides more material for discussion of a supposed change in ceramic technology in this period. Our results support the idea of a change in firing at the beginning of the EBA, consisting of improved control of firing in terms of duration, temperature and atmosphere. This produces vessels with homogeneously microstructure and colour through the vessel section. This change seems not to be linked with the achievement of high temperature firing nor to any specific ware produced. It rather includes all the wares found at the site, which seem initially to be preferably fired at low temperature ranges. Potters were aware since the Final Neolithic of the ways in which to obtain dark or light-coloured surfaces by manipulating the amount of oxygen present during firing and therefore this is not a feature that can be considered typical of EM phases. Reducing and oxidising firing, while present since the earlier phases, stand visibly in great contrast by the end of EM I, when painted jugs-jar, painted pyxid and *pithoi* (DOL, W&W, LOD, PW) are constantly fired at high temperature and in oxidised atmosphere compared to the low and reduced firing used for dark burnished chalices (DGPB) and cooking pots (CPW).

The picture emerging from other studies in Crete for the same phases seems similar. Wilson and Day (1994) observed that potters in EM I Crete adopted different firing procedures in terms of atmosphere and temperature according to the ceramic ware being manufactured. A similar picture was suggested for EM I ceramics in west Crete (Nodarou 2011). The study of FN IV-EM I material from Kephala Petras revealed that firing procedures in EM I changed slightly compared to those of the FN, entailing a better control of atmosphere (Papadatos et al., in press). Do these data allow us to suppose the introduction of new firing structure in the procedures used by potters at Phaistos and more widely in Crete? It is difficult to give a confident answer to this, as there is currently no primary evidence on the island for structures of this kind. More importantly, this can be considered only one aspect of research into firing technologies and in the reconstruction of technological change in ceramics from Phaistos.

Of course, the reconstruction of firing technologies is of uncertain value if not embedded in an understanding of all the other steps of the vessel production sequence and of its context of consumption. In a recent paper (Mentesana et al. 2016), it has been argued that by the end of the EM I a novel

consumption etiquette (cf. also Hood and Cadogan 2011), which involved the entire island, channelled ceramic manufacture to the production of specific ware according to specific technological choices. Those are not totally novel in the local manufacture at Phaistos, but they comprise a re-elaboration, creating distinct wares from both visual and technological point of view. In a few words, the change in firing technology, whatever it implies in terms of change of equipment used, is just the tip of the iceberg of much wider technical and cultural transformations happening at the site in the FN-EM transition.

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