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Plasters and mortars from the theatre in Nea Paphos (Cyprus): A multidisciplinary study

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A R T I C L E I N F O

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A B S T R A C T

The study of plasters and mortars constitutes a relevant tool in reconstructing the technological knowledge of the workforces at play. Through a multidisciplinary and multiscale approach, this project characterizes selected samples from the Hellenistic-Roman theatre in Nea Paphos (Cyprus), highlighting the characteristics of the raw materials, the productive processes, and the functional properties. Petrographic analysis combined with x-ray diffraction, thermal analysis and scanning electron microscopy allowed to collect a complete set of elemental, mineralogical and chemical data, all essential for the correct characterization of the samples.

According to our results, it appears clear that both Hellenistic and Roman workforces were able to exploit all the raw materials locally available, displaying a remarkable knowledgeability on how to enhance the performance of the mortar mixtures creating a durable and resistant material that survived to this day. Our results display how a conscient choice was made in the selection of the typologies of plasters and mortars for the fulfilment of different purposes. Furthermore, natural hydraulic lime (NHL) was identified in association with a water-related structure.

1. Introduction

Plasters and mortars have regained a prominent role in the Cypriot research field during the last few decades (see the works of Amadio, 2018; Balandier et al., 2017; Theodoridou et al., 2013; Philokyprou, 2012a, 2012b). Although interest in understanding this widely available material has risen, studies concretely focusing on them are still scarce and are mostly interconnected with the field of conservation rather than archaeology. The techniques used to characterize the samples are similar in both approaches, but the differentiation in aims and objectives between the two disciplines have resulted in limited intercommunication and exchange of data between the two fields. The lack of a comparative database, and in some cases of any available published data, has pushed this research team to start investigating the plaster production in Cyprus in a wide area and across a protracted chronological span. In particular, our research has been focusing on the wide region of modern-day Paphos, an area interested in intense settling activities since the Early Bronze Age. Five archaeological sites, across the Late Bronze Age to the Early Roman periods, have been studied in order to identify synchronic and diachronic developments or changes in the industry of plaster production. In this article, we will present the results of our first case study, the theatre of Nea Paphos. The profuse availability of material in this specific site allowed us to use it as a trial and a stand-alone case study (see Table 1).

The foundation of this research consisted in agreeing in a univocal definition of what plasters and mortars are. De facto, different science fields have different definitions. The main components of plaster and mortar mixtures are binders – the choice of which largely depends on the state of the art, fashion and the geological availability (Marinowitz et al., 2012; Philokyprou, 2012a) – and aggregates, whose function is to enhance the properties of the mixture (Weiner, 2010, 185, 189). Lime is among the most commonly historically employed binders (Theodoridou et al., 2013, 3263; Weiner, 2010, 185, 186); thus, unexceptionally, lime binders are widespread in Cyprus, geologically rich in limestone deposits (Philokyprou, 2012a, 2012b). Other binders commonly found in the archaeological record include gypsum and mud. For this research, mud plasters have been not taken into account, as our main aim is to answer open questions concerning the study of the lime and gypsum plaster production in Cyprus. In particular, our attention was focused on the characterization of the binders, with the specific purpose of recognizing whether or not there would be compatibility with the raw material locally geologically available. Considering the long life of the

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Table 1
Briefly summarises the major features of the paphian theatre from the foundation, around 300 BCE, to the final abandonment. All data and information contained in the table are reported in the website of the paphos theatre archaeological project (www.paphostheatre.org).

Period	Major features
Early Hellenistic (4th-2nd century BCE)	The foundation date of the theatre is around 300 BCE. Few remains date to this chronological period. The orientation of the cavea is believed to be roughly the same as today. It is not possible to concretely define the dimension and shape of the theatre for this earlier phase. Several post-holes in the area of the stage led archaeologists to believe the stage building must have been a removable wooden structure. In the area of the orchestra, scant remains of mud-packed floor are visible beneath the later levels.
Late Hellenistic (2nd-1st century BCE)	During the 2nd century BCE, the theatre underwent its first major refurbishment, following the traditional Alexandrian implant, with particular resemblances to the theatre in Alexandria, Egypt. The stage building was constructed in stone. To this phase also belongs the construction of the so-called "Charonian" tunnel, which runs below the stage and orchestra, at the time built with perishable materials on an elevated level.
Early Roman Age (1st century BCE-2nd century CE)	Augustan phase After a devastating earthquake that hit the island, and particularly the region of Paphos, either in 15 or 17 BCE, a major reconstruction phase happened during the reign of Augustus. The western containment wall of the cavea was completely replaced, after the original collapsed. Antonine phase Another devastating earthquake seemingly hit Paphos around the year 126 CE. Areas across the city of Nea Paphos were subjected by major reconstructions under the auspices of Emperor Antoninus Pius. The renovations in the theatre were commemorated in a partially preserved inscription thanking the Emperor and his adoptive successor, Marcus Aurelius. During this phase, the cavea was cut back into the hill, while the rest of the theatre was profusely embellished and brought up to date with the Roman standards. The parodoi were vaulted and the inner walls frescoed, with part of the painted decorations being still visible today. The orchestra was paved with imported marble slabs, and the stage building – whose foundations are still visible – was decorated with marble or marble-covered superstructures. The stage was a double storey building with colonnaded facade.
Late Roman Age (3rd century CE)	During the 3rd century CE the theatre underwent its last major reconstruction. The reason for the transformation was due to a change in the purpose of the building, which was now altered to allow the flooding of the orchestra for water spectacles. For this reason, a 1 m high parapet wall with netting above was built between the orchestra and the proedria (the first rows of seats) for combat and venationes. The marble slabs paving the orchestra's floor were overlayed by a pink waterproof cement revealed by excavation. The parodoi, which would have normally granted access to the proedria were partially closed, probably as a water-containment measure.
After the 4th century CE	The theatre was officially abandoned during the late 4th century CE. After the abandonment, the site became a quarry for materials, employed – among others – in the construction of the Chrysopolitissa Basilica (located not far South from Fabrika Hill), which took place over centuries beginning during the 5th century. There are traces of Medieval activities tied to metalworking and ceramic production in the whole area of southern Fabrika, as well as inside the theatre perimeter.

theatre, we attempted a sampling strategy covering the different phases of the theatre's main structures, with the aim of identifying eventual chronological changes in fashion, or technological developments.

In order to achieve our aim, we employed a multidisciplinary analytical approach involving archaeological and geological sampling, optical microscopy, chemical and mineralogical analyses. With this system, we were able to investigate the raw materials, the production processes and the technological tools.

2. The context: Site and geology of the area

Nea Paphos was founded during the 4th century BCE by King Nikokles as the new central harbour town of the region. The pre-existing seat of Nikokles' dynasty was the town of Paphos, located in the modern-day village of Kouklia. Nea Paphos served as main trading port for the easily and readily available geological and mineralogical resources of the region: copper outcrops on the Troodos foothills, and lavish timber forests (Papuci-Władyka, 2020, 73). Spanning between the Hellenistic period and modern day, Nea Paphos is one of the most long-lasting sites in Cyprus.

2.1. The theatre

The Theatre is located in the area of Fabrika Hill, the North-Eastern quarter of the ancient city of Nea Paphos, near to where the N-E entrance gate to the city is supposed to have been located. The theatre has been in function as a venue for spectacles for almost seven centuries (Barker, 2015; Green et al., 2015; more information and documentation available at https://www.paphostheatre.org) and was used continuously for different purposes for at least three more.

The first excavations on the site of the theatre date back to the 60 s, when archaeologist K. Nicolaou discovered the top rows of the seating (Nicolaou, 1966). The presence of the theatre, however, remained merely a hypothesis until 1987, when the University of Trier opened a test trench in the orchestra area (Barker, 2015). The Paphos Theatre Archaeological Project (PTAP), an Australian research team, resumed excavations in 1995, and has since directed over two decades of successful working seasons. The methodology adopted by the PTAP project involves stratigraphic excavations in trenches, although the whole area is nowadays mostly uncovered.

The plan of the theatre differs from the standard Hellenistic models – characterized by a horseshoe shape – by displaying a semi-circular implant; it is likely that the original shape followed the Hellenistic tradition and was modified under development during the 1st century BCE, in order to follow the Roman standards (on the theatre's Hellenistic phases see Green et al., 2015). The date of foundation is still under discussion. Pottery findings in the area have been dated as early as the 4th century BCE, suggesting that the theatre was built for a settlement pre-dating the foundation of Nea Paphos, the presence of which has been long hypothesised and discussed by archaeologists and historians (Green et al., 2015; Hayes, 1991). Furthermore, inscribed letters unearthed towards the top of the *cavea* have been dated around 300 BCE (Green et al., 2015). More definitive data concern the abandonment phase of the structure. After several major and minor refurbishments and reworks, the theatre was definitively abandoned during the 4th century CE, most likely due to heavy damages caused by a devastating earthquake (Barker, 2015). The increasing spread of Christian religion might have contributed to the decline of the theatre venue (Barker, 2015; Green et al., 2015), as the difficult relationship between these two institutions is well documented in several areas of the Empire (Davis, 2010). After the abandonment, the theatre was used as a source for building materials to be used in other locations, including the nearby Chrysopolitissa Basilica. Quarrying activities ceased around the 7th century CE. During the Medieval period, the site against Fabrika Hill was utilised for extensive productive activities, with the presence of structures related to metallurgic activities and a major workshop for sgraffito

Table 2
Displays the samples object of this study divided by functional category. For each sample, the identification code, number of sub-samples, number of fragments, sampling location, and general characteristics are indicated.

Functional group	Sample ID	Sub-Samples	Location	General characteristics
Masonry mortars	NPT 2	—	W parodos	Binding mortar joining the masonry of the vaulting wall of the Western parodos. Thick and compact, no visible surface finishing. Stone impressions on all the surfaces
	NPT 8	—	Vomitorium	Binding mortar originally joining the masonry of the vomitorium wall. The samples were collected from the crest of the wall, thus the exposed surface presented traces of weathering.
Wall plasters	NPT 1	—	South of W parodos	Thin fragments of wall plaster with traces of red pigment, and possibly green. Collected from a small niche in the wall.
	NPT 9	—	W parodos wall	Fragment of historical wall plaster encapsulated in modern repair mortar. The surface appears polished.
	NPT 10	—	W parodos wall	Fragment of thick wall plaster with traces of pigment applied on a polished surface.
	NPT 11	NPT 11a	E parodos wall	Fragment of very thin wall plaster with traces of brushstrokes.
		NPT 11b	E parodos wall	Fragment of very thin wall plaster with traces of brushstrokes.
		NPT 11c	E parodos wall	Fragment of very thin wall plaster with traces of brushstrokes. These three samples were collected from different parts of the same wall.
Hydraulic	NPT 3	NPT 3a*	Orchestra	Pink mortar covering the floor of the orchestra. Ceramic aggregates are visible at the naked eye. The surface appears smooth and even.
		NPT 3b*	Orchestra	Bulk sample of floor substratum with waterproof layer in between. The sample was the understructure of NPT 3a.
	NPT 12	—	E parodos	Fragments of pink waterproof cement collected from the wall and the floor of a structure associated with water containment purposes. Ceramic aggregates are well visible at the naked eye. The surface appears smooth and even with evident traces of weathering.
Seat sealing	NPT 4	—	Cavea – 2nd row	Fragments of plaster coating the seatings in the cavea. The surface is smoothed and evened, but shows no traces of pigments.
	NPT 6	NPT 6a	Cavea – 6th row	Fragments of plaster coating the seatings in the cavea. The surface is smoothed and evened, but shows no traces of pigments.
		NPT 6b	Cavea – 9th row	Fragments of plaster coating the seatings in the cavea. The surface is smoothed and evened, but shows no traces of pigments.
		NPT 6c	Cavea – 11th row	Fragments of plaster coating the seatings in the cavea. The surface is smoothed and evened, but shows no traces of pigments.
		NPT 6d	Cavea – 9th row	Fragments of plaster coating the seatings in the cavea. The surface is smoothed and evened, and shows traces of a dark reddish brown pigment.
	NPT 7	NPT 7a	Displaced	Fragments of plaster coating the seatings in the cavea. The surface is smoothed and evened, but shows no traces of pigments.
		NPT 7b	Displaced	Fragments of plaster coating the seatings in the cavea. The sample is brittle and crumbly.
Floors	NPT 5	—	Corridor	Soft but compact fragment of stone topped by a bright white layer, originally interpreted as a plaster coating or a lime wash.
	NPT 3a-3b*		Orchestra	See above.

* Sample NPT 3b and NPT 3a are contemporarily waterproofing and flooring mortars.

pottery.

Despite the theatre is still occasionally being referred to as “Hellenistic”, not much of this first phase is currently visible (Barker, 2015; Green et al., 2015), and most of the samples analysed in this study concern indeed the Roman phases. When attributing our samples to specific chronological periods, we decided to refer to the dating of the structures associated, fully aware that there might be discrepancies between the construction phase and the decoration, other than superimposing refurbishment of different periods.

2.2. The geological context

The Paphian region on the west coast of Cyprus is located near the geological interface between the Circum Troodos Sedimentary Succession and offshore Facies of Paleogene, Neogene and quaternary deposits. The outcrops of the Circum Troodos Sedimentary Succession are located approximately 5 km northwest of the central part of Paphos. A typical representative of these rocks are the carbonate sediments of the Miocene *Pakhna* formation (Eaton and Robertson, 1993). Is characterised by alternating of marls, chalks and limestone deposits (Scirè-Calabrisotto et al., 2017). The local limestone types are referred as the *Havara* and *Kafkalla* deposits. *Havara* is a surficial deposit of porous limestone type with presence of chalk or marl. As *Kafkalla* are referred the hardened

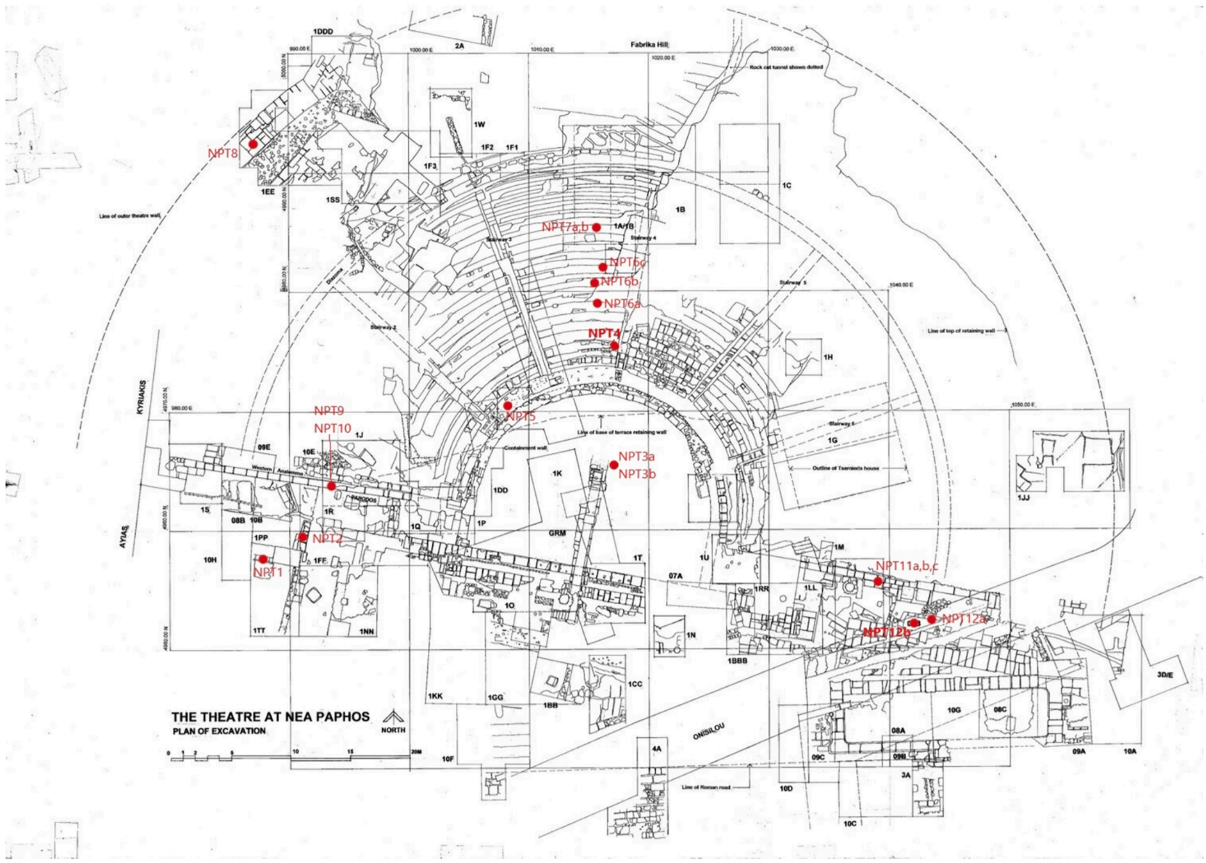

Fig. 1. Displays the exact locations in which samples were collected. Plan of the theatre courtesy of the Paphos Theatre Archaeological Project archives, created by Geoff Stennett, altered by author (addition of the sampling locations).

upper portion of crust of *Havara,* which is the result of soil forming process due to lime enrichment (Schirmer, 1998).

The central part of the Paphos region is formed by geologically younger formations of Cenozoic age. These are the outcrops of Pliocene Nicosia formation (silty or sand marl deposits), Pleistocene marine terrace deposits and aeolian deposits (calcarenite formed by cementation of fine-grained sit deposited in shallow marine environment or coastal sand dunes) and Pleistocene/Holocene gravels, sands and silty sediments or clays fluvial deltaic, marine, aeolian or lacustrine deposits (Amadio, 2018; Zomeni, 2012).

Due to the geological and topographical conditions in the drift area of Troodos Mountains, the fragments of igneous rocks from the central part of the island may be found in the sedimentary rocks around Paphos. These can be mainly rocks from ophiolite complexes, pillow lavas, gabbro or serpentinite. These fragments occur mainly as components of river sediments that are brought to the Paphos area by the Ezousa River or Agriokalami stream.

3. Materials and methods

A total of 45 fragments have been collected from the archaeological site of Nea Paphos Theatre, under the auspices and with the permission of the Department of Antiquities of Cyprus. The collected samples have been subdivided into 12 groups and attributed a specific code and number (see Table 2). The sampling strategy followed a pre-existing, and still unpublished, study – carried out by the PTAP mission – focusing on dating the theatre's plasters. The aim of this sampling was to cover all the available plastered features, in order to obtain a holistic overview (Fig. 1). Sampling was minimally invasive, while all the performed analyses were destructive.

We sampled plasters with different functions, which can be summarized in the following five categories: masonry mortars, comprising mortar mixtures used as binding material; wall plasters, encompassing the samples applied on wall surfaces with coating and/or decorative functions; waterproofing mortars, consisting of samples employed as waterproofing coatings; seat sealing, the plasters specifically coating the seats on the *cavea*; and flooring surfaces. At a first macroscopic evaluation, the samples appeared well preserved with no relevant issues of conservation. Moss and plant traces were visible, especially in the samples collected in the *cavea* area. The masonry mortar samples, collected respectively from the W *parodos* area and the *vomitorium*, presented traces of superficial recrystallization, possibly due to the exposition to weathering agents. Quite a few samples preserved traces of pigmentation on the surface, especially in the area of the W *parodos*. With the exception of the two masonry mortars, all the samples collected in the theatre are lime-based plasters.

The analytical procedure adopted is based on previous studies (Kozlovcev and Válek, 2021; Philokyprou, 2012b; Válek et al., 2020; Kozlovcev et al., 2023; Letourneux and Feneuille, 2012; Válek, 2015; for characterization of the material also see Groot et al., 2004; Middendorf et al., 2004) and combines multidisciplinary and multiscalar approaches. After the preliminary, macroscopic assessment – which aimed at recording generic features, including weight, dimensions, surface appearance, and conservation status – fifteen samples and sub-samples were selected for the production of blue-stained, uncovered, polished thin sections. Two sub-samples were not suitable for thin section preparation due to lack of material (NPT 6c, NPT 7b), while one sample (NPT 9) presents extensive modern repair, which would invalidate the characterization of the historic mortar. The selected samples were first analysed by means of petrography (optical microscopy OM) in order to gain information about composition and technological features; subsequently, high resolution images of the structure, in addition to the

Table 3
Lists all the samples and the analysis performed on them.

Sample ID	OM	SEM-EDS	XRD-QPA	TA-DSC
NPT 1	X	—	X	X
NPT 2	X	X	X	X
NPT 3a	X	X	X	X
NPT 3b	X	X	X	X
NPT 4	X	X	—	—
NPT 5	X	—	—	—
NPT 6a	X	X	—	—
NPT 6b	X	X	X	X
NPT 6c	—	—	—	—
NPT 6d	X	X	—	—
NPT 7a	—	—	X	X
NPT 7b	—	—	—	—
NPT 8	X	—	X	X
NPT 9	—	—	—	—
NPT 10	X	X	X	X
NPT 11a	X	X	—	—
NPT 11b	X	X	—	—
NPT 11c	X	X	—	—
NPT 12	X	X	X	X

elemental composition of the binder and selected aggregates particles, were obtained with SEM-EDS (scanning electron microscopy coupled with an energy dispersive spectrometer) analyses. Mineral composition data were acquired using XRD-QPA (x-ray powder diffraction with quantitative phase analysis by Rietveld (1969) method) and compared with the results of TA-DTG (derivative thermogravimetry) (for a complete list of the analysis, see Table 3 below).

For the petrographic analysis, a standard polarized light microscope (PLM), Olympus BX53M with an Olympus DP27 digital camera, was utilized. A "cold cathode" type Mk 5-2 was associated to the microscope to further investigate binders and binder-related particles; the analysis was performed under the following conditions: the electron beam current was at 260 μA at 15 kV voltage. SEM-EDS analyses were performed on carbon-coated samples with a Tescan MIRA II LMU scanning electron microscope with an energy-dispersive analytical system (Bruker AXS) under the following conditions: back-scattered electron mode (BSE) with electron accelerating voltage corresponding to 15 kV, at a WD of 15 mm, in low vacuum. The chemical composition was quantified by Brucker Esprit 2.5 software, without standardization. The analytical results were expressed in oxide form.

Thermal, as well as XRD analysis, were performed on samples ground to analytical fineness. Each sample was firstly gently crushed in a mortar and sieved through a set of different sieves ranging from 90 to 63 μm. The fraction above 90 μm was considered to be corresponding mainly to the aggregates, while the fraction below 63 μm was considered to be rich in binder (Diaz et al., 2022). Before the XRD analysis, an internal standard (ZnO, 10 wt%) was homogenized with the sample. Data were collected on a diffractometer D8 Bruker Advance pro (Cu Ká radiation, 40 kV and 40 mA) with 0.01 °C step size 2Θ and counting time 0.4 s/step. Quantitative phase analysis (QPA) – to determine crystalline and amorphous phases – was performed by the Rietveld method (1969) using Topas 4.2 from Bruker AXS. Derivative thermogravimetry was performed on TA Instruments Discovery SDT 650 under the following conditions: Nitrogen atmosphere, heat rate 20 °C/minute, temperature range 50–1000 °C. TG, DTG and heat flow curves were collected and analysed with MS Discovery; special focus was directed towards the regions between 50–250 °C (detection of gypsum), 250–550 °C (estimation of hydraulic phases) and between 600–850 °C (carbonate decomposition) (Földvári, 2011). When the spectrum displayed possible traces of organic materials the sample was analysed again with thermogravimetry coupled with a mass spectrometer (TGA-EGA, evolved gasses analysis), measuring the eventual exothermic processes in Nitrogen and air atmospheres. The detection and identification of evolved gases were realised by quadrupole mass spectrometry MS Discovery.

Fig. 2. Sample NPT 8, in situ before the collection, on the crest of the wall of the vomitorium. On the top part it is possible to observe traces of weathering and recrystallization.

4. Results

4.1. Masonry mortars

Masonry mortars were preserved in different areas of the theatre, however it was possible to safely sample – without causing any structural or aesthetical damage – in two areas: the southern wall running parallel to the western *parodos* (sample NPT 2), and in the walls of the *vomitorium* (sample NPT 8), located on the North-West sector of the *cavea*. It is noteworthy to mention that these two samples are likely belonging to the earliest phases of the theatre's history.

Preliminary macroscopic observation immediately highlighted strong similarities between the two samples, which appeared remarkably different from the other plasters collected in the theatre. The mortars display a fine, homogeneous, compact, light-grey binder matrix, with well-sorted and evenly-distributed particles. The outer, exposed surfaces present similar responses to weathering agents, with extensive surface recrystallization (Fig. 2). OM analysis (Fig. 3) allowed us to identify the binder as well-sorted gypsum – as highlighted by the maximum particle size inferior to 0.5 cm. Silica and carbonate particles are distributed in the matrix as a result of the burning process of the raw material, rather than intentional addition of aggregates. According to the XRD-QPA and TA (respectively Table 4 and Table 5) analyses on the binder-rich fractions, the gypsum content is over 90 % in both cases (see Table 4), while the calcite content is around 7 %.

Conclusively, the petrographic, mineralogical and chemical analyses confirm the similarities between the two samples, allowing us to suggest that the gypsum used for their production comes from the same source, and that a similar production process was followed. This statement is supported by the presence of limestone fragments with natural Si-rich infills detected in both NPT 2 and NPT 8 (see Fig. 3B). This type of particles has not been observed in any of the geological samples collected.

Technologically speaking, the thickness of samples (up to 5 cm) suggests the employment of construction techniques that required slow setting gypsum. One possible method to achieve it is to produce the plaster with heterogeneous calcination temperatures that affect and modify setting times (Elert et al., 2023). Furthermore, the observation of the matrix allowed us to estimate a firing temperature for the raw gypsum stone lower than 900 °C, as demonstrated by the incomplete burning of limestone and siliceous particles.

4.2. Wall plasters

Wall plaster samples were collected from different areas of the theatre, with focus on the *parodoi* walls (NPT 9 and 10 for the western

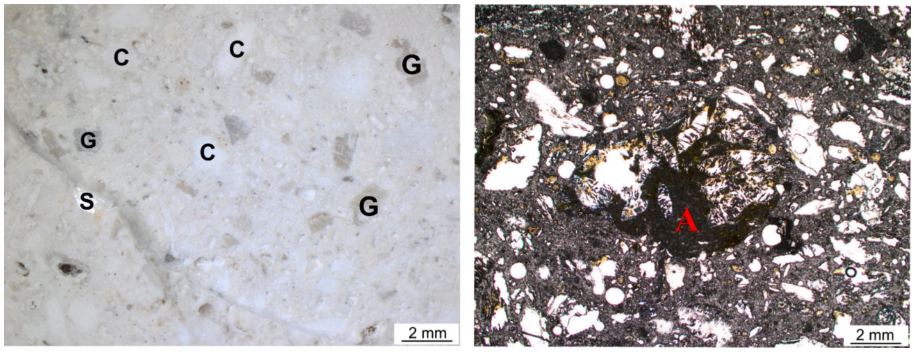

Fig. 3. A (left) shows the freshly cut section of sample NPT 2 under the stereomicroscope, with gypsiferous particles (G), limestone fragments (C) and siliceous particles (S) visible at low magnifications; while (B) (right) shows the same sample under OM-PPL, with the Si-rich limestone fragment in the centre (A).

Table 4
Summarizes the XRD-QPA results on the binder-rich fractions of each sample, taking into consideration the amorphous and the three main compositional mineral phases: calcite ($CaCO_3$), gypsum ($CaSO_4*2H_2O$) and silica (quartz or chert; SiO_2). The samples with two layers (NPT 6b and NPT 7a) were mechanically cut and separated to obtain: NPT6b1/NPT7a2 corresponding to the finishing layers; and NPT6b2/NPT7a1 consisting of the ground layer. Sample NPT 10 displays a sequence of two layers mechanically detached and analysed separately. XRD-QPA was performed on the superficial part of the sample (10a) and in the lower area (10b), which contained remnants of a waterproofing mortar layer. Amorphous phases can be indicators of possible hydraulicity.

Sample ID	$CaCO_3$%	$CaSO_4$%	SiO_2%	Amorphous%
NPT 1	66.1	1.9	1.7	23.2
NPT 2	6.7	92.8	<0.5	0.0
NPT 3a	47.6	<0.5	2.1	49.4
NPT 3b	71.4	n.d.	1.0	27.0
NPT 6b1*	95.0	<0.5	<0.5	4.5
NPT 6b2*	75.0	n.d.	1.1	21.9
NPT 7a1*	72.5	n.d.	1.2	23.6
NPT 7a2*	77.4	n.d.	1.5	15.0
NPT 8	7.5	91.4	0.7	0.0
NPT 10a	60.1	0.6	<0.5	37.8
NPT 10b	61.6	<0.5	1.1	29.9
NPT 12	91.3	<0.5	1.7	6.4

Table 5
Summarises the TA results on the binder-rich fractions of each lime-based sample, highlighting the percentage of weight loss in the temperature range of interest for the decomposition of $CaCO_3$. the expected temperature range is set between 650 °C and 850 °C, however the analysed samples display an earlier start of the process, possibly due to the presence of different carbonates (i.e. aragonite). Calcium carbonate content was calculated following the following formula: $CaCO_3\%content = \frac{wt.loss\%(600-850^{\circ}C)*100}{CO_2molarmass}$.

Sample ID	Wt loss % 600 °C-850 °C	Wt. loss% 550 °C-850 °C	Wt. loss% 500 °C-850 °C	$CaCO_3$% content
NPT 1			37.6	85.5
NPT 3a			24.6	55.9
NPT 3b*		32.7		74.3
NPT 6b1*	41.8			95.0
NPT 6b2*	39.2			90.5
NPT 7a1	37.6			85.5
NPT 7a2*	39.8			90.5
NPT 10a			30.7	69.7
NPT 10b			36.9	83.9
NPT 12			35.1	79.8

parodos; NPT 11a, b, c for the eastern one). One additional wall plaster was collected from a wall running parallel to the western *parodos* (NPT 1). The parapet wall erected between the orchestra and the *proedria* preserved traces of a thin wall plaster, impossible to sample. In the area around the theatre, scattered architectural elements – including columns, capitals and blocks of stone – preserved scanty traces of pigmented decorative plasters; however, being their original location, function, and date unknown, it was deemed less relevant to sample them.

The wall plaster samples in object of study have different structures, compositions and finishing treatments (Fig. 4), making connections and comparisons hazardous. However, it is possible to observe a certain degree of similarity between the samples collected from the same structures. Furthermore, the type of aggregates employed in the mortar mixtures are similar to what has been observed in the wider context of the theatre: river sand, limestone fragments and crushed shells.

4.2.1. *Western parodos wall plasters*

The two samples collected from the western *parodos* wall consist of up to 7 cm thick blocks of compact and well-sorted lime plaster distributed in layers. The sequence of layers appears as follows: a thin more porous layer was set directly on the stone blocks and let to partially dry before a thicker and more heterogeneous plaster layer was laid on top of it. The pigment seems to have been applied directly on the fresh plaster (more evident in sample NPT 1, see Section 4.2.3). The first layer, applied directly on the stone, consists of a mixture of lime binder with finely crushed clay-based materials (possibly bricks or ceramic fragments) and sand. Characteristic of this layer is the presence of a highly irregular pore structure with traces of deposited salts inside (Fig. 5). The second layer consists of a heterogeneous mixture of lime binder with limestone fragments, river sand, crushed shells, and occasionally crushed clay particles. Phenomena of calcite dissolution and precipitation are well documented (Fig. 6).

Chemical and mineralogical analysis on the binder-rich fractions of the samples highlight the presence of a relatively pure lime binder ($CaCO_3$% above 60 %) with traces of gypsum and silica minerals. XRD-QPA detects a considerable percentage of amorphous phase (between 30 and 40 %), possibly linked to the presence hydrated hydraulic phases.

4.2.2. *Eastern parodos wall plasters*

The samples from the eastern *parodos* wall are just a few millimetres thin, with a bright white finishing and clear brushstrokes marks (Fig. 7A). Despite the reduced thickness, all three samples (NPT 11a, b, and c) present a double layered structure, remarkably similar to the one observable in the seat sealing functional category discussed further (see Section 4.5). The layer directly attached to the wall is coarser, more porous and less well-sorted. It consists of a mixture of highly pure lime binder with river sand of fine grain (max. grain size 1 mm). On top of it lays the finishing layer, a thinner stratum consisting of pure lime mixed

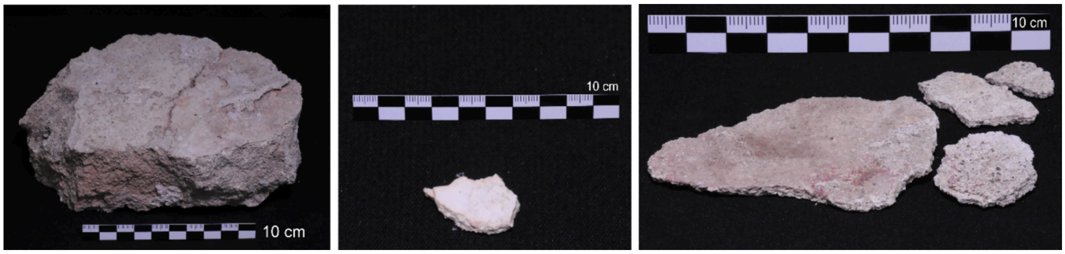

Fig. 4. The three different types of wall plasters collected in the theatre as photographed during the documentation phase, after a preliminary cleaning. On the left, sample NPT 10, a thick double layered wall plaster, with a smooth, polished surface with possible traces of pigments; in the centre, NPT 11a a double layered, thin wall plaster with a bright white finish applied with brush; on the right, sample NPT 1, a single layer of lime plaster topped with bright red and yellow pigments, applied with a fresco or semi-fresco technique.

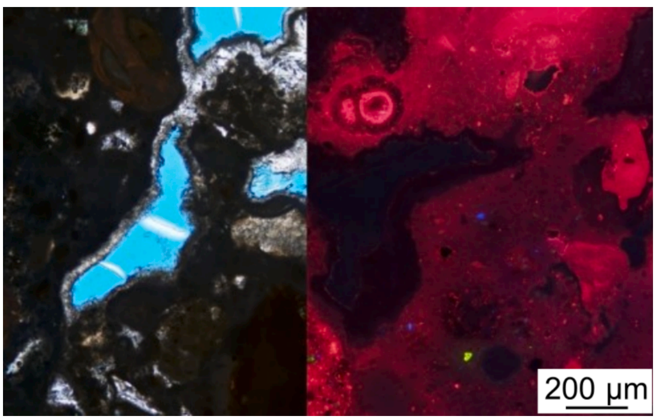

Fig. 5. OM-PPL (left) and cathodoluminescence (right) microphotograph of sample NPT 1; the dark matrix corresponds to the lime binder, while the needle-shaped crystals correspond to salts. Cathodoluminescence allowed us to completely exclude the identification of the crystals with calcite recrystallization, as they would have appeared as bright red in CL.

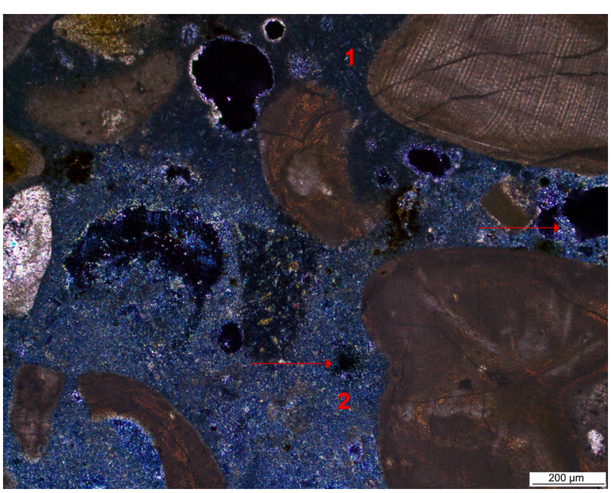

Fig. 6. OM-XPL microphotograph of sample NPT 10 with focus on the interface between layers 1 and 2. Legend: 1 = first layer; 2 = second layer; arrows = precipitation and recrystallization traces.

with crushed shells. No traces of pigments are visible. Both layers well cautiously smoothed and evened, and some time must have passed between the applications of the two: in fact, traces of dark, organic pollution are visible in the interface (Fig. 7B).

Due to the scarcity of available material, XRD and TA analyses were not performed on the sample. All the chemical information about the elemental composition come from the SEM-EDS analysis (CaO above 86 %; SiO_2 around 3.5 %; presence of SO_3 and MgO in most cases between 0.5 % and 3 %; traces (below 1 %) of Al_2O_3 and FeO – this corresponds to the average of measurements taken on the binders of samples NPT 11a, b and c; for each sample 5 different points were measured).

4.2.3. *Other wall plasters*

The only other wall plaster collected is NPT 1, gathered from a structure with a niche located south of the western *parodos* wall. This sample is the only one to have a single layer structure among all the wall plasters analysed. The exterior appearance is similar to the one of the eastern *parodos* wall samples: thin lime plaster with a smooth finish and traces of brushstrokes. However, the mortar mixture was visibly different, with NPT 1 displaying a much denser, lime-richer binder with higher concentration of aggregates. These mostly consist of fine (below 1 mm) river sand, limestone, and crushed shells. The plaster was smoothed with the help of a tool, whose action resulted in the horizontal orientation of the aggregates and in the presence of a crack running parallel to the surface. The surface was then completed by adding a bright red pigment, which was applied directly on the surface as proven by the colour seeping through the underlying layer (Fig. 8).

In conclusion, it appears evident that the decorative plasters were not applied at the same time on the two walls of the *parodoi* and on the other structure. This might be the result of minor refurbishments happening during different moments of the long history of the theatre. At any rate, despite being ascribable to different phases, the overall composition of the theatre wall plasters is similar, and the materials employed are all of local sourcing. In fact, the presence of radiolarian chert from the Dhiarizos river, as well as the limestone fragments remarkably similar to the geological formations of the Paphian region are both element in support of a local provisioning of the materials. Nonetheless, a precise sourcing location has not been identified yet.

4.3. *Waterproofing mortars*

The definition "hydraulic" is contradictory and often discussed by scholars of different discipline. The term hydraulic means the ability of a binder to set and harden in wet conditions and highly hydraulic lime-based systems can harden under water. These binders are not water soluble and thus provide a certain water resisting properties to a mortar. The distinguishing feature of hydraulic mortars is the presence of unstable silicate phases (Weiner, 2010, 188). Silica minerals can be naturally present in and to produce a natural hydraulic lime suitable raw material has to be found and burnt to form hydraulic phases that react with water during the hardening phase of the binder. Similar hydrated hydraulic phases are formed by a reaction of uncarbonated lime – i.e. slaked lime in the form of calcium hydroxide – with certain rocks/sand of volcanic origin. The pozzolanic reaction is often manifested by a reaction rim around the reacting aggregate, but its presence is not always clearly identifiable. The absence of a reaction rim does not mean that a pozzolanic reaction has not occurred in the binder (Calzolari et al.,

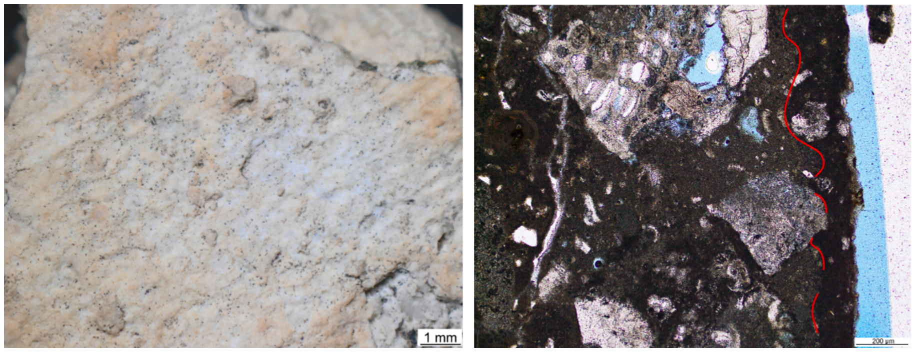

Fig. 7. A (left) stereo-microphotograph of sample NPT 11a with well visible brushstrokes; 7B (right) OM-PPL microphotograph of sample NPT 11a with focus on the interface between the two layers.

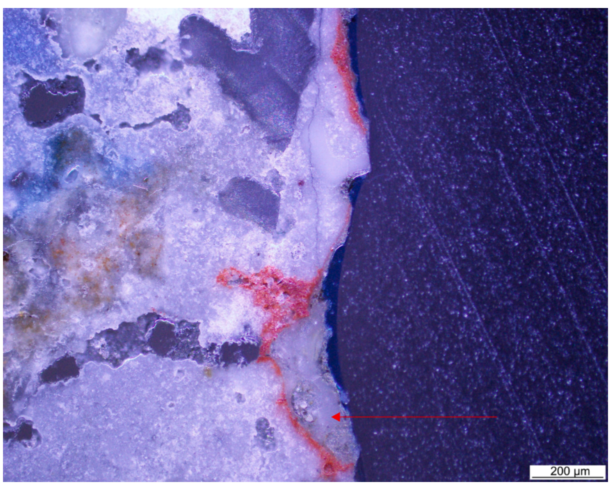

Fig. 8. Sample NPT 1 in thin section under the optical microscope combined with UV light. The red pigment was applied with a fresco technique, as highlighted by the pigment seeping through the binder. On top of the pigment, a new layer of mortar is visible, hinting to possible repairs (arrow).

2023).

In this paper, we use the term "waterproofing" to refer to this category of samples, pointing out their function rather than the material property.

Waterproof features associated with the theatre mainly consisted of the waterproof flooring of the orchestra (sample NPT 3a), and a pink mortar associated with a structure related to the sewage of water (NPT 12), located between the eastern *parodos* and the Nymphaeum. Both these features are dated to the Roman phases of the theatre, with the orchestra floor refurbishment being securely dated not earlier than the 3rd century CE (Barker, 2015). On a macroscopic level, these two samples appear quite similar: they consist of up to 5 cm thick fine lime mortar mixed with considerable amount of finely crushed backed-clay particles. Crushed bricks or pottery fragments had been previously observed in minor quantities in the other samples from the theatre. In the case of the waterproofing samples, however, the percentage of clay content is much more significant.

At the moment of sampling, we were informed that the structures on which the samples were applied had been associated with water-related functions (Barker, 2015), however we could not be sure whether they possess hydraulic properties. Chemical and mineralogical analyses were fundamental for the understanding of this. According to the XRD-QPA results, these macroscopically similar samples have little in common on the mineralogical composition level. While the orchestra floor (NPT 3a) presents a high percentage of amorphous content (amorphous – 49.4 %, $CaCO_3$ – 47.6 %) – generally associated with hydrated hydraulic phases – sample NPT 12 is a lime-rich binder ($CaCO_3$ – 91.3 %, amorphous – 6.4 %), with scanty traces of silica mineral phases. Thermal analysis confirms this dissonance, pointing to the possible use of natural hydraulic lime (hereinafter NHL) in the production of NPT 3a – the orchestra floor – as hinted by the CO_2/H_2O ratio being 4.75 (Bakolas et al.,1998). In the case of NPT 12, this same ratio was equal to 27, pointing towards the use of a non-hydraulic lime (Calzolari et al., 2023). To conclude, SEM-EDS mapping further strengthens the idea that the

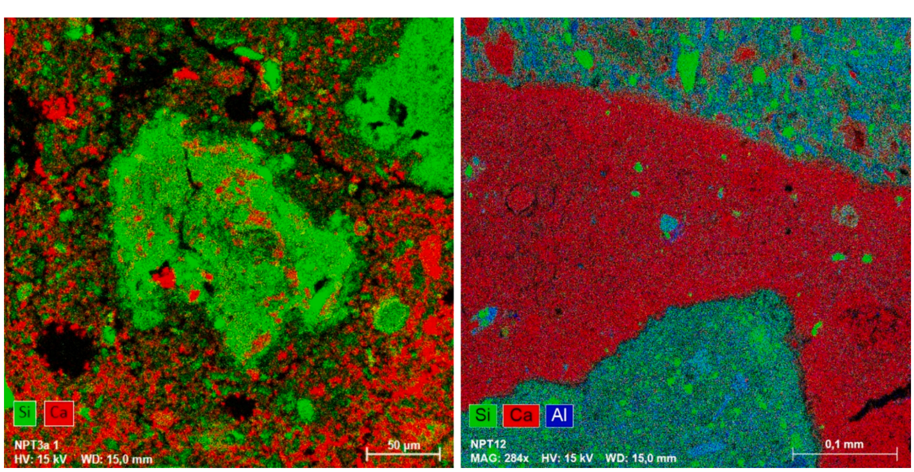

Fig. 9. SEM-EDS maps of samples NPT 3a (left) and NPT 12 (right). In NPT 3a silica (green) particles are distributed in the calcite (red) binder, while in NPT 12Si is almost exclusively contained in the pozzoloanic aggregates.

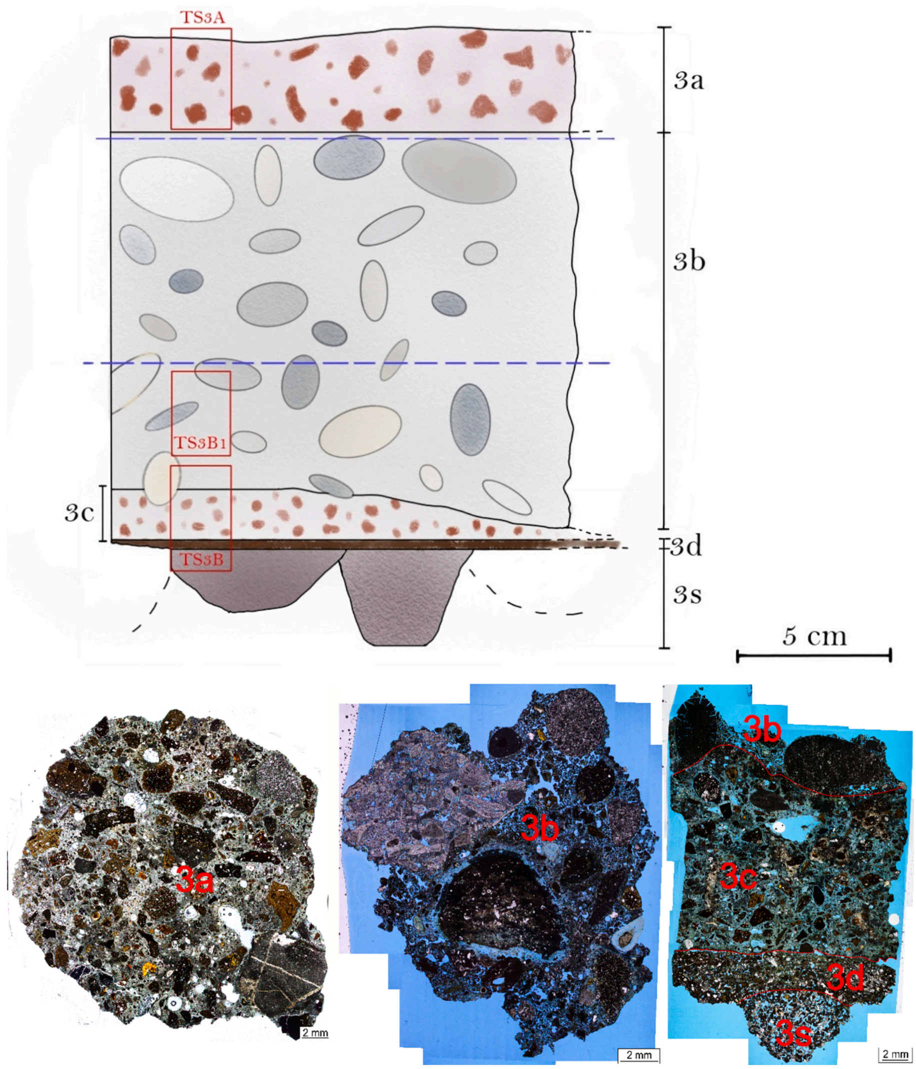

Fig. 10. A (top)) Schematic representation of the orchestra floor section. From top to bottom: layer 3a, waterproofing mortar; layer 3b, coarse and thick lime plaster layer (blue lines indicate the part not sampled and only ideally reconstructed); layer 3c, the irregular patches of waterproofing mortar; layer 3d, the binding and smoothing mortar; layer 3 s, the sandstone blocks. The three squares represent the thin sections produced from this sample, highlighting the layers visible in each of them. Drawing by author. 10B (bottom)) scan of the thin sections represented schematically in Fig. 10A (red rectangles); from left to right: TS3A (=layer NPT 3a), TS3B1 (=layer NPT 3b); TS3B (=layer NPT 3b, 3c, 3d, 3 s).

orchestra floor sample (NPT 3a) was produced using NHL (Fig. 9), while the water sewage-related sample was crafted employing regular air lime, and its waterproofing properties were achieved by adding burnt clay particles. The cementitious index (CI) of both samples was calculated following this formula (after Arizzi and Cultrone, 2021; Figueiredo et al., 2016):

$$CI = \frac{1.1Al_2O_3 + 2.8SiO_2 + (0.7Fe_2O_3)}{\mathrm{CaO} + 1.4\mathrm{MgO}}$$

The results, however, were surprising similar with NPT 3a having an average CI of 0.33, and NPT 12 of 0.27. According to the classification proposed by Holmes and Wingate (2002), sample NPT 3a is slightly hydraulic, while NPT 12 is on the border between fat lime and slightly hydraulic – the threshold being at 0.3.

Finally, it is worth mentioning that pozzoloanic plasters and mortars were by far more widespread in Roman times than earlier (Theodoridou et al., 2013; Jackson et al., 2012).

4.4. Floors

Apart from the floor of the orchestra (sample NPT 3b), not many

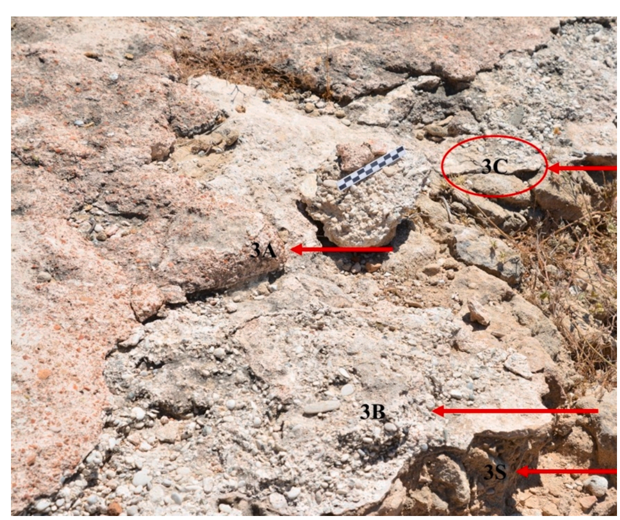

Fig. 11. Photograph of sample NPT 3a and 3b in situ (next to scale bar).

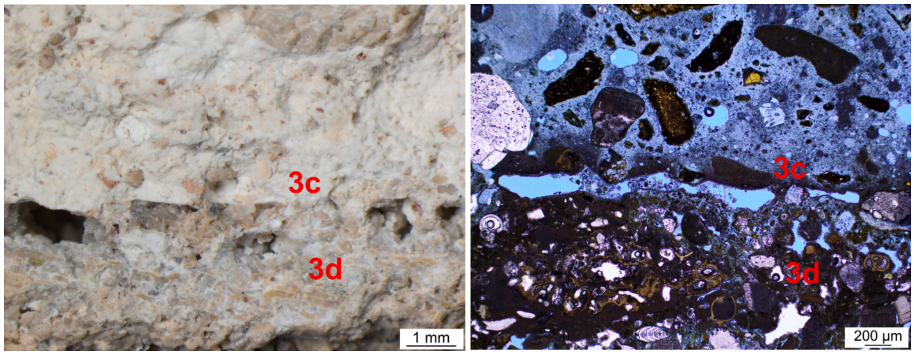

Fig. 12. Picture of the detachment between layers 3c and 3d (left: stereomicroscope picture; right: om-ppl picture).

other floor surfaces were visible in the theatre. Scanty traces of lime plaster or lime wash were visible on the floor of the narrow corridor between the parapet wall and the *proedria* but they were not sampled. Thus, all the information about the floor coatings come from the single orchestra floor sample. This structure is related to the Roman phases of the theatre, and more specifically to the 3rd century CE.

Sample NPT 3b consists of a 10 cm thick block, displaying a sequence of at least three layers, on top of which laid sample NPT 3a (discussed in Section 4.3). The whole structure was about 20 cm thick, and it was not possible to collect a cohesive block with all four layers. Sample NPT 3b alone encompasses four distinguished layers with different binders, aggregates, porosity, and, possibly, even functions (see Figs. 10 and 11). Construction starts with small sandstone blocks of similar dimensions but irregular shapes (layer 3 s in Fig. 10) topped and bound together by a thin, brown lime mortar (layer 3d). This mixture of lime and sand was likely applied to smoothen and even the surface before adding the subsequent layers. Between layer 3d and 4c, a series of flat and elongated pores highlights the presence of adhesion problems, with the waterproofing layer (3c) having detached from the underlying structure (Fig. 11 and Fig. 12). Layer 3c presents a fine, light-grey lime binder mixed with clay-based materials, limestone fragments and sand. This stratum is not evenly distributed throughout the sample and rather appears in patches of different thickness. The thicker layer (3b) consists of a mixture of lime binder and coarse, well-rounded limestone fragments.

XRD and TA analysis of the binder-rich fraction of layer 3b show a lime-rich binder with moderate content of silica minerals. Considerable amorphous content – 27 % – and an earlier start of the decomposition of carbonates in TA curves can be ascribed to the presence of hydraulic phases.

This sample raised a series of questions concerning the construction techniques of floors structures. At the moment of publication, we lack any comparative data either from other theatres or from other public structures in Nea Paphos. Samples gathered from the agora of Nea Paphos are currently under examinations, and the results will be published soon. Until then, this sample remains a *unicum* and its interpretation requires cautiousness.

4.5. Seat sealings

A unique feature of the Nea Paphos theatre is the presence of plasters coating the seating rows of the *cavea.* While this feature is known in several other Hellenistic and Roman theatres – including the above-mentioned one in Alexandria of Egypt – comprehensive studies of seat sealing plasters have never been completed in Cyprus. Functionally speaking, these plasters serve contemporarily an aesthetical purpose and a practical one, as they cover the seats from weathering agents (Barker, 2015, 35). Considering their function, these plasters were likely cleaned and even replaced in short intervals of time. Therefore, it is impossible to offer a precise chronological window, and it is only logical to assume that they must belong to the latest phases of use of the theatre, during

Fig. 13. Stereomicrophotograph of sample NPT 7b section. Finishing layer is on top.

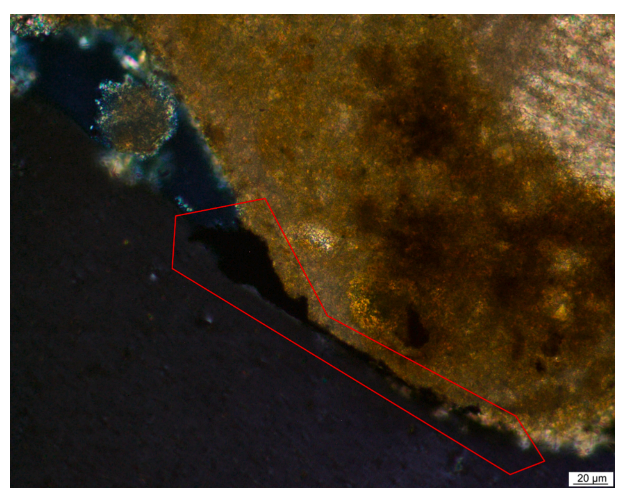

Fig. 14. OM-PPL microphotograph of the top surface of sample NPT 6a, with possible traces of a dark pigment or coating (in red polygon).

Roman times. In the Paphian theatre traces of seat coating are visible throughout all the *cavea*, with a remarkable status of preservation. The sampling procedure aimed at avoiding any damage to the preserved layers, thus we collected detached fragments visibly belonging to still-in-place features. In total, seven samples were collected from the central sector of the *cavea* between the *proedria* and the 11th row (NPT 4, 6a, 6b, 6c, 6d, 7a, and 7b).

Observing the various samples collected, it seems plausible to retrace

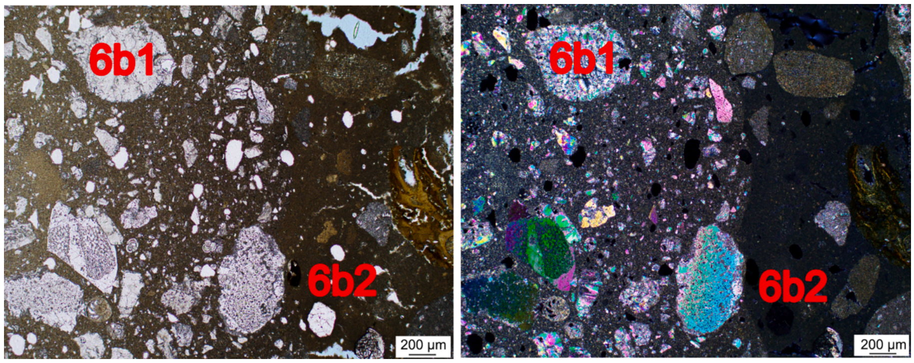

Fig. 15. OM-PPL (left) and XPL (right) of sample NPT 6b with the layer bond well visible in XPL due to the different density of the binder.

a production model consisting of a double-layered system (Figs. 13 and 15) of lime plasters with a well-smoothed, polished, and occasionally painted surface (Fig. 14). The first layer, in direct contact with the stone blocks of the seats, consists of a coarser mortar mixture of lime and well sorted river sand. The presence of radiolarian chert and magmatic rocks – including olivine, serpentinite and basalt – allowed us to identify the source of this sand in the hydrogeological basin of the Diarhizos river, which collects magmatic rocks and minerals from the Circum Troodos catch. The second, thinner, layer, also defined as “finishing layer”, consists of a much finer mixture of lime binder and shells’ fragments. Through the observation of the thin sections it was possible to deduce that the first layer was levelled and partially dried before the application of the finishing one (Fig. 15).

Chemical analyses confirm the higher content of calcite in the finishing layer, indicating richer and more refined binders were used to produce these specific plasters. SEM and OM further highlight the fact that both layers were levelled, in fact, it is possible to observe a denser binder in the upper surfaces of both layers. Pigment analysis have yet to be carried; however, preliminary observations in OM coupled with UV light highlighted the possible presence of organic material – either from the pigment or its binder. Additional RAMAN spectroscopic analysis are in order for the identification of the pigments, which – at the naked eye – appear as faded away in all the samples except NPT 6d.

Below are summarizing tables of the compositional analyses carried out on the theatre samples.

5. Conclusions

At the conclusion of this trial study, it could be safely supposed that the binder used in the theatre sample was the result of processing of local stones. Limestone is a widely available resource in the area surrounding the archaeological site of Nea Paphos. Quarrying sites have been identified even within the premises of the ancient theatre itself (Green et al., 2015), signifying that the materials for the construction were possibly acquired directly in situ. Lime production could have not been an exception. Nonetheless, all the limestones collected from the catchment of the modern district of Paphos displayed chemical and morphological similarities to a relevant degree, making the identification of a specific source not possible. In order to obtain such an information, it would have been relevant to analyse partially burnt lime particles. However, no features as such were identified in the theatre samples, suggesting that the firing process occurred under carefully monitored conditions and that the burnt stones were attentively selected before the slaking. Lime and gypsum lumps, on the other hand, were identified in relevant quantities. The analysis of these binder-related particles, however, did not allow any assumption on the type of slaking or mixing utilised.

The study of the aggregates reveals the prevalent use of readily available materials. In particular, the substantial presence of seashells suggests the use of sea sand, which was easily accessible in the immediate proximity of the building site. The predominant surface treatment consisted in smoothing the surface, possibly with polished tools that left no marks; in several cases inorganic pigments, mostly containing iron, have been applied on the surface with the aid of brushes (as revealed by the clear brushstrokes marks, see Fig. 7 above). It was not possible to identify particular or clear changes in the diachronic perspective, as overall the samples presented relevant similarities. The only notable exception, in this regard, is the appearance of waterproof samples in the later Roman phases. In regard to the hydraulic mortars, it is noteworthy to underline again the use of NHL in one sample, although whether it was casual or intentional cannot be established.

From the analytical data gathered from this site, it is also possible to hypothesise that masonry mortars were preferably produced out of gypsum. This preliminary assumption seems to be further corroborated by the analysis of the materials sampled in the Agora of Nea Paphos, currently under study.

In conclusion, this study might not provide extensive information on the diachronic developments and evolutions of the plaster industry from Hellenistic to Roman times; however, it contributes to the knowledge of the productive processes and the raw materials selection in use at the times. Up to now, little was known about Cypriot plaster industry; this research aimed at answering prompt and urgent questions such as the raw material sourcing, the mastery of stone burning and any relevant trend in the choice of plaster and mortar making. Further analysis on samples from the Agora of Nea Paphos, from Kissonerga-*Skalia*, Palaepaphos and Yeronisos Island – currently under study – will allow to outline a clear overview of the industry from the end of the Bronze Age to the Roman times.

CRediT authorship contribution statement

Paola Pizzo: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Jan Válek:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Petr Kozlovcev:** Writing – original draft, Data curation. **Dita Frankeová:** Formal analysis, Data curation. **Alberto Viani:** Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Available data are included in the manuscript.

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