arts

MDPI

Article

New Insight into Hellenistic and Roman Cypriot Wall Paintings: An Exploration of Artists' Materials, Production Technology, and Technical Style

Roxanne Radpour [1,2,*], Christian Fischer [2,3] and Ioanna Kakoulli [1,2,3]

1 Materials Science and Engineering Department, Henry Samueli School of Engineering and Applied Science (HSSEAS), University of California, Los Angeles, CA 90095, USA; kakoulli@ucla.edu
2 Molecular and Nano Archaeology Laboratory, Henry Samueli School of Engineering and Applied Science (HSSEAS), University of California, Los Angeles, CA 90095, USA; chrisfischer@ucla.edu
3 The UCLA/Getty Conservation Program, University of California, Los Angeles, CA 90095, USA
* Correspondence: radpour@ucla.edu

Received: 13 May 2019; Accepted: 18 June 2019; Published: 24 June 2019

Abstract: A recent scientific investigation on Hellenistic and Roman wall paintings of funerary and domestic contexts from Nea ('New') Paphos, located in the southwest region of Cyprus, has revealed new information on the paintings' constituent materials, their production technology and technical style of painting. Nea Paphos, founded in the late 4th century BC, became the capital of the island during the Hellenistic period (294–58 BC) and developed into a thriving economic center that continued through the Roman period (58 BC–330 AD). A systematic, analytical study of ancient Cypriot wall paintings, excavated from the wealthy residences of Nea Paphos and the surrounding necropoleis, combining complementary non-invasive, field-deployable characterization techniques, has expanded the scope of analysis, interpretation and access of these paintings. The results from in situ analyses, combining X-ray fluorescence (XRF) and fiber-optic reflectance spectroscopy (FORS), forensic imaging in reflectance and luminescence, and digital photomicrography, were informative on the raw materials selection, application technique(s) and extent of paintings beyond the visible. Data collected through the integration of these techniques were able to: (1) show an intricate and rich palette of pigments consisting of local and foreign natural minerals and synthetic coloring compounds applied pure or in mixtures, in single or multiple layers; (2) identify and map the spatial distribution of Egyptian blue across the surface of the paintings, revealing the extent of imagery and reconstructing iconography that was no longer visible to the naked eye; and (3) visualize and validate the presence of Egyptian blue to delineate facial contours and flesh tone shading. This innovation and technical characteristic in the manner of painting facial outlines and constructing *chiaroscuro* provides a new insight into the artistic practices, inferring artists/or workshops' organization in Cyprus during the Roman period.

Keywords: Hellenistic and Roman wall paintings; Cypriot wall paintings; Nea Paphos; Cyprus; natural and synthetic pigments; Egyptian blue; forensic imaging; pigment mapping; spectroscopy; archaeometry

1. Introduction

Hellenistic and Roman Cypriot wall paintings, which decorate residences, public spaces and tombs in the areas of ancient Nea Paphos ("New" Paphos), the eastern and western necropoleis, the Tomb of the Kings funerary complex and tombs in modern day Paphos city center (Figure 1), have been systematically analyzed using a protocol of combined field-deployable imaging and spectroscopic techniques. In 320 BC, the last king of Palaepaphos ("Old" Paphos) Nicocles founded the city of Nea

Paphos to serve as the administrative and economic center for the island during the Hellenistic and Roman periods (Kakoulli 1995). Following the death of Alexander the Great, the Ptolemies, who ruled ancient Egypt at the time, took control over Cyprus (Guimier-Sorbets and Michaelides 2003) and established Paphos as the new capital of the island. Nea Paphos continued to be a strong economic center when the Ptolemies lost control in 58 BC and Cyprus was annexed to the Roman empire, under which it remained until the 4th century AD. The thriving signature of the ancient city can be seen in the remains of the domestic spaces, where beautiful mosaics adorned the floors of wealthy residences such as the Villa of Theseus, residence of the Roman governor of Cyprus.

Figure 1. Contextual photographs of archaeological sites analyzed from ancient Nea Paphos: (**a**) The Paphos Archaeological Park; (**b**) The location of Tomb Roma 1, under the present-day Roman Boutique Hotel; (**c**) The Tomb of the Kings.

As Cyprus underwent transitions of power, infusions of Hellenistic and Roman political, philosophical and artistic traditions became integral to the culture of Cyprus (Pappalardo 2009). The expansion of Alexander the Great's kingdom produced a Macedonian empire of multiculturalism; his death, marking the start of the Hellenistic period, saw the split of his kingdom and the subsequent extensive exchange of wealth, people and materials across the old empire (Miller 2014).

Hellenistic painting tradition can be characterized by three major categories: the Masonry Style, the Relief Architectural Style, and the Painted Architectural Style. Evidence of Hellenistic paintings in domestic, civic and funerary monuments varied regionally. The best surviving domestic paintings are those of the Stuccoed House of Pella, though presently there is a lack of evidence for figurative paintings in Macedonian domestic spaces. Furthermore, there is little remaining evidence of palatial wall decoration in the Hellenistic period (Miller 2014). Funerary monuments, on the other hand, being mostly subterranean, are well preserved. Tomb architecture and surviving wall painting decoration provide excellent examples to establish connections between Cyprus, Macedonia, and Alexandria. Alexandrian tombs characteristically featured open-air peristyle courts, while Macedonian tombs were sealed formed chambers; the latter feature also appeared in Alexandrian monuments, and both types of structures can be found in the necropoleis of Nea Paphos. Common decorative motifs from Alexandrian tombs such as fictive architectural elements, that is, false doors and isodomic masonry blocks, as well as floral garlands with ribbons appeared throughout the Hellenistic and Roman Cypriot tombs in this region (Guimier-Sorbets and Michaelides 2003).

The death of Cleopatra in 30 BC marked the end of the Hellenistic period and the start of the Roman empire. At this time, the Roman influence over Greek territories was already evident, with elements of both Greek and Roman culture, seen in key locations in Greece (i.e., Delos) and Italy (Miller 2014). There was a significant effort by the new Roman leaders and citizens to lay claim to Hellenistic lineage by incorporating elements of the Hellenistic culture and art into their homes through the inclusion of ideas, images and iconography by importation, smuggling and reproduction of artworks (Pappalardo 2009). More importantly, they understood the artistic techniques from which the paintings and objects were derived, thus cementing Hellenistic influences into Roman decorative arts. Roman wall paintings are today characterized according to the four Pompeian styles, successive in time ranging from the 4th century BC to 79 AD. The First Style is the most closely linked temporally and stylistically to Hellenistic art and seems to show similar themes to those found in ancient Cypriot

paintings in their depictions of imitation marble, architectural elements and geometric shapes. There is not enough remaining decoration intact to comment on potential representations of the Second, Third and Fourth Style.

Hellenistic and Roman paintings in Cyprus also reflect access to, and use of, economic minerals such as ochres, umbers and green earth, knowledge of production methods and the trade from and to Cyprus of natural and synthetic pigments. The geology of Cyprus (Figure 2) and its richness in copper, umbers, ochres and green earth (Ren et al. 2015) have not only influenced the economic status of Nea Paphos but also its artistic culture. These resources were readily available, easy to extract and process, and provided the raw materials in paintings and an invaluable economic resource through trade (Apostolaki et al. 2006; Kakoulli 2009b). The gossans of the sulfide ores of the Troodos mountains and its ophiolitic rocks are particularly rich in colored rocks and minerals, such as hematite, goethite, and umber (iron oxide and manganese oxide) and celadonite (Cohen et al. 2011; Hradil et al. 2003; Kakoulli 1995; Kassianidou 2013). In the Mesaoria basin, the weathering of umbers from the sedimentary rock produced pyrolusite (MnO_2), which served as a black pigment in the paintings (Elderfield et al. 1972; Kakoulli 1995). The Lefkara formation in the southwest region of the island was the major source of chalk used as aggregate in the preparatory plaster layers of the paintings (Kakoulli 2002, 2009b). Ancient artists in Paphos used the natural and synthetic pigments, pure or in mixtures, to achieve particular hues and aesthetic effects such as translucency, transparency and three-dimensionality achieved by *chiaroscuro* (*skiagraphia*), innovations that characterized the painting of these periods.

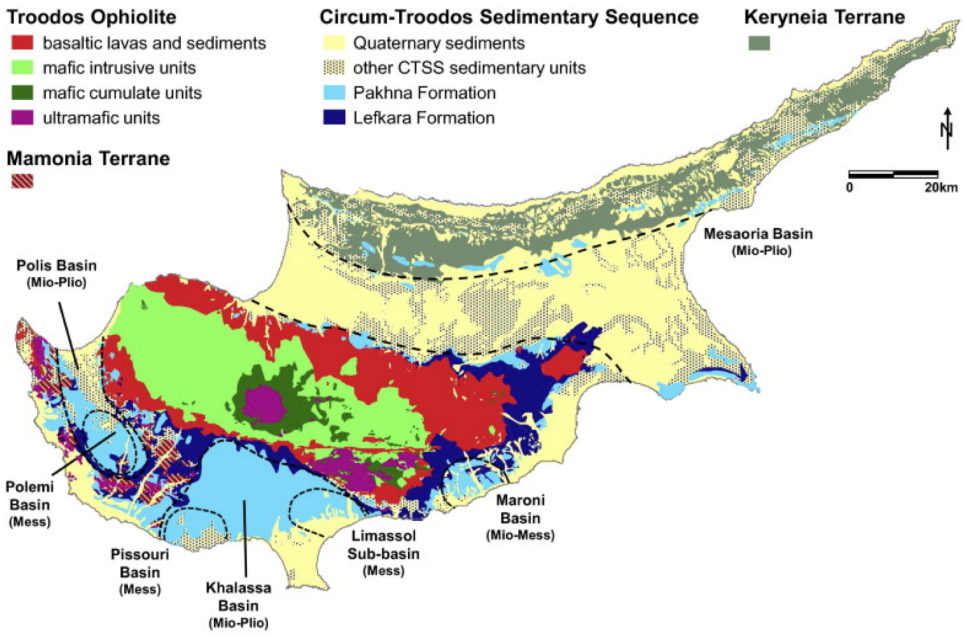

Figure 2. A map showing the geological formations of Cyprus. The Troodos Massif, the Mesaoria basin, and the Lefkara formation provided the natural resources that ancient artists used to prepare their pigments and plasters layers for wall paintings (image adapted from Ren et al. 2015).

Attribution and absolute dating of the Hellenistic and Roman Cypriot paintings face several challenges. Cypriot funerary and domestic built heritage shows evidence of multiple construction phases (most likely linked to severe damages by earthquakes and other events), re-use and re-painting of the walls. The physical and 'restoration' history of these monuments make the dating and attribution of the wall painting fragments to specific time periods unreliable. Reconstructions of fragmented paintings from the Roman villas in Nea Paphos have provided a glimpse into the stylistic and technical approach towards decorative and figurative representations in Roman Cyprus. Figurative paintings in particular, from both domestic and funerary contexts, provided valuable findings elucidating our

understanding on local technical trends in the treatment of painting (artistic techniques) and/or artists/or workshops' organization.

This research aimed to address the challenge of attributing contextual information and providing a global understanding to the paintings by looking deeper into their chemistry and production technology. This study presents the first systematic non-invasive scientific survey on the polychromy of Hellenistic and Roman Cypriot monumental wall paintings, with the objective of: (1) identifying, mapping and interpreting the extent of polychromy and iconography through the characterization and imaging of the spatial distribution of pigments; and (2) exploring the function and use of pigments in the making of the wall paintings, thus obtaining new insight into the artistic expression and technical skills of the artists from the 4th century BC to the 4th century AD.

Our knowledge of the materials used in Cypriot funerary and domestic wall paintings thus far is only based on a few previous micro-analytical investigations, employing selective sampling to provide the first characterization of wall painting materials (pigments and plasters) and technology (Balandier et al. 2017; Wood Conroy 2004; Kakoulli 2002, 1995). Building on these previous researches, this study aimed to mitigate this knowledge gap on ancient Cypriot wall paintings by applying a new methodology, harnessing the capabilities of field deployable and high specificity imaging and spectroscopic technologies, enabling a detailed analysis of monumental painted surfaces without the need for taking samples. This investigation was important in expanding our understanding of the artists' palette, function of pigments and extent of painting iconography.

2. Hellenistic and Roman Cypriot Wall Paintings and Their Contexts

The study of Cypriot wall paintings included the analysis of fragments from funerary and domestic contexts, either still surviving in situ or stored in museum collections. The sites under study and their locations are listed in Table 1 and the spatial mapping of the sites is found in Figure 3. Paintings analyzed included fragments from five villas in Nea Paphos, located within the Paphos Archaeological Park (Figures 4 and 5); six tombs excavated within the western and eastern necropoleis; two tombs located in the modern day of Paphos; and two tombs located within and near the Tomb of the Kings funerary complex (Figures 6 and 7).

Figure 3. Satellite images: (**a**) satellite map of the southern half of the island of Cyprus, with the region of Nea Paphos highlighted in the red box; (**b**) map of present day Paphos showing the locations of the sites analyzed.

Table 1. A list of the sites with wall paintings analyzed and their location. A painting ID (letter) is assigned for reference in the Results and Discussion section where the pigments are discussed. Numbers following the ID letter refer to a specific location, painting or collection of fragments from the site.

Site	Period	Location	Paintings ID
House of Four Seasons	Roman	Nea Paphos	A
House of Orpheus	Roman	Nea Paphos	B
Hellenistic House	Hellenistic	Nea Paphos	C
Villa of Theseus	Roman	Nea Paphos	D
House of Aion	Roman	Nea Paphos	E
Tomb at Glyky Nero (P.M. 2518)	Roman	Western Necropolis	F
Tomb Annabelle 47 (P.M. 3005)	Roman	Eastern Necropolis	G
Tomb at Costis Palamas Sq.	Roman	Pano (upper) Paphos	H
Tomb 3510	Roman	Tomb of the Kings avenue	I
Tomb Roma 1	Roman	Western Necropolis	J
Tomb Roma 2	Roman	Western Necropolis	K
Tomb Silver House 1 (P.M. 2902)	Roman	Eastern Necropolis	L
Tomb Silver House 2 (P.M. 2892)	Roman	Eastern Necropolis	M
Tomb 3882	Roman	Pano (upper) Paphos	N
Tomb 6 (P.M. 1983)	Hellenistic	Tomb of the Kings	O

2.1. Paphos Archaeological Park: Hellenistic and Roman Residences

From the center of Nea Paphos, several villas of ancient wealthy citizens were excavated dating back to the Hellenistic (Hellenistic House) and Roman periods (Houses of Orpheus, Aion, and the Four Seasons). One of the more impressive residences is the Villa of Theseus, a palatial-style residence of the Roman governor of Nea Paphos, built over the foundations of earlier Hellenistic structures.

Nea Paphos suffered from the devastation of several earthquakes from the late 1st century BC to the 4th century AD (Kakoulli 1995; Nicolaou 1980), leaving little of the walls and their polychrome decoration intact, resulting in thousands of fragments such as those seen in Figure 4f. The best surviving paintings from the domestic sites, each named after the mosaics found within their respective contexts, were discovered in the Villa of Theseus and the House of Aion, the latter being the only residence where figurative paintings were found. Ten figurative paintings were recovered in fragments from the same room in the House of Aion—one example can be seen in Figure 4a. Due to fragmentary nature of the domestic wall paintings, it is difficult to reconstruct the entire iconography, though from in situ surviving fragments, in addition to figurative paintings, the decoration consists mostly of geometric patterns and bands, imitation marble revetment, and monochrome paneling (Figure 5).

Evidence of re-use and re-plastering for new decorative scenes were evident from remaining walls on site as well as recovered fragments (Figure 5d); due to the multiple layers of wall paintings and the successive earthquakes that have destroyed the residences, attribution of the fragments' time period is extremely difficult.

Figure 4. Examples of figurative paintings, colored fragments, and pigment pellets excavated from the residences of Nea Paphos, designated now as the Paphos Archaeological Park: (**a**) figurative painting E9, from the House of Aion; (**b**) fragments from House of the Four Seasons; (**c**) Egyptian blue pellets; (**d**) madder lake pellets; (**e**,**f**) colored fragments from the House of Orpheus.

Figure 5. Examples of domestic in situ wall paintings in the Paphos Archaeological Park: (**a**,**b**) Imitation marble revetment and geometric designs in the Villa of Theseus; (**c**,**d**) the Hellenistic House.

2.2. Tomb of the Kings, the Western and Eastern Necropoleis, and Tombs in Modern-Day Paphos

Owing to the subterranean construction of tombs, Hellenistic and Roman funerary complexes survived the major earthquakes, and they preserve today much of the original wall painting iconography featuring floral decoration, isodomic bands, garlands, household utensils, animals and birds, and figurative paintings. The wall paintings decorating these tombs (Figures 6 and 7) follow conventions of contemporary paintings in northern Greece (Vergina, Pella, Demetrias), Alexandria and other parts of the empire (Kakoulli 2009b; Miller 2014; Pappalardo 2009; Westgate 2000). A notable Cypriot example of funerary wall painting decoration is found in Tomb Ammoi A with imitation of masonry, garlands and a unique ceiling carpet similar to that of the tomb of Lyson and Kallikes at Lefkadia and the Anfushi II Tomb (within loculus 5 of Hypogeum 5) in Mustafa Kamel necropolis in Alexandria (Guimier-Sorbets and Michaelides 2003; Kakoulli et al. 2010; Michaelides 2004; Savvopoulos 2011).

Figure 6. Examples of funerary decoration featuring figurative paintings, fragments and in situ paintings featuring common decorative motifs: (**a**) a figure painted on a limestone slab from Tomb 3510; (**b**) two faces reconstructed from fragments from the tomb in Costis Palamas square; (**c**) a fragment displaying an egg and dart pattern, recovered from Tomb 3882; (**d**) a fragment with garlands recovered from Tomb Annabelle 47; (**e**) painting of a door in Tomb 6; (**f**) floral decoration in the tomb at Glyky Nero.

Most characteristic iconography in the tombs features geometric patterns (diamonds, triangles, bands); *trompe l'oeil* architectural elements, such as marble revetment, doors, and masonry blocks outlined with painted incised lines. Similar features are seen in Tomb Roma 1 and 2 (Figure 7f,g), as well as the tomb at Glyky Nero. The Hellenistic Tomb 6 from the Tomb of the Kings funerary complex (Figure 6e) shows a painted door above the loculus. These monumental tombs compare to the Macedonian tombs and Alexandrian Hypogea (Michaelides 2004). All tombs except for Tomb 6 display examples of vegetal and floral decoration. Tomb Roma 1 also shows depictions of animals and birds, as well as furniture (chest, chair), at the dado level of the central arcosolium. Other consistent

motifs include egg and dart patterns, as noted in Tomb Roma 1 and fragments recovered from Tomb 3882 (Figure 6c).

Figure 7. Examples of tombs and their funerary paintings, found in the western and eastern necropoleis, as well as modern-day upper Paphos: (**a**,**b**) Tomb Silver House 1; (**c**–**e**) Tomb 3882; (**f**) Tomb Roma 1; (**g**) Tomb Roma 2.

Human figures are also found in funerary contexts, though less frequently in Cypriot tomb pictorial programs; one full figure was found on a large limestone slab in the Tomb 3510 (Figure 6a), the centerpiece of a triptych of limestone slabs that was used to seal an ossuary (Raptou 2007). Two other paintings with surviving faces with floral decoration in the background were also reconstructed from fragments in the tomb discovered in the Costis Palamas square (Figure 6b) (Raptou 2007). The personification of one of the four seasons (Summer) also survives in one of the pendentives in fragmentary condition in Tomb Annabelle 48.

Similar to the domestic sites, the tombs were re-used. The structure and material finds of numerous tombs indicate Hellenistic origin, but continuous construction and modification to the tombs' architecture as well as decorative schemes point to use well into the Roman periods (Michaelides 2004; Raptou 2007). Notable examples showing evidence of multiple painting phases are found in Tombs Roma 1 and 2, Tomb 3882, and Tomb Ammoi B. Compared to the domestic wall paintings, the tombs show a greater extent of intact iconography remaining in situ. However, tombs throughout the city such as 3882 have suffered from environmental and anthropogenic effects. The most disastrous from the latter group are due to modern-day construction projects, making recovered fragments difficult to date to specific painting phases.

3. Results

The composition and application of the paint through pigment mixtures and layering was significant in providing specific aesthetic qualities, tonal variations and three-dimensionality to the paintings. Unique shades of green were attained by combining green and blue pigments, applied directly over white plaster or layered over a uniform application of yellow ochre, as well as by mixtures of green and yellow and black pigments. Purple hues were created through mixing and layering of blue and red pigments. Various tones of red and orange were also featured through the application of red pigments and mixtures of reds and yellows.

Paintings of this period used a variety of natural inorganic mineral pigments such as green earth (celadonite), yellow and red ochre (mainly goethite and hematite), cinnabar, umbers and pyrolusite and synthetic inorganic pigments such as Egyptian blue and red lead, applied over a single or multiple plaster layers (Balandier et al. 2017; Kakoulli 1995). The arsenical compound, realgar, and the hybrid organic-inorganic pigment known as madder lake were identified as raw materials (powders and pigment pellets) in museum storage containers from the House of Orpheus. It is unknown if these were intended for painting or if they fulfilled other functions, such as medicines and/or cosmetics (Kakoulli 2009b; Retief and Cilliers 2006; Scott 2016).

3.1. Preparatory Drawing and Setting out Techniques

Previous studies on ancient Cypriot paintings revealed that plaster preparation in the domestic spaces was more complicated than those found in funerary settings. Plaster layers in wall paintings feature two types: the *arriccio* and the *intonaco*. The *arriccio* layer is the first preparatory layer, the coarsest and thickest of a wall painting's stratigraphy. The subsequent layers are the *intonaco* layers, which are thinner and built up layer by layer to prepare for a smooth painting surface. The Cypriot paintings in the domestic spaces featured up to four *intonaco* layers applied over the *arriccio* layer (Kakoulli 1995). The tomb paintings seemed to have only one or two plaster layers, which included the *arriccio* layer. Plaster layers closer to the wall are hydraulic (set by hydration) with hydrophobic properties, providing more strength and insulating the walls from moisture. The successive superimposed plaster layers are aerial (set by the carbonation of the calcium hydroxide–lime) and were used to provide optimal support for fresco painting. At the macroscale, several of the plasters layers in Cypriot paintings still preserved evidence of the original application technique, as can be seen in other parts of the Hellenistic and the Roman world. One such example are the herringbone incisions as seen on the *arriccio* in the remaining structure of the House of Orpheus (Figure 8), a technique known to roughen the *arriccio* layer to receive the successive *intonaco* layer. Similar features can also be seen in the Hellenistic Houses of the island of Delos and elsewhere in the empire (Balandier et al. 2017; Kakoulli 2009b).

Figure 8. Herringbone incisions in the *arriccio* layer (base plaster layer) as preparation for subsequent plaster layers, from the House of Orpheus.

Preparatory techniques for painting include incised lines to guide geometric decoration as seen in Tomb 3882 (Figure 9), isodomic bands as seen in Ammoi A and figural outlines, unique to the figurative painting from Tomb 3510 (Figure 9d–f). Incised inscriptions have also been found in Tomb Silver House 2 and below the figurative painting from Tomb 3510 (Figure 9b,c).

Figure 9. (**a**) Geometric and line incisions in Tomb 3882; (**b**) Tomb Silver House 2 funerary inscription; (**c**–**f**) Figurative painting from Tomb 3510. A partially legible funerary inscription is found below the feet of the figure (**c**) and incision lines in the wet plaster created outlines of the face, arms, and garments (**d**–**f**).

Finally, amongst the fragmentary paintings analyzed, several from the House of Orpheus feature a pink wash in the plaster, most likely due to red ochre, as the basis for the top red paint layer (Figure 10).

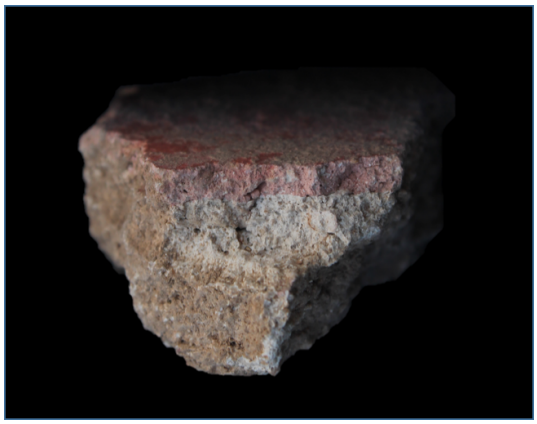

Figure 10. Wall painting fragment from the House of Orpheus. From top: dark red paint layer over a pink plaster layer, possibly a red ochre wash to increase the brilliance of the top red paint layer through light scattering, over a white plaster layer.

3.2. Pigments and Methods of Application

Pigments included a variety of natural minerals that can be found abundant in Cyprus, as well as a few synthetic pigments. These were used pure or mixed in single paint or multiple paint layers fulfilling different functions, for example, for shading creating the effect of *chiaroscuro*, or to create different hues and tonal variations. A list of pigments identified at the various sites showing the extent or limited use of a pigment is provided in Table 2; each pigment's application (in pure form or mixtures), the hues they produced, and their context is summarized in Table 3. In Appendix A, a detailed list of hues found throughout the sites is provided; for each hue, the main colorants and minor phases were identified, as well as the application, location, and function of the pigment in each painting's context. See Table 1 for site identification.

Table 2. Pigments identified at each site.

	H. Four Seasons	H. Orpheus	Hellenistic House	Villa of Theseus	H. Aion	T. Glyky Nero	T. Annabelle 47	T. Costis Palamas	T. 3510	T. Roma 1	T. Roma 2	T. Silver House 1	T. 6	T. 3882
Egyptian blue	x				x	x	x	x	x	x	x	x		x
Green Earth	x	x		x	x		x	x		x	x	x		x
Red Ochre	x	x	x	x	x		x	x	x	x	x	x	x	x
Yellow Ochre		x	x	x	x		x	x	x	x	x	x	x	x
Red lead	x		x											
Cinnabar		x												
Umber					x									

Table 3. The hues, application methodology, and function of pigments identified in the ancient Cypriot wall paintings. The main hues listed here were found in shades of light to dark applications.

Main Pigment	Other Phases	Hues	Location/Function
Egyptian blue	Green earth; red ochre; $CaCO_3$	Blue; bluish-purple; grey-blue; bright ('cold') white	Background shading; tunic shading; animals; geometric patterns; floral decoration
Green earth	Egyptian blue; yellow ochre; Mn-compounds; $CaCO_3$	Green; green-blue; olive green	Wreaths; tunic shading; geometric patterns; floral/ vegetal decoration; architectural elements; imitation marble revetment
Red ochre	Yellow ochre; Egyptian blue; $CaCO_3$	Red, purple; red-purple; pink; pink-red; orange-red; dark brown	Hair; geometric patterns; clothing; background; flesh tones; animals; architectural elements; imitation marble revetment
Red lead	$CaCO_3$	Orange	N/A
Cinnabar	Red ochre; Pb-based compounds	Bright pink-red	Uniform (*monochromata*)
Yellow ochre	Red ochre, $CaCO_3$	Yellow; red-yellow; orange-yellow; cream; white-yellow	Hair; geometric patterns; clothing; background; flesh tones; architectural elements; floral/vegetal decoration; imitation marble revetment; preparation layer for blue/green paint
Umber	Egyptian blue	Brown-black	Wreaths

3.2.1. Blue

Egyptian blue, a synthetic high-fired polycrystalline material (frit), composed of a major crystal phase of calcium copper tetrasilicate ($CaCuSi_4O_{10}$), unreacted quartz and glass, was the sole blue pigment identified in Cypriot paintings. It was identified either pure or in combination with other pigments (Table 3, Table A1).

Egyptian blue is the oldest known synthetic pigment (dating to the fourth millennium BC) (Berke 2007; Grifa et al. 2016; Hatton et al. 2008; Jaksch et al. 1983; Kakoulli 2009a) and the most common blue coloring compound among the ancient Mediterranean world during the Hellenistic and Roman period. Indigo was another synthetic pigment used during this period, though its use was mainly on panel paintings as indicated by its frequent occurrence in Greco-Roman funerary portraiture (Radpour et al. 2017; Salvant et al. 2018). While Cyprus was known for its rich copper resources with copper named as 'Aes Cyprium' by the Romans (Kassianidou 2013), to date, there is no archaeological evidence of Egyptian blue production on the island. However, pellets of the 'raw' pigment (ingots) have been found in different archaeological sites on the island.

The identification of Egyptian blue was established by fiber-optic reflectance spectroscopy (FORS), X-ray fluorescence (XRF) and forensic photography (Kakoulli et al. 2017). Using FORS, the pigment was identified by its diagnostic absorptions at 560, 630, and 790 nm (Figure 11a). XRF also indicated characteristic fluorescence emissions of copper (Cu K_α and K_β peaks at ~8.05 keV and ~8.90 keV, respectively), providing additional evidence of the pigment.

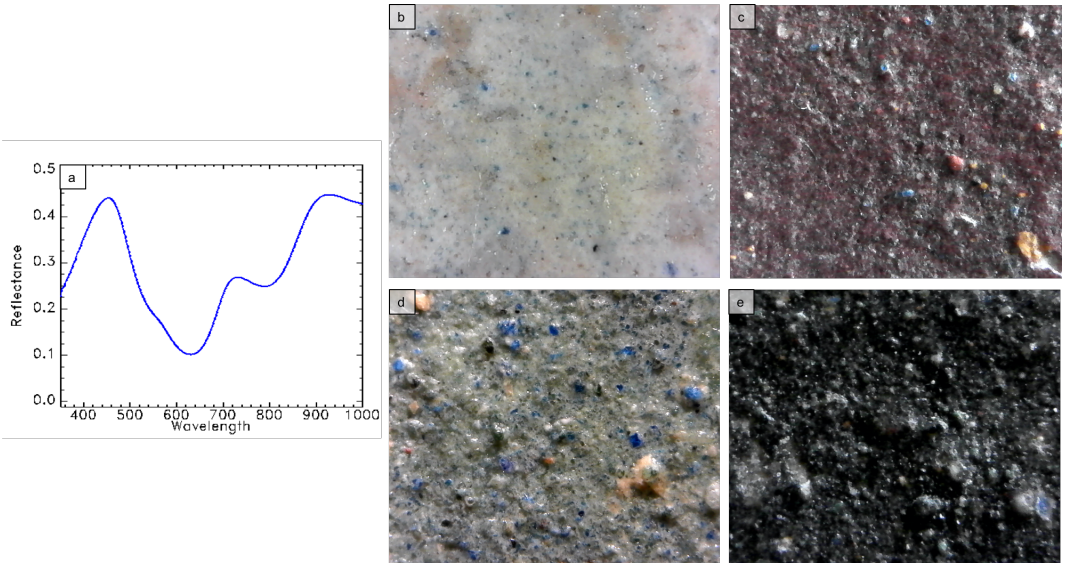

Figure 11. (**a**) Reflectance spectrum of Egyptian blue, featuring characteristic absorptions at 560, 630, and 790 nm. Photomicrographs (250x) of different wall painting fragments containing Egyptian blue: (**b**) Egyptian blue in a white paint (E5); (**c**) Egyptian blue in a purple paint mixed with hematite (E5); (**d**) Egyptian blue and green earth mixture applied over yellow ochre (N2); (**e**) Egyptian blue in a black paint (E5).

In painting, Egyptian blue was used undiluted and in mixtures (at different ratios) with other pigments, producing different hues and tonalities (Table 3 and Table A1). When mixed in small concentrations with white pigments—scattered in a white paint matrix—it produces 'colder' white tones creating specific optical and aesthetic qualities to the paint. This 'colder' white tone was encountered in the coloration of the white of the eyes in sculptures and figurative paintings, as well as in decorative elements (Figure 11b) (Radpour et al. 2017). This mixture was also applied as the backdrop for the figurative paintings in the House of Aion and in accessory items of the figures such as headpieces. Egyptian blue was further mixed with green earth and hematite to create light to dark blue-green and purple hues, respectively (Figure 11c,d), as well as with goethite, green earth, and

pyrolusite (manganese dioxide) to produce olive green and grey-blue tones and for tunic shading. Black wreath leaves in a House of Aion figurative painting (E5) were found to be a mixture of black, green and Egyptian blue particles.

Forensic photography confirmed the presence of Egyptian blue in mixtures and unique shading applications based on its characteristic visible-induced near-infrared (NIR) luminescence, and also aided in the mapping of this pigment providing important information not previously known on the function of this pigment in *skiagraphia*. This constitutes a new discovery on this unique application and function of Egyptian blue, appearing as wash on a muse's face from the House of Aion.

3.2.2. Green

Green earth, consisting of the mineral celadonite ($K(Mg,Fe^{2+})(Fe^{3+},Al)[Si_4O_{10}](OH)_2$), was the only green pigment identified in Cypriot wall paintings. It was discovered in different paintings either pure or in combination with other pigments (Table 3, Table A2).

The presence of celadonite in Cypriot paintings is not surprising, as Cyprus is one of the major Mediterranean sources of this mineral (Apostolaki et al. 2006; Gallahan and Duncan 1994; Hradil et al. 2003; Kakoulli 1995). In this research, the identification of green earth was based on its characteristic reflectance spectrum, featuring an asymmetrical reflectance peak at 550 nm and absorptions at 750 nm and further into the near-infrared due to electronic transitions from charge transfer and crystal field effects, resulting in a diagnostic reflectance peak at 830 nm. Absorptions in the short-wave infrared specific to celadonite (~2257, 2302, and 2358 nm) helped to distinguish it from the mineral glauconite (Figure 12b).

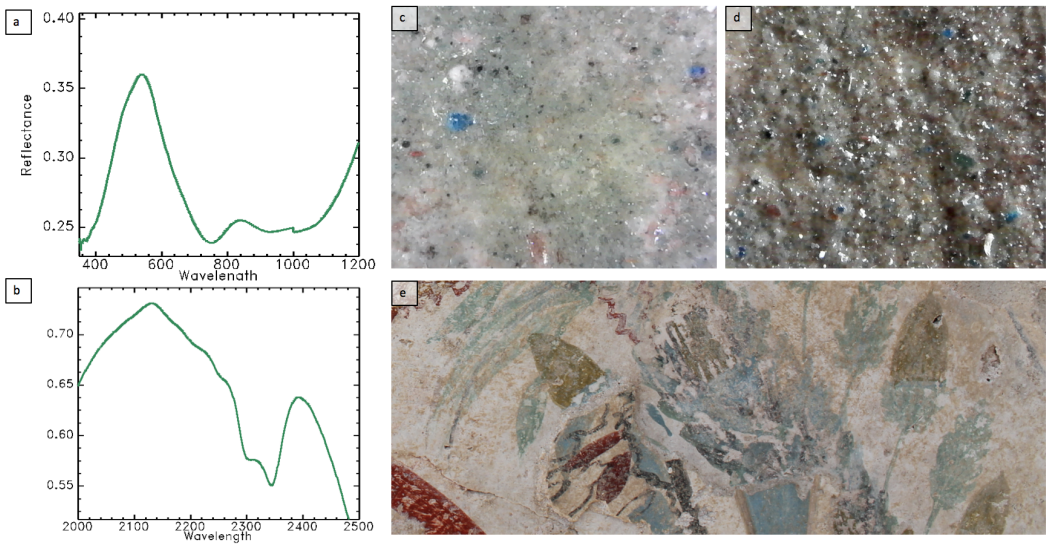

Figure 12. (**a**,**b**) Reflectance spectra featuring diagnostic absorption features of green earth (celadonite) in the visible range (400–1200 nm) and the short-wave infrared (2000–2500 nm) of a green painting fragment from the House of Orpheus. The following are photomicrographs (250x) of different wall painting fragments containing green earth: (**c**) light green hue consisting of green earth and Egyptian blue (E5); (**d**) dark olive green tone consisting of green earth, Egyptian blue, goethite, and a manganese-containing compound (E5); (**e**) example applications of various shades of green applied in Tomb 3882 (N1).

Its application was versatile, as a wide range of hues was noted containing green earth (Table 3 and Table A2), including light and dark blue-greens (mixed with Egyptian blue), light and dark olive greens (mixed with goethite and sometimes pyrolusite), and other tones of green in mixtures with white or carbon black (Figure 12). Mixtures of green and blue were also applied over yellow ochre to create a bright blue-green tone.

In Cypriot paintings, green earth was used in imitations of marble revetment, geometric bands, floral motifs, and in the wreaths of figures. Additionally, the dark olive green tones were used in the shading of the tunic of figures.

3.2.3. Red

Three distinct red pigments were identified within the paintings: a hematite-rich red ochre, red lead and cinnabar (Table 3, Table A3).

Hematite

Hematite (Fe_2O_3) is a mineral found abundantly in the gossans (iron cap) of the sulfide deposits of the Troodos mountains (e.g., Skouriotissa mine) in Cyprus (Kassianidou 2013). The dominant red colorant in the paintings was a hematite-rich red ochre pigment, applied pure or in mixtures to produce tones of red, reddish orange, pinks, purples, and flesh coloration (Table 3 and Table A3). It was used as the main pigment in geometric patterns, animals, furniture, floral decoration, marble imitation, and in figurative paintings (flesh and garments) (Figure 13a,b). It also most likely served as the colorant in the pink wash of the plasters of decorated fragments from the House of Orpheus.

Figure 13. (**a**) Depiction of an arm chair featuring light and dark purple hues painted on the northern end of the dado of the central arcosolium in Tomb Roma 1 (J); (**b**) A red painted dog on the southern end of the dado of the arcosolium (J); (**c**) reflectance spectrum of hematite.

FORS was used to identify hematite, as XRF alone could not distinguish between different Fe compounds, namely goethite and other iron oxyhydroxides. Hematite's reflectance spectrum shows a characteristic inflection point in the visible region at 575 nm, arising from crystal field transitions of the Fe^{3+}, as well as a broad absorption at 885 nm due to the Laporte-forbidden transitions (Figure 13c).

Cinnabar

Cinnabar (HgS) was identified in painting fragments from the House of Orpheus. It was mixed with hematite and produced a bright pink-red hue (Table 3) (Figure 14a), applied over a pink plaster most likely colored with hematite. XRF showed photon emissions of characteristic X-rays of Hg and S, at 9.89 and 11.82 keV (L_α and L_β of Hg) and at 2.31 keV (K_α of S) respectively. Emissions of characteristic X-ray of Fe (with K-lines at 6.40 keV and 7.06 keV) (Figure 14b) may derive from the pink plaster layer and/or from the top red paint.

The presence of cinnabar in Cypriot paintings constitutes an interesting finding, as cinnabar is not native to Cyprus. The procurement and processing of natural resources of cinnabar was described by Greek philosopher, Theophrastus (4th–3rd century BC), in his treatise *On Stones* (Theophrastus [c. 4th century BC] 1956 [*De lapidibus:* 58–59]). Whether the cinnabar detected here is natural or synthetic cannot be determined non-invasively. The lack of geological resources and evidence of production in Cyprus suggest that cinnabar was imported and used in specific commissions.

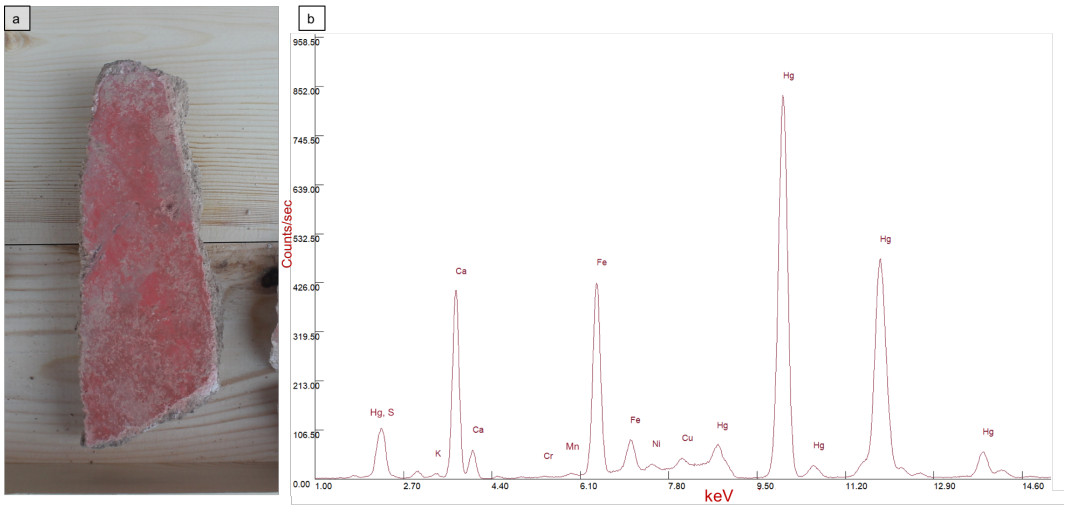

Figure 14. (**a**) A wall painting fragment decorated with cinnabar and red ochre from the House of Orpheus (B2); (**b**) an X-ray fluorescence (XRF) spectrum of the cinnabar-rich paint layer with elemental abundances from the preparation layers. The presence of Cr in the spectrum may be indicative of provenance.

Red lead

Red lead (Pb_3O_4), also known as minium, is an artificially produced pigment with an orange-red color. In a mostly pure application, it has a bright orange hue and is distinguishable from other orange hues produced from mixing red and yellow earth pigments (Figure 15a,b). This was noted in several painting fragments excavated from the House of the Four Seasons and the Hellenistic House, which prompted spectroscopic analyses to confirm its chemical structure. Red lead was identified by XRF from its characteristic Pb photon emissions at 10.55 and 12.61 keV (L_α and L_β, respectively) (Figure 15d), complemented by FORS showing a sharp reflectance transition, characteristic of the band gap in the red lead chemical structure (Figure 15c).

While the production of this synthetic pigment in Cyprus cannot be excluded, the lack of Pb ores available on the island and the absence of any archaeological evidence, points to an imported pigment, most likely as red lead powder. From the surviving painted fragments, it seems that its application in the paintings was limited to geometric designs and monochrome decorations.

3.2.4. Yellow

In the set of paintings analyzed in this study, only a goethite-rich yellow ochre was detected, used either pure or in mixtures with other colors (Table 3, Table A4). As with hematite, goethite (FeO(OH), a hydrated ferric oxide, is another abundant mineral in the gossans of sulfide ores in Cyprus. Mixtures of yellow ochre with red ochre produced reddish and orange-yellow hues, as well as flesh tones. It was also mixed with green earth and pyrolusite to produce shades of olive green. Like red ochre, the application of this yellow earth mineral was found in both funerary and domestic contexts and employed in both decorative motifs, as well as, figurative paintings.

The reflectance spectrum of goethite is characteristic to the mineral (Figure 16c), with absorptions at ~430 and 480 nm and diagnostic inflection point at 550 nm attributed to crystal field transitions and a broad absorption at ~900 nm due to the Laporte-forbidden transitions.

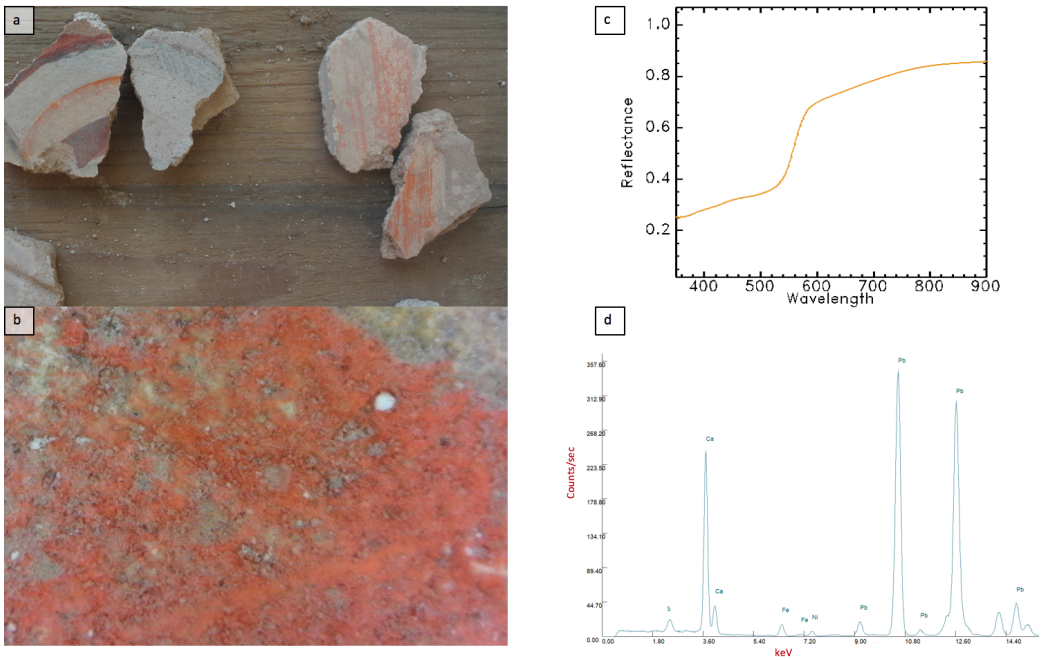

Figure 15. (**a**) Fragments featuring red lead from the House of the Four Seasons (A1); (**b**) Micrograph (250x) of a fragment from the Hellenistic House (C5); (**c**) reflectance spectrum and (**d**) XRF spectrum of a fragment from the House of the Four Seasons (A1).

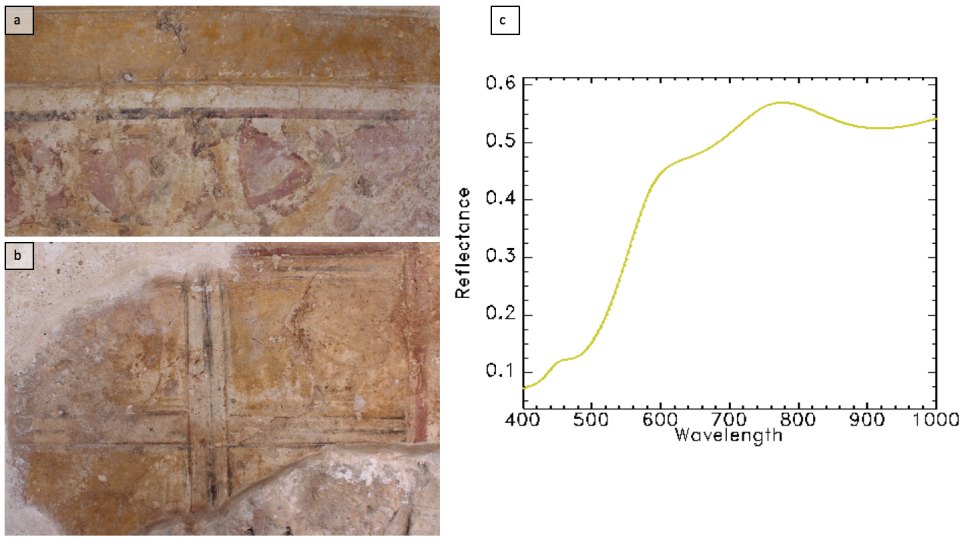

Figure 16. (**a**) A yellow band in the thalamos chamber of Tomb 3882 (N3); (**b**) A false door in Tomb 6, painted with yellow ochre (O); (**c**) The reflectance spectrum of goethite.

3.2.5. White and Black Pigments

White pigments were mixed with colored minerals and compounds in various concentrations to adjust the intensity of the hues and provide lighter tonal variations. This can be seen in the figurative paintings of the House of Aion where white was mixed with other pigments to produce facial highlights and more naturalistic flesh tones. Calcium carbonate ($CaCO_3$) was identified by its absorption feature at 2340 nm. Previous micro-analytical studies also identified the presence of $CaCO_3$ in the paintings (Balandier et al. 2017; Kakoulli 1995).

White pigments mixed with Egyptian blue served as the backdrop for the figurative paintings in the House of Aion. Several examples of intentional bright white hues in geometric and pattern

decorations appear in the thalamos chamber and the arcosolium on the northwest side of Tomb 3882, as well as in the accessory items in the figurative iconography of the House of Aion (Figure 17).

Figure 17. Details of paintings from Tomb 3882: (**a**) white geometric patterns alternating with blue geometric patterns (N1); (**b**) A brushstroke of white pigment is applied over a pink triangle (N3). From a figurative painting recovered from the House of Aion, (**c**,**d**) earrings and a central decorative headpiece are produced with white pigments on the figurative painting (E5).

Black pigments were also found in mixtures to create unique tones and dark shades in the paintings. XRF analysis of the black hues such as the wreath leaf of E5 showed X-ray emissions of Mn and Fe, suggesting the use of umber (iron oxide and manganese oxide) (Figure 18). Carbon black may also have been used based on observations from in situ photomicrography.

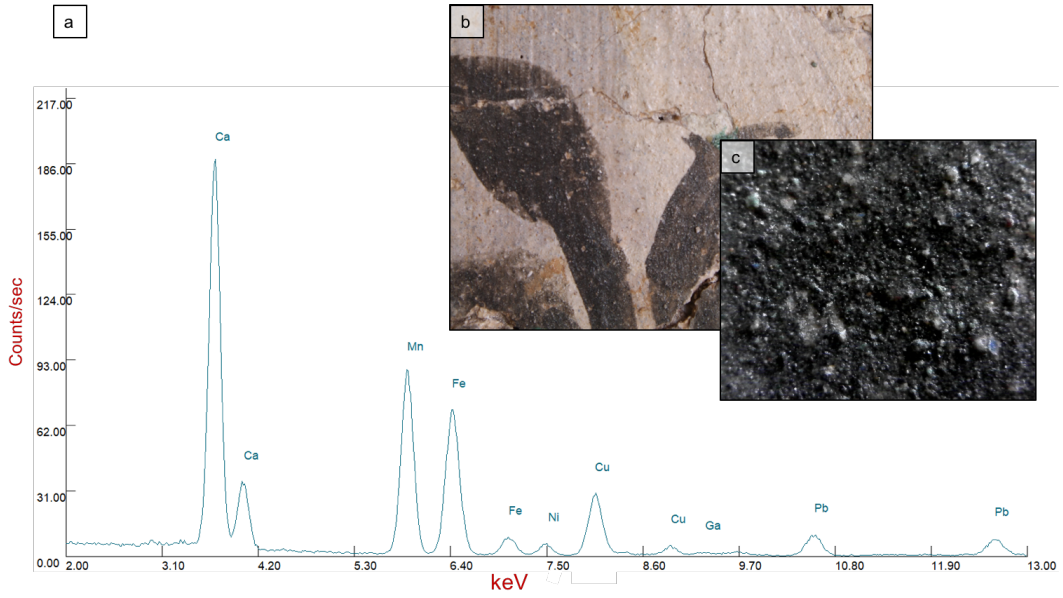

Figure 18. From a figurative painting from the House of Aion (E5), (**a**) an XRF spectrum taken of a black wreath leaf shows characteristic X-ray emission of Mn; (**b**) detail and (**c**) photomicrograph (250×) of the wreath leaf shows blue particles within the black matrix, most likely Egyptian blue, the source of the Cu peaks in the XRF spectrum.

Black paint was used to mark incised architectural lines, as well as in tunic shading (Figure 19a), and in the wreaths of the figurative paintings. It was also applied as outlines for different colorful geometric patterns in Tomb 3882 (Figure 19b).

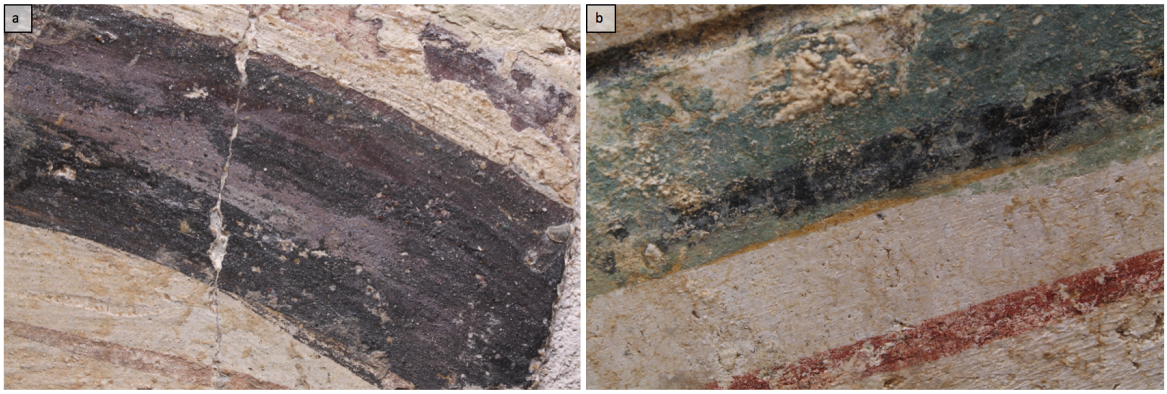

Figure 19. (**a**) Details of a figurative painting from the House of Aion: tunic shading is achieved using layers of purple and black to produce optical effects of light and dark purple hues (E5); (**b**) From Tomb 3882, a black pigment was used for outlining geometric bands (N2).

4. Discussion

4.1. Significance of Technical Applications to Painting Aesthetics

The analysis of ancient wall paintings indicated that a variety of pigments, either natural minerals or synthesized compounds, comprised the palette of the Cypriot painter during the Hellenistic and Roman periods. Most common natural minerals included celadonite, yellow and red ochres (goethite and hematite, respectively), umber (iron oxide and manganese oxide) and calcium carbonate. Cinnabar and realgar (the latter identified by XRF, only found in a preparatory state) were also present. Synthetic inorganic and inorganic-organic hybrid pigments include Egyptian blue, red lead and madder lake (the latter identified by FORS, only found in a preparatory state). While analyses conducted non-invasively were limited in providing data necessary to geosource the natural minerals, it is most probable that green earth, yellow and red ochre and umber are of local origin, owing to their abundance on the island and their known use in antiquity as pigments. As with copper, timber and asbestos, these natural resources were part of an extensive trade and communication network that provided great wealth to Cyprus during the Roman period. Cypriot green earth (celadonite mineral) provided one of the most important economic minerals during antiquity. Evidence of its trade is indicated by the identification of this pigment on Mediterranean wall paintings outside Cyprus (Apostolaki et al. 2006). Cinnabar, one of the most celebrated pigments in ancient times, was most likely brought from Spain and/or Ephesos (modern-day Turkey) as these were well-known sources of cinnabar in the ancient Mediterranean world (Pliny [c. 77 AD] 1954 [*Naturalis historia XXXIII: 37*]; Theophrastus [c. 4th century BC] 1956 [*De lapidibus:* 58–59]; Gettens et al. 1972). The use of cinnabar seems to be in line with practices described in ancient texts, as it was applied in a mixture of red ochre, most likely to balance the 'harsh' tone of a pure application (Pliny [c. 77 AD] 1954 [*Naturalis historia XXXIII: 39*]). Only found in the House of Orpheus, its limited application implies that it was valued and employed for specific applications such as 'monochromata' (single-color painting) of important commissions.

Red lead was most likely imported to Cyprus as a prepared pigment. Its use in Cypriot paintings is rare; it was only found in two sites (the House of the Four Seasons and the Hellenistic House). However, as red lead is known to blacken to form other lead compounds when used in wall paintings (Aze et al. 2008), its rare use in this form of painting may not be surprising. Realgar (arsenic sulfide) has not yet been identified in Cypriot wall paintings; as it is not a local resource, it was most likely imported. Madder lake (an inorganic-organic hybrid pigment) could have been produced locally as the plant from the Rubiacae family was cultivated on the island since ancient times.

Egyptian blue is not known to have been produced in Cyprus, but the copper mines of Skouriotissa served as an important resource for the production of Egyptian blue in Egypt (Theophrastus [c. 4th century BC] 1956 [*De lapidibus:* 55]). Its use in Cypriot wall paintings presents an original application in

delineating facial outlines an in *chiaroscuro*. The ancient artists used this core palette of locally-inspired resources, mixed with black and white pigments, to produce an impressive range of hues in the wall paintings.

The most diverse range of hues present in the ancient Cypriot paintings were found in shades of green, purple and flesh tones. Changing the relative concentrations of the constituent pigments in mixtures, or by layering relatively pure pigments or pigment mixtures over other paint layers, as well as grinding and using pigments of variable grain sizes, influenced the optical properties of the paint layer through light scattering and produced different perceived colors. Light and dark olive green hues whose tones shifted between a deeper green and yellow-green, were produced by various combinations of green earth, yellow ochre, Egyptian blue and a Mn-based black pigment (most likely pyrolusite). For example, an olive-green color representing a plant stem (N2) was produced by mixing a relatively small amount of Egyptian blue into a green earth matrix, and then applied over a base layer of yellow ochre. Nearby, a strong yellow-toned olive green was present in the plant decoration, which was produced by a mixture of green earth and yellow ochre (N3). In regions of paintings where the application of multiple pigment layers is not obvious, the presence of yellow ochre may be due to an intentional mixture of yellow and green, or due to a partial alteration of green earth in its natural environment (Kakoulli 2009b). In other wall painting fragments, a larger relative concentration of Egyptian blue mixed with green earth and applied over yellow ochre produced a bright blue-green hue (B, Figure 20a).

Figure 20. (**a**,**b**) Fragments recovered from the House of Orpheus (B); (**c**) photomicrograph (250×) from Tomb 3882 (N2).

Mixtures of green earth and Egyptian blue have been reported in ancient Roman paintings (Linn 2017; Perez-Rodriguez et al. 2015; Siddall 2006; Kakoulli 1995, 2009b), as well as ancient Cypriot polychrome sculptures (Gasanova et al. 2018). Theophrastus discussed how different hues were produced by Egyptian blue based on the state of its preparation, with larger grains producing darker blue hues, and finer grains producing light or pale blue hues (Theophrastus [c. 4th century BC] 1956 [*De lapidibus:* 55]). Figure 20b shows an example of significant density of large-grained Egyptian blue crystals applied over a matrix of green earth containing a low concentration of finer-grained Egyptian blue particles, applied over an undercoat of yellow ochre. This seems to be the first documentation of this extensive mixture/application process with these three core pigments by artists in antiquity.

One of the most valuable materials for producing the color purple was the organic dye known as Tyrian purple, derived from mollusk shells. Pliny described the process of using this dye and how to produce the intended optical effects by applying different undercoats such as sandyx (a lead white and red ochre mixture heat-treated to produce a red-orange hue) to produce a cinnabar-type hue, or Egyptian blue as a base coat to produce a deep purple hue (Pliny [c. 77 AD] 1954 [*Naturalis historia XXXV: 26*]; Delaney et al. 2017). The high cost and demand of natural resources to produce Tyrian purple meant that other means were used to achieve purple hues in ancient painting. This included mixtures and layering of Egyptian blue or indigo with madder lake, a red lake dye pigment and one of

the most prolific synthetic pigments in the ancient world (Brecoulaki 2014; Kakoulli 2002). In ancient Cypriot wall paintings, however, no evidence for the presence of red or purple dye pigments has been found. Though madder root is easily accessible in Cyprus and found in the decoration of pottery and votive shards (Chenciner 2003), pellets of prepared madder lake pigment have been found in archaeological excavations, and it is one of the most ubiquitous red dye pigments in antiquity, its use did not seem to extend to Cypriot wall painting applications.

Ancient Cypriot painters predominantly used mixtures and layering of red ochre and Egyptian blue to produce purple tones, most of which were found in the figurative paintings from the House of Aion. Two exceptions were the faint purple lines used in the shading of the blue tunic of the figurative painting from Tomb 3510, and the outline of the chair found at the dado level of the central arcosolium in Tomb Roma 1 (Figure 13a). Purple tones were also mixed and layered with black pigments to give the effect of shading in the tunic of figure E5 (Figure 12c). Finally, similar to the light blue background washes produced by mixtures of white pigments with Egyptian blue, mixtures of low concentrations of red ochre with Egyptian blue and white pigments produced faint purple background washes and architectural features.

Mixtures and layering of pigments also helped to develop the flesh tones of the figurative paintings in the funerary and domestic spaces. The artistic skill and technological creativity of ancient Cypriot painters are showcased in the figurative paintings recovered from the House of Aion, Tomb 3510, and the tomb from Costis Palamas square. The garments, accessories, flesh tone and facial shading applications, as well as surrounding floral decorations highlighted the application of complex pigment mixtures and layering to produce a wide variety of hues, as well as the artful rendering of the figures' facial features, jewelry, and clothing (Figure 21).

Figure 21. (**a**) From Tomb 3510, a funerary figurative painting exhibits fine brush strokes with juxtaposition of different colors in small details such as the eyebrows and hair and the blending of ochres to produce naturalistic shading in the face are a testament to the skill of the artist (I); (**b**) From the House of Aion, a figurative painting features extensive color mixing and shading to produce multiple tones in the skin and a heavy *skiagraphia* effect (E9); (**c**) A funerary figurative painting from the tomb in the Costis Palamas square shows a simpler depiction of facial features; there is less skin tone variation than the other two figures, and shading mostly appears with the application of a red wash around the face (H1).

To produce the flesh tones of the figurative paintings and give a naturalistic effect to these faces, red and yellow ochres were mixed together with white pigments. The relative concentrations of each pigment produced tones that ranged from dark pink to a soft cream-colored tone; additionally, the artists used these pigments to create highlights in the face along the bridges of the nose and the forehead, complemented by shading around the eyes, chin and neck, to give the effect of *skiagraphia* (Figure 21a,b). This technique was developed by Apollodorus, a 5th century BC painter from Athens,

who Pliny referred to as "*lumen artis*" and lauded him as the first to achieve realistic figurative painting through his *skiagraphia* (Keuls 1975; Pliny [c. 77 AD] 1954 [*Naturalis historia XXXV: 36*]). Theophrastus also discussed in his treatise how red ochre was used to create flesh tones, a practice clearly seen in the Cypriot paintings (Theophrastus [c. 4th century BC] 1956 [*De lapidibus:* 51]). However, with the aid of forensic photography, an important discovery was made in the technological approaches to figurative paintings that are not noted in ancient records. Egyptian blue was found to be mixed with the flesh tones to create regions of brighter hue. Thus, the well-known practice of mixing Egyptian blue with white pigments to create a 'cold' white tone, an effect previously noted in background washes of the figures and a practice applied throughout the ancient world, was applied in facial shading to enhance naturalistic features.

In one of the two faces recovered from the tomb in the Costis Palamas square, forensic imaging revealed Egyptian blue in the outline of the cheeks (Figure 22b). This provided a brighter foundation to lighten the hue of subsequent layering of a red ochre wash, creating a shading effect around the face. This practice of using Egyptian blue with white pigments to build up the flesh tones in ancient figurative painting for naturalistic appearances was also discovered in the Greco-Roman Egyptian funerary mummy portraits from the 1st–4th century AD (Radpour et al. 2017). From the House of Aion, figurative paintings E3, E5, and E7 all showed the use of Egyptian blue to enhance facial tones as well as 'cold' white accents to the eyes, while paintings E1, E3, and E9 had Egyptian blue appear in white jewelry and head accessories.

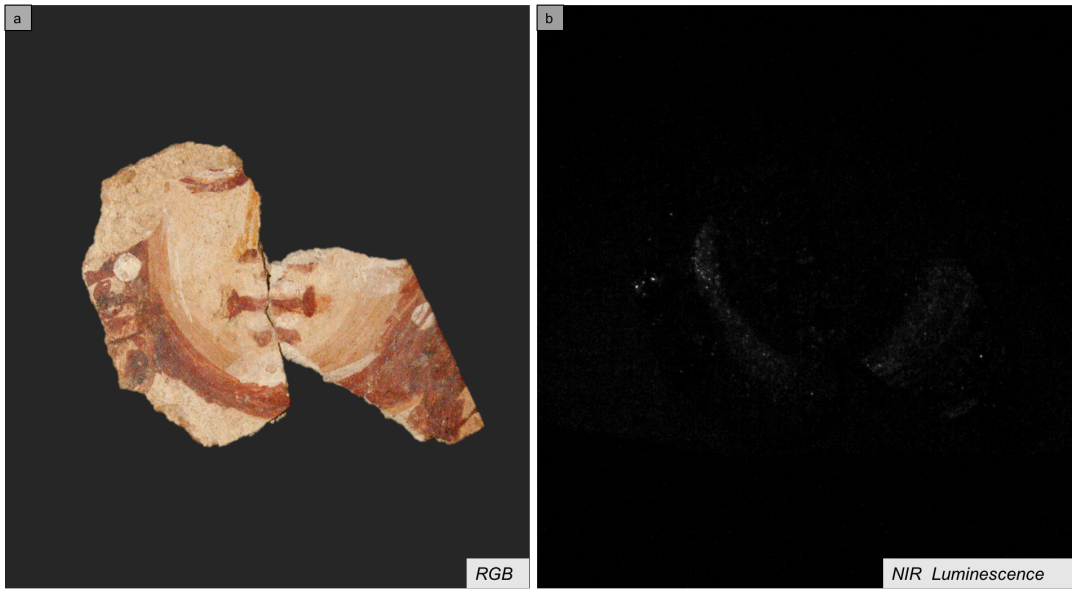

Figure 22. (**a**) A color (RGB) image of a reconstructed face from the painting fragments recovered in the tomb in the Costis Palamas square (H2); (**b**) Forensic imaging shows near-infrared (NIR) luminescence of Egyptian blue in the cheeks, indicating a mixture of Egyptian blue with white pigments to facilitate brighter tones in the shading of the cheeks.

In figurative painting E9 from the House of Aion, a unique approach to facial shading with Egyptian blue was discovered. Near-infrared luminescence imaging and microscopic observations revealed a dense wash of Egyptian blue over the eyebrows and around the cheeks of the face (Figure 23). Egyptian blue was further detected within the flesh tones, a practice similar to the paintings previously discussed and the funerary mummy portraits. However, the blatant outline of the face using a wash of Egyptian blue, a truly unique technique in the art of shading, is the first example noted amongst figurative paintings, and the only one found amongst the Cypriot collection. The application of Egyptian blue in this manner provides new insight into artistic practices and a characteristic marker for attribution to a specific artist, or group of artists.

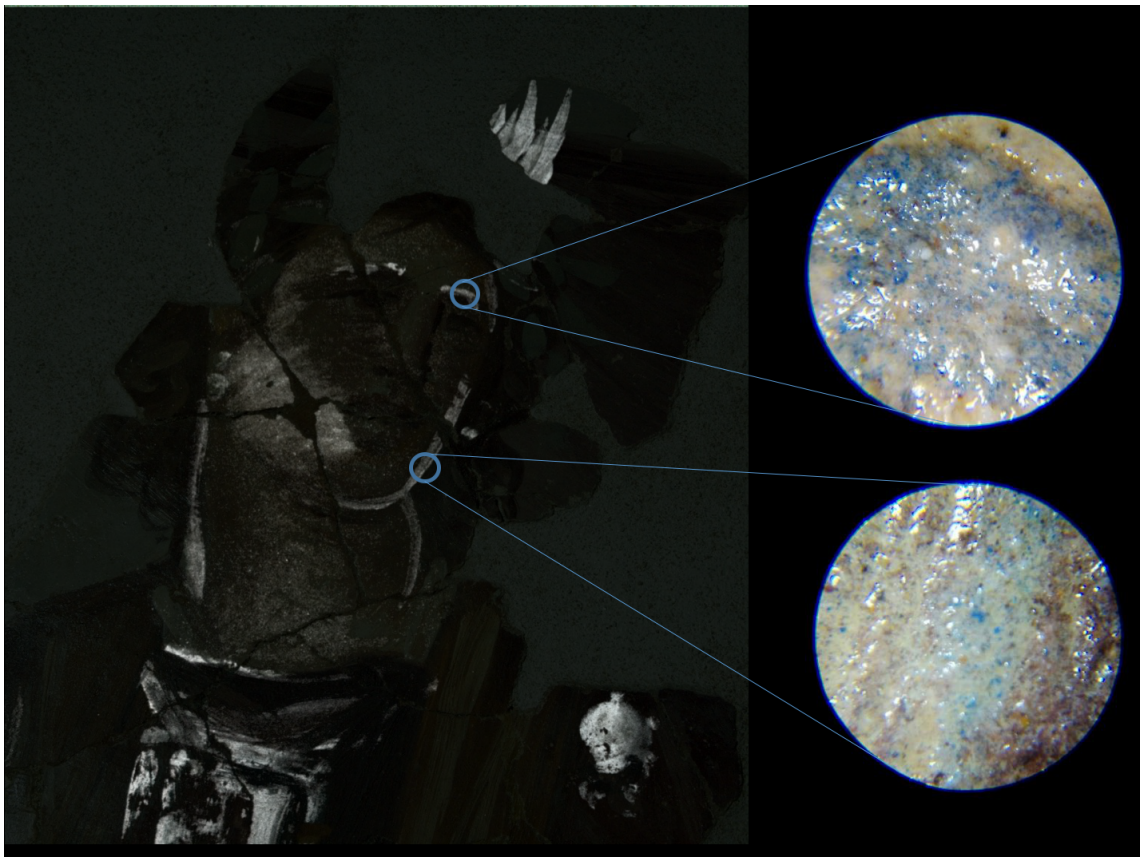

Figure 23. The NIR luminescence image of figurative painting E9 from the House of Aion, overlaid onto the color (RGB) image of painting E9, reveals different uses of Egyptian blue to enhance facial features. In the flesh tones, it was mixed with white pigments to promote brighter tones to contrast the shading of the skin, while along the eyebrows, cheeks, and neck, a dense wash of Egyptian blue was applied for outlining, as noted in the micrographs.

Due to the limited availability of figurative paintings in funerary spaces and the discovery of figurative paintings in domestic spaces only coming from the House of Aion, it is difficult to identify specific technological patterns and isolate trends between the two settings to classify approaches in ancient figurative painting on Cyprus. However, even amongst this set, a wide variety of technological approaches and artistic skill is observed amongst the paintings. This suggests that the artists were developing and testing new methodologies in their paintings. This raises the question whether external influences and/or adaptations contributed to this creative use of color.

4.2. Contributions of Non-Invasive Technology to Art Historical Interpretations and Preservation of Ancient Paintings

Analytical forensic photography aided to identification and mapping of Egyptian blue, based on its luminescence. When excited by red light, Egyptian blue 'glows' owing to its high near-infrared luminescence quantum yield, even when it only survives as ghost paint, or is concealed by salt encrustations and is rendered invisible to the naked eye. Harnessing this property of Egyptian blue, it was possible to recover partially lost and hidden iconography. In Tomb Roma 1, visible-induced near-infrared luminescence imaging recovered the partridge's head painted on the dado of the central arcosolium, which in its present state is almost completely indiscernible. Egyptian blue's quantum yield of 10.5% and lifetime luminescence of ∼138 µs allows forensic imaging to reconstruct these images (Accorsi et al. 2009; Comelli et al. 2016) (Figure 24). The tail and legs, both heavily weathered, were also decorated with Egyptian blue. Micrographs show a base layer of red and yellow pigment,

and it appears that Egyptian blue particles were mixed into this base layer. A top layer of black pigment defines the legs.

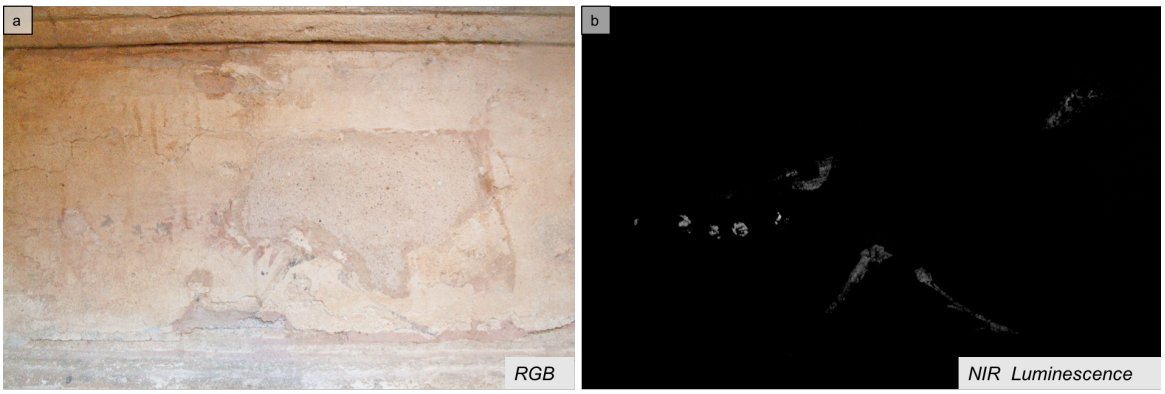

Figure 24. (**a**) A color (RGB) image of a partridge painted on the dado of the central arcosolium (J); (**b**) The NIR luminescence image identifying the blue dots on the tail as Egyptian blue and providing recovery of the leg, tail, and head details that have disappeared due to deterioration.

At the north end of the dado, a smaller bird in grey-blue hue was only partially visible. The center part of the bird's body seems to be completely weathered away. Using visible-induced near-infrared luminescence imaging, it was possible to recover much of the bird's outline and central iconography (Figure 25).

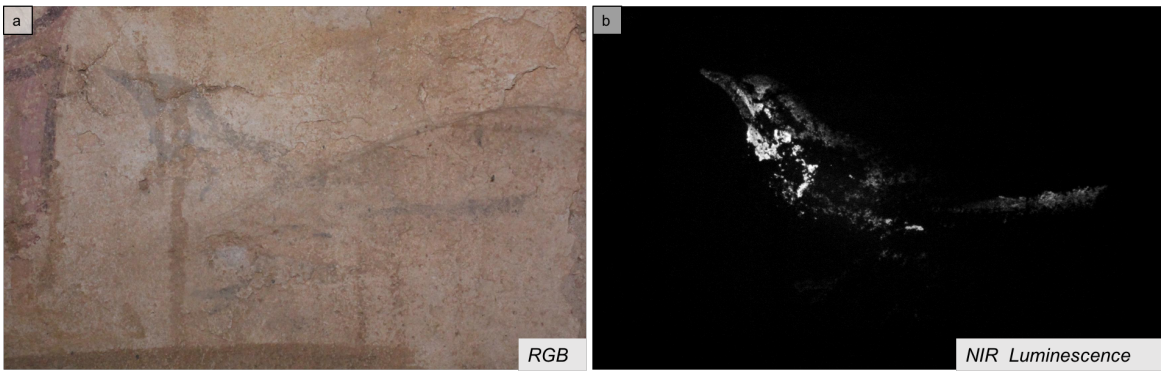

Figure 25. (**a**) A color (RGB) image of a small, faded grey-blue bird on the dado of the central arcosolium (J); (**b**) The near-infrared luminescence image identifies Egyptian blue as one of the major pigment constituents for the hue and recovers the figure of the damaged depiction.

In Tomb Roma 2, analytical imaging was able to revive decorative patterns under the heavy salt encrustation on the stone slab concealing a loculus (Figure 26). Visual observation gave no indication of the outlines and dot patterns revealed by the luminescence of Egyptian blue. This is an extremely important finding as it will provide vital information for wall painting conservators in developing their approach to treating the slab. These results confirm the efficacy of this non-invasive and field deployable technique to reveal unknown, degraded and/or concealed iconography painted with Egyptian blue.

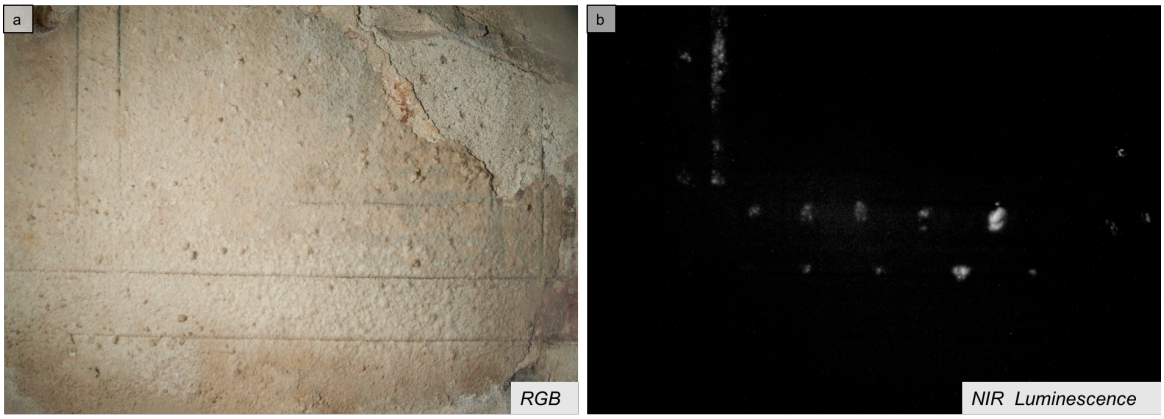

Figure 26. (**a**) A color (RGB) image of the painted slab sealing the loculus in Tomb Roma 2 (K). The heavy salt encrustation covers much of the surface and leaves only incision lines noticeable. (**b**) The NIR luminescence of Egyptian blue capture reveals patterns of dots and lines under the crust.

5. Methods

An integrated approach using non-invasive, non-destructive scientific portable technologies was applied in this investigation. The ease of field-deployment and point collection with real-time feedback on the data with these instruments facilitated extensive data collection spanning across the surface of the paintings, as well as amongst the sites, not only providing materials characterization but also insight into the spatial distribution of the materials used. The high sensitivity of the chemical sensing instruments and photomicrography also revealed materials that were not easily detected by the naked eye. Forensic imaging also facilitated visualization and spatial mapping of Egyptian blue through the capture of its diagnostic luminescence.

5.1. Fiber Optic Reflectance Spectroscopy (FORS)

Two instruments were employed for analysis of Cypriot paintings and natural minerals using principles of reflectance spectroscopy.

1. A field-deployable spectroradiometer, the ASD Inc. Fieldspec 3, operating between 350–2500 nm, was used to collect reflectance spectra of Cypriot paintings, pigment pellets, and natural minerals. Its hand-held contact probe with a flexible optical cable provided spot size collection of 10 mm diameter. The high spectral resolution (3 nm at 700 nm, 10 nm at 1400/2100 nm) allowed material identification of minerals in relatively pure applications as well as separation of constituents in pigment mixtures in the surface decoration of the wall paintings by analysis of characteristic electronic transitions and vibrational absorptions in the reflectance spectrum.
2. A hand-held Miniscan EZ Colorimeter from Hunterlab, operating from 400–700 nm, was used for the characterization of standard red and yellow earth pigments from Cyprus.

Analysis of the FORS data in reflectance and 1st and 2nd derivatives of the reflectance spectra, with comparison to reference spectra in spectral libraries and of local minerals, provided determination of diagnostic absorption and inflection values to separate spectral signatures and identify constituent materials in multiple pigment layers and mixtures.

5.2. X-Ray Fluorescence Spectroscopy (XRF)

Elemental analysis was performed by a hand-held Thermo Scientific Niton® XL3t GOLDD^{+} X-ray fluorescence (XRF) spectrometer with a silver anode (50 kV, 200 μA). Data was collected using the soil and mining modes at 90 s and 120 s, respectively, with a spot size of 8 mm diameter. Analysis utilized internal pre-set Fundamental Parameter and Compton Normalization calibrations.

5.3. Optical Microscopy (OM)

Optical microscopy was performed with a Plugable USB2 Digital Microscope. This portable, lightweight, hand-held microscope was attached to a laptop and provided imaging at maximum magnification of 250x, allowing visualization of large mineral grains and preliminary assessment of pigment mixtures.

5.4. Forensic Photography (FP)

Forensic photography to identify the presence of Egyptian blue (Kakoulli et al. 2017) utilized narrow band illumination with wavelength excitation maximum at 600 nm using a red LED light ($\lambda_{ex,max}$ = 600 nm) and captured in the near infrared (between λ ~900 and 1000 nm) with a modified Fuji digital single-lens reflex (DSLR) camera (internal hot mirror removed) filtered by a PECA 910 filter.

6. Conclusions

This research characterized Hellenistic and Roman Cypriot wall paintings in funerary and domestic contexts from Nea Paphos and provided new information that has expanded present understanding of material use and technological practices by ancient Cypriot artists. The list of pigments identified through portable and non-invasive analytical point measurement techniques, forensic photography, and in situ photomicrography confirmed the results of previous microanalytical investigations conducted on ancient wall paintings from Nea Paphos with the exception of the yellow mineral pigment, jarosite, which was not detected in this study. Red lead, or minium, was a new discovery amongst the pigment palette employed by in Hellenistic and Roman Cyprus. In comparing the pigments used between funerary and domestic wall paintings, the main difference lies in the absence of cinnabar and red lead in the former context; destruction and severe damages caused by natural disasters such as earthquakes may account for the loss of important wall paintings that could have been painted with cinnabar and other brilliant colors. The absence of madder lake and realgar pigments in the paintings may indicate that these materials fulfilled other functions. As madder lake has been used in Cyprus for other polychrome decoration and the madder root is easily accessible, it is not clear why the pigment seems so elusive in wall painting decoration when it was identified in other contemporary wall paintings elsewhere (Brecoulaki 2014; Kakoulli 2002).

The results of this non-invasive analytical survey of the ancient wall paintings also emphasizes the strength of portable chemical sensing technologies to provide crucial information of polychrome objects and wall paintings that remain in situ. The application of FORS, XRF, forensic photography, and in situ photomicrography facilitated fast, reliable data collection with real-time feedback on the data collected, facilitating an in-depth exploration of the mixtures and layering techniques employed in the wall paintings. The results have provided new insights into the artistic practices of ancient Cypriot painters; forensic photography was especially powerful in producing chemical maps of Egyptian blue to reveal the presence and distribution of the pigment in mixtures and the detection of a characteristic approach for facial outlining and shading in figurative paintings. As technical studies continue to be integrated in the exploration of ancient Mediterranean wall paintings, it may be possible to connect the works of ancient Cypriot painters and potentially attribute these stylistic techniques to local artists, or those traveling to Cyprus. Furthermore, it was shown that forensic imaging of Egyptian blue has the capability to retrieve and visualize deteriorated and concealed iconography, significant for reconstructing the original imagery for art historical interpretations and for the design of effective conservation approaches to ensure the preservation of these important paintings.

Author Contributions: Data collection, R.R., C.F. and I.K.; data analysis, R.R.; writing—draft preparation, R.R. and I.K.; writing—review and editing, R.R., C.F. and I.K.

Funding: This research was supported by a Fulbright U.S. Student Research Award, the Danielle Parks Memorial Fellowship from The Cyprus American Archaeological Research Institute (CAARI) and the Molecular and Nano Archaeology Laboratory at UCLA.

Acknowledgments: The authors would like to give many thanks to the Department of Antiquities of Cyprus, and particularly to the Director of the Department, Marina Solomidou-Ieronymidou, Demetrios Michaelides, Henryk Meyza, Eustathios Raptou, Sophocles Hadjisavvas, and Margarita Kouali for permission to access the archaeological sites and their respective materials for study. The authors are also extremely grateful to the archaeological officers, conservators, and staff of the Cyprus Museum and Paphos Archaeological Museum for support and access to materials and sites for analyses. Finally, much gratitude is offered to Andreas Zissimos from the Geological Survey of Cyprus and Ioannis Ioannou from the University of Cyprus for their guidance and support during research activities. The success of this project relied on and benefited from the support of all of the above.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The following tables detail the location of hues identified and analyzed, along with their corresponding location, pigment components, application, and function.

Table A1. Detailed list of the identification and application methodology of Egyptian blue in the Cypriot wall paintings.

Painting	Hue	Main Colorant(s)	Other Phases	Application	Location/Function
A1	Blue	Egyptian blue	Green earth	Applied over plaster	Decorative feature
A2	Blue	Egyptian blue	Green earth	Applied over yellow ochre	N/A
B3	Blue	Egyptian blue	N/A	Applied over plaster	N/A
E2	Sky blue	Egyptian blue	N/A	N/A	Background
E2	Pinkish blue	Egyptian blue	N/A	N/A	Background shading; applied over light blue wash
E5	Light blue-purple	Egyptian blue	Red ochre	N/A	Background
E5	Light white-blue	Egyptian blue	N/A	Applied over plaster	Background; tunic
E6	Light white-blue	Egyptian blue	N/A	Applied over plaster	Background
E6	Light blue	Egyptian blue	N/A	Applied over light blue background wash and red head decoration	Head decoration
E6	Grey-blue	Mn-compounds	Egyptian blue	Applied over yellow	Tunic shading
E8	Light blue	Egyptian blue	N/A	Applied over plaster	Background
E9	Light blue	Egyptian blue	N/A	Applied over tunic	Tunic decoration
E9	Faded blue	Egyptian blue	N/A	Applied over tunic	Tunic decoration
E10	Light blue	Egyptian blue	N/A	Applied over plaster	Background
F1	Light blue	Egyptian blue	N/A	N/A	Dado level
F1	Hazy white	Egyptian blue	N/A	Applied over red pigment	Inner arch; flower decoration
G	Blue	Egyptian blue	N/A	Applied over plaster	Floral decoration
H3	Blue	Egyptian blue	N/A	Applied over green	Leaf
H3	Dark blue	Egyptian blue	N/A	Applied over plaster	Dot decoration
H3	Light blue	Egyptian blue	N/A	Applied over plaster	Line
I	Blue	Egyptian blue	N/A	Applied over plaster	Aedicule; chiton
J	Light blue	Egyptian blue	N/A	Applied over red dot	Dot decoration on bird's tail
J	Dark grey-blue	Egyptian blue	N/A	Applied over plaster	Small bird
K	Blue	Egyptian blue	N/A	Applied over plaster; concealed by encrustation	Dot decoration
L1	Blue	Egyptian blue	N/A	Layered over red/yellow	Oval decoration
L2	Blue	Egyptian blue	N/A	Applied over plaster	Floral decoration
N1	Blue	Egyptian blue	N/A	Applied over plaster	Triangle
N2	Blue	Egyptian blue	N/A	Applied over plaster	Leaf
N3	Blue	Egyptian blue	N/A	Applied over plaster	Geometric pattern

Table A2. Detailed list of the identification and application methodology of green earth in the Cypriot wall paintings.

Painting	Hue	Main Colorant(s)	Other Phases	Application	Location/ Function
A1	Green-blue	Green Earth	Egyptian blue	Applied over yellow ochre on white plaster layer	Band
B1	Light blue-green	Green Earth	Few particles of Egyptian blue	Undercoat for Egyptian blue; applied over black, then over yellow ochre on white plaster layer	N/A
B1	Dark blue-green	Green Earth	N/A	Applied over black on white plaster layer	N/A
B1	Olive green	Green Earth	Yellow ochre	Applied over white plaster layer	N/A
C4	Green	Green Earth	N/A	N/A	Older paint layer - mostly concealed
E5	Light green	Green earth	Yellow ochre; Cu-compounds	Applied over hair and background	Wreath leaf
E5	Dark olive green	Green earth	Yellow ochre; Cu and Mn-compounds	Applied over white tunic (containing Egyptian blue)	Tunic shading
E6	Light blue-green	Green earth	Mn-compounds	Applied over dark purple	N/A
E9	Light green	Green earth	Cu-compounds	Applied over red hair	Wreath leaf
G	Green	Green Earth	N/A	Applied over plaster	Floral decoration
H3	Green	Green Earth	N/A	Applied over plaster	Floral decoration
H3	Green (weathered)	Green Earth	N/A	Applied over plaster	Floral decoration
I	Faint green	Egyptian blue	Green earth	Applied over plaster	Garland, 2nd slab.
J	Green	Green earth	N/A	N/A	Arch and floral decoration
K	Green (weathered)	Green earth	N/A	N/A	N/A
L1/L2	Green	Green earth	Egyptian blue	Applied over plaster	Floral decoration
L2	Green	Green earth	N/A	Applied over plaster	Floral decoration
N1	Olive green	Green earth	Yellow ochre	Applied over plaster	Floral decoration
N2	Olive green	Green earth	Yellow ochre	Applied over plaster	Stem
N2	Dark blue-green	Green earth	Egyptian blue	Applied over yellow ochre	Triangle band
N3	Green	Green earth	N/A	Applied over plaster	Plant decoration

Table A3. Detailed list of the identification and application methodology of red pigments in the Cypriot wall paintings.

Painting	Hue	Main Colorant(s)	Other Phases	Application	Location/Function
A1	Orange	Red Lead	N/A	Applied over white layer with blue particles	Band
A1	Red	Red Ochre	N/A	Applied over plaster	N/A
B1	Red	Red Ochre	N/A	Applied over yellow ochre	Band
B2	Bright pink-red	Cinnabar	Red ochre; Pb- compounds	Applied over pink plaster	N/A
B3	Orange-red	Cinnabar	Red ochre; Pb- compounds	Applied over plaster	N/A
B3	Red	Cinnabar	Red ochre; Pb- compounds	N/A	N/A
C1	Red	Red Ochre	N/A	Applied over plaster	N/A
C2	Red	Red Ochre	N/A	Applied over plaster	N/A
C3	Red	Red Ochre	N/A	Applied over plaster	Older paint layer; N/A
C4	Red	Red Ochre	N/A	Applied over plaster	Older paint layers; N/A
D	Red	Red Ochre	N/A	N/A	Bands; Uniform wall decoration
E1	Orange-red	Red ochre	N/A	Applied over flesh	Eye crease shading
E1	Purple	Red ochre	N/A	Applied over flesh	Tunic
E1	Light purple	Red ochre	N/A	Applied over purple	Tunic lightening
E1	Reddish purple	Red ochre	N/A	N/A	Band
E3	Brown-red	Red ochre	N/A	N/A	N/A
E3	Flesh	Red ochre	N/A	N/A	Cheek
E3	Dark brown	Red ochre	N/A	Touches of yellow paint above; applied over brown-red	Hair layering
E5	Red	Red ochre	N/A	N/A	Band
E6	Cream	Red ochre	N/A	Facial toning	Cheek
E5	Orange-red	Red ochre	N/A	N/A	Cape
E5	Purple	Red ochre	Egyptian blue	Layered shading with Mn-based black pigment	Tunic

Table A3. *Cont.*

Painting	Hue	Main Colorant(s)	Other Phases	Application	Location/Function
E5	Dark purple	Red ochre	N/A	Micrograph shows mixture with black and blue pigments	Shoulder
E5	Light purple	Red ochre	Egyptian blue	N/A	Background bands
E6	Dark purple	Red ochre	N/A	N/A	Tunic
E6	Red	Red ochre	N/A	N/A	Hair layering
E6	Reddish pink	Red ochre	N/A	Facial toning	Cheek
E6	Light pink	Red ochre	N/A	N/A	Neck
E8	Purple	Red ochre	N/A	N/A	N/A
E9	Dark purple	Red ochre	N/A	layering	Garment
E9	Light orange-red	Red ochre	N/A	N/A	Background
E9	Light purple	Red ochre	N/A	N/A	Background
E9	Red	Red ochre	N/A	N/A	Garment
E9	Flesh	Red ochre	N/A	N/A	Cheek
E10	Light purple	Red ochre	Egyptian blue	N/A	N/A
E10	Red	Red ochre	N/A	N/A	Band
E10	Light pink	Red ochre	Egyptian blue	N/A	N/A
G	Red	Red Ochre	N/A	Applied over plaster	Band
H3	Reddish Orange	Red Ochre	Yellow ochre	Applied over plaster	Band
H3	Red	Red Ochre	N/A	Applied over plaster	Bands/lines
H3	Pink	Red Ochre	N/A	Applied over plaster	Floral decoration
I	Dark Red	Red Ochre	N/A	N/A	Shoe
I	Dark Pink-red	Red Ochre	N/A	N/A	Himation
I	Light Pink	Red Ochre	N/A	N/A	Neck
I	Pink	Red Ochre	N/A	N/A	Garlands

Table A3. *Cont.*

Painting	Hue	Main Colorant(s)	Other Phases	Application	Location/Function
I	Flesh	Red ochre	N/A	Shading - light wash over plaster	Arm
J	Red	Red Ochre	N/A	Applied over plaster	Dog
J	Red	Red Ochre	Pb-compounds	Applied over plaster	Arch decoration
J	Pink	Red Ochre	N/A	Applied over plaster	Chair
J	Purple	Red Ochre	N/A	Applied over plaster / pink chair	Outline of chair
K	Red	Red Ochre	N/A	Applied over plaster	Band
K	Pink	Red Ochre	N/A	Applied over plaster	Marble imitation
L1	Red	Red Ochre	N/A	Applied over plaster	lines
L2	Pink	Red Ochre	N/A	Applied over plaster	Floral decoration
L2	Red	Red Ochre	N/A	Applied over plaster	N/A
N1	Red	Red Ochre	Pb-compounds	Applied over plaster	Line
N1	Pink	Red Ochre	N/A	Applied over plaster	N/A
N2	Dark red	Red Ochre	N/A	Applied over plaster	Wave pattern
N2	Pink	Red Ochre	N/A	Applied over plaster	Marble imitation
N2	Red	Red Ochre	Pb-compounds	Applied over plaster	Marble imitation
N3	Red	Red Ochre	N/A	Applied over plaster	Square border
N3	Pink	Red Ochre	N/A	Applied over plaster	Triangles
O	Red	Red Ochre	N/A	Applied over plaster	Band

Table A4. Detailed list of the identification and application methodology of yellow ochre in the Cypriot wall paintings.

Painting	Hue	Main Colorant(s)	Other Phases	Application	Location/Function
B1	Yellow	Yellow ochre	N/A	Uniform	N/A
C3	Yellow	Yellow ochre	N/A	Applied over plaster	N/A
C4	Yellow	Yellow ochre	N/A	Applied over plaster	Top layer
D	Yellow	Yellow ochre	N/A	Applied over plaster	N/A
E1	Dark yellow	Yellow Ochre	N/A	N/A	N/A
E1	Light yellow	Yellow ochre	N/A	N/A	N/A
E2	Yellow	Yellow ochre	N/A	Over blue background of Egyptian blue	N/A
E3	Yellow	Yellow ochre	N/A	N/A	N/A
E5	Yellow	Yellow ochre	N/A	N/A	Cape
E5	Cream	Yellow ochre	N/A	Facial toning	Forehead
E6	Dark yellow	Red ochre	Yellow ochre	N/A	Belt
E6	Light Yellow	Yellow ochre	N/A	N/A	Tunic, background
E9	Light Yellow	Yellow ochre	N/A	N/A	Belt
E9	Yellow	Yellow ochre	N/A	Applied over red	Mantle
E10	Light yellow-white	Yellow ochre	Red ochre	N/A	Cheek
E10	Dark yellow	Yellow ochre	N/A	N/A	Hair
G	Reddish Yellow	Yellow ochre	Red ochre	N/A	Floral decoration
G	Yellow	Yellow ochre	N/A	Applied over plaster	Floral decoration
H3	Orange-Yellow	Yellow ochre	Red ochre	N/A	Decorative fragment
H3	Yellow	Yellow ochre	N/A	Applied over plaster	Decorative fragment
I	Reddish Yellow	Yellow ochre	Red ochre	Shading	Skirt
J	Reddish Yellow	Yellow ochre	N/A	Preparation layer for red pigment	Floral decoration
K	Yellow	Yellow ochre	Red ochre	Applied over plaster	N/A
L	Yellow	Yellow ochre	N/A	Applied over plaster	Line
N1	Yellow (discolored)	Yellow Ochre	N/A	N/A	N/A
N2	Yellow	Yellow Ochre	N/A	Applied over plaster	Band
N3	Yellow	Yellow Ochre	N/A	N/A	Floral decoration
N3	Yellow	Yellow Ochre	N/A	Applied over plaster	Band
O	Yellow	Yellow Ochre	N/A	Applied over plaster	Window

References

Accorsi, Gianluca, Giovanni Verri, Margherita Bolognesi, Nicola Armaroli, Catia Clementi, Costanza Miliani, and Aldo Romani. 2009. The exceptional near-infrared luminescence properties of cuprorivaite (Egyptian blue). *Chemical Communications* 23: 3392–94. [CrossRef] [PubMed]

Apostolaki, Chryssa, Vassilis Perdikatsis, E. Repuskou, Harikleia Brecoulaki, and Sarah Lepinski. 2006. Analysis of Roman wall paintings from ancient Corinth/Greece. Paper presented at 2nd International Conference on Advances in Mineral Resources Management and Environmental Geotechnology, Hania, Greece, September 25–27; pp. 729–34.

Aze, Sebastien, Jean-Marc Vallet, Vincent Detalle, Olivier Grauby, and Alain Baronnet. 2008. Chromatic alterations of red lead pigments in artworks: A review. *Phase Transitions-PHASE TRANSIT* 81: 145–54. [CrossRef]

Balandier, Claire, Celine Joliot, Matthieu Menager, Frederique Vouve, and Catherine Vieillescazes. 2017. Chemical analyses of Roman wall paintings recently found in Paphos, Cyprus: The complementarity of archaeological and chemical studies. *Journal of Archaeological Science: Reports* 14: 332–39. [CrossRef]

Berke, Heinz. 2007. The invention of blue and purple pigments in ancient times. *Chemical Society Reviews* 36: 15–30. [CrossRef] [PubMed]

Brecoulaki, Harikleia. 2014. Precious colours in ancient Greek polychromy and painting: Material aspects and symbolic values. *Revue Archéologique* 1: 3–35. [CrossRef]

Chenciner, Robert. 2003. *Madder Red: A History of Luxury and Trade*. Abingdon: Routledge.

Cohen, Dave, Andreas Zissimos, and Eleni Georgiou-Morisseau. 2011. *Geochemical Atlas of Cyprus*. Lefkosia: Geological Survey Department of Cyprus.

Comelli, Daniela, Valentina Capogrosso, Christian Orsenigo, and Austin Nevin. 2016. Dual wavelength excitation for the time-resolved photoluminescence imaging of painted ancient Egyptian objects. *Heritage Science* 4: 21. [CrossRef]

Delaney, John K., Kathryn A. Dooley, Roxanne Radpour, and Ioanna Kakoulli. 2017. Macroscale multimodal imaging reveals ancient painting production technology and the vogue in Greco-Roman Egypt. *Scientific Reports* 7: 15509. [CrossRef] [PubMed]

Elderfield, Henry, Ian G. Gass, A. Hammond, and L.M. Bear. 1972. The origin of ferromanganese sediments associated with the Troodos Massif of Cyprus. *Sedimentology* 19: 1–19. [CrossRef]

Gallahan, William E., and Robert A. Duncan. 1994. Spatial and temporal variability in crystallization of celadonites within the Troodos ophiolite, Cyprus: Implications for low-temperature alteration of the oceanic crust. *Journal of Geophysical Research: Solid Earth* 99: 3147–61. [CrossRef]

Gasanova, Svetlana, Sandrine Pagès-Camagna, Maria Andrioti, and Sorin Hermon. 2018. Non-destructive in situ analysis of polychromy on ancient Cypriot sculptures. *Archaeological and Anthropological Sciences* 10: 83–95. [CrossRef]

Gettens, Rutherford J., Robert L. Feller, and W. T. Chase. 1972. Vermilion and Cinnabar. *Studies in Conservation* 17: 45–69.

Grifa, Celestino, Laetitia Cavassa, Alberto De Bonis, Chiara Germinario, Vincenza Guarino, Francesco Izzo, Ioanna Kakoulli, Alessio Langella, Mariano Mercurio, and Vincenzo Morra. 2016. Beyond Vitruvius: New insight in the technology of Egyptian blue and green frits. *Journal of the American Ceramic Society* 99: 3467–75. [CrossRef]

Guimier-Sorbets, Anne-Marie, and Demetrios Michaelides. 2003. Alexandrian influences on the architecture and decoration of the Hellenistic tombs of Cyprus. Paper presented at the International Conference Egyptand Cyprus in Antiquity Nicosia, Nicosia, Cyprus, April 3–6; pp. 3–6.

Hatton, Gareth D., Andrew J. Shortland, and Michael S. Tite. 2008. The production technology of Egyptian blue and green frits from second millennium bc Egypt and Mesopotamia. *Journal of Archaeological Science* 35: 1591–604. [CrossRef]

Hradil, David, Tomáš Grygar, Janka Hradilová, and Petr Bezdička. 2003. Clay and iron oxide pigments in the history of painting. *Applied Clay Science* 22: 223–36. [CrossRef]

Jaksch, Heiner, Wilfried Seipel, Karl-Ludwig. Weiner, and Ahmed El Goresy. 1983. Egyptian blue—Cuprorivaite a window to ancient Egyptian technology. *Naturwissenschaften* 70: 525–35. [CrossRef]

Kakoulli, Ioanna. 1995. Hellenistic and Roman Wall Paintings in Cyprus: A Scientific Examination of Their Technology. Master's thesis, Courtauld Institute of Art, University of London, London, UK.

Kakoulli, Ioanna. 2002. Late Classical and Hellenistic painting techniques and materials: A review of the technical literature. *Studies in Conservation* 47: 56–67. [CrossRef]

Kakoulli, Ioanna. 2009a. Egyptian blue in Greek painting between 2500 and 50 BC. In *From Mine to Microscope: Advances in the Study of Ancient Technology*. Oxford: Oxbow Books, pp. 101–12.

Kakoulli, Ioanna. 2009b. *Greek Painting Techniques and Materials from the Fourth to the First Century BC*. Oakville: Archetype Books.

Kakoulli, Ioanna, Christian Fischer, and Demetrios Michaelides. 2010. Painted rock-cut tombs in Cyprus from the Hellenistic and Roman periods to Byzantium: Material properties, degradation processes and sustainable preservation strategies. *Studies in Conservation* 55: 96–102. [CrossRef]

Kakoulli, Ioanna, Roxanne Radpour, Yuan Lin, Marie Svoboda, and Christian Fischer. 2017. Application of forensic photography for the detection and mapping of Egyptian blue and madder lake in Hellenistic polychrome terracottas based on their photophysical properties. *Dyes and Pigments* 136: 104–15. [CrossRef]

Kassianidou, Vasiliki. 2013. Mining landscapes of prehistoric Cyprus. *Metalla* 20: 5–57.

Keuls, Eva. 1975. Skiagraphia once again. *American Journal of Archaeology* 79: 1–16. [CrossRef]

Linn, Ravit. 2017. Layered pigments and painting technology of the Roman wall paintings of Caesarea Maritima. *Journal of Archaeological Science: Reports* 11: 774–81. [CrossRef]

Michaelides, Demetrios. 2004. Cypriot painted tombs and their ceilings. In *Plafonds et Voûtes à L'époque Antique. Actes du VIIIe Colloque International de l'Association Internationale pour la Peinture Murale Antique*. Calabash: Pytheas Publishing.

Miller, Stella. 2014. Hellenistic painting in the eastern Mediterranean, mid-fourth to mid-first century b.c. In *The Cambridge History of Painting in the Classical World*. Edited by J. J. Pollitt. Cambridge: Cambridge University Press.

Nicolaou, Kyriakos. 1980. Archaeological News from Cyprus, 1977–1978. *American Journal of Archaeology* 84: 63–73. [CrossRef]

Pappalardo, Umberto. 2009. *The Splendor of Roman Wall Painting*. Los Angeles: Getty Publications.

Perez-Rodriguez, Jose Luis, Maria del Carmen Jimenez de Haro, Belinda Siguenza, and José María Martinez-Blanes. 2015. Green pigments of Roman mural paintings from Seville Alcazar. *Applied Clay Science* 116–17: 211–19. [CrossRef]

Pliny. 1954. Natural History, Vol. IX: Books XXXIII–XXXV with an English translation by H. Rackham. (Loeb Classical Library.). *The Classical Review* 4: 136–38. First published c. 77 AD.

Radpour, Roxanne, Yuan Lin, Marie Svoboda, Giacomo Chiari, Christian Fischer, and Ioanna Kakoulli. 2017. Materials characterization of Greco-Roman mummy portraits using forensic photography and noninvasive spectroscopy. Presented at Technart 2017, Bilbao, Spain, May 3.

Raptou, Eustathios. 2007. Painted tombs of Roman Paphos. In *Κυπριακή Αρχαιολογία Τόμος V (Archaeologia Cypria, Volume V)*. Association of Cypriot Archaeologists.

Ren, Limin, David R. Cohen, Neil F. Rutherford, Andreas M. Zissimos, and Eleni G. Morisseau. 2015. Reflections of the geological characteristics of Cyprus in soil rare earth element patterns. *Applied Geochemistry* 56: 80–93. [CrossRef]

Retief, Francois P., and Louise Cilliers. 2006. Lead poisoning in ancient Rome. *Acta Theologica* 26: 147–64. [CrossRef]

Salvant, Johanna, Jane Williams, Monica Ganio, Francesca Casadio, Celine Daher, Ken Sutherland, Letizia Monico, Frederik Vanmeert, Steven De Meyer, Koens Janssens, and et al. 2018. A Roman Egyptian painting workshop: Technical investigation of the portraits from Tebtunis, Egypt. *Archaeometry* 60: 815–33. [CrossRef]

Savvopoulos, Kyriakos. 2011. Alexandria in Aegypto: The Role of Egyptian Tradition in the Hellenistic and Roman Periods. Ph.D. thesis, Universiteit Leiden, Leiden, The Netherlands.

Scott, David A. 2016. A review of ancient Egyptian pigments and cosmetics. *Studies in Conservation* 61: 185–202. [CrossRef]

Siddall, Ruth. 2006. Not a day without a line drawn. *InFocus Magazine: Proceedings Royal Microscopical Society* 2: 18–23. [CrossRef]

Theophrastus. 1956. *On Stones*. Introduction, Greek Text, English Translation, and Commentary by Caley and Richards. Columbus, Ohio: The Ohio State University Press. First published c. 4th century BC.

Westgate, Ruth C. 2000. Space and decoration in Hellenistic houses. *The Annual of the British School at Athens* 95: 391–426. [CrossRef]

Wood Conroy, Diana. 2004. *Roman Wall Paintings in the Pafos Theatre*. Nicosia: Department of Antiquities, Cyprus.