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Metals and pigments at Amara West: Cross-craft perspectives on practices and provisioning in New Kingdom Nubia

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A R T I C L E I N F O

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A B S T R A C T

This paper presents the results of elemental and lead isotopic analysis of copper alloys, copper-based pigments and an extremely rare tin-based alloy from the town of Amara West (Sudan), the centre for pharaonic control of occupied Upper Nubia between 1300 and 1070 BCE. It is the first assemblage of its kind to be analysed for Upper Nubia during this period. This research examines the selection and consumption of alloys in a colonial context, in light of earlier and contemporaneous practices and patterns in both Egypt and Nubia, to assess broader systems of resource management and metal production. Drawing on the complementary information obtained from pigment analysis, novel insights into interactions between different high-temperature crafts are obtained, particularly in terms of shared provisioning systems. From this unique perspective, pigment analysis is used for the first time to illuminate copper sources not reflected in metal assemblages, while scrap copper alloys are identified as a key colourant for Egyptian blue manufacture. The integrated application of strontium isotope analysis further highlights the potential for identifying links between glass, faience and Egyptian blue production systems within Egypt and for distinguishing these from other manufacturing regions such as Mesopotamia. The analysis of a tin artefact further expands our understanding of potential tin sources available during the New Kingdom and their role in shaping copper alloy compositions. Overall, this holistic approach to copper alloys and their application in other high-temperature industries ties together different strands of research, shaping a new understanding of New Kingdom technological practices, supply networks and material stocks circulating throughout the Nile Valley.

1. Introduction

The region of Upper Nubia, referred to as Kush in ancient Egyptian texts, came under the control of the pharaonic state in around 1500 BCE, ushering in over four centuries of colonial rule (Smith, 2021; Valbelle, 2021). Following the conquest, the pharaonic state founded new towns at key locations, notably at Sai (Budka, 2020), Tombos (Smith and Buzon, 2018) and Sesebi (Spence, 2017). These provided a focus for the administration of the region, with the extraction and control of resources – notably gold – being a major driver for this annexation (Fig. 1). Around 1300 BCE, an additional town was established by the pharaonic state at Amara West, halfway between the Second and Third Cataracts and close to Sai, to act as a new centre for the colonial administration and as the seat of the highest pharaonic official based in Upper Nubia, the Deputy of Kush (Spencer, 2017). The town (Fig. 2), located upon an island, comprised an enclosure wall that surrounded a decorated sandstone temple, the residence of the Deputy of Kush as well as storage and production facilities, and housing (Spencer, 2014). Within two to three generations, many of the official buildings were repurposed into additional houses, and further dwellings were constructed outside the town walls. The town's inhabitants were buried in two burial grounds located across the river channel to the north, in tombs marked by pyramids and

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chapels but also by tumuli distinctive of Nubian funerary traditions (Binder, 2017). The town seems to have been abandoned around 1000 BCE, likely prompted by climatic developments including changes to the Nile regime, increased aridification and influx of aeolian sand (Woodward et al., 2017), though the cemeteries remained in use into the 8th century BCE.

The site was originally excavated by the Egypt Exploration Society in the late 1930s and 1940s (Spencer, 1997, 2016), with new fieldwork undertaken by the British Museum's Amara West Research Project between 2008 and 2019. Over five hundred metal artefacts were recovered

Fig. 1. Map of Egypt and Nubia showing key sites mentioned in the text. Underlying map: Claire Thorne, with additions by Johannes Auenmüller.

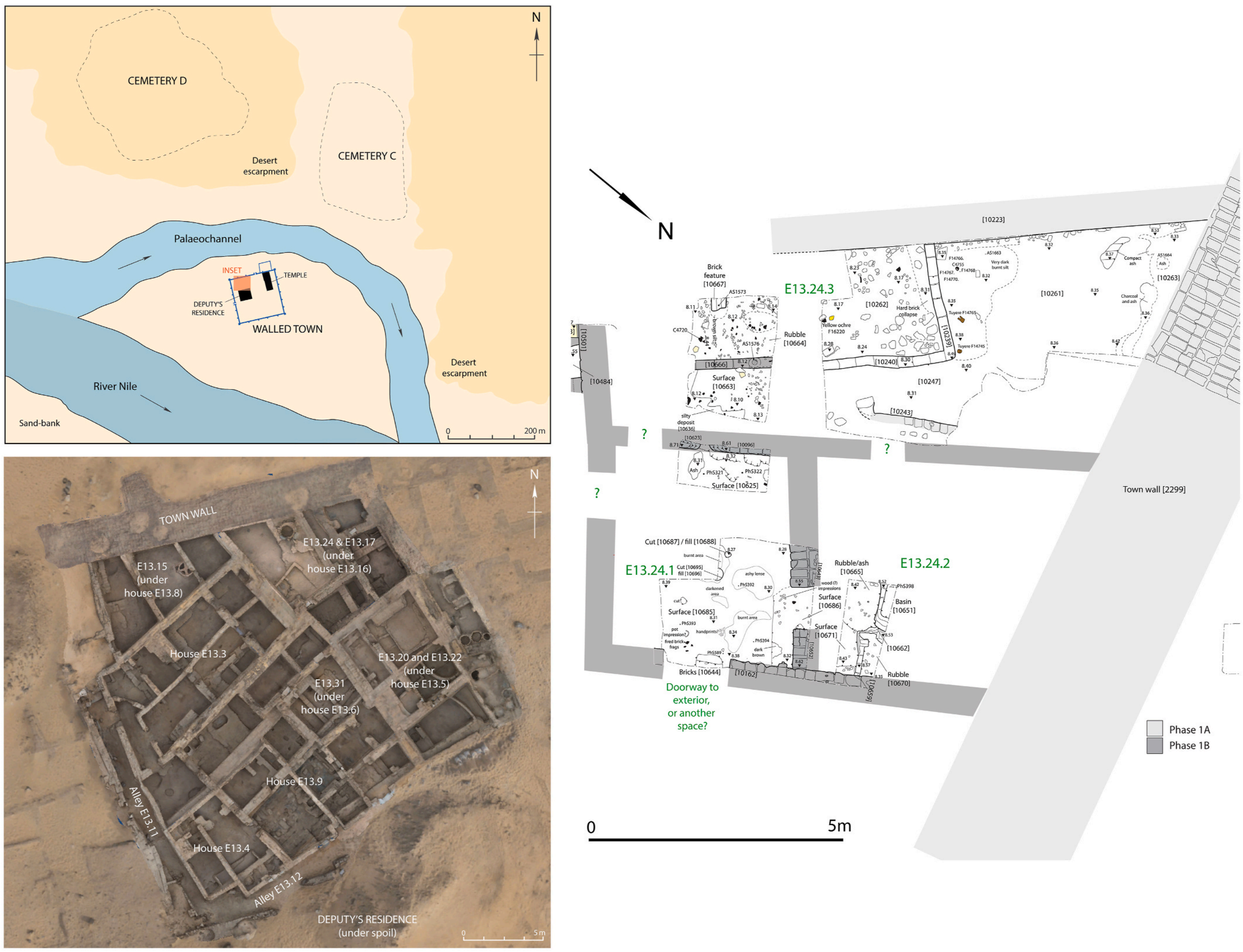

Fig. 2. Map of Amara West with orthophotograph of area E13, highlighting key buildings in which evidence of metalworking was recovered, and (right) plan of metalworking facility E13.24. Map and plan: Neal Spencer; orthophoto: Susie Green and David Fletcher.

in these excavations, including chisels and blades (e.g. Spencer, 2009: p. 55, Pl. 17), siphons, vessels, hooks, nails and pins, mirrors (e.g. Binder, 2017: p. 598, Fig. 7), jewellery, such as rings and bracelets (e.g. Spencer, 2014: p. 478, Pl. 23), tweezers and applicators (e.g. Binder, 2017: p. 604, Fig. 15) as well as fittings from statues and ceremonial objects (e.g. Binder, 2017: p. 605, Fig. 16).[1] These were found in occupation deposits within houses, storage facilities and production/workshop spaces, in rubbish and abandonment layers, or placed with burials in the cemeteries.

In area E13, between the Deputy's Residence and the town wall, a facility for the production of metal artefacts was identified (E13.24, Fig. 2). In operation by phase 1B (c. 1250–1210 BCE, Table 1), thus very early in the history of the town, the building comprised a first room (E13.24.1) with hard earthen surfaces, fireplaces and vessel emplacements, giving access to two further spaces. A small room (E13.24.2) to the east was only partly excavated, revealing two mud-plaster basins. The other – much larger and likely open-air – space (E13.24.3) had a small area defined by thin brick walls, in which significant concentrations of crucible and tuyère fragments, production waste, and broken pieces of metal objects were found, alongside fragments from a series of plaster trays bearing impressions of linen fabric. An adjacent building to the west (E13.15, Fig. 2), though not directly accessible from E13.24, provided a space for another high-temperature industry, with a kiln for pottery production (Spencer, 2017: pp. 343–349). Building E13.24 was then renovated with new internal walls, creating a new building (E13.17), in which further examples of artefacts and materials related to metal production were found, along with a cluster of clay seals bearing stamped impressions. The latter suggests the careful control of materials, tools or other goods, but it is not clear whether the other artefacts from E13.17 reflect the continued use of the space for metallurgy, or rather represent residual material from E13.24, though several large kilns/ovens were present in the space.

Amara West offers the potential to explore how resource access, high-temperature production processes and material consumption played out within a pharaonic colonial town in Upper Nubia, and whether that was consistent with contemporaneous practice and patterns in Egypt itself, informed by the evidence from Pi-Ramesse/Qantir and Tell el-Amarna, or indeed at Aniba in Lower Nubia. A complete overview of metal artefacts from Amara West, the archaeological contexts of their production and further scientific analyses of production materials and waste will be part of future publications. The present paper reports on the use of elemental and isotopic analysis of selected metal artefacts (Fig. 3) and copper-based pigments (Egyptian blue and

[1] Description, photographs, and drawings of all metal objects found during the British Museum excavations, and details of their provenance, are available at https://amara-west.researchspace.org/[accessed July 2022].

Table 1
Occupational phases at Amara West, with key buildings related to sample analysis.

Phase	Dates (approximate)	Equivalence with pharaonic chronology	Key buildings (earliest phase occupied) related to article and samples
0	Natural island	–	
1A	1300–1250 BCE	Early Dynasty 19	Town wall, construction and decoration of temple and Deputy's Residence; pottery production in E13.15
1B	1250–1210 BCE	Early – mid Dynasty 19	Facilities E13.14 (magazines and production?); E13.24 (metal production)
2A	1210–1180 BCE	Late Dynasty 19 – early Dynasty 20	Houses E13.7 and E13.8; workshop E13.31 and open space E13.22; production area E13.17
2B			Area E13.20
3A	1180–1140 BCE	Early – mid Dynasty 20	House E13.16
3B			Houses E13.4, E13.6, E13.9
4	1140–1100 BCE	Mid – late Dynasty 20	
5	1100–1000 BCE	Late Dynasty 20 and after	

atacamite; Fig. 4) to explore technological practices as well as supply networks and the material stock available to both craftspeople and consumers at Amara West.

2. Materials and methods

This paper discusses the analysis of twenty-three copper alloy, one tin, one atacamite and five Egyptian blue samples from Amara West (Table 2). Six artefacts found during Egypt Exploration Society excavations (1938-9, 1947–1950, Spencer, 1997), and now housed in the British Museum, were sampled. The remainder of samples derives from fieldwork undertaken by the British Museum Amara West Research Project (2008–2019), generously lent to the British Museum by the National Corporation for Antiquities and Museums (Sudan) for scientific analysis. None of the artefacts or samples come from the production spaces (E13.17 and E13.24): the production waste will be considered in future publications. Rather, this study assesses the evidence from metal objects in circulation in the town, found in houses, storage facilities, workshops, and surface deposits; it was not possible to export artefacts from the tombs for analyses.

Metallic core material was sampled from all metal artefacts using a clean 1 mm drill bit or a rotary cutting tool following the mechanical removal of surface corrosion. Prior to sampling, the presence of core metal in the artefacts was evaluated using radiography to define sampling locations. Nonetheless, out of the twenty-three copper alloy samples, four were only partially metallic with varying corrosion products and one was fully corroded (cf. Table 2). The tin artefact was completely corroded as well. The Egyptian blue and atacamite samples were homogenised and powdered using an agate mortar.

Metal and pigment samples were fully dissolved following a high-temperature acid digestion procedure. One aliquot was retained for elemental analysis using ICP-OES (Inductively Coupled Plasma-Optical Emission Spectroscopy), while a second aliquot was used for lead isolation and subsequent lead isotopic (LI) analysis using MC-ICP-MS (Multi-Collector Inductively Coupled Plasma-Mass Spectrometry). ICP-OES results have a precision and accuracy better than 5% for the reported elements (bias up to 20% for silver and gold). Lowered analytical totals for Egyptian blue and atacamite samples reflect their important hydroxide, chloride, and silicate bulk fraction. All elemental concentrations are expressed in weight percent (%) or μg/g (and presented as non-normalised results in Table 3). Precision for LI ratios (presented in Table 4) after correction for mass bias are better than 0.03% for ratios involving ^{204}Pb. All plots involving LI ratios are presented with 2SD error bars. Full details of laboratory procedures for sample preparation,[2] elemental and LI analysis are provided by Rademakers et al. (2020).

A third aliquot of the digested Egyptian blue samples was retained for strontium isotopic analysis (following the methodology described by Blomme et al., 2017; Ganio et al., 2012; the precision accompanying the ^{87}Sr/^{86}Sr isotope ratios is better than 0.005%), reported in Table 5. While it would have been desirable also to determine the neodymium isotopic composition of the Egyptian blue, reflective of its silica source, sample volumes were too small and neodymium concentrations too low to permit this.

3. Results

The results of the analyses are discussed separately below for each material category: atacamite, copper alloys, tin, and Egyptian blue. Atacamite represents a natural material, which may have been mechanically treated but which has not undergone any high-temperature processes distorting its composition with respect to its original geological formation. Copper alloys, however, have undergone at least two stages of metallurgical treatment: primary smelting, whereby raw copper is extracted from copper ore, and secondary metallurgy, whereby the base metal is melted and may have been alloyed with an additional component such as arsenic, tin and/or lead. Beyond this, metal may have been repeatedly re-melted, alloyed and mixed with other metal components and alloys over time before being deposited in its final archaeological context. These processes strongly affect the final composition of the artefacts and need to be considered when comparisons are made to geological and artefact reference data. Here, comparisons are based on the currently available knowledge of ancient Egyptian smelting and alloying processes, as outlined by Rademakers et al. (2017, 2021a, 2021b, and references therein). Similarly, metallurgical operations should be accounted for when considering the composition of tin metal artefacts.

3.1. Atacamite pigment

The green pigment (F17309) was identified as an atacamite ($Cu_2Cl(OH)_3$) type mineral by Fulcher et al. (2021a).[3] Its elemental composition is broadly similar to that of (mixed) malachite and (clino)atacamite ores exploited during the Old Kingdom (c. 2700–2195 BCE) and Middle Kingdom (2035–1680 BCE) in Sinai (Rademakers et al., 2021b) and other exploited copper ores from Sinai and the Eastern Desert characterised by Abdel-Motelib et al. (2012) and Pfeiffer (2013). However, its arsenic and tin concentrations are tenfold higher than those in previously characterised Sinai ores and its antimony concentration is relatively high too. Its lead concentration is low at 45 μg/g, but within the common range for Sinai and Eastern Desert copper ores. The measured concentration of ca. 400 μg/g niobium is noteworthy and may point to the formation of this mineral in a particular geological environment.[4] However, it is not possible to locate this based on currently available reference data.

[2] Contrary to the copper alloys and pigments, the tin sample was directly dissolved in a 1M HNO_3 solution.

[3] F17309 is referred to as sample PS118 by Fulcher et al. (2021a): identification by Optical Microscopy, FTIR (Fourier Transformed Infra-Red Spectroscopy) and SEM-EDS (Scanning Electron Microscopy – Energy Dispersive Spectroscopy) analysis.

[4] Niobium is commonly associated with tantalum (and tin) in mineralisations, and is found with alkali granite magmatism in the Egyptian Nubian Shield (e.g. at Wadi Abu Dabbab, Wadi Nuweibi, Igla, El-Muelha, Nugrus, Umm Naggat, and Abu Rushied in the Eastern Desert; cf. Abdalla et al., 2008; Hamimi et al., 2020; Obeid et al., 2001; Said, 1990). It has not been previously reported as a trace element in atacamite minerals. Tantalum could not be detected in this sample (DL ca. 10 μg/g).

Fig. 3. Selection of analysed artefacts. Photographs: British Museum Amara West Research Project. © The Trustees of the British Museum, shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence

The lead isotope (LI) ratios for the atacamite sample (Fig. 5) fall in the broader range of Sinai copper ores, although they do not match exactly with any deposit characterised so far, particularly in terms of the uranogenic ratios ($^{206\text{-}207}Pb/^{204}Pb$). The latter may favour an origin in the southern Sinai mining regions (Wadi el-Regeita, Sheikh Mukhsen) rather than the mines surrounding Umm Bogma. $^{206\text{-}207}Pb/^{204}Pb$ ratios for Egyptian Eastern Desert copper ores analysed by Abdel-Motelib et al. (2012) are mostly lower.[5] The Amara West atacamite may fall along a trend line of Eastern Desert copper ore LI ratios (for which more limited data is available, cf. Rademakers et al., 2021a) and one could wonder if the particular trace element concentrations are reflective of Nubian Eastern Desert copper deposits hitherto not characterised. Based on currently available reference data, a Sinai provenance appears most likely. The relatively higher $^{208}Pb/^{204}Pb$ ratio also strongly favours Sinai over Timna as a possible mining origin. The atacamite pigment LI ratios fall in the range of the Amara West (cf. below) as well as earlier Egyptian and Kerma copper alloy LI ratios (cf. Rademakers et al., 2022 and references therein).

3.2. Copper alloys

The copper alloy artefacts were confirmed by analysis to be tin bronzes, with tin concentrations following an approximately normal distribution varying between ca. 1% and 15% and averaging ca. 7%. Overall, the elemental composition of the Amara West alloys (Fig. 6) is very similar to that of New Kingdom (c. 1550–1070 BCE) alloys from Tell el-Amarna (Stos-Gale et al., 1995a), Aniba (Odler and Kmošek, 2020), Pi-Ramesse (Rademakers et al., 2017) and artefacts from various other New Kingdom sites currently under study by the authors. The most pronounced difference compared to other assemblages is a higher average concentration of cobalt and lower average concentrations of manganese and especially zinc.

Thirteen samples have lead concentrations below 0.2%. Lead concentrations in the remaining ten samples vary evenly between 0.2% and 1.3%. These lead concentrations do not appear to correlate to any other element concentration, nor to LI ratios. Arsenic concentrations are normally distributed around ca. 0.4%, with one outlier (F7303). Arsenic concentrations weakly correlate to antimony concentrations and exhibit no relation to tin or lead concentrations. F7303 has ca. 1.1% arsenic, 0.1% antimony (outlier in the assemblage), 1.3% iron (high) and 3.8% tin (relatively low). Gold and silver concentrations vary between ca. 10–250 μg/g and correlate quite well (ignoring outliers EA86287, F5932 and F7674 with gold or silver concentrations up to ca. 500 μg/g). These trace element patterns are mirrored in the New Kingdom assemblages of Aniba, Tell el-Amarna and Pi-Ramesse (Fig. 6).

There is a strong overlap in the elemental compositions of New Kingdom copper alloys and Middle Kingdom and Middle Kerma copper alloys in terms of their trace element concentrations, while an obvious discrepancy exists in terms of the alloying agents arsenic and tin: as discussed in Rademakers et al. (2021b, 2022), tin makes a gradual appearance during the Middle Kingdom and Middle Kerma periods in the Nile Valley.[6] Furthermore, it is noteworthy that lead concentrations for the Amara West assemblage, as for other New Kingdom assemblages, are on average higher than those of Old and Middle Kingdom (Rademakers et al., 2018b, 2021b) and of Middle Kerma (Rademakers et al., 2022) copper alloys, although some lead concentrations reported for C-Group artefacts from Aniba fall within a similar range (Odler and Kmošek, 2020).

Beyond elemental compositions, the LI ratios for the Amara West copper alloys can be considered. It is important to bear in mind that the LI ratios for copper alloy artefacts (especially those with low lead concentrations, such as F5633A, F6116 and F14607: all ca. 100 μg/g) may have been affected by contamination occurring during primary (Rademakers et al., 2020) and/or secondary metallurgical operations (Rademakers et al., 2017, 2018b, 2021a, 2021b). As such, direct comparisons to ore LI ratio data should be undertaken very carefully, and preference is given here to artefact comparisons as a means to characterise local or regional metal stocks at different periods. Combining information from

[5] It is emphasised here that the two Eastern Desert copper ore samples analysed by Abdel-Motelib et al. (2012) from Ayn Soukhna reflect ores mined in Sinai and smelted at Ayn Soukhna (cf. Rademakers et al., 2021b).

[6] Although much earlier attestations can be noted, e.g. from Abydos (Cowell, 1987) and Buto (Pernicka and Schleiter, 1997) – see footnote 28 in Rademakers et al. (2021b).

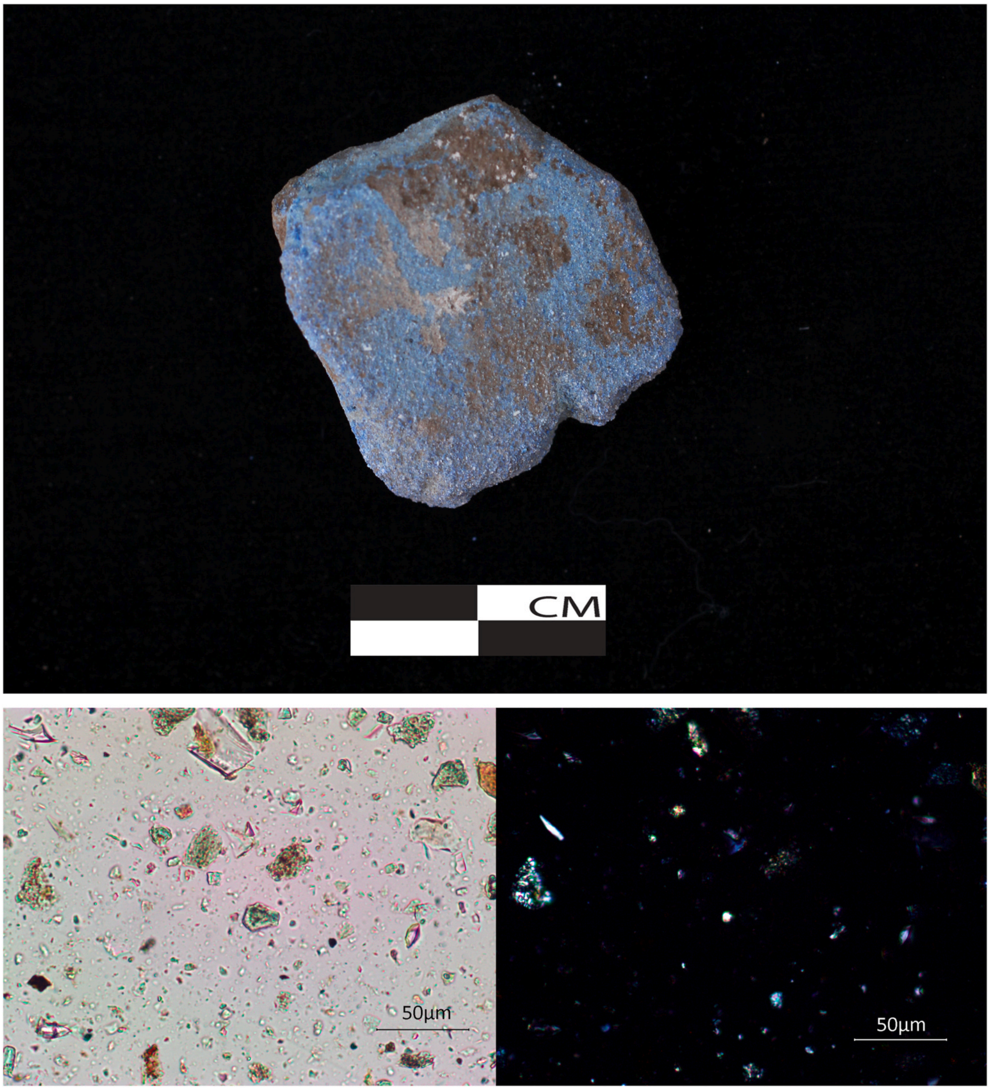

Fig. 4. Top: Lump of Egyptian blue pigment (F7353). Photograph: British Museum Amara West Research Project. Bottom: micrograph of atacamite translucent green crystals (F17309) in plane-polarised (left) and cross-polarised (right) light (Fulcher et al., 2021). © The Trustees of the British Museum, shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mining, smelting and secondary workshop practices with copper alloy compositional data from this perspective enables the development of a more nuanced understanding of copper provisioning in the Nile Valley over time.

The Amara West copper alloys cover a relatively wide LI ratio range (Figs. 7–8). The major group (fifteen out of twenty-three artefacts) has LI ratios overlapping with those of Middle Kingdom copper alloys and production waste from Sinai (Rademakers et al., 2021b) and Kerma Period alloys (Rademakers et al., 2022), as well as some of the "Intermediate copper" identified at Pi-Ramesse (Rademakers et al., 2017).

Only two (F6722 and F14607) overlap directly with the most prolific cluster of copper alloys (in terms of LI ratios) identified at Pi-Ramesse and interpreted as circulating, "Domestic" copper by Rademakers et al. (2017), with counterparts in Tell el-Amarna copper alloys, and Egyptian blue and "green frit" from Zawiyet Umm El-Rakham (Shortland, 2006). Both have relatively low lead concentrations, but their elemental compositions are not distinct relative to the Amara West assemblage on the whole. By contrast, six/seven out of fifteen analysed New Kingdom alloys from Aniba are consistent with the Pi-Ramesse "Domestic" group[7] (while four/five are consistent with the "Intermediate copper" group at Pi-Ramesse and Amara West's major group noted above).

Finally, six of the Amara West copper alloys fall outside of the range attested by Middle Kingdom and Kerma Period artefacts (except for the Middle Kerma copper needle KV736: Rademakers et al., 2022). Five of these (F5932 [Phase 3A/o], F7578, F5999, F7641 [Phase 2B/o], and

[7] One of these Aniba copper alloys (the disk ÄMUL 2171) is almost indistinguishable from Amara West copper alloy F6722 in terms of LI ratios (with highly similar elemental composition), while copper alloy ÄMUL 2146 (which might date to the Second Intermediate Period) has LI ratios identical to those of Amara West Egyptian blue sample F7353.

Table 2
Summary of sampled artefacts. Phase refers to the architectural and stratigraphic phasing of the urban area, with suffix "/o" designating an occupation deposit, "/a" an abandonment layer. (EB = Egyptian blue).

Lab number	British Museum number	Excavation number	Artefact type	Building	Context	Phase	Date	Sample weight (g)	Sample type
SL_1	–	F7530	Small piece of raw pigment - Egyptian Blue	E13.16.2	5583	3B/o	c.1180–1140 BCE	0.0997	Powdered pigment
SL_2	–	F7537	Small piece of raw pigment - Egyptian Blue	E13.16.2	5583	3B/o	c.1180–1140 BCE	0.1001	Powdered pigment
SL_3	–	F7353	Piece of raw pigment - Egyptian Blue	E13.7.8	5702	2B/o	c.1210–1180 BCE	0.1029	Powdered pigment
SL_4	–	F5273	Small piece of raw pigment - Egyptian Blue	E13.7.8	4762	2B/o	c.1210–1180 BCE	0.0991	Powdered pigment
SL_5	–	F17315	Lump of raw pigment - Egyptian Blue	E13.6.3	5301	3B/o	c.1180–1140 BCE	0.1035	Powdered pigment
SL_6	–	F17309	Very small fragment of raw pigment - Atacamite	E13.14.1	5365	1B/o	c.1250–1210 BCE	0.0046	Powdered pigment
SL_14	–	F4464	Tin(-lead) ring	E13.4.1	4526	3B/o	c.1180–1140 BCE	0.0294	Fragment, fully corroded
SL_7	EA86281	–	Copper alloy tool/ implement	D14.7	–	3A/o-4/o	c.1300–1000 BCE	0.0301	Metallic sample, cut sample, surface corrosion removed
SL_8	EA86284	–	Copper alloy bobbin	West of town, surface, AW 789	–	?	c.1180–1000 BCE	0.0198	Metallic sample, drilled core material
SL_9	EA86285	–	Copper alloy tool/ implement	N/A	–	?	c.1300–1000 BCE	0.0523	Strongly corroded, thin slices of metal remaining within grey corrosion product
SL_10	EA86287	–	Copper alloy tool/ implement	N/A	–	?	c.1300–1000 BCE	0.0300	Strongly corroded, thin slices of metal remaining within grey corrosion product
SL_11	EA86293	–	Copper alloy tool/ implement	N/A	–	?	c.1300–1000 BCE	0.0181	Metallic sample, cut sample, surface corrosion removed
SL_12	EA87258	–	Copper alloy vessel	Surface, redim	–	?	c.1300–1000 BCE	0.0313	Metallic sample, cut sample, surface corrosion removed
SL_13	–	F2752	Copper alloy chisel	E13.20.5	10411	2B/o	c.1210–1180 BCE	0.0442	Metallic sample, drilled core material
SL_15	–	F5535	Copper alloy fragment (vessel?)	E13.28	4949	1B/o	c.1250–1210 BCE	0.0542	Metallic sample, drilled core material
SL_16	–	F5609	Copper alloy pin	E13.8.3	4673	2B/ 0–5/a	c.1210–1000 BCE	0.0470	Metallic sample, drilled core material
SL_17	–	F5633A	Copper alloy uraeus	E13.8.3	4673	2B/ 0–5/a	c.1210–1000 BCE	0.0737	Metallic sample, cut sample, surface corrosion removed
SL_18	–	F5633B	Copper alloy uraeus tail (separate piece)	E13.8.3	4673	2B/ 0–5/a	c.1210–1000 BCE	0.0505	Metallic sample, cut sample, surface corrosion removed
SL_19	–	F6116	Copper alloy chisel	E13.31.11	5345	3A/o	c.1180–1140 BCE	0.0442	Metallic sample, drilled core material
SL_20	–	F6414	Copper alloy pin	E13.31.2	5334	2B/o	c.1210–1180 BCE	0.0515	Partially metallic sample, significant corrosion (mostly grey), drilled core material
SL_21	–	F6447	Copper alloy tool/ implement	E13.31.3	5339	2B/o	c.1210–1180 BCE	0.0550	Metallic sample, drilled core material
SL_22	–	F6722	Copper alloy pin/ needle	E13.11	10700	3A/o-4/o	c.1180–1100 BCE	0.0452	Metallic sample, drilled core material
SL_23	–	F7303	Copper alloy blade	E13.9.9	4109	3A/o	c.1180–1140 BCE	0.0697	Metallic sample, drilled core material
SL_24	–	F7578	Copper alloy pin	E13.20.5	10339	2B/o	c.1210–1180 BCE	0.0479	Metallic sample, drilled core material
SL_25	–	F7674	Copper alloy chisel	E13.22.5	10414	2A/o	c.1210–1180 BCE	0.0486	Metallic sample, drilled core material
SL_26	–	F7681	Copper alloy pin	E13.22.5	10414	2A/o	c.1210–1180 BCE	0.0547	Cuprite core sample (square section), cut sample, surface corrosion removed
SL_27	–	F14607	Copper alloy rods/ fitting	E13.26	10204	3A/o	c.1180–1140 BCE	0.0417	Metallic sample, cut sample, surface corrosion removed
SL_28	–	F5999	Copper alloy chisel	E13.31.3	5339	2B/o	c.1210–1180 BCE	0.0573	Metallic sample, drilled core material
SL_29	–	F5932	Copper alloy pin	E13.31.2	5318	3A/o	c.1180–1140 BCE	0.1242	Metal and cuprite core sample (square section), cut sample, surface corrosion removed
SL_30	–	F7641	Copper alloy pin	E13.20.5	10347	2B/o	c.1180–1140 BCE	0.0670	Metallic sample, cut sample, surface corrosion removed

Table 3
Element concentrations for sampled artefacts (all in µg/g, except for Cu and Ca in wt%; * in µg/g; EB = Egyptian blue).

Lab number	Museum or excavation number	Artefact type	Cu (%)	Ag	As	Au	Bi	Co	Fe	Mn	Ni	P	Pb	S	Sb	Se	Sn	Te	Zn	Totals
SL_1	F7530	Small piece of raw EB	8.3	<8	<40	<8	<80	10	1600	25	16	610	65	1600	<40	<16	5500	<40	17	15.5
SL_2	F7537	Small piece of raw EB	7.8	<8	45	<8	<80	8	1800	35	30	650	105	880	<40	<16	5400	<40	20	14.3
SL_3	F7353	Piece of raw EB	8.0	<8	90	<8	<80	5	2800	35	870	1100	260	740	<40	<16	5800	<40	24	16.0
SL_4	F5273	Small piece of raw EB	8.2	<8	75	<8	<80	6	3200	50	18	720	45	860	<40	<16	5000	<40	15	15.9
SL_5	F17315	Lump of raw EB	7.1	<8	200	<8	<80	18	2600	35	170	630	230	3400	<40	<16	2900	<40	30	16.5
SL_6	F17309	Very small atacamite fragment	27.5	12	1300	<8	<80	150	22000	390	110	1400	45	830	75	22	340	100	110	37.2
SL_14	F4464	Tin(-lead) ring	230*	<8	55	<8	<80	3	1300	50	<4	210	6500	230	<40	<16	68000	<40	7	9.1
SL_7	EA86281	Copper alloy tool/implement	81.2	100	4100	25	<80	135	3400	2	240	<40	1700	170	290	<16	70000	140	270	89.3
SL_8	EA86284	Copper alloy bobbin	86.3	230	2800	210	<80	100	210	<1	330	<40	8300	1100	225	25	34000	145	21	91.0
SL_9	EA86285	Copper alloy tool/implement	76.3	160	3000	90	<80	170	650	20	540	730	7500	180	260	50	101000	140	95	87.8
SL_10	EA86287	Copper alloy tool/implement	70.8	240	690	40	170	105	5300	4	460	130	6100	7400	105	25	80000	125	50	80.9
SL_11	EA86293	Copper alloy tool/implement	83.3	125	6200	75	<80	220	3400	2	310	<40	4100	800	410	35	51000	145	320	90.0
SL_12	EA87258	Copper alloy vessel	68.8	60	2600	35	<80	180	580	12	210	310	440	700	80	55	128000	125	40	82.2
SL_13	F2752	Copper alloy chisel	85.2	115	5400	45	<80	200	1400	8	370	140	1300	800	225	60	71000	190	15	93.3
SL_15	F5535	Copper alloy fragment (vessel?)	87.9	75	2600	60	<80	520	21000	10	270	50	840	3100	100	50	13000	125	25	92.1
SL_16	F5609	Copper alloy pin	86.9	135	4200	55	<80	360	330	2	340	<40	850	1600	105	55	36000	180	19	91.3
SL_17	F5633A	Copper alloy uraeus	81.7	60	4200	10	<80	700	9100	7	520	40	110	1300	420	75	27000	125	30	86.1
SL_18	F5633B	Copper alloy uraeus tail (separate piece)	69.1	80	2700	50	<80	40	1400	30	370	160	640	1200	135	50	60000	140	30	75.8
SL_19	F6116	Copper alloy chisel	79.7	40	3400	10	105	145	910	8	220	130	75	1700	45	35	123000	170	14	92.7
SL_20	F6414	Copper alloy pin	73.3	120	5300	70	85	500	3400	2	260	110	1400	2900	150	65	92000	180	25	84.0
SL_21	F6447	Copper alloy tool/implement	73.2	120	3400	45	<80	230	1200	14	340	85	8700	1500	180	45	87000	140	19	83.5
SL_22	F6722	Copper alloy pin/needle	84.4	50	2600	11	130	130	220	1	650	<40	500	790	140	40	39000	145	17	88.8
SL_23	F7303	Copper alloy blade	80.8	55	11000	10	<80	200	13000	25	740	180	1900	1600	1000	80	38000	120	35	87.6
SL_24	F7578	Copper alloy pin	72.7	160	3500	95	<80	190	1500	9	380	150	3700	1900	290	65	100000	170	18	84.0
SL_25	F7674	Copper alloy chisel	84.6	210	4300	300	<80	135	1700	8	320	<40	1700	790	210	65	71000	145	11	92.7
SL_26	F7681	Copper alloy pin	60.0	120	5200	100	<80	360	7900	70	610	360	11500	3700	340	60	67000	135	23	69.8
SL_27	F14607	Copper alloy rods/fitting	62.6	40	4000	10	<80	580	740	15	460	360	140	1000	310	30	149000	110	21	78.3
SL_28	F5999	Copper alloy chisel	78.3	150	3900	125	<80	190	1100	10	380	50	6200	1800	320	45	95000	140	10	89.2
SL_29	F5932	Copper alloy pin	54.5	130	3000	300	130	270	7100	9	290	740	12600	2300	250	70	81000	125	35	65.3
SL_30	F7641	Copper alloy pin	72.3	100	2700	65	<80	160	670	8	350	105	4300	1800	370	45	61000	120	11	79.5

Lab number	Museum or excavation number	**Artefact type**	Al	B	Ba	Ca (%)	Cr	K	Mg	Na	Nb	Sr	Ti
SL_1	F7530	Small piece of raw EB	2500	20	18	5.2	15	960	2600	3100	<40	500	220
SL_2	F7537	Small piece of raw EB	2600	8	17	4.7	24	1300	1400	3000	<40	470	250
SL_3	F7353	Piece of raw EB	4100	<8	30	5.4	22	1800	3100	3800	<40	540	360
SL_4	F5273	Small piece of raw EB	4700	15	35	5.4	23	1600	1800	3600	45	550	430
SL_5	F17315	Lump of raw EB	3300	13	20	6.8	35	1900	4800	4800	<40	610	320
SL_6	F17309	Very small atacamite fragment	25400	600	175	2.1	85	5100	8600	5800	390	200	3800
SL_14	F4464	Tin(-lead) ring	3100	<8	35	5900	12	900	3100	1100		70	280

Table 4
Pb isotope ratios for sampled artefacts (EB = Egyptian blue).

Lab number	Museum or excavation number	Artefact type	206Pb/ 204 Pb	207Pb/ 204 Pb	208Pb/ 204 Pb	207Pb/ 206 Pb	208Pb/ 206 Pb	SD 206Pb/ 204 Pb	SD 207Pb/ 204 Pb	SD 208Pb/ 204 Pb	SD 207Pb/ 206 Pb	SD 208Pb/ 206 Pb
SL_1	F7530	Small piece of raw EB	18.664	15.692	38.767	0.84075	2.07705	0.001	0.002	0.004	0.00003	0.00007
SL_2	F7537	Small piece of raw EB	18.623	15.684	38.724	0.84221	2.07936	0.002	0.002	0.005	0.00005	0.00010
SL_3	F7353	Piece of raw EB	18.885	15.704	38.960	0.83158	2.06305	0.002	0.001	0.004	0.00003	0.00007
SL_4	F5273	Small piece of raw EB	18.538	15.679	38.616	0.84578	2.08304	0.002	0.002	0.004	0.00003	0.00008
SL_5	F17315	Lump of raw EB	18.503	15.687	38.606	0.84782	2.08643	0.002	0.002	0.004	0.00002	0.00006
SL_6	F17309	Very small atacamite fragment	18.611	15.641	38.687	0.84038	2.07865	0.003	0.002	0.005	0.00002	0.00008
SL_14	F4464	Tin(-lead) ring	18.372	15.658	38.503	0.85230	2.09578	0.004	0.003	0.008	0.00004	0.00011
SL_7	EA86281	Copper alloy tool/implement	18.583	15.655	38.807	0.84241	2.08826	0.005	0.005	0.011	0.00006	0.00017
SL_8	EA86284	Copper alloy bobbin	18.552	15.647	38.666	0.84341	2.08419	0.005	0.004	0.010	0.00006	0.00013
SL_9	EA86285	Copper alloy tool/implement	18.621	15.683	38.806	0.84222	2.08401	0.003	0.003	0.006	0.00004	0.00008
SL_10	EA86287	Copper alloy tool/implement	18.402	15.659	38.588	0.85095	2.09700	0.003	0.002	0.006	0.00004	0.00009
SL_11	EA86293	Copper alloy tool/implement	18.487	15.639	38.468	0.84598	2.08086	0.003	0.002	0.006	0.00005	0.00009
SL_12	EA87258	Copper alloy vessel	17.943	15.586	37.885	0.86865	2.11147	0.002	0.002	0.004	0.00003	0.00008
SL_13	F2752	Copper alloy chisel	18.604	15.687	38.708	0.84320	2.08060	0.002	0.002	0.004	0.00003	0.00006
SL_15	F5535	Copper alloy fragment (vessel?)	18.694	15.665	38.841	0.83798	2.07766	0.003	0.003	0.007	0.00004	0.00008
SL_16	F5609	Copper alloy pin	18.474	15.645	38.465	0.84689	2.08215	0.002	0.002	0.005	0.00002	0.00007
SL_17	F5633A	Copper alloy uraeus	18.478	15.634	38.446	0.84610	2.08061	0.003	0.003	0.006	0.00003	0.00008
SL_18	F5633B	Copper alloy uraeus tail (separate piece)	18.707	15.685	38.902	0.83845	2.07956	0.002	0.001	0.004	0.00003	0.00007
SL_19	F6116	Copper alloy chisel	18.725	15.649	38.699	0.83576	2.06674	0.002	0.002	0.005	0.00003	0.00006
SL_20	F6414	Copper alloy pin	18.498	15.679	38.596	0.84761	2.08645	0.002	0.001	0.003	0.00002	0.00006
SL_21	F6447	Copper alloy tool/implement	18.592	15.680	38.754	0.84339	2.08449	0.003	0.002	0.006	0.00004	0.00009
SL_22	F6722	Copper alloy pin/needle	18.867	15.700	38.942	0.83213	2.06398	0.002	0.001	0.004	0.00003	0.00008
SL_23	F7303	Copper alloy blade	18.827	15.701	38.914	0.83397	2.06701	0.002	0.002	0.005	0.00006	0.00010
SL_24	F7578	Copper alloy pin	18.209	15.675	38.342	0.86084	2.10571	0.002	0.002	0.004	0.00003	0.00007
SL_25	F7674	Copper alloy chisel	18.275	15.676	38.401	0.85778	2.10128	0.002	0.002	0.004	0.00003	0.00008
SL_26	F7681	Copper alloy pin	18.600	15.691	38.706	0.84361	2.08097	0.002	0.001	0.004	0.00002	0.00006
SL_27	F14607	Copper alloy rods/fitting	18.882	15.688	38.914	0.83087	2.06096	0.003	0.002	0.006	0.00003	0.00006
SL_28	F5999	Copper alloy chisel	18.215	15.671	38.338	0.86032	2.10469	0.002	0.002	0.005	0.00004	0.00008
SL_29	F5932	Copper alloy pin	18.274	15.671	38.373	0.85750	2.09982	0.003	0.003	0.007	0.00003	0.00008
SL_30	F7641	Copper alloy pin	18.115	15.667	38.238	0.86488	2.11086	0.002	0.002	0.004	0.00004	0.00009

F7674 [Phase 2A/o]) cluster together[8] and overlap with LI ratios for Old and Middle Kingdom production waste (ore, slag, and raw copper: Rademakers et al., 2021b) and other raw copper from Sinai (Pfeiffer, 2013), as well as Timna copper ores. F5932, a pin, has the highest lead concentration in the assemblage (ca. 1.3%), while the other four contain 0.2–0.6% lead. Their elemental composition is otherwise average compared to the rest of the assemblage (except for relatively higher gold and silver concentrations). This group is similar to a tin-bronze dagger (1987_0512) from Pi-Ramesse with a lead concentration of 0.3%, interpreted as an "Intermediate copper" type rather than Wadi Arabah copper (even if the latter may be a constituent of "Intermediate copper", cf. discussion below). Two of the New Kingdom Aniba copper alloys

[8] F7578 and F5999 are indistinguishable in terms of LI ratios and elemental composition. F7641 differs slightly from these two in terms of LI ratios and less so in terms of elemental composition. Apart from the lead concentration, the elemental composition of F5932 is almost identical to that of F7674, and their LI ratios are nearly indistinguishable.

Table 5
Sr isotope ratios for sampled Egyptian blue (EB) artefacts.

Lab number	Excavation number	Artefact type	87Sr/86Sr	2SD
SL_1	F7530	Small piece of raw EB	0.70772	0.00007
SL_2	F7537	Small piece of raw EB	0.70773	0.00006
SL_3	F7353	Piece of raw EB	0.70770	0.00007
SL_4	F5273	Small piece of raw EB	0.70770	0.00006
SL_5	F17315	Lump of raw EB	0.70765	0.00007

(ÄMUL 2143 and 2180) have similar LI ratios too.[9]

The final artefact (EA87258, a 13% tin bronze vessel rim) has LI ratios similar to some Protodynastic and Old Kingdom copper alloys (Rademakers et al., 2018b), as well as Sinai and Wadi Arabah (both Timna and Faynan) copper ores (but not to Faynan copper ingots). The low lead concentrations in this artefact indicate that a Sinai origin for the raw copper is perhaps more likely, though this cannot be ascertained with confidence based on currently available data.[10] Furthermore, LI ratios for this bronze artefact may have shifted away from those of the copper ore during metallurgical treatment (Rademakers et al., 2020). Being a surface find, its dating is poorly constrained. The fragmentary and corroded state of the artefact also renders it difficult to identify the object typology for dating purposes. In terms of its form, diameter (ca. 12 cm) and available typologies, the closest parallels seem to be bowls with a handle which can be dated to the 19th–20th Dynasties (c. 1295–1070 BCE; Radwan, 1983: pp. 109 and 113, Pl. 57, nos. 316A-B, 318).

In addition to the comparative data discussed above, it can be noted that Bronze Age artefacts from the United Arab Emirates (Weeks, 1999, 2003) and particularly Oman (Begemann et al., 2010) have LI ratios similar to those reported here (cf. plots by Rademakers et al., 2017, 2022). However, they differ on average in terms of cobalt and nickel concentrations. As such, they are unlikely to constitute the bulk of metal stock circulating in the Nile Valley, even if they may contribute to it to some degree, as has been previously argued for copper alloys at Pi-Ramesse (Rademakers et al., 2017). The slightly higher average concentration of cobalt in this assemblage could indicate that Omani copper may constitute a more important contributor to the metal stock available at Amara West.

Finally, it is of course possible that copper produced from Nubian deposits (e.g. Harrell and Mohamed, 2020; Herbert, 1984) underlies (part of) the production of these copper alloys at Amara West. As discussed by Rademakers et al. (2022), our perspective on Nile Valley copper provisioning remains biased by the more abundant research on Egyptian archaeological objects and contexts, as well as less intensive survey and analysis of geological deposits in Sudan.

3.3. Tin

A preliminary radiography of F4464, a corroded segment of a ring, indicated some core metal to be preserved. However, no metallic sample could be recovered. The elemental compositional data of the artefact is characterised by very low analytical totals (ca. 9%), reflecting dominant light element phases (which constitute corrosion products such as stannic oxides observed on Late Bronze Age ingots: Berger et al., 2019b). As such, these data are considered qualitative only.

The ring's main constituent is tin (6.8% or ca. 75% after normalisation), with lead (6500 μg/g or ca. 7% after normalisation) and iron (1300 μg/g or ca. 1.5% after normalisation) as the most important minor constituents. Environmental contamination in the corrosion is reflected by concentrations of 0.3% aluminium, 0.6% calcium, 0.3% magnesium, and 0.1% sodium and potassium. Furthermore, copper, sulphur and phosphorus can be noted at concentrations around 200 μg/g. Along with iron, these elements may reflect contamination as well as undergone metallurgical processes and are difficult to interpret.

The relatively high lead concentration does, however, stand out, for example when compared to Late Bronze Age tin ingots, which typically contain lead in the order of 1–10 μg/g and rarely up to a few 100 μg/g (e. g. Begemann et al., 1999; Berger et al., 2019b; Galili et al., 2013; Stos-Gale et al., 1998; Wang et al., 2016). Exceptions do exist, however, among the tin ingots of the Uluburun shipwreck. Hauptmann et al. (2002) report that the majority have lead concentrations below 100 μg/g, but six have lead concentrations between 0.17 and 0.5% and one contains almost 1% lead, all considered to be natural impurities. Powell et al. (2021) have identified a similar distribution in a larger selection of Uluburun ingots, with a correlation between high-lead tin ingots and LI ratio values (cf. below). If the normalised lead concentration of F4464 is considered as an order of magnitude, the alloy would qualify as pewter, an alloy known almost exclusively from the Roman period onwards in Egypt.[11] However, the highly corroded state of the artefact makes it impossible to reconstruct the original lead concentration of this artefact. It seems more likely to have been made of (high lead) tin rather than pewter.

New Kingdom tin artefacts are extremely rare, with only three analysed examples currently known: a (probably) 18th Dynasty tin ring from Gurob (Petrie Museum UC27845i; Petrie, 1890: p. 19, Pl. XXII; Gladstone, 1892), a tin metal foil application to the cartonnage mask of the late 18th/early 19th Dynasty mummy of Katebet found at Thebes (British Museum EA6665; Fletcher et al. 2014: p. 110, Table 1; unpublished internal report on qualitative XRF analysis: M.R. Cowell, 1999) and a small tin bead from the Assasif (Metropolitan Museum of Art 26.7.1375; Tomb CC 37, Burial 53; Brill et al., 1993; Carnarvon and Carter 1912: p. 80, Pl. LXXIII).[12] While tin ingots may have circulated in the Nile Valley, for example through Egypt's participation in Eastern Mediterranean trade networks, none have been recovered from archaeological excavations. The analysis of crucible remains has shown that tin bronze alloying through direct cassiterite cementation took place during the New Kingdom, likely alongside copper and tin metal mixing (Rademakers et al., 2017, 2018a). The use of tin metal, in its own right or as an intermediate product for bronze production, thus remains very poorly attested.

Regarding the interpretation of LI ratios for this artefact, several potential problems need to be considered. Firstly, due to severe corrosion, the artefact could have exchanged lead with its burial environment. However, the relatively high concentration and "old" isotopic composition would argue against contamination by recent

[9] Odler and Kmošek (2020: p. 145) identify these two objects as representatives of Wadi Arabah copper, even though their lead concentrations are quite low (below 0.1% detection limit). A more specific comparison could be made to a Timna ingot which has ca 0.1% lead (Roman, 1990: ingot A1, sample 559 SF 67) and similar LI ratios (Yahalom-Mack et al., 2014).

[10] Lead concentrations are not consistently reported along with LI ratio data for Timna ores and may be similar for ores with LI ratios in this range. Furthermore, combined elemental and LI ratio data are available for only three Timna copper ingots (Roman, 1990; Yahalom-Mack et al., 2014), which does not facilitate direct comparisons to copper (alloy) artefacts.

[11] A pewter flask from Abydos (Ashmolean Museum of Art and Archaeology, Oxford, E2442: Ayrton et al., 1904; Douglas 1989) containing ca. 4.75% lead was recovered from a New Kingdom tomb, although its dating is debatable (Ogden 2000).

[12] A tin wire from Tell el-Amarna (find number 31769) was reported by Nicholson (2007), but its actual composition has not been determined, and it may not consist of tin at all (Nicholson, pers. comm. 2022). Furthermore, it may represent a modern contamination (stratigraphic unit 9431 contained ancient as well as modern materials).

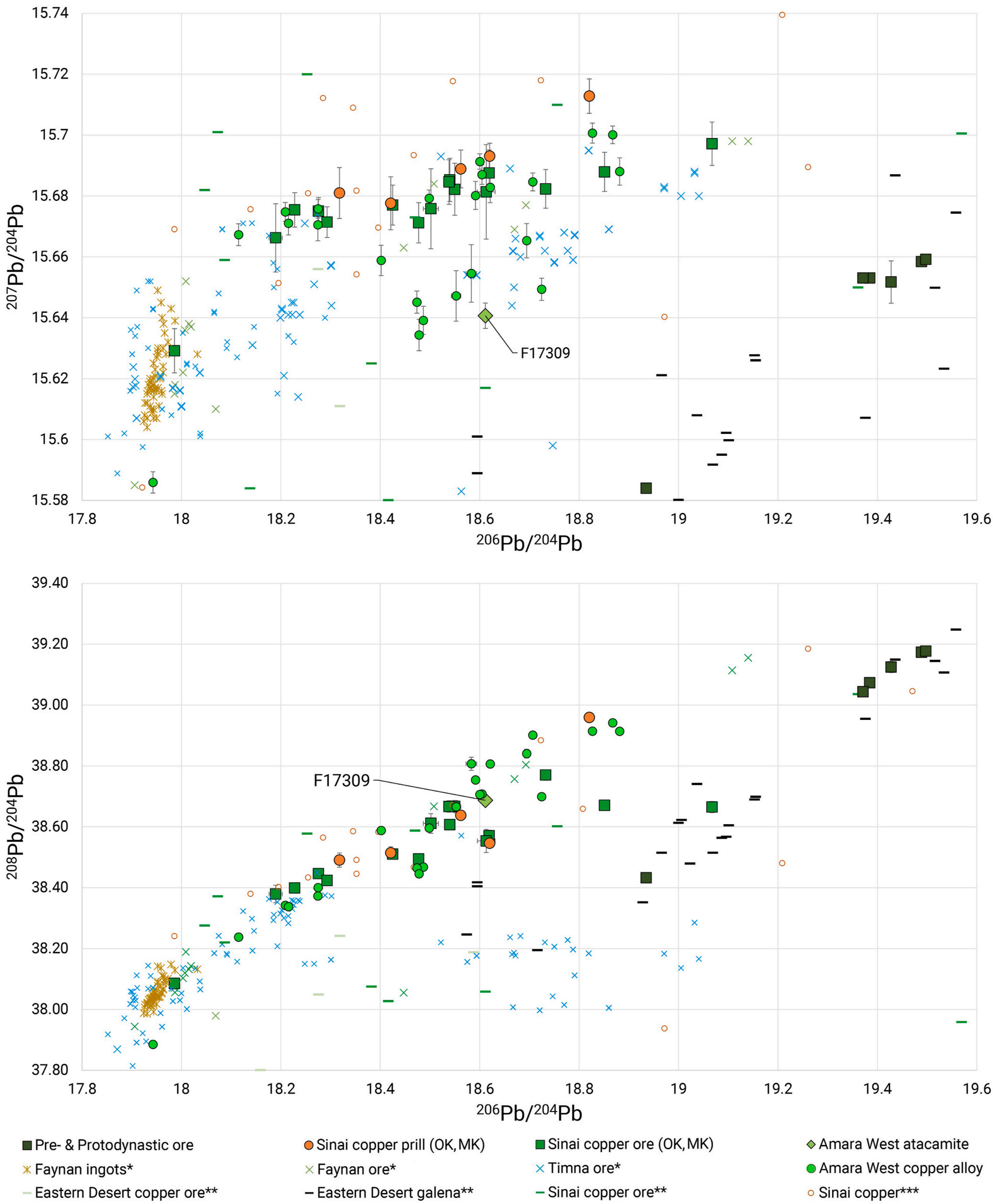

Fig. 5. LI ratios of atacamite pigment compared to ore and raw copper from Pre- and Protodynastic, Old Kingdom (OK) and Middle Kingdom (MK) contexts (Rademakers et al., 2018b, 2021b), *Arabah valley copper ore and ingot data (Faynan: Hauptmann, 2007; Hauptmann et al., 1992, 2015; Timna: Asael et al., 2012; Gale et al., 1990; Harlavan et al., 2017; Hauptmann, 2007), **Sinai and Eastern Desert copper ore and galena data (Abdel-Motelib et al., 2012; Brill et al., 1974; Shortland, 2006; Stacey et al., 1980; Stos-Gale and Gale, 1981), ***Sinai copper data (compiled by Pfeiffer, 2013: presumably "raw" copper, from various contexts).

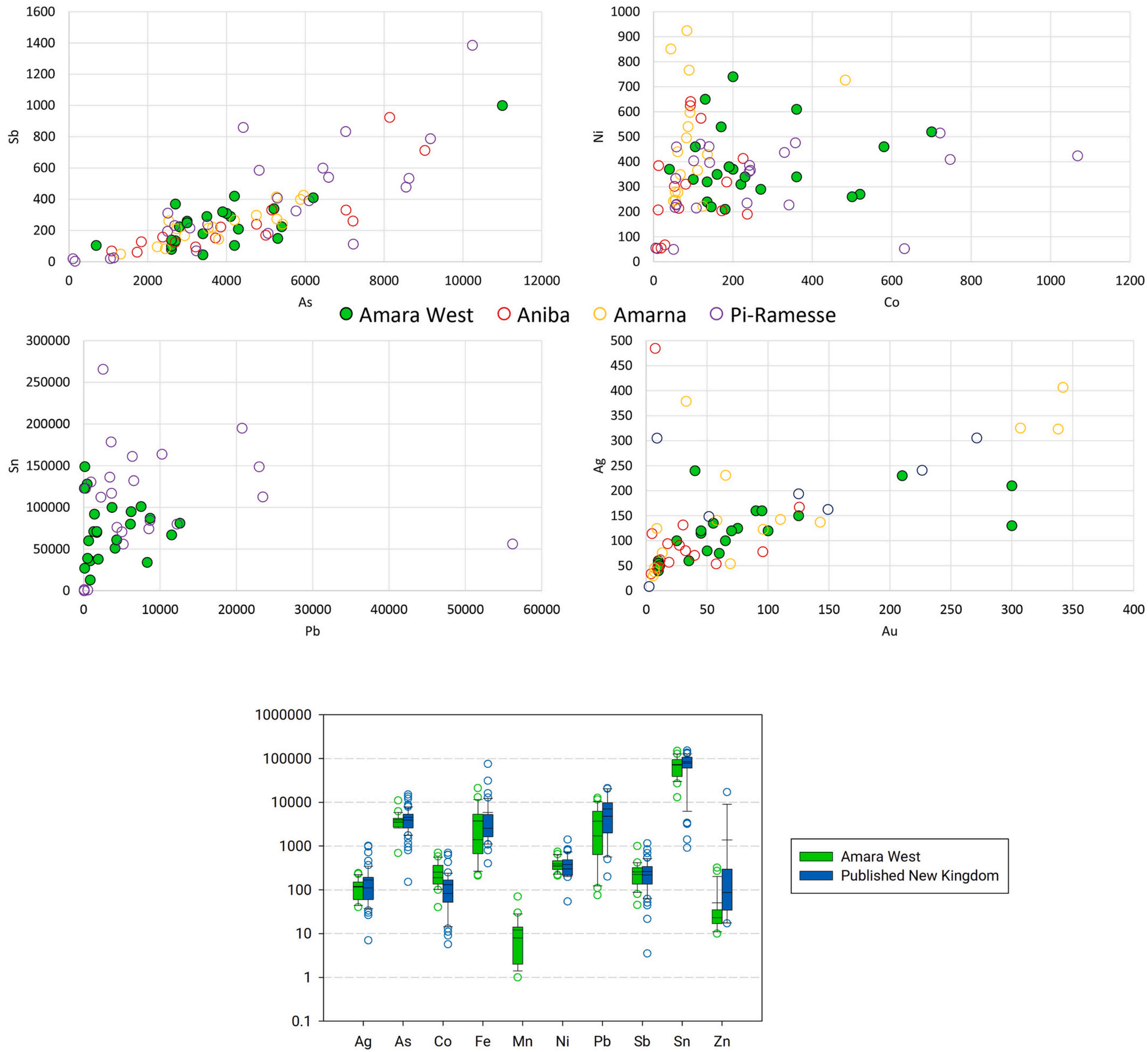

Fig. 6. Bi-plots and box plot of elemental composition (in µg/g) of Amara West copper alloys compared to composition of copper alloys from Tell el-Amarna (Stos-Gale et al., 1995a), Aniba (Odler and Kmošek, 2020) and Pi-Ramesse (Rademakers et al., 2017).

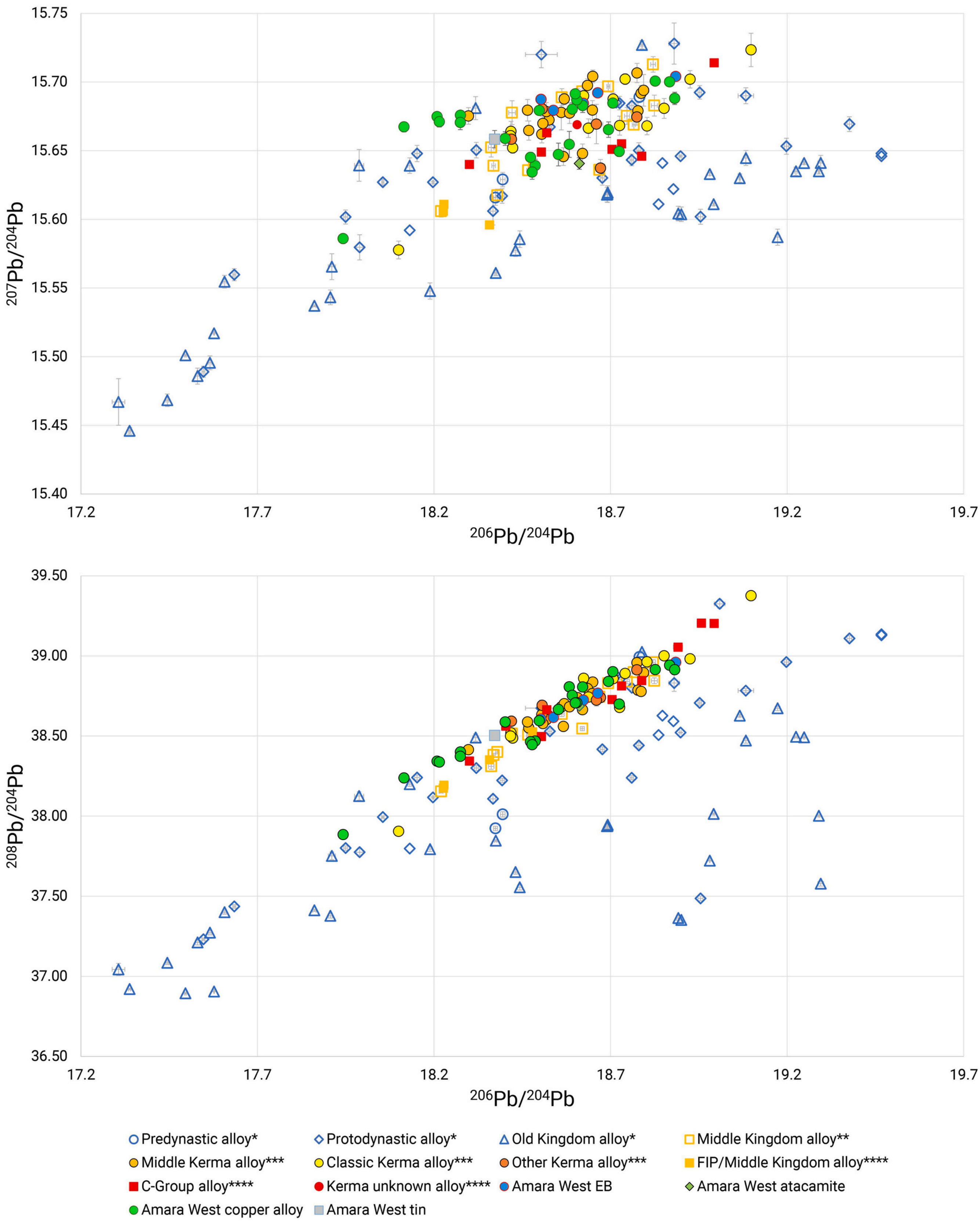

Fig. 7. LI ratios for Amara West copper alloys, Egyptian blue (EB), tin and atacamite compared to earlier copper alloys from the Nile Valley (*Predynastic to Old Kingdom Egypt: Kmošek et al., 2018; Odler et al., 2021; Rademakers et al., 2018b, 2021b; Rehren and Pernicka, 2014; **Middle Kingdom Egypt: Rademakers et al., 2021b; ***Kerma: Rademakers et al., 2022; ****various: Odler and Kmošek, 2020). Radiogenic LI ratios not shown.

Fig. 8. LI ratios for Amara West copper alloys, Egyptian blue (EB), tin and atacamite compared to New Kingdom copper alloys (Tell el-Amarna: Stos-Gale et al. 1995; Aniba: Odler and Kmošek, 2020; Pi-Ramesse: Rademakers et al., 2017), Egyptian blue (EB) and green frit (GF) from Zawiyet Umm el-Rakham (Shortland, 2006), tin from the Assasif (Brill et al., 1993), copper ingots from Timna and Bir Nasb (Yahalom-Mack et al., 2014), and Uluburun tin ingots (Begemann et al., 1999; Berger et al., 2019b; Powell et al., 2021).

(anthropogenic) lead. Secondly, the LI ratios for cassiterite may differ significantly for those obtained for smelted tin (e.g. Clayton, 2001; Powell et al., 2021; Stos-Gale et al., 1998), for example due to contamination by sulphides adhering to cassiterite or by other sources of lead introduced during metallurgical processes. Indeed, the artefact's lead content (both absolute and relative to tin) is at least an order of magnitude higher than that commonly found in mineral cassiterite, implying that the LI ratios likely reflect another source of lead. As such, other tin and tin-lead objects provide more archaeologically useful and reliable LI ratio reference groups. While it may not be possible to identify the original geological deposits underlying tin production, production centres or groups of material in circulation may be identified.

The ring's LI ratios are clearly distinct from those of the 18th Dynasty tin bead from the Assasif, which has concentrations of ca. 0.6% lead and 2.1% copper and whose LI ratios overlap with Taurus 1A ores and slag (Brill et al., 1993; Ogden, 2000; Yener et al., 1991). Powell et al. (2021) have recently argued that high-lead tin ingots from the Uluburun wreck most likely consist of tin smelted in the Bolkardağ mining district (cf. Pulak, 2000), with LI ratios reflecting lead contaminants from the production environment (where other metals, including lead, were processed). The tin bead from the Assasif, not discussed by Powell et al. (2021), may well adhere to this group, with LI ratios consistent with (high-lead) Uluburun tin ingots, tin and "lead-tin" artefacts from the wreck, and Taurus 1A ores and slag (cf. Fig. 8).

The Amara West ring's LI ratios are distinct from any of the currently characterised Late Bronze Age tin ingots and artefacts from the Uluburun (Begemann et al., 1999; Berger et al., 2019b; Powell et al., 2021; Stos-Gale et al., 1998; Oxalid database[13]), Salcombe (Berger et al., 2022), and Levantine (Berger et al., 2019b) shipwrecks, having relatively lower $^{206}Pb/^{204}Pb$. No other available LI ratio data for tin-based objects are consistent either. As such, it cannot be connected to previously characterised exchange goods.

No further reference data exists for Bronze Age tin or tin-lead artefacts from the Nile Valley, but some LI ratio data (Fig. 9) for New Kingdom lead artefacts is available from Tell el-Amarna, Pi-Ramesse and Qau (Shortland 2006; Oxalid). The Amarna artefacts are consistent with lead from Lavrion, while the Pi-Ramesse and Qau artefacts reflect additional sources.[14] None of these are consistent with the Amara West ring, nor does the latter sit on a trend line through those artefacts. Lead ores from the Bulgarian Lesovo (Udemski) mine have comparable LI ratios (Gale et al., 2000), but no Late Bronze Age production evidence (for either lead or tin) currently exists for this mine. The only other analysed lead ores with similar LI ratios are those from Sardinia, which are similarly reflected in Sardinian copper alloys (likely erasing the signature of abundant Cypriot ingot copper probably being used in their production: Begemann et al., 2001).

Interestingly, the ring's LI ratios fall in the range of previously characterised copper alloys from Egypt and Kerma (Fig. 7). Yet the concentration of copper in the sample does not indicate copper (alloys) to have contributed to the ring's LI ratios. Conversely, it should be considered that the alloying of copper with (leaded) tin of the type found in this ring could have played a role in defining the Amara West copper alloys' LI ratios.

Even if direct evidence for cassiterite mining during the Pharaonic period is not available, Eastern Desert cassiterite is likely to have been discovered and extracted by the ancient Egyptians, whose presence in areas holding rich deposits has been attested (e.g. Wadi Mueilha: Rothe et al., 1996), and may underlie tin bronze production in Egypt to some extent (cf. discussion by Rademakers et al., 2017, 2018a; Stos-Gale et al., 1995a). Hamimi et al. (2020: pp. 385-386) report New Kingdom tin mining of the Eastern Desert deposits at Wadi Abu Dabbab, Wadi Nuweibi, Igla and Wadi Mueilha, basing their overview on internal reports compiled by Afia (2006a, 2006b, 2006c) (see also Klemm and Klemm, 2014; Wertime, 1978). Apart from the well-known gold mining, they further report pharaonic activity at a wide range of copper mines and lead mining at Umm Semiuki, Hilgit, Maakal and Atshan during the New Kingdom; but these identifications remain tentative in the absence of in-depth archaeological analysis. Yet, relevant malachite deposits have been noted by Klemm and Klemm (2008, 2013), often with indications of their extraction during New Kingdom (and possibly earlier) times, e.g. at Uar and Umm Fahm. Said (1990: pp. 530-531) further notes that malachite is found associated with cassiterite at Wadi Nuweibi, Igla and Wadi Mueilha. At Umm Fahm, in northern Sudan's Eastern Desert, extraction of malachite appears to have taken place during the Old to Middle Kingdom already. As such, strong indications exist of pharaonic mining of Eastern Desert deposits other than gold, even if these are not reflected in the epigraphical evidence.

However, Eastern Desert cassiterite remains poorly characterised (but see Abdalla et al., 2008; Rothe and Rapp, 1995) and its LI ratios were never determined. The LI ratios of characterised (Egyptian) Eastern Desert ore deposits are mainly restricted to galena (Brill et al., 1974; Stacey et al., 1980; Stos-Gale and Gale 1981) and very few copper ore samples (Abdel-Motelib et al., 2012), none of which match those of the Amara West tin ring. Tin deposits in the Eastern Desert consist of granite-hosted hydrothermal cassiterite and its placer deposits, with geological ages between ca. 650 to 530 Ma[15] (Amin, 1955; Hamimi et al., 2020; Lehmann et al., 2020; Mohamed, 2013; Obeid et al., 2001; Said, 1990). It is unclear if Eastern Desert cassiterites have similar LI ratio values to the base ores. Even if they do, it would remain difficult to compare them to those of (lead-contaminated) tin metal artefacts. As such, the possible attribution of an Eastern Desert origin for the tin encountered in the Amara West artefact cannot be rejected or confirmed at this stage.

3.4. Egyptian blue

Egyptian blue is a synthetic pigment (e.g. Riederer, 1997), made by mixing powdered quartz, lime and a copper compound (at the

[13] All cited Oxalid data from https://oxalid.arch.ox.ac.uk/, accessed May 2022.

[14] A formal interpretation of the Pi-Ramesse lead (and silver) artefacts has not yet been published*, but the data produced by Z.A. Stos-Gale and colleagues has been kindly made available in the Oxalid database. While a few of these lead (and silver) artefacts are consistent with Lavrion ore LI ratios, the others scatter widely (Fig. 9): some fall within the overlapping ranges of Cycladic, Thasos, and Anatolian ores, while one overlaps with Bulgarian lead ore ratios. Four (characterised by relatively lower $^{206}Pb/^{204}Pb$ ratios) do not overlap with any of the aforementioned, but with Sardinian lead ores (the lower two with ore from the Iglesiente region, the other two with deposits with overlapping LI ratios). It is worth noting that the LI ratios for these lead artefacts cluster along a trend line cross-cutting LI ratios for these myriad deposits, which may represent a mixing line of different sources of lead. It is thus possible that a mixture of lead from two (or more) sources (with the two artefacts possibly made of Sardinian lead representing an endmember of that mixing line) was used for artefact production at Pi-Ramesse. Such lead mixing may have taken place at Pi-Ramesse or prior to its arrival there. The Qau lead ring's LI ratios (data in Oxalid refer to Ashmolean Museum of Art and Archaeology inventory number 1923–553 and 18th Dynasty Qau Tomb 1038, but this ring is not listed by Brunton, 1926) do not overlap with this mixing line nor with available data for exploited Bronze Age lead deposits (but most closely resemble Rhodope ore data).* Yagel and Ben-Yosef (2022) published an interpretation a few weeks after this manuscript was submitted. Our interpretation has not been revised to include their discussion (which largely dismisses lead mixing).

[15] The geological model age estimated from the ring's LI ratios (using the toolbox developed by Albarède et al., 2012) is ca. 53 Ma (with $\mu = 9.28$ and $\kappa = 3.94$). It should be kept in mind, however, that this estimate is based on single-stage growth curves to calculate the age of individual samples rather than the more complicated (and accurate) multi-stage growth curves for global lead evolution (e.g. Dickin, 2006; Stacey and Kramers, 1975).

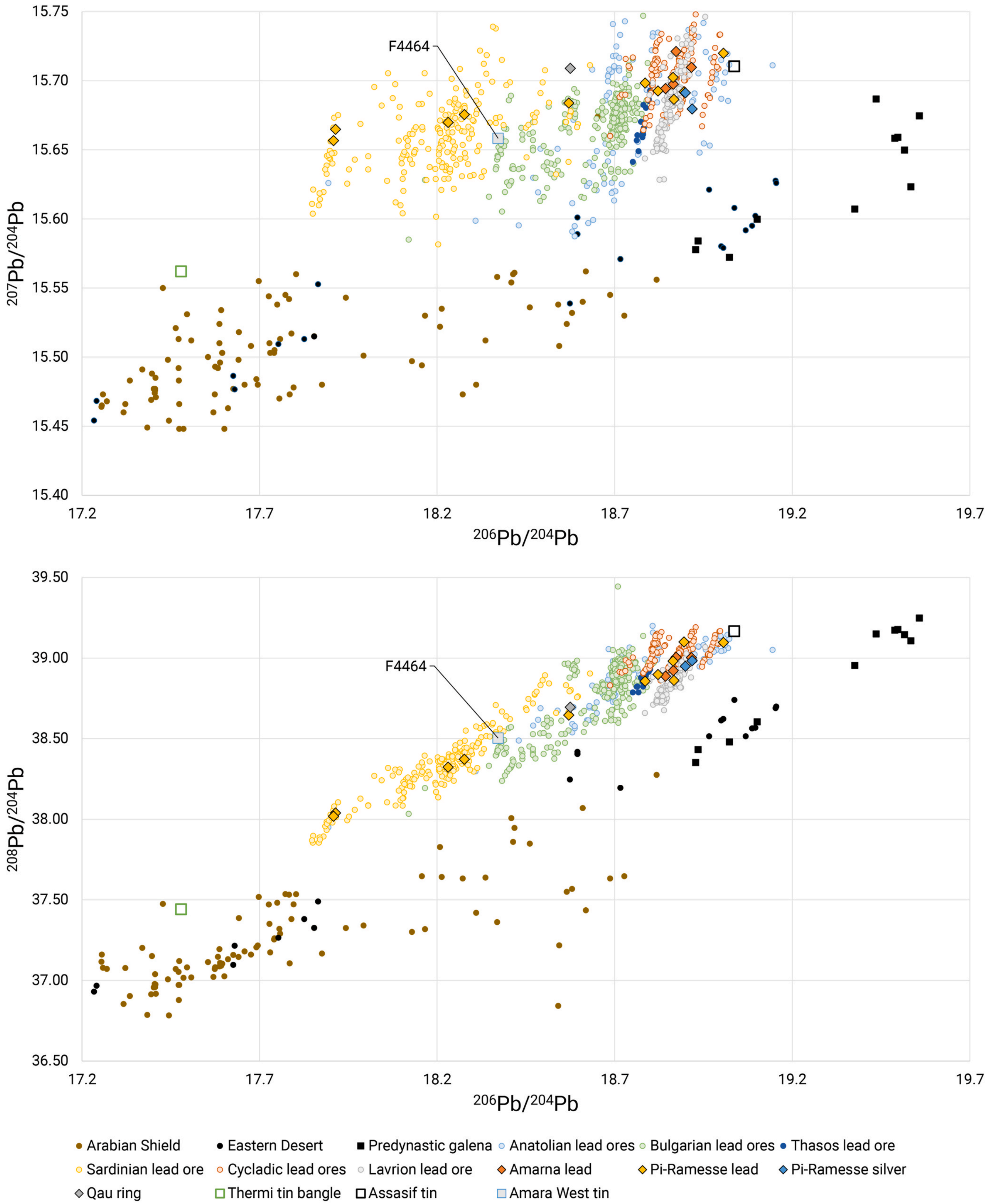

Fig. 9. Comparison of Amara West tin(-lead) ring LI ratios to data for lead ores (Arabian shield: Bokhari and Kramers, 1982; Ellam et al., 1990; Stacey et al., 1980; Eastern Desert and Predynastic galena: cf. Fig. 5; Anatolia: Sayre et al., 2001; Yener et al., 1991; Bulgaria: Gale et al., 2000; Thasos and the Cyclades: Stos-Gale et al., 1996; Sardinia: Begemann et al., 2001; Stos-Gale and Gale, 1992; Stos-Gale et al., 1995b, 1997; Lavrion: Oxalid database), lead and silver artefacts (Amarna: Shortland, 2006; Pi-Ramesse and Qau: Oxalid database) and tin artefacts (Thermi, Anatolia: Begemann et al., 1992; Assasif: Brill et al., 1993).

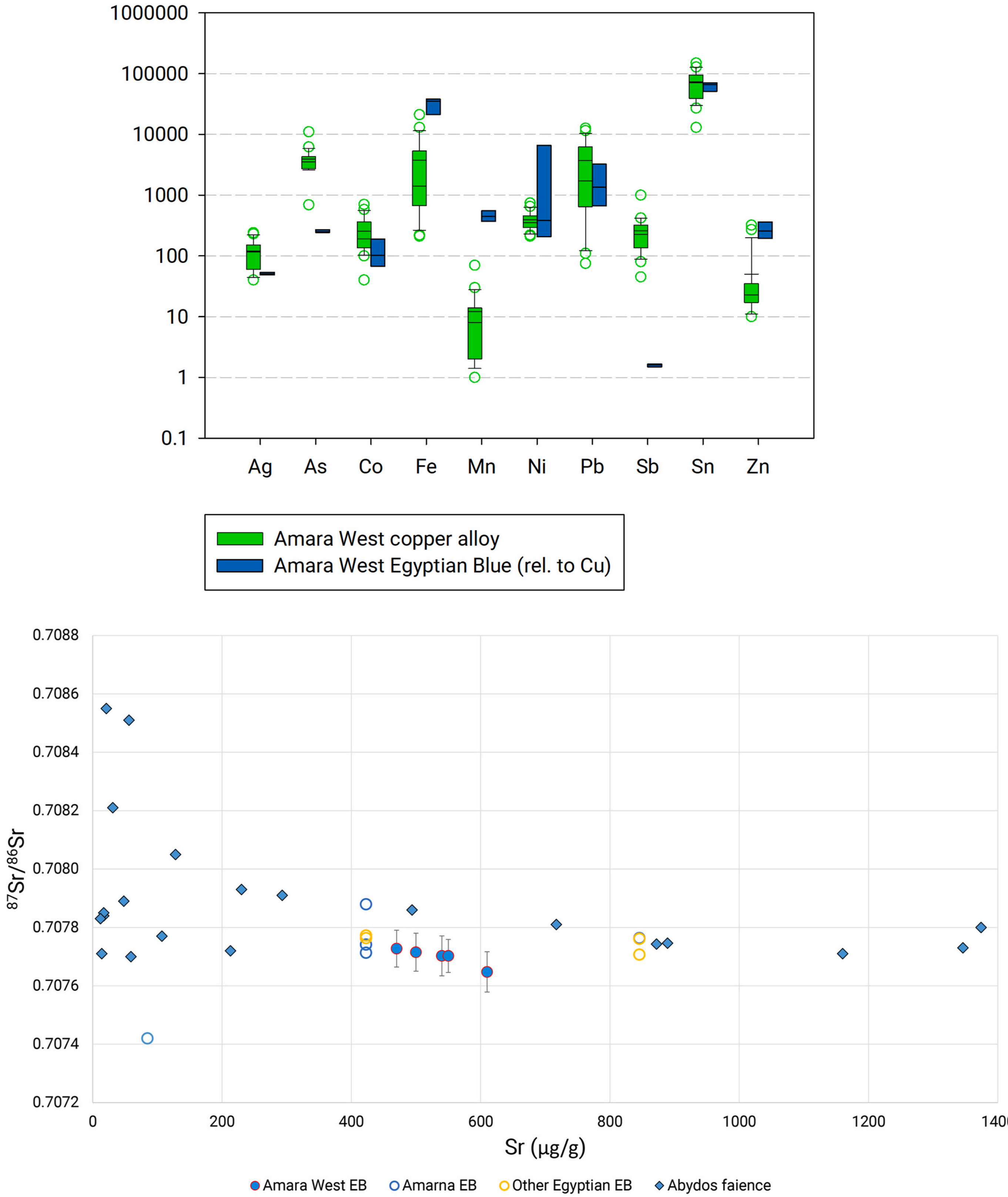

Fig. 10. Top: Box plot of elemental composition of Amara West copper alloys compared to composition of Egyptian blue (EB) normalised to copper (in μg/g). Bottom: Sr isotopic ratios and concentrations for Amara West Egyptian blue compared to Egyptian blue from Amarna and Malkata (Brill and Fullagar, 2012) and faience from Abydos (Hammerle, 2012; high concentration data omitted).

approximate ratio of 4:1:1), and an alkali flux (plant ash or natron). Upon heating (in a crucible), the mixture fuses (without complete melting) to form synthetic cuprorivaite ($CaCuSi_4O_{10}$), alongside any unreacted quartz and copper-rich wollastonite. Depending on initial ingredient ratios, the degree to which the end product is powdered and the addition of organic binders, different shades of blue are obtained. The powder can be applied as a pigment or, more rarely, shaped into a three-dimensional form and fired again (e.g. F8750: a small bowl placed in an infant burial next to tomb G322 at Amara West).

The five Egyptian blue samples were previously analysed by Fulcher (2022) and Fulcher et al. (2021a).[16] They were found to consist of cuprorivaite ($CaCuSi_4O_{10}$), with varying excess gypsum or calcite. While elemental analysis via ICP-OES does not allow the quantification of silicon following acid digestion, a consistent concentration of 7–8% copper and 4.5–6.5% calcium was observed, approximating the ratio of 1:1 Ca:Cu (by atomic weight). Typical flux element concentrations are ca. 0.1–0.2% potassium, 0.2–0.5% magnesium and 0.3–0.5% sodium, while iron and aluminium concentrations are ca. 0.2–0.3% and 0.3–0.5%, respectively. These elemental concentrations are very similar to those reported for 18th Dynasty Egyptian blue from Tell el-Amarna and Malkata by Brill (1999).

It is instructive to consider the metal concentrations in more detail, as these most likely entered the Egyptian blue with the copper colourant. For example, tin concentrations average 0.5–0.6% for F7530, F7537, F7353 and F5273, and 0.3% for F17315. When normalised to copper (or the sum of copper and tin), this gives relative tin concentrations of ca. 6–7% and 4%, respectively. Such concentrations mirror those observed in the copper alloys at Amara West (Fig. 10). For those first four samples, however, arsenic concentrations normalised to copper average $\leq 0.1\%$, lower than those in the Amara West alloys, while F17315 has similar relative arsenic concentrations. Cobalt concentrations normalised to copper average ca. 50–250 μg/g, compatible with the Amara West copper alloys. Nickel concentrations normalised to copper for three artefacts are ca. 200–400 μg/g (like the alloys) but 0.2% and 1% in F17315 and F7353, exceeding nickel concentrations observed in Amara West copper. Finally, the lead concentrations normalised to copper vary between ca. 0.05–0.3%, which is comparable to those in the copper alloys.

The former observations indicate that copper alloys most probably were used as copper colourants for these Egyptian blue pigments. As such, the LI ratios of the Egyptian blue most likely reflect the lead entering the pigment with the copper colourant, with lead contributions from the silica and lime component being negligible (cf. Rademakers et al., 2017; Rodler et al., 2017; Shortland 2006). The varying concentrations of arsenic and tin indicate that different alloys may have been used. However, it is possible that some elemental fractionation occurred during pigment production too, such as a partial loss of arsenic. Experimental reproductions of Egyptian blue often require heating during ten to one hundred hours at temperatures of ca. 800–950 °C (Riederer, 1997 and references therein), which could facilitate losses through oxidation and/or volatilisation of elements such as arsenic, tin and zinc.[17] If so, the original zinc concentrations of the alloy colourants used likely exceeded those of most Amara West copper alloys.

The LI ratio data for the Egyptian blue samples closely mirror those of the Amara West copper alloys, further strengthening the hypothesis that they were made using similar copper alloys. Four samples fall within the “Intermediate” range exhibited by the major group of Amara West copper alloys, while the fifth closely resembles the two copper alloys (with relatively lower lead concentrations) matching the Pi-Ramesse “Domestic group” (with typical lead concentrations ranging from ca. 0.1–1%). Interestingly, the latter (F7353) stands out because of its relatively high nickel concentration, which has no counterparts in the Pi-Ramesse, Tell el-Amarna or Aniba copper alloy assemblages. As such, it may rather be representative of a different copper alloy type, such as Wadi Suq period alloys from Oman which have similar arsenic/cobalt/nickel concentrations and LI ratios (Begemann et al., 2010). However, it is equally possible that copper (alloy) sources within Nubia existed which may explain this outlier composition; the likely smelting of arsenic-nickel-rich ore at Buhen (Davey et al., 2021; no LI ratio data) offering just one example.

Strontium isotope ratios in Egyptian blue have barely been investigated previously. As for glass, it is expected that strontium reflects the lime component, which is incorporated as part of the deliberately added lime, silica (calcareous sand) and/or alkali flux (particularly plant ash) components (Degryse et al., 2013). Strontium concentrations in the five samples are ca. 500–600 μg/g, like those encountered in ancient glasses. However, lime[18] and especially flux concentrations are lower in the Egyptian blue samples (lime concentrations reported by Brill (1999) are closer to those of glass). Therefore, it is possible that the relative contributions of each ingredient to the resulting strontium concentrations in Egyptian blue differ from those in glass, even if both are produced from the same types of raw ingredients. As such, the strontium isotope ratios for Egyptian blue may reflect the use of different sources of the same ingredients identified for glass, or different ingredients altogether (flux contributions may be significantly lower). Comparisons of strontium isotope ratio data for Egyptian blue are thus more straightforward to interpret than comparisons to glass data.

The strontium isotope ratios for the five Amara West samples (Fig. 10) are indistinguishable and average around 0.7077 $^{87}Sr/^{86}Sr$. This is indistinguishable from values measured for three out of four (and close to the fourth) Egyptian blue samples from Tell el-Amarna and three Egyptian blue samples from Malkata (Brill and Fullagar, 2012).[19] By contrast, strontium isotope ratios for Egyptian blues from Mesopotamia and Iran are clearly distinct (ranging between 0.7079 and 0.7082) from those of (the few) Egyptian samples analysed so far (Brill and Fullagar, 2012).

In terms of potential raw materials from archaeological contexts, a fragment of limestone from Tell el-Amarna shows an identical $^{87}Sr/^{86}Sr$ ratio, while three sand samples from Tell el-Amarna have distinct ratios (Brill and Fullagar, 2012). Strontium isotope ratios for the Egyptian blue from Amara West exceed those measured for most alluvial sediments in the Northern Dongola Reach and Amara West during the Holocene (Woodward et al., 2015). A few Amara West (non-alluvial, late 20th Dynasty to Napatan) soil samples have higher $^{87}Sr/^{86}Sr$ ratios, but no relation to Egyptian blue production can be inferred. The Egyptian blue $^{87}Sr/^{86}Sr$ ratios differ from those for all but one dental enamel sample of nineteen New Kingdom individuals from Amara West (Spencer et al., forthcoming), yet are similar to those measured for (some) New Kingdom individuals from Tombos and Egyptian sites (Buzon and Simonetti, 2013; Buzon et al., 2007) and to New Kingdom Nile Delta

[16] Except for F17315 (referred to as PS103 by Fulcher, 2022). Corresponding find numbers and sample numbers used by Fulcher et al. (2021a) are F7530 = PS305, F7537 = PS304, F7353 = PS317, F5273 = PS394.

[17] Note that archaeological finds of Egyptian blue production waste are extremely limited and much remains to be explored in terms of its production processes, not least how copper colourants were added (e.g. ore, metal, or corrosion products, in powder or as fragments). Indeed, all previous experiments exclusively use (synthetic) copper carbonates, putting them in a different *chaîne opératoire* from those attested by these alloy-coloured pigments.

[18] Note that calcium concentrations exceeded the calibration range and are thus of lower accuracy.

[19] Egyptian blue samples from Tell el-Amarna for which elemental analysis were performed are Petrie Museum UC 25039, UC 25040, UC 25041, UC 25044, UC 24684, UC 24685, and UC 24686 (Petrie, 1894: pp. 25–26; Bourriau, 1981: p. 151) and a flat object from the Brooklyn Museum of Art (no artefact number specified). Strontium isotopic analysis was conducted for UC 25040, UC 2468, UC 24685, and the flat object. Three Egyptian blue fragments from the Palace of Amenhotep III at Malkata, now in the Brooklyn Museum of Art and the Egyptian Museum, Cairo, were analysed (no artefact numbers specified).

sediment records (Krom et al., 2002). However, the geological background reflected in dental enamel or alluvial sediments does not necessarily correspond to the specific quartz and/or limestone sources exploited for Egyptian blue production in specific locations.

Clearly, there is a need for targeted strontium isotopic analysis of glass, faience, and Egyptian blue raw materials from Late Bronze Age workshop contexts in order to establish whether strontium isotopic signatures can be defined for specific production areas. For now, this case study establishes a similarity between Egyptian blue found at Amara West and Tell el-Amarna as reflected in its sand and/or lime source, yet a difference in terms of the employed copper alloy colourants.

Furthermore, it can be remarked that the strontium isotope ratios for Egyptian blue from Amara West (and Tell el-Amarna) are lower than those of blue glass from Tell el-Amarna and Malkata, which are in turn lower than those of 14th-13th century BCE Mesopotamian glass from Nippur, Nuzi, and Tell Brak (Brill and Fullagar, 2012; Degryse et al., 2010, 2015). While this illustrates again differences between Egyptian and Mesopotamian production centres, it is unclear whether the raw material sources for Egyptian blue and glass production in Egypt differed, or rather that the strontium isotope ratios reflect a different *chaîne opératoire* based on the same or similar ingredients.

Strontium isotope ratio studies for faience remain similarly limited and their interpretation is not expected to be straightforward.[20] Nonetheless, it can be noted here that the strontium isotope ratios determined for faience from Abydos by Hammerle (2012) overlap both with those of glass and Egyptian blue discussed above (Fig. 10; faience strontium concentrations scatter much wider – up to 1.8%, not shown – than those of Egyptian blue). This could reflect differences in the material resources employed for faience production, scattering more widely than those for the other two production systems, sample variations and/or the different processes themselves. Given the very low sample numbers currently available and the limited methodological exploration of strontium isotopic analysis for these materials, these questions currently cannot be resolved.

4. Discussion

4.1. Alloy selection and metal circulation

The results of this study shed new light on alloy choices, metal stock and material provisioning for – and within – a pharaonic town in Upper Nubia. The objects analysed in the present paper come from a variety of depositional and use contexts, including houses (E13.4, E13.6, E13.7, E13.8, E13.9, E13.16), storage facilities (E13.14), workshops (E13.29, E13.31), open areas and alleys (E13.11), and buildings of unclear purpose (E13.20, E13.22). As such, they are representative of the consumption side of the metallurgical life cycle – the objects that were in circulation and used by the ancient inhabitants. By contrast, the areas where metal was processed at Amara West (E13.24, E13.17) yielded evidence for melting, alloying, and casting. The latter are the subject of ongoing study by the authors, aimed at illuminating metallurgical practices through crucible remains and workshop spaces in relation to those observed at New Kingdom capitals Pi-Ramesse (Rademakers et al., 2017, 2018a) and Tell el-Amarna (Eccleston and Kemp, 2008; Nicholson, 2007; Rademakers, forthcoming).

The metal object assemblage presented here offers the first insights into the use and provisioning of copper alloys during the later New Kingdom, and specifically within Upper Nubia under pharaonic rule. Other strands of evidence reveal the availability of both local and imported materials and finished products in the town. Ceramics were produced locally, in both the Egyptian and Nubian tradition (Spataro et al., 2014), but vessels made in Cyprus, the Peloponnese, the Levant, the Nile Delta, the oases and Upper Egypt were also in circulation (Spataro et al., 2019; Gasperini, 2023). Locally available sandstone and schist were favoured as building materials, but quartzite (e.g. the statue of Amenemhat: Spencer, 2015), limestone and granite – all stones not available in the region – were also used by Amara West's inhabitants for different purposes. Bitumen, used both as a pigment and as a substance in funerary rituals at Amara West, seems to originate from the Dead Sea area (Fulcher et al., 2021b). Epigraphic evidence attests to the circulation of elite officials in Nubia (Auenmüller, 2018), providing a possible vector for the arrival of materials and prestige goods from Egypt (see also Auenmüller and Lemos, 2021) and beyond. In contrast, all analysed wood samples were species local to Amara West (sycamore fig, acacia, doum-palm, tamarisk, and Christ's thorn); no ebony or cedar were identified (Ryan et al., 2012).

In terms of alloy selection, the tin concentrations observed may be considered "typical" for New Kingdom Egypt. As noticed elsewhere, arsenic concentrations are significantly lower than those attested in copper alloys from preceding periods and "plain" arsenical copper alloys appear no longer in use at Amara West. However, arsenic still appears as a recurrent contaminant at concentrations of ca. 0.4%,[21] as observed in the assemblages at Pi-Ramesse, Tell el-Amarna and Aniba. This pattern may indicate the recycling of old copper (alloy) stocks which remained in circulation in the Nile Valley, whether from Egyptian or Kerma sites, from which arsenic was progressively lost over time and to which tin was later added to create fresh alloys. Other artefact groups attest to the circulation of older objects at Amara West, including royal (Rondot, 2022: p. 78 [23]) and private (Spencer, 2016: Pl. 206 [e]) stelae, linen textiles (Meadows et al., 2012), seal impressions (Spencer, 1997: p. 57) and stone axe-heads (Spencer, 2014: p. 57, Fig. 23). The inhabitants likely availed of objects and materials brought from earlier and existing pharaonic settlements in Nubia – such as nearby Sai (e.g. Minault-Gout and Thill, 2012: pp. 393–398, Planches: pp. 180–181, Figs 174–175; Budka, 2020: pp. 193–194, Fig. 66) – but also from the palimpsest of remains in the hinterland, where evidence of Mesolithic, Neolithic and Pre-Kerma/Kerma activity has been recovered (Vila, 1977; Garcea et al., 2016).

Reinforcing the notion of recycling, a strong lead isotopic similarity exists between the Amara West assemblage and older circulating metal stocks, with broadly similar trace element concentrations. It is therefore more likely that those metals were reused over time, rather than another (unknown) type of metal with low arsenic concentrations but otherwise same composition being imported as a new raw copper source. This supports the idea that the tons of copper produced during the Old and Middle Kingdom periods, as evidenced by major smelting sites primarily in the southern Sinai (e.g. Tallet 2012, 2018; Tallet et al., 2011), but equally at Ayn Soukhna (Abd el-Raziq et al., 2011; Tallet, 2016–2017; Verly, 2017; Verly et al. 2021), constituted a massive stock of metal, which remained in circulation in the Nile Valley over centuries. The scale of this resource should not be underestimated, even if significant parts of it were progressively removed from circulation (e.g. in funerary

[20] Indeed, the interpretation of strontium isotopes for this multi-phase material may be more complex and could potentially differ throughout the faience body, e.g. as a result of interactions with lime-based parting layers in the moulds or the use of different production techniques. Nonetheless, the development of this method offers a promising avenue for further investigations of cross-craft interaction through shared material resource use (Freestone et al., 2003; Rehren, 2008). An examination of variations between bulk samples and separate analysis of core, inter-particle glaze and surface glaze samples (e.g. using LA-MC-ICP-MS and experimental reproductions) could illuminate possibilities for developing this research avenue.

[21] F7303, with ca. 1% arsenic, may constitute an exception still more like ternary alloys identified at Kerma (Middle Kerma period) and Middle Kingdom Egypt (Rademakers et al., 2021b, 2022). Similarly elevated arsenic concentrations are encountered in a few of the Pi-Ramesse and Aniba alloys and represent the long tail of the distribution.

deposits, through accidental loss, or via international exchange, etc.).

A relative decrease over time in large-scale mining expeditions into Sinai, observed in epigraphic and archaeological sources (e.g. Gardiner et al., 1952, 1955; Tallet, 2003), may have prompted an increasing reliance on recycling to supplement a lowered influx of fresh copper from Sinai, alongside the import of copper through more extensive Late Bronze Age exchange networks (Rademakers et al., 2017). However, it must be emphasised that continued primary production is attested in Sinai during the New Kingdom, most notably at Bir Nasb where several thousand tons of copper were likely produced (e.g. Abdel-Motelib et al., 2012) but equally at other mining zones exploited earlier (e.g. Tallet, 2003). As such, the reliance on multiple resources may reflect a response to an increased demand for copper in Egypt, at its greatest imperial expansion during the New Kingdom, and abroad. The network of pharaonic settlements in Nubia would also, in themselves, have created a demand for copper alloy, for use as weaponry, tools, fishing equipment, jewellery and funerary goods. Indeed, the focus of earlier studies on Egyptian metal has mainly been to validate the use of Sinai and Eastern Desert copper and identify possible imports (Rademakers et al., 2021a). The growing body of data should allow for a reversal of this perspective to explore the possible export and use of "Egyptian copper" across the wider region.

4.2. New Kingdom copper (alloy) stocks

The patterns for New Kingdom copper provisioning along the Nile Valley are expected to vary regionally and along different social contexts of production and consumption, and so should their reflection in compositional data. This study can therefore expand our understanding of the proposed groupings of "Domestic" and "Intermediate" copper observed at the Ramesside capital city Pi-Ramesse, which were expected to represent local snapshots of a continuous spectrum of circulating metal (Rademakers et al., 2017: p. 68). Indeed, the strong cluster ("Domestic group") at Pi-Ramesse may represent a particular stock of metal that was available and used within the exceptionally large-scale and state-controlled workshop setting – alongside (freshly) imported metal from Cyprus and the Arabah. The mixing and casting of large amounts of metal, including monumental objects such as bronze doors, within a single workshop environment could have resulted in a narrowing of compositional variability. One could imagine these large quantities of metal remaining under state control over longer periods of time (representing strategic stockpiling: e.g. Rehren and Pusch, 2012), with characteristic compositions developing for groups of objects by repeated melting and mixing (large bronzes of the New Kingdom testifying to this by their absence). It is only through the characterisation of contextualised assemblages from different periods and sites that such different stocks and their evolution over time can be evaluated.

The circulating metal stock identified at Pi-Ramesse was proposed to consist of copper freshly smelted from Sinai and Eastern Desert ores, and more limited Arabah, Cypriot and Omani copper supply,[22] as well as recycled, circulating alloys (with copper originally also from these sources). It was further argued that the geochemical signature of those raw metals would have been progressively lost through primary and secondary metallurgical processes, in particular for low-lead ore types such as those from Sinai and Cyprus (Rademakers et al., 2017). In the meantime, more compositional data has become available for copper alloys from earlier Egyptian periods (Kmošek et al., 2018; Odler et al., 2021; Rademakers et al., 2018b, 2021b, 2022), validating that much of the Pi-Ramesse "Intermediate" copper may indeed include recycled copper alloys and have similar origins to the "Domestic group". The combined effects of various metallurgical operations (Rademakers et al., 2020, 2021a, 2021b) as well as partial compositional overlaps between raw copper from Sinai, Wadi Arabah and Oman indicate that it may not be possible to distinguish between individual mining sources for most copper alloy objects. Rather, a long-term diachronic perspective is required to identify the overall evolution of metal stocks and reveal changes to the underlying provisioning networks.

The general interpretation proposed for Pi-Ramesse and Tell el-Amarna thus appears equally valid for Amara West (and for New Kingdom alloys from Aniba[23]), although the relative contribution of different sources to local stocks may differ slightly, reflecting distinctive local histories of metal availability.[24] For example, the relatively higher concentrations of cobalt in the Amara West assemblage compared to Aniba and Tell el-Amarna may suggest a relatively higher (historical) contribution of copper from Oman or the Arabian Peninsula over time, in terms of the regional provisioning network rather than at the site itself, founded only in the 19th Dynasty. Early 18th Dynasty encampments in the desert hinterland of Amara West attest to activity in this region shortly after the Egyptian conquest (Stevens and Garnett, 2017): a fragment of copper alloy (F1109) was recovered from one site (2-R-19) but was not analysed. Earlier second millennium BCE sites in the desert hinterland of Amara West also yielded metal artefacts (Vila, 1977: p. 101, Fig. 48 [B9], p. 103, pp. 112–114, Fig. 57 [5]).

Nubian copper sources may have played a more important role too, but these cannot be distinguished from Egyptian sources, as potential deposits remain uncharacterised (cf. the discussion of metal sources available at ancient Kerma: Rademakers et al., 2022). Potential

[22] Anatolian copper was not identified at Pi-Ramesse by Rademakers et al. (2017), although it cannot be formally excluded as a source candidate. Compelling copper mining evidence is currently lacking, and Late Bronze Age Egyptian metals so far show little indication of Anatolian copper use – although it may be a (minor) contributor to the overall stock (see also discussion for earlier periods: Rademakers et al. 2021a). Anatolia's broader role in Mediterranean exchange networks of metals during the (especially Early) Bronze Age remains a topic of ongoing research (e.g. Gale and Stos-Gale 2005; Stos-Gale 2016; Yalçin 2011).

[23] Except for ÄMUL 2191 and ÄMUL 8213, LI ratios for all analysed Aniba copper alloys fall within the LI range attested at Amara West. All these copper alloys have trace element concentrations comparable to the Amara West alloys (except for slightly lower cobalt concentrations, similar to other New Kingdom assemblages) and as such no direct indications exist to propose a different provisioning system. ÄMUL 2191 and ÄMUL 8213 appear to be outliers to this system, with LI ratios incompatible with known Sinai, Eastern Desert, Arabian or Omani ores and metals. LI ratios for ÄMUL 2191 are closest to those of oxhide ingots found in Sardinia (Begemann et al., 2001; these are likely to derive from Cyprus, with LI ratios bordering the range attested by Cypriot ingots and Ambelikou [Solea axis] ores). ÄMUL 2191 consists of unalloyed copper (Odler and Kmošek, 2020: Table 13), but is described as arsenical copper by Odler and Kmošek (2020: p. 112) likely confusing this with ÄMUL 2192. This makes its identification as Cypriot oxhide ingot copper more likely (cf. discussion on the visibility of Cypriot copper in LI analysis of copper alloys by Rademakers et al., 2017) – in contrast with some of the other proposed Cypriot origins for Aniba alloys and Abusir mirror ÄMUL 2178 (cf. comments by Rademakers et al., 2022: p. 3, p. 14). For tin bronze ÄMUL 8213 (with 0.7% arsenic), however, no artefacts with compatible LI ratios are currently known, although it falls within the (poorly defined) range of Eastern Desert copper and lead ores (albeit with relatively high $^{208}Pb/^{204}Pb$). Odler and Kmošek (2020: p. 111) assign an "Egyptian Metal II" provenance (a group coinciding with Pi-Ramesse "Domestic copper", but defined without much reference to the interpretational framework by Rademakers et al., 2017), yet it can be considered an outlier with respect to this group as it conforms poorly to its commonly identified stock contributors. Its LI ratios may reflect the use of high-lead (Uluburun-type) tin (cf. section 4.3 and Fig. 8).

[24] There is no outspoken phase-related clustering in the compositional data for the Amara West alloys, nor do artefact typology and composition appear to correlate. LI ratios for the phase 3B/o Egyptian blue samples are most similar to those of phase 2B/o (and 2A/o) copper alloys (no 3B/o copper alloys analysed), as for one of the 2B/o Egyptian blue samples (the other being more similar to 3A/o-4A/o copper alloys). As such, it is not possible to identify from this sample the arrival and use of distinct metal stocks over time at Amara West.

contributions from Cypriot copper circulating in the Mediterranean during the Late Bronze Age may be masked in terms of LI ratios by progressive mixing and alloying (cf. Begemann et al., 2001; Rademakers et al., 2017).

4.3. High-lead tin as a source of confusion

Taking a step back from Amara West, overall higher lead concentrations can be noted in New Kingdom artefacts compared to those from preceding periods in Egypt and Nubia (Rademakers et al., 2022: Fig. 5).[25] This could reflect new sources of copper coming into circulation, such as Wadi Arabah ores, although no strong LI ratio clustering is observed to reflect the pull from a more dominant lead contribution of any particular source. The intentional addition of lead to New Kingdom alloys is unlikely, as leaded bronzes become widespread only later in the Nile Valley and the observed low lead concentrations are not usually considered intentional (e.g. Pernicka et al., 1990).

One possibility to consider is that the addition of tin to the bronze alloys plays a role in explaining this pattern of average higher lead concentrations (cf. Begemann et al., 2001; Rademakers et al., 2017). For example, LI ratios for the Uluburun tin ingots partially overlap with the major "Domestic group" cluster from Pi-Ramesse and Tell el-Amarna. The addition of relatively lead-rich Uluburun tin (ca. 0.5% lead: Hauptmann et al., 2002; Powell et al., 2021) to a "Middle Kingdom" or "Middle to Classic Kerma" arsenical copper (ca. 0.01–0.5% lead: Rademakers et al., 2022) or to a "Middle Kingdom" raw copper or copper alloy (<0.01% or 0.01–0.2% lead: Rademakers et al., 2021b) to form a 10% tin bronze would result in a relative shift of the LI ratios towards those of the tin (i.e. the lead contaminant of that tin) by 10–100%.

An alternative explanation to the exceptional LI ratio cluster of the Pi-Ramesse and Tell el-Amarna assemblages (cf. section 4.2) may then be the importance of Mediterranean tin ingots for bronze production there (the tin bead from the Assasif may represent a first direct identification of such "Anatolian tin" in Egypt). Yet the identification of cassiterite cementation in bronze production contexts at Pi-Ramesse suggests that this hypothesis can only provide a partial explanation. Furthermore, relatively higher lead concentrations in copper alloys do not correlate to tin concentrations or LI ratios. It is possible that the above-mentioned mechanisms of stockpiling and the contribution of high-lead tin are jointly responsible towards explaining this phenomenon, in a pattern that can no longer be disentangled. Furthermore, the influx of more lead-rich copper sources with overlapping LI ratios (e.g. from Oman or Anatolia) cannot be excluded.

For the specific case of Amara West, the finding of a relatively lead-rich tin ring further adds to this discussion. The LI ratios for this piece differ strongly from the Uluburun tin, reflecting lead (contamination) from a different and currently unknown production context. If this type of tin was used for bronze production at Amara West (and elsewhere along the Nile Valley during the New Kingdom), it may equally have played a role in determining the overall lead isotopic composition of the resulting bronzes. As the LI ratios fall within the range of those for Sinai copper deposits, the addition of such tin to circulating copper (alloys) could not easily be identified through bronze analysis (although tin isotopic analysis may provide an alternative perspective, e.g. Berger et al., 2019a).

Regardless, this tin artefact represents an extremely rare discovery for this period and might be indicative of more direct access to particular tin resources at Amara West. Although production evidence has not yet been identified, the possibility of Eastern Desert cassiterite exploitation (especially in Egypt, cf. Rademakers et al. 2018a and references therein, but perhaps also in Sudan, e.g. at Sabaloka or Gash Amir: Almond, 1967; Vail, 1987; Whiteman, 1971) cannot be discarded. Importantly, LI ratios for tin smelted from Eastern Desert cassiterite might not match those for the underlying deposits, as a result of possible lead contamination during smelting. Alternatively, one could consider the possibility that tin contaminated by Sardinian lead (and thus perhaps made in Sardinia) was used in this case. At this point, little strong evidence for tin smelting in Nuragic Sardinia has been identified, although it may have been produced locally (Artioli et al., 2020; Begemann et al., 2001; Berger et al., 2019b) – aside from Sardinia's role as a trading hub for copper and tin.

4.4. Craft interaction: pigments and copper alloys

The atacamite analysed here was used as a pigment, but it might also reflect ore sources available (locally) for extractive copper metallurgy, even if no evidence for smelting is attested at Amara West (atacamite ore was smelted in Sinai, cf. Rademakers et al. 2021b). As such, it may have arrived on site through trajectories different from those of the metals discussed above. Overall, its composition differs only slightly (in terms of arsenic and tin) from previously characterised Sinai and Eastern Desert ores. If this ore type was ever smelted, it could have contributed to the Amara West metal stock without standing out (its LI ratios being similar and easily shifted due to the low lead concentration). It might reflect (Nubian) Eastern Desert deposits (particularly considering the elevated tin and niobium concentrations), although these cannot be distinguished based on currently available geological data. The potential use of another (likely local) copper ore type rich in arsenic and nickel, attested much earlier at Buhen (Davey et al., 2021), might be reflected in the Egyptian blue at Amara West.

The Egyptian blue pigment at Amara West sheds additional light on the use of copper alloys. Indeed, the widespread use of copper alloys in Egyptian blue production was noted already by Jaksch et al. (1983) and Schiegl et al. (1990). They proposed that the study of pigments could offer complementary insights into the history of bronze technology in Egypt, yet this unique perspective has not been exploited explicitly since. The combined elemental and LI ratio analyses presented here have confirmed the cross-craft connection of shared materials use (see also Rademakers et al., 2017; Rodler et al., 2017; Shortland, 2006). They have furthermore revealed that circulating alloys of the same composition were used in the production of Egyptian blue (accounting for arsenic loss), highlighting the integration of secondary metallurgy and primary pigment production chains. This raises significant questions about the particular technical steps involved in making Egyptian blue, involving the use of metal (scrap) rather than (powdered) minerals or raw copper. It remains unclear whether filings, fragments, or powders (perhaps produced through active corrosion/heating) were used and how this would have influenced the end product (mineralogy, trace elements and isotope ratios). More exhaustive experimental work (e.g. Kakoulli, 2009) is needed to identify whether diagnostic markers remain in the pigments (or in the technical ceramics used for their production) to elucidate manufacturing processes. In turn, complementary analysis of Egyptian blue workshop remains and technical ceramics (e.g. Cavassa, 2018; McGovern, 1989; Rehren et al., 2001) is necessary to reconstruct its production technology and highlight further potential inter-relations to other high-temperature crafts.

Regardless, the use of copper alloys for making Egyptian blue appears to have been widespread: elemental compositions are highly similar to those reported for Egyptian blue from the 18th–19th Dynasty sites Tell el-Amarna, Zawiyet Umm El-Rakham, Malkata and Thebes (Brill, 1999: pp. 446–447; Hatton et al., 2008: p. 1594; Nicholson, 2007:

[25] This concerns an average increase: about half of the Amara West bronzes still have <0.2% lead, as do the majority of Aniba bronzes and one out of three Pi-Ramesse bronzes. Lead concentrations for Tell el-Amarna alloys are not reported (all below 0.3%). There is no correlation observed between lead concentrations and LI ratios or tin concentrations.

p. 186).[26] At Amara West, the relatively nickel-rich pigment sample highlights a source of copper not attested in the metal samples, vindicating Jaksch et al.'s (1983) hypothesis. The use of copper alloys as a material resource in other crafts has similarly been observed for Egyptian glass production, notably at Tell el-Amarna and Pi-Ramesse (and in glass at Amara West: Meek, in preparation), in contrast to copper-coloured Mesopotamian glass (Brill, 1999; Pusch and Rehren, 2007; Shortland and Eremin, 2006 – see also Uluburun glass data in Brill, 1999 and Lankton et al., 2022). This key cross-craft indicator may provide further insights into other Egyptian material technologies, particularly faience making, for which the use of copper alloys is similarly attested (e.g. Frame et al., 2011; Tite et al., 2007).

While the (New Kingdom) pharaonic state exerted considerable control over copper alloy supply and production through mining expeditions, stockpiling, and recycling of metal tools and artefacts, some degree of informal copper alloy production surely existed outside of state-controlled networks (e.g. Rademakers et al., 2017; Rehren and Pusch, 2012; and references therein). It is unclear whether this is the case for Egyptian blue, whereas (primary) glass production appears an exclusively state-controlled affair. For example, finds of Egyptian blue at Amara West (and Elephantine: Pagès-Camagna and Raue, 2016) are rare compared to those at Amarna and Pi-Ramesse (Pusch and Rehren, 2007; Weatherhead, 1995), where it was produced within state-controlled, albeit slightly different, workshop settings alongside glass, faience and copper alloys (e.g. Hodgkinson 2018). Alternative blue pigments were also available at Amara West (Fulcher et al., 2021). This might suggest that, as for glass, Egyptian blue production was even more specialized than that of copper alloys, with fewer craftspeople possessing this knowledge living along the Nile Valley. In such a situation, Egyptian blue would more likely have traveled along the Nile Valley from selected production centres. The use of scrap alloys as a colourant does not elucidate this further – it was used in large-scale state-controlled bronze workshops (e.g. at Pi-Ramesse) but would equally be the form of copper most likely available in an informal economy. As such, an assessment of degrees of specialisation and state control over Egyptian blue (and faience) production requires more in-depth study of its production contexts and waste, as well as analysis of larger artefact assemblages.

Thus, whether Egyptian blue was locally made at Amara West cannot be proven – nor ruled out – based on this evidence: the copper alloys may have traveled there with Egyptian blue pellets, but both could equally have been made locally. The strontium isotope ratio data is similarly insufficient at this point, given the limited available reference data. Yet it is striking that the limited data shows consistency within Egypt (as compared to Mesopotamia) and within material types (Egyptian blue compared to glass and faience). This highlights the potential for combining isotopic and trace element analysis in defining possible production centres for Egyptian blue and their links to other high-temperature industries within New Kingdom Egypt, against the background of studies of production technologies.

5. Conclusion

This paper illuminates the circulation of tin bronzes at Amara West, a New Kingdom centre for the pharaonic administration of the colony of Upper Nubia (Kush), through the complementary analysis of metal artefacts and pigments. These data reveal the selection of copper alloys in the same tradition attested downstream in Egypt and have identified similarities in the provisioning networks along the Nile, encompassing both Egyptian and Nubian cultures. However, these results indicate that the composition of New Kingdom metal stocks was influenced by distinct historical trajectories in these different areas along the Nile, reflective of more local spheres of interaction and exchange. In the case of Amara West, this may include the use of copper extracted from Nubian deposits, a slightly higher influx of copper from the Arabian Peninsula traded along the Red Sea, and different levels of stockpiling and recycling over time.

The colonial context of Amara West provides important insights into how production chains and material availabilities and supply mirrored – or digressed from – those in contemporaneous Egypt, including the partial reliance upon the recycling of metals in long-time circulation and the possible import of highly specialised products such as Egyptian blue. It is hoped that well-contextualised datasets from other pharaonic towns in Nubia, as well as Kerma sites, will allow more detailed understandings to emerge of these complex interactions.

Pigment analysis has underlined the entangled nature of different high-temperature industries, with the use of copper alloys playing a fundamental role in Egyptian blue (as well as glass and faience) production. Furthermore, the application of strontium isotopic analysis highlights the potential for comparing sand and flux selection between glass, faience and Egyptian blue. Beyond the shared networks of raw and recycled materials used in these different production chains, technological links should be investigated through choices for adapted crucibles and other technical ceramics, the multifunctional use of workspaces and the vocabulary used to describe ancient crafts. This perspective on craft interactions will help to further illuminate not only the mobility of goods and ideas along the Nile Valley, but that of people across crafts which remain mostly perceived – and researched – as distinct.

Declaration of competing interest

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

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[26] With a few exceptions, all of these samples have tin concentrations of ca. 5–10% relative to copper (arsenic concentrations not reported), and relative lead concentrations of ca. 150 µg/g up to several percent (notably higher in Hatton et al., 2008 and Nicholson, 2007 (SEM-EDS data) compared to Brill, 1999 (AAS and ICP-AES data); these high percentage values are likely to be less accurate, as the reported PbO values often approximate detection limits).

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