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The ceramic of the "Palace of the Copper Axes" (Khirbet al-Batrawy, Jordan): A palatial special production

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Abstract

Selected ceramic samples from the archeological site of Khirbet al-Batrawy (north-central Jordan), unearthed in the "Palace of the Copper Axes" (Early Bronze Age III, 2500–2300 BC), were analyzed with the aim to address their technology. These ceramics were characterized by means of a combined use of optical microscopy (OM), X-ray powder diffraction (XRPD) and electron microscopy (SEM–EDS). The results indicate that the main mineral inclusions are quartz and calcite, with minor amount of feldspar, pyroxene, olivine and gehlenite. Fragments of igneous and sedimentary rocks as well as grog (crushed ceramics) and fossil shells have also been identified. The mineral assemblage indicates that the maximum firing temperature of these sherds falls in the 700–850 °C thermal range. The presence of hematite supports the hypothesis of an oxidizing atmosphere of firing. The occurrence of sedimentary and magmatic rocks supports a local provenance of raw materials as these rocks outcrop in the vicinity of the archeological site. Concerning the microstructure, it is established the occurrence of ceramic fabrics not identified until now at the site, suggesting that they were exclusively produced for the Palace.

Keywords: Early Bronze Age ceramic technology; Khirbet al-Batrawy; Palace of the Copper Axes; OM-XRPD-SEM–EDS

1. Introduction

This work represents a part of a large-scale systematic analytical approach to the Early Bronze Age Batrawy ceramic assemblage with the aim to reconstruct the technological aspects of pottery production at the site, and to study the cultural and material development in the wide range of the site development [1,2].

Previous studies proved that the technological evolution of the ceramic production in 3rd millennium BC Jordan as documented in the case study of Batrawy was marked by an initial exploration and evaluation of the raw materials and shapes in the Early Bronze II (3000–2700 BC). Lately, a major and diffuse experimentation in the use of materials and procedures of modeling is observed in the Early Bronze III (2700–2300 BC). Finally, the ceramic production was standardized and a minor number of fabrics with specific features to satisfy the request and necessity of an everyday life ceramic production has been observed in the Bronze Age IV (2200–2000 BC) [3].

Despite the analytical studies already carried out about the ceramic production of Khirbet al-Batrawy, no data about the ceramic unearthed in the "Palace of the Copper Axes" was reported in literature thus far.

Therefore, this research aims to provide information on ceramic finds from this important archeological context, where pottery was associated with many dated items, and to determine whether it represents a specialized production, exclusively intended for the use of the Palace. The analytical examination of the pottery wares from the Palace could provide new evidence to investigate the role of technology

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and innovation during the development of the earliest urban culture of the Levant during the 3rd millennium BC.

Here is reported a detailed analysis on archeological potteries from the "Palace of the Copper Axes" using optical microscopy analysis (OM), X-ray diffraction (XRPD) and scanning electron microscopy coupled with energy dispersive spectroscopy (SEM–EDS) with the aim to define the technological skill deployed for that specific ceramic production.

The results provide information about the nature of mineralogical assemblage and firing process of the ceramics; from these results we can infer the technological background of the élite driving the emergence of the urban model in Early Bronze Age Jordan. In addition, these data can be very useful to trace the provenance of raw materials [4].

2. Archeological context

Khirbet al-Batrawy was an ancient city located on the top of a limestone cliff overlooking the ford through the Zarqa River (Biblical Jabbok) in north-central Jordan (Fig. 1).

Monumental remains dating back to the 3rd millennium BC were discovered by Rome "Sapienza" Expedition to Jordan [5,6]. The archeological excavations, carried out under the aegis of the Department of Antiquities of the Hashemite Kingdom of Jordan, revealed a strongly fortified city, the life of which spans over about a millennium, across the four major historical periods of the Levantine Early Bronze Age.

During the Early Bronze III, the city experienced a period of prosperity in which grew up in a monumental way. In this period, a palatial building was erected, serving as administrative center of a territorial kingdom ruling over the Upper Wadi Zarqa Valley. The Palace was built in the northern part of the hill and it had an articulated layout with two major pavilions. Since the Palace was heavily destroyed when the city was set on fire at the end of Early Bronze III, excavations uncovered a wide set of archeological finds. Among them a hoard of copper axes [7,8], luxury goods, and a highly representative assemblage of pottery; also some potter's wheels were found stored into the Palace, as a proof of the innovative technological role played by the ruling élite. The ceramic repertoires, big *pithoi*, containing carbonized seeds of barley, as well as a plea of complete vessels belonging to the table service (jugs and bowls, but also *amphoriskoi*, miniature vases, and so on), and two decorated vessels with applied figures of scorpions and snakes, illustrate the cultural flourishing of the city around the middle of the 3rd millennium BC.

3. Geological setting

Jordan region is characterized by a complex granitic metamorphic basement covered by a succession of sandstones and limestones (Fig. 2) [9]. The Pre-Cambrian basement is composed by granitic, metamorphic and basic rocks of the Aqaba Granite Complex, and conglomerates of the Saramuj Series [10].

Limestones, dolostones, sandstones, marls, evaporites, cherts, and phosphatic rocks were deposited in marine, lacustrine and continental sub-environments during Mesozoic and Tertiary ages.

Since Middle Miocene, basaltic rocks in the north-east sector of the region are associated with the formation of the Rift Valley.

Supergene processes formed recent continental sediments [11]. Nearby Khirbet al-Batrawy, lenses of marl, chert and fossiliferous beds [12] are interbedded into Upper Cretaceous limestones (Wadi As Sir and Hummar, Shua'yb Formations). Moreover, marl, gypsum and gravels, typical lacustrine sediments of Pleistocene age, outcrop in the area. Along the slopes and in the wadi beds marlstones are intercalated within the

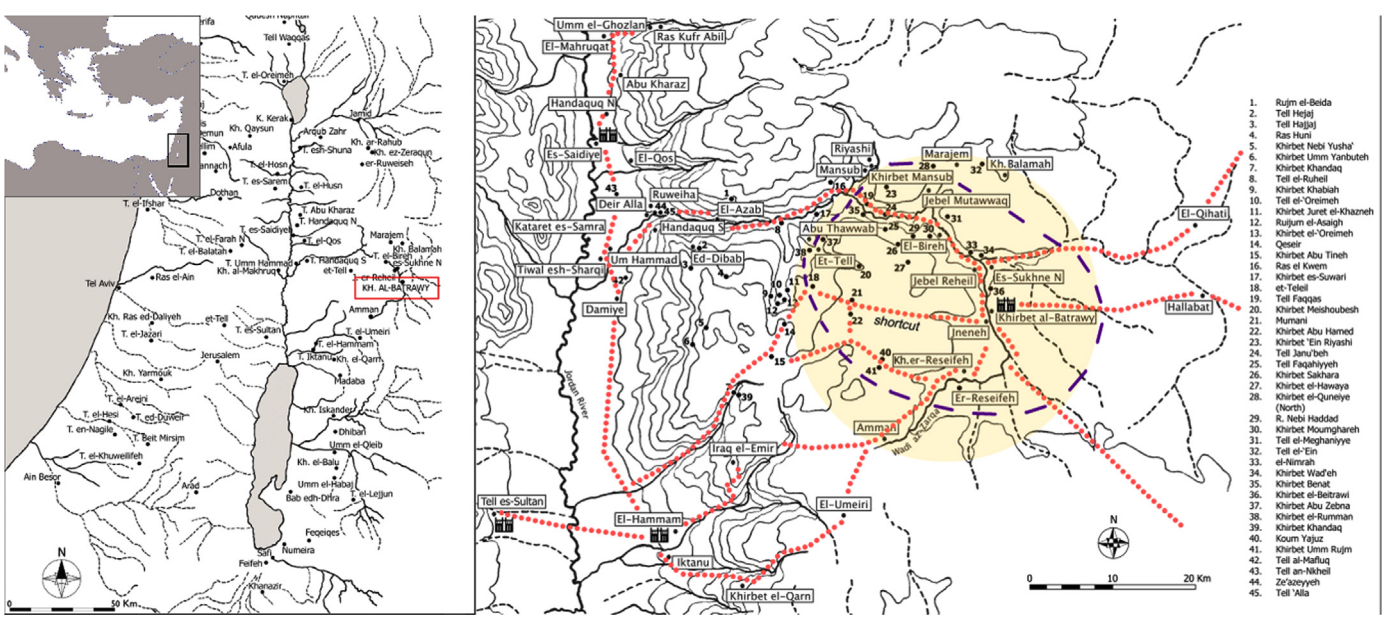

Fig. 1. Map of Palestine in 3rd millennium BC (courtesy of Rome "La Sapienza" Expedition to Palestine and Jordan), reporting the most important Early Bronze Age archeological sites.

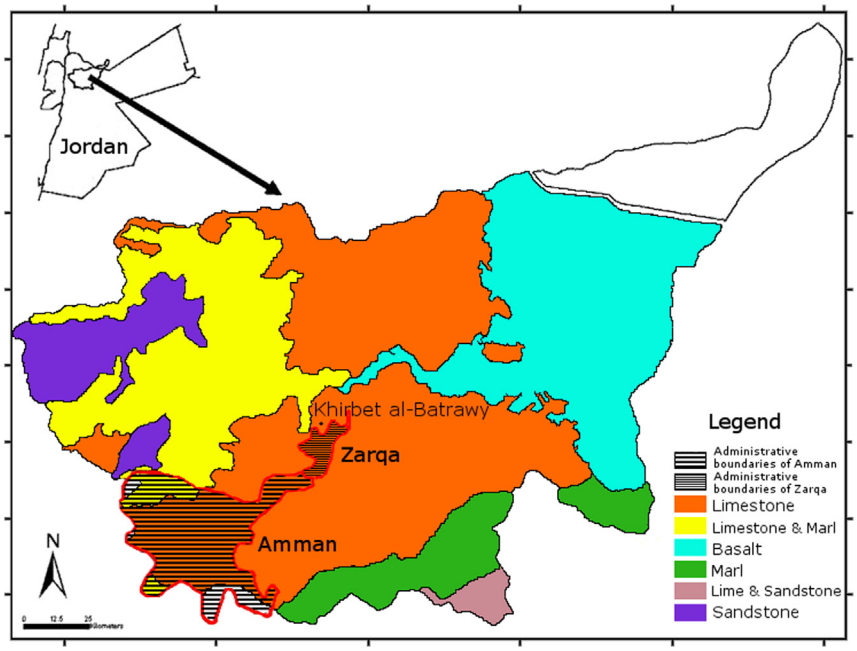

Fig. 2. Geological map of Jordan [2].

limestones forming a mixture of clay, mud, sand and shells [13].

4. Materials and methods

Fifteen samples from the "Palace of the Copper Axes" were selected among different functional classes which usually bear diversified technological features such as Simple Ware (SW), Storage Ware (StW) and Red Burnished Ware (RBW).

Selected samples belong to different classes attested in the Palace; the big *pithoi* (KB.10.B.1040/6, KB.10.B.1040/7, KB.11.B.1124/28, KB.11.B.1054/2), jars for daily storage (KB.10.B.1054/56, KB.10.B.1054/12, KB.10.B.1054/45), vats for food preparation (KB.10.B.1054/2, KB.11.B.1124/19), and pieces of the palatial table service: *amphoriskoi* (KB.10.B.1054/83), jugs (KB.10.B.1054/63) and Red Burnished jugs and juglets (KB.10.B.1054/35, KB.10.B.1054/95, KB.11.B.1124/12; KB.11.B.1124/31) (Figs. 3, S1, S2).

Petrographic analysis of thin sections was performed by polarizing microscopy according to Whitbread criteria [14,15] using a Zeiss D-7082 Oberkochen polarized optical microscope (Department of Earth Sciences, Sapienza University of Rome, Italy).

The XRPD analysis of potsherds was carried out using a Siemens D5000 automatic powder diffractometer (Department of Earth Sciences, Sapienza University of Rome, Italy). The instrument was equipped with a graphite monochromator using Cu Kα radiation, operating at 40 kV and 25 mA. The XRPD data were collected from 3° to 70° 2θ with a step-size of 0.02° and counting time of 2 s. X'Pert High score Plus software was used to identify the mineralogical assemblage.

The ceramic fragments were also investigated by SEM–EDS using a FEI-Quanta 400 instrument, operating at 20 kV, equipped with X-ray energy dispersive spectroscopy (Department of Earth Sciences, Sapienza University of Rome, Italy). SEM images were collected both in secondary electron (SE) and back scattered electron (BSE) modes to evaluate micromorphology, microstructure and chemistry of matrix and inclusion as well as grog.

5. Results and discussions

5.1. Petrographic analysis

Petrographic analysis by OM allowed us to discriminate two main fabrics (*A* and *B*) on the basis of the features of matrix, inclusions (roundness, size and distribution), and pores (distribution and dimensions), according to the Whitbread criteria [14,15] (Table 1).

Fabric A-Ca-rich, including the majority of the samples, is characterized by the presence of fragments of sedimentary rocks (mainly limestone) and has been divided into six subgroups on the basis of the main inclusions, percentage and grain size.

Fabric A1 (samples KB.11.B.1124/19, KB.10.B.1054/12, KB.10.B.1054/56, KB.11.B.1124/28, KB.11.B.1054/2, KB.10.B.1040/7) shows a homogeneous distribution of predominant coarse-grain fragments of sedimentary rocks, mainly limestone, from angular to rounded and ranging from 0.1 to 2.0 mm, diffuse fragments of fossils, iron oxides nodules and rare quartz. The inclusions (~20 vol%) are distributed from single to double-spaced in a brown-reddish calcareous matrix (in PPL), optically active. The grain size distribution of this fabric is unimodal. The porosity (~20 vol%) consists of large *vughs* (from mega to micro) and smaller vesicles (from meso to micro), mainly aligned to the margin of the sample (Fig. 4).

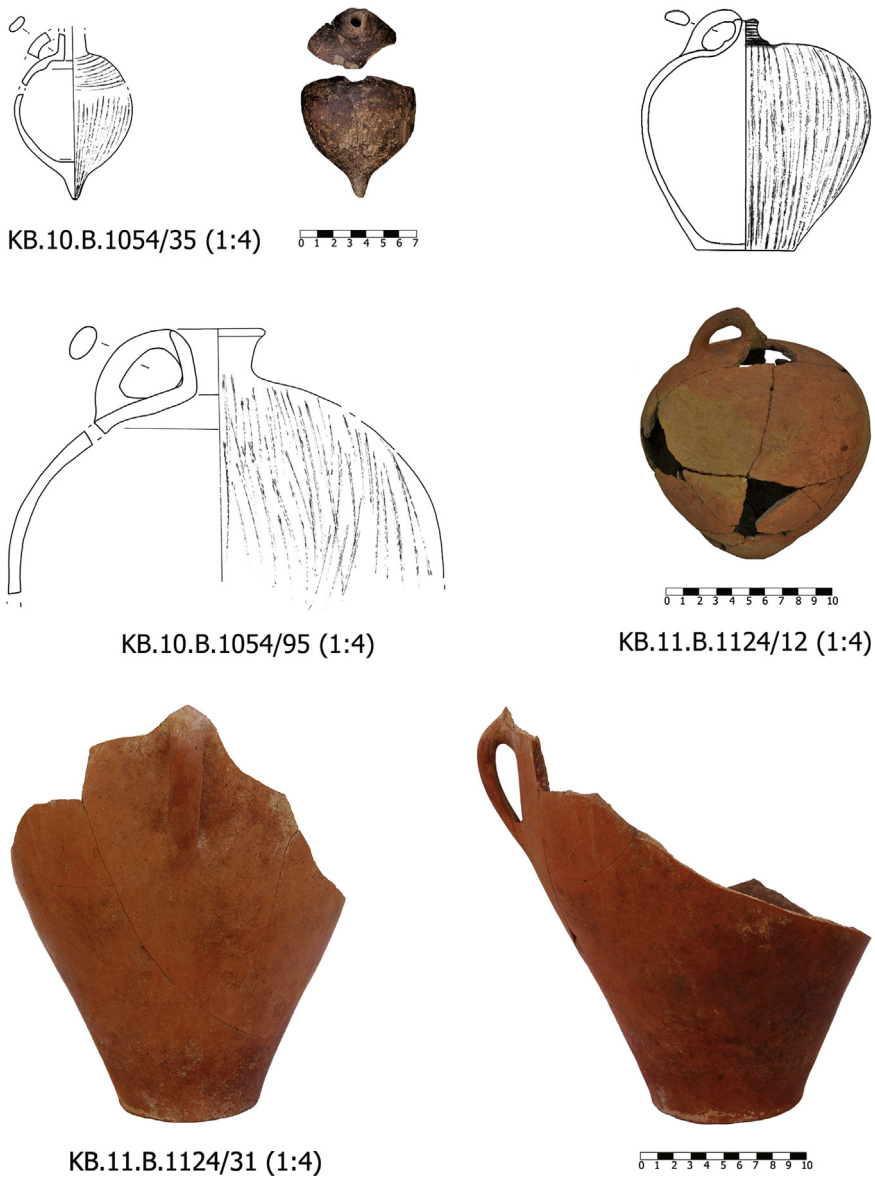

Fig. 3. Representative pottery vessels of Red Burnished Ware from the "Palace of the Copper Axes" Khirbet al-Batrawy.

Fabric A2 (sample KB.11.B.1124/12) contains the same inclusions of *Fabric A1* with different distribution, from open to single-spaced having a smaller grain size (0.1–0.6 mm). These inclusions (10 vol%) have a unimodal grain-size distribution and are enclosed in an optically active calcareous groundmass (70–80 vol%). The color ranges from light yellow to dark beige (in PPL). Porosity is estimated between 10 and 20 vol% consisting mainly in vesicles (from macro to micro) without any alignment to the margins of the sample (Fig. 4).

The main feature of *Fabric A3* (sample KB.10.B.1054/83) is the presence of large and very angular crystals of calcite as inclusions. In addition, fragments of calcareous sedimentary rocks, frequent fragments of igneous rocks, diffuse iron oxides nodules and rare quartz also occur as inclusions (20 vol%). They are homogeneously distributed in the space (from single to open-spaced) with a unimodal grain size distribution and size ranging from 0.1 to 1.5 mm. The pores (~10 vol%) consist mainly of meso and micro-vesicles with rare *vughs* not aligned to the margin of the sample. Matrix is calcareous and optically active with the color ranging from beige to reddish (in PPL) (Fig. 4).

The petrographic group *Fabric A4* (samples KB.10.B.1054/2, KB.10.B.1040/6, KB.10.B.1054/95 and KB.10.B.1054/35) is primarily characterized by abundant fragments of sedimentary rocks, nodules of iron oxides and fragments of igneous rocks. This fabric is homogenous, with equant and elongate inclusions (~10 vol%), unimodal distributed, with a shape ranging from angular to sub-rounded. The matrix has a color ranging from black to reddish in PPL and it is strongly optically active (Fig. 4).

Fabric A5 (sample KB.10.B.1054/45) is characterized by a bimodal distribution of inclusions (20 vol%) primarily represented by coarse grain fragments of igneous rocks (angular and equant, with dimensions ranging from 0.2 to 2.5 mm). Other

Table 1
Brief description of macroscopic and microscopic features of Khirbet al-Batrawy samples.

Sample	Class	Shape	Porosity	Matrix	Inclusions	Fabric
KB.11.B.1124/19	SW	Hole-mouth jar	10% Meso-micro-vesicles and *vughs*	6% Calcareous	30% Predominant: fragments of sedimentary rock	A1
KB.10.B.1054/12	SW	Jar	5% Meso, micro-vesicles	70% Calcareous	25% Predominant: fragments of sedimentary rock, microfossils	A1
KB.10.B.1054/56	SW	Jar	20% Macro-meso-*vughs*	50% Calcareous	30% Predominant: fragments of sedimentary rock, microfossils Common: iron oxides nodules	A1
KB.11.B.1124/28	StW	*Pithos*	20% Macro-micro-*vughs*/Meso-micro-vesicles	50% Calcareous	30% Predominant: fragments of sedimentary rock, microfossils Frequent: fragments of fossils Common: iron oxides nodules	A1
KB.11.B.1054/2	StW	*Pithos*	20% Mega-micro-*vughs*	60% Calcareous	20% Predominant: fragments of sedimentary rock, microfossils	A1
KB.10.B.1040/7	StW	*Pithos*	20% Meso-microvesicles/Mega-meso-*vughs*	50% Calcareous	30% Predominant: fragments of sedimentary rock, microfossils	A1
KB.11.B.1124/12	RBW	Jug	10–20% Macro-micro-vesicles	70–80% Calcareous	10% Predominant: fragments of sedimentary rock	A2
KB.10.B.1054/83	SW	*Amphoriskos*	10% Meso-micro-vesicles	70% Calcareous	20% Predominant: fragments of sedimentary rock Frequent: fragments of igneous rocks Common: crystals of calcite	A3
KB.10.B.1054/2	SW	Hole-mouth jar	30% Meso-micro-vesicles/Micro-*vughs*	60% Calcareous	10% Predominant: fragments of sedimentary rock Frequent: grog Common: iron oxides nodules	A4
KB.10.B.1040/6	StW	*Pithos*	20% Mega, macro-*vughs*/Macro, meso-vesicles	70% Calcareous	10% Predominant: grog Common: fragments of sedimentary rock, iron oxides nodules	A4
KB.10.B.1054/95	RBW	Jug	10% Mega-micro-*vughs*/Meso-micro vesicles	80% Calcareous	10% Predominant: fragments of sedimentary rock Common: fragments of igneous rocks, iron oxides nodules, grog	A4
KB.10.B.1054/35	RBW	Juglet	5% Meso-micro-vesicles	90% Calcareous	5% Predominant: fragments of sedimentary rock	A4
KB.10.B.1054/45	SW	Jar	10% Macro-micro-*vughs*/Meso-micro-vesicles	70% Calcareous	20% Dominant: fragments of sedimentary rock, fragments of igneous rocks Common: fragments of fossils, iron oxides nodules	A5
KB.10.B.1054/63	SW	Jug	10% Mega, macro-*vughs*/Macro-micro-vesicles	80% Calcareous	10% Predominant: fragments of igneous rocks. Common: fragments of sedimentary rock	A6
KB.11.B.1124/31	RBW	Jug	20% Meso-micro-vesicles	60% Calcareous	20% Predominant: quartz	B

inclusions consist of fragments of calcareous sedimentary rocks (equant and elongated, from sub-angular to well rounded, between 0.2 to 1.0 mm). Common fragments of fossils, nodules of iron oxides and rare quartz crystals also occur in a calcareous groundmass (70 vol%) with a light-brown color in PPL and optically active. The porosity (10 vol%) consists mainly of macro and micro-*vughs* aligned to the margin of the samples with meso and micro-vesicles. Secondary calcite occurs in the pores (Fig. 4).

Fabric A6 (sample KB.10.B.1054/63) shows abundant angular olivine and both ortho- and clinopyroxene crystals as inclusions. Fragments of igneous rocks are predominant in association with fragments of calcareous sedimentary rocks. Rare crystals of quartz, and nodules of iron oxides have also been identified in a calcareous matrix (80 vol%), weakly optically active, with a color ranging between brown and beige in PPL. The pores (10 vol%) mainly consist of mega and macro-*vughs*, with macro and micro-vesicles without any preferred alignment (Fig. 4).

Finally, *Fabric B-quartz rich* (KB.11.B.1124/31) is distinguished from the other samples for the dominant presence of quartz inclusions. Microscopic observation showed that this sample has a unimodal grain size distribution, with inclusions around 20 vol%, equant, from angular to rounded and grain size ranging from 0.1 to 0.7 mm. The color of the calcareous matrix (60 vol%) ranges from yellowish to brown (in PPL) and it is optically active. Rare fragments of sedimentary rocks (equant, sub-angular, less than 0.3 mm in size), nodules of iron oxides (equant, from angular to sub-angular, around 0.2 mm in size) and clay pellets have also been identified. Porosity (20 vol%) is mainly represented by meso and micro vesicles without any preferred alignment to the margin of the sample. Secondary calcite also occurs in the pores (Fig. 4).

Samples KB.11.B.1124/28 (*Fabric A1*), KB.11.B.1054/2 (*Fabric A1*), KB.11.B.1124/12 (*Fabric A2*), KB.10.B.1054/2 (*Fabric A4*), KB.10.B.1054/95 (*Fabric A4*), KB.10.B.1040/6 (F*abric A4*) and KB.11.B.1124/31 (F*abric B*) contain from rare to frequent fragments of grog; the latter is noticeably frequent in *Fabric A4*.

Concerning the inclusions, the petrographic analysis reveals the presence of very angular calcite crystals and angular fragments of igneous rocks. The angular shape could suggest the voluntary addition of these inclusions by potter to improve technical features [16]. The natural deposits of clays nearby the archeological site of Khirbet al-Batrawy contain rounded sediments that suggest morphological and mineralogical maturity as they have experienced multiple sedimentary cycles. Therefore, the inclusions of carbonate sedimentary rock and microfossils with rounded shape (from sub-rounded to well rounded) and homogeneous distribution of size identified in our samples could suggest their occurrence in the local clays [2]. However, Quinn [16] suggested the hypothesis that inclusions could be added as tempers with different grain sizes and rounding; which preclude establishing their natural

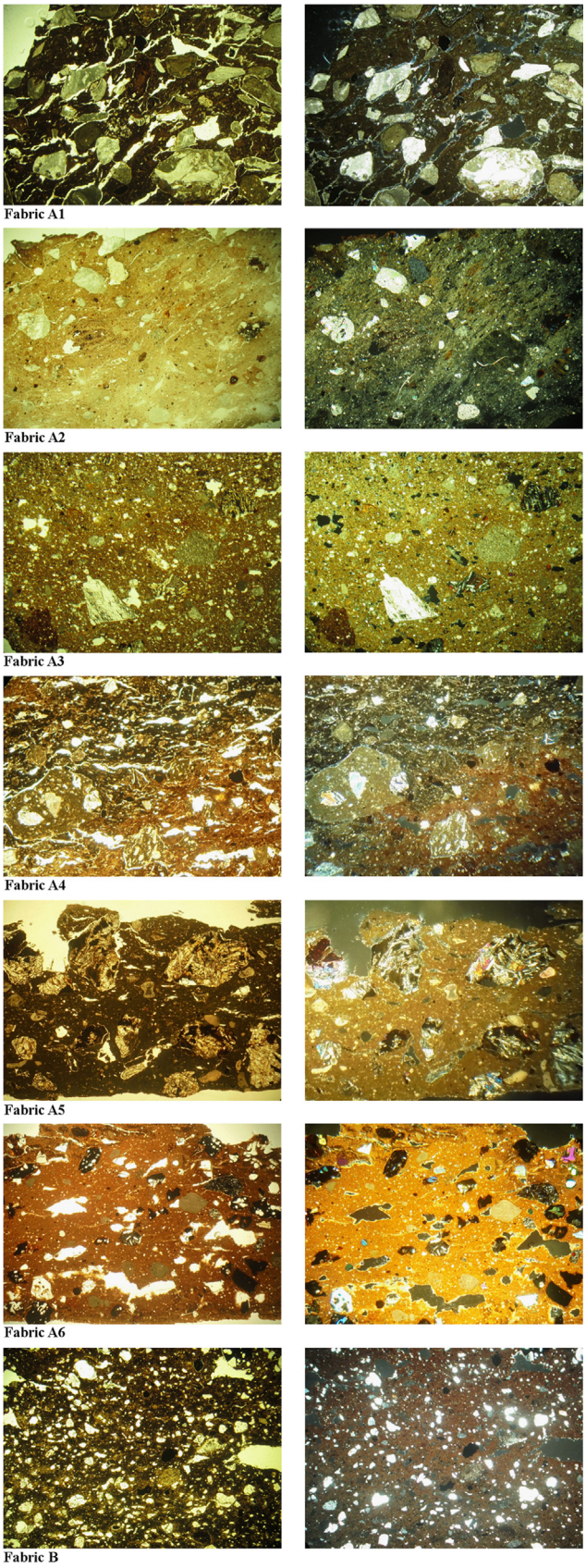

Fig. 4. Thin-section photomicrographs representative of different petrographic fabrics (in plane polarized light (PPL) and in cross polarized light (XP), magnification ×20). *Fabric A1* sample KB.11.B.1124/28; *Fabric A2* sample KB.11.B.1124/12; *Fabric A3* sample KB.10.B.1054/83; *Fabric A4* sample KB.10.B.1040/6; *Fabric A5* sample KB.10.B.1054/45; *Fabric A6* sample KB.10.B.1054/63; *Fabric B* sample KB.11.B.1124/31.

presence or voluntary addition.

The presence of grog in some samples of fabrics *A1*, *A2*, *A4 and B* would indicate the human intervention, suggesting a tempering process involved to improve the plasticity and workability of the clay. However, the possibility to find rare fragments of grog in ancient ceramic could also be explained as accidental contamination of the clay during processing [16]. In the case of *Fabric A4*, ceramic samples from Khirbet al-Batrawy show high abundance of grog inclusions, with coarse dimensions that can allow hypothesizing its voluntary addition by the potter.

The optical activity of the matrix indicates that the firing temperature was below 850 °C as the sintering process starts over this temperature [17,18].

5.2. X-ray diffraction analysis

The XRPD analysis was performed on representative samples of the different petrographic fabrics with the aim to acquire qualitative and semi-quantitative data of the mineralogical composition. The mineral assemblage provides indications about the firing conditions (i.e., temperature and fO_2), allowing to reconstruct the technological level reached by the ancient population.

The results show that the main phases are quartz and calcite, followed by plagioclase and alkali feldspars with minor amount of hematite, illite, and rare enstatite, diopside, olivine and dolomite. Gehlenite was found only in sample KB.10.B.1054/2 (*Fabric A4*) (Table 2).

The decomposition of primary phases, naturally contained in the clay, occurs at different temperatures. The breakdown of primary phases releases in the system different chemical species which can react together forming new minerals. The crystallization of neoformed minerals is governed by the firing temperature, the redox conditions of the system (fO_2), the nature of the clay and inclusions [19–21].

The occurrence of quartz was identified by OM and confirmed by XRPD results. Quartz remains stable up to 1050 °C, and its presence indicates firing temperatures below this limit [20,22].

Petrographic analysis allowed the identification of calcareous inclusions, i.e. fragments of sedimentary rocks and primary calcite, with very rare reaction rims [23]; XRPD results show that this carbonate mineral is dominant among inclusions and matrix, allowing the definition of a calcareous raw material used in the ceramic production. The decomposition of carbonates (dolomite and calcite) takes place between 650 °C and 900 °C, releasing in the system CaO and carbon dioxide. Primary calcite starts to decompose at temperatures around 750 °C and it completely disappears around 850 °C [22,24,25].

The breakdown of phyllosilicates, i.e. the loss of the hydroxyl groups, takes place at various temperatures starting from 500–550 °C. However, XRPD results indicate the presence of illite, the clay mineral more persistent to firing that starts the breakdown at about 700–750 °C to complete the decomposition at temperatures close to 900 °C [26,27]. The reaction of free oxides CaO (and/or MgO), SiO_2 and Al_2O_3, released from breakdown of carbonates and clay minerals, forms melilite-group minerals, i.e. gehlenite-åkermanite, according to the reaction (1) [21,22,28]:

$$CaO + MgO + Al_2O_3 + SiO_2 \rightarrow CaMgAl_2SiO_7 \quad (1)$$

In our samples the Ca-rich member, gehlenite, has been identified.

The XRPD analysis detected also the presence of clinopyroxene, plagioclase, K-feldspar and olivine. However, as confirmed by optical analysis, these are all primary phases that start to be unstable at temperatures above 1000 °C [18,22].

The mineralogical assemblage and the stability temperature ranges of minerals in the studied ceramics allow estimating a firing temperature between 700 and 850 °C. Moreover, samples containing illite were fired at lower temperatures, whereas the presence of gehlenite suggests a high firing temperature.

Concerning the redox conditions of firing environment, the classic reddish color of the ceramic is related to the oxidation of iron oxides and hydroxides. Indeed, in an oxidizing atmosphere, at temperatures greater than 300 °C, the iron present in the system drives to the formation of maghemite and hematite. On the contrary, in reducing conditions the iron compounds form spinels, magnetite, which lead to a black color of the ceramic [18]. Ceramics analyzed here show an inhomogeneous color, suggesting firing conditions not completely controlled.

5.3. SEM–EDS analysis

SEM analysis was performed to acquire information on morphological and microstructural features (by SEM images)

Table 2
Mineral assemblages of potsherds and their relative abundances (++++ very abundant; +++ abundant; ++ present; + scarce; tr. traces) occurring in representative samples. Cal: calcite; Qtz: quartz; Ill: illite; Hem: hematite; Kfs: K-feldspar; Di: diopside; Gh: gehlenite; Pl: plagioclase; Dol: dolomite; Opx: ortopyroxene; Ol: olivine.

Samples	Fabric	Cal	Qtz	Ill	Hem	Kfs	Di	Gh	Pl	Dol	Opx	Ol
KB.10.B.1054/2	A1	++	++++	+	tr	++	–	tr	–	–	–	–
KB.10.B.1054/83	A3	+++	++	–	tr	–	–	–	tr	–	–	–
KB.10.B.1054/35	A4	+++	++++	++	–	+	–	–	++	tr	–	–
KB.10.B.1054/45	A5	+++	+	tr	+	++	++	–	++	–	++	+
KB.10.B.1054/63	A6	++++	+++	–	–	–	tr	–	+++	–	tr	–

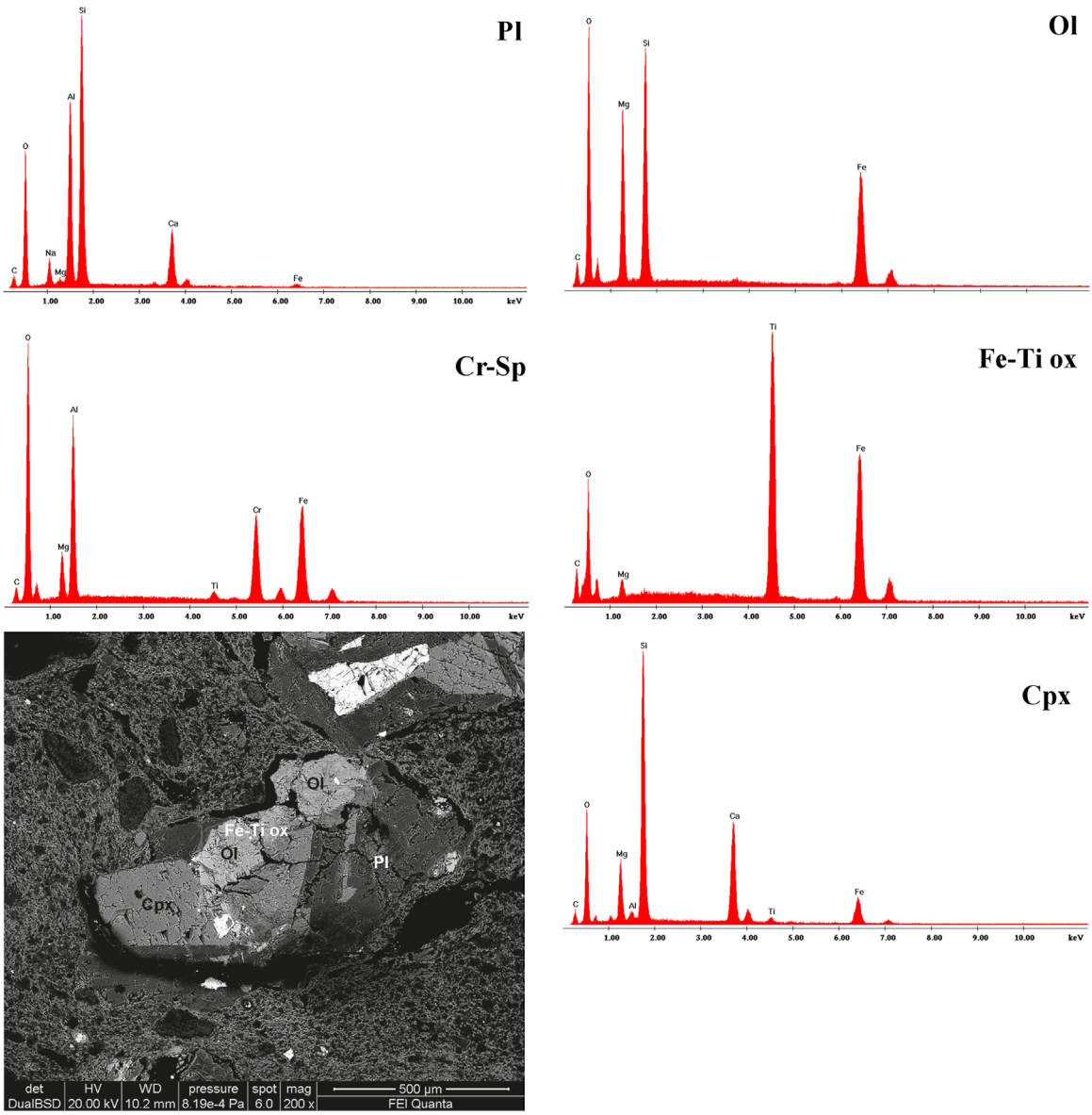

Fig. 5. BSE image and EDS spectra of the paragenetic assemblage of a magmatic rock inclusion, i.e., Cr-spinel (Cr-Sp), Fe-Ti-oxide (Fe–Ti ox), olivine (Ol), clinopyroxene (Cpx) and Ca-rich plagioclase (Pl) (sample KB.10.B.1054/45).

and semi-quantitative chemical data of inclusions and matrix (by BSE and EDS spectra) [17].

In particular, we analyzed in detail fragments of magmatic and sedimentary rocks and grog to infer information about the provenance of the raw material. In addition, morphological investigation permits a preliminary classification of microfossil, occurring as inclusions.

Among inclusions, fragments of magmatic rocks occur in the matrix. EDS analysis highlights the following paragenetic assemblage as shown in Fig. 5: Cr-spinel + Fe-Ti-oxide + olivine + clinopyroxene + Ca-rich plagioclase; this paragenesis is comparable with that of basic-intermediate rocks outcropping nearby of Khirbet al-Batrawy site.

Moreover, coarse single crystals of orthopyroxenes are also present in the matrix of sample KB.10.B.1054/63 (*Fabric* A6), suggesting that the sourcing material is probably the ultramafic rocks occurring as xenoliths or large nodules in the basaltic and pyroclastic rocks of north-eastern Jordan [29].

Inclusions of sedimentary rocks were also analyzed and some of them show the dominant presence of planktonic foraminifera (*orbulina*, *globigerina* and *globigerinoides*) and other benthic organisms (Fig. 6). The occurrence of these inclusions allows the identification of sediments used in the ceramics production, probably the Miocene-Pliocene rocks outcropping in the area.

Concerning grog inclusions, they contain magmatic and sedimentary fragments (Fig. 7). The magmatic rocks included in the grog have the following paragenetic assemblage (Fig. 7a) − Fe–Ti-oxide + clinopyroxene + Ca-rich plagioclase.

Other fragments of grog contain microfossils and carbonaceous fragments (Fig. 7b). The mineralogical composition of grog is consistent with the nature of rocks outcropping in the

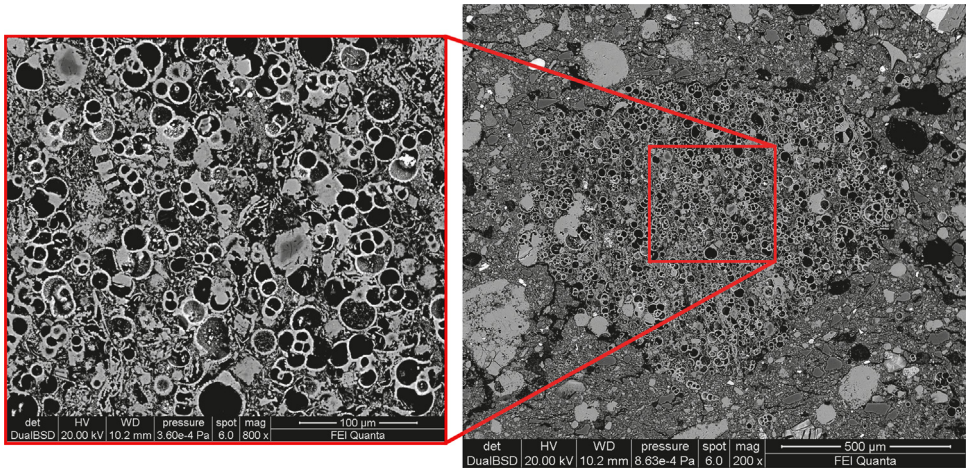

Fig. 6. Sedimentary rocks fragment showing planktonic foraminifera (*orbulina*, *globigerina* and *globigerinoides*) and benthic organisms (sample KB.10.B.1054/83).

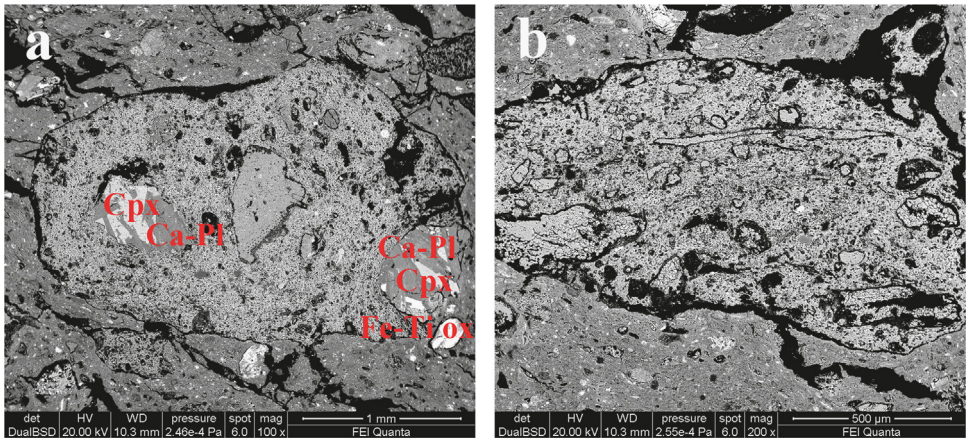

Fig. 7. Fragment of grog containing fragments of magmatic rocks composed by Fe–Ti-oxide (Fe–Ti ox), clinopyroxene (Cpx) and Ca-rich plagioclase (Ca–Pl) (a); fragment of grog containing microfossils and carbonaceous fragments (b) (sample KB.10.B.1040/6).

vicinity of Khirbet al-Batrawy, supporting the use of local crushed pottery. The degree of maturity of the inclusions, their grain size distribution and the presence of grog allow hypothesizing a tempering process with the aim to improve the plasticity of the raw material.

The presence of crystals of calcite as inclusions in *Fabric A3* has been confirmed by SEM–EDS analysis. They could derived from the weathering of calcareous local lithotypes in which crystals of calcite are interbedded in marl and limestone outcrops [9], supporting the hypothesis of a local production for this fabric.

Finally, SEM images do not show the presence of vitrification or reactions rims around the calcareous inclusions. These evidences further support the hypothesis of firing temperatures lower than 950 °C [20,22].

6. Literature review

The results obtained on samples of "Palace of the Copper Axes" have been compared to those obtained from sample retrieved in other contexts of the archeological site of Khirbet al-Batrawy [3].

Fabric A1 can be associated to fabrics *M1 e M2* [3]. This particular raw material is typical of Simple and Storage ware of Early Bronze Age III production in Khirbet al-Batrawy; there are no indications of its use in other historical periods. However, samples belonging to this fabric were also found in contexts different from the Palace, supporting the hypothesis of a not-specialized production. *Fabric A5* is related to *Fabric H* [3] which includes jars and *pithoi* of Simple and Storage Ware. Its attestation starts in Early Bronze Age III and it is present in contexts older than the Palace. It is also attested in later periods, testifying that its productions are not strictly connected to the context of Palace.

Fabrics A2, A3, A4 and *A6* do not show any correspondence with fabrics previously identified [3] and this result seems to support the hypothesis of wares expressly made for the Palace uses.

In particular, *Fabric A2* is used for Red Burnished Ware. This particular fabric shows the same inclusions of *Fabric A1*, but with a smaller grain size. In this view, we can conclude that the raw material of *Fabric A2* was the same of *Fabric A1*, and it was purified with the aim to burnish the surface and to produce much more refined vessels such as the simplest type of Red Burnished palatial jugs (KB.11.B.1124/12).

Fabric A4 includes different types of ceramics such as Simple Ware, Storage Ware, and especially Red Burnished Ware; it is characterized by a low percentage of inclusions with fine grain size. The percentage and size of inclusions in this fabric allow hypothesizing a controlled production with a purification process of the starting raw material to produce higher quality vessels.

The sample KB.10.B.1054/63 (*Fabric A6*) is different from the productions analyzed. At the actual state of the art, none of the samples from Khirbet al-Batrawy shows single crystals of olivine and clinopyroxene as inclusions, also supporting the hypothesis of a specialized production for the Palace of this very distinguished type of jug.

Finally, it is not possible to associate *Fabric B* to other samples from the same site. The quality of the vessels (a big Red Burnished Jug of fine ware) may indicate a special production or an importation [30]. However, the calcareous matrix and the limestone inclusions identified allow concluding that it is also compatible with a local production with addition of quartz-rich sand.

7. Conclusions

The analysis performed on Early Bronze Age ceramic fragments discovered in the "Palace of the Copper Axes" of Khirbet al-Batrawy by using OM, XRPD and SEM–EDS allowed the definition of firing temperature and the provenance of the raw materials involved in the pottery production.

In particular, petrographic analysis allowed the identification of seven petro-fabrics. The presence of coarse size inclusions indicates the use of clay without purification process. However, some samples belonging to the Red Burnished Ware show fine inclusions suggesting a probable purification process allowing the superficial treatments aiming at imitating metal (copper) prototypes.

The XRPD analysis defined the mineralogical assemblage of samples composed by $Qtz \pm Cal \pm Pl \pm Kfs \pm Ill \pm Px \pm Ol \pm Gh \pm Hem$, suggesting a firing temperature in the range 700–850 °C, as supported also by the absence of vitrification phase.

The nature of inclusions has been deeply analyzed by SEM–EDS analysis. Moreover, the inclusions' degree of maturity, the grain size distribution and the presence of artificial inclusions, i.e. grog, allowed hypothesizing a tempering process with the aim to improve the plasticity of the paste.

The results allow the definition of a calcareous raw material used for the ceramic from Khirbet al-Batrawy, composed by an illitic clay containing quartz, calcite feldspars and minor amounts of iron oxides and dolomite. The diffuse occurrence of carbonaceous inclusions, i.e. sedimentary rocks, sedimentary rocks containing microfossils and crystals of calcite, supports the hypothesis of a significant contribution of sedimentary rocks outcropping in the area. Moreover, the basic rocks fragments identified support the hypothesis of a local supply of the raw material used in the pottery production and consequently a local production for the analyzed samples.

Finally, some fabrics identified here are not comparable to previous published data and show some specific technological traits aiming at a finer production which may be connected with the needs of the ruling class living in the palatial context. This was observed for fabrics employed both for big *pithoi*, some of which bear applied symbols referred to the palatial administration (KB.10.B.1040/6) (S1) as well as for the very peculiar class of Red Burnished Ware jugs which are a typical shape of the Palace table service.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.ceramint.2015.12.143.

References

[1] L. Medeghini, S. Mignardi, C. De Vito, D. Bersani, P.P. Lottici, M. Turetta, M. Sala, L. Nigro, Is Khirbet Kerak, Ware from Khirbet al-Batrawy (Jordan) local or imported pottery?, Anal. Methods 5 (2013) 6622–6630.

[2] L. Medeghini, S. Mignardi, C. De Vito, D. Bersani, P.P. Lottici, M. Turetta, J. Costantini, E. Bacchini, M. Sala, L. Nigro, The key role of micro-Raman spectroscopy in the study of ancient ceramics: the case of Jordan potteries from the archaeological site of Khirbet al-Batrawy, Eur. J. Miner. 25 (2013) 881–893.

[3] L. Medeghini, Multi-analytical study of ceramic materials from the archaeological site of Khirbet al-Batrawy (Jordan) (Ph.D. thesis), 2014.

[4] M.A. Al Maadeed, N.J. Al Thani, M. Sadeq, R. Sobott, Pottery from Halat Aobeer and Hazem Al-Jasrah, Qatar, Ceram. Int. 39 (2013) 8301–8309.

[5] L. Nigro, Khirbet al-Batrawy: An Early Bronze Age City at the fringes of the desert, Syria 90 (2013) 189–209.

[6] L. Nigro, Khirbat al-Batrawy, in: G.J. Corbett, D.R. Keller, B.A. Porter, Ch.A. Tuttle (Eds.), Archaeology in Jordan, 2012 and 2013 Seasons, 118, American Journal of Archaeology, 2014, pp. 644–645.

[7] L. Nigro, The Copper Axes Hoard in the Early Bronze IIIb Palace of Batrawy, Jordan, in: K. Rosińska-Balik, A. Ochał-Czarnowicz, M. Czarnowicz, J. Dębowska-Ludwin (Eds.), Copper and Trade in the South-Eastern Mediterranean: Trade routes of the Near East in Antiquity, 2753, British Archaeological Reports International Series, Oxford, 2015, pp. 77–83.

[8] L. Nigro, The Copper Routes and the Egyptian Connection in 3rd millennium BC Jordan seen from the caravan city of Khirbet al-Batrawy, Vicin. Oriente XVIII (2014) 39–64.

[9] D.J. Burdon, A.M. Quennell, in: Handbook of the Geology of Jordan, Government of the Hashemite Kingdom of Jordan, Colchester, UK, 1959.

[10] A.M. Quennell, The geology and mineral resources of (former) Trans-Jordan, Colon. Geol. Min. Resour. 2 (1951) 85–115.

[11] A. Al-Zoubi, Z. Ben Avraham, Structure of the earth's crust in Jordan from potential field data, Tectonophysics 346 (2002) 45–59.
[12] A. Margane, M. Hobler, M. Al-Momani, A. Subah, Contributions to the hydrogeology of Northern and Central Jordan, Geologisches Jahrbuch C Band C 68, Hannover, 2002.
[13] B.R. Khrisat, Geoarcheological investigations at Khirbet al-Batrawy, in: L. Nigro (Ed.), Khirbet al-Batrawy. An Early Bronze Age Fortified Town in North-Central Jordan. Preliminary report of the First Seasons of Excavations, 3, Rome «La Sapienza» Studies on the Archaeology of Palestine & Transjordan, Rome, 2005, pp. 251–261.
[14] I.K. Whitbread, The characterization of argillaceous inclusions in ceramic thin sections, Archaeometry 28 (1986) 79–88.
[15] I.K. Whitbread, Greek transport amphorae: a petrological and archaeological study, British School at Athens, Fitch Laboratory Occasional Paper 4, Athens 1995.
[16] P.S. Quinn, Ceramic Petrography: The Interpretation of Archeological Pottery and Related Artefacts in Thin Section, Archaeopress, Oxford, 2013.
[17] M.S. Tite, Y. Maniatis, Examination of ancient pottery using the scanning electron microscope, Nature 257 (1975) 122–123.
[18] C. De Vito, L. Medeghini, S. Mignardi, D. Orlandi, L. Nigro, F. Spagnoli, P.P. Lottici, D. Bersani, Technological fingerprints of Black-Gloss Ware from Motya (Western Sicily, Italy), Appl. Clay Sci. 88–89 (2012) 202–213.
[19] C. Rathossi, Y. Pontikes, P. Tsolis-Katagas, Mineralogical differences between ancient sherds and experimental ceramics: Indices for firing conditions and post-burial alteration, Bull. Geol. Soc. Greece (2010) 856–865.
[20] M.P. Riccardi, B. Messiga, P. Duminuco, An approach to the dynamics of clay firing, Appl. Clay Sci. 15 (1999) 393–409.
[21] P. Ballirano, C. De Vito, L. Medeghini, S. Mignardi, V. Ferrini, P. Matthiae, D. Bersani, P.P. Lottici, A combined use of optical microscopy, X-ray powder diffraction and micro-Raman spectroscopy for the characterization of ancient ceramic from Ebla (Syria), Ceram. Int. 40 (2014) 16409–16419.
[22] M.J. Trindade, M.I. Dias, J. Coroado, F. Rocha, Mineralogical transformations of calcareous rich clays with firing: a comparative study between calcite and dolomite rich clays from Algarve, Portugal, Appl. Clay Sci. 42 (2009) 345–355.
[23] G. Cultrone, C. Rodriguez-Navarro, E. Sebastian, O. Cazalla, M.J. De La Torre, Carbonate and silicate phase reactions during ceramic firing, Eur. J. Miner. 13 (2001) 621–634.
[24] C. De Vito, L. Medeghini, S. Mignardi, P. Ballirano, L. Peyronel, Technological fingerprints of the Early Bronze Age clay figurines from Tell Mardikh-Ebla (Syria), J. Eur. Ceram. Soc. 35 (2015) 3743–3754.
[25] L. Medeghini, P.P. Lottici, C. De Vito, S. Mignardi, D. Bersani, Micro-Raman spectroscopy and ancient ceramics: applications and problems, J. Raman Spectrosc. 45 (2014) 1244–1250.
[26] M. Özçatal, M. Yaygıngöl, A. İssi, A. Kara, S. Turan, F. Okyar, Ş. Pfeiffer Taşc, I. Nastovad, O. Grupčed, B. Minčeva-Šukarovad, Characterization of lead glazed potteries from Smyrna (İzmir/Turkey) using multiple analytical techniques; Part II: Body, Ceram. Int. 40 (2014) 2153–2160.
[27] M. Bayazit, I. Işık, A. Issi, E. Genç, Spectroscopic and thermal techniques for the characterization of the first millennium AD potteries from Kuriki-Turkey, Ceram. Int. 40 (2014) 14769–14779.
[28] L.V. Ferreira, L.V., A. Gonzalez, M.F.C. Pereira, L.F. Santos, T. M. Casimiro, D.P. Ferreira, D.S. Conceição, I. Ferreira Machado, Spectroscopy of 16th century Portuguese tin-glazed earthenware produced in the region of Lisbon, Ceram. Int. 41 (2015) 13433–13446.
[29] H. Al-Fugha, M. Al-Amaireh, Petrology and origin of ultramafic xenoliths from Northeastern Jordan volcanoes, Am. J. Appl. Sci. 4 (2007) 491–495.
[30] C. Fiaccavento, Two EB III red polished jugs from palace B in Khirbet al-Batrawy and Jugs with reserved alternate-hatching decoration (RAHD) from Palestine and Transjordan, Vicin. Oriente XVIII (2014) 83–100.