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Simply red: A Late Bronze Age glass ingot from Amarna

Caroline M. Jackson [a,*], Paul T. Nicholson [b]

[a] Department of Archaeology, University of Sheffield, Minalloy House, 10-16 Regent Street, Sheffield S1 3NJ, UK
[b] Department of Archaeology and Conservation, School of History, Archaeology and Religion, Cardiff University, John Percival Building, Colum Drive, Cardiff CF10 3EU, UK

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ABSTRACT

Chemical analysis of a visually opaque, turquoise-blue ingot from the Late Bronze Age royal capital at Amarna, housed in the Garstang Museum, University of Liverpool, shows an excess of copper colourant which indicates that the intended colour was opaque red. Trace element analysis places the location of manufacture in Egypt, and the date, finds location, dimensions and analysis suggest that the glass was made at Amarna. This, coupled with other recent finds of ingots/part ingots at the site, suggests that Amarna was producing not only blue glass, but a variety of different colours in this early period of Egyptian glassmaking. Other royal locations, such as the later site at Qantir where red glass predominates, appear to specialise in specific colours. These findings suggest that the political and economic focus of different ruling elites during the New Kingdom (1550–1069 BCE) influenced the volume and range of colours of the glasses manufactured.

1. Introduction: Glassmaking in Late Bronze Age Egypt

Studies of early Egyptian glass have rapidly developed in the last thirty years to the extent that it is generally accepted that by the 18th dynasty of the New Kingdom, and certainly the Amarna period (from c.1352 BCE), glass was manufactured in Egypt as well as in the Near East (Mesopotamia) (Jackson and Nicholson, 2007; Smirniou and Rehren, 2011). This glass was made using quartz or sand and the ashes of desert plants high in soda. The resulting glass was a soda-lime silica glass, which was generally highly coloured deep blue, turquoise, opaque white, yellow or red by the inclusion of metal ions in the glass (Lilyquist and Brill, 1993).

Where in Egypt the glass was produced has led to some speculation. It is now clear, however, that there are a number of New Kingdom sites which may have evidence for primary and/or secondary glass production. These include Malkata (possibly the earliest), Gurob, Lisht and Menshiyeh (for a discussion see Nicholson, 2007: 20-22). The most substantial evidence has been found at Amarna, ancient Akhetaten (18th dynasty; c. 1352–1332 BCE), and Qantir, ancient Pi-Ramesse (19th dynasty; primarily c.1279–1213 BCE), which appear to have been major glass production centres in New Kingdom Egypt. Refractory remains recovered from Qantir suggest red and blue glasses coloured with copper were produced, although no glass furnaces have been identified. At Amarna glass furnaces have been uncovered, and waste indicative of glassmaking and working (Nicholson, 2007; Jackson and Nicholson, 2007; Smirniou and Rehren, 2011). Cobalt blue and copper blue glasses were almost certainly produced at Amarna, but evidence for the production of other glass colours at the site has not yet been elucidated.

The excavated evidence indicates glass production involved the melting of the raw materials in crucibles in furnaces. For red glass at Qantir, Rehren and Pusch (2008) propose a two-stage process, whereby the colour (mineral or metal) was added to a primary 'frit' which was ground up, remixed and then re-melted to form a glass. At Amarna, and possibly other earlier sites such as Malkata, it is not clear whether this two-stage process, in the way Rehren and Pusch describe, was also the method used to produce glass (Nicholson and Jackson, 2018).

The presence of cylindrical ceramic vessels with glass adhesions, and fully formed ingots, at Amarna, Qantir and from the Uluburun shipwreck, suggests the glass was often worked elsewhere. However, finds of ingots are rare in most contexts and particularly in Egypt. A single red ingot was recovered in the 1930′s from Qantir (Hamza, 1930). Despite finds of other production debris in more recent excavations at the site (Pusch and Rehren, 2007), no further whole ingots have been found. A very small number of red and turquoise-blue glass ingots from elsewhere in Egypt have been noted, but many were not found in datable contexts (see discussion in Nicholson, 2007: 23). This is not unexpected as ingots would have been valuable commodities, used for long-distance trade and exchange. Compositional analysis has identified artefacts in the

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* Corresponding author.
E-mail address: c.m.jackson@sheffield.ac.uk (C.M. Jackson).

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Mycenaean world made of Egyptian glass (Walton et al., 2009; Jackson and Nicholson, 2010). Therefore, the presence of another Egyptian ingot, from Amarna and now held in the Garstang Museum at the School of Archaeology, Classics and Egyptology (SACE), University of Liverpool, is of interest.

1.1. Glass production at Amarna

It is accepted that cobalt blue glass was manufactured at Amarna using a cobalt alum, a mineral primarily composed of aluminium sulphate containing cobalt, probably obtained from the Kharga or Dakhla oases in the desert to the east of Amarna (Kaczmarczyk, 1986; Jackson and Nicholson, 2007; Shortland et al., 2007). Access to the mineral cobalt and its use were directly controlled, a royal prerogative, which may link this material more directly to glass production, which was probably also controlled at the royal city (Nicholson, 2007: 7). However, glass working into objects may have happened both in royal (for 'high status' items) and 'private' workshops (Hodgkinson, 2016). The mechanism or route of supply of glass to these workshops is at present not known.

Glass production evidence at Amarna comprises at least one large circular furnace thought to have been used for primary production as it was also associated with semi-fused glasses (some blue, some without added colour) and drips and trails of glass (Jackson and Nicholson, 2007). Ceramic cylindrical vessels, which may have been used as melting vessels or crucibles, bearing the remains of mainly deep-blue cobalt and copper-coloured glass residues are also present (Jackson and Nicholson, 2007; Smirniou and Rehren, 2011; Merkel and Rehren, 2007), supporting in situ production of both colours. These vessels generally have diameters between 160 and 240 mm and an average wall height of 100 mm (Nicholson, 2007: 123), which define the shape and dimensions of the ingots. The profile of these ingots would mimic the cobalt blue ingots found in the Uluburun shipwreck (maximum dimensions 70 mm high × 150 mm diameter), which were generally larger than the copper blue ingots (typically > 130 mm diameter × > 50 mm) (Nicholson et al., 1997).

Chips of ingots have also been reported amongst glass-working debris (Hodgkinson, 2016: 4). Other glass rods, trails and melted fragments destined to be used as decorative elements are also present (Jackson and Nicholson, 2007; Hodgkinson, 2016) in opaque white, opaque yellow, opaque powder blue, opacified with antimony (sometimes in conjunction with lead), and as trails of red glass (Jackson and Nicholson, 2007). Red glass also contains antimony, but this was used to control the internal redox rather than as a crystalline opacifer (Cable and Smedley, 1987). These opacified glasses may have been imported to Egypt as a small number of pieces have been identified as originating in Mesopotamia (Varberg et al., 2016), but local production using imported minerals cannot be ruled out (Smirniou 2012: 388).

1.2. Colour specialisation and Late Bronze Age glass production

Rehren (2000) and Pusch and Rehren (2007) use the evidence of finds of predominantly red glass manufacturing evidence at Qantir and cobalt blue glass at Amarna to argue for glass manufactories specialising in particular colours. Certainly, at Qantir the evidence indicates colour specialisation based on the addition of copper, and its association with contemporary large copper-melting and casting installations in the same strata would support this (Rehren and Pusch, 1997). Smirniou (2012: 388) suggests the same model can be applied at Amarna for blue glass using copper and cobalt. The evidence from other New Kingdom sites such as Gurob, Lisht and Menshiyeh is ephemeral and in some cases, such as at Menshiyeh and Lisht, the occurrence of evidence for primary glass production is extremely limited (Keller, 1983: 20, Smirniou et al. 2018). The evidence from Malkata is also inconclusive (Nicholson, 2007: 20) and so cannot be used to support this colour specialisation model. It is therefore likely other colours were produced at Amarna and Qantir, as these sites are not contemporary but belong to different dynasties, despite the perceived preference for particular glass colours at each site. The dominance of cobalt and copper blue glass at Amarna fits with the predominant glass colours used for New Kingdom artefacts, but the emphasis on red glass production at Ramesside Qantir cannot currently be paralleled in contemporary artefactual evidence such as vessel decoration or jewellery. Red glass is relatively rare during the New Kingdom.

In the light of this evidence, this paper provides a detailed typological and compositional study of this 'new' glass ingot from Amarna in order to determine its provenance, and throw light on the organisation of glass production in New Kingdom Egypt. These findings have the potential to influence our understanding about glass as a commodity and how its production was influenced by different ruling elites or political events through time.

2. Materials: the Garstang ingot from Amarna

The glass ingot, which is the focus of this paper, is presently held in the University of Liverpool's Garstang Museum. Its acquisition is documented in the Liverpool University Yearbook for 1920–21 (page 14), as part of a donation from the Egypt Exploration Society, which notes 'including a group of objects illustrating the famous glass manufactures of Tell el Amarna, from the raw flint to the finished bead' (Nicholson, 2007: 23). This supposes that the ingot originated in Amarna and is associated with glassmaking (Jackson et al., 1998; Jackson and Nicholson, 2007; Smirniou and Rehren, 2011).

A little more than half the ingot (E5654) remains, although it is unclear whether the fracture is a 'modern' break as the broken face is much less corroded than the exterior surfaces (Fig. 1). The underside of the ingot, where it has been in contact with the ceramic mould, is uneven. It has a crater on its upper surface which suggests either that it was in contact with something whilst molten or that the glass contracted irregularly upon cooling. The estimated ingot diameter is 139 mm and the maximum thickness of what remains is 37.8 mm. Its present weight is 600 g (Nicholson, 2007: 23). It is similar in size to some of the copper blue ingots found on the Uluburun ship, shown to originate from Egypt (Nicholson et al., 1997; Jackson and Nicholson, 2010; Lankton et al., 2022).

The glass is semi-opaque, turquoise-blue, which is a colour not typically seen in contemporary glasses. Nicholson (2007: 23) tentatively proposes that it may be the product of recycled copper glass because of its 'muddy' colour. Kemp (in Nicholson, 2007), however, suggests that the ingot's morphology reveals no clues as to whether the glass was manufactured in the mould or is the product of re-melted glass.

3. Methods: compositional analysis of the ingot

Chemical analysis was undertaken to determine the composition and colourants of the ingot. Major and minor elements were analysed with a JEOL JXA-8200 electron microprobe housed in the Microanalysis Research Facility, University of Nottingham. The probe was run at an accelerating voltage of 20 kV, beam current of 5nA, and X-rays were counted for 20 s (100 s for magnesium) and 10 s for background (20 s for magnesium). A defocused electron beam (diameter of 50 mm) was used to reduce volatilisation of light elements. The Corning B glass standard was used to check for accuracy and precision and to monitor drift (see Meek et al., 2012: 790). The precision and accuracy data have been published in Jackson and Cottam (2015), as the ingot sample was included in the same analytical run reported in the paper.

Trace elements were determined using a CETAC LSX-100 laser ablation system in conjunction with an Agilent 7500c ICP-MS instrument at Imperial College, Ascot. Samples were mounted and ablated under an atmosphere of argon. Ablation conditions were: laser spot operated at 10 Hz and a laser power delivery of ~ 0.2 mJ in raster mode. The gas flow rate was 1.38 $\mathrm{l\,min^{-1}}$ and the plasma at a power of 1500 W. Analyses were calibrated against NIST SRM 610 glass reference material,

Fig. 1. The Amarna ingot from the Garstang Museum. Top left – base view (in contact with the crucible), Top right – top view (air contact), Bottom left – profile view, Bottom right – close-up of glass profile (photographs CMJ).

doped with a nominal concentration of 500 ppm for most trace elements, and using the consensus values (Pearce et al., 1997). NIST610 was measured throughout the duration of the session to allow for correction of instrument drift. Detection levels were calculated using a blank and only those above mean background concentrations (3δ, 99 % confidence) are reported. Precision and accuracy are reported in Jackson and Nicholson (2010) as the sample was analysed at the same time.

Photomicrographs (and spot analyses to confirm compositions) were taken using an FEI Inspect F scanning electron microscope (SEM) with attached X-act energy dispersive spectrometer (EDS) at the Centre for Archaeology, Historic England, Portsmouth.

4. Results of the analysis and key observations

4.1. Glass composition and colour

The composition of the Garstang ingot is shown in Table 1, alongside other glass ingots and manufacturing debris from Amarna and Qantir, in a variety of colours (Freestone, 1987; Jackson and Nicholson, 2007; Schoer and Rehren, 2007).

The Garstang ingot is a soda-lime glass, with concentrations of potash and magnesia above 1.5 wt%, typical of Late Bronze Age Egyptian glasses manufactured using a soda-plant ash alkali (Sayre and Smith, 1967; Lilyquist and Brill, 1993). It falls into the higher potash range (>2 wt%) more typical of copper coloured blue glasses; low potash glasses tend to be mostly, although not exclusively, coloured with cobalt. The concentration of alumina is low, but within the accepted range for Egyptian Bronze Age glasses, suggesting the use of quartz rather than sand as the glass former. Silica is also low, below 60 wt%, but this is accounted for by the higher concentrations of the colouring elements, also seen in red glasses of this period (Table 1).

The ingot is coloured by copper (Lilyquist and Brill, 1993). In turquoise or blue glass, copper is usually present at 2-3 wt% and is in an oxidised cupric (Cu^{2+}) state. However, the ingot has a copper oxide concentration of 11.42 wt%; it also has a high antimony oxide at 1.62 wt %. This composition is typical of Late Bronze Age Egyptian red glasses rather than dark blue or green glasses coloured with copper (see Table 1).

In red glasses, a greater degree of control of raw materials, colouring elements and furnace conditions are needed than in the production of copper blue glasses. Copper is present in the reduced cuprous (Cu^{+}) state to minimise the effect of the blue or green base glass matrix, and in a reducing atmosphere some copper separates from the melt as metal microparticles or as cuprous oxide crystals (Cu_2O). This causes the red colour (Bandiera et al., 2020). To reduce the copper further, internal reducing agents such as charcoal, antimony or sometimes iron could be added to the glass (Cable and Smedley, 1987). If cuprite glass is heated in oxidising conditions, the cuprite is oxidised to CuO, which dissolves and produces a translucent turquoise-blue colour. Whether resulting from glass manufacture or reworking, the ‘muddy’ or ‘dirty’ turquoise-blue colour of the ingot is due to a combination of very high concentrations of copper, the mix of oxidation states of the copper present (Freestone 1987, 183), and the presence of high concentrations of antimony. The latter would act as an opacifer, producing calcium antimonate crystals and hence affecting the translucency of the ingot. This can be seen in Fig. 2 which shows calcium antimonate crystalline structures. These are typical of those seen in 18th dynasty Egyptian glasses and the complementary experimental glass melts by Lahlil et al 2010. Fig. 2b shows orthorhombic structures which are characteristic of $Ca_2Sb_2O_7$ and Fig. 2a and c show calcium antimonate opacifiers in rosary shape aggregates which Lahlil et al. suggest are not compatible with in situ crystallization but with the introduction of ex situ synthesized $Ca_2Sb_2O_7$ crystals into a fully formed glass (in the Sb^5 form) (Lahlil 2010, Figs. 3 and 4). No crystalline dendritic copper crystals typical of

Table 1
Compositional analysis of the Garstang ingot (far right) and comparative glass data.

Cat/ accession No.	**HZ 024**	**HZ 022**	**GT 504**	**PA 024**	**HZ 014**	**HZ 013**	**GT 174**	**GT 198**	**GT 175**	**EA 1894.8–16.241**	**EA1924.10–11.124**	**EA1984.8–16.193**	**UC 22917b***	**Liverpool**
Site	**Qantir[1]**	**Qantir[1]**	**Qantir[1]**	**Qantir[1]**	**Qantir[1]**	**Qantir[1]**	**Qantir[1]**	**Qantir[1]**	**Qantir[1]**	**Amarna[2]**	**Amarna[2]**	**Amarna[2]**	**Amarna[3]**	**Amarna**
Colour	**Red**	**Red**	**Red**	**Red**	**Light blue**	**Dark blue**	**Dark blue**	**Purple**	**Bottle green**	**Red**	**Red**	**Red**	**Red**	**Turq-green**
Form or Container	Plate	Plate	Crucible	Crucible	**Glass fragment**		Crucible	Crucible	**Interface glass**	**Flat strip**	**Curved Strip**	**Trailing rod**	**Rod**	**Ingot**
SiO_2	62.7	64.6	55.3	56.3	62.8	66.0	61.9	65.3	54.9	57.79	54.36	59.58	63.68	**55.5**
Na_2O	16.3	15.7	16.8	15.7	19.1	13.9	16.5	17.7	12.1	14.31	16.61	17.15	14.79	**14.1**
CaO	7.93	6.58	6.38	6.20	7.04	8.33	5.88	6.47	4.95	7.84	9.12	8.87	7.50	**9.02**
K_2O	1.93	2.13	1.73	1.81	1.99	1.46	0.41	1.54	3.19	1.70	1.65	1.74	1.31	**2.04**
MgO	3.46	4.03	3.21	3.92	4.34	3.75	3.85	3.78	2.47	4.10	3.85	3.32	2.65	**3.30**
Al_2O_3	0.38	0.47	0.43	0.41	0.39	3.13	3.36	0.50	9.91	1.09	0.76	0.47	1.03	**0.73**
Fe_2O_3	0.25	0.31	0.29	0.30	0.27	0.94	2.10	0.33	4.69	0.69	0.65	0.40	0.61	**0.44**
TiO2	0.04	0.07	0.03	0.03	0.04	0.12	0.13	0.07	0.90	–	–	–	–	**0.09**
Sb_2O_5	–	–	1.50	1.94	–	0.35	1.73	0.02	0.28	0.98	1.67	–	–	**1.62**
MnO	–	–	–	–	–	0.12	0.64	0.64	0.07	–	–	–	–	**0.07**
CuO	3.01	3.58	11.22	10.13	2.10	0.06	0.03	0.02	3.06	10.95	10.07	5.76	4.34	**11.42**
CoO	–	–	–	–	–	0.07	0.35	–	–	–	–	–	–	**b.d.**
SnO_2	0.20	0.28	1.31	1.33	0.19	–	–	–	0.17	–	–	–	–	**0.42**
ZnO	–	–	–	–	–	0.11	0.15	0.02	0.04	–	–	–	–	**n.d.**
P_2O_5	0.15	0.21	0.19	0.23	0.20	0.17	0.07	0.16	0.80	–	–	–	–	**n.d.**
SO_3	0.23	0.20	0.39	0.48	0.30	0.17	0.22	0.15	0.06	0.52	0.45	0.42	0.27	**0.36**
Cl	1.06	1.08	1.06	0.72	0.97	0.31	0.81	1.25	0.28	0.58	0.80	1.10	0.94	**0.56**
PbO	–	–	–	–	–	–	–	–	–	–	–	–	–	**0.06**
Total	97.64	99.24	99.84	99.50	99.73	98.99	98.13	97.95	97.90	100.55	99.99	98.81	97.37	**99.57**

Compositional analysis of the Garstang ingot (far right) and comparative glass data. Published data from the analysis of Ramesside Egyptian glass from Qantir[1] (Schoer and Rehren, 2007: 180); Amarna samples held in the British Museum[2] (Freestone, 1987: 176) and the Petrie Museum of Egyptian Archaeology, University College London (UCL)[3] (Jackson and Nicholson, 2007: 182). – not measured or below detection.

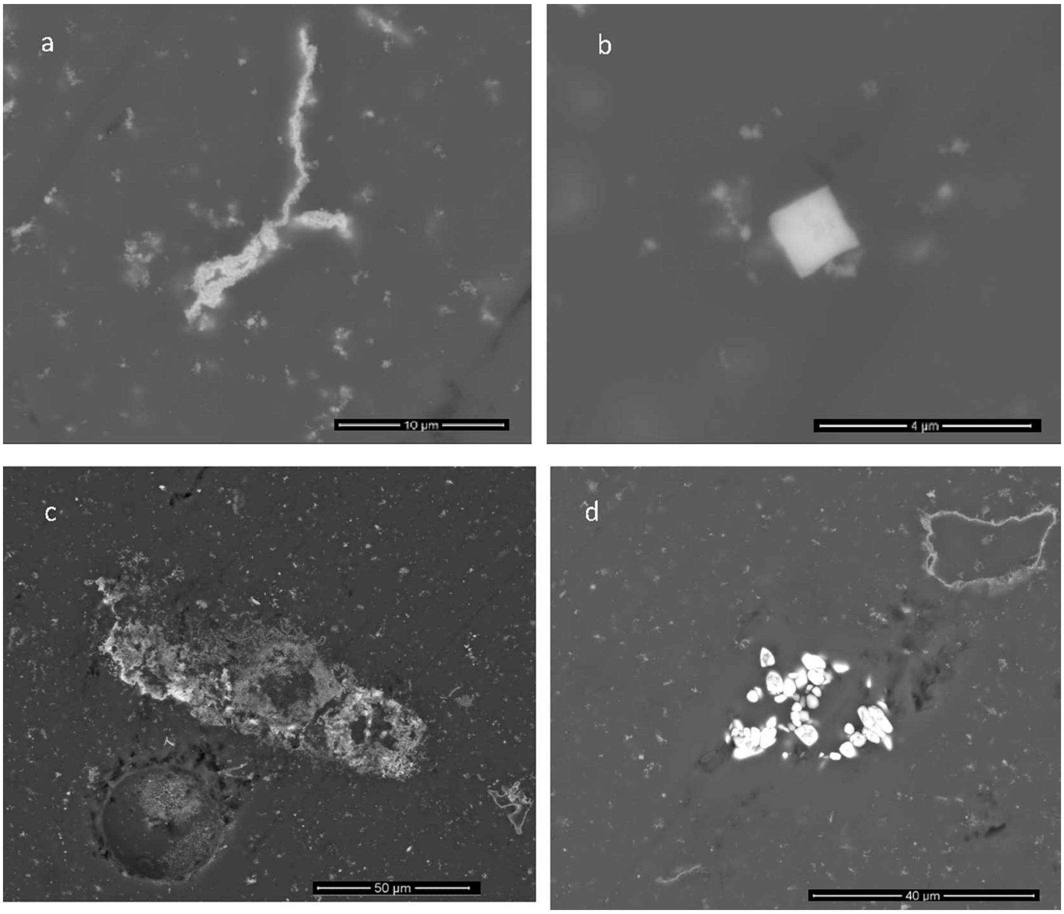

Fig. 2. SEM backscattered electron images. a and c) calcium antimonite crystals forming rosary shaped aggregates, causing opacity in the glass, b) isolated orthorhombic calcium antimonite crystals, d) clusters of tin crystals.

opaque red glasses were observed in the SEM photomicrographs. All the copper had dissolved into the glassy matrix to produce a blue-green colour, although there were rare isolated clusters of tin crystals suggesting this might have been added separately (Fig. 2d).

The composition of the Garstang ingot is similar to other red glasses (strips and rods) from Amarna, especially samples EA 1984.8–16.241 (flat strip) and EA1924.10–11.124 (curved strip) (Table 1). These samples also have high concentrations of copper and antimony, and similar concentrations of soda, lime, potash, magnesia and alumina. The Garstang ingot and these other glasses have no measurable lead concentration, which is generally typical of red glasses appearing in the ancient Near East from the 15th century BCE (Freestone, 1987).

Some glass recovered from crucibles found at Qantir also contains high concentrations of copper and antimony (Table 1). However, up to 1.3 wt% tin oxide is also present in these samples, a concentration not seen in the Amarna samples (no detectable tin) or the ingot (tin oxide at 0.42 %), suggesting that the red glasses melted at Qantir were coloured using tin bronze at approximately 1:10 tin:copper, whilst 'low' tin/tin-bronze, or more probably a mixture of metals, was used in the ingot at Amarna (see Fig. 2d).

The results of the analysis presented here therefore indicate that the most likely explanation for the colour of the Amarna ingot from the Garstang Museum is that it is a failed red glass.

4.2. Provenance

Shortland et al. (2007) demonstrated that there was a compositional difference between Late Bronze Age glasses found in Egypt and in Mesopotamia, based on the trace elements La, Ti, Cr and Zr. The Egyptian glass analysed in their study included samples of colourless glass rods from Amarna (held in Copenhagen Museum) and some colourless and blue glasses from Malkata of a slightly earlier date. Glasses from Mesopotamia included samples from Tell Brak in northern Syria and Nuzi in northern Iraq. This data is plotted here, alongside some blue Uluburun ingots (Jackson and Nicholson, 2010). The Garstang ingot falls well within the trace element distribution attributed to Late Bronze Age Egyptian glass (Fig. 3, supplementary data).

5. Discussion

5.1. Assessing the production evidence

The failure to produce a red glass could arise through a number of different technological routes, all of which have implications for whether red glass was being made or manipulated at Amarna. Thus, the ingot could be:

a) an import to the site from another production location in Egypt

In this case, the glassworkers at Amarna would have obtained the ingot in its present opaque, turquoise-blue state. This, however, is unlikely: i) 'muddy', opaque turquoise-blue is not a colour that is generally considered to be in the Egyptian glassworkers' palette, neither for vessels, inlays nor jewellery; ii) the ingot was made in Egypt and at present there is no evidence for other contemporary sites producing glass ingots; iii) red glass is difficult to produce, and hence potentially of greater value than blue glass, and so would be far more desirable as a gift from another Egyptian elite.

b) Melted waste ingot chips or re-melted cullet (broken or waste glass), cast into an ingot

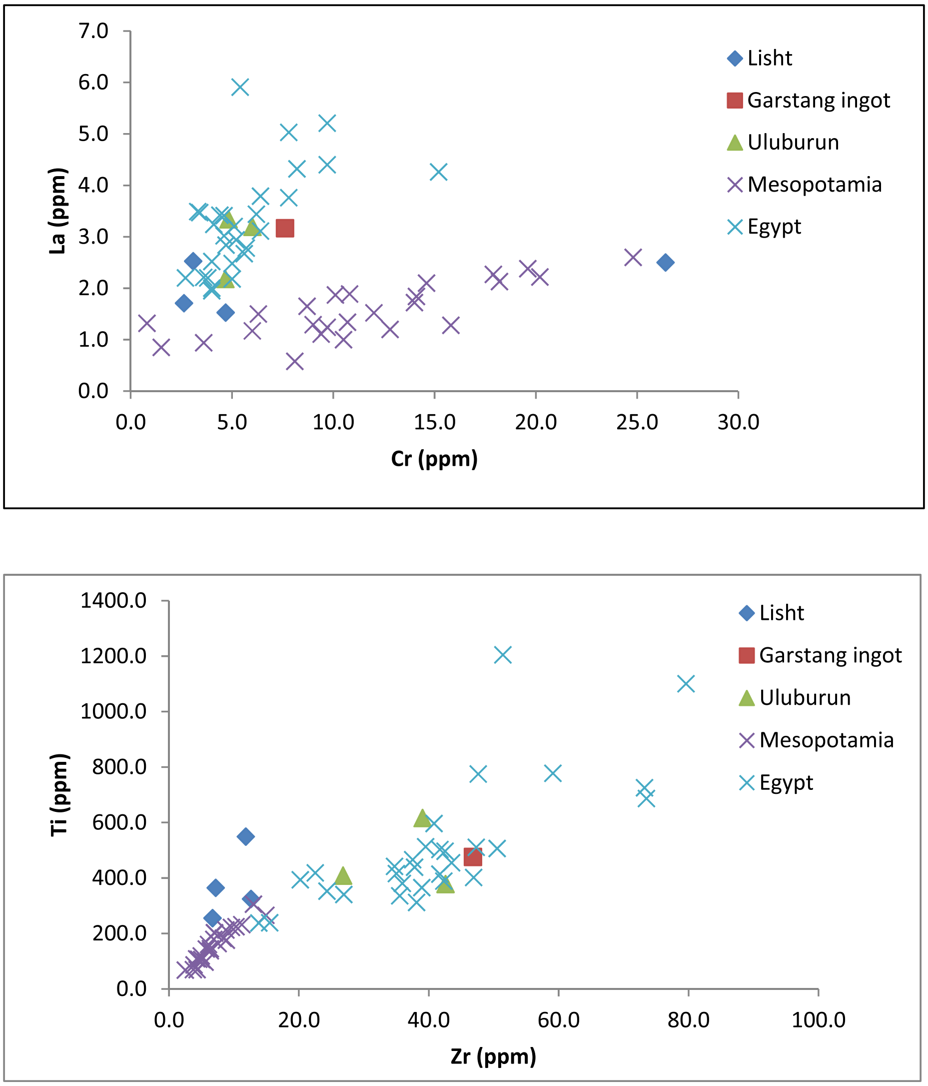

Fig. 3. Trace element ratios for La and Cr (top) and Ti and Zr (bottom) for glass found in New Kingdom Egypt and contemporary glass from Mesopotamia (from Shortland et al. 2007), compared to the compositions of the ingots from the Uluburun shipwreck (Jackson and Nicholson, 2010) and the Garstang ingot.

Reworking or re-heating at low temperatures for long periods, or in oxidation conditions that were unfavourable for the maintenance of the red colour, may have made the glass turquoise-blue (Freestone, 1987: 183). However, it is unlikely that chips from fully-formed ingots of red glass would be re-melted to form another ingot, as even small pieces of red glass could be used directly as decorative elements. Red glass was not generally used for monochrome vessels, consequently monochrome red vessels would rarely be available for recycling. As red is usually used as a decorative element on other glasses it would be too difficult to recycle from polychrome cullet.

c) The result of failed red ingot production at Amarna

The most obvious explanation is that the Garstang ingot is a failed attempt to produce a red glass from the raw materials. This may have been the result of the inexperience of the glassmakers, or because of poor control of reducing conditions within the furnace, or upon cooling. Once spoiled, this glass would have been very difficult to rescue and the glassmaker would only have known it had failed once the ingot had been cast and cooled. It is very unusual to find a nearly whole ingot at the site, as these were valuable commodities. This failed ingot may have been discarded as it did not conform to the usual palette of colours used in the New Kingdom.

5.2. Where in Egypt was it produced?

Amarna is a known production site for glass ingots. Although a large proportion of this glass was blue, there is no reason to suppose that the glassmakers did not also produce copper red glass. The supporting evidence for this hypothesis is as follows:

5.2.1. Ingot size and shape

The dimensions of the ingots found on the Uluburun shipwreck match those of the ceramic ‘crucibles’ found at Amarna and therefore can be used as a proxy for the size of the Amarna ingots (Fig. 4). The Garstang ingot falls within this size range. The ingots and ceramic ‘crucibles’ from Qantir fall within the same range of diameters, but are taller, indicating a change in the volume of glass produced through time.

5.2.2. Composition

The chemical composition of the ingot is typical of New Kingdom glass. Coloured with copper, it is similar in composition to other red glass strips and trails found at Amarna (Table 1). The compositions of glass in the crucibles from the later Ramesside capital suggest a slightly different colouring technology was used at the later Ramesside capital using a higher ratio tin bronze, an alloy which may have been readily available.

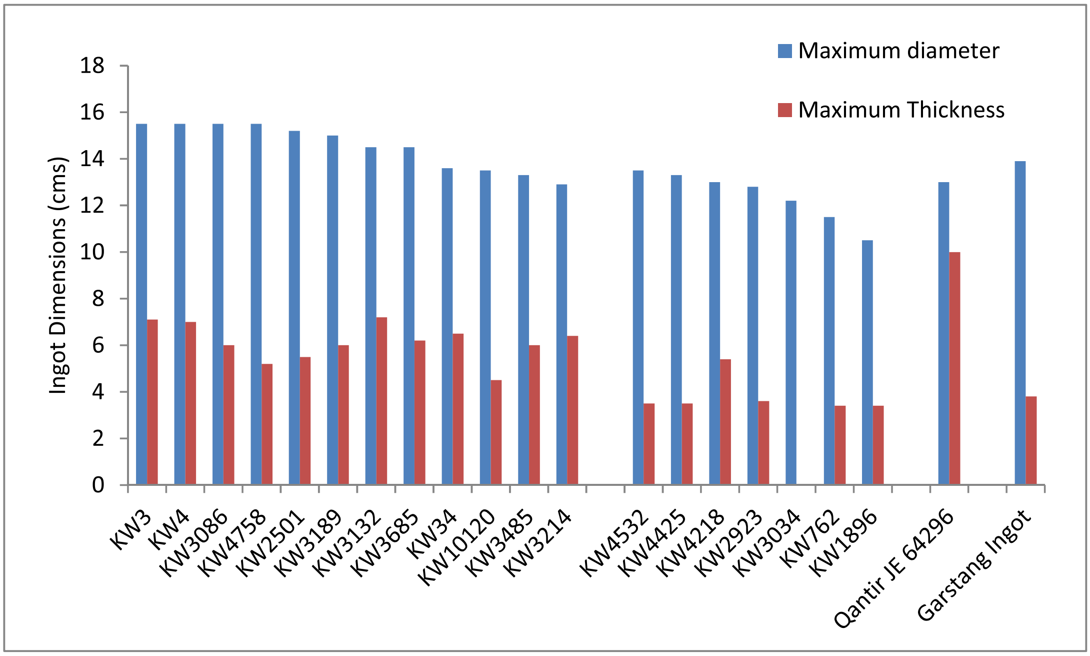

Fig. 4. Dimensions of the Uluburun ingots (prefix KW; cobalt blue glass to the left (KW3 to KW3214)), copper blue to the right (KW4532 to KW1896)) compared to the ingots from Qantir and the Garstang shown at the far right.

5.2.3. *Date and location*

Finally, the Garstang ingot was found at the short-lived capital at Amarna, where glass is known to have been produced. Glass was not widely made, and the required knowledge and expertise were not shared by many. Presently, no glass-making sites contemporary to Amarna have been found in Egypt. Thus, it is likely that the royal city may have been the only Egyptian centre producing glass at that time.

Together, these strands of evidence provide a persuasive argument that the Garstang ingot was produced at Amarna.

6. Concluding thoughts: Implications for development of Late Bronze Age glass production in Egypt

Each of these strands of evidence gives an insight into glass technology and the organisation of glass production at Amarna and also in New Kingdom Egypt.

6.1. *Glass production in royal centres and colour-centred complexes*

Published finds to date suggest that Late Bronze Age Egyptian glass manufacture was a royal prerogative and a high-status industry under elite control, taking place in cities that were royal centres. Excavated evidence for glass making from Malkata (reign of Amenhotep III, c. 1390–1352 BCE), then Amarna (Akhenaten, c.1352–1336 BCE) and much later at Qantir (Ramesses II, c. 1279–1213 BCE) supports this model, as it shows that the location of production followed the sequential relocation of the royal centre over time. With the likelihood of royal control, it might therefore be expected that a variety of colours were produced at each site to satisfy a demand for polychrome items. Colours such as red and yellow required expert knowledge and technological sophistication in production. A range of colours would also have been desirable as part of the glass repertoire, to enhance the owner's and also the pharaoh's status. As these cities were also major manufacturing centres for other goods, such as metals, ceramics and stoneworking, the potential existed for transfer of associated knowledge, materials and skills to the glass industry from other technologies.

If this were the case, Amarna as a 'colour-centred' complex (Rehren, 2000: 22) may be reviewed. Whilst it is likely that Amarna produced larger volumes of blue glass compared to other colours, and so could be regarded as a centre specialising in blue glass (Shortland et al., 2007), this may be easily explained by observing that blue glass dominates not only local vessel and jewellery production, but it was also the predominant colour of the Uluburun glass ingots, which were destined for export. Its dominance may be because blue glass was relatively easy to manufacture, it embodied and enhanced prestige, and symbolised fertility and birth (Aufrére 1998, Bianchi 1998). The new evidence presented here suggests that the glassmakers also attempted to produce red glass. Finding only one ingot is not unusual and in fact the discovery of an ingot is itself remarkable given the value of glass. Other potential part-ingots and glass manufacturing waste have also been recovered from Amarna. These include a semi-fused white glass, opacified and decolorised with antimony and identified as working waste, in the Petrie collection in London (Smirniou and Rehren, 2011); and ingot fragments of various colours at glassworking sites at Amarna (Hodgkinson, 2016). Therefore, it seems other glass colours were also made at this royal city.

6.2. *The development of New Kingdom glass technology in context*

Recent analysis has shown that glasses were being produced in Egypt as early as the reign of Thutmose III (c. 1479–1425 BCE), much earlier by decades than has previously been anticipated (Nicholson and Jackson, 2012; 2013; 2015). However, glass production at Amarna in the 14th century BCE was still in its relative infancy and this may explain the presence of failed glass, as the glassmakers were still experimenting and developing their skills. It is during and after this nascent phase that that the colour palette and hence technology in glass (as with faience) started to expanded rapidly (Patch, 1998).

By the time the Ramesside capital at Qantir was increasing in size and importance in the 13th century BCE, glass was more common, the glassmakers' skills honed, and the technology probably more developed. This backdrop, of a developing city strategically placed in Lower Egypt looking out to the Mediterranean, with new building programmes and a large military presence from the expanding Ramesside army, influenced what was made there. Excavations at Qantir show evidence for large-scale, copper-melting installations, partly in response to a demand for weaponry and chariots for the military stationed in the city (Pusch, 1996). Copper, and bronze, was therefore readily available for colouring glass. Red glass, produced in volume, in particular seems to have been the focus of production, which is difficult to explain as it is a relatively rare colour in vessels and jewellery at this time. One possibility to explain its predominance is that it was used in this rapidly developing city in architectural decoration, and to furnish inlays for weaponry/military furniture produced on site. Bright red glass would be very highly sought after and a very visible display of power and wealth.

Amarna, although also a rapidly built city and new capital, was not strategically placed for controlling the Mediterranean, and appears to have been ruled by a pharaoh who was not predisposed to military expeditions. Excavations at Amarna have not uncovered a large military base such as that seen at Qantir. There is much less evidence for large copper-melting installations or for the city receiving significant consignments of copper via the Mediterranean. Re-working copper may have been less important for military ware and this, coupled with a glass industry that was still in its relative infancy in Egypt, may explain why blue rather than red glass was the focus of production. Blue was also the predominant colour of glass traded or exported as diplomatic gifts to the Mycenaean world, where it was re-melted to produce glass inlays and jewellery. At Amarna, red glass may have been produced and used locally primarily for vessel decoration, jewellery and inlays in furniture, and so would have been only a small portion of a repertoire of glass colours, dominated by blue glass.

Therefore, the political and economic changes throughout the Late Bronze Age period, including the changing geopolitical focus of the different ruling regimes of the New Kingdom, influenced the character of the cities they built, the focus of manufacturing they relied on, and hence the nature of the glass produced. These reasons together may explain in part the different types of manufacturing evidence recovered at Amarna and Qantir; the development of a technologically advanced, two-stage production sequence for red glass by the 19th dynasty; and the changing emphasis on different glass colours at the two royal centres over time.

Note

All dates quoted in the text follow those given in Shaw 2000.

CRediT authorship contribution statement

Caroline M. Jackson: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing - original draft, Writing - review & editing. **Paul T. Nicholson:** Resources, Conceptualization.

Declaration of Competing Interest

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

Data availability

No unpublished data was used for the research described in the article.

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Appendix A. Supplementary data

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