Making and working Egyptian blue – a review of the archaeological evidence

Published in ***Journal of Archaeological Science* 153, 2023, paper 105772**.

https://www.sciencedirect.com/science/article/pii/S030544032300050X

https://doi.org/10.1016/j.jas.2023.105772

Kovalev, I. [a,*], *Rodler, A.S.* [b,c], *Brøns, C.* [d], *& Rehren, Th.* [a,e]

[a] Science and Technology in Archaeology and Culture Research Center, The Cyprus Institute, Konstantinou Kavafi Street 20, Nicosia 2121, Cyprus

[b] Research Group Object Itineraries, Department Historical Archaeology, Austrian Archaeological Institute, Austrian Academy of Sciences, Franz Klein-Gasse 1, 1190 Vienna, Austria

[c] Department of Lithospheric Research, University of Vienna, Josef-Holaubek-Platz 2, 1090 Vienna, Austria

[d] Ny Carlsberg Glyptotek (NCG), Dantes Plads 7, Copenhagen 1556, Denmark

[e] UCL Institute of Archaeology, 31-34 Gordon Square, London, UK

* Corresponding author. *E-mail address:* i.kovalev@cyi.ac.cy (I. Kovalev).

Abstract

As the earliest artificial pigment, Egyptian blue has a millennia-long history of production, processing / working, and use. This paper offers a review of the published archaeological evidence for Egyptian blue production, aiming to identify common and potentially diagnostic criteria for each process step to aid future identification and interpretation of Egyptian blue workshops *sensu lato*. We identify systematic differences in the production evidence between Late Bronze Age and Hellenistic to Late Roman sites, respectively, and propose a model to distinguish between primary production and secondary / artistic processing of Egyptian blue. Finally, we note the absence of direct evidence for the production and processing of Egyptian blue for much of the known period of its use.

Keywords: Egyptian blue, Ancient pigment manufacturing, Crucibles, High-temperature processes

1. Introduction

The oldest human-made inorganic pigment is Egyptian blue (EB, hereafter) that made its appearance in Early Bronze Age Egypt (late 4th—3rd millennia BCE), at about 3100 BCE (Newman, 2014). It is a versatile and stable blue pigment and one of the earliest examples of an artificially produced artistic material. It had a wide range of applications including for making small objects and as a pigment for use in ancient art. Introduced in the very early third millennium BCE in Egypt (if not earlier – see Corcoran 2016: 49-53) and Mesopotamia, EB was probably the most important addition to the ancient artistic palette until it disappeared sometime during the Medieval period. EB contributed to the polychromy of various artefacts and artistic media, whether in wood, terracotta, stone, or stucco. So far, the latest attestation of its use is in Raphael's fresco *The Triumph of Galatea* at Villa Farnesina, Rome, from 1511-1512 (Anselmi et al., 2020) and in a painting by Giovanni Battista Benvenuto from 1524 (Bredal-Jørgensen et al., 2011).

Several naturally occurring and human-made blue colourants and materials were used from the Bronze Age onwards. The most famous is lapis lazuli, which was used for inlays, amulets, figurines, and other objects, but also to produce a bright and stable blue pigment, in later times known as ultramarine. However, there are no known deposits of this mineral in the Old World outside Afghanistan, and its availability in the

Mediterranean littoral or Middle East would have been dependent on trade from afar, thus adding to the expense of the material (Plesters, 1993; Hatton, 2005: 16). A further disadvantage of using lapis lazuli as a pigment is that it consists of a mixture of minerals, which means that grinding it into a fine powder will result in a greyish-blue tint rather than the bright, deep blue of pure lapis lazuli (Delamare, 2013). Despite this, lapis lazuli has been used as a pigment for painting over a long period and wide geographic area, ranging from the 16th century BCE to at least the 16th century CE (Brysbaert, 2006; Brøns et al., 2020), and from Central Asia (Colomban 2003) and across the Middle East and Europe (Clark et al. 1997; Radini et al. 2019). Another option was the naturally occurring mineral azurite ($Cu_3(CO_3)_2(OH)_2$), which is found in many parts of the world in copper ore deposits. However, the pigment is unstable and can turn green with time due to oxidation; it is so far not widely attested in ancient polychromy (Gettens and Fitzhugh, 1993), although more recent studies have proven its use on e.g. the Parthenon (Aggelakopoulou and Bakolas, 2022). Since the Late Bronze Age (LBA), copper, bronze, and various copper-cobalt-nickel minerals were used as colourants to produce glass and glazes, for example in the dark blue glass inlay of the gold mask of Tutankhamun or for the Neo-Babylonian glazes of the Ishtar Gate and Processional Way (Fitz, 1982; Matson, 1986; Rodler et al., 2019), or the countless faience objects from ancient Egypt and beyond.

Another important human-made blue pigment, a cobalt aluminium oxide ($CoAl_2O_4$), also known as ‘Amarna blue’, was used in Egypt for about 200 years, from the middle of the 18th Dynasty (c. 1550 –1292 BCE) to the 19th Dynasty (1292 – 1189 BCE) for decorating ceramic vessels (Riederer 1974; Shortland et al., 2006; Abe et al., 2009). However, it does not appear to have been used as a pigment in the form of a powder mixed with a binder for painting artefacts in wood or stone. Rather, this blue colour could only be achieved directly on pottery during the firing process (Loschwitz, 2012). Finally, indigo was also exploited as an organic colourant, not only for dyeing textiles, but also for painting. Yet, so far, the use of indigo for painting has mainly been attested in the polychromy of panel paintings from Roman Egypt (Dyer and Newman, 2020; Bradley et al., 2020).

None of these blue colourants were as favourable as EB. Even though EB paint can appear brownish green to black either due to adhering materials or to the discolouration of the varnish or binder, as observed for Egyptian coffins (Daniels et al., 2004), EB generally retains its colour and is considered to be stable in all artistic media (Riederer, 1997). Depending on the batch composition, production technique, and grain size, the hues of EB vary from saturated dark to light blue (Pagès-Camagna et al., 1999; Bianchetti et al., 2000). A further great advantage of EB is that its production is based on easily, often locally accessible raw materials, allowing a constant supply of the blue pigment. Despite this, EB was likely widely exchanged and travelled long distances before undergoing further processing and final application. Trade in artistic materials is well-attested in Antiquity, although trade in pigments can be harder to establish. Among the few clear examples of pigment trade are ancient shipwrecks recovered in the Mediterranean Sea, which confirm that pigments were traded from the Bronze Age onwards, as shown by the finds of orpiment on the Uluburun shipwreck, dated to the 14th century BCE (Pulak, 2008). However, direct evidence of maritime trade of EB is only known for the Roman period (for a detailed account of these shipwrecks, see Blet, 1994; Delamare, 2013; for a more recent investigation, see Gambin et al., 2021). Other archaeological evidence consists of the rare examples of pigment shops. Although such shops evidently do not allow us to conclude long-distance trade since the pigments may have been produced locally, they confirm the use of EB as a commodity in ancient trade and commerce. Such shops have been found around the Mediterranean, e.g., in Egypt and in Pompeii. An example is the 2nd – 4th century CE pigment shop at the area Sacra di S. Omobono in the Forum Boarium in Rome, where more than two kilos of raw pigments, including EB, were recovered (Beeston and Becker, 2013). Epigraphy also informs us about trade in pigments during the Roman period. The Latin designation *pigmentarius* (e.g., Cic. *Fam.* 15,17,2; *CIL* VI 9795) refers to a producer of and trader in pigments, which demonstrates the existence of commerce in such goods, including pigments for painting as well as for cosmetics and medicine (Becker, 2021).

While the chemical and physical properties of the material itself, including recent advances in provenance research, as well as its modern-day reproduction have been widely studied before, archaeological evidence of its production is scarce. This paper reviews the available evidence of EB production in order to identify common aspects of the various workshop practices, and to propose criteria for the identification and characterization of EB workshops in the archaeological record. We situate our discussion within the *chaîne opératoire* concept to study workshops and structures of ‘industries’, considering the ancient artisan’s technological choices within the physico-chemical constraints of the specific processes, and exploring whether different technological styles can be identified. Addressing EB production as a *chaîne opératoire* allows to identify important steps of the production process and its relationship with and similarities to (or differences from) other industries such as faience, glass, and metal production.

2. Egyptian blue workshops

The raw materials for EB production are widely accessible, and the technical skills required to produce EB are not very demanding; despite this and considering the popularity and cultural value of blue (e.g., Pastoureau, 2018), not many production sites are currently known. Within the *chaîne opératoire*, there are three conceptually different archaeological contexts within which EB is encountered: a. production sites, b. sites where EB was worked into objects and pigments, and c. the final products, whether objects such as figurines, amulets, beads, pendants, small vessels, or mosaic tesserae made entirely in EB, or objects and surfaces painted with the pigment. Following the model of the late antique to Byzantine glass industry (e.g., Freestone et al., 2002), we hypothesize a structure for the *chaîne opératoire* of EB based on a physical separation of these three basic contexts, and explore the archaeological evidence to test our hypothesis.

In this model, the centralized primary production sites would procure, process, and then fire the raw materials, producing a bulk product, ready to be distributed to the secondary working sites (see below, *3.a.* to *c.*). The secondary sites, which were most likely artistic workshops, would obtain the bulk product and process it to a pigment powder for painting, or re-work it into small objects (*3.d.*). These secondary activities could take place in close proximity to the primary production sites, as an integrated workshop complex. Alternatively, they could take place near to, or at, the site of the final use of the finished material, for instance through itinerant artisans preparing their colour palette on the spot when decorating a building or an artwork such as a sculpture. Within the *chaîne opératoire* concept, the primary sites extend back to the extraction and selection of the raw materials, and link to the secondary sites through a trade and storage network.

The third, and certainly largest and most wide-spread type of archaeological context with evidence for EB is not covered here, comprising everything from remains of blue-painted plaster on architectural building materials, to polychrome statues, vases, and other painted surfaces, and funerary contexts with beads, pendants, and similar grave goods.

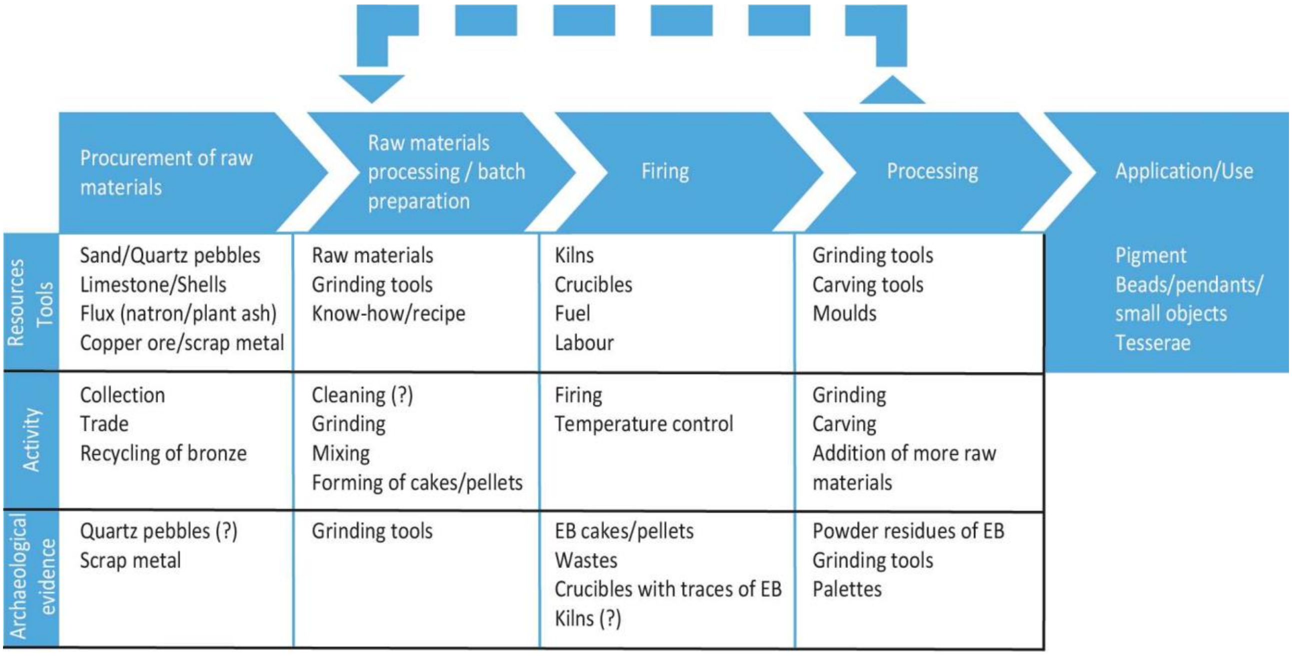
3. The production of Egyptian blue

Egyptian blue forms when finely-ground quartz, calcium carbonate, and copper oxide are fired at temperatures between circa 850 and 1050 °C (Tite and Hatton, 2007). The presence of a small amount of alkali-rich flux is necessary for the reaction to take place and to support the formation of the blue crystal phase, compositionally and structurally equivalent to the very rare mineral cuprorivaite ($CaCuSi_4O_{10}$) (Tite and Hatton, 2007). The requirement for a relatively narrow temperature range and controlled atmosphere necessitated the use of crucibles as reaction vessels. The remains of crucibles in turn serve as crucial archaeological evidence for the primary production of EB and enable identifying a site as EB workshop or area in which EB was produced (Lazzarini and Verita, 2015).

The first insight into EB production is provided by Vitruvius (c. 1st century BCE; Vitr. *De arch.* 7.11.1), who described the production technique of Hellenistic and Roman periods, mentioning raw material selection and mixing, shaping of EB pellets, and the use of crucibles:

> “The recipes for blue were first discovered in Alexandria, and subsequently Vestorius began to manufacture it in Puteoli as well. Its story and how it was invented are quite marvelous. Sand is ground with flower of natron so finely that it almost becomes like flour. Copper, broken by coarse files until it is like sawdust, is sprinkled with this sand until it clings together. Then it is formed into balls by rolling it between the hands and bound together to dry. Once dry, the balls are put into a ceramic pitcher, and the pitchers are put into a kiln. In this way the copper and the sand, boiling with the energy of the fire, bond together, and exchanging their sweat between them they leave off their original properties; with their natures merged they produce a blue color.” (Translation: Rowland, 1999: 94)

Supplementing this literary source with archaeological finds and material study of both, ancient EB samples and modern laboratory reproductions, we can define four main stages of the *chaîne opératoire* of EB production.



	Procurement of raw materials	Raw materials processing / batch preparation	Firing	Processing	Application/Use
Resources Tools	Sand/Quartz pebbles Limestone/Shells Flux (natron/plant ash) Copper ore/scrap metal	Raw materials Grinding tools Know-how/recipe	Kilns Crucibles Fuel Labour	Grinding tools Carving tools Moulds	Pigment Beads/pendants/ small objects Tesserae
Activity	Collection Trade Recycling of bronze	Cleaning (?) Grinding Mixing Forming of cakes/pellets	Firing Temperature control	Grinding Carving Addition of more raw materials	
Archaeological evidence	Quartz pebbles (?) Scrap metal	Grinding tools	EB cakes/pellets Wastes Crucibles with traces of EB Kilns (?)	Powder residues of EB Grinding tools Palettes	

Figure 1. Model illustrating the *chaîne opératoire* of EB production.

a. Procurement of raw materials. Each of the EB ingredients may come from various sources. The quartz can come either from crushed quartz pebbles or clean sand. Lime can be added as a separate component, such as crushed limestone or shell, or it can be incorporated in the batch as lime-rich sand. The copper phase has an even greater variety of possible sources. Copper metal, alloy, or ore (malachite or azurite) can all be used as well as copper oxide scale produced by roasting scrap copper metal or its alloys (Tite and Hatton, 2007). Potential raw materials for the alkali include mineral natron or halophytic plant ash (Tite and Hatton, 2007). This allowed a wide variety of opportunities for ancient craftspeople to adapt their batch recipe according to local availability. Thus, analysis of EB with the aim to identify the raw materials used in its production has the potential of identifying specific material characteristics of individual workshops as well as potential source areas of copper raw materials (Shortland, 2006; Rodler et al., 2017). Besides mineralogical/petrographic analysis (e.g., recently by Dariz and Schmid, 2021), isotope analysis has also been used to characterize the raw material provenance, which has implications for ancient trade contacts. Briefly, the lead isotope approach was developed to differentiate the geological origin of ancient metal artefacts by excluding regions or mining districts that were least likely source areas (e.g., Stos-Gale & Gale

2009). Hatton (2005) and Shortland (2006) applied this to investigate EB produced in Memphis, Egypt (Supplementary Material c), and proposed a provenance of copper from outside of Egypt. Later, Rodler et al. (2017) analysed the lead and copper isotope composition of EB of two fragments from the EB workshop in Memphis, Egypt. In agreement with Shortland (2006), they also proposed that copper from outside of Egypt – likely from the Aegean – was used for EB production in Memphis.

b. Raw materials processing and preparation of the mixture. The proper ratio between the components of the mixture as well as the quality of mixing the ingredients are crucial for EB production. Non-ideal recipes may limit the formation of cuprorivaite crystals and / or lead to the formation of other mineral phases. An excess of copper can lead to the formation of copper oxides such as tenorite and cuprite (Jaksch et al., 1983). An excess of quartz will result in the formation of free silica phases, and wollastonite forms when both quartz and lime are in excess (Jaksch et al., 1983; Mirti et al., 1995). The alkali content of the mixture was also extremely important for successful production. Laboratory reproductions by Hatton showed that in a mixture with a low alkali content (~0.3%), the growth of EB crystals is limited, and formation of the glass phase is reduced (Hatton, 2005: 74). On the other hand, an excessive alkali content (~10%) upon firing led to the formation of a green glassy mass with only occasional EB crystals present (Hatton, 2005: 83). Similar results appear if NaCl was present in the mixture in substantial quantities (~5-10%) (Giménez et al., 2017). Giménez and co-workers hypothesize that NaCl brought in either with sand or with plant ash flux could contaminate the mixture and result in unsuccessful products. This might have affected the choice of raw materials, or it might have led to the development of a cleaning procedure aimed at removing excess NaCl from the raw materials such as washing, sieving, and separating quartz from a sand matrix (Giménez et al., 2017).

The composition of EB may reflect choices in the raw materials selection and production procedure. While bulk analysis of primary EB cakes and pellets are likely the most reliable source of information, analytical data obtained through the analysis of finished EB objects and paint layers can potentially still provide relevant information about the production of EB (e.g., Dariz and Schmid, 2022) or provenance of raw materials (Rodler et al., 2017, 2021; Dariz and Schmid, 2021).

Despite being produced for over a millennium in different environments, EB shows high consistency in its elemental composition; this can be explained by the natural constrains of the cuprorivaite synthesis reaction. It should be noted that most of the analysed cakes/pellets have a significant excess of SiO_2 in comparison with stoichiometric EB (Fig. 2). Comparing composition of experimentally reproduced samples (Fig. 4) with archaeological samples (Fig. 2) it appears that deficiency of SiO_2 led to the formation of a dark grey mass.

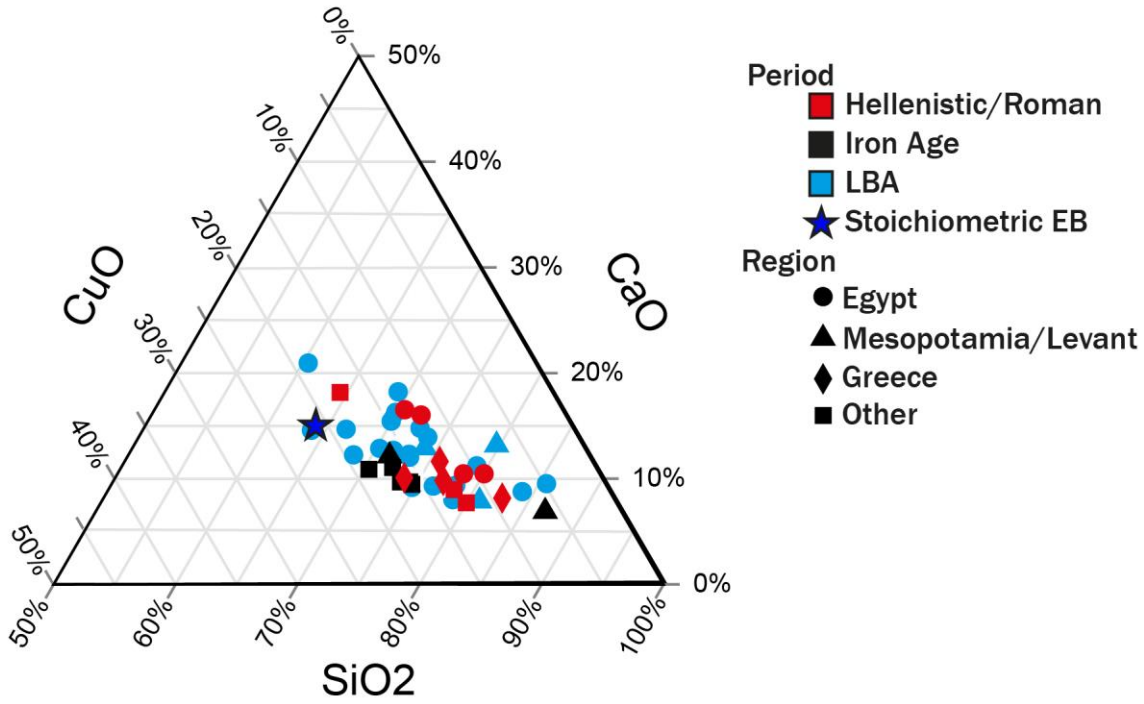


Figure 2. Ternary diagram showing relation between three main constituents of EB in archaeological samples from different periods and sites (bulk analyses of EB fragments; the raw data is in the Supplementary Material a).

The composition and nature of the alkali flux used for EB production might also reflect variability in the production procedure, thus having the potential of helping to differentiate between different production centres and identify diachronic shifts in production recipes. In the archaeological EB samples, the alkali content is represented in the glass phase surrounding cuprorivaite crystals (Jaksch et al., 1983). Correct evaluation of its composition is complicated by the fact that the glass phase is highly subjected to post-depositional changes, and in most cases appears to be partly or completely weathered (Hatton et al., 2008). A direct comparison of glass phase elemental composition in archaeological EB cakes and pellets shows relatively high variation in K_2O content, seemingly reflecting the use of plant ash as a flux (e.g. Hatton, 2005: 64, and see Supplementary Material b).

Furthermore, the grain size and quality of mixing are other important factors that affect the growth of cuprorivaite crystals during firing. This has already been pointed out by Vitruvius who noted that the raw materials should be finely ground and mixed homogeneously (Rowland, 1999: 94), using the word '*farina*', which is usually referring to fine powder or flour (Glare, 2012: 742). The grain size is not defined, but may be assumed to measure in fractions of a mm, as proposed by Hatton et al. (2008). In their study of archaeological EB, Hatton and co-workers identified the use of coarse-grained quartz (>100 µm in length) in the primary stage of production and less homogenous mixing during the Late Bronze Age.

The archaeological evidence indicates distinct traditions within this production step. During LBA primary production, EB was formed in round cakes or rectangular blocks (Weatherhead and Buckley, 1989) reaching diameters or maximum lengths of 15 to 20 cm. Iron Age cakes appear to be smaller, with known examples from the Ayanis fortress (Ingo et al., 2013) forming small rectangular blocks of 65-80 x 35-40 mm and a thickness of 18-22 mm. In contrast, Hellenistic and Roman workshops produced much smaller pellets of pigment in the range of 1-4 cm in diameter, as described by Vitruvius and reported for several sites (e.g., Kostomitsopoulou Marketou et al., 2020; Zerobin et al., 2021). The transition from cakes to pellets may mark a technological innovation or reflect changes in the organization of the EB *chaîne opératoire*; the reason for this change remains unclear and needs further investigation.

Parallel to the bulk composition of EB and the transition from cakes to pellets, traces of specific elements such as the presence of tin can also serve as chronological identifier, as proposed by Jaksch and co-workers

(1983). Tin is not present in EB samples dated before the 18th dynasty, when it appears in most of the available datasets of EB cakes and pellets, likely pointing towards the use of bronze as the source of the copper phase. Moreover, the reported concentration of lead is significantly higher for EB pellets from the Roman period (Fig. 3). This can potentially indicate the use of lead-rich bronze during Roman times; however, this assumption is based on the limited amount of analysed samples and should be tested when more analytical data is available. When the copper source for producing EB was derived from likely highly recycled material such as (lead-rich) bronze, then identifying the provenance of the copper raw material used for producing EB (see *a.*) is challenging (Rodler et al., 2017, 2021).

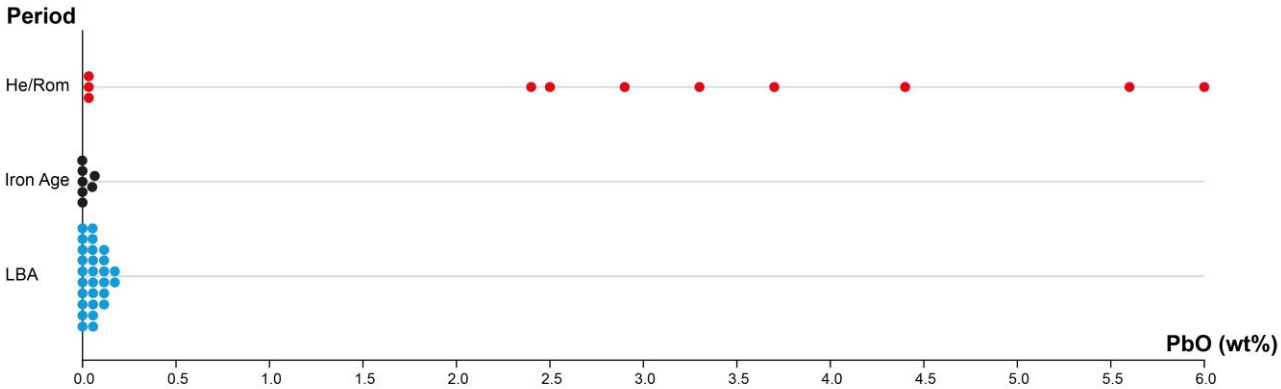


Figure 3. Lead concentration in the archaeological EB pellets and cakes from different periods (n=46). Data sources as cited in the Supplementary Material a.

c. Initial thermal treatment (firing). Based on laboratory reproductions, cuprorivaite forms under moderately reducing conditions in the range of circa 850 to 1000 °C, depending on the initial mixture composition and firing conditions (Mirti et al., 1995). Therefore, successful production required tight temperature control for a period of time sufficient for cuprorivaite formation and crystal growth (Wiedemann and Bayer, 1982).

Bianchetti et al. (2000) observed complete transformation of cuprorivaite into green glass in samples heated to 1050 °C, in line with other reproduction experiments (Chase, 1971; Ullrich, 1987; Riederer, 1997). Even higher temperatures (~1350 °C) led to the formation of a dense grey glassy material (Hatton, 2005: 84). The length of firing also affects the quality of the final product, with EB fired for a longer duration said to be forming smaller and more regular cuprorivaite crystals (Fontana et al., 2020). The exact duration of the firing procedure in the ancient production sites is unknown; Riederer (1997) assumed that it could have ranged from ten to one hundred hours. The correct initial firing would usually produce a coarse-grained dark blue friable material (Tite et al., 1984; Pradell et al., 2006).

The successful production of EB required the use of crucibles. This statement is both supported by Vitruvius and archaeological finds (see section 3). The selection of clay for the crucibles and their overall design were crucial technological choices within the EB *chaîne opératoire*. LBA crucibles recovered from Qantir demonstrate the deliberate selection of a porous calcareous fabric (Vienna System VIII.03) over more common iron-rich Nile silt fabrics (Rehren et al., 2001; Aston et al., 2007: 546). The later Hellenistic/Roman technological style, represented by crucibles unearthed in Memphis, used local Nile silt fabrics with a lime-rich internal parting layer applied on the vessels, unlike the LBA ones (Tite and Hatton, 2007). That technological choice resembles the LBA glass-making practices in Egypt, when the use of Nile silt crucibles with a lime-rich parting layer was common (Turner, 1954; Rehren, 1997; Smirniou and Rehren, 2016; Pusch and Rehren, 2007). At the same time, Roman crucibles from Cumae, investigated by Grifa and co-workers, had no parting layer and were made of CaO-rich clay with volcanic temper (Grifa et al., 2016). The rationale for these particular selections of ceramic material remains unclear, but the choice of lime-rich fabrics is a common feature for all of them which requires further research.

d. Further processing and application. After the initial firing, further processing of EB was required. The material could be ground into a powder, which could be used as a pigment as is, or after a second firing. A second high-temperature treatment (as part of a two-stage firing procedure) produced a lighter, more finely textured quality of EB (Tite et al., 1984; Hatton et al., 2008; Kostomitsopoulou Marketou, 2022). Analytical investigation of EB samples from LBA Mesopotamia showed an excess of silica, which may indicate that during the two-step firing procedure the initial EB batch was diluted with an additional amount of quartz to manipulate the colour of the resulting product (Hatton et al., 2008).

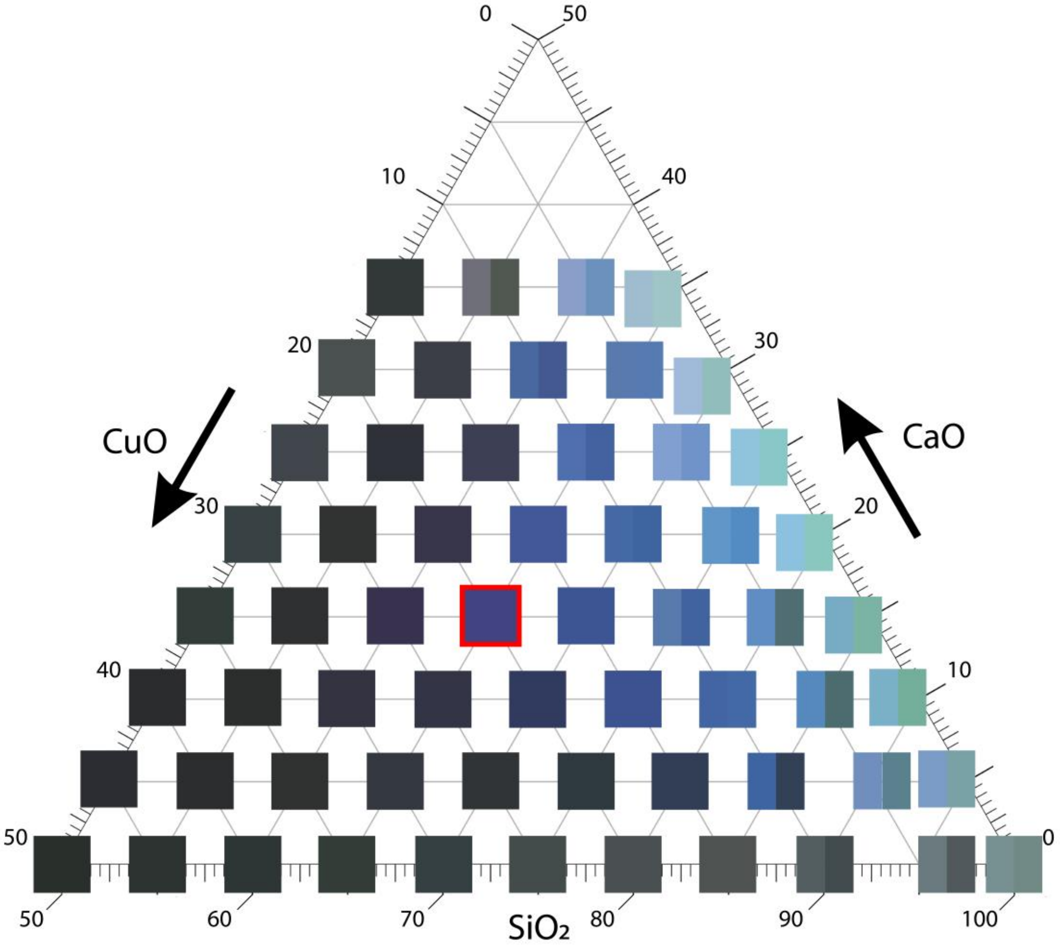


Figure 4. Ternary diagram showing relation between batch composition and the colour of resulting EB after two-stage firing procedure. Stoichiometric EB is marked with red. Initial mixture was fired at 1000 °C for 1 hour; right side of half-plates represents samples fired for a second time at 1100 °C. Modified after Busz and Sengle, 1999.

Another purpose of re-firing was the production of small EB objects such as inlays, beads, scarabs, amulets, etc., as well as vessels or small figurines (e.g., Riederer, 1997; Franzmeier, 2021). For this purpose, the pigment powder was placed in a mould of the required shape and then heated to harden the material (Panagiotaki et al., 2015). In the Roman period, EB was also used to produce mosaics (Tite and Hatton, 2007; Boschetti, 2011). For this purpose, spherical pigment pellets were cut into tesserae (Boschetti, 2011).

In addition to its use for producing small objects, EB was powdered, mixed with binders, and widely used in ancient polychromy to paint artefacts in various media such as sculpture, figurines, reliefs, furniture, sarcophagi, vases, as well as in architecture for wall-painting and architectural elements (e.g., Kakoulli, 2009; Skovmøller et al., 2016; Gasanova et al., 2018). As a pigment, EB was used alone or mixed with other pigments to obtain various hues, e.g., with white pigments such as gypsum or lead white to obtain lighter hues, and with black pigments, particularly carbon black to obtain darker hues (e.g., Fulcher et al., 2021). EB was also used in mixtures with other pigments such as red ochre, organic red lakes, and even shellfish purple to obtain purple nuances (e.g., Dyer et al., 2017; Dyer and Newman, 2020; Brøns, forthcoming), or with yellow ochre or green earth for greens (Siddall, 2006). In fact, EB was used in all sorts of paint mixtures, which by first impression do not appear to include blue, such as for rendering hair, skin, and eyes as well as for shading as attested in Greco-Roman sculpture, for example. These final preparations could be executed at the primary production site, or EB ingots/pellets could be processed at secondary workshops.

4. Archaeological evidence: workshops, cakes, and pellets

The following section compiles published evidence for EB workshops and the finished bulk product. The list is necessarily incomplete, since much information on this material is often unpublished, or might be provided in excavation reports of which we are unaware. Moreover, the initial identification of an 'Egyptian blue workshop' is only rarely based on a consistent, or even defined, set of criteria; this is something we aim to provide through the synopsis of the collated evidence in this paper. For the identification of the bulk raw material produced in the primary workshops we follow established terminology and refer to either 'cakes' or 'pellets', depending on the shape and size of the material; as a more generic term, we also use the word 'ingot', implying its nature as finished material, but not finished shape. Generally, it appears that the Late Bronze Age primary workshops produced rectangular brick-shaped blocks c. 17x17 cm and larger, or round cakes with a diameter of 9-25 cm and 2-3 cm thick (Fig. 5: a, b). The Iron Age workshops produced smaller, roughly rectangular ingots with a size of 6.5-8 x 3.5-4 cm and a thickness of around 2 cm (Fig. 5: c), while the Hellenistic to Roman workshops produced rounded pellets, rarely exceeding 2 to 3 cm in diameter (Fig. 5: d, e).

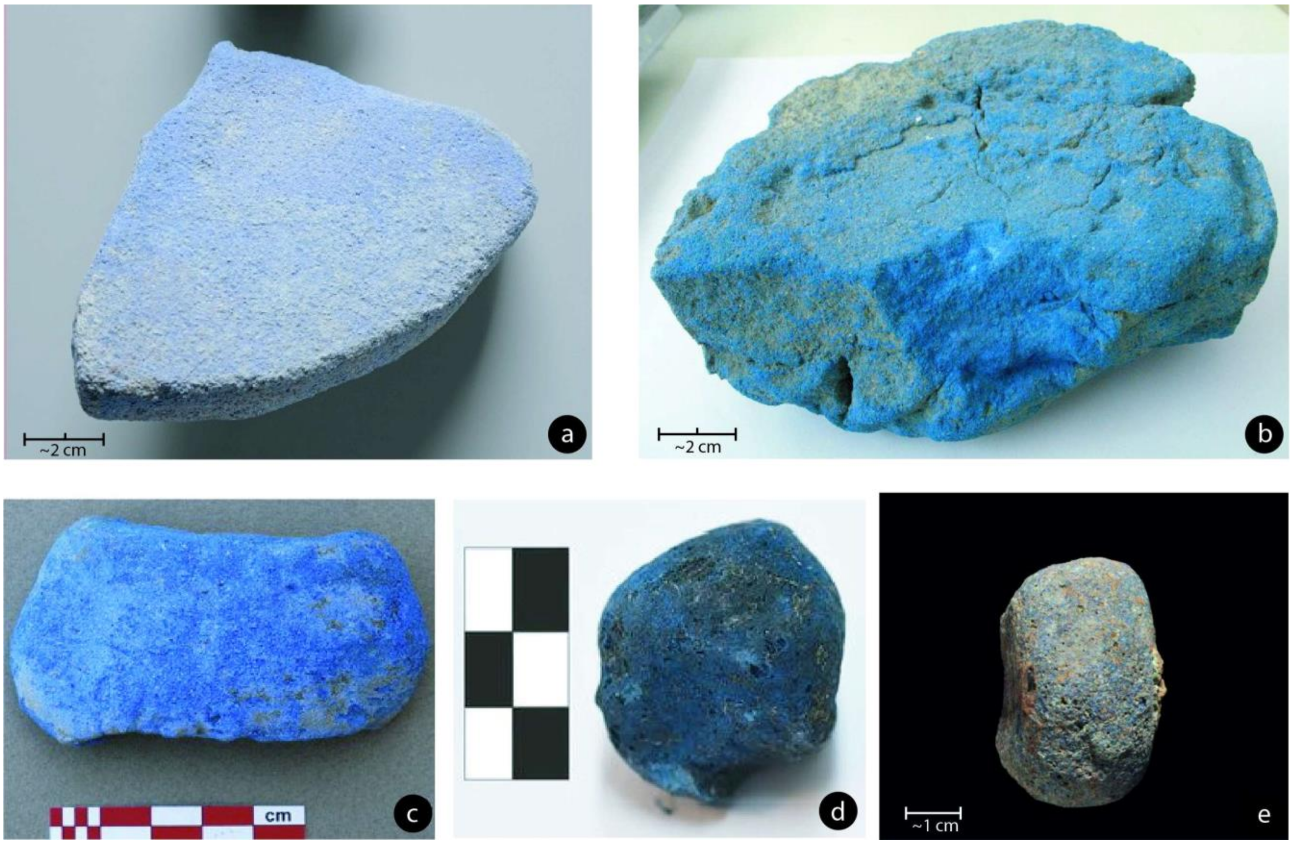


Figure 5. EB cakes and pellets from LBA to Hellenistic and Roman periods. a – flat round cake from Akhmim, 14th century BCE (Staatliche Museen zu Berlin, Ägyptisches Museum und Papyrussammlung, photo: Sandra Steiß, CC BY-NC-SA-4.0); b – bowl-shaped cake from Tel Sera, LBA (Israel Antiquities Authority, IAA: 1992-1208); c – EB cake from Ayanis (photo: from Ingo et al., 2013); d – EB pellet from Kos, Hellenistic period (photo: from Kostomitsopoulou Marketou et al., 2021); e – EB pellet with flattened top and bottom from Naucratis, 6th century BCE (© Dundee City Council, photo: François Leclère, British Museum, CC BY-NC-SA 4.0).

4.1 The Late Bronze Age

Amarna (Egypt). A short-lived capital during the 18th dynasty in the 14th century BCE, Amarna was located on the eastern bank of the Nile in Middle Egypt. Despite the site being occupied only for several decades, its administrative significance during this period led to the rapid development of the settlement, including accompanying industrial activities. Early excavations led by W.M.F. Petrie identified industrial debris associated with glassmaking, such as crucible fragments, frits, fritting pans, glass rods, and glass spills (Petrie, 1894: 25-30). Tens of thousands of faience moulds provide compelling evidence for local production of this material as well. The EB materials recovered from the site include both primary cakes of the pigment and ground powder, indicating both primary and secondary EB working at Amarna. A typology of the primary cakes was suggested by Weatherhead and Buckley (1989), who identified five main shapes: large flat round cakes, large flat rectangular cakes, bowl-shaped cakes, small sack-shaped pieces, and spheres or balls that date to the later Ptolemaic to Roman periods (Weatherhead and Buckley, 1989). The shapes of the cakes derived from the technical pottery used in their production, as is evident in the case of one of the bowl-shaped cakes, which on its underside has an impression of a wheel-mark from a vessel. The sack-shaped pieces have a distinctive shape and bear impressions of cloth and seams (Fig. 6). Weatherhead and Buckley hypothesize that either the ingredients for the primary production were placed in a small bag before firing, or it was the ground pigment placed for second firing and further processing (Weatherhead and Buckley, 1989: 213). Analysing other vitreous industries of Amarna, Shortland (2000) concluded that faience and glass manufacturing were closely connected, with the workshops using the same materials, sharing the same space, and perhaps operated by the same craftspeople (Hatton, 2005: 105; Hodgkinson, 2019:130; Hodgkinson, 2020:86; Nicholson, 2007:157-159; Shortland, 2000). Spatial analysis of finds related to glass-working showed that firing activities performed in domestic context could be connected with both production and processing of vitreous materials and processing of food (Hodgkinson, 2020:102). The question to which extent EB production was also allied to these industries remains open. However, it is worth noting that EB production required a similar set of raw materials and high-temperature treatment as the vitreous industries, therefore a convergence between the two industries seems to be highly likely.

Figure 6. Egyptian blue in shape of a bag. Unknown provenance, probably New Kingdom. Circa 8 x 5 cm, weight 135 g. Egyptian Museum Cairo, no. JE 96788. Photo: Chr. Eckmann, Römisch-Germanisches Zentralmuseum

Qantir/Pi-Ramesses (Egypt). Pi-Ramesses was another new capital of Egypt, established during the 19th Dynasty. Located in the eastern Nile Delta, the site had access to both maritime trade routes of the Mediterranean Sea and land routes into the Levant. Being a centre of political power from the late 13th to the early 11th centuries BCE, Pi-Ramesses accumulated craftspeople of different specialities to serve the court and adorn the new capital (Pusch, 1990; Pusch and Herold, 2005; Prell, 2012). The excavation exposed large-scale high-temperature workshops, producing bronze (Pusch, 1990; 1994) and vitreous materials (Rehren et al., 1998), as well as other workshops processing organic materials, specifically leather and wood. Pottery sherds of a particular lime-rich fabric (Vienna System VIII) with adhering layers of EB have been interpreted as crucible fragments and hence serve as the first evidence of local pigment production (Fig. 7: c, d). In their overview of ceramic fabrics present at the site, Aston and co-workers (2007: 546) noted that EB traces correspond with the particular fabric type VIII.03. Unlike the dominant Nile silt pottery, this one is off-white to lightly reddish in colour, lime-rich, porous, and chaff-tempered. EB crystals appear on the interior surface of the sherds (Fig. 7: a, b), the external side shows slight vitrification, pointing to high-temperature treatment (Aston et al., 2007: 546). Significantly, pottery fabric VIII.03 is rare in the archaeological record and appears almost exclusively in high-temperature workshop contexts.

Figure 7. LBA crucible fragments from Qantir. a – FZ 1998/0206; b – FZ 1998/0778; c and d – ceramic fabric type VIII.03. (Vienna system). Photos: M. Kitti.

Other sites in LBA Egypt. A wooden chest containing pigments was recovered from the courtyard of the tomb of Kheruef (TT192, 18th dynasty), near Thebes. EB materials from the chest include five round cakes (diameter ~18 cm, height ~3 cm), each with two sack-shaped EB pieces attached on their tops and two separate sack-shaped pieces (Thomas, 2000: 69; Weatherhead and Buckley,1989). The texture of sack-shaped EB appeared to be finer than that of the round cakes (Thomas, 2000: 69). Both types of the material appeared to be fused together during the thermal treatment, which hints toward a specific practice of the firing procedure: bags of already fired EB were placed for secondary firing with the initial batch.

Fragments of EB cakes were also found at Zawiyet Umm el-Rakham, a Ramesside fortress located in the western fringe of Egypt (13th century BCE). The pigment finds mainly came from a storage context within the temple area (Thomas, 2000: 20-38). One small pottery sherd with traces of EB was found as well

(Thomas, 2000: 32). However, this find was interpreted as a palette, due to the presence of similar pottery sherds with traces of other pigments (Thomas, 2000: 35-36). A few samples from this site were analysed for their Pb-isotope composition by Hatton (2005) and Shortland (2006), who proposed that copper from outside of Egypt was used in the production process.

Levant and Mesopotamia. Numerous LBA EB cakes were retrieved from other archaeological contexts outside Egypt. A bowl-shaped cake was discovered in Tel Sera in Israel (12th century BCE; Fig. 5: b). Based on its shape and composition it was identified as an import commodity from Amarna (Panagiotaki et al., 2008). The same applies to the cake from a working area at a Temple at Beth Shean (13th century BCE; Panagiotaki et al., 2008). A complete ingot, described as "*an irregular sphere with one almost flat side (17.5 x 15.4 x 14.9 cm)*", was retrieved from Assur (Iraq), dated to the 12th century BCE (Panagiotaki et al., 2008: 1781). According to the authors, unlike the cakes found in Egypt, this example appears to be formed by manipulation rather than acquiring its shape from the pot. A wide assemblage of EB objects including twenty ingots was recovered from Ugarit (14th century BCE) (Matoïan and Bouquillon, 2000). Most of the ingots have an inconsistent shape, apart from one example that is similar in appearance to that from Assur, although smaller in size (Matoïan and Bouquillon, 2000). The number of EB ingots and their context (Royal Palace and South City trench) could indicate that a secondary EB workshop existed in Ugarit, where EB was processed for artistic purposes and worked into final objects. However, most of the published cakes and ingots from the Levant and Mesopotamia were found outside specific workshop contexts, and more likely represent the trade in or storage of the raw material, ready to be used at a later stage. The production origin of these items remains unclear. The analytical investigation of EB samples from Mesopotamia undertaken by Hatton and his colleagues points to independent production of EB in the region, with a high silica content being the most distinguishing feature compared to Egyptian examples (Hatton et al., 2008). The available data is, however, not conclusive (Fig. 2), with similarly quartz-rich EB cakes found also in Egypt. Unfortunately, to date, no archaeological remains of primary EB workshops were identified in Mesopotamia.

Tiryns (Greece). The glass workshop at the Mycenaean citadel of Tiryns can be considered an example of a secondary processing site for EB, tentatively dated to the late 13th century BCE (Panagiotaki et al., 2005). In the absence of evidence of local glass production, the finds of glass waste indicate that the workshop was processing imported raw glass into final products. In addition to glass, one EB piece was recovered, with a spherical shape less than 2 cm in diameter. The attribution of this find is uncertain, and the authors refer to it as an '*ingot-like lump*', bearing resemblance with much later spherical ingots (Panagiotaki et al., 2008). Due to the absence of any evidence of local production, it is assumed that EB was imported and processed in the workshop, together with glass. The social significance of the workshop is highlighted by its location, either in the lower part of the citadel together with bronze and lead working workshops, or in the upper citadel closer to the courtyards (Panagiotaki et al., 2005). Despite this uncertainty, it is evident that the workshop processing artistic materials was organized in close proximity to the palatial complex, the centre of political and religious power, which is comparable to the evidence from the Levant and Mesopotamia.

While the Egyptian LBA sites Amarna and Qantir offer evidence for both primary and secondary EB production and processing, the sites in the Levant, Mesopotamia, and Greece so far only have evidence for secondary EB workshops.

4.2 The Iron Age

The amount of archaeological evidence for EB production remains from the Iron Age is extremely limited. At the same time, the pigment did not fall from use, and finished EB objects appear in various archaeological contexts in the Mediterranean region. One of the few cases implying local production of EB is at Ayanis.

Ayanis (Turkey). Located in eastern Anatolia, the Ayanis fortress was an important centre within the kingdom of Urartu, inhabited for a short period in the 7th century BCE. Remains of pyro-metallurgical tools, slags, and tuyères point toward the existence of local bronze production. Several EB cakes, rectangular in shape, with a size of 6.5-8 x 3.5-4 cm and a thickness of 1.8-2.2 cm, were excavated at this site (Ingo et al., 2013; see above, Fig. 5: c). The unique shape of cakes found in Ayanis, the absence of tin in the studied samples, and the use of mineral alkali sources led Ingo et al. (2013) to suggest local production. Another feature of local EB cakes identified by these authors is the presence of zinc, seemingly corresponding with the composition of locally produced bronze artefacts. Yet, unlike at LBA Amarna or Qantir, no technical ceramic with traces of EB was reported from this site. Leaving the question of local primary production open for further investigation, we can assume that EB cakes were certainly processed in Ayanis, potentially within secondary workshops to be used for artistic purposes. Archaeological excavations revealed walls decorated with blue paint as well as blue-coloured powder residues believed to be EB in the Temple area, in the domestic area, and in parts of the outer city (Ingo et al., 2013; Çilingiroğlu, 2014).

At least seven EB ingots were found in another Urartian fortress, Bastam (7th century BCE), together with blue wall decorations (Kroll, 1988). The size and shape of these ingots seem to be similar to those from Ayanis. EB cakes were also found in the Urartian fortresses Çavuştepe (8th- 7th century BCE) and Van (9th-7th century BCE), located in the east of lake Van. In addition, EB was identified on two fragments of wall paintings, which attests to the local use of EB (Ormanci, 2020). Similar to the evidence from Tiryns, the Levant and Mesopotamia, there is no clear indication of primary EB workshops at these Iron Age sites in Turkey; however, the evidence again matches secondary processing.

Naucratis (Egypt). Located in the western part of the Nile Delta, Naucratis was founded as a Greek colony and became an important riverine port with access to the Mediterranean Sea and a contact point for Hellenic and Egyptian cultures. In 1885, Petrie excavated layers of production debris associated with local faience production and recovered large numbers of finished faience objects (amulets, beads, seals, scarabs) as well as moulds used for their production (Petrie, 1886: 36-38). The workshop that became known as the Scarab factory was operating for a short period between 600 and 570 BCE (Masson, 2018).

Most of the retrieved objects were faience; however, further studies allowed to distinguish a group of EB artefacts (Masson, 2018). Petrie mentioned “twenty lumps of blue paste, evidently kept as raw material; made up much like old-fashioned balls of indigo, rounded with hollowed sides” (Petrie, 1886: 37). Unfortunately, the chemical composition of these raw materials was not specified, but the description matches spherical pellets of EB, widely produced since the Hellenistic period. Several lumps of pigment from Naucratis and similar to the ones described by Petrie are kept in the British Museum (accession numbers E18; E9101; 1975-60(2)). Their dimensions and general appearance are similar to late Hellenistic and Roman pellets. However, unlike them, some of the EB pellets from Naucratis have flattened top and bottom (see above, Fig. 5: e). Was it a deviation in production or rather a development of a new tradition that continued to evolve in the following periods? Unfortunately, the limited number of such finds does not allow to come to a definitive conclusion. Nevertheless, it should be noted that EB materials from Naucratis appear to be different from LBA cakes and bear a closer resemblance with Hellenistic and Roman EB.

Considering the absence of known EB production sites in Egypt after the LBA and before the Hellenistic period, it is tempting to identify Naucratis as a primary production site. However, despite large amounts of EB objects found on site, no crucibles or unsuccessfully produced EB pellets were reported. Therefore, while local production remains a possibility, it is more likely that the Scarab factory of Naucratis operated as a secondary processing workshop. In his excavation report, Petrie also mentioned a vessel with the remains of blue pigment (Petrie, 1886: 38). If the material he referred to was EB, we can see a rare example of the evidence of EB secondary processing before the application. Some moulds from Naucratis bear traces of EB (Masson, 2018), therefore we can conclude that EB pellets were ground, moulded, and then refired to produce small objects at secondary production workshops.

Eastern Mediterranean and Iran. EB ingots were also found at other Iron Age sites in the eastern Mediterranean and Iran. Most of the finds come from palatial contexts. The lack of accompanying finds of crucibles, unsuccessfully produced cakes, or general associations with local high-temperature workshops lead us to interpret these ingots either as trade or storage items, or as markers of secondary processing EB workshops. A fragment of an EB ingot was retrieved from the excavation of a palatial complex in Karkemish in southern Anatolia dated to the Iron Age III (720-550 BCE; Zaina et al., 2019). Based on the presence of platinum in the analysed EB as well as other archaeological and literary evidence, Zaina et al. (2019; and references therein) suggest that the ingot was potentially imported from Egypt and then further processed on-site. Secondary EB workshops also existed in Nimrud in the 9th to 7th centuries BCE (Moorey, 1999; Tite et al., 1984). An amphora containing EB ingots was recovered from the north-west Palace, and a storage room in Fort Shalmaneser also contained EB ingots (Moorey, 1999: 187). An EB ingot of the same period from Nineveh was reported and analysed by Tite and co-workers (Tite et al., 1984).

EB was known in the Achaemenid Empire (550 – 330 BCE), as attested by finds of finished EB objects in its capital Persepolis (Oudbashi and Hessari, 2021). Moreover, a pottery sherd encrusted with EB on its interior surface was found in the Apadana palace (6th century BCE; Matson, 1957). However, in the absence of any other evidence of a high-temperature workshop, it is likely that this pottery sherd belongs to a storage vessel rather than a crucible, marking secondary processing of EB in Persepolis.

These Iron Age contexts in Turkey, Egypt, the eastern Mediterranean, and Iran are not indicative of primary EB production and rather exemplify secondary EB processing. Strikingly, besides Naucratis (Egypt), where primary EB production remains a possibility due to local high-temperature workshops, all identified secondary EB processing sites of the Iron Age are in palatial contexts.

4.3 The Hellenistic to Late Roman period

Kos (Greece). A late Hellenistic production site was discovered in the Aegean island of Kos, dated to the 1st century BCE and located in the central part of the city (Kostomitsopoulou Marketou, 2019, 2020). Here, 138 EB pellets were recovered. This study distinguishes groups of successful, unsuccessful, and semi-successful products based on their colour, ranging from deep blue for successful to grey, green, and brown for unsuccessful ones. Most of the finds have a size of 2-3 cm across (Kostomitsopoulou Marketou, 2019; see above, Fig. 5: d), however, no correlation between the size and quality of EB materials was reported. Apart from EB pellets, lumps of earth pigments and litharge rods were discovered as well, testifying to the broader specialization of this workshop. The coexistence of EB production and metallurgical activities may be supported by several finds, including an EB pellet with an outer layer of corroded silver; a pellet attached to an iron nail, and an unsuccessfully produced pellet adhered to corroded copper material. The presence of metal impurities, including gold, revealed by a further analytical study of EB pellets may be interpreted as contamination from the metallurgic activities performed in the same workshop, while a pottery sherd with ground EB adhering to its interior surface indicates secondary treatment of EB (Kostomitsopoulou Marketou et al., 2020). Besides the Egyptian LBA sites at Amarna and Qantir, this late Hellenistic site can therefore be identified as both a primary and secondary EB production workshop.

Figure 8. Materials from W.M.F. Petrie's excavations in Memphis. a – EB pellets fused together with an overfired ceramic vessel, ÆIN 1185; b – a large fragment of a ceramic vessel with EB crust, possibly a piece of a saggar, ÆIN 1262. 1st century BCE. Courtesy of the Ny Carlsberg Glyptotek. Photos: O. Haupt.

Memphis (Egypt). The early excavations at the site carried out by W.M.F. Petrie brought to light an industrial area at the Kom Helul sector of the city, and several fragments indicative of EB production were donated by Petrie to the Ny Carlsberg Glyptotek, Denmark (Bagh, 2011; Fig. 8: a, b). This work was complemented by later excavations led by P.T. Nicholson (2003; 2013), and ongoing work at the site of Kom Tuman elsewhere in the Memphis area by The Centre for Egyptological Studies of the Russian Academy of Sciences (Belova and Ivanov, 2022). The exact date of the Kom Helul workshop remains uncertain, but it likely belongs to the period between the 3rd century BCE and to or later than the 2nd century CE (Nicholson, 2003). Most of the kilns excavated in the area were attributed to faience production; however, in the Kom Tuman area there is also evidence of primary production of EB. Analysis of pottery remains from the kilns showed a distinctive group of sherds with traces of EB. These objects, similar in size and shape to the cylindrical saggars used for faience firing, were interpreted as crucibles for pigment production. Two types of vessels appeared to be used, convex jars and cylindrical shaped, their insides were lined with a white slip to which a layer of EB adheres in the form of crust and pellets (Hatton, 2005: 151-152). Petrie already assumed that the crucibles were stacked on top of each other inside the kiln and then sealed together with clay (Petrie, 1911). This assumption is based on the presence of EB adhered to the underside of some of the crucible bases and an excessive layer of clay on their rims, as shown by Cavassa (2018). Analysis of crucibles revealed the use of non-calcareous iron-rich Nile silt as the main material for their production (Hatton, 2005: 153; Tite and Hatton, 2007), with a lime-rich white slip layer applied on the interior side of the crucibles. Based on the adhering EB crust, Tite and Hatton (2007) assumed that this layer was meant to separate the final product in the form of EB pellets from contamination from the fabric of the crucibles.

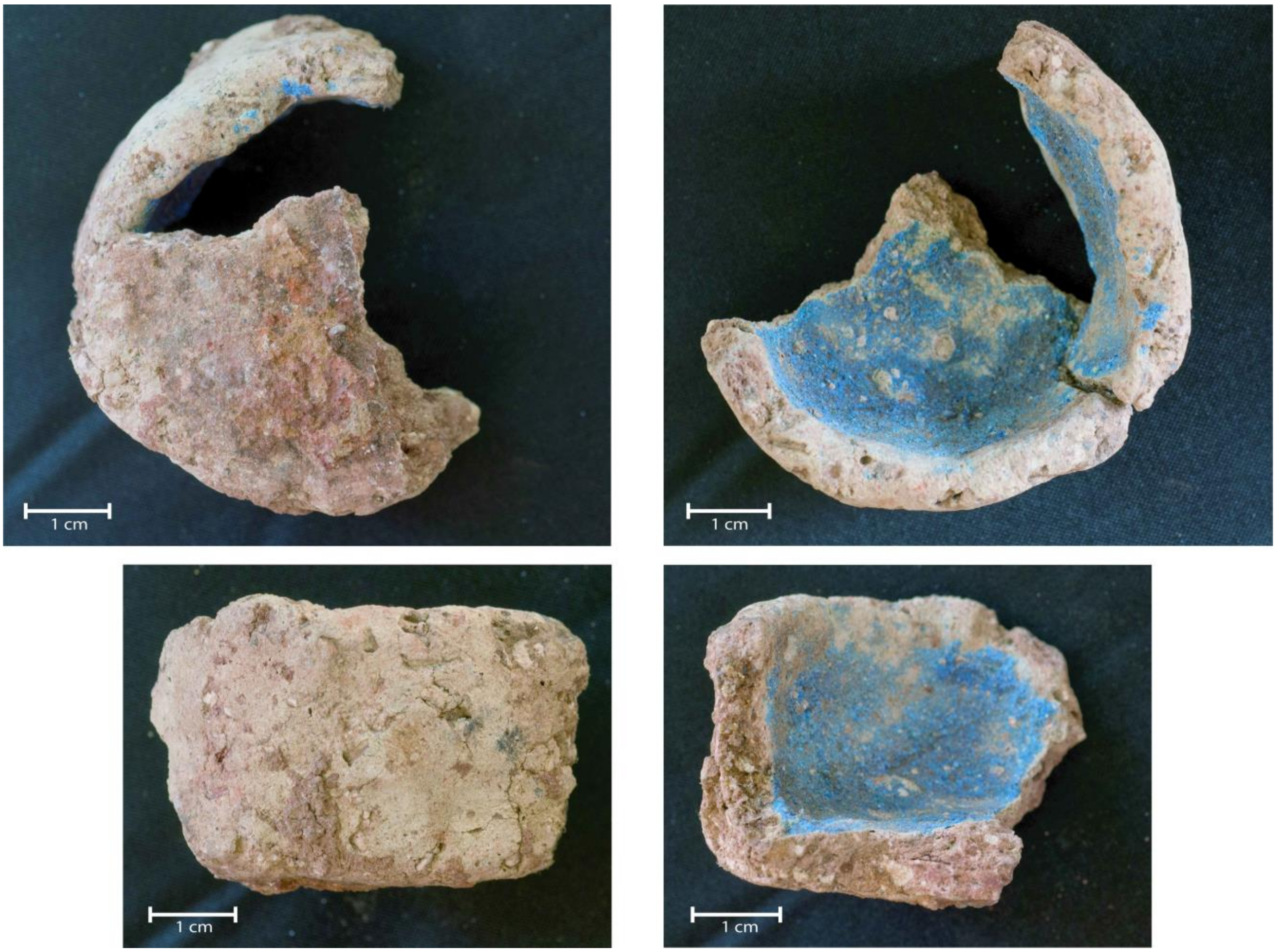


Figure 9. Fragments of a crucible with traces of EB from Memphis, Kom Tuman, 6th - 4th centuries BCE. Photos: S. Ivanov, courtesy of the Centre for Egyptological Studies of the Russian Academy of Sciences.

Puteoli (Italy). While Vitruvius (*De Arch*. 7.11.1) and Pliny (*NH* 33.57) provide us with written evidence of EB production in the Bay of Naples, the archaeological evidence of local workshops is extremely limited. Cavassa et al. (2010) mention excavations from the late 19th century in the assumed location of Vestorius' workshop. According to the excavation record, some pottery pieces with green and blue incrustation were unearthed (Cavassa et al., 2010). Apart from that, no other finds of crucibles or production waste at this site are mentioned. The fact that Puteoli itself was a large port and had strong trade connections with the eastern Mediterranean could explain the transfer of EB production technology to this particular area of Italy (Cavassa et al., 2010). The archaeological evidence is not sufficient for a conclusive identification of Puteoli as a primary EB production site; however, literary evidence and possible finds of crucible remains strongly support such identification.

Cumae (Italy). Archaeological excavation at the site recovered hundreds of crucible fragments covered with blue and green crusts, that later were recognized as Egyptian blue and Egyptian green, respectively (Caputo and Cavassa, 2009). These production wastes, dated to the 1st century CE, were not localized in a specific area of the site, but were unearthed throughout several parts of the ancient city. Two types of crucibles were recognized: closed convex jars (height ~30-40 cm; diameter at the base and rim ~20 cm) and open cylindrical forms (height ~40-50 cm; diameter ~30 cm). The wall thickness of both types is ~2 cm (Grifa et al., 2016; Fig. 10: b). The differences in the shape and composition of the various crucibles can be explained by their use in separate production processes. Both analytical and archaeological evidence showed that closed-form crucibles are associated with Egyptian green production, while open-form crucibles are associated with the production of EB (Grifa et al., 2016). Grifa et al. hypothesize that these two materials could be produced simultaneously by being fired in different sectors of the same kiln, characterized by different temperatures (Grifa et al., 2016). The crucibles with traces of EB serve as major evidence of local primary and/or secondary production. However, the EB workshop(s) was not traced archaeologically yet.

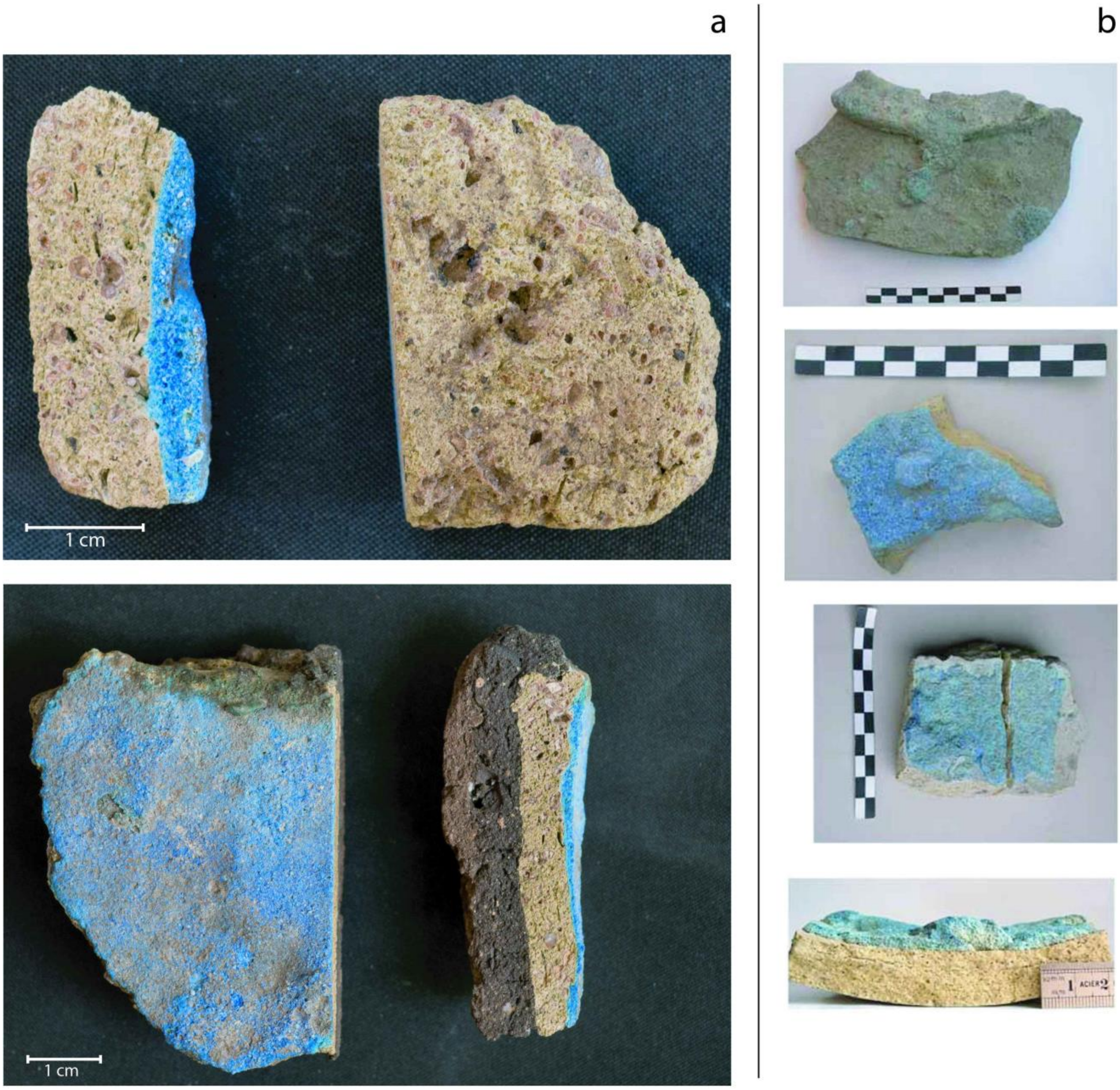


Figure 10. Fragments of crucibles used in EB production. a - crucibles from Memphis, Kom Tuman, 6th - 4th centuries BCE (Photos: S. Ivanov. Courtesy of Centre for Egyptological Studies of the Russian Academy of Sciences.); b – Roman crucibles from Cumae (photos: from Cavassa et al., 2010).

Liternum (Italy). Like Puteoli and Cumae, Liternum is located in the Bay of Naples. Archaeological evidence from this site shows that EB production could have operated there. The excavation revealed an area with a large amounts of kiln wastes, crucibles, and EB pellets (Lazzarini and Verita, 2015). It is assumed that the area, dated no later than the 1st century CE, was used for deposition of production waste from a nearby workshop (Lazzarini and Verita, 2015). A complete crucible was unearthed in the local necropolis, where it was deposited in a child burial. Cavassa et al. (2010) describe the vessel as an open shape with flat bottom and slightly thickened rim. The vessel measures 51 cm in height, 37 cm in diameter at the opening and 39 cm at the base, which is equivalent to a capacity of approximately 50 litres (Cavassa et al., 2010). Unfortunately, just as at Cumae, the EB workshop(s) at Liternum are not yet located and no kilns have so far been recovered. Regardless, a large number of pottery sherds with EB incrustation points to local primary production.

Individual and up to several hundred pellets of EB have been recovered at other Roman sites. However, these usually belong to secondary processing contexts or appear to be trade commodities. Thus, EB pellets are either found together with other pigment pellets (e.g., Zerobin et al., 2021; Berden & Košir, 2021) or as pigments adhering to processing vessels (e.g., Jeschek, 1993) rather than in primary high-temperature workshops, associated with technical crucibles or unsuccessful products.

For example, recently, several hundred EB pellets were excavated at the Roman city Aguntum in East Tyrol, Austria (Zerobin et al., 2021). However, no indications of local primary (or secondary) processing were associated with this find. Another example from a site nearby, at Magdalensberg, Austria, was described as locally produced EB due to its distinctly different oval shape compared to contemporary EB pellets (Delamare and Repoux, 2018). This is comparable to the reasoning by Ingo et al. (2013) for the examples from the Ayanis fortress. However, while high-temperature workshops were located at this site and EB was used abundantly for Roman wall paintings indicating secondary processing, no crucibles with adhering EB were found. These examples for EB pellets excavated in the Roman province of Noricum in the northern periphery are therefore more probably indicators of trade and secondary processing of EB during the 1st to 3rd centuries CE.

The workshops at Kos (Greece) and Memphis (Egypt), on the other hand, both provide conclusive evidence for primary EB production as well as for further secondary processing. This is also indicated for the Italian sites at Puteoli, Cumae, and Liternum, but there, the evidence of primary production is less clear as no workshops have so far been identified.

Figure 11. Overview of known EB production sites and processing workshops. * - Roman examples of secondary processing and/or storage context.

4.4 Medieval period

The use of EB sharply decreased in late Antiquity, even though the pigment did not fall from use completely. Recent studies show a geographically relatively wide application in post-Roman polychromy, for example, in Spain, Italy, Switzerland and Austria, up until the 16th century CE (Bredal-Jørgensen et al., 2011;Dariz and Schmid, 2022; DeVivo et al. 2019; Gaetani et al., 2004; Lluveras et al., 2010; Nicola et al., 2019;). However, all these examples are isolated cases of pigment use rather than evidence of a functioning large-scale industry. Currently, there is no archaeological record of any medieval primary or secondary EB workshops. This fact raises several questions to be addressed in the future.

Does the lack of archaeological evidence for primary and secondary production and the decrease in EB use correspond primarily to a loss of technical knowledge, or does it signify a shifting focus to using other pigments? In the case of later EB occurrences in art, what was the source of the material, was it a small-scale production or the application of old stock by later craftspeople? The re-use of Roman material remains during the early Medieval period is well attested (Freestone, 1992; Freestone, 2015), and abandoned late Roman buildings or storage facilities might have provided at least some of the EB used in early Medieval art and even for the Renaissance paintings, created at a time of extensive excavations of Roman remains in central Italy.

The recently reported mineralogical and chemical composition of EB used for a wall painting from a 5th-6th century CE church in South Tyrol, Northern Italy, indicates that the production comprised raw materials from the northern Phlegrean Fields (Campania, Southern Italy; Dariz and Schmid, 2021). The area of the Phlegrean Fields was also proposed as a source of sand for the EB production in the Bay of Naples (Lazzarini and Verita, 2015; Grifa et al., 2016). This could indicate medieval re-use of EB that was produced in the Bay of Naples during the Roman period. Alternatively, it could indicate continued medieval EB production with raw materials that were already used during the Roman period. However, the currently known medieval examples of EB use indicate neither primary nor secondary EB workshops during this period.

5. Discussion: identification criteria and missing pieces of the puzzle

5.1 Common aspects and chronological differences of EB production

The review of the archaeological and archaeometric literature provides incontrovertible evidence for the primary production of EB during the Bronze Age and Hellenistic to Roman periods, while at least secondary processing is evident for the Iron Age and Medieval periods. The number of known primary production sites includes Qantir and Amarna for the LBA period; possibly Naucratis for the Iron Age, while a few palatial contexts might represent secondary workshops; and Kos, Memphis, and several Roman sites in the Bay of Naples for Hellenistic and Roman periods. A common feature is the presence of crucibles, often with closed forms. Another common characteristic is the flat bottom of most of the production crucibles, and for the Hellenistic and Roman periods, their significant size, with diameter of open-form crucibles reaching 30 cm compared to, e.g., contemporary metal casting crucibles with diameters rarely exceeding 10 cm (see for example: König and Serneels, 2013; Rademakers, 2015: 338; Rehren, 1999)

The production of EB during the LBA bears significant resemblance with other high-temperature industries of that period such as the production of faience, glass, and to a lesser extent bronze metallurgy. The production of vitreous materials shares a common set of raw materials, including quartz, lime, and alkali fluxes. Moreover, finds from Amarna and Qantir show the closely associated production of glass, faience, and EB (Nicholson, 2007:157-159; Petrie, 1894:25-31; Rehren et al., 1997, 2001) with a certain level of interconnection between the workshops. In Qantir, these vitreous workshops are embedded in a large-scale but seemingly short-lived industrial area centred on copper processing, while in Amarna, the workshops were near a large-scale pottery production area. In both cases, one can argue that the management of these industrial areas with their common need for resources such as fuel, clay, copper, water, and labour determined their co-location and perhaps a centralised oversight. While the degree of interconnection between the industries in terms of raw material management remains open for discussion, the hypothesis that workshops did share raw materials or procured them from the same sources is backed with analytical data. For example, the examination of copper that was worked in Qantir and copper of EB cakes from this site show that similar source of metal was used in their production (Shortland, 2006; Rademakers et al., 2017), which might have been imported from the Aegean (Rodler et al., 2017). However, the similarities between identified primary EB and, for example, glass workshops are not limited to the raw materials only. The effective firing temperature for EB is within the range of 850-1000 °C. The working temperatures for LBA glassmaking are in a similar range with around 900 °C for the first melting and 1000 °C and higher for the second melting (Rehren and Pusch, 2005). The requirement of reaching and maintaining such high temperatures for both successful EB and glass production could have promoted knowledge exchange and the application of similar protocols in these industries. Both EB, glass, and copper production required the use of crucibles, although their characteristics vary between these industries (Rehren et al., 1998).

At the same time, for the LBA period, it seems that the location of the EB production sites was likely due to socio-political rather than economic reasons such as the proximity to resources and/or trade routes. For a limited time span, both Qantir and Amarna were established as the central political places, accompanied by a demand for large quantities of artistic materials for major building projects.

In contrast, the Roman sites provide little insight into the organization of production, since no workshops have been identified archaeologically in neither Cumae, Puteoli nor Liternum. The common features of these sites as likely primary production sites are literary evidence, crucibles, and crucible fragments with adhering EB as well as their favourable geographic position, with easy access to trade routes for raw material procurement and subsequent distribution of the product. These later EB primary production sites appear more specialized than the LBA ones, although some of them also coexist with other industries, such as metallurgy on Kos and faience at Memphis.

Details of the secondary processing workshops are more difficult to assess due to the lesser amount of archaeological evidence. The case of Tiryns shows that the artistic processing of EB could take place within a palatial context, also hosting a secondary glass workshop, where similar skills and tools were required. The discovery of a storage room with EB ingots in Nimrud, as well as other finds of EB ingots in palatial contexts, show that EB during the Bronze and Iron Ages was considered a valuable commodity. This shows that EB was stored by the authorities before being processed by craftspeople on-site or close to where it was then used for painting walls, rather than in individual artistic workshops. A relatively large find of EB pellets at the trading city Aguntum in the Roman peripheral province Noricum, north of Italy, also highlights the role of this pigment in ancient trade. Here, neither primary production nor secondary processing of EB are indicated, and the pellets were found in a storage room together with other pigments (Zerobin et al., 2021). Archaeological evidence for secondary production such as vessels with adhering EB or EB used for wall paintings could indicate secondary processing. However, this site might have served for trading EB produced elsewhere for use at yet another site.

5.2 Criteria for the identification and characterization of EB workshops

The amount of archaeological evidence of EB production and processing remains scarce, especially in comparison with the large number of unearthed finished objects and its widespread use in ancient polychromy. Therefore, the correct attribution and interpretation of these materials are crucial. As was shown in the previous paragraphs, not all stages of the *chaîne opératoire* of EB production are represented archaeologically, nor are all periods represented. The main categories of the materials include the crucible remains and EB cakes/pellets of both successfully and unsuccessfully produced examples. Both categories can serve as an indicator of EB production. At the same time, the distinction between production sites and processing workshops should be considered while interpreting these materials.

The current literature follows two main approaches to the identification of the primary production sites. The analytical approach focuses primarily on the chemical composition and the potential raw material origin of the EB cakes/pellets or finished objects, including the characterisation of the glass phase, the relative proportion of cuprorivaite and excess raw materials, respectively, and isotope ratios for specific raw materials. Hence, trace elements, impurities, isotopic abundance ratios, and the character of raw materials become the main criteria (Hatton et al., 2008; Ingo et al., 2013; Rodler et al., 2017; Dariz and Schmid, 2021, 2022). The use of such indirect evidence allows to group finds of EB according to their chemical composition and physical properties, potentially revealing different geographical groups and recipes. This data may be also interpreted as fingerprints of specific workshops, thus allowing tracing the EB imports. However, in many cases, the characteristic glass phase of the recovered EB objects is lost due to weathering, and therefore some of the key analytical data cannot be retrieved (Hatton et al., 2008).

The second approach is based on archaeological evidence. Panagiotaki et al. (2008) showed that the shape of LBA cakes can also be used to trace their origin, and the same argument was used by Ingo et al. (2012), for the Iron Age ingots from Ayanis, and for an approximately 1st century CE EB pellet from a Roman hilltop city in Noricum (Delamare and Repoux, 2018). This approach could potentially be applied to the EB pellets from Naucratis as well. At the same time, the number of excavated cakes/pellets is limited, and they usually are in a poor conservation state, often coming in pieces and therefore complicating their typological attribution. To our knowledge, no systematic study of external attributes for EB has been done so far.

The presence of EB cakes/pellets at a given site provides only indirect information regarding their origin, and might just as well be indicative of transport, storage, or local processing of the pigment. Therefore, we propose to take the presence of crucible fragments as the only type of archaeological material directly involved in the EB production that can be considered a decisive criterion for the identification of a primary EB production site (Cavassa, 2018). Unsuccessfully produced cakes/pellets also have diagnostic value, as it is unlikely that such materials were traded and travelled long distances (Kostomitsopoulou Marketou, 2019). The presence of other high-temperature workshops is not indicative for EB primary production; however, related industries share a certain level of technological knowledge and their presence can therefore be considered an additional criterion.

Secondary workshops would not be expected to have fragments of production crucibles; however, they may have shallow ceramic vessels used to store the pigment, or to mix it with a binder and/or other pigments to obtain the desired hue. Similarly, these workshops can be identified by the presence of other pigments than EB, ready to be applied, either in separate vessels or on colour palettes. Sets of grinding stones to prepare the pigment(s) for application are further indicators of secondary workshops, particularly if they have pigment residues. Here, the sensitive detection of EB through visible-induced luminescence (VIL) photography (Verri, 2009) can assist in the identification of tools that show no traces visible to the naked eye.

Table 1: Criteria for identifying primary and secondary EB workshops

Primary → **Secondary**

Period	Site	Crucibles (fragments)	Unsuccessfully produced EB	HT workshop setting (kilns)	HT tools/waste, industrial debris	Other HT products (glass, metal)	Processing (EB objects, moulds)	Distinct chemical composition *	Distinct shape of EB products	EB on-site consumption	EB in storage/trade context
Late Bronze Age	Amarna (Egypt)	✓		✓	✓	✓			✓		
	Qantir (Egypt)	✓		✓	✓	✓					
	Zawyet Umm El Rakham (Egypt)						✓			✓	✓
	Kheruef tomb, Thebes (Egypt)										✓
	Tel Sera (Israel)								✓		✓
	Beth Shean (Israel)								✓		✓
	Assur (Iraq)								✓		
	Ugarit (Syria)						✓		✓		
	Tiryns (Greece)				✓	✓			✓	✓	
Iron Age	Ayanis (Turkey)				✓	✓		✓	✓	✓	
	Bastam, Çavuştepe, Van (Turkey)							✓	✓	✓	
	Naucratis (Egypt)			✓	✓	✓	✓		✓		
	Karkemish (Turkey)							✓		✓	
	Nimrud (Iraq)									✓	✓
	Niniveh (Iraq)									✓	
	Persepolis (Iran)									✓	
Hellenistic/Roman**	Kos (Greece)		✓	✓	✓	✓		✓		✓	
	Memphis (Egypt)	✓		✓	✓	✓					
	Puteoli (Italy)										
	Cumae (Italy)	✓									
	Liternum (Italy)	✓			✓						✓
	Aguntum (Austria)					✓					✓
	Magdalensberg (Austria)			✓	✓	✓			✓	✓	✓

Notes: Criteria for primary and secondary workshops are listed together with indications for storage and use contexts (e.g., EB on fragments of pigment preparation vessels, EB used for wall paintings or found in storage and trade contexts). All sites follow their sequence of appearance in ***4.***, relevant references are listed there; the Medieval period is omitted here as all currently known examples are for EB used in art; HT = high-temperature; * while shape and workshop environment were usually investigated, the chemical composition was not always analysed; ** the sites included here are not exhaustive of EB pellets found in Roman contexts, only known production workshops and a few examples for most likely secondary workshop contexts in provinces north of Italy are included here.

6. Conclusion, outlook, and future work

EB has received considerable scholarly attention as the first artificially produced inorganic pigment and as one of the few ancient materials whose production technique was described in literary sources. Previous studies have identified large numbers of EB objects and paint layers and proven its wide geographical and chronological use. However, the importance of EB is not limited to the material itself. Being a product of an elaborate pyro-chemical process, EB can serve as a source of information on the technological advances of past societies, their limitations, and their ways to overcome them. Direct evidence of EB production is relatively scarce, and entirely lacking for major periods of EB use such as the Early and Middle Bronze Age or the Medieval period, and for entire regions with known consumption such as the Levant and Mesopotamia. The current study reviewed the existing evidence to identify diagnostic criteria for EB production, detect possible similarities and differences between EB production sites, observe emerging spatial and chronological patterns in EB use, and in the end facilitate a deeper and more comprehensive understanding of the production of the material.

Based on analytical and archaeological data supplemented by comparisons with other high-temperature workshops we propose a *chaîne opératoire* of EB production, distinguishing primary production sites and secondary processing workshops. Not all stages of EB production are equally represented in the archaeological record. The primary archaeological evidence consists of EB cakes/pellets, crucible fragments, terracotta moulds, and possibly remains of raw materials and grinding/carving tools. Among these materials, the finds of EB cakes/pellets present the largest category. However, isolated finds are usually insufficient for further interpretation, since EB cakes and pellets can be associated not only with production, but also with storage or trade contexts and even different stages of EB processing. Introducing additional criteria such as the presence of crucible remains, unsuccessfully produced EB, and adjacent high-temperature workshops producing chemically related materials allow identifying primary production and secondary processing contexts of EB finds.

The current bibliography on EB heavily focuses on the identification of the material in finished objects and paint layers. Enhancing our understanding of the role this material played in the technological repertoire of past societies requires more research effort regarding the production process(es) and organization, both in the field and in the laboratory. It is important to unequivocally recognize technical ceramics linked to EB production, and to accumulate more analytical data on the bulk composition of EB cakes/pellets. Such data may provide first insight into the production site identification and will also reflect possible patterns and temporal changes in the production procedure. Expanding the library of isotopic data will allow the provenancing of raw materials, e.g. through lead isotope analysis to narrow down the potential source of copper. The few published analyses are insufficient to draw conclusions; however, they demonstrate the viability of the analytical approach.

In the current paper, we suggested the presence of EB crucibles as the primary criterion for the identification of primary production. Therefore, the identification of these materials is crucial both *in situ* during ongoing excavation projects and among the archaeological materials excavated in the past. Such identification can be performed by visual examination for traces of EB, which can be enhanced by VIL-imaging, capable of highlighting even minute particles of the material. However, such identification needs to be combined with an assessment of the nature of the ceramics, whether they are crucibles or storage vessels or palettes. In addition to classical typological criteria of vessel identification, this can be enhanced by developing a protocol for the identification of crucibles based on the compositional changes that their fabric underwent during the production of EB. Moreover, approaches for the characterization of EB traces, cakes and pellets include mineralogical/petrographic, elemental and recently also isotopic analysis scaled to the available material and research questions. Ideally, the hierarchy in analytical approaches should begin with *in situ* visual inspection of ‘unusual’, i.e. technical ceramics for traces of EB, supported by VIL-imaging or semi-quantitative *in situ* analysis (e.g., with a portable X-Ray Fluorescence instrument), before samples are collected for analysis by, for example, SEM-EDS or (MC-) ICP-MS.

Archaeological and analytical data show that EB production techniques, recipes, and possibly even workshop organization remained largely consistent from the LBA to late Antiquity, while the crucibles and the shape of the initial product evolved over time. This raises the question of the transfer of technological knowledge over this long period of time and between different regions. However, it also makes observable deviations in the EB *chaîne opératoire* even more significant. Among these deviations are the choices of key raw materials such as the copper source, the flux and the silica source, the shapes of the final EB cakes/pellets, and the use of different crucibles. Understanding the reasons behind these choices and changes is the main challenge for future research.

Acknowledgements

The project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie grant agreement No 956410. Moreover, ASR is grateful to the Austrian Archaeological Institute of the Austrian Academy of Sciences for their support and the project that generated the data for this work has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 845075.

We a very grateful to G. Belova and S. Ivanov (The Centre for Egyptological Studies of the Russian Academy of Sciences) for providing access to the Kom Tuman materials and allowing the use of their photographs (Figs. 9, 10). Additional information was provided by K. Broschat, L. Cavassa, and A. Kostomitsopoulou Marketou to whom we are grateful for their help. This is a publication of the A.G. Leventis Chair in Archaeological Sciences at the Cyprus Institute; the support of the A.G. Leventis Foundation is gratefully acknowledged. None of the funding bodies had any involvement in the content of this publication.

References

Abe, Y., Nakai, I., Takahashi, K., Kawai, N., Yoshimura, S., 2009. On-site analysis of archaeological artifacts excavated from the site on the outcrop at Northwest Saqqara, Egypt, by using a newly developed portable fluorescence spectrometer and diffractometer. Analytical and Bioanalytical Chemistry 395, 1987–1996. https://doi.org/10.1007/s00216-009-3141-x

Aggelakopoulou, E., Bakolas, A., 2022. What were the colors of the Parthenon? Investigation of the entablature's cornice blocks. Journal of Archaeological Science 140, 105553. https://doi.org/10.1016/j.jas.2022.105553

Anselmi, C., Vagnini, M., Seccaroni, C., Azzarelli, M., Frizzi, T., Alberti, R., Falcioni, M., Sgamellotti, A., 2020. Imaging the antique: unexpected Egyptian blue in Raphael's *Galatea* by non-invasive mapping. Rendiconti Lincei. Scienze Fisiche e Naturali 31, 913–917. https://doi.org/10.1007/s12210-020-00960-4

Aston, D.A., Mommsen, H., Mountjoy, P., Pusch, E.B., Rehren, Th., 2007. Die in- und ausländischen Werkstoffe der Grabung Qantir in Wort und Bild. In: Pusch, E.B., Bietak, M. (Eds.), Die Keramik des Grabungsplatzes Q I. Teil 2. Schaber – Scherben – Marken, 513–548.

Bagh, T., 2011. Finds from W.M.F. Petrie's Excavations in Egypt in the Ny Carlsberg Glyptotek. NCG, Copenhagen.

Becker, H. 2021. Technology and Trade. In: D. Wharton (ed.) *A Cultural History of Color in Antiquity*, London – New York: Bloomsbury, 35-48.

Beeston, R.F., Becker, H., 2013. Investigation of ancient Roman pigments by portable X-ray Fluorescence Spectroscopy and Polarized Light Microscopy. In: Armitage, R. A., Burton, J. (Eds.), Archaeological Chemistry VIII (American Chemical Society Symposium Series). Washington, D.C.: American Chemical Society, 19–41.

Belova, G.A., Ivanov, S.V., 2022. Preliminary results of archaeological research conducted by the CES RAS at Kom Tuman (Memphis) in the season 2021. Egypt and neighbouring countries. 3, 1–34. https://doi.org/10.24412/2686-9276-2022-00008

Berden, T., Košir, A., 2021. SEM-EDS elemental analysis of the pigments from Nauportus. Adriatlas 4, 135–144. https://doi.org/10.46608/primaluna8.9782356134073.8

Bianchetti, P., Talarico, F., Vigliano, M.G., Ali, M.F., 2000. Production and characterization of Egyptian blue and Egyptian green frit. Journal of Cultural Heritage 1, 179–188. https://doi.org/10.1016/S1296-2074(00)00165-5

Blet, M., 1994. Analyse d'échantillons de bleu égyptien. Bordeaux III University, Mémoire de Diplôme d'Etudes Approfondies.

Boschetti, C., 2011. Vitreous materials in early mosaics in Italy: faience, Egyptian blue, and glass. Journal of Glass Studies 53, 59–91.

Bradley, L., Ford, J., Kriss, D., Schussler, V., Pozzi, F., Basso, E. and Bruno, L. 2020. Evaluating Multiband Reflectance Image Subtraction for the characterization of indigo in Romano-Egyptian funerary portraits. In: Svoboda, M., Cartwright, C.R. (Eds.), Mummy Portraits of Roman Egypt. Emerging Research from the APPEAR Project. J. Paul Getty Museum, Los Angeles.

Bredal-Jørgensen, J., Sanyova, J., Rask, V., Sargent, M.L., Therkildsen, R.H., 2011. Striking presence of Egyptian blue identified in a painting by Giovanni Battista Benvenuto from 1524. Analytical and Bioanalytical Chemistry 401, 1433–1439. https://doi.org/10.1007/s00216-011-5140-y

Brysbaert, A., 2006. Lapis lazuli in an enigmatic 'purple' pigment from a thirteenth-century BC Greek wall painting. Studies in Conservation 51, 252–266.

Brøns, C., Hedegaard, S.B., Bredal-Jørgensen, J., Buti, D., Pastorelli, G., 2020. The rarest blue: An exceptional find of lapis lazuli in the polychromy of a funerary portrait from ancient Palmyra. Archaeometry 62(3), 506–520. https://doi.org/10.1111/arcm.12533

Busz, R., Sengle, G., 1999. Zur Kieselkeramik - Begriffe, Werkstoffe, Verfahren. In: Busz, R., Gercke, P. (Eds.), Türkis und Azur. Quarzkeramik im Orient und Okzident, Kassel, 192-221.

Caputo, P., Cavassa, L., 2009. La fabrication du bleu egyptien a Cumes. In: Brun, J.-P. (Ed.) Archeologie de l'artisanat antique, Vol. 2, Coll. Centre Jean Berard, 32, Artisanats antiques d'Italie et de Gaule. Melanges offerts a Maria Francesca Buonaiuto, 169–179.

Cavassa, L., 2018. La production du bleu égyptien durant l'époque hellénistique et l'Empire romain (IIIe av. J.-C.-Ier s. apr. J.-C.). In: Jockey, P. (Ed.), Bulletin de Correspondance Hellénique. Supplément. Les Arts de la Couleur en Gréce Ancienne . . . et Ailleurs. Approches Interdisciplinaires, Vol. 56, 13–34.

Cavassa, L., Delamare, F., Repoux, M., 2010. La fabrication du bleu égyptien dans les champs phlégréens (Campanie, Italie) durant le Ier siècle de notre ère. In: Chardron-Picault, P. (Ed.), Aspects de l'arisanat en milieu urbain: Gaule et Occident romain. Revue Archéologique de l'Est, Suppl. 28, 235–249.

Chase, W.Th., 1971. Egyptian blue as a pigment and ceramic material. In: Brill, R.H. (Ed.), Science and Archaeology, Leiden, 80–90.

Çilingiroğlu, A., 2014. Ayanis Kalesi'nde Mısır Mavisi (Egyptian Blue). In: Özfırat, A. (Ed.), SCRIPTA: Essays in Honour of Veli Sevin, A Life Immersed in Archaeology, 137–142.

Clark, R.J.H., Curri, L., Henshaw, G.S., Laganara, C., 1997. Characterization of brown–black and blue pigments in glazed pottery fragments from Castel Fiorentino (Foggia, Italy) by Raman Microscopy, X-Ray Powder Diffractometry and X-Ray Photoelectron Spectroscopy. Journal of Raman Spectroscopy 28(2-3), 105-109.

Colomban, P., 2003. Lapis lazuli as unexpected blue pigment in Iranian Lâjvardina ceramics. Journal of Raman Spectroscopy 34, 420–423. https://doi.org/10.1002/jrs.1014

Corcoran, L.H., 2016. The color blue as an 'animator' in ancient Egyptian art. In: Goldman, R.B. (Ed.), Essays in global color history - interpreting the ancient spectrum; Gorgias studies in classical and late antiquity. Piscataway, USA: Gorgias Press, 41–64.

Daniels, V., Stacey, R., Middleton, A., 2004. The blackening of paint containing Egyptian blue. Studies in Conservation 49, 217–230. https://www.jstor.org/stable/25487699

Dariz, P., Schmid, T., 2021. Trace compounds in Early Medieval Egyptian blue carry information on provenance, manufacture, application, and ageing. Scientific Reports 11, 11296. https://doi.org/10.1038/s41598-021-90759-6

Dariz, P., Schmid, T., 2022. Raman focal point on Roman Egyptian blue elucidates disordered cuprorivaite, green glass phase and trace compounds. Scientific Reports 12, 15596. https://doi.org/10.1038/s41598-022-19923-w

Delamare, F., 2013. Blue pigments: 5000 Years of Art and Industry. Archetype Publications, London.

Delamare, F., Repoux, M., 2018. Compterendu d'analyse d'une boulette bleue provenant de Magdalensberg. Römisches Österreich 41, 43–50.

De Vivo, G.S., Van Loon, A., Noble, P., Hirayama, A., Abe, Y., Nakai, I., Bull, D., 2019. An unusual pigment in 16th century Ferrara: 'Egyptian blue' in Garofalo's *Adoration of the Magi* and Ortolano's *St. Margaret*. In: Christensen, A.H., Jager, A. (Eds.), Trading Paintings and Painter's Materials, 1550-1800. Archetype Publications, 136-148.

Dyer, J., Newman, N., 2020. Multispectral imaging techniques applied to the study of Romano-Egyptian funerary portraits at the British Museum. In: Svoboda, M., Cartwright, C.R. (Eds.), Mummy Portraits of Roman Egypt. Emerging Research from the APPEAR Project. J. Paul Getty Museum, Los Angeles, 54–67.

Dyer, J., Tamburini, D., Sotiropoulou, S., 2018. The identification of lac as a pigment in ancient Greek polychromy - The case of a Hellenistic oinochoe from Canosa di Puglia, Dyes and Pigments 149, 122–132.

Fitz, S.C., 1982. The colored glazes of Neo-Babylonian wall facings. Ceramic Forum International: Berichte der Deutschen Keramischen Gesellschaft, 59, 179–85.

Fontana, R., Baraldi, P., Fedi, M.E., Galeotti, M., Omarini, S., Zannini, P., Striova, J., 2020. Notes on Vestorius' Blue – New findings and investigations. Journal of Cultural Heritage 45, 370–378. https://doi.org/10.1016/j.culher.2020.03.002

Franzmeier, H., 2021. Eine blaue Schönheit: Ein ungewöhnlicher Kelch aus der Ramsesstadt. In: Hoffmann, F., Bayer, C. (Eds.), Up and Down the Nile–ägyptologische Studien für Regine Schulz, Münster, 89–98.

Freestone, I.C., 1992. Theophilus and the composition of medieval glass. MRS Proc. 267, 739–745. https://doi.org/10.1557/PROC-267-739

Freestone, I.C., 2015. The recycling and reuse of Roman glass: analytical approaches. Journal of Glass Studies 57, 29–40.

Freestone, I.C., Ponting, M., Hughes, M.J., 2002. The origins of Byzantine glass from Maroni Petrera, Cyprus. Archaeometry 44, 257–272.

Fulcher, K., Siddall, R., Emmett, T.F., Spencer, N., 2021. Multi-scale characterization of unusual green and blue pigments from the Pharaonic town of Amara West, Nubia. Heritage 4, 2563–2579. https://doi.org/10.3390/heritage4030145

Gaetani, M.C., Santamaria, U., Seccaroni, C., 2004. The use of Egyptian blue and lapis lazuli in the Middle Ages — the wall paintings of the San Saba Church in Rome. Studies in Conservation 49, 13-22.

Gambin, T., Said, S., Sausmekat, M., Yates, P., 2021. Revisiting the Mellieha Bay Wreck: A report of two seasons of survey and excavation (2013-2014). Malta Archaeological Review, 1–18 https://doi.org/10.46651/mar.2021.3

Gasanova, S., Pagès-Camagna, S., Andrioti, M., Hermon, S., 2018. Non-destructive in situ analysis of polychromy on ancient Cypriot sculptures. Archaeol. Anthropol. Sci. 10, 83–95. https://doi.org/10.1007/s12520-016-0340-1

Gettens, R. J., Fitzhugh, E.W. 1993. Azurite and blue verditer. In: Roy A. (Ed.), Artists' Pigments: A Handbook of their History and Characteristics, vol. 2, Washington. D.C.: National Gallery of Art, 23–35.

Giménez, J., Espriu-Gascon, A., Bastos-Arrieta, J., de Pablo, J., 2017. Effect of NaCl on the fabrication of the Egyptian blue pigment. Journal of Archaeological Science: Reports 14, 174–180. https://doi.org/10.1016/j.jasrep.2017.05.055

Glare, P. G., 2012. Oxford Latin Dictionary (Vol. 22012). Oxford.

Grifa, C., Cavassa, L., De Bonis, A., Germinario, C., Guarino, V., Izzo, F., Kakoulli, I., Langella, A., Mercurio, M., Morra, V., 2016. Beyond Vitruvius: new insight in the technology of Egyptian blue and green frits. Journal of the American Ceramic Society 99, 3467–3475.

Hatton, G.D., 2005. The technology of Egyptian blue. Doctoral dissertation, University of Oxford, Oxford, UK.

Hatton, G.D., Shortland, A.J., Tite, M.S., 2008. The production technology of Egyptian blue and green fits from second millennium BC Egypt and Mesopotamia. Journal of Archaeological Science 35, 1591–1604.

Heck, L., 1999. Blaue Pigmentkugeln aus der römischen Villa von Borg: Frühe chemische Industrie auf der Basis des Azuritbergbaus zwischen Mosel und Saar. Metalla (Bochum) 6, 13–40.

Hodgkinson, A.K., 2019. Manufacturing colourful glass objects in New Kingdom Egypt: a spatial and statistical analysis. In: Thavapalan, S., Warburton, D.A. (Eds.), The Value of Colour: Material and Economic Aspects in the Ancient World, 125–176.

Hodgkinson, A.K., 2020. Using spatial analysis for understanding the manufacture and manipulation of Late Bronze Age Egyptian and Ancient Near Eastern glass. In: Hodgkinson, A.K., Tvetmarken, C.L. (Eds.), Approaches to the Analysis of Production Activity at Archaeological Sites, 84–106.

Ingo, G.M., Çilingiroğlu, A., Di Carlo, G., Batmaz, A., De Caro, T., Riccucci, C., Parisi, E., Faraldi, F. 2013. Egyptian blue cakes from the Ayanis fortress (eastern Anatolia, Turkey): micro-chemical and-structural investigations for the identification of manufacturing process and provenance. Journal of Archaeological Science 40, 4283–4290.

Jaksch, H., Seipel, W., Weiner, K.L., Goresy, A.E., 1983. Egyptian blue - cuprorivaite a window to ancient Egyptian technology. Naturwissenschaften 70, 525–535. https://doi.org/10.1007/BF00376668

Jeschek, G., 1993. Einige Überlegungen zu einer geschlossenen keramischen Fundgruppe aus Kalsdorf, Parz. 421/1. Karlsdorfer Kulturberichte der Archäologischen Gesellschaft Karlsdorf 1, 7–9.

Kakoulli, I., 2009. Egyptian blue in Greek painting between 2500 and 50 BCE. In: Shortland, A.J., Freestone, I.C., Rehren, Th. (Eds.), From Mine to Microscope. Advances in the Study of Ancient Technology. Oxbow Books, 79–92. https://www.jstor.org/stable/j.ctt1cd0p5n

Kostomitsopoulou Marketou, A., 2019. The pigment production site of the ancient agora of Kos (Greece): Revisiting the material evidence. THIASOS: Rivista di archeologia e architettura antica 8, 61–80.

Kostomitsopoulou Marketou, A., 2020. A matter of colour: Pigment on late Hellenistic Kos through the material remains of a 1st c. BCE workshop. Doctoral dissertation, University of Oslo, Oslo, Norway.

Kostomitsopoulou Marketou, A., 2022. The materialisation of colour: Reconstructing Egyptian blue manufacture on late Hellenistic Kos. Norwegian Archaeological Review 55(1), 21–37. https://doi.org/10.1080/00293652.2022.2052746

Kostomitsopoulou Marketou, A., Andriulo, F., Steindal, C. and Handberg, S., 2020. Egyptian blue pellets from the first century B.C.E workshop of Kos (Greece): Microanalytical investigation by Optical Microscopy, Scanning Electron Microscopy-X-ray Energy Dispersive Spectroscopy and micro-Raman Spectroscopy. Minerals 10, 1063. https://doi.org/10.3390/min10121063

Kroll, S., 1988. Grabungsbericht. In: Kleiss, W. (Ed.), Bastam II, Ausgrabungen in den urartäischen Anlagen 1977—1978, 75–174.

König, D., Serneels. V., 2013. Roman double-layered crucibles from Autun/France: a petrological and geochemical approach. Journal of Archaeological Science 40, 156-165.

Lazzarini, L., Verità, M., 2015. First evidence for 1st century AD production of Egyptian blue frit in Roman Italy. Journal of Archaeological Science 53, 578–585.

Lluveras, A., Torrents, A., Giráldez, P., Vendrell-Saz, M., 2010. Evidence for the use of Egyptian blue in 11th century mural altarpiece by SEM-EDS, FTIR and SR XRD (church of Sant Pere, Terrassa, Spain). Archaeometry 52, 308–319. https://doi.org/10.1111/j.1475-4754.2009.00481.x

Loschwitz, N., 2012. Cobalt blue pottery painting of the Amarna period. In: Seyfried, F. (Ed.), In the Light of Amarna – 100 Years of the Find of Nefertiti, Petersberg: Imhof, 132–135.

Masson, A., 2018. Scarabs, scaraboids and amulets. In: Villing, A., Bergeron, M., Bourogiannis, G., Johnston, A., Leclère, F., Masson, A. and Thomas, R. (Eds.) 2013–19, Naukratis: Greeks in Egypt. https://www.britishmuseum.org/research/online_research_catalogues/ng/naukratis_greeks_in_egypt/material_culture_of_naukratis/scarabs_scaraboids_and_amulets.aspx

Matoïan, V., Bouquillon, A., 2000. Le «bleu égyptien» à Ras Shamra-Ougarit (Syrie). In: Matthiae, P., Enea, A., Peyronel, L., Pinnock, F. (Eds.), Proceedings of the First International Congress on the Archaeology of the Near East, Rome, May 18th-23rd 1998, 983–1004.

Matoïan, V., Bouquillon, A., 2003. Vitreous materials in Ugarit: new data. In: Potts, T., Roaf M., Stein, D. (Eds.), Culture through Objects: Ancient Near Eastern Studies in Honour of P.R.S. Moorey, Griffith Institute Oxford, 333–346.

Matson, F. R., 1986. Glazed bricks from Babylon—Historical setting and microprobe analyses. In: Kingery, W. D. (Ed.), Technology and Style. Ceramics and Civilization II, 133–56.

Matson, F.R., 1957. Egyptian blue. In: Schmidt, E.F. (Ed.), Persepolis II: Contents of the Treasury and Other Discoveries, OIP 69, University of Chicago Press, Chicago, 133–134.

Mirti, P., Appolonia, L., Casoli, A., Ferrari, R.P., Laurenti, E., Amisano Canesi, A., Chiari, G., 1995. Spectrochemical and structural studies on a Roman sample of Egyptian blue. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy 51, 437–446. https://doi.org/10.1016/0584-8539(94)E0108-M

Moorey, P.R.S., 1999. Ancient Mesopotamian Materials and Industries: the Archaeological Evidence. Eisenbrauns.

Newman, R., 2014. Technology. In: Hartwig, M.K. (Ed.), Oxford Companion to Ancient Egyptian Art, Oxford, England: Wiley-Blackwell, 504-521.

Nicholson, P.T., 2003. New excavations at a Ptolemaic-Roman faience factory at Memphis, Egypt. Annales du 15e Congres de l'Association Internationale pour l'Histoire du Verre. AIHV, 49–52.

Nicholson, P.T., 2007. Brilliant things for Akhenaten: the Production of Glass, Vitreous Materials and Pottery at Amarna site O45.1. Excavation Memoir 80. London: Egypt Exploration Society.

Nicholson, P.T., 2013. Working in Memphis: the production of faience at Roman period Kom Helul. Excavation Memoir 105. Egypt Exploration Society, 2013.

Nicola, M., Seymour, L.M., Aceto, M., Priola, E., Gobetto, R., Masic, A., 2019. Late production of Egyptian blue: synthesis from brass and its characteristics. Archaeol. Anthropol. Sci. 11, 5377–5392. https://doi.org/10.1007/s12520-019-00873-w

Ormanci, O., 2020. Non-destructive characterization of Egyptian blue cakes and wall painting fragments from the east of Lake Van, Turkey. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy 229, 117889. https://doi.org/10.1016/j.saa.2019.117889

Oudbashi, O., Hessari, M., 2021. A “Western” imported technology: An analytical study of the Achaemenid Egyptian blue objects. Journal of Cultural Heritage 47, 246–256. https://doi.org/10.1016/j.culher.2020.11.001

Pagès-Camagna, S., Colinart, S., Coupry, C., 1999. Fabrication processes of archaeological Egyptian blue and green pigments enlightened by Raman microscopy and scanning electron microscopy. Journal of Raman Spectroscopy 30, 313–17. https://doi.org/10.1002/(SICI)1097-4555(199904)30:4<313::AID-JRS381>3.0.CO;2-B

Pagès-Camagna, S. Colinart, S., 2003. The Egyptian green pigment: its manufacturing process and links to Egyptian blue. Archaeometry, 45(4), pp.637-658.

Panagiotaki, M., Papazoglou-Manioudaki, L., Chatzi-Spiliopoulou, G., Andreopoulou-Mangou, E., Maniatis, Y., Tite, M. S., Shortland, A., 2003. A glass workshop at the Mycenaean citadel of Tiryns in Greece. Annales du 16e congrès de l’Association internationale pour l’histoire du verre, AIHV, 14–18.

Panagiotaki, M., Tite, M., Maniatis, Y., 2008. Egyptian blue in Egypt and beyond: the Aegean and the Near East. In: Kousoulis, P., Lazaridis, N. (Eds.), Proceedings of the Tenth International Congress of Egyptologists: University of the Aegean, Rhodes 22-29 May 2008, 1769–1789.

Pastoureau, M., 2018. Blue: The History of a Color, Princeton University Press.

Petrie, W. M. F., 1886. Naucratis. Part I., 1884–5. London

Petrie, W. M. F., 1911. The pottery kilns at Memphis. In: Knobel, E.B., Midgley, W.W., Milne, J.G., Murray, M.A., W.M.F. Petrie, W.M.F. (Eds.), Historical Studies. London: British School of Archaeology in Egypt, Vol 2, 34–37.

Petrie, W.M.F., 1894. Tell el-Amarna. Methuen, London.

Plesters, J., 1993. Ultramarine blue, natural and artificial. In: Roy, A. (Ed.), Artists’ Pigments. A Handbook of their History and Characteristics, Vol. 2. Oxford University Press, 37–66.

Pradell, T., Salvado, N., Hatton, G.D., Tite, M.S., 2006. Physical processes involved in production of the ancient pigment, Egyptian Blue. J American Ceramic Society 89, 1426–1431. https://doi.org/10.1111/j.1551-2916.2005.00904.x

Prell, S., 2012. A glimpse into the workshops of the Chariotry of Qantir-Piramesse. In: Veldmeijer, A.J., Ikram, S. (Eds.), Chasing Chariots. Proceedings of the First International Chariot Conference, 157–174.

Pulak, C., 2008. The Uluburun shipwreck and Late Bronze Age trade. In: Aruz, J., Benzel, K., Evans, J.M. (Eds.), Beyond Babylon. Art, Trade, and Diplomacy in the Second Millennium B.C., New York, 288–310.

Pusch, E.B., 1990. Metallverarbeitende Werkstätten in Qantir/Piramesse-Nord. Ägypten und Levante 1, 75–113.

Pusch, E.B, 1994. Divergierende Verfahren der Metallverarbeitung in Theben und Qantir? Bemerkungen zu Rekonstruktion und Technik. Ägypten und Levante 4, 145–170.

Pusch, E., Herold, A., 2005. Qantir/Pi-Ramesses. In: Bard, K.A. (Ed.), Encyclopedia of the Archaeology of Ancient Egypt. Routledge, 647–649.

Pusch E.B., Rehren, Th., 2007. Hochtemperatur-Technologie in der Ramses-Stadt Rubinglas für den Pharao, Vol 1 and 2, Forschungen in der Ramsesstadt 6, Gerstenberg, Hildesheim.

Rademakers, F., 2015. Into the crucible. Methodological approaches to reconstructing crucible metallurgy, from New Kingdom Egypt to Late Roman Thrace. Doctoral dissertation, University College London, London.

Rademakers, F.W., Rehren, Th., Pernicka, E., 2017. Copper for the Pharaoh: Identifying multiple metal sources for Ramesses’ workshops from bronze and crucible remains. Journal of Archaeological Science 80, 50–73. https://doi.org/10.1016/j.jas.2017.01.017

Radini, A., Tromp, M., Beach, A., Tong, E., Speller, C., McCormick, M., Dudgeon, J.V., Collins, M.J., Rühli, F., Kröger, R., Warinner, C., 2019. Medieval women's early involvement in manuscript production suggested by lapis lazuli identification in dental calculus. Science Advances 5, eaau7126. https://doi.org/10.1126/sciadv.aau7126

Rehren, Th., 1997. Ramesside glass-colouring crucibles. Archaeometry 39, 355–368. https://doi.org/10.1111/j.1475-4754.1997.tb00812.x

Rehren, Th., 1999. Small size, large scale Roman brass production in Germania Inferior. Journal of Archaeological Science 26, 1083-1087.

Rehren, Th., Pusch, E.B., 2005. Late Bronze Age glass production at Qantir-Piramesses, Egypt. Science 308, 1756–1758. https://doi.org/10.1126/science.1110466

Rehren, Th., Pusch, E.B., Herold, A., 1998. Glass coloring works within a copper-centered industrial complex in Late Bronze Age Egypt. In: McCray, P. (Ed.), Ceramics and Civilization, Vol. 8, The Prehistory and History of Glassmaking Technology. American Ceramic Society, Westerville, 227–250.

Rehren, Th., Pusch, E.B., Herold, A., 2001. Qantir-Piramesses and the organisation of the Egyptian glass industry. In: Shortland, A. (Ed.), The Social Context of Technological Change: Egypt and the Near East, 1650-1150 BC, 223–238.

Riederer, J. 1974. Recently identified Egyptian pigments. Archaeometry 16, 102-109.

Riederer, J., 1997. Egyptian blue. In: FitzHugh, E.W. (Ed.), Artists' Pigments: A Handbook of Their History and Characteristics, National Gallery of Art: Washington, DC, USA, Volume 3, 23–46.

Rodler, A.S., Klein, S., Artioli, G., Brøns, C., 2019. Probing the provenance of archaeological glaze colorants: Polychrome faunal reliefs of the Ishtar Gate and the Processional Way of Babylon. Archaeometry 61(4), 837–855. https://doi.org/10.1111/arcm.12455

Rodler, A.S., Artioli, G., Klein, S., Petschick, R., Fink-Jensen, P., Brøns, C., 2017. Provenancing ancient pigments: Lead isotope analyses of the copper compound of Egyptian blue pigments from ancient Mediterranean artefacts. Journal of Archaeological Science: Reports 16, 1–18. https://doi.org/10.1016/j.jasrep.2017.09.008

Rodler, A.S., Matthys, S.M., Brøns, C., Artioli, G., Snoeck, C., Debaille, V., Goderis, S., 2021. Investigating the provenance of Egyptian blue pigments in ancient Roman polychromy. Archeometriai Műhely XVIII/2, 97–108. http://www.ace.hu/am/2021_2/2021_2_tartalom.html

Rowland, I.D., 1999. Vitruvius: The Ten Books of Architecture. Cambridge University Press.

Shortland, A.J., 2000. Vitreous Materials at Amarna: The Production of Glass and Faience in 18th Dynasty Egypt. BAR IS827, Oxford.

Shortland, A.J., 2006. Application of lead isotope analysis to a wide range of Late Bronze Age Egyptian materials. Archaeometry 48, 657–669. https://doi.org/10.1111/j.1475-4754.2006.00279.x

Shortland, A.J., Hope, C.A., Tite, M.S., 2006. Cobalt blue painted pottery from 18th Dynasty Egypt. Geological Society London Special Publications 257, 91–99. https://doi.org/10.1144/GSL.SP.2006.257.01.07

Siddall, R., 2006. Not a day without a line drawn: Pigments and painting techniques of Roman artists. Infocus, 18–31. https://doi.org/10.22443/rms.inf.1.4

Skovmøller, A., Brøns, C., Sargent, M.L., 2016. Egyptian blue: modern myths, ancient realities. Journal of Roman Archaeology 29, 371–387. https://doi.org/10.1017/S1047759400072184

Smirniou, M., Rehren, Th., 2016. The use of technical ceramics in early Egyptian glass-making. Journal of Archaeological Science 67, 52–63. https://doi.org/10.1016/j.jas.2016.01.009

Stos-Gale, Z.A., Gale, N.H., 2009. Metal provenancing using isotopes and the Oxford Archaeological Lead Isotope Database (OXALID). Archaeological and Anthropological Sciences 1, 195–213.

Thavapalan, S., Stenger, J., Snow, C., 2016. Color and meaning in Ancient Mesopotamia: The case of Egyptian Blue. Zeitschrift für Assyriologie und Vorderasiatische Archäologie 106, 198-214. https://doi.org/10.1515/za-2016-0014

Thomas, S., 2000. Aspects of technology and trade in Egypt and the Eastern Mediterranean during the Late Bronze Age. Doctoral dissertation, University of Liverpool, Liverpool.

Tite, M.S., Bimson, M., Cowell, M.R., 1984. Technological examination of Egyptian Blue. Archaeological Chemistry 3, 215–242.

Tite, M.S., Hatton, G.D., 2007. The production technology and trade in Egyptian blue pigment in the Roman world. In: Gosden, C., Hamerow, H., de Jersey, P., Lock, G. (Eds.), Communities and Connections: Essays in Honour of Barry Cunliffe. Oxford University Press, Oxford, 75–92.

Tite, M.S., Shortland, A.J, 2008. Production Technology of Faience and related early Vitreous Products, Oxford University School of Archaeology, Monograph 72.

Turner, W.E.S., 1954. Studies in ancient glass and glassmaking processes: Part 1. Crucibles and melting temperatures employed in ancient Egypt at about I370 BC. Journal of the Society of Glass Technology 38, 436–444

Ullrich, D., 1987. Egyptian blue and green frit: characterization, history and occurrence, synthesis. In: Delamare, F., Hackens, T., Helly, B. (Eds.), Datation-Charactérisation des peintures pariétales et murals. PACT, Ravello, 323–332.

Verri, G., 2009. The spatially resolved characterisation of Egyptian blue, Han blue and Han purple by photo-induced luminescence digital imaging. Analytical and Bioanalytical Chemistry 394, 1011–1021. https://doi.org/10.1007/s00216-009-2693-0

Weatherhead, F., Buckley, A., 1989. Artists' pigments from Amarna. In: Kemp, B. J. (Ed.), Amarna Reports V. Egypt Exploration Society, London, 207–240.

Wiedemann, H.G., Bayer, G., 1982. The bust of Nefertiti. Analytical Chemistry 54, 619–628. https://doi.org/10.1021/ac00241a001

Zaina, F., Baraldi, P., Cardini, V., Cavriani, M., Zannini, P., 2019. Archaeometric characterization of a blue ingot from the Palace of Sargon II at Karkemish (Turkey) and the distribution and function of Egyptian blue in the Near East during the Iron Age. Mesopotamia 54, 181–197.

Zerobin, B., Goldenberg, G., Auer, M., Töchterle, U., Angerer, T., Hejny, C., Tropper, P., 2021. Ägyptisch Blau: Pigmentfunde aus Raum 289 des römischen Municipium Claudium Aguntum. In: Auer, M., Stadler, H. (Eds.), Alpine Landschaftsnutzung im Ager Aguntinus. Wiesbaden: Harrassowitz (= Ager Aguntinus, 5), 183–192. ISBN 978-3-447-11692-3, https://d-nb.info/1247126412