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The use of Cobalt in 18th Dynasty Blue Glass from Amarna: the results from an on-site analysis using portable XRF technology

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ABSTRACT
Cobalt was commonly used as a colourant in the Egyptian glass industries of the 18th dynasty, dark blue glass being a regular find at palatial and settlement sites, including Amarna and Malqata. The main source of cobalt ore used during this period has been identified in the Egyptian western desert, around the oases of Kharga and Dakhla. In order to better understand the *chaîne opératoire* of Late Bronze Age glass production and -working, in particular with regard to cobalt ore, at Amarna, chemical analysis by portable X-Ray fluorescence was carried out in the field. This was done on contextualised archaeological material excavated at the site of Amarna, which cannot be exported from Egypt for analysis. The results of this study demonstrate how cobalt ore was used in the various known workshop sites at Amarna, resulting in a deeper understanding of raw materials use and exchange across this settlement.
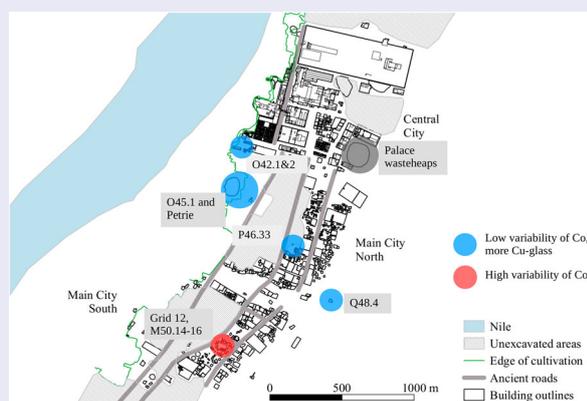
Introduction and background

On-site chemical analysis by portable X-Ray fluorescence (pXRF) was carried out at the Late Bronze Age (LBA)/New Kingdom Egyptian site of Amarna on contextualised archaeological material, which cannot be exported from Egypt. Previous scholars (e.g. Kaczmarczyk 1986; Shortland, Tite, and Ewart 2006; Abe et al. 2012) have already identified the chemical properties of cobalt ore used in LBA Egypt, as well as demonstrating that the overall source in the Egyptian western desert can be determined using pXRF by means of transition element analysis. By contrast, the present study aims to establish whether it is possible to identify any further sub-sources of Egyptian cobalt ore, in particular with regard to the various glass workshops excavated at Amarna, based on pXRF analysis of transition metals (Ni, Mn, Zn) only. In order to verify the latter, and to establish whether museum objects from Amarna without their original find locations can be re-assigned to their original find locations, an additional series of pXRF analyses was carried out in the Egyptian Museum and Papyrus Collection of the National Museums in Berlin. This study demonstrates how cobalt ore was used in the various glass workshop sites at Amarna, resulting in a deeper understanding of raw materials use and exchange across this settlement.

Dark blue glass was used widely during the Egyptian 18th dynasty (c. 1550–c. 1290 BC). It was produced in order to imitate the semi-precious and highly popular blue stone lapis lazuli (Nicholson 2012, 16–18, 22–23; Shortland 2012, 55, 140–145: p. 140 for the Mesopotamian analogy), which had to be imported from

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Afghanistan (Harrell 2012, 3, 8–10). In fact, almost half of all glass found at Amarna is blue in colour,[1] the lighter blue and turquoise variants stemming from a colouration using copper, probably in the form of shavings as a by-product from local metal-working. The dark blue glass was usually coloured by cobalt, and frequently by a combination of cobalt and copper, resulting in a deep blue colour. It is only by means of chemical analysis that the mixture of the colourants can be determined (Smirniou and Rehren 2013).

Although more widely owned and used in New Kingdom Egypt than lapis lazuli, dark blue glass was considered a valuable commodity: the Annals of Thutmosis III (c. 1479–1425 BC) at Karnak, for instance, describe the import of both light and dark blue glass, the dark blue glass being described as "Menkheperre" lapis lazuli (Menkheperre being the praenomen of Thutmosis III), while the light blue glass ingots are described as "Menkheperre" turquoise (Nicholson 2012, 17–18; Shortland 2012, 142). This inclusion of the king's name implies a certain level of royal control over the acquisition and working of glass at this stage in Egyptian history. About 100 years later, from the second half of the 18th dynasty onward, glass making began to develop in Egypt. An industrial centre producing objects from faience and glass was established at Malqata, a settlement site dating to the reign of Amenhotep III (the predecessor of Akhenaten, c. 1391–c. 1353 BC) surrounding a set of palaces and a temple near modern Luxor. It is possible that glass was produced at Malqata from raw materials, although no semi-fused glass has been identified from Malqata and discrete workshop sites are still absent from the archaeological record, most objects having been found in spoil heaps (Hodgkinson 2017, 223–225). The overall chemical fingerprint of glass found at Malqata matches that of other LBA glass produced in Egypt (Shortland, Rogers, and Eremin 2007, 787), thus the compositional similarity suggests identical glass manufacturing technology for all LBA Egyptian glass.

The first identifiable LBA Egyptian glass production took place at Amarna (c. 1353–c. 1336 BC). The latter city was established as a new capital for the cult of the sun god Aten during the reign of Akhenaten and his wife, Nefertiti. After the death of Akhenaten, the city was mostly abandoned, resulting in a more or less single-period site and a unique case study for daily life and urban industries during the LBA. Excavations carried out at Amarna during the past 100 years have yielded huge quantities of – mainly dark blue – glass from a variety of workshop sites.

Previous research on the geological source of cobalt ore used in Ancient Egypt

Previous research has already demonstrated that the cobalt ore was most likely brought to the workshops from the Egyptian western desert, around the oases Dakhla and Kharga (notably Kaczmarczyk 1986; Shortland, Tite, and Ewart 2006). This source has been identified by means of chemical analysis focussing on transition metals and trace elements. However, no uniform chemical pattern exists for this overall, larger source, but a variety of sub-sources are discernible, according to different, albeit heterogeneous, geological sources in the same area (Shortland, Tite, and Ewart 2006, 154–159). With exception of the above studies conducted on cobaltiferous alums, all other past analyses were carried out using glass and faience objects from Amarna, which, for historical reasons, have lost their archaeological context (for example, Smirniou and Rehren 2013).

The cobalt mines of the 18th dynasty were surveyed by a number of scholars, notably A. Kaczmarkczyk. Recent surveys in the region of Kharga and Dakhla have been carried out by geologists J. Harrell and P. Storemyr, who have located a wide area to the north and northwest of Kharga, and a main cobalt source to the south of Dakhla (Figure 1).

The authors of this paper received two samples of cobalt ore, which had originally been collected by A. Kaczmarkczyk at the site of Ain Asil near Mut (south of Dakhla oasis).[2] Two phases can be observed in these samples, described as "granular kieserite and/or pentahydrite, with hair-like crystals of pickeringite" (Shortland, Tite, and Ewart 2006, 156). Both have high levels of cobalt, together with nickel (Ni), manganese (Mn) and elevated zinc (Zn), with a strong correlation, as well as aluminium (Al) and magnesium (Mg), although with no, or only a weak correlation.

Y. Abe and colleagues (Abe et al. 2012) carried out an analysis using a custom-made portable XRF instrument, which was used to detect transition element patterns in glass and faience objects from various Egyptian sites of the New Kingdom, including the Ramesside period (c. 1292–1069 BC) and the Ptolemaic period (c. 323–330 BC). The study has demonstrated that it is possible to distinguish between cobalt from various sources based on the pattern of the accompanying transition metals, resulting in the distinction between the following cobalt sources (Abe et al. 2012, 1800, Figure 4):

- Type A: used in the 18th dynasty, with the transition metal patterns mentioned above.
- Type R: used in the Ramesside period, of an unknown source. Possibly from the same general source in the western desert, but with the main overall source depleted. This type of cobalt is low in Zn.
- Type N: used in Ptolemaic / Roman times – source unknown, although Iran has been suggested as a possible source (Kaczmarczyk 1986). Two variants exist, both of which are low in Ni, and either high or low in Mn.
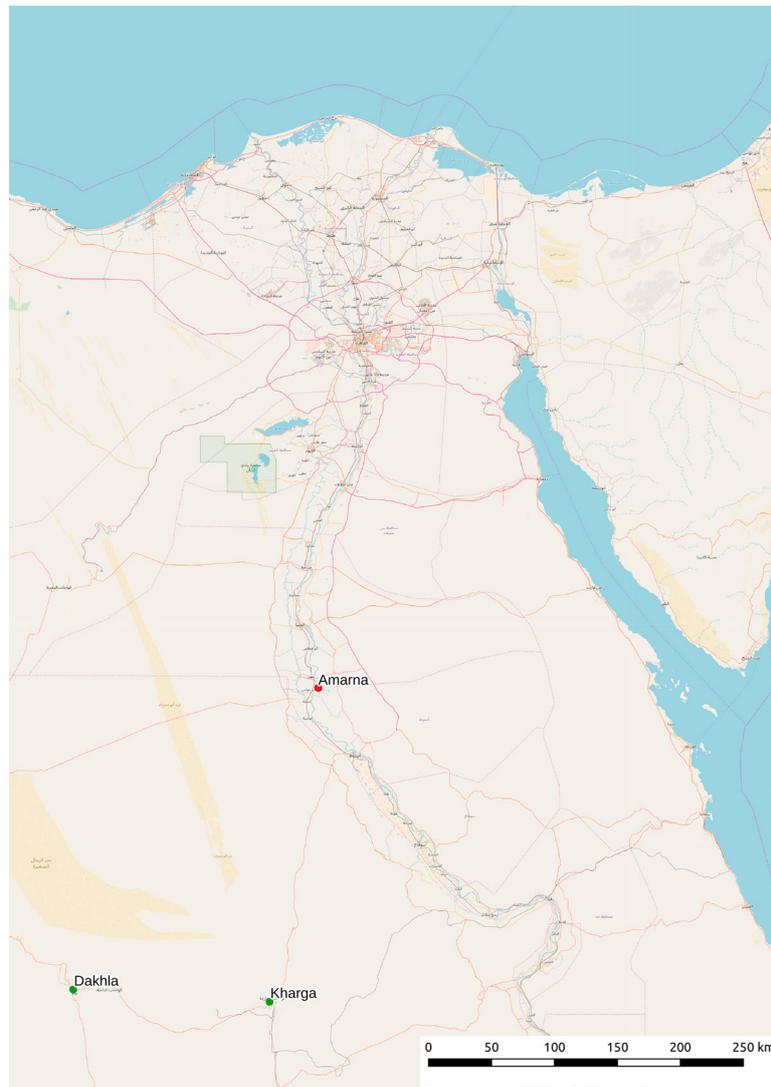
Figure 1. Map of Egypt showing the locations of Amarna and the Dakhla and Kharga Oases. Basemap: © OpenStreetMap contributors.

The chaîne opératoire *of dark blue glass-making and -working*

The cobalt containing alum, which had been mined in the form of small chunks of rock, was ground down and then mixed with water and sodium carbonate. Natron, which is native to Egypt, may have been used for the latter ingredient (Noll 1981; cf. Shortland, Tite, and Ewart 2006, 159). Subsequently, a precipitate developed, and the mixture was heated to 800–1000°C. This resulted in the formation of cobalt blue (cobalt alum spinel), which could be used as a blue pigment (Shortland 2000, 48–49; Shortland, Tite, and Ewart 2006, 159–162). It is not certain whether this took place at the mine or within the urban workshop. The prepared colourant was then added to the raw glass mixture, which consisted of silica, lime and soda, although the precise moment of adding the colourant (whether prior to, or after the fluxing of the raw materials) is still being debated. The typical composition of cobalt-coloured glass objects from Amarna is generally low in potassium (K), which possibly points to variations in the production technique of cobalt-coloured glass as opposed to other colours (Shortland 2012, 135).

Glass ingots were then shaped inside cylindrical ceramic crucibles, which were more or less standardised. This standard size is reflected in a series of larger ingot chunks from Amarna, in addition to the ingots from the Uluburun shipwreck (Nicholson, Jackson, and Trott 1997). The finished glass ingots were then chipped out of the crucibles and broken into manageable chunks, which appeared to have been distributed among the glass-working workshops for further processing. This included the drawing of glass rods (which may also have been drawn from the whole ingot) and manufacture of glass bars, which were frequently cold-worked into inlays and pieces of jewellery. Glass rods were used to produce beads and to decorate core-formed vessels, fragments of which were found on a regular basis in the houses of the elite and the communal waste heaps (the so-called palace waste heaps in the Central City, see Petrie 1894, 25–27; Nicholson

2007, 14). These vessels were made by coating a core of sand and dung with glass; the most frequently found body colour is either translucent or opaque, dark blue, glass, decorated with white and yellow wavy lines. While these vessels and pieces of jewellery form the ultimate output of the glass workshops, this study focusses on the raw glass items (unfinished products), such as ingot fragments, glass rods, bars and lumps, since these, in their original archaeological workshop context, can provide most information on the *chaîne opératoire* present at one particular workshop.

As outlined above, in order to achieve an understanding of the use of cobalt ore in the glass workshops of Amarna, this paper addresses the following specific research questions:

- Can the cobalt ore used in the glass workshops at the site of Amarna be traced to one single source, and can sub-sources be identified?
- Is it possible to identify sub-sources of cobalt ore mined in the general Kharga / Dakhla area and used in glass production during the 18th dynasty in Egypt by means of pXRF analysis for cobalt and transition metals (Ni, Mn, Zn, and, possibly, Fe) only?
- Finally, can museum objects from Amarna, without an archaeological workshop context be re-assigned to their original find locations?

Materials and methods

The glass workshops of Amarna and their characteristics

As the new residential and capital city of Egypt, Amarna (which was known as *Akhetaten* in ancient Egyptian) contained a large number of workshops, which sprang up in the settlement in order to cater for a population demanding luxury goods, including items of glass, faience, metal and stone. While a small number of these workshops were large and could be considered institutional or state-controlled – and thus potentially more specialised – in nature, much working took place in the courtyards of both larger and smaller houses throughout the city. Despite most of these smaller workshops being domestic in nature, they frequently included multiple high-temperature industries, such as glass, faience and metal. These industries were most probably controlled by the members of the elite living in the surrounding houses, who acted on behalf of the royal court to which they reported. While it is likely that some of the produce was retained and used by the producing households, the members of the elite in charge had the majority of the goods delivered to the royal court (Stevens and Eccleston 2007, 156–157).

Although a large part of the city was excavated by the Deutsche Orient-Gesellschaft (DOG: Borchardt and Ricke 1980) and the Egypt Exploration Society (EES: Peet and Woolley 1923; Frankfort and Pendlebury 1933; Pendlebury 1951; cf. Kemp 2012a) at the beginning of the last century, and huge quantities of raw glass objects, including ingot fragments, rods and bars were excavated, most of these have since been detached from their original archaeological context. However, excavations carried out under the direction of Barry Kemp since the late 1970s have revealed a number and variety of glass workshops, dispersed throughout the city (Kemp 2012b, 281–300). The material excavated from these is plentiful, and, when not registered and taken to a local museum by the Egyptian authorities, has been deposited in the magazine of the Amarna excavation house, thus being accessible for study. The following workshop complexes and areas containing glass working related objects have been identified over the years – from north to south, and objects from these have been included in the present analysis (Figure 2):

(1) The so-called "palace waste heaps": This area, which measures almost 200 m in diameter from north to south, was given the above determination by Petrie, who first investigated it in 1892. In fact, this area was most likely a communal waste deposit for both the Central City and the Main City North. The area contained much waste related to pyrotechnical activities, such as oven debris and technological ceramics including metal-working crucibles and cylindrical vessels for making glass ingots. In addition, Petrie collected around 1,500 fragments of core-formed glass vessels, which would have been used throughout the houses of the elite and in the institutional buildings of the Central City (Petrie 1894, 25–27).

(2) O42.1 and 2: This possible workshop site lies to the southeast of the royal palace and may have been directly associated with it. The area was excavated by Pendlebury in 1934 (Pendlebury 1951, 81–82, 85) and later investigated again by Kemp, the later work yielding more than 30 glass objects. Some of these items may be later in date, possibly Roman, while others optically appear to date to the 18th dynasty, making the interpretation of this assemblage somewhat difficult. No kilns or furnaces associated with this site were found. In total, 24 dark blue glass objects, including some polychrome vessel fragments with a blue body and some beads from this site were analysed.

(3) O45.1: This significant workshop site, which lies just south of the Central City, was excavated by P. Nicholson and colleagues in the 1990s (Nicholson 2007). The industrial site lies in the bounds of a far larger building, most of which has not yet

Figure 2. Map of Amarna showing the workshop sites discussed in this paper. Anna Hodgkinson.

been excavated, and in the vicinity of an area, in which Petrie collected several thousand faience moulds. O45.1 contained four kilns, two of which measure over 2 m in diameter, and which, according to a series of firing experiments using a copy of one of the structures, were capable of producing raw glass by reaching up to 1,150°C (Nicholson and Jackson 2007, 94). The site yielded much raw glass, including some dark blue semi-fused glass (Jackson and Nicholson 2007, 108–111), while much of the glass excavated here is of lighter shades of blue or turquoise in colour, indicating its production using copper as a colourant.

(4) Q48.4: This workshop is located in the southeastern extreme of the Main City North and is somewhat isolated. It contained several glass rods and unfinished beads, together with some small oven structures. It was excavated in the 1980s by Kemp and colleagues (Kirby 1989; Rose 1989).

(5) P46.33: This building, which was also excavated in the late 1980s, can be found in the southwestern part of the Main City North. It did not contain as many pieces of raw glass as the other sites listed here, but has been included since it was clearly manipulating glass (Bomann 1995).

(6) Grid 12, the House of Ranefer and N50.23 excavation: All these buildings were re-examined, and partially re-excavated under the direction of B. Kemp in the early 2000s (Kemp and Stevens 2010a, 2010b). This complex of sites actually consists of three different areas: the house of chariotry officer Ranefer to the north, which had already

been excavated by the EES in 1922 (Peet and Woolley 1923, 9–15), the new excavation site Grid 12, which encompasses eight small houses (Kemp and Stevens 2010a, 299), and house N50.23 to the southeast, which had already been investigated by the DOG under L. Borchardt in 1911–1912 (Borchardt and Ricke 1980, 311–312). While N50.23 contained a fair amount of raw glass, this house included some small oven structures, which were probably used for industrial purposes (Kemp and Stevens 2010a, 395–397). The street next to the house of Ranefer yielded a rubbish dump of waste glass products including several rods (Peet and Woolley 1923, 15). The Grid 12 houses contained much raw glass, including several bars in the progress of being chipped into inlays, in addition to evidence of glass rods for lamp-working (Kemp and Stevens 2010b, 501–504, 510–521).

(7) M50.14–16: These two houses, surrounded in the south by an industrial courtyard, were excavated by Anna Hodgkinson in 2014 and 2017 (Hodgkinson 2015; Hodgkinson 2019a). Over 700, mainly glass-working related, objects were found during the two seasons, a large portion of which are dark blue in colour. In addition, the site yielded over 80 fragments of cylindrical vessels. According to an optical guide established by M. Smirniou and T. Rehren (Smirniou and Rehren 2016) on the basis of characteristic layering in the ceramic matrix, a good portion of these vessels may be interpreted as having been used for the production
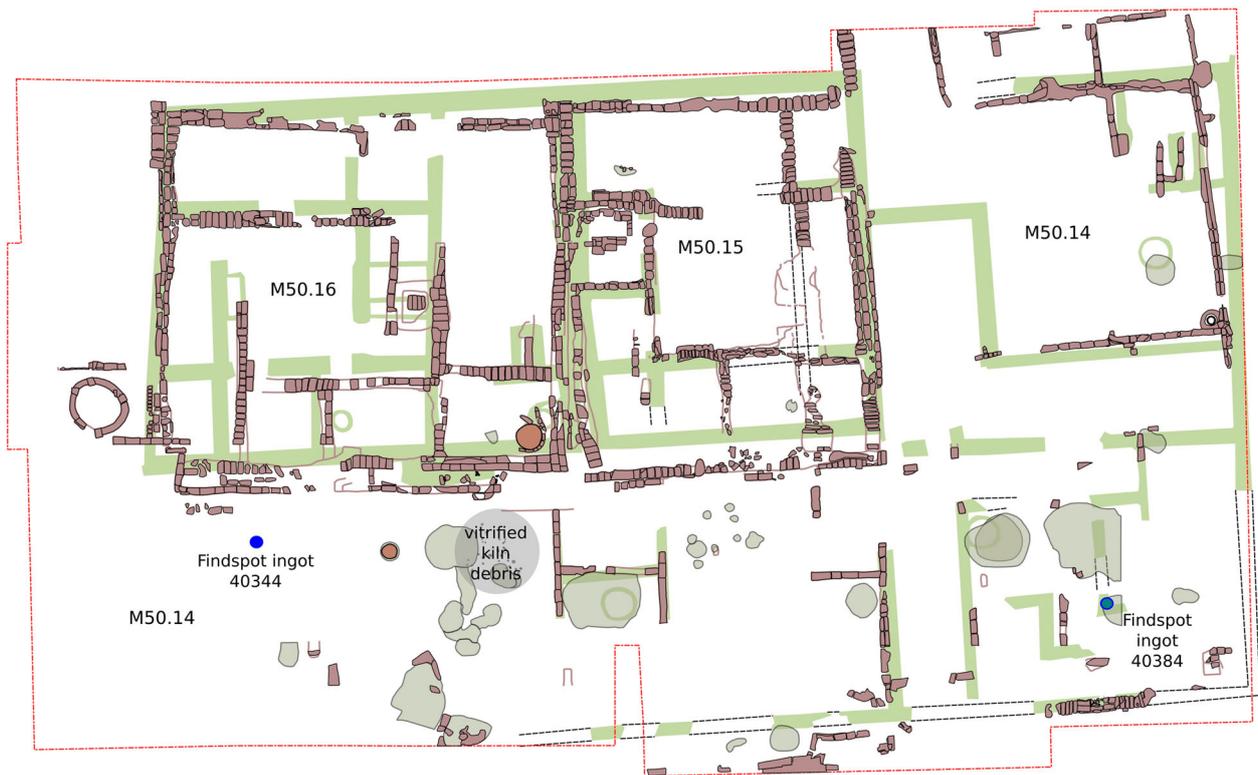
Figure 3. Plan of Amarna site M50.14–16 as excavated in 2014 and 2017, showing the findspots of the two glass ingots and the concentration of vitrified kiln debris. The green outlines are based on the original plan produced by the EES in 1922 (Peet and Woolley 1923). Anna Hodgkinson.

of raw glass. In fact, one large fragment of an opaque blue glass ingot (object no. 40344) has been found to fit more or less exactly into most of these cylindrical vessels. This ingot is therefore a direct parallel to those found aboard the Uluburun shipwreck. A second, smaller, heavily weathered, blue, and almost complete ingot (object no. 40384 – for both objects see Hodgkinson 2015, 284, Figure 7) was also found at the site. These two objects are the only glass ingots from Amarna from a known archaeological context. The site furthermore contained a (mainly superficial) concentration of vitrified oven debris, possibly pointing to a destroyed structure which may have operated at a high-temperature. This concentration of debris was found in the southern courtyard of the houses, alongside a series of shallow pits with ashy fills, which may have been used as fire pits for lampworking (Figure 3). Based on the additional archaeological evidence of metal-working, together with glass- and faience production, and the proximity of this complex to the house of Ranefer and the Grid 12 houses, it is highly possible that these buildings formed an industrial complex in this part of the Main City South.

The Egyptian antiquities law prohibits the export of even the smallest archaeological sample, which means that all analytical equipment has to be brought into

the country. Because of this, the investigation was carried out by means of a mobile pXRF device (ELIO by XGLab) on-site at the excavation house at Amarna in early 2018.

A total of 589 objects from the above workshops and areas at Amarna were analysed, including 22 faience items and 47 fragments of cylindrical vessels and shards of other ceramic vessels with glass adhering to them. The glass objects were selected according to their optical appearance, with a preference for blue or dark-, and mid-blue objects (349 in total: Figure 4).[3] Most glass objects that were analysed came from site M50.14–16, and this workshop, together with the nearby Grid 12, contained the largest number of dark blue glass objects (Figure 5).

For comparative purposes, a set of pXRF analyses was carried out on glass objects from Amarna in the Egyptian Museum and Papyrus Collection of the National Museums in Berlin (see below). This collection contains at least 1,500, glass objects from Amarna, a large number of which are raw glass objects, such as rods, bars, fragments and unfinished inlays. Most of these objects had been brought back to Germany after the excavations carried out at Amarna by L. Borchardt on behalf of the Deutsche Orient-Gesellschaft (DOG: Borchardt and Ricke 1980) between 1911 and 1914. These objects have, unfortunately, lost their archaeological context, probably having been collected as technological samples rather than

Figure 4. The two glass ingots found at Amarna site M50.14–16 in 2014 with ingot fragment 40344 placed into one of the cylindrical vessels found at the site. Anna Hodgkinson.

considered artefacts in their own right. They do not appear in the archival record of the DOG and, in addition, had been mixed up and disassociated from any records during World War II.

The authors analysed a total of 371 of these objects, 163 of which were dark blue in colour (or contained some dark blue) and which were considered raw glass for further processing. Again, these raw glass objects, rods and bar fragments, were selected for analysis based on their colour, which, on observation appeared dark blue. The aim of this pXRF analysis was to find out whether these might be re-assigned to a workshop context based on their transition element pattern and correlation. The same instrument and measurement conditions as used at Amarna were applied in the Berlin storerooms.

Analytical methods

The portable XRF device, which works in a contact-free, non-invasive manner, was equipped with an X-Ray tube with Rh target and an SDD detector, while the X-Ray spot was 1 mm in size. The analyses were run without vacuum or helium conditions.[4] For most objects the analyses were carried out under the following conditions: tube voltage of 50 kV and a tube current of 20μA using 4096 acquisition channels, with an acquisition time of 120 s. Corning A was used as a primary reference standard and was measured for 120 s after every 20–30 samples. See Table 1 for a summary of readings obtained from the Corning A measurements. The data were exported from the proprietary ELIO-software in MCA format and the processing was done using open source PyMCA software. Peak detection was based on Corning A readings, and the "batch fitting" method and background reduction was used for groups of similar objects (based on colour).

The output from PyMCA is a spreadsheet containing the analytical results for each measured element in counts per second (cps) together with the associated standard deviations deriving from the calculation of the signal surface on the sample; i.e. an error deriving
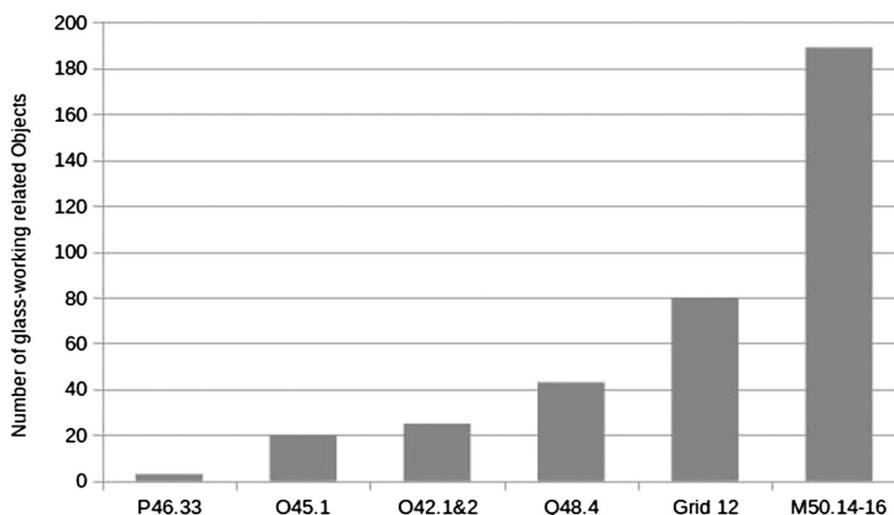
Figure 5. The number of mid- and dark blue glass-working related items analysed by pXRF for each site at Amarna. Only six cylindrical vessel fragments were included from the "palace waste heaps", which is why these are not included in this graph. Anna Hodgkinson.

Table 1. The average values obtained by measuring the Corning A reference standard by pXRF at Amarna in cps, and the consensus values for each element published in Vicenzi et al. 2002.

Element	Corning A, AVG pXRF (120 sec.) in cps	Corning A (Vicenzi et al. 2002) in ppm
Si-K	1068	310883
K-K	1825	23817
Ca-K	5093	35954
Ti-K	1560	4736
Mn-K	4054	7745
Fe-K	5057	7624
Co-K	1151	1337
Ni-K	289	157
Cu-K	10406	9586
Zn-K	621	402
Sr-K	2091	1184
Zr-K	204	N/A
Sn-K	726	1812
Sb-K	3695	13174
Pb-L	1053	928

from the instrument. Results for elements with a standard deviation ratio higher than 1:4 were subsequently dismissed. Since the analyses were carried out without a vacuum atmosphere or helium, it was not possible to gain information on any elements lighter than silicon (Si). Consequently, it was decided to treat the analysis as semi-quantitative, and as an internal comparison of objects from Amarna, rather than to attempt to convert the results into µg/g or % wt values. Thus, the elemental spectrum gained from the analyses includes semi-quantitative information on the following chemical elements: Si, K, Ca, Ti, Mn, Fe, Co, Ni, Cu, Zn, As, Sr, Zr, Sn, Sb and Pb. The only two elements for which nominal ppm values were calculated were cobalt and copper,[5] which can be indicative of the colourants used: cobalt, by a combination of cobalt and copper, or mainly copper (Smirniou and Rehren 2013, 4732).[6] Average values were calculated when objects had been measured more than once, unless a measurement showed a large discrepancy for one or a number of

elements. Since the latter case might point towards a measurement error or an inclusion in the glass, such measurements were not included in the averages calculated. The same was the case if an object had only been measured once, but it did not fall into the broader range of values covered by the majority of dark blue glass objects.

In order to establish to what extent the presence and thickness of the weathered, or corroded surface layer affects the results of the analyses, 29 blue and dark blue objects from site M50.14-16 were cleaned using a Dremel power tool with a diamond glass-cutting head. The weathered surface (less than 1 mm in thickness) was removed to reveal the core glass, and any remaining dust from the surface was wiped off. It was noted that the cps values obtained for the relative intensities of the transition elements (Mn, Ni, Zn) and Co did not vary significantly from the original measurement, and thus it was decided that the remaining analyses were to be done in a non-invasive fashion. See Table 2 for a comparison of average values before and after cleaning for two objects.

Analytical results and discussion

Colourants

When calculating nominal ppm values for Co and Cu from cps values, and following the definition published by Smirniou and Rehren (2013, 4732, see above), the authors discovered that a large proportion of dark blue and blue objects were in fact Co-Cu (between 33 and 51%), or Cu-coloured (between 20 and 33%), rather than purely Co-coloured (between 26 and 36%, of all blue objects analysed for each site) (Figure 6). In numbers, the largest groups of Co and Co-Cu coloured objects came from M50.14–16 and Grid 12. These two sites also yielded

Table 2. The results before and after cleaning using a Dremel diamond tool for two Co- and Co-Cu-coloured glass objects from Amarna M50.14–16 in cps.

Colour	Blue opaque		Blue opaque		Dark blue translucent		Dark blue translucent	
Site	M50.14–16		M50.14–16		M50.14–16		M50.14–16	
Measurement time	300 sec.		300 sec.		300 sec.		300 sec.	
Object ID	40344 original	40344 original normalised counts	40344 cleaned	40344 cleaned normalised counts	41744 original	41744 original normalised counts	41744 cleaned	41744 cleaned normalised counts
Si-K in cps	2378	4.4	1647	3.4	674	3.6	978	4.7
K-K in cps	1266	2.3	1013	2.1	464	2.5	519	2.5
Ca-K in cps	13437	24.8	17701	36.1	5366	28.8	6674	32.0
Ti-K in cps	341	0.6	225	0.5	105	0.6	99	0.5
Mn-K in cps	3361	6.2	2704	5.5	613	3.3	713	3.4
Fe-K in cps	4382	8.1	3388	6.9	3005	16.1	2708	13.0
Co-K in cps	4315	8.0	3574	7.3	729	3.9	762	3.7
Ni-K in cps	3050	5.6	2596	5.3	655	3.5	818	3.9
Cu-K in cps	442	0.8	328	0.7	308	1.7	463	2.2
Zn-K in cps	6140	11.3	4859	9.9	1816	9.7	1840	8.8
Sr-K in cps	6006	11.1	4683	9.6	4502	24.1	4816	23.1
Zr-K in cps	911	1.7	739	1.5	345	1.8	282	1.3
Sb-K in cps	8170	15.1	5462	11.1	0	0.0	0	0.0
Pb-L in cps	0	0.0	89	0.2	73	0.4	172	0.8
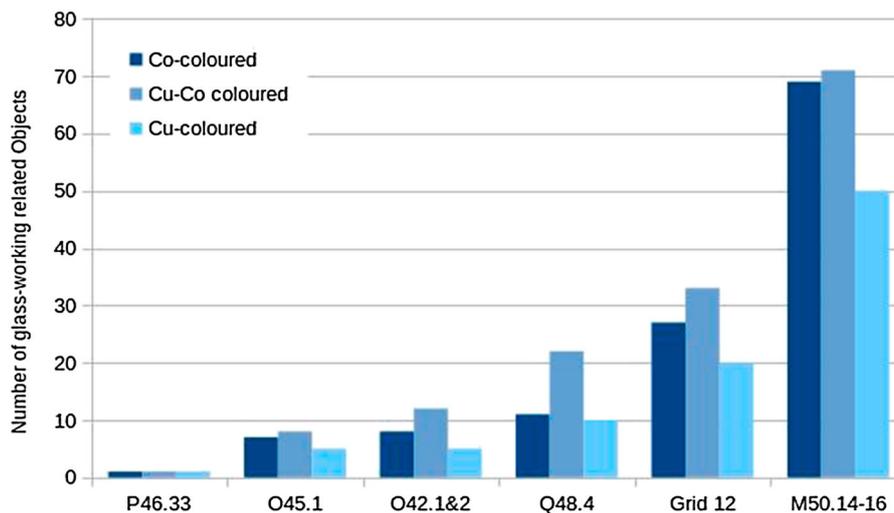
Figure 6. The ratio of Cu-, Co-Cu and Co-coloured glass objects of all mid- and dark blue glass objects analysed for each site at Amarna. Anna Hodgkinson.

the largest numbers of mid- and dark blue glass items overall. However, it was noticed that the largest number of glass objects from O45.1 were obviously copper blue and turquoise in colour, i.e. Cu-coloured. The large fragment of an ingot (object no. 40344) from site M50.14–16 was found to be Co-coloured and opacified with antimony, while the smaller, almost complete ingot (object no. 40384) was coloured with Cu (Figure 4).

Transition elements

The present evaluation of the transition element data relies heavily on the study mentioned above carried out by Abe and colleagues (Abe et al. 2012), during which regional and temporal groups of cobalt types were identified using ternary diagrams based on transition element patterns. However, in this case, the units used were cps, rather than ppm or % wt, and the diagrams in Figures 7–9 contain both Co-coloured and Co-Cu coloured glass objects.

When the authors plotted the Co-Ni-Zn correlation (Figure 7(a)), clusters in the same general area of the "Type A" cobalt, defined by Abe (Abe et al. 2012, 1800, Figure 4(a), 1804, Figure 7(a)), became visible.[7] It is evident that the workshops yielding smaller quantities of glass objects containing cobalt form tighter clusters than Grid 12 and M50.14–16 in the Main City South, which cover a significantly wider area (Figure 7(b)). In addition, some scattering is visible around the general area covered by "Type A" cobalt. In addition, some outliers are visible, especially with regard to workshop O42.1 and 2, making a slight shift in geographical cobalt sources in the area of the western oases possible.

The comparison of the Co-Ni-Zn and Co-Ni-Mn correlation plots (Figure 8(a and b)), highlight the same groups and clusters of objects,[8] although a

wider area is covered in the area of the "Type A" cobalt by the Main City South workshops, i.e. Grid 12 and M50.14–16. There is again some scattering in the area to the left of "Type A", but no distinct groups. The two outliers from O42.1 and 2 are the same objects as have been identified above. Although this may point towards a different source of cobalt and thus a different period of time, it is not possible to differentiate optically between these two blue glass rods from any of the other 18th dynasty rods. There is a level of uncertainty regarding this correlation, as can be seen in Figure 8(a), where an area of those objects analysed by Abe and colleagues, coloured with "Type R" cobalt, falls into the range of the "Type A" cobalt, this being due to the similar amounts of Mn in both object groups.

The same clusters as already identified in the case of the Co-Ni-Zn correlation can be identified in Figure 9 (a and b), which combine the data for only the transition metals, Mn, Ni and Zn. Here, the variability, in particular, of the amount of Zn present in the glass is decisive. Due to the fact that the Ramesside glass and faience investigated by Abe and colleagues can be clearly distinguished from the 18th dynasty glass and faience objects by the fact that they contain far smaller amounts of Zn, the Co-Ni-Zn or the Ni-Mn-Zn correlations appear to be the most useful in separating objects coloured with cobalt from various geographical sources.

Of the cylindrical vessels fragments with adhering glass which were analysed by pXRF, only 26 objects were in fact Co- or Co-Cu coloured, and these came from only two sites at Amarna: six came from the so-called palace waste heaps in the Central City, and 16 were found at site M50.14–16. Both of these sites also contained vessels with turquoise glass, but dark blue was the most prevalent colour. When plotted according to their Co-Ni-Zn and Ni-Mn-Zn correlations
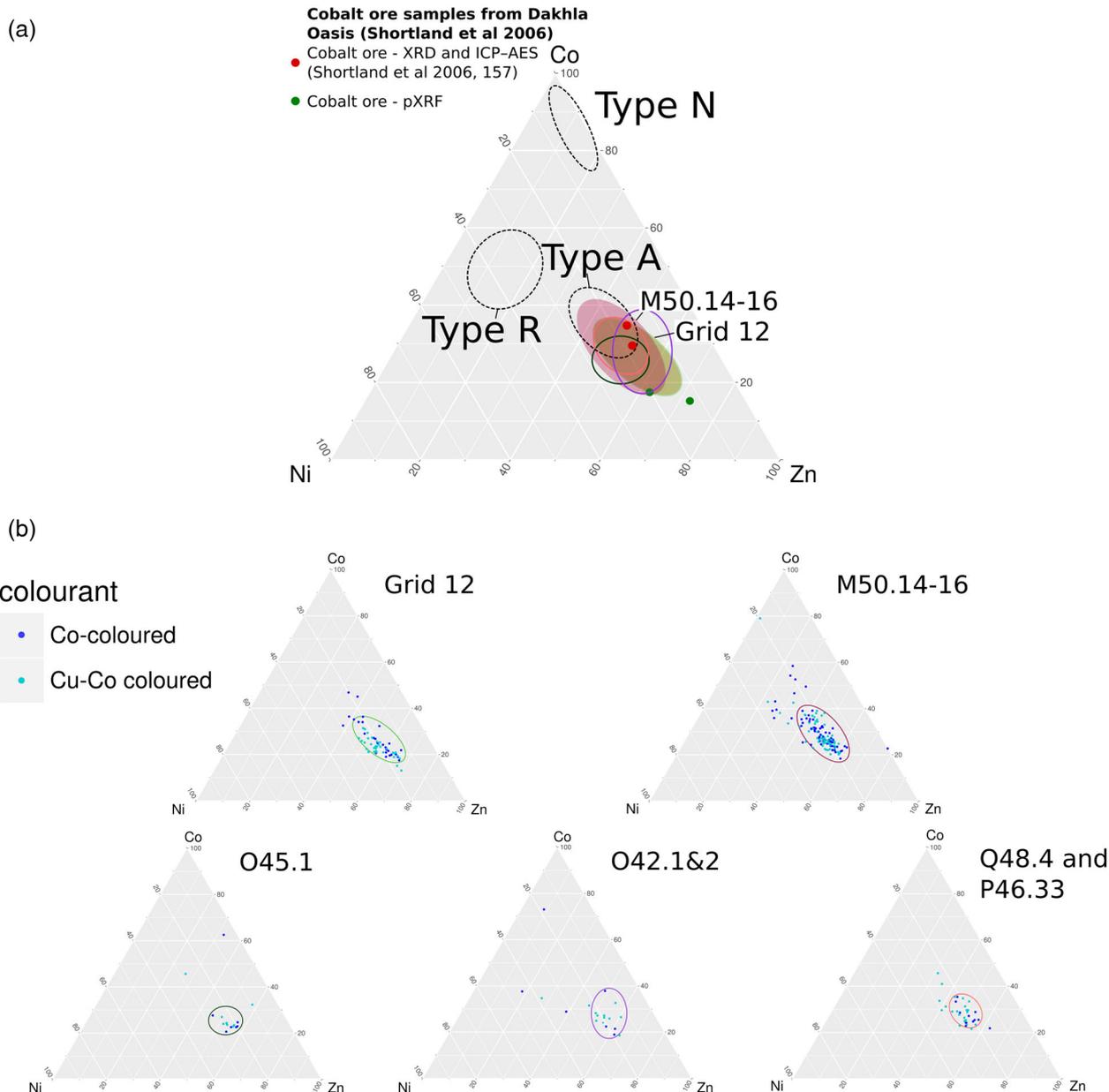
Figure 7. (a) Correlation plot showing the Co, Ni and Zn ratios (in cps) for each site at Amarna as analysed by pXRF, together with the values obtained for the two cobalt ore samples from Dakhla (green: in cps (pXRF), red: in ppm from Shortland, Tite, and Ewart 2006). The dashed ellipses for cobalt "types" are taken from Abe et al. 2012. The colours of the ellipses with solid lines outline the data from the various sites: purple (filled): M50.14–15, green (filled): Grid 12, dark green (not filled): O45.1, dark purple (not filled): O42.1&2 and orange (not filled): Q48.4 and P46.33. Anna Hodgkinson. (b) Individual correlation plots showing the Co, Ni and Zn ratios for each site at Amarna as analysed by pXRF. Anna Hodgkinson.

(Figure 10), it becomes obvious that these vessels, too, fall into the range of "Type A" cobalt. Some scattering can be observed, but it is not possible to say whether or not this is due to the use of a different cobalt source or to some impurities from the ceramic spectrum analysed by the pXRF alongside the glass. It is, however, possible to point out that any dark blue glass ingots produced in these particular vessels were made using the same broad cobalt source.

As stated above, the authors had access to two samples of cobalt alum from Ain Asil near Dakhla oasis. These, too, were analysed by pXRF using the same instrument, measurement conditions and

reference standards as was done at Amarna, albeit in Berlin. The samples were analysed in several places and average values were calculated, and the correlations of these objects with the transition metals are also shown in Figures 7–9(a). They roughly fall within the area of "Type A" cobalt alongside the Co- and Co-Cu coloured glass objects, although with some discrepancy, which is probably due to contamination and heterogeneity in the sample matrix. It thus becomes apparent that the glass objects analysed at Amarna fall into the same area as the alum from near Dakhla oasis. This may indicate that the glass found at Amarna relates mainly to a larger source in the region of Dakhla
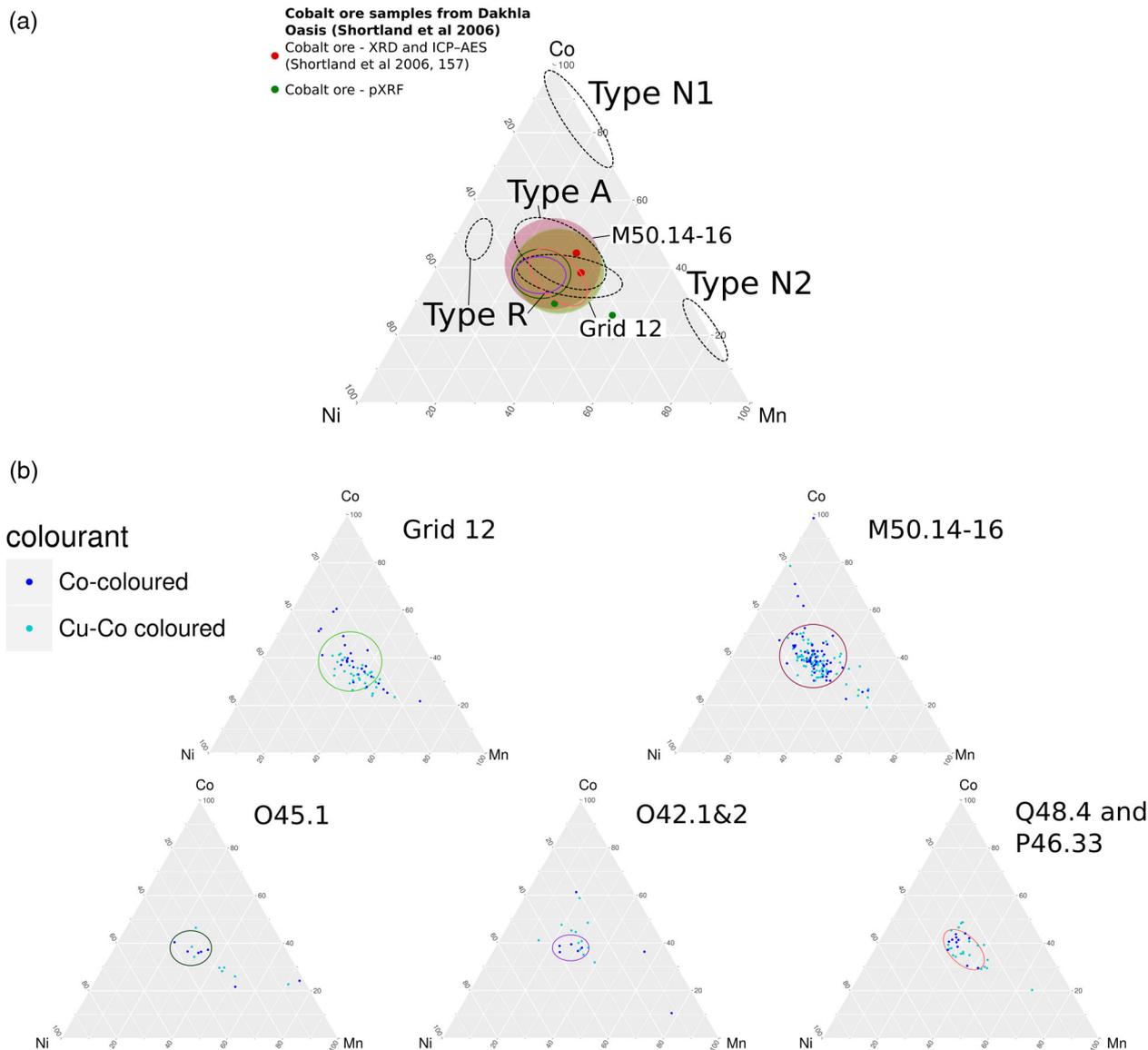
Figure 8. (a) Correlation plot showing the Co, Ni and Mn (in cps) ratios for each site at Amarna as analysed by pXRF, together with the values obtained for the two cobalt ore samples from Dakhla (green: in cps (pXRF), red: in ppm from Shortland, Tite, and Ewart 2006). The dashed ellipses for cobalt "types" are taken from Abe et al. 2012. Note that "Type R" has a low- and a medium-high Mn variant. The colours of the ellipses with solid lines outline the data from the various sites: purple (filled): M50.14–15, green (filled): Grid 12, dark green (not filled): O45.1, dark purple (not filled): O42.1&2 and orange (not filled): Q48.4 and P46.33. Anna Hodgkinson. (b) Individual correlation plots showing the Co, Ni and Mn ratios for each site at Amarna as analysed by pXRF. Anna Hodgkinson.

oasis, but with some cobalt ore also being brought in from other sub-sources for use in the glass workshops.

Comparative analysis of glass from Amarna in the Egyptian Museum, Berlin

As mentioned above, a comparative set of analyses was carried out on glass objects from Amarna in the storerooms of the Egyptian Museum and Papyrus Collection in Berlin. When Co and Cu were converted into nominal ppm values, it became apparent that the larger portion of these objects, 120 in total, were in fact Co-Cu coloured, rather than Co-coloured (only 43 in total) according to the definition by Smirniou and Rehren (2013, 4732). Furthermore, by plotting the transition metal correlations (Figure 11), it can be

observed that while the largest number of these objects fall into the range of "Type A" cobalt, five objects form a group plotting in the low-Zn range, coinciding with the "Type R" range with a slight offset, which is possibly due to the pXRF data being presented in cps, rather than in quantitative values. These five objects are polychrome red, white, yellow and blue mosaic glass strips and rods, dating to the Greco-Roman period, and which also come from Amarna, although they must have come from a later context. Only the dark blue portions of these objects were analysed.

Some of the objects coloured using "Type A" cobalt fall into the broader range as defined by the objects from the Main City South workshops, rather than the narrow clusters described by the other workshops. Its not possible to say whether or not any of the 163
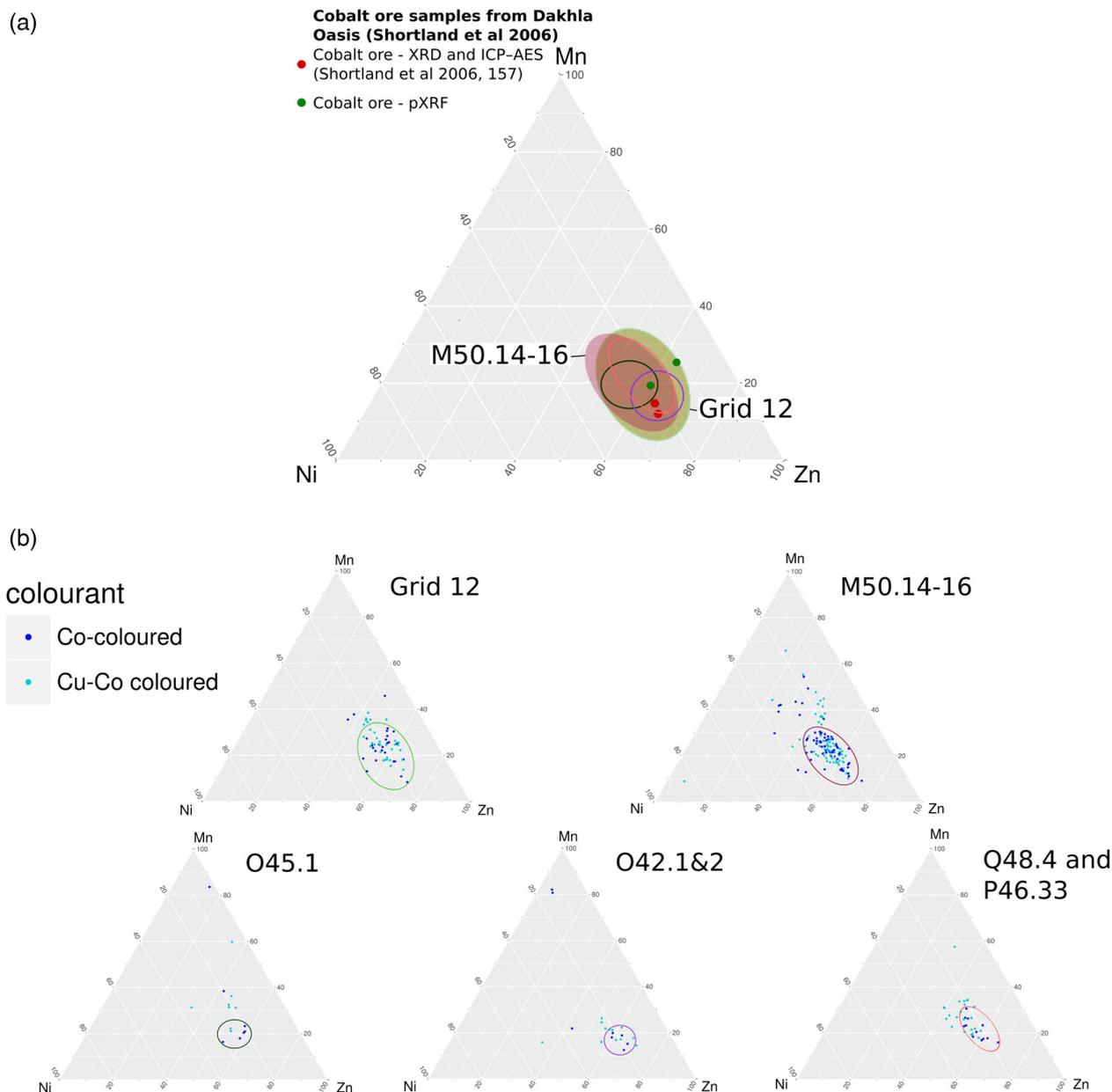
Figure 9. (a) Correlation plot showing the Ni, Mn and Zn (in cps) ratios for each site at Amarna as analysed by pXRF, together with the values obtained for the two cobalt ore samples from Dakhla (green: in cps (pXRF), red: in ppm from Shortland, Tite, and Ewart 2006). The colours of the ellipses with solid lines outline the data from the various sites: purple (filled): M50.14–15, green (filled): Grid 12, dark green (not filled): O45.1, dark purple (not filled): O42.1&2 and orange (not filled): Q48.4 and P46.33. Anna Hodgkinson. (b) Individual correlation plots showing the Ni, Mn and Zn ratios for each site at Amarna as analysed by pXRF. Anna Hodgkinson.

dark blue objects analysed from the Berlin collection can be assigned to any of the physical glass workshops found at Amarna. However, it is possible to say that they all – with the exception of the five Greco-Roman objects –adhere to the same pattern of transition elements associated with the cobalt used at Amarna. While, as stated above, LBA glass from Malqata cannot be chemically distinguished from that found at Amarna (Shortland, Rogers, and Eremin 2007, 787), the Egyptian Museum in Berlin does not hold any glass objects from Malqata. Thus, it is possible to re-confirm the settlement as the original finds location of these objects.

The lighter and alkaline elements and their role in defining the cobalt source

By using a purpose-built pXRF device with vacuum conditions, Abe and colleagues have been able to detect and semi-quantify Mg and Al, and this has not been possible to achieve with the ELIO device used for the above study. By plotting the correlation of Co to Al_2O_3 (both in % wt), it has been possible to differentiate between the "Type A" (18th dynasty) and the "Type R" (Ramesside) cobalt used in glass objects. This type of analysis has not been possible to carry out using the pXRF device used in the present study.
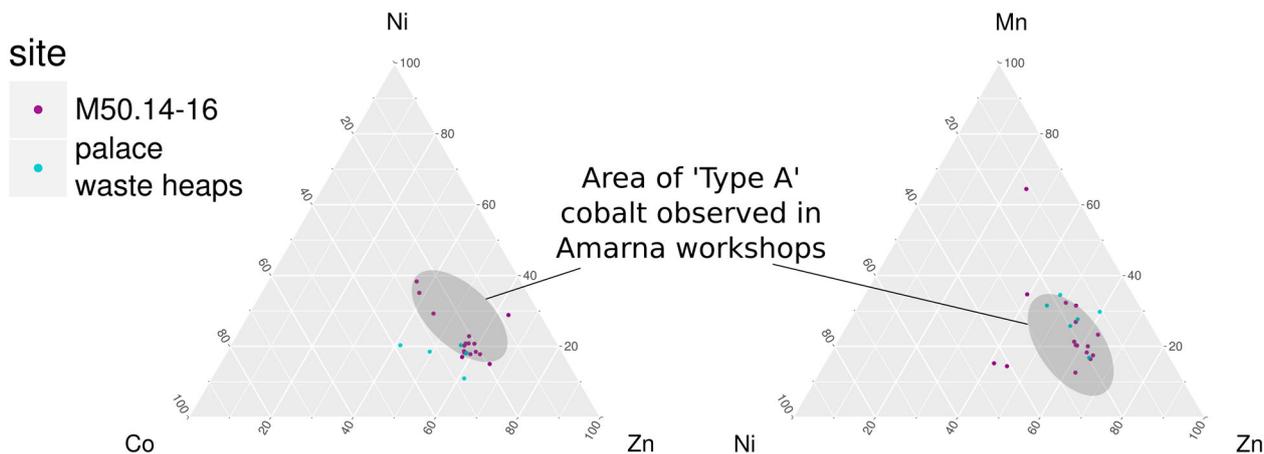
Figure 10. Correlation plots showing the Co-Ni-Zn and the Ni-Mn-Zn ratios for cylindrical vessels containing remains of cobalt-blue glass found at Amarna M50.14–16 and the palace waste heaps, as analysed by pXRF. Anna Hodgkinson.

However, LA-ICP-MS work is planned on the objects analysed in Berlin in order to verify this correlation.

## Archaeological discussion of the results and conclusions

The evaluation of the ternary plots of transition elements indicates the possibility of a generally higher chemical variety of cobalt ore used in the production of dark blue glass in Main City South workshops (Figure 12). This is expressed in the less tight clustering of transition elements in glass objects from these two sites, regardless of whether these objects were coloured by Co or a combination of Co and Cu. This may point to the use of cobalt ore from a larger number of smaller sources belonging to the same general geographical area in the western desert, around the oases of Kharga

and Dakhla. Alternatively, it may demonstrate the influence of the inhomogeneity in the samples of cobalt ore, as well as that of the analytical method on the output.

This potentially greater variety of cobalt used in the Main City South workshops may result from the larger number of dark blue glass samples from this area in contrast to the workshops found in the Main City North. No archaeological evidence points to the former workshops having functioned for a longer or shorter period of time than the latter.[9] However, they do reflect a wider range of other industrial activities, including metal- and stone-working, suggesting them to be more industrial establishments. If Co-and Co-Cu coloured glass was one of the Main City South workshops' main produce, it might also be possible that these workshops received cobalt ore for a longer
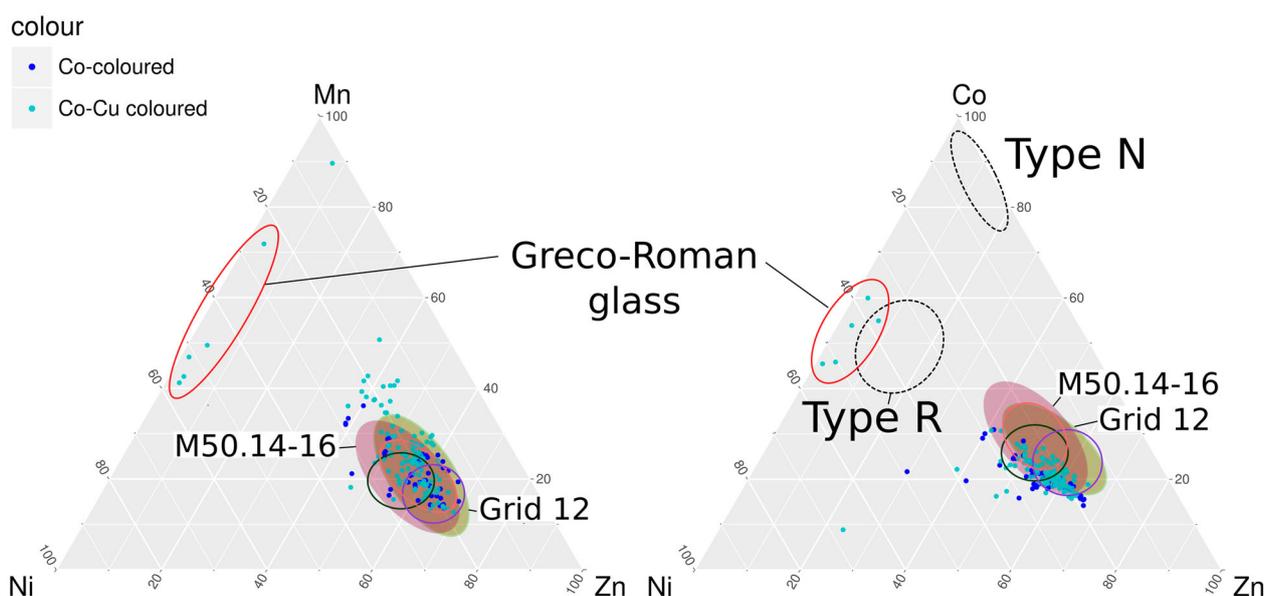
Figure 11. Correlation plots showing the Ni-Mn-Zn and the Co-Ni-Zn ratios for mid- and dark blue glass objects from Amarna, as analysed by pXRF in the Egyptian Museum, Berlin. The colours of the ellipses with solid lines outline the data from the various sites from the analyses conducted on-site: purple (filled): M50.14–15, green (filled): Grid 12, dark green (not filled): O45.1, dark purple (not filled): O42.1&2 and orange (not filled): Q48.4 and P46.33. Anna Hodgkinson.
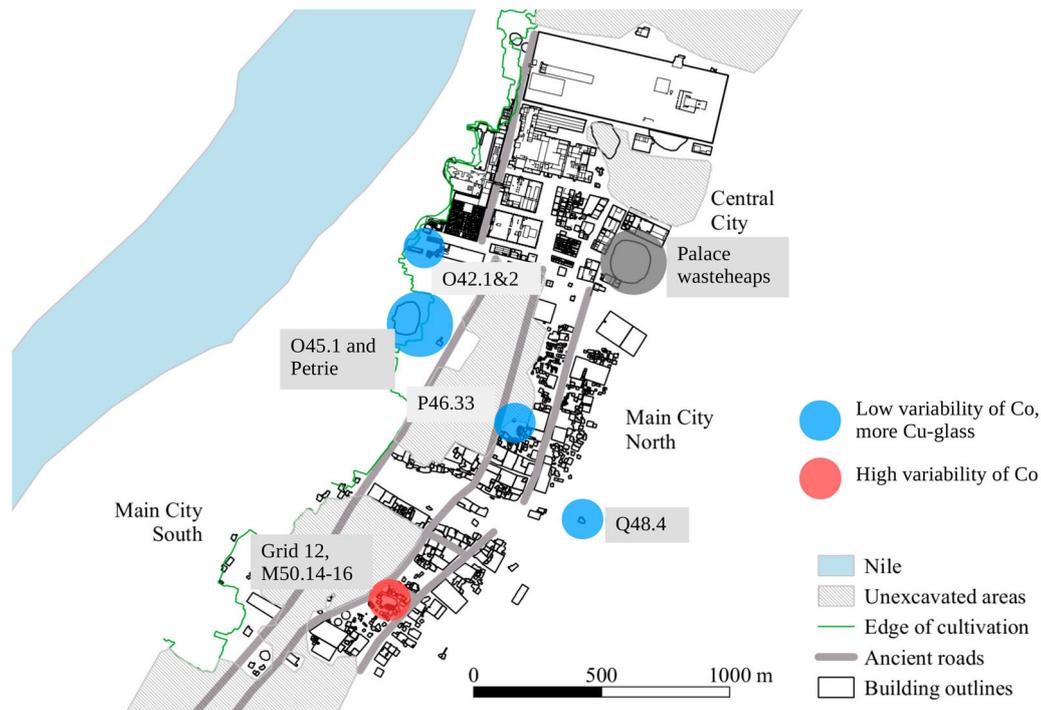
Figure 12. Map of Amarna showing the variability of cobalt used in the workshops at Amarna analysed for this paper. Anna Hodgkinson.

period of time. The cobalt ore would have been provided to the workshops in order to consistently produce dark blue glass, and this may also be related to the presence of the large quantity of cylindrical vessel fragments containing blue glass, regardless of whether this workshop was involved in primary or secondary glass production. This set of workshops may have formed one of the primary production, or processing centres for dark blue glass at Amarna, and would have functioned together with the unknown workshop, the debris of which was found in the so-called palace waste heaps.

In consequence, it may be possible that the smaller workshops of the Main City North, which contained fewer Co- and Co-Cu coloured glass objects in general, used cobalt ore from a single, or more restricted source only. These workshops would thus have specialised in the production of colours using primarily copper as a colourant, such as light blue, turquoise, green and red. It is possible, however, that these workshops produced either a single batch of dark blue glass towards the end of the Amarna period, or received these raw glass objects from elsewhere.

Therefore, we can state that it is possible to identify sub-sources of the same general geographical region as a cobalt source in the workshops of Amarna, although these sub-sources cannot be pinpointed. Rather more, it is possible to characterise the glass workshops of the settlement tentatively by their use of cobalt from various sub-sources.

The comparison of the various ternary plots describing the correlations of cobalt and transition elements obtained through pXRF in Amarna and Berlin with the published data signifies that it is possible – using pXRF analysis for cobalt and transition metals (Ni, Mn, Zn) only – to identify sub-sources of cobalt ore used during the 18th dynasty in Egypt. It is, however, also possible that light elements may deliver further information on the grouping of objects coloured with cobalt from a variety of sources.

Unfortunately, it has not been possible to re-assign the museum objects from Amarna without an archaeological workshop context to their original find locations. However, it has been possible at least to associate these objects with the site of Amarna as a whole by means of their transition element pattern.

Further work is planned on the subject of cobalt ore use in the glass workshops of Amarna, including comparative analyses using LA-ICP-MS, PIXE and PIGE technologies, in addition to a quantification procedure for the pXRF data, which will allow further statistical evaluation of the semi-quantitative data using PCA, for instance.

Notes

1. This is based on the optical and literature analysis of c. 9,000 raw glass objects from Amarna in over 10 museums and at the site and does not include any finished objects. See also Hodgkinson (2019b).
2. These two alum samples are K3 and K6 in Shortland, Tite, and Ewart (2007).
3. A number of glass objects from other colours were also analysed, although these do not feature in the present analysis.
4. The ELIO device has no vacuum option, and helium is difficult to source in Egypt. The equipment used

belongs to the Staatliche Museen zu Berlin (National Museums in Berlin), notably the Ägyptisches Museum und Papyrussammlung (Egyptian Museum and Papyrus Collection) and the Rathgen-Forschungslabor (Rathgen-Research Laboratory).

5. This was done according to the average Co and Cu pXRF readings for the Corning A standard using consensus values published in Vicenzi et al. (2002), since this reference standard best reflects the Co and Cu values of Late Bronze Age Egyptian glass. The obtained readings for Co and Cu were thus converted to nominal ppm values by multiplication with the following factors: Co = 0.861, Cu = 1.085. See table 1.

6. Smirniou and Rehren (2013, 4732) define Co-Cu coloured glass as containing at least 300 ppm of Co and 850 ppm of Cu, while Cu-coloured glass contains less than 100 ppm of Co and above 3500 ppm of Cu, with Co-coloured glass containing at least 300 ppm of Co and less than 850 ppm Cu. The authors furthermore defined: Cu > 10000 ppm and Co < 1000 ppm = Cu-coloured and Co > 300 ppm with Cu > 3500 ppm, but Cu also < 6000 ppm = Co-Cu coloured, in addition to Co > 100 ppm, but < 300 ppm and Cu < 3500 ppm = Co-Cu coloured.

7. It is necessary to bear in mind that the values published in Abe et al. (2012) are quantitative, rather than cps values, which is the reason for a slight shift in the data presented in the ternary diagrams in relation to the "Type" areas defined be Abe and colleagues.

8. Because of the cps (rather than ppm) values used, it was not necessary to multiply the Mn values by 3 (as done by Abe and colleagues when using % wt or ppm values) in order to obtain the same cluster location in the ternary diagram.

9. Although M50.14–16 may post-date O45.1, the former being built on an older waste pit and the latter dating to the earlier stages of the Amarna Period.

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Disclosure statement

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