

DIRECT EVIDENCE OF PRIMARY GLASS PRODUCTION IN LATE BRONZE AGE AMARNA, EGYPT*

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This paper presents direct archaeological evidence for the primary production of glass at the LBA site of Tell el-Amarna, in the form of numerous finds of semi-finished glass. The diagnostic microstructural and chemical composition of these finds is presented alongside macroscopically similar finds, of shapeless lumps of finished white glass. The semi-finished glass was found to contain numerous inclusions of residual quartz and newly formed lime-rich crystal phases, but no added colorant. However, several samples of semi-finished glass have antimony oxide levels comparable to those of finished white glass, suggesting that the opacifier was added to the initial glass-making batch. The results are discussed in comparison with the evidence for glass-making from Qantir – Pi-Ramesse, identifying some close technical similarities, which indicate that the same technological processes were used at both sites for the production of glass.

KEYWORDS: GLASS, GLASS-MAKING, EGYPT, LATE BRONZE AGE, AMARNA, ELECTRON MICROPROBE ANALYSIS

INTRODUCTION

Glass and glass workshops in the LBA Near East and Egypt

There is abundant evidence that glass was being produced and worked during the Late Bronze Age (LBA), as attested by the numerous glass artefacts that have been found in Mesopotamia, Egypt and the Eastern Mediterranean. It is widely accepted that regular glass production must have started in Mesopotamia around 1550 BC (Moorey 1994, 193), but no direct evidence for LBA glass production from raw materials is known from anywhere in Mesopotamia. Finds from Tell Brak (Oates *et al.* 1998), in what is now Syria, are the closest to localizing Mesopotamian glass-working, but have so far failed to demonstrate its primary production at this site (Henderson 1998). It is generally assumed that glass-working then spread to Egypt, with Tuthmosis III's military campaigns in Mitanni and his import of 'Mesopotamian' glassworkers to Egypt around 1480 BC (Petrie 1926, 229; Oppenheim *et al.* 1970; Nicholson and Henderson 2000)—as indicated, for instance, by the Mesopotamian style of the earliest glass objects found in Egypt (Nolte 1968; Lilyquist and Brill 1993, 23), or the possible affiliation of a glassworker in Amarna to Mesopotamian material culture (Shortland 2009, 109). However, glass objects were soon made in genuinely Egyptian style, indicating their manufacture within Egypt and probably by Egyptian

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artisans, and several glass workshops have been identified archaeologically in Egypt. Evidence for glass-working elsewhere during the LBA includes numerous glass objects from Greece in a uniquely Mycenaean style, strongly suggesting that they were manufactured somewhere in the Aegean world; most recently, Panagiotaki (2008) reports archaeological evidence for a LBA glass workshop in Knossos.

The long-distance trade in LBA glass is documented both archaeologically and in pictorial and written sources. The Uluburun shipwreck, dated to around 1300 BC and found eight miles south-east of the town of Kas in modern Turkey, was carrying, amongst many other things, around 175 glass ingots, most probably en route to the Aegean (Pulak 1998, 190; Pulak 2008, 299). The Amarna letters, dated to the mid-14th century BC, refer most frequently to the import of glass from eastern countries into Egypt, with at least one instance of the export of glass objects from Egypt (Moran 1992), and Egyptian tomb paintings record such deliveries in detail, with the carriers of what looks like glass ingots wearing Syrian dress and hairstyles (Brock 2000).

Recently, Rehren *et al.* (2001, 233–4) and Pusch and Rehren (2007, 161–3) have suggested an outline model for the LBA glass industry. This model suggests that a number of primary glass-making workshops in both Egypt and Mesopotamia were producing monochrome glass ingots as an exchange item, and were possibly specializing in just one or two colours that reflected local raw material availability and technical skills, in addition to the generic copper blue, which was probably produced in every glass-making site. These primary producers were linked through an LBA network facilitating the exchange of elite goods and services (Sherratt and Sherratt 1991). That network was ensuring that the secondary glass workshops and artistic studios, which were working glass into polychrome objects, had access to glass in all available colours.

Several LBA glass workshops are known to have been making glass objects, such as Tell Brak in northern Mesopotamia or Tell el-Amarna, Malkata, Lisht and Menshiyeh in Egypt (Nicholson 2007, 13–24), and have been mostly identified by fragments of glass and half-finished objects, together with characteristic glass rods, probably used for both core-forming and bead-making. However, very little archaeological evidence is known for the actual primary production: glass-making from its raw materials. Crucibles, ingot moulds, vessels and glassy slag pointing to primary glass production have been excavated at the New Kingdom sites of Amarna, Lisht and Qantir. The finds from Qantir – Pi-Ramesse have been comprehensively studied to the extent of demonstrating direct evidence for primary glass-making there (Rehren and Pusch 2005; Pusch and Rehren 2007).

Recent analyses of Mycenaean glass (Panagiotaki 2008; Walton *et al.* 2009) have shown that some of the raw glass that the objects had been made from had been produced in Egypt and some in Mesopotamia, while stylistic analyses suggest that the objects were manufactured locally in Greece, thus pointing to secondary glass-working sites there, such as the ones recently identified at Tiryns (Panagiotaki *et al.* 2005) and Knossos (Panagiotaki 2008). These finds strengthen the model in which only a few primary glass production sites existed, and glass was traded in the form of ingots from the primary production centres to secondary glass workshops scattered around the Mediterranean, and extend it to include the Aegean world.

It had long been assumed that Amarna was one of the sites for Egyptian glass-making. Although the finds excavated there by Petrie—such as semi-finished vessel fragments, rods and beads (Petrie 1894; presented by Stern and Schlick-Nolte 1994)—mostly point to glass-working, Petrie had suggested early on that there was also primary glass production at Amarna, based on his understanding of the ‘frits’ that he found in ceramic vessels (Petrie 1894, 26). This was subsequently accepted by Turner (1954), Kaczmarczyk (1986), Nicholson *et al.* (1997) and Rehren *et al.* (1998), among others. Most of this, however, was based on circumstantial evidence, such as the presence of cylindrical crucibles used for glass ingot production and thought to

represent the final stage in primary glass-making (Rehren 1997), more or less enigmatic finds of 'frits' and other intermediate materials only tentatively associated with glass-making (Tite and Shortland 2003; Shortland *et al.* 2006). The only direct evidence for glass-making at Amarna so far appears to be the find of a single fragment (TA22) of semi-finished glass (Jackson and Nicholson 2007, 109–10, 115) among the newly excavated material from site O45.1. A pair of furnaces excavated by Nicholson in the 1990s at site O45.1 are said to have been used for glass-making (see, most recently, Nicholson 2007), but other possibilities for their interpretation exist (Rehren 2010).

The almost complete lack of direct and substantial evidence for the primary production of glass anywhere in the Near East constitutes a major obstacle in our understanding of the organization of the LBA glass industry. It also hinders our understanding of the role of glass in connecting the three main cultural regions of the time: Mesopotamia, Egypt and the Aegean world. This paper now presents numerous finds of semi-finished glass, constituting direct evidence for and adding to our existing knowledge of primary glass production in Amarna, Egypt.

Stages in the primary production of LBA glass

Coloured glass can be made in a one-step process fusing together the necessary raw materials (Turner 1954, 443T; Jackson *et al.* 1998). However, practical considerations such as the volume of unreacted batch material or crushed semi-finished glass relative to the depth of the cylindrical crucibles and the thickness of the finished glass ingots (Merkel and Rehren 2007, 217, fig. 26; Pusch and Rehren 2007, 153), textual indications from Mesopotamian cuneiform tablets from the first millennium BC (Brill 1970), even though they should be interpreted with some caution (Nicholson 2007), and the archaeological evidence from Qantir all make us favour a model in which there were at least two stages in LBA primary glass production. This paper attempts to show that also at Amarna a semi-finished glass was first produced in some quantity before it was melted into glass ingots.

In a suggested two-stage process, the raw materials (that is, the plant ash and crushed quartz pebbles) were first melted and fused together in ceramic vessels to form a colourless semi-finished glass. This semi-finished glass is thought to have formed at relatively low temperatures, as indicated by numerous residual quartz particles from the initial charge and the chemical composition of the surrounding melt. It is often chemically less homogeneous than finished glass, and contains less calcium oxide, both indicative of a relatively low melting temperature (Rehren 2000a; Tanimoto and Rehren 2008). The reaction vessels and glass crucibles found in Qantir and the crucibles from Amarna contain a lime-based parting layer first identified and studied by Turner (1954), and further analysed by Rehren (1997) and Schoer and Rehren (2007). Experimental work (Merkel and Rehren 2007) confirmed Turner's original assumption that the parting layer was used to facilitate the removal of the glass from the vessel and to prevent contamination of the glass batch by the ceramic. It would also have contributed to the overall lime content of the final glass melt, through partial absorption (Rehren 2008).

The pre-fused semi-finished glass was then removed from the initial vessel in which it was made, most likely crushed and then re-fired in a cylindrical crucible at a higher temperature, possibly with additional flux, to form an ingot of fully fused homogeneous glass free of quartz inclusions or gas bubbles.

It is still uncertain whether the colorant was mixed with the initial raw materials or added to the crushed semi-finished glass during the second stage, or whether there even was a third stage where the colorant was added. It is possible that this was done differently at different workshops

and for different colorants. This stage of adding colorants to the base glass and melting it to monochrome ingots is represented in the archaeological record by the cylindrical crucibles. Within the wider picture of the LBA glass industry, this is considered the final step of primary glass production (Rehren 1997), since all traded glass we know of from the LBA is in the form of fully coloured ingots or finished artefacts such as beads and vessels.

Glass-making and glass-working at the site of Amarna

Amarna was the capital of ancient Egypt during the reign of Amenhotep IV, later known as Akhenaten. The city was founded around 1350 BC and was abandoned 20 years later, when Tutankhamen—Akhenaten's successor—returned to the old capital of Memphis soon after his ascendance to the throne (Shaw 2000, 290). During these brief 20 years the city flourished: it became a metropolis with large and important buildings—temples, government establishments and palaces, as well as extended living quarters for workmen—and a rich variety of artefacts and structures preserved in the archaeological record (Kemp 1989).

The site was excavated since 1887 and by a succession of German and British teams. Petrie's excavations in 1891 and 1892 discovered evidence of faience and glass manufacturing, making Amarna for more than a century the most important site of Late Bronze Age Egypt for the study of the production of vitreous materials (Petrie 1894; Turner 1954; Tite 1987; Nicholson 1996; Shortland 2000). After the discoveries of glass waste, Petrie (1894) and then Turner (1954) were the first to discuss possible primary glass production in Egypt.

Petrie excavated what he describes as the sites of 'three or four glass factories and two large glazing works' (Petrie 1894, 25). In these sites, Petrie found fragments of glass waste, glass frit, frothy and semi-fused pieces of glass, fragments of ceramic vessels ('pans') where the frit was fired, ceramic cylindrical jars (crucibles) with remains of glass or drips of glaze running out, coloured glass rods, as well as numerous fragments of finished glass objects such as vases and beads (Petrie 1894, 26). Petrie's glass-related finds from Amarna are now stored at a number of museums, including the Ashmolean Museum, the British Museum and the Manchester Museum, while the majority is at the Petrie Museum of Egyptian Archaeology, University College London. These finds have been studied for over a century, and provide the most detailed information currently available about Egyptian glass-working techniques (e.g., Tatton-Brown and Andrews 1991; Stern and Schlick-Nolte 1994).

Turner (1954, 440T) was the first to identify the cylindrical crucibles as vessels used to melt coloured glass. He also showed by experiments using modern materials that Amarna-type glass could be produced in a one-step melting process (Turner 1954, 443T). Later, Nicholson and Jackson (1998) conducted an experiment based on a replica of excavated furnaces from Amarna, showing that these furnaces were suitable for glass-making. Turner (1954), though, did not question Petrie's suggested two-step glass-making process, based on an initial fritting of raw material in shallow pans. He remains careful (Turner 1956, 293T) in attributing the idea of a two-stage recipe in Egyptian glass-making to Petrie (1894), without giving his own comment or discussing the Amarna material any further. Rehren and Pusch (1997) pointed out that these cylindrical crucibles probably marked the end of the primary glass-making process, and as such their presence should indirectly point at primary glass-making. In reaction to the presentation of the Qantir crucibles (Rehren and Pusch 1997), Nicholson *et al.* (1997) linked the inner profile of the Amarna crucibles to the shape of the glass ingots of the Uluburun shipwreck, thus confirming the suggested use of these crucibles as moulds for the production of glass ingots more generally and beyond Qantir.

In 1993 and 1994, Nicholson targeted the area marked ‘moulds’ in a map from Petrie’s field notes in search for additional information about Egyptian glass-making practices. During this research, he excavated two furnaces that—with the aid of reconstruction and experimentation—were shown to be capable of primary glass production, although no direct evidence has so far been provided that they had actually been used for this process (Nicholson 1996; Jackson *et al.* 1998; Nicholson 2007; Pusch and Rehren 2007, 141–4). Jackson and Nicholson (2007) present analytical data of some of the glass and technical debris from Nicholson’s recent excavation. They identify one piece (TA22; Jackson and Nicholson 2007, 115) as being ‘clearly related to the glass production process’, while other fragments are described as being more enigmatic or possibly related to the production of other vitreous materials.

Independent work by Shortland and Tite focused on the processing of vitreous materials within the city of Amarna, including faience and pigment production, and contributing to the identification of the raw materials used. Of particular relevance for the possible identification of glass-making is the enigmatic cobalt-blue frit extensively examined by them (Shortland and Tite 1998; Shortland 2000; Shortland and Tite 2000; Tite and Shortland 2003; Shortland *et al.* 2006). They are reluctant, however, to commit to either a one- or two-step process of glass-making, and the specific role therein of the enigmatic cobalt-blue frits found abundantly in Amarna by Petrie. As a result, the association of this frit to glass-making is still ambiguous (Rehren 2001), even though it has also been found among the other glass-related debris in Nicholson’s recent excavations (see above; Jackson and Nicholson 2007). However, its presence not only underlines the possible existence of local glass-making, but also the potentially complex nature of the materials and processes involved in LBA glass-making, as indicated by the cuneiform texts (Oppenheim *et al.* 1970).

In summary, the archaeological finds from Amarna show that there was a substantial glass-working industry present, most likely as part of a wider vitreous materials industrial complex (Shortland 2000; Jackson and Nicholson 2007, 115). Evidence for primary glass-making at Amarna is so far mostly circumstantial, such as the presence of cylindrical crucibles (Turner 1954; Nicholson *et al.* 1997; Rehren 1997), although at least one fragment from the recent excavations has been directly linked to glass-making (Jackson and Nicholson 2007, 115). On the other hand, correspondence between Akhenaten and several rulers in the Levant, preserved in the Amarna letters (Moran 1992), suggests that significant amounts of glass were imported from the Levant into Egypt during the reign of Akhenaten, while the only reference for export of glass from Egypt to Babylonia (Moran 1992, 28) concerns a finished piece of glass. Thus, it is still not certain whether the glass studios of the site relied predominantly on imported glass, or whether substantial quantities of glass were being made there.

The evidence available indicates that secondary or artistic workshops and primary glass-making sites are not necessarily situated in the same place (Rehren *et al.* 2001, 233–4; Pusch and Rehren 2007, 158–60), but may well be in close proximity or even overlap (Rehren 1997, 366; Nicholson 2007, 129). The presence of glass-working does not automatically imply the primary production of glass as well.

In both Amarna and Qantir, the glass industry is closely associated with other high-temperature industries, such as faience- and pigment-making (Shortland 2000; Nicholson 2007), or faience-making, pigment-making and bronze-working (Pusch and Rehren 2007). The resulting mix of waste material in the archaeological record makes it difficult to identify from which workshop part the individual finds originated. We know that Petrie collected material from several workshops related to glass and glaze production, but his documentation does not allow us to resolve the picture for his material further. In Qantir, finds related to primary glass production were found

to be strongly concentrated in sites Q IV and Q V, and those linked to Egyptian blue production mostly in Q IV, while Q I showed an overwhelming dominance of bronze-related finds *in situ*, mixed with unusually large fragments of glass-colouring crucibles in tertiary position (Pusch and Rehren 2007, 130).

Research background

Archaeological work in Qantir coupled with experimental work (Shugar and Rehren 2002; Merkel and Rehren 2007; Tanimoto and Rehren 2008) has provided us with a better understanding of the production process, the firing temperature and other technicalities regarding LBA Egyptian glass-making, building on the pioneering work by Turner (1954) and Brill's (1970) interpretation of the Mesopotamian cuneiform texts, and complementing more recent work by Shortland (e.g., Shortland 2000) and Jackson and Nicholson (most recently 2007). In addition, new analytical techniques such as LA-ICPMS shed new light on the differences between Mesopotamian and Egyptian LBA glass compositions at trace element level (Shortland 2005; Shortland *et al.* 2007; Walton *et al.* 2009). These strongly suggest that there was indeed separate glass production in Egypt and Mesopotamia at the time of Amarna, about a century earlier than the evidence from Qantir, despite the overall close compositional similarities of the glass found in both regions.

With that new evidence in hand, this paper will investigate and analyse glass-rich material from Amarna that has not been studied before, in order to better understand the full range of glass-making and -working activities represented there. In particular, the present study will test whether the argument for primary glass production at the LBA site of Amarna can be strengthened, by the identification of semi-finished glass.

METHODOLOGY

The samples

The samples studied here were found during the excavations by Sir Flinders Petrie and are currently stored at the Petrie Museum of Egyptian Archaeology. We focus on two groups of samples that have previously received little or no attention:

(i) *Raw glass* (Fig. 1): the objects classified as raw glass are mostly white, porous and opaque, with a frothy appearance. They are unworked glass, some having a shape resembling fragments of an ingot, others with no special shape. They are not completely fused, and most show the presence of quartz grains when studied using a low-power optical microscope. The objects are not associated with technical ceramics, but occasionally have parting layer material attached to them. These criteria are strongly suggestive of semi-finished glass as produced during primary glass-making. There are 35 such fragments in the Petrie Museum collection, with a size of around 3–5 cm long. The analysis of 32 of these objects by non-invasive X-ray fluorescence spectrometry showed that 15 had been opacified with calcium antimonate, while 17 had no opacifier added. These two groups were visually indistinguishable. None of the objects contain any colorant. Samples were taken from 11 objects (five with opacifier and six without) to be studied in detail; their inventory numbers are given in Table 1.

(ii) *White working waste* (Fig. 2): these objects are also white, but not porous, and are well-fused, with a peculiar waste shape, and often have fragments of charcoal—possibly from the firing fuel—still attached to them. Their smooth, non-frothy surface, suggestive of a well-formed

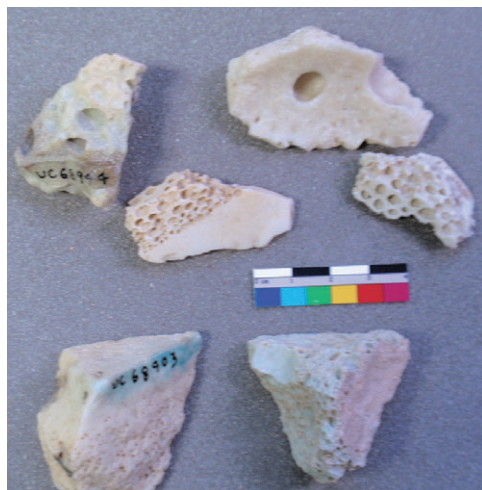


Figure 1 Samples of raw glass from Amarna; Petrie Museum.

Table 1 Glass samples analysed from the Petrie Museum of Egyptian Archaeology

| Museum number | Classification | |
|---------------|---------------------|-----------------------|
| UC68901 | Raw glass | NonSb (non-opacified) |
| UC68906 | Raw glass | |
| UC68915 | Raw glass | |
| UC68940 | Raw glass | |
| UC68946 | Raw glass | |
| UC68900 | Raw glass | Sb (opacified) |
| UC68902 | Raw glass | |
| UC68903 | Raw glass | |
| UC68907 | Raw glass | |
| UC68944 | Raw glass | |
| UC68881 | White working waste | www |
| UC68887 | White working waste | |
| UC68908 | White working waste | |
| UC68938 | White working waste | |

glass, differentiates them visually from the first group of raw glass. There are no quartz grains visible when examined under the optical microscope. There are six such objects in the museum's collection, and samples were taken from four of them for further analysis. All six objects have antimonate added as opacifier, but no colorant present.

Defining semi-finished glass

According to textual (Oppenheim *et al.* 1970) and archaeological evidence (Rehren and Pusch 2005; Pusch and Rehren 2007), and the experimentally tested Partial Melting and Two Melt Models (Rehren 2000b, 2008; Shugar and Rehren 2002; Tanimoto and Rehren 2008), glass



Figure 2 *White working waste (www) samples from Amarna; Petrie Museum.*

formation in the LBA most likely consisted of a sequence of discrete stages, with the first one resulting in a semi-finished product that required further processing in a second stage before it was suitable for the manufacture of objects. No evidence of trade or long-distance transport of this semi-finished glass is known from the LBA. Therefore, the presence of semi-finished glass at an excavation site is a strong indication for local primary glass-making. Developing and applying a set of analytical criteria to reliably identify semi-finished glass is therefore crucial.

Below, we define certain criteria that need to be satisfied in order to identify a sample as semi-finished glass:

- The presence of significant quantities of residual quartz grains in a matrix of soda–lime–silica glass is taken as evidence that raw materials were fired at relatively low temperatures, or with insufficient flux, or for insufficient time, so that not all the quartz has been dissolved.
- The presence of lime-rich newly formed crystalline phases, such as wollastonite or diopside, can be a strong indication that the raw materials have been partially reacted, resulting in semi-finished glass. Often, these crystals form in or near the lime-rich parting layer. Wollastonite can also form as part of the devitrification process during glass-working, or during weathering of the glass, although typically in much smaller grain sizes. Thus, the presence of a lime-rich phase has to be evaluated along with other semi-finished glass indications, such as the presence of residual quartz grains. Furthermore, the morphology of the crystals is diagnostic to differentiate whether they were formed during glass formation or as part of devitrification or weathering.
- Rehren and Pusch (2007, 153) have noted levels of around 3–5% of lime in the semi-finished glass from Qantir, as compared to 6–9% of lime in typical LBA Egyptian finished glass objects. Experiments by Shugar and Rehren (2002) and Tanimoto and Rehren (2008) have shown that, under assumed LBA firing and batch preparation conditions, the lime content of glass and the formation of lime-rich phases such as wollastonite is substantially controlled by the firing temperature. During re-melting at higher temperatures, semi-finished glass can absorb these lime-rich phases, together with further lime from the parting layer of the ceramic vessel, resulting

in higher lime levels in the finished glass. Thus, we expect to see lower contents of lime in semi-finished than in finished glass. However, raw materials genuinely low in lime may also result in low-lime glass even if fired at higher temperatures, and the heterogeneity of the semi-finished glass can lead to locally lime-rich areas even if fired at low temperature. Thus, lime content on its own is not a sufficient indicator of firing temperature or primary glass-making.

Analytical techniques

Samples 2–4 mm² in size were taken and mounted in epoxy resin. The mounted samples were inspected and photographed using an optical microscope, and then coated with a thin carbon layer in preparation for electron beam analysis. All samples were first studied by scanning electron microscope (SEM) with energy-dispersive spectrometry (EDS) and then analysed by electron probe micro-analyser (EPMA) with wavelength-dispersive spectrometry (WDS).

The JEOL superprobe JXA 8100 of the UCL Institute of Archaeology was used for the wavelength-dispersive spectrometric analysis of the samples. Analyses were conducted at $\times 800$ magnification, representing an area of approximately 120 μm by 90 μm . Eight to ten areas of each sample were analysed and an average was obtained. The instrument was calibrated on pure elements and simple stoichiometric compounds; Corning A glass was analysed at the beginning of each session to check the accuracy of the calibration. The JEOL values are within 5% relative of the given values for most oxides present at above 1 wt%. For alumina—with a given value of 1%—our data are systematically around 15% relative below the given value (Table 2).

The Hitachi S3400N SEM-EDS with INCA software of the UCL Institute of Archaeology was used for studying the microstructure of the samples as well as for spot analyses of individual particles. An accelerating voltage of 20 kV, a beam current of 10 nA and a working distance of 20 mm were used. All SEM-EDS results have been normalized and reported as oxide-weight percentages.

RESULTS

Morphology of raw glass

All samples of raw glass (both with and without antimony) are white and porous, and 10 of the 11 samples have a frothy appearance. One of the samples (UC68907-Sb) is not frothy and is less porous, but not completely fused either. All samples contain numerous unevenly distributed residual quartz grains, various lime-rich phases (Table 3), and clusters of semi-reacted crystals in a fully reacted and formed glass matrix (Fig. 3). All samples, therefore, match the first two criteria for semi-finished glass. Five of the 11 samples, the ones that were intentionally opacified, show clusters of angular calcium antimonate particles scattered throughout. The six non-antimonate glasses also have a white opaque appearance, but this is attributed to the voids and crystalline phases present, and not to the addition of any opacifier.

Most of the samples show microscopic cubic impressions from residual salt crystals that have now been dissolved (Fig. 4). While we can see the impressions of the salt crystals, when analysed, only the glass matrix composition is determined. This is most probably due to the solubility of the salts in water, washing out the salt during sample preparation.

Morphology of the white working waste

The four samples of the white working waste group (UC68881-www, UC68908-www, UC68887-www and UC68938-www) are non-porous and fused, with a fully formed glass matrix.

Table 2 EPMA analyses of Corning A, and comparison with the published data (Brill 1999)

| | SiO ₂ | Na ₂ O | CaO | K ₂ O | MgO | Al ₂ O ₃ | TiO ₂ | Sb ₂ O ₅ | Fe ₂ O ₃ | MnO | CuO | CoO | PbO | ZnO | BaO | P ₂ O ₅ |
|-------------------------------|------------------|-------------------|------|------------------|------|--------------------------------|------------------|--------------------------------|--------------------------------|------|-------|-------|-------|-------|------|-------------------------------|
| Corning A | 66.70 | 14.60 | 5.06 | 2.97 | 2.73 | 0.86 | 0.793 | 1.70 | 1.07 | 0.95 | 1.29 | 0.13 | 0.14 | 0.048 | 0.52 | 0.07 |
| Given | 67.33 | 14.30 | 5.03 | 2.87 | 2.66 | 1.00 | 0.790 | 1.74 | 1.09 | 1.00 | 1.17 | 0.17 | 0.12 | 0.044 | 0.56 | 0.13 |
| <i>d</i> _{abs} (wt%) | 0.63 | 0.30 | 0.03 | 0.10 | 0.07 | 0.14 | 0.003 | 0.04 | 0.02 | 0.05 | 0.12 | 0.04 | 0.02 | 0.004 | 0.04 | 0.06 |
| <i>d</i> _{rel} (%) | 0.93 | 2.10 | 0.60 | 3.48 | 2.63 | 14.00 | 0.38 | 2.30 | 1.56 | 4.50 | 10.51 | 21.76 | 14.17 | 9.09 | 7.14 | 48.46 |

Table 3 Various phases found throughout the raw samples; SEM-EDS data in atomic%

| Phase | Na | Mg | Si | K | Ca | O |
|--------------|------|------|------|-----|------|------|
| Diopside | 0.0 | 10.0 | 21.0 | 0.0 | 10.0 | 60.0 |
| Diopside | 1.2 | 10.0 | 21.0 | 0.0 | 8.0 | 60.0 |
| '1:2:3'? | 14.4 | 0.4 | 19.5 | 0.1 | 9.5 | 56.0 |
| '1:2:3'? | 10.0 | 0.3 | 19.5 | 0.2 | 13.0 | 57.0 |
| Wollastonite | 5.0 | 0.4 | 20.0 | 0.8 | 16.5 | 58.0 |
| Wollastonite | 0.0 | 0.0 | 21.0 | 0.0 | 19.0 | 60.0 |
| Quartz | 0.0 | 0.0 | 33.3 | 0.0 | 0.0 | 66.7 |

All samples contain remains of charcoal embedded in them, a possible contamination from the fuel used during working. They are all deliberately opacified by calcium antimonate particles scattered throughout. There are no residual quartz grains or intermediate lime-rich phases present; according to our criteria, they cannot be classified as semi-finished glass.

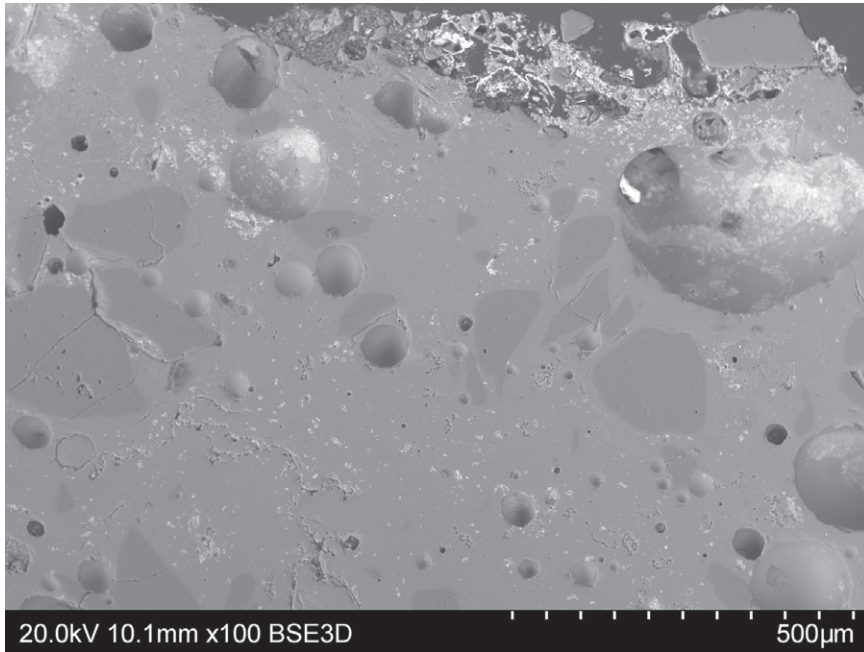
Chemical composition of the glass matrix

All 15 samples analysed here conform to the typical range of LBA Egyptian glass compositions as known from the literature (as compared with the colourless and cobalt-blue glasses from Amarna/Malkata published in Brill 1999, and in Shortland and Eremin 2006), although with a noticeable shift towards lower soda and higher silica levels (see Fig. 5). They are soda–lime–silica glasses with a silica content averaging around 66–68.5%, soda levels of 17–19% and lime levels of 4.8–8% (Table 4). Magnesia levels range mostly between 2.6% and 4.3%, suggesting that plant ash was used for all samples. Compared to the literature data, the concentrations of both earth alkali oxides in the semi-finished glass samples are shifted to slightly lower levels (Fig. 6). Sample UC68901-NonSb shows exceptionally high levels of lime and magnesia; this reflects lime- and magnesia-rich diopside particles scattered all around the sample (Fig. 7; Table 3), making it impossible to find a large enough area of clean glass matrix to analyse; therefore, it was excluded from the further analysis. When semi-quantitative spot analysis was performed using SEM-EDS, the levels of both lime (6.8%) and magnesia (3.2%) in the glass matrix were found to be comparable to those of the other samples.

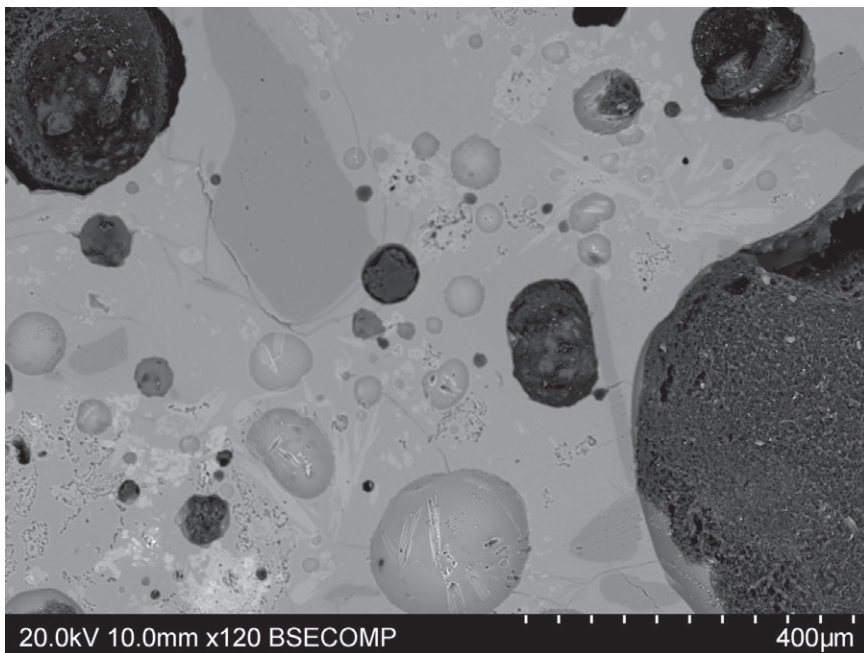
The five antimonate semi-finished glasses and four white working waste samples have antimony levels in the range of 1.0–3.2%, consistent with opaque finished LBA Egyptian glass as found in the literature (Lilyquist and Brill 1993; Brill 1999; Shortland 2002).

Potash levels scatter relatively widely, possibly falling into two broad groups, although the separation is not very sharp. A low-K group comprising five samples, including three of the four white working waste samples, has about 1.1–1.5 wt% K₂O, while the other samples have more than about 2 wt% K₂O, and reach nearly 4 wt% in the extreme.

The identification of a low-potash group among the LBA glass compositions was previously reported in the literature, where low potash levels were seen predominantly as a characteristic of cobalt-blue glass, typically together with elevated alumina levels of 1% or more, suggesting the use of varying plant ashes (Lilyquist and Brill 1993, 42). These low-potash glasses were mostly, but not exclusively cobalt-coloured (Lilyquist and Brill 1993; Shortland and Eremin 2006,



(a)



(b)

Figure 3 Examples of quartz grains (mid grey, rounded) and various lime-rich crystalline phases (lighter grey, angular) within a glass matrix: samples UC68902-Sb and UC68944-Sb.

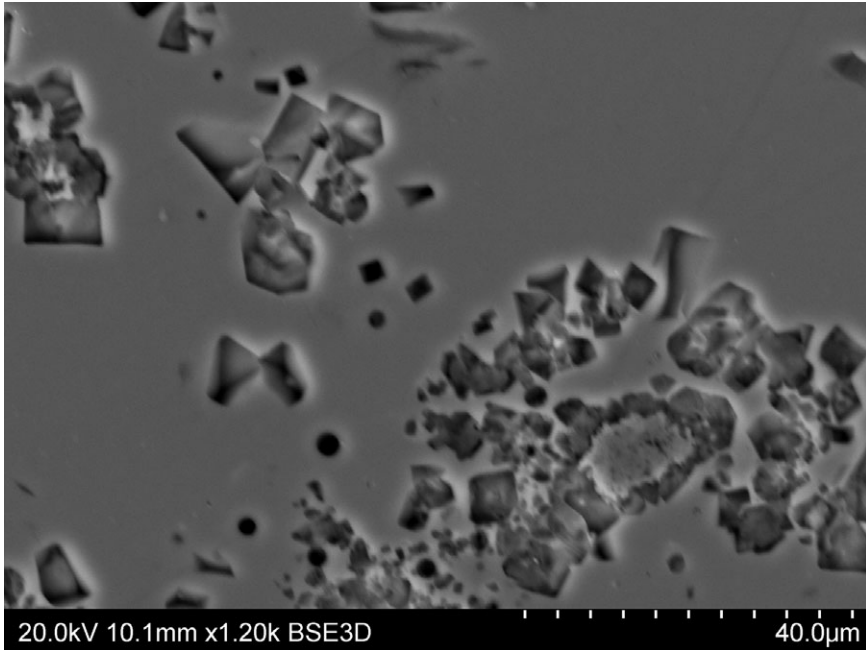


Figure 4 Cubic impressions from residual salt crystals within the glass matrix.

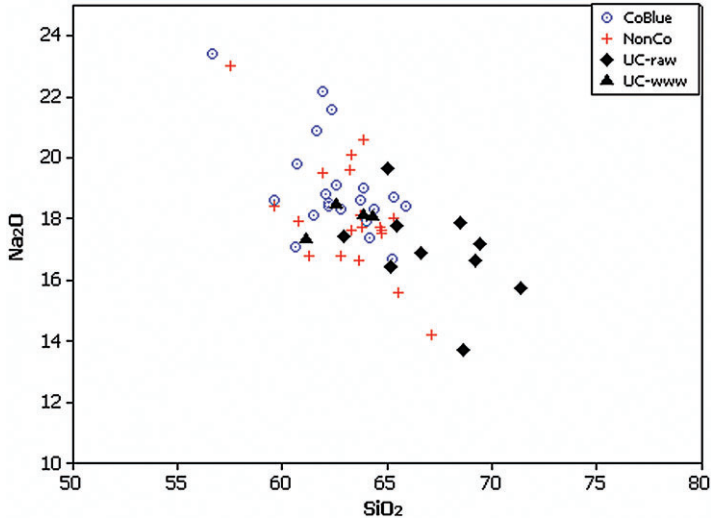


Figure 5 Soda and silica levels of all samples (UC-raw, UC-www) are within typical levels of Amarna cobalt-blue (CoBlue) and colourless (NonCo) finished glass (data taken from Brill 1999; Shortland and Eremin 2006).

Jackson and Nicholson 2007). The identification of a low-K group among the semi-finished glass at Amarna indicates that at least some of it may have been made there.

The remaining nine of the semi-finished glasses (UC68906-NonSb, UC68915-NonSb, UC68946-NonSb, UC68901-NonSb, UC47508-NonSb, UC68902-Sb, UC-68903-Sb,

Table 4 Chemical compositions in wt% from microprobe analyses

| | SiO ₂ | Na ₂ O | CaO | K ₂ O | MgO | Al ₂ O ₃ | FeO | TiO ₂ | Sb ₂ O ₃ | MnO | CuO | CoO | SnO ₂ | PbO | SO ₃ | Cl | ZnO | P ₂ O ₅ |
|-------|------------------|-------------------|------|------------------|------|--------------------------------|------|------------------|--------------------------------|------|------|-----|------------------|------|-----------------|------|------|-------------------------------|
| NonSb | UC68906 | 65.2 | 19.8 | 4.81 | 3.98 | 4.19 | 0.48 | 0.05 | bdl* | bdl | bdl | bdl | bdl | 0.06 | 0.38 | 0.86 | 0.01 | 0.15 |
| | UC68915 | 65.6 | 17.9 | 7.11 | 3.22 | 4.30 | 0.44 | 0.04 | bdl | bdl | bdl | bdl | bdl | bdl | 0.34 | 0.84 | 0.02 | 0.12 |
| | UC68946 | 69.4 | 16.7 | 6.64 | 2.19 | 2.94 | 0.45 | 0.03 | bdl | bdl | bdl | bdl | bdl | 0.16 | 0.24 | 0.81 | 0.02 | 0.12 |
| | UC68901 | 62.9 | 14.1 | 12.14 | 1.90 | 6.09 | 0.75 | 0.07 | 0.06 | 0.28 | 0.37 | bdl | bdl | bdl | 0.31 | 0.60 | 0.01 | 0.15 |
| | UC68940 | 68.6 | 18.0 | 6.39 | 1.46 | 2.86 | 0.88 | 0.41 | bdl | bdl | bdl | bdl | bdl | bdl | 0.31 | 0.88 | 0.01 | 0.15 |
| | UC47508 | 69.6 | 17.3 | 6.30 | 2.41 | 2.62 | 0.45 | 0.04 | bdl | bdl | bdl | bdl | bdl | 0.20 | 0.26 | 0.61 | 0.01 | 0.10 |
| Sb | UC68907 | 63.1 | 17.5 | 8.02 | 2.24 | 3.79 | 0.69 | 0.07 | 3.25 | bdl | bdl | bdl | bdl | bdl | 0.31 | 0.67 | 0.01 | 0.15 |
| | UC68903 | 65.3 | 16.5 | 6.55 | 2.58 | 4.20 | 0.72 | 0.07 | 2.26 | 0.03 | 0.06 | bdl | bdl | 0.10 | 0.29 | 0.70 | 0.12 | 0.17 |
| | UC68902 | 66.7 | 17.0 | 5.55 | 2.56 | 3.79 | 0.58 | 0.08 | 1.72 | bdl | bdl | bdl | bdl | 0.46 | 0.22 | 0.88 | 0.04 | 0.12 |
| | UC68900 | 68.8 | 13.8 | 5.47 | 2.64 | 4.02 | 0.59 | 0.07 | 2.74 | bdl | 0.22 | bdl | bdl | 0.38 | 0.20 | 0.63 | 0.05 | 0.16 |
| | UC68944 | 71.6 | 15.8 | 5.38 | 1.25 | 2.64 | 0.80 | 0.14 | 1.05 | bdl | bdl | bdl | bdl | bdl | 0.21 | 0.73 | 0.03 | 0.12 |
| www | UC68881 | 64.5 | 18.1 | 7.30 | 1.18 | 3.60 | 1.20 | 0.13 | 2.37 | bdl | bdl | bdl | bdl | bdl | 0.33 | 0.87 | 0.01 | 0.16 |
| | UC68908 | 62.7 | 18.6 | 7.35 | 1.12 | 3.82 | 0.98 | 0.10 | 3.77 | bdl | bdl | bdl | bdl | 0.05 | 0.33 | 0.88 | 0.02 | 0.16 |
| | UC68887 | 61.3 | 17.4 | 9.06 | 1.99 | 3.92 | 0.68 | 0.31 | 3.92 | bdl | bdl | bdl | bdl | bdl | 0.30 | 0.87 | 0.02 | 0.15 |
| | UC68938 | 64.0 | 18.2 | 7.47 | 1.23 | 3.64 | 1.22 | 0.12 | 2.29 | bdl | bdl | bdl | bdl | bdl | 0.39 | 0.79 | 0.03 | 0.18 |

*bdl, Below detection limit.

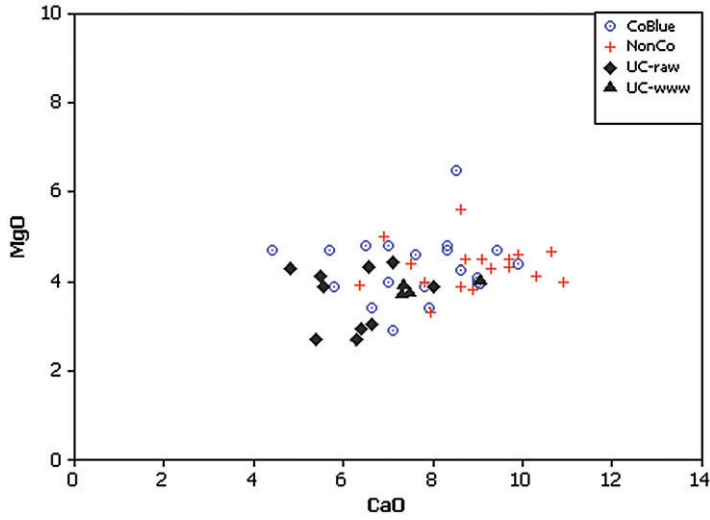


Figure 6 Lime and magnesia levels of all samples (UC-raw, UC-www) are within typical levels as of Amarna cobalt-blue (CoBlue) and colourless (NonCo) finished glass (data taken from Brill 1999; Shortland and Eremin 2006).

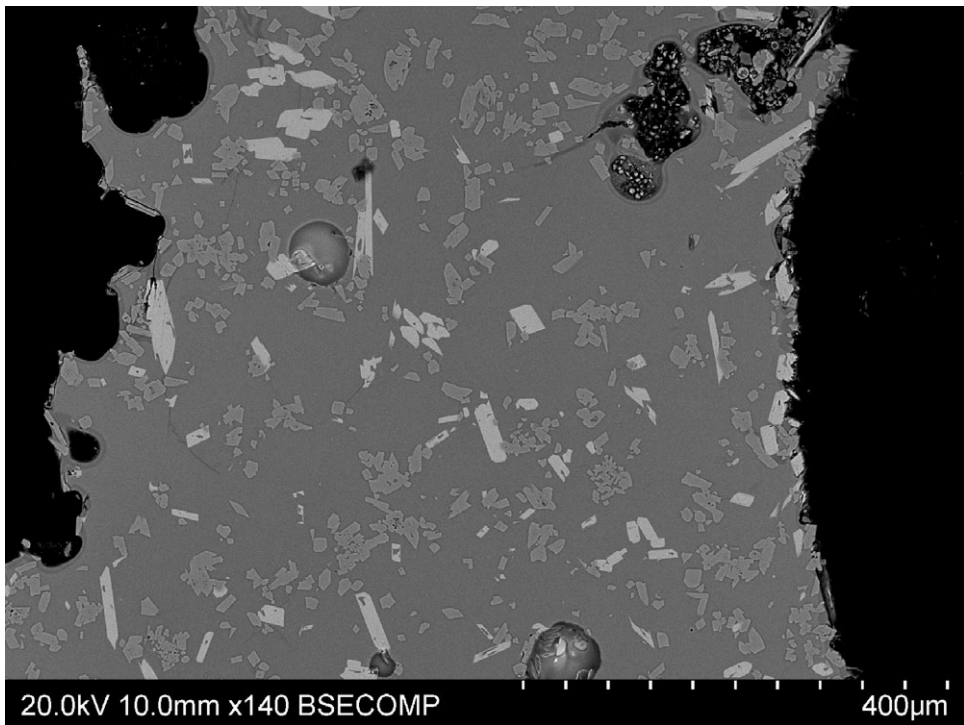


Figure 7 Sample UC68901-NonSb, with diopside (dark grey) and wollastonite (light grey) particles scattered throughout.

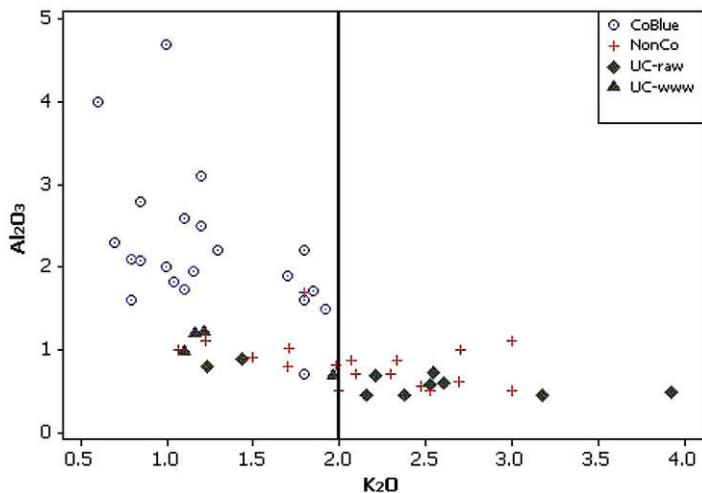


Figure 8 Alumina and potash contents of Amarna cobalt-blue (CoBlue) and colourless (NonCo) finished glasses as published in Brill (1999) and Shortland and Eremin (2006), in comparison with our samples (UC-raw, UC-www).

UC68907-Sb and UC68900-Sb) and one of the white working waste fragments (UC68887-www) have a typical LBA Egyptian non-cobalt-blue base glass composition, with consistent alumina levels around 0.4–0.7% and potash of 2% or more (Fig. 8).

Firing temperature

One of the criteria developed above for semi-finished glass is their generally lower lime level compared to finished glasses, probably reflecting the assumed low-temperature first melting stage of the two-step primary glass-making process. This criterion has been developed based on theoretical considerations (Rehren 2000b) and experimental and analytical observations during investigation of the material from Qantir – Pi-Ramesse (Shugar and Rehren 2002; Tanimoto and Rehren 2008). In order to test whether the same low lime level can be found in the suspected semi-finished glass from Amarna, we re-calculated the analytical data to match the relevant ternary liquidus diagram for soda–lime–silica with a constant level of 5 wt% magnesia (Shahid and Glasser 1972; Rehren 2000b). Table 5 shows the reduced glass compositions of all samples, assuming 5% magnesia. The reduced lime levels normalized to 5 wt% magnesia ('lime**') are systematically lower than those of finished LBA glasses (Rehren 2000a); interestingly, sample UC68907-Sb, which has the highest lime** level, was already macroscopically identified as the sample with the most 'fused' appearance, suggesting that it was fired at a higher temperature than the other analysed samples of semi-finished glass.

The plotting of the new data on the SLS diagram (Fig. 9) allows further visualization of this aspect. The semi-finished samples have theoretical firing temperatures between 800°C and 900°C, with UC68907-Sb and UC68903-Sb being closer to 900°C. In contrast, the white working waste, already identified as finished glasses according to the first two criteria, lay in the range of around 900–1000°C, in line with published glasses from finished artefacts. This is consistent with the visual observation that these samples are all completely fused, and have virtually no residual quartz grains. The same difference between theoretical melting temperatures for semi-finished glass and finished glass was found in Qantir (Schoer and Rehren 2007; Tanimoto and Rehren

Table 5 *Reduced compositions to the three major elements of all samples after adjusting the magnesia level to 5 wt%, following the procedure detailed in Rehren (2000b)*

| | <i>Silica**</i> | <i>Lime**</i> | <i>Soda**</i> |
|---------------|-----------------|---------------|---------------|
| UC68906-NonSb | 67.7 | 4.1 | 23.0 |
| UC68915-NonSb | 67.9 | 6.6 | 20.5 |
| UC68946-NonSb | 71.6 | 4.7 | 18.6 |
| UC68940-NonSb | 71.3 | 4.4 | 19.3 |
| UC47508-NonSb | 71.7 | 4.1 | 19.2 |
| UC68907-Sb | 67.6 | 7.4 | 20.0 |
| UC68903-Sb | 69.6 | 6.2 | 19.1 |
| UC68902-Sb | 70.8 | 4.7 | 19.5 |
| UC68900-Sb | 73.6 | 5.0 | 16.4 |
| UC68944-Sb | 74.7 | 3.2 | 17.1 |
| UC68881-www | 68.9 | 6.3 | 19.7 |
| UC68908-www | 67.8 | 6.8 | 20.4 |
| UC68887-www | 66.3 | 8.8 | 19.9 |
| UC68938-www | 68.5 | 6.6 | 19.9 |

2008), underlining further the strong similarity in technical detail between the glass-making practices at the two sites.

INTERPRETATION

The data presented above identified 11 samples as semi-finished glass, matching visual, micro-structural and chemical criteria developed at the glass-making site of Qantir – Pi-Ramesse. Five of these samples are opacified by antimony. Another four samples, broadly similar in appearance but with subtle though significant visual differences, were identified as working waste of fully fused white glass, opacified by antimony. Overall, this allows a number of interpretations to be made that are relevant for our understanding of Amarna as a primary glass-making site.

First, and provided that semi-finished glass was not traded or transported between workshops, they represent direct archaeological evidence that glass was being made at Amarna from its raw materials.

Second, from our analyses we can conclude that antimony was considered a raw ingredient that was added with the initial batch for producing an opaque base glass, prior to the addition of any colorant. The occurrence of semi-fused but cobalt-coloured glass at Amarna (Jackson and Nicholson 2007) indicates that also some colorants were added in that first stage of the production process together with the raw materials.

Third, the glass-making process carried out at Amarna appears to be technically similar, if not identical, to that at Pi-Ramesse, comprising an initial low-temperature incomplete fusion including the addition of antimony as an opacifier, and a second step of higher temperature firing resulting in complete fusion.

Lastly, there appears to be a particular base glass composition, possibly made at or near Amarna, characterized by a very low potash content and elevated levels of alumina, iron oxide and titania. The possible relationship of this group to the widely recognized low-K glass found elsewhere (Lilyquist and Brill 1993; Brill 1999; Shortland and Eremin 2006; Jackson and Nicholson 2007) requires further investigation, and is outside the scope of this paper.

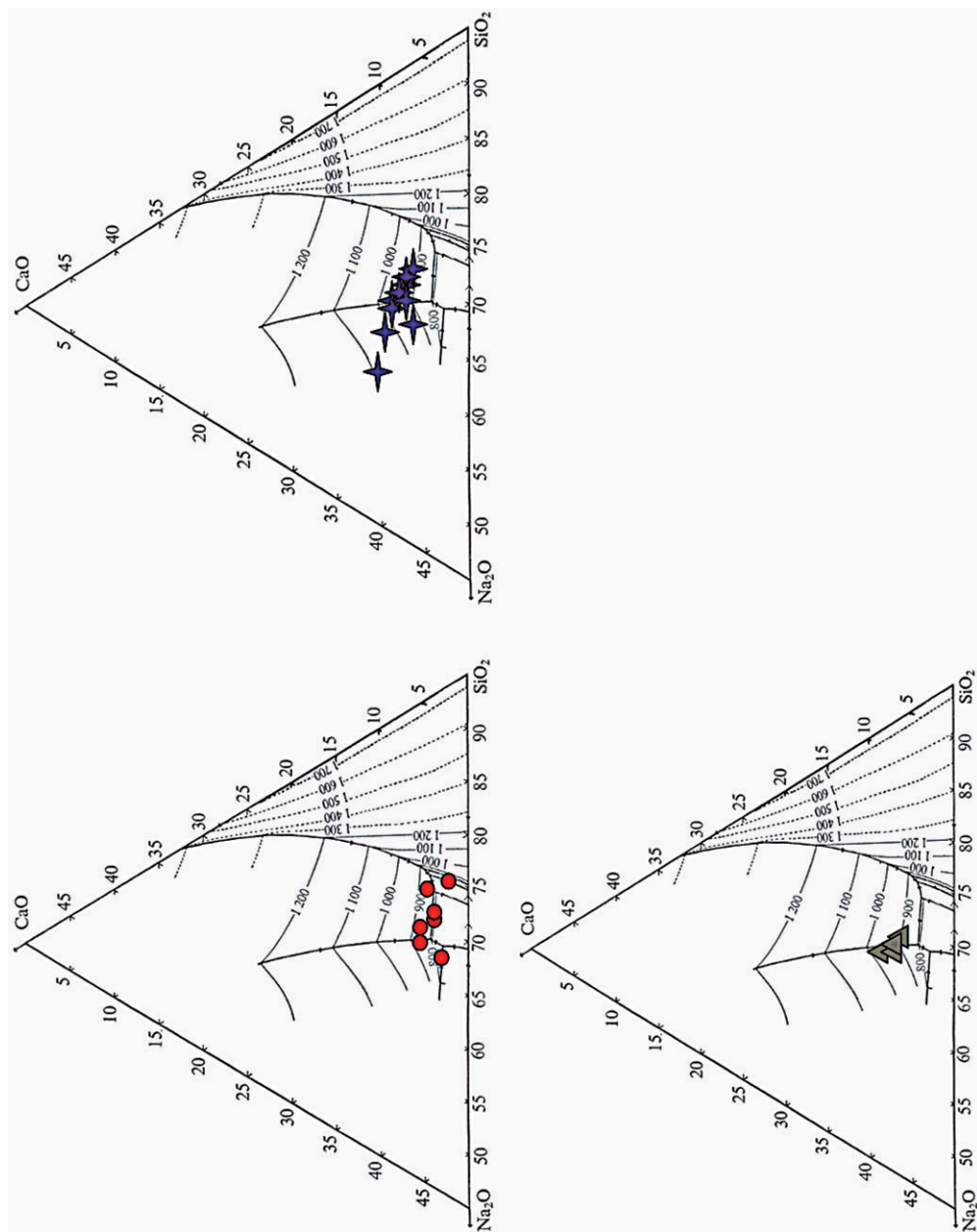


Figure 9 Soda–lime–silica diagrams of the semi-finished samples (upper left), finished Amarna glass as published by Brill (1999) (upper right) and the white working waste samples (lower left), assuming 5% MgO.

Amarna as primary production centre

Eleven samples of semi-finished glass from Amarna, representing some 35 larger and numerous smaller fragments of similar appearance now stored at the Petrie Museum of Egyptian Archaeology, were analysed. All 11 samples had been incompletely fused, have numerous unreacted residual quartz grains throughout and show various newly formed lime-rich crystalline phases. These are mainly wollastonite, devitrite ($\text{Na}_2\text{Ca}_3\text{Si}_6\text{O}_{16}$), '1:2:3' ($\text{Na}_2\text{Ca}_2\text{Si}_3\text{O}_6$) and diopside, as well as various ternary soda–lime–silicate phases in a range of oxide ratios. Because of this, and the presence of unreacted residual quartz, we can securely identify the crystalline phases representing an intermediate stage during glass-making as a result of incomplete melting of the initial batch. Therefore, the samples can be categorized as semi-finished glass made during a first stage of primary glass production.

Although Petrie (1894) strongly felt that he had excavated remains of glass-making, it is only recently that his view has been accepted by others too (Turner 1954; Nicholson and Jackson 1998; Rehren *et al.* 1998; Nicholson 2007). Glass-making, while reasonable to assume, had not been demonstrated (Pusch and Rehren 2007, 141–4) until Jackson and Nicholson (2007, 109, 115) presented a fragment of cobalt-coloured semi-finished glass from Nicholson's recent excavations in Amarna. With the substantial evidence from Petrie's excavations, represented by significant quantities of semi-finished glass, we are now able to securely claim that primary glass production did indeed take place in Amarna.

It is unlikely that the semi-finished glass of the present study would have been imported into Amarna. To finish the processing of imported semi-finished glass would require the Amarna workers to have the same skills and access to raw material such as plant ash and colorants as were used by the producers of the semi-finished glass, in order to re-melt and colour it, at higher temperatures of around 900–1000°C. A spatial or organizational dispersion of primary glass-making would make little sense if the same set of skills and raw materials would still be required at both ends of the chain. It has been argued earlier that the separation between primary and secondary glass-working most likely falls after the production of coloured and fully fused glass ingots (Rehren 1997; Pusch and Rehren 2007, 140), based on technological arguments and on the ample evidence for long-distance trade in coloured glass ingots, such as those found at the Uluburun shipwreck, or mentioned in the Amarna letters. The presence of glass-colouring crucibles at Amarna was already seen as an indication for primary glass-making there (Petrie 1926; Turner 1954; Rehren 1997), although they could have also been used for a simple re-melting of imported glass as part of the artistic glass-working. The identification of significant amounts of semi-finished glass now makes the primary production of glass at Amarna a virtual certainty, and reinforces the position of Egypt as a primary glass producer during that period. Amarna, several decades earlier than the date of the Uluburun shipwreck (Pulak 1998, 2008) and about a century earlier than Qantir, is the earliest site that has, until today, provided concrete evidence of glass-making. It is important, however, to remember that glass-working in Egypt predates the evidence from Amarna by at least a century, and that Egyptian glass-making can be expected to have started well before the foundation of Amarna in 1350 bc.

Consistency of glass-making practice between Amarna and Pi-Ramesse

The identification of semi-finished glass at Amarna enables a direct comparison with the evidence from Qantir. The semi-finished glass is indistinguishable between the two sites; it is consistent with a two-stage process, with an initial firing of the semi-finished glass at around 800–900°C

and then a second firing at higher temperatures. This is reflected in residual quartz grains in the semi-finished glass, and in the lime content of most samples of semi-finished glass being notably lower than that of finished glass objects. In both sites, the semi-finished glass is free of intentionally added colorants, while in both sites antimony is present in some of the semi-finished glass in concentrations equal to those found in intentionally opacified finished glass. Both sites present ample evidence for the preparation of coloured glass ingots in cylindrical crucibles made from local Nile silt; the main difference being that the Amarna crucibles may be shorter than those used at Qantir, although this hypothesis is based on rather limited data (Pusch and Rehren 2007, 72).

In contrast, there is no evidence for the use of ovoid jars as reaction vessels at Amarna, and rim extensions (Rehren and Pusch 2005, 1757) are only known from Qantir – Pi-Ramesse. However, this could be attributed to the different recording and retention practices between Petrie's excavation at Amarna in 1891–2 and Pusch's practice at Qantir since the 1980s. The only real difference visible between the glass-making practices at the two sites is the apparent preference for cobalt-blue glass at Amarna and the vast predominance of red glass at Qantir, accounting for more than 80% of all identified glass produced at Pi-Ramesse (Pusch and Rehren 2007, 139).

CONCLUSIONS

The material excavated by Petrie more than a century ago at Tell el-Amarna yielded unparalleled rich evidence for the working of glass of different colours into a range of artefacts, including beads, inlays and core-formed vessels (Stern and Schlick-Nolte 1994). Our investigation of hitherto neglected finds among the glass-related material identified two technologically different glass groups, namely a group of circa 35 semi-finished glass fragments, half of which were opacified by calcium antimonate, and a smaller group of six white opacified glass lumps in nondescript shapes, here called 'white working waste'.

The identification of significant quantities of semi-finished glass indicates beyond reasonable doubt that glass was being made at Amarna from its raw materials. This had been suspected before, but no conclusive evidence had yet been published. Not all elements of the primary production of glass at Amarna are documented; however, those that are present, such as the semi-finished glass, cylindrical crucibles with lime-based parting layers and occasionally adhering coloured glass, and fragments of coloured ingots, mirror very closely the evidence from Qantir – Pi-Ramesse. The key exception concerns the dominant colour, copper red in Qantir and cobalt and copper blue in Amarna; this discrepancy is in line with the suggested model of a network of interconnected colour-specialized glass-making centres (Pusch and Rehren 2007, 162). Furthermore, at both sites there is frequent evidence for the addition of antimony-based opacifier already during the primary glass-making.

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