A technological study of ancient faience from Egypt

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Abstract

The chemical compositions and microstructures of some 35 faience objects from Egypt spanning the period from the Middle Kingdom through to the 22nd dynasty are determined using analytical scanning electron microscopy. Replicate faience beads glazed in the laboratory using the efflorescence and cementation methods are similarly investigated. In efflorescence glazing, there appears to be preferential efflorescence of soda over potash, and in cementation glazing, preferential take up of potash over soda into the glaze. These data are then used to try to infer the raw materials and methods of glazing employed in the production of the ancient faience. The glaze/glass phases present in the faience differ significantly in composition from that of New Kingdom glass. This could be due either to the use of different plant ashes or to changes in the composition of the plant ashes during the production of faience and/or glass. Although it is only rarely possible to determine with certainty whether ancient faience was glazed by efflorescence, cementation or application, the observed microstructures provide an indication of the approach adopted to achieve desired performance characteristics such as strength.
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Keywords: Faience; Plant ash; Cobalt; Copper; Colorant; Glazing method; Scanning electron microscopy; Wavelength-dispersive spectrometry; Replication; Egypt; Middle Kingdom; New Kingdom

1. Introduction

Faience, which consists of a ground quartz or quartz sand body coated with a soda-rich glaze, was first produced in both Egypt and the Near East as early as the 4th millennium BC, and continued in production through until the Roman period. The material was used to produce bowls and tiles as well as small objects such as amulets, beads, rings and scarabs. Initially the principal colorants were copper and manganese producing turquoise and black glazes, respectively. Then, with the beginning of glass production around 1500 BC, the glaze colours were extended to include cobalt blue, manganese purple and lead antimonate yellow.

The most comprehensive survey of the production technology of ancient Egyptian faience has been provided by Kaczmarczyk and Hedges (1983) with an appendix by Vandiver (1983). Kaczmarczyk and Hedges presented semi-quantitative analyses of a large number of faience glazes spanning the period from Predynastic through to the 1st century AD, the main emphasis being on the identification of the colorants used. Vandiver extended the study with visual and low-power optical microscopic examination of the faience objects in an attempt to determine, on the basis of macroscopic evidence, whether the faience was glazed by the efflorescence, cementation or application method. Tite et al. (1983) and Tite and Bimson (1986) extended the investigation of the methods used to glaze faience through the examination of the microstructures of both ancient and laboratory replicate faience using scanning electron microscopy (SEM). On the basis of these results, they proposed microstructural criteria for distinguishing between the different methods of glazing. Tite and Shortland (2003) included faience in an investigation of the production technology of the overall range of copper- and cobalt-blue vitreous

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materials from the New Kingdom site of Amarna. On the basis of the microstructures and the chemical compositions of the glazes and the glass phases present in the faience bodies, as determined using an analytical SEM, they attempted to infer both the raw materials and methods of glazing used in the production of the faience.

However, published quantitative compositional data for Egyptian faience still remains somewhat limited. Therefore, a primary aim of the present study is to significantly extend the available compositional and microstructural data for Egyptian faience, an analytical SEM again providing the principal method of examination. Faience bowls, finger rings and beads from Abydos, Amarna and Esna spanning the period from the Middle Kingdom through to the 22nd dynasty have been examined. In order to assist in the interpretation of the data for the ancient faience, replicate beads glazed in the laboratory by both the efflorescence and cementation methods have

been similarly examined. For both groups of material, the compositional profiles through the glaze into the body of the samples have been investigated. From these data, an attempt is made to determine for the ancient faience the nature of the raw materials, and in particular the plant ashes providing the alkali flux used in producing the glaze, as well as the methods of glazing.

2. Experimental procedures

2.1. Samples

The faience objects studied included bowls, finger rings and beads, the majority of which were blue-green in colour. The nine Abydos bowls were glazed on both their inner and outer surfaces which in most cases were decorated with black painted designs (Fig. 1a, b). Related to the bowls in terms of
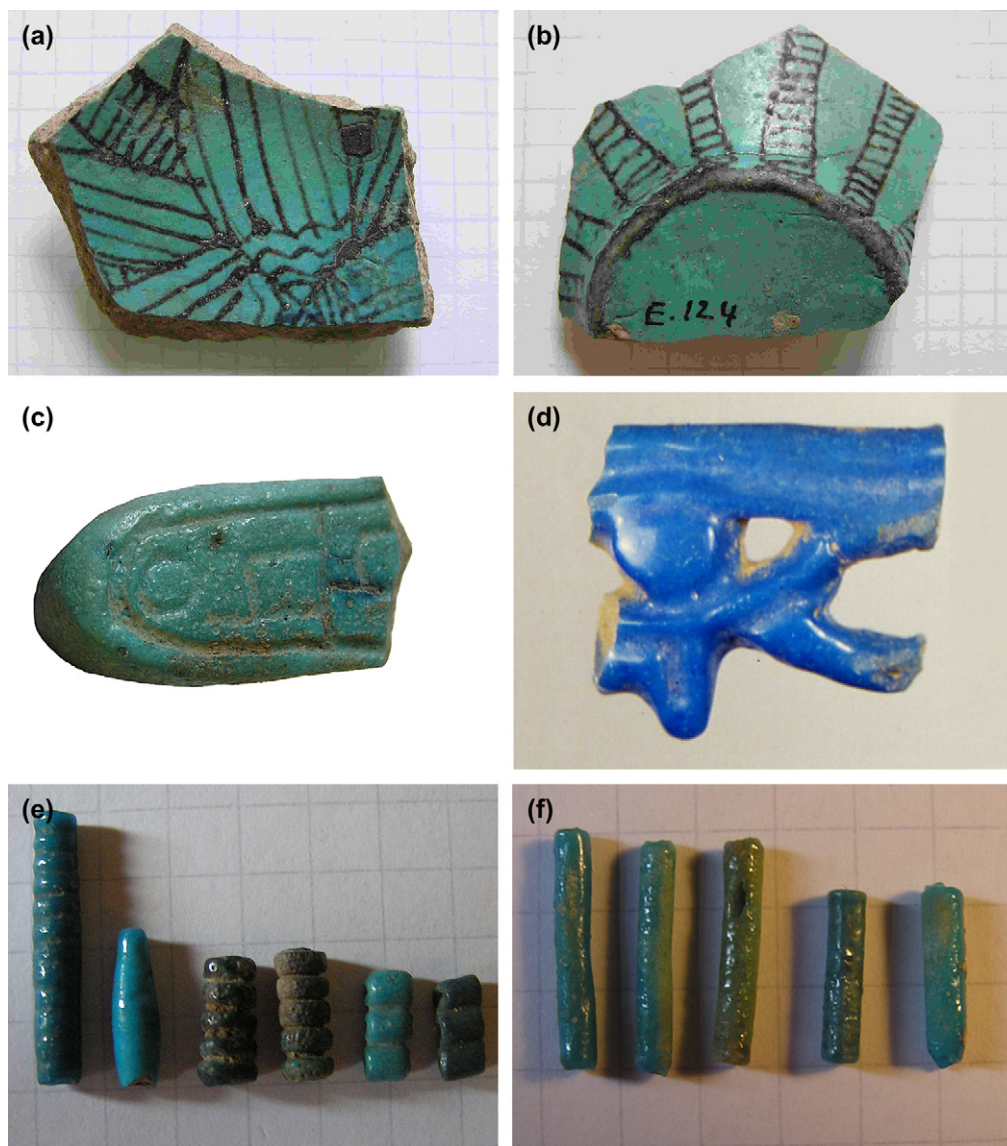

Fig. 1. Photographs of a selection of examined faience objects (background squares are 10 mm × 10 mm): (a) Abydos bowl (E124) − inner side, (b) Abydos bowl (E124) − outer side, (c) Abydos finger ring (E174), (d) Amarna finger ring (5053/6), (e) Amarna beads (from left to right 5033/1−6) (18th dynasty), (f) Abydos beads (from left to right 2221/1−5) (22nd dynasty).

context are the hippopotamus and an egg-shaped object which were similarly glazed over their outer surfaces. This group of material, together with the Abydos finger ring (Fig. 1c), all come from tombs, and most can be dated to somewhere in the period from the Middle Kingdom through to the Second Intermediate Period. However, when they come from a tomb that has been re-used or where the tomb context is not known, their date could be as late as the early New Kingdom. The single Amarna bowl, which is also glazed on both surfaces, and the six Amarna finger rings (Fig. 1d) can be securely dated to the 18th dynasty.

The beads, which come from Abydos, Esna and Amarna, were all tubular or elongated oval in shape, with some being of the segmented type (Fig. 1e, f). Except for two black beads from Abydos, all the beads studied were blue-green in colour. The Abydos beads fall into two groups: one again dated to somewhere in the period from the Middle Kingdom through to the Second Intermediate Period, and the other to the 22nd dynasty. The Esna beads also fall into two groups: one dated to the Second Intermediate Period and the other to the early 18th dynasty, and the Amarna beads can again be securely dated to the 18th dynasty.

2.2. Determination of microstructures and chemical compositions

The faience objects were first examined using an optical stereomicroscope. Small samples were then removed from the objects, and polished sections through the glaze and into the body were prepared. These polished sections were first examined in a Cameca SEM (SU30) in order to determine their microstructures, the backscattered electron mode in which the different phases can be distinguished on the basis of their atomic number contrast being used.

The chemical compositions of the glazes and the glass phases present in the faience bodies were then determined using wavelength-dispersive spectrometers (WDS) attached to a JEOL superprobe (JXA-8800R), which had been calibrated using appropriate primary standards. The instrument was run at 15 kV and 5 nA with a spot size of about 10 μm and a 20 s count time per element. The sodium peak was the first to be analysed in order to minimise any loss of soda during analysis. The detection limits were around 0.05 wt%, and the relative errors on the analyses were in the range 2–5% for major and minor elements, and up to 10% for elements present at the 1% or less level. Both before and after a series of analyses of ancient material, the accuracy of the system was checked by the analysis of the Corning A glass standard. Comparison of the published and as analysed compositions of this glass standard show excellent agreement, except for the as analysed silica and soda contents which are lower by about 1% absolute than the published values (Table 1).

For much of the ancient faience, the actual glaze layer was severely weathered such that most of the soda and potash had been lost, and meaningful analyses were not possible. Therefore, the great majority of analyses presented below are for the glass phase bonding together the quartz particles in the

Table 1
Comparison of Corning A glass standard compositions as published and as analysed

| Oxide | As published | As analysed | |
		Average[a]	SD
SiO_2	66.56	65.63	0.49
Na_2O	14.52	13.57	0.25
K_2O	2.93	2.89	0.05
CaO	5.30	5.18	0.11
MgO	2.81	2.90	0.06
Al_2O_3	1.01	1.01	0.04
FeO	0.98	0.98	0.09
MnO	1.18	1.00	0.08
CuO	1.22	1.16	0.08
SnO_2	0.28	0.20	0.02
CoO	0.15	0.19	0.04
Total[b]	96.94	94.73	0.44

[a] Average is based on 10 analyses.
[b] Totals are for the 11 oxides analysed, the published total for all element being 100.46.

body. Because of the small area of these glass phases, together with the need to use a 10 μm spot size in order to minimise the loss of soda, the analyses will often include adjacent quartz particles and/or pores. When this happens, all the oxide concentrations, other than silica in the former case, will be reduced. In addition the inclusion of pores will reduce the analytical total to well below 100% although these analyses will still be meaningful, provided that the soda contents are no less than about 2–3% and there is no direct evidence of weathering.

2.3. Laboratory replications

For the laboratory replication of efflorescence glazing, small round beads approximately 10 mm in diameter were prepared from a mixture of quartz (∼90%) and the glazing components in the form of sodium, potassium, calcium and magnesium carbonates and copper oxide (see *Bead mixtures* in Table 3 for compositions). The quartz was a mixture of 80% grains with diameter less than 63 μm, and 20% grains with diameter in the range 125–250 μm, the other components all having grain size less than 63 μm. For the first group of replicates, only sodium and calcium carbonates and copper oxide were mixed with the quartz (BM1) whereas, for the second group, all five glazing components were included (BM2). The mixtures were moistened with a small amount of water or with a 5 wt% gum Arabic solution, and the beads were modelled by hand. The beads were left to dry and effloresce under various temperature, humidity and air flow regimes, and were then fired at 950 °C for up to 5 h.

For cementation glazing, small round beads approximately 10 mm in diameter were prepared from quartz of grain size less than 63 μm. The quartz was moistened with a small amount of water or with a 5 wt% gum Arabic solution, and the beads were modelled by hand. In these replicate beads, no glazing mixture was added to the quartz. Instead, the beads were then buried in a glazing mixture consisting of quartz

(grain size 250–500 μm), sodium, potassium, calcium and magnesium carbonates, copper oxide, alumina and charcoal (see *Glaze mixtures* in Table 3 for compositions), and fired to 1000 °C for up to 12 h.

3. Results

In describing the faience microstructures, as observed in the SEM (Figs. 2, 5–7), it is convenient to distinguish between (1) the essentially quartz-free glaze layer (GLZ), (2) the interaction layer (IAL) between the glaze and body which consists of quartz embedded in a more-or-less continuous matrix of glass, and (3) the body itself which can contain varying amounts of interparticle glass (IPG) that bonds together the quartz particles. (NB Following the recommendation of Vandiver (1998, p. 124), the term interparticle glass is now used instead of the term interstitial glass that was used in previous papers by the present authors.)

The glaze and interaction layer thicknesses, the nature of the interaction layer − body boundaries, the particle sizes for the body quartz, and the trends in the soda, potash, lime, magnesia and copper oxide contents as between the glaze, the glass phase in the interaction layer and the interparticle

glass in the body are summarised in Table 2 for the replicate faience beads, and the archaeological bowls, rings and beads. The average chemical compositions (each typically based on 2–4 analyses) for those glaze layers, interaction layer glass phases, and interparticle glass that have not lost their alkalis as a result of weathering are given in Tables 3–6. Also included in Table 3 are the Na_2O/K_2O, Na_2O/CaO, Na_2O/MgO and Na_2O/CuO ratios which are used to compare the compositions of the glaze and glass phases with those of the glaze mixtures used in the replication experiments. For the ancient faience (Tables 4–6), the Na_2O/K_2O, Na_2O/CaO and Na_2O/MgO ratios provide an indication of the composition of the alkali flux used in its production.

3.1. Laboratory replicates

3.1.1. Efflorescence

After firing, a number of the efflorescence glaze replicates exhibited a shiny blue surface. However, the extent of efflorescence was very variable for the different samples, and the thickness of the glaze layers as observed in the SEM varied from less than 50 μm up to about 200 μm (Fig. 2a, b). Similarly, the interaction layers, formed between the glaze and
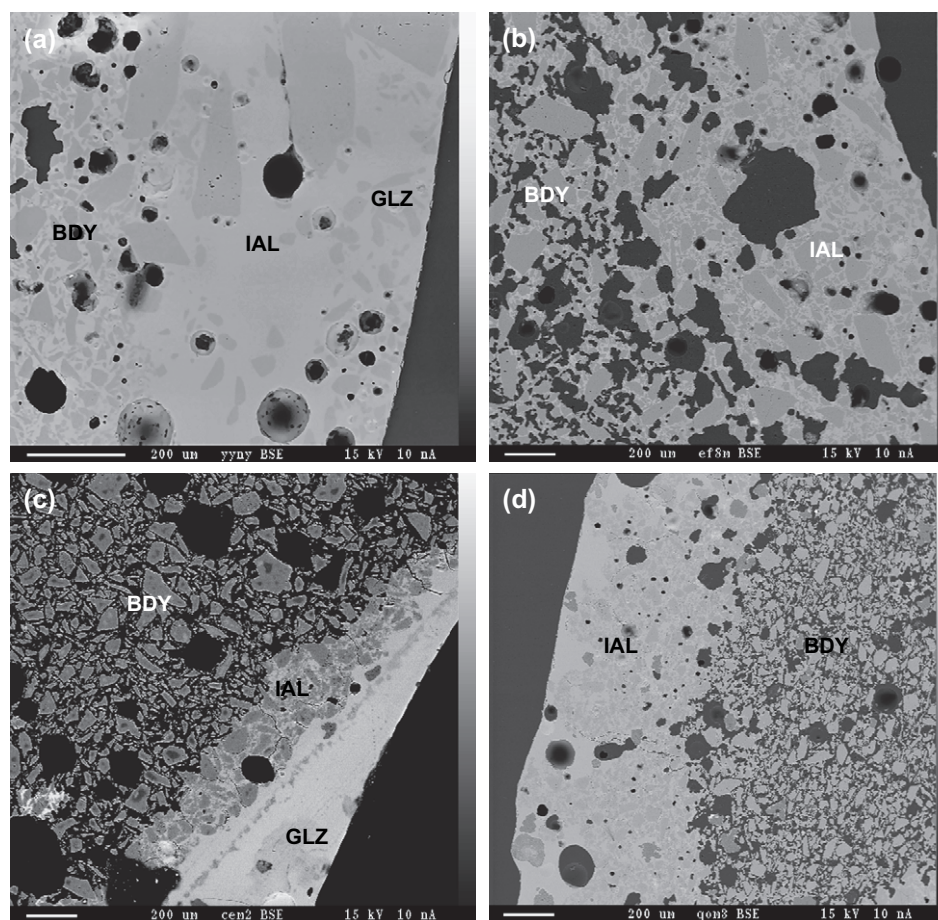
Fig. 2. SEM photomicrographs of sections through glaze (GLZ), interaction layer (IAL) and body (BDY) of replicate efflorescence faience (a) sample E1 and (b) sample E3; and replicate cementation faience (c) sample C2 and (d) sample C4. Extensive interparticle glass is visible in the efflorescence faience bodies but not in those of the cementation faience. [Quartz particles are darker grey and glass phase lighter grey; pores are black.]

Table 2
Summary of microstructural and compositional data

	Glaze thickness (μm)	IAL thickness (μm)	IAL boundary	Body particle size (μm)		Na$_2$O	K$_2$O	CaO	MgO	CuO
Efflorescence replicates	<50−200	1000−2500	Diffuse	<63	GLZ-IAL	←	→	→	→	→
				(125−250)	IAL-IPG	←	→		→	→
Cementation replicates	<50−200	up to 1000	Defined	<63	GLZ-IAL	←				←
Bowls	20−70	70−250	Defined	500 (<70)[a]	IAL-IPG	←	←	→		←
Ring − Abydos − Cu; rings − Amarna − Cu	20−70	300−500	Diffuse	<100	IAL-IPG	←	←	→		←
Ring − Amarna − Co	200	No IAL	Continuous + pores	<100	IAL-IPG					
Beads − Esna	<50	No IAL	Continuous	<150	IAL-IPG					(←)
Beads − Abydos	<30	No IAL	Continuous + pores	<100	IAL-IPG					(←)
Beads − Amarna − cobalt	20−50	No IAL	Continuous + pores	<70	IAL-IPG	(←)	(←)	(←)		(←)
Beads − Amarna − copper	<50	400	Diffuse	<70	IAL-IPG					←
Beads − Abydos − black	∼40	100−200	Defined	<150	GLZ-IAL	←	→			←
					IAL-IPG	←	←			←

→ Increase in oxide content from GLZ (glaze) to IAL (interaction layer) to IPG (interparticle glass).

← Decrease in oxide content from GLZ to IAL to IPG.

(#) Indicates that increase or decrease occurs through the more-or-less continuous glass matrix (CGM).

[a] Slip particle size in brackets.

the body, varied in thickness from about 1000 to 2500 μm, and as a result of the significant amounts of interparticle glass bonding together the quartz particles in the body, the boundaries between the interaction layers and the bodies were often diffuse. Also, as a result of the interparticle glass, the bodies were bluish in colour.

Composition profiles of the glass phase from the glaze layer through the interaction layer to the interparticle glass in the body indicated a decrease in the soda contents, and a corresponding increase in the potash (when added), lime, magnesia (when added) and copper oxide contents (Table 3 and Fig. 3). However, in all cases, the Na$_2$O/K$_2$O, Na$_2$O/CaO, Na$_2$O/MgO and Na$_2$O/CuO ratios for the original glazing mixture added to the quartz (see *Bead mixture* in Table 3) more-or-less matched those for the glass phase somewhere within the interaction layer.

3.1.2. Cementation

After firing, the partially fused cementation glazing mixture could be broken away from the beads which were shiny over the majority of their surface but coloured blue only in patches. As previously noted by Vandiver (1998, Fig. 3a−d), the thickness of the glaze layers as observed in the SEM varied both within and between samples, with an overall range from less than 50 μm up to 200 μm (Fig. 2c, d). The thickness of the interaction layer was similarly very variable extending up to some 1000 μm in some places. The boundary between the interaction layer and body, although irregular, was well defined with negligible interparticle glass present in the body which in the current replications consisted only of quartz.

Composition profiles from the glaze layer through the interaction layer indicated a decrease in the soda and copper oxide

contents, and both increases and decreases in the potash, lime and magnesia contents (Table 3 and Fig. 4). Vandiver (1998, p. 132, Fig. 4) previously highlighted the decrease in copper content from the exterior to the interior of the glaze as being a defining characteristic of cementation glazing. However, perhaps the most significant result is the observation that the absolute percentages of potash are significantly higher and the Na$_2$O/ K$_2$O ratios are significantly lower in the glaze and interaction layer than in the original glazing mixture (see *Glaze mixtures* in Table 3).

3.2. Bowls (Fig. 1a, b and Table 4)

The glazes of the Abydos bowls, hippopotamus (E128) and egg-shaped object (E175), and the Amarna bowl (E5048) were all coloured by copper with trace amounts of cobalt (less than 0.1% CoO) being present in some cases, and manganese oxide being used for the black decoration. The glaze layers (typically 20−70 μm in thickness) and associated interaction layers (typically 70−250 μm in thickness) were formed on fine textured quartz slips (typically 500−1500 μm in overall thickness) which had been applied to the coarse textured quartz body (Fig. 5). The exception was the egg-shaped object which was made entirely from fine textured quartz. The quartz particles were, in most cases, angular, and ranged up to about 500 μm across in the coarse body and up to about 70 μm across in the fine slip. The exception was the quartz particles in the body of the Amarna bowl (E5048) which were more rounded in shape. The boundary between the interaction zone and the underlying slip was generally well defined even though some interparticle glass bonding together the quartz particles was present throughout the slip layer. Interparticle glass was also present in the coarse textured quartz body.

Table 3
Average glaze/glass phase compositions for replicate faience (%wt normalised to 100%)

Component[a]	SiO$_2$	Na$_2$O	K$_2$O	CaO	MgO	CuO	Al$_2$O$_3$	Charcoal	Na$_2$O/K$_2$O	Na$_2$O/CaO	Na$_2$O/MgO	Na$_2$O/CuO
Efflorescence replicates[b]												
E1 (BM1-H$_2$O-Room)												
GLZ	80.66	14.46	0.06	1.92	0.02	2.87				7.52		5.04
IAL	74.85	15.51	0.10	4.33	0.07	5.14				3.58		3.02
IPG	75.24	10.15	0.19	3.44	0.09	10.89				2.95		0.93
E2 (BM1-H$_2$O-Furnace)												
GLZ	80.11	14.99	0.30	2.04	0.03	2.54				7.35		5.91
IAL	71.94	15.87	0.31	6.33	0.08	5.48				2.51		2.90
IPG	71.27	10.48	0.32	5.56	0.15	12.23				1.89		0.86
Bead mixt 1	**90.00**	**6.00**	**0.00**	**1.70**	**0.00**	**2.30**				**3.53**		**2.61**
E3 (BM2-H$_2$O-Dessicat)												
GLZ	75.11	15.68	5.63	0.71	0.71	2.15			2.78	21.94	22.01	7.28
IAL	73.27	11.81	6.47	1.88	1.53	5.04			1.82	6.27	7.74	2.34
IPG	73.78	11.07	6.93	1.70	1.54	4.99			1.60	6.53	7.18	2.22
E4 (BM2-GA-WmRoom)												
GLZ	75.02	14.47	6.31	0.92	0.74	2.54			2.29	15.69	19.57	5.70
IAL	73.36	11.99	6.92	2.07	1.59	4.05			1.73	5.79	7.52	2.96
IPG	73.73	9.84	7.43	1.92	2.76	4.33			1.32	5.14	3.56	2.27
Bead mixt 2	**91.60**	**4.00**	**2.00**	**0.50**	**0.30**	**1.60**			**2.00**	**8.00**	**13.33**	**2.50**
Cementation replicates[b]												
C1 (GM1-H$_2$O)												
GLZ	69.50	13.06	5.95	8.58	1.14	0.93	0.81		2.19	1.52	11.48	14.00
IAL	74.20	10.77	6.17	6.08	1.79	0.62	0.37		1.74	1.77	6.01	17.33
C2 (GM1-GA)												
GLZ	63.54	16.09	6.34	8.17	1.41	1.18	3.23		2.54	1.97	11.42	13.61
IAL	75.10	9.33	7.00	5.57	0.60	0.25	2.01		1.33	1.67	15.45	37.81
Glaze mixt 1	**39.00**	**25.00**	**2.70**	**17.50**	**2.00**	**1.00**	**5.50**	**7.30**	**9.26**	**1.43**	**12.50**	**25.00**
C3 (GM2-GA)												
GLZ	76.03	12.53	6.28	3.77	0.16	1.02	0.18		2.00	3.32	79.56	12.25
IAL	76.44	9.65	5.72	5.56	0.51	0.68	1.34		1.69	1.73	19.01	14.10
Glaze mixt 2	**39.00**	**25.00**	**3.00**	**19.00**	**2.00**	**1.00**	**3.00**	**8.00**	**8.33**	**1.32**	**12.50**	**25.00**
C4 (GM3-GA)												
GLZ	76.04	12.95	6.82	2.63	0.26	0.58	0.68		1.90	4.92	49.15	22.49
IAL	75.55	10.96	6.33	4.52	0.83	0.34	1.31		1.73	2.42	13.20	32.28
Glaze mixt 3	**38.24**	**24.51**	**2.94**	**18.63**	**1.96**	**2.94**	**2.94**	**7.84**	**8.33**	**1.32**	**12.50**	**8.33**

[a] GLZ-glaze layer; IAL-interaction layer glass phase; IPG-body interparticle glass.
[b] H$_2$O − quartz moistened with water only; GA − 5 wt% gum Arabic solution used. Efflorescence occurred in room (20 °C), in furnace (45 °C), in dessicator (20 °C), and in warm room (30 °C).

With the exception of two bowls (E173 and E5048) on which unweathered outer glaze layers survive, the composition profiles start with the outer glaze interaction layer, continue through the interparticle glass in the outer slip layer and in the body, to the inner slip layer and inner glaze interaction layer. Comparison of the average compositions indicates that, in the majority of cases, the soda, potash and copper oxide contents decrease from both the outer and inner interaction layers into interparticle glass in the slip layer and the body, whereas the lime contents increase. The changes in the magnesia contents are less consistent, sometimes increasing and sometimes decreasing (Table 4).

3.3. Rings (Fig. 1c, d and Table 5)

The microstructures of the rings can be divided into two groups depending on whether they were coloured by copper or by cobalt. For the five rings from Amarna and one ring from Abydos coloured by copper, the glaze layers and associated interaction layers were formed on a fine textured quartz body consisting of angular quartz (Fig. 6a). The boundary between the interaction zone and the underlying body was diffuse, and tended to merge with the extensive interparticle glass bonding together the quartz particles and present throughout the body. In contrast, for the one ring from Amarna coloured by cobalt (5053/1), the glaze layer is much thicker (about 200 μm as compared to 20−70 μm for copper coloured rings) and there is no obviously distinguishable separate interaction layer (Fig. 6b). Instead, as confirmed under the optical microscope, the entire faience body consists of quartz particles in a more-or-less continuous glass matrix containing an increasing amount of porosity with distance away from the glaze layer.

With the exception of ring 5053/3, the glaze layers were again all too weathered to obtain a valid composition so

Table 4

Average glass and glaze phase compositions for faience bowls from Abydos and Amarna (%wt normalised to 100%)

Code[a]	Period[b]	Component[c]	SiO_2	Na_2O	K_2O	CaO	MgO	Al_2O_3	FeO	MnO	CuO	SnO_2	CoO	Total	Na_2O/K_2O	Na_2O/CaO	Na_2O/MgO
E142	MK−eNK	O-IAL	70.33	11.98	4.75	1.19	0.39	0.57	0.70	0.02	10.03	0.03	0.02	98.97	2.52	10.06	30.38
		IPG(BDY)	89.00	3.74	1.28	3.22	0.53	0.58	0.66	0.04	0.92	0.02	0.02	64.79	2.92	1.16	7.08
E139	MK−eNK	O-IAL	65.40	15.60	2.18	1.29	0.19	0.35	0.48	1.21	13.30	0.00	0.00	98.79	7.16	12.06	83.70
		IPG(BDY)	78.12	7.11	1.59	0.91	0.15	8.86	0.51	0.03	2.68	0.01	0.03	91.00	4.47	7.77	48.97
		I-IAL	75.15	10.76	2.02	0.70	0.17	0.43	1.40	0.05	9.31	0.00	0.01	97.31	5.34	15.35	64.24
E131	MK−eNK	O-IAL	64.42	13.07	5.45	0.79	0.35	0.53	0.49	0.19	14.72	0.00	0.00	98.72	2.40	16.52	37.17
		O-IPG(SLP)	82.94	5.10	2.81	1.41	1.03	0.97	0.40	0.00	5.25	0.00	0.08	98.11	1.81	3.61	4.93
		I-IAL	73.88	10.92	2.25	1.26	0.33	0.54	0.50	1.56	8.75	0.00	0.01	95.85	4.85	8.67	33.13
E130	MK−SIP	IPG(BDY)	82.05	5.18	5.04	0.31	0.93	1.50	3.80	0.15	0.98	0.00	0.06	97.49	1.03	16.55	5.57
		I-IAL	79.86	9.13	3.10	0.46	0.06	0.08	0.21	0.01	6.92	0.12	0.05	98.41	2.94	20.05	160.41
E173	SIP	O-GLZ	68.30	13.13	6.78	0.57	0.04	0.08	0.12	4.04	6.85	0.00	0.07	98.96	1.94	22.89	309.02
		O-IAL	84.69	5.53	3.24	1.01	0.10	0.31	0.20	2.22	2.68	0.01	0.00	98.73	1.70	5.45	56.20
		IPG(BDY)	76.74	8.16	4.59	4.59	0.08	0.01	0.86	0.15	4.72	0.04	0.05	99.60	1.78	1.78	100.35
E121	MK−SIP	O-IAL	87.25	5.33	2.77	0.75	0.44	0.16	0.15	1.45	1.70	0.00	0.00	100.85	1.92	7.09	12.21
		O-IPG(SLP)	75.98	8.23	4.46	2.75	0.19	0.47	1.42	4.75	1.69	0.01	0.05	99.91	1.84	2.99	44.21
		I-IAL	81.17	8.88	3.44	1.06	0.50	0.28	0.45	0.04	4.15	0.05	0.00	101.07	2.58	8.40	17.75
E124	MK−SIP	O-IAL	84.76	7.21	2.72	1.43	0.13	0.31	0.34	0.06	3.03	0.01	0.00	101.09	2.65	5.05	57.17
		O-IPG(SLP)	86.04	4.01	2.72	1.95	0.17	0.66	2.94	0.51	0.99	0.00	0.00	95.62	1.47	2.06	22.93
		I-IAL	76.48	9.36	4.29	1.46	0.21	1.08	2.38	0.07	4.54	0.11	0.03	101.40	2.18	6.41	45.62
E125	MK−eNK	O-IAL	76.62	8.09	5.15	0.92	0.14	0.64	1.08	0.07	7.29	0.00	0.00	101.07	1.57	8.82	57.46
		O-IPG(SLP)	79.50	6.53	4.63	2.00	0.47	0.81	3.15	0.85	2.00	0.00	0.00	98.75	1.41	3.27	13.83
		I-IAL	79.99	6.95	4.62	0.89	0.30	1.49	2.51	0.08	3.15	0.03	0.00	98.28	1.50	7.83	23.06
E129	MK−SIP	O-IAL	73.38	11.74	4.16	0.66	0.08	0.38	0.38	0.03	9.15	0.01	0.02	99.10	2.82	17.69	139.47
		O-IPG(SLP)	86.07	4.33	2.83	0.45	0.04	0.15	5.15	0.10	0.88	0.00	0.00	96.87	1.53	9.54	104.90
		I-IAL	70.39	14.00	4.63	1.49	0.19	0.56	1.09	0.54	7.08	0.01	0.01	100.10	3.02	9.40	71.79
E128 Hippopot	MK	O-IAL	88.18	4.80	2.26	0.72	0.09	0.40	0.26	0.01	3.27	0.00	0.00	99.54	2.12	6.66	53.00
		O-IPG(SLP)	80.92	5.62	3.72	4.13	0.30	1.10	1.13	0.21	2.83	0.01	0.03	92.72	1.51	1.36	18.65
E175 Egg	SIP−eNK	IAL	70.70	12.00	3.46	0.55	0.19	1.41	0.54	0.03	11.09	0.03	0.01	99.07	3.46	21.89	63.44
		IPG(SLP)	89.19	2.83	1.11	0.46	0.06	0.23	0.10	0.03	5.99	0.00	0.00	95.39	2.55	6.10	46.52
E5048 Amarna	18D	O-GLZ	72.18	14.61	2.53	1.80	0.29	0.14	0.16	0.03	8.23	0.02	0.01	98.68	5.77	8.13	50.72
		O-IAL	70.83	14.97	2.34	2.23	1.00	0.39	0.36	0.00	7.29	0.56	0.03	99.96	6.40	6.71	15.01
		O-IPG(SLP)	85.10	6.07	1.20	3.06	0.79	0.24	1.57	0.07	1.74	0.15	0.01	97.99	5.07	1.98	7.67
		IPG(BDY)	73.59	9.35	3.04	2.28	0.42	0.91	8.51	0.05	1.85	0.00	0.00	95.76	3.07	4.11	22.21

[a] All from Abydos except E5048 from Amarna.
[b] MK − Middle Kingdom; SIP − Second Intermediate Period; eNK − early New Kingdom; 18D − 18th dynasty.
[c] O − outer surface; I − inner surface; GLZ − glaze layer; IAL − interaction layer glass phase; IPG(BDY) − coarse body interparticle glass; IPG(SLP) − fine slip interparticle glass.

that the composition profiles span only the interaction layers and the interparticle glass in the body. Comparison of the average compositions of the copper coloured rings from both Abydos and Amarna indicates that the soda, potash and copper oxide contents decrease from interaction layer into interparticle glass in the body, whereas lime contents increase. The changes in the magnesia contents are again less consistent, sometimes increasing and sometimes decreasing (Table 5). In the case of the cobalt coloured ring from Amarna, there is no consistent decrease or increase in the soda, potash or cobalt oxide contents through the more-or-less continuous glass matrix.

3.4. Beads (Fig. 1e, f and Table 6)

The wall thicknesses of the beads, all of which are tubular or elongated oval in shape, varied considerably from 400 to 600 μm for the four Esna beads, up to 1200 μm for the four copper and cobalt coloured Abydos beads, and up to 2000 μm for the two black Abydos beads and seven Amarna beads. The majority of the beads were again coloured by copper, but one Abydos bead (2221/4) and two Amarna beads (5032/1 and 5033/6) were coloured by cobalt, and two Abydos beads (2335/4 and 2394/4) were coloured black using manganese oxide.

With the exception of the black Abydos beads, the observed microstructures vary more-or-less according to the bead wall thicknesses. Thus, for the Esna beads, the glaze layers are formed on bodies consisting of angular quartz particles in more-or-less continuous glass matrices which in some cases contain a scatter of pores (Fig. 7a). The thinnest Abydos bead (2221/1 with 300 μm wall thickness) exhibits a similar microstructure. For the other Abydos beads, both copper and cobalt coloured, whose wall thicknesses are in the range 800–1200 μm, the interaction layers are still barely distinguishable and the bodies again consist of angular quartz particles in more-or-less continuous glass matrices (Fig. 7b, c). However, in contrast to the Esna beads, porosity now increases with distance away from the glaze layer. The cobalt coloured Amarna beads, although having thicker walls, exhibit a similar microstructure (Fig. 7d). In contrast, for the thicker walled copper coloured Amarna beads (1600–2000 μm wall thicknesses), interaction layers can be distinguished. However, their boundaries with the underlying body are diffuse, and tend to merge with the extensive interparticle glass bonding together the quartz particles and present throughout the body (Fig. 7e). In contrast to the above trend, the boundaries between the interaction layers and the bodies, which contain some interparticle glass, are reasonably well defined for the two black Abydos beads (Fig. 7f), even though their wall thicknesses are not significantly greater than those of the copper coloured Amarna beads.

It is difficult to see any consistent pattern in the variations in composition either through the more-or-less continuous glass matrices, or between the interaction layers and the interparticle glass when present (Table 6). The principal exceptions are the two manganese black beads from Abydos for

Table 5
Average glaze and glass compositions for faience rings from Abydos and Amarna (%wt normalised to 100%)

Code[a]	Component[b]	SiO_2	Na_2O	K_2O	CaO	MgO	Al_2O_3	FeO	MnO	CuO	SnO_2	CoO	Total	Na_2O/K_2O	Na_2O/CaO	Na_2O/MgO
E174 Abydos	IAL	76.95	11.91	3.54	1.57	0.17	1.28	0.63	0.04	3.82	0.08	0.02	97.74	3.36	7.59	69.78
	IPG	86.24	4.52	2.73	0.68	0.20	1.66	0.86	0.03	3.00	0.06	0.02	93.52	1.66	6.63	22.25
5053/3	GLZ	77.30	7.85	3.30	0.32	0.00	0.03	0.03	0.00	11.13	0.05	0.00	93.10	2.38	24.62	
	IAL	78.40	9.35	2.48	0.34	0.06	0.16	0.21	0.01	8.52	0.45	0.01	95.83	3.77	27.59	148.79
	IPG	85.73	6.38	1.25	0.44	0.05	0.13	0.34	0.00	5.41	0.26	0.00	97.94	5.09	14.55	122.56
5053/4	IAL	73.73	11.16	3.54	1.89	0.64	0.43	0.26	0.00	7.78	0.54	0.02	98.33	3.15	5.91	17.30
	IPG	81.83	6.90	2.19	1.97	0.48	0.43	0.31	0.02	5.24	0.63	0.01	100.64	3.15	3.50	14.48
5053/6	IAL	75.24	12.05	2.11	1.19	0.60	0.68	0.56	0.00	6.64	0.92	0.00	97.07	5.72	10.09	20.07
	IPG	87.08	6.30	1.02	0.92	0.38	0.36	0.42	0.01	2.99	0.53	0.00	94.27	6.18	6.86	16.74
5057/1	IAL	76.05	9.68	4.23	0.57	0.13	0.17	0.14	0.01	8.88	0.13	0.02	97.37	2.29	16.85	74.56
	IPG	84.25	6.17	2.54	0.70	0.17	0.21	0.15	0.01	5.70	0.10	0.01	99.72	2.43	8.82	36.22
5057/2	IAL	73.74	10.45	4.98	1.31	0.70	0.35	0.30	0.01	7.32	0.85	0.00	97.02	2.10	7.96	14.85
	IPG	83.80	6.55	2.95	1.43	0.70	0.23	0.08	0.03	4.06	0.17	0.01	99.26	2.22	4.58	9.38
5053/1 Cobalt	IAL(O)	73.79	10.91	2.87	1.29	1.52	8.64	0.41	0.18	0.02	0.01	0.36	100.05	3.80	8.46	7.20
	IAL(I)	77.17	10.21	1.83	2.01	1.82	5.87	0.44	0.21	0.05	0.01	0.40	99.71	5.57	5.08	5.62

[a] All from Amarna (18th dynasty) except E174 from Abydos (Middle Kingdom—Second Intermediate Period).
[b] GLZ — glaze layer; IAL — interaction layer glass phase; IAL(O) and IAL(I) refer to outer and inner regions of more-or-less continuous glass matrix (CGM); IPG — body interparticle glass.

which the soda and copper oxide contents decrease from the glaze layer through the interaction layer into the interparticle glass in the body, and potash content increases from the glaze into the interaction layer and then decreases in the body interparticle glass. Otherwise, the copper oxide contents normally decrease from the outer to the inner regions of the more-or-less continuous glass matrices or from the interaction layer into the body interparticle glass, and for the cobalt-blue Amarna beads, the soda, potash and lime contents also decrease (Table 6). However, there are no corresponding decreases in the cobalt oxide contents in the two cobalt-blue Amarna beads.

4. Discussion

4.1. Laboratory replicates

4.1.1. Efflorescence glazing

The composition profiles for the replicate efflorescence glazes indicate that there was preferential efflorescence of sodium carbonate as compared to potassium, calcium and magnesium carbonates and copper oxide. The differential efflorescence of sodium and potassium carbonates is perhaps surprising since the solubility of potassium carbonate is significantly greater than that of sodium carbonate (i.e. 100 g/cm^3 compared to 7 g/cm^3). One possible explanation is that, because of its lower solubility, sodium carbonate will precipitate first at the air–water interface at the surface of the bead. This preferential precipitation of sodium carbonate continues as more solution wicks out from the bead to replace that was lost due to evaporation. Thus, a layer richer in sodium carbonate than in potassium carbonate builds up at the surface of the bead. It is also possible that some preferential enrichment in sodium occurs during firing either as a result of preferential vaporisation of potassium from the surface or preferential diffusion of potassium back into the bead via the interaction layer glass.

Even though some movement of fine micron or submicron insoluble particles to the surface by surface tension during drying will probably occur (Vandiver, 1998, p. 127), the reduced efflorescence of the insoluble calcium and magnesium carbonates and copper oxide is more to be expected. However, even in the absence of significant efflorescence of these insoluble components, the observed microstructures and composition profiles can be explained in terms of the effloresced soluble carbonates reacting, during the subsequent firing, with the underlying quartz, lime, magnesia and copper oxide to form the glaze layer.

4.1.2. Cementation glazing

Paynter (2001, p. 236) has suggested that, in the case of cementation glazing, the silica in the body reacts during firing with the glazing mixture to form a melt at the surface of the bead. As the firing continues, this melt continues to react with and penetrate into the silica body of the bead to form the glaze and interaction layers. Because potash is more effective than soda as a flux of silica, it will be taken up into the melt in preference to soda so that, as compared to the original glazing mixture, the melt will be enriched in potash, and the excess soda will crystallise as sodium-calcium silicates. Therefore, as observed, the absolute percentages of potash will be higher and the Na_2O/K_2O ratios will be lower in the glazes and interaction layers than in the original glazing mixtures.

4.2. Raw materials

4.2.1. Quartz

The two possible sources of quartz are crushed quartz pebbles or quartz sand. The crushed quartz pebbles are characterised by high purity, in particular low alumina, lime and iron oxide contents (Brill, 1999, vol. 2, p. 474), and angular particles. In contrast, quartz sand can contain significant amounts of limestone or shell fragments, feldspars and iron-titanium oxides, and the sand particles tend to be rounded rather than angular.

For the present material, it is not always easy to use these criteria. First, with the exception of the coarse quartz used in the bowl bodies, the very fine particle size of the quartz means that even if sand was used it would almost certainly have been subjected to further grinding. Therefore, the angular shape of the quartz particles does not necessarily indicate the use of crushed quartz pebbles. Second, since the glass phases analysed typically make up less than 10% of the interaction layers and less than 1% of the bodies, the measured alumina and iron contents for the glass phase will be more than those in the bulk raw material by factors of between 10 and 100. Therefore, although the alumina and iron oxide contents of the glass phases can be as much as 3%, the corresponding contents of the bulk material would be significantly lower. Therefore, it seems probable, although not fully proven, that the faience examined was made using crushed quartz. The exception is the body of the Amarna bowl (E5048) for which the rounded quartz particles and high iron oxide content of the interparticle glass in the body (Table 4) suggest that quartz sand was used.

4.2.2. Alkali flux

The two possible sources of the soda-rich flux used to produce the faience glazes and glass phases are the natural evaporite, natron, and the ashes derived from salt tolerant, halophytic plants growing in coastal, salt marsh and desert regions. Natron, the most well known source of which is the Wadi Natrun on the edge of the Western Desert of Egypt (Shortland, 2004; Shortland et al., 2006b), consists predominantly of sodium carbonate and sodium bicarbonate, and is characterised by very low potash, lime and magnesia contents. Therefore, the high potash contents of all the faience analysed (Tables 4–6) provide clear evidence that plant ashes were the source of the alkali flux (Sayre and Smith, 1974).

The Middle Kingdom-Second Intermediate Period Abydos faience exhibits the lowest Na_2O/K_2O ratios in the interaction layer and interparticle glass (majority in the range 1.5–3.5), followed by the Amarna faience (majority in range 3–5), then the Esna faience (majority in the range 6–7), and finally

Table 6
Average glaze and glass phase compositions for faience beads from Esna, Abydos and Amarna (%wt normalised to 100%)

Code	Period[a]	Component[b]	SiO$_2$	Na$_2$O	K$_2$O	CaO	MgO	Al$_2$O3	FeO	MnO	CuO	SnO$_2$	CoO	Total	Na$_2$O/ K$_2$O	Na$_2$O/ CaO	Na$_2$O/ MgO
Esna																	
2011/1	18th D	IAL(O)	71.75	15.28	2.21	1.87	0.21	0.49	0.47	0.07	7.25	0.38	0.03	99.18	6.93	8.18	73.94
		IAL(I)	73.65	13.94	1.98	2.25	0.18	0.72	0.37	0.14	6.27	0.50	0.00	99.34	7.04	6.19	77.63
2011/2	18th D	IAL(O)	71.51	15.11	2.25	2.09	0.25	0.59	0.53	0.06	6.96	0.63	0.02	99.46	6.72	7.24	59.28
		IAL(I)	71.85	15.07	2.48	1.70	0.57	1.95	1.65	0.03	4.40	0.31	0.00	99.86	6.07	8.84	26.23
2323/1	SIP	IAL(O)	73.51	13.72	2.24	2.20	0.39	2.58	1.83	0.01	3.32	0.17	0.02	99.42	6.13	6.24	34.85
		IAL(I)	69.17	10.43	4.36	1.07	0.26	10.89	1.92	0.00	1.85	0.03	0.01	99.61	2.39	9.76	39.45
2323/2	SIP	IAL	72.91	14.34	2.22	3.10	0.31	1.95	1.14	0.04	3.83	0.16	0.00	99.52	6.47	4.63	46.52
Abydos																	
2221/1	22nd D	GLZ	72.76	12.63	2.18	1.04	0.12	0.84	0.50	0.19	9.66	0.05	0.04	88.49	5.79	12.16	108.25
		IAL(O)	83.12	10.17	1.19	0.49	0.12	0.95	0.72	0.10	3.00	0.14	0.02	92.88	8.56	20.84	85.65
		IAL(I)	76.10	13.62	1.10	1.66	0.31	1.16	1.51	0.09	3.89	0.56	0.00	96.87	12.37	8.19	43.99
2221/5	22nd D	IAL(O)	74.05	15.39	1.34	0.83	0.23	0.68	1.28	0.05	5.74	0.40	0.00	96.22	11.48	18.57	68.01
		IAL(I)	77.97	12.77	1.00	1.23	0.25	0.97	1.60	0.05	3.59	0.58	0.00	97.42	12.82	10.34	50.69
2221/4 Cobalt	22nd D	IAL	74.52	15.24	2.10	1.04	0.08	0.23	0.85	0.70	4.37	0.21	0.66	96.87	7.27	14.65	186.85
2335/2	MK−SIP	IAL(O)	72.72	13.55	2.36	1.01	0.36	0.73	1.88	0.40	7.00	0.01	0.00	99.12	5.75	13.47	37.92
		IAL(I)	83.92	7.65	1.44	0.55	0.22	0.53	1.90	0.18	3.59	0.01	0.00	98.85	5.31	13.80	35.53
2335/4 Black	MK−SIP	GLZ	62.43	14.38	4.43	4.96	0.20	0.22	0.63	3.54	9.20	0.02	0.00	99.10	3.25	2.90	72.05
		IAL	68.20	11.03	5.44	3.84	0.42	0.50	1.05	6.79	2.71	0.01	0.03	98.33	2.03	2.88	26.42
		IPG	75.38	3.44	2.73	5.97	0.27	0.89	1.68	8.95	0.67	0.00	0.01	84.38	1.26	0.58	12.59
2394/4 Black	MK−SIP	GLZ	65.46	15.13	4.05	0.61	0.03	0.16	0.18	0.29	14.09	0.00	0.01	99.03	3.74	24.62	542.95
		IAL	71.42	9.73	4.92	0.96	0.76	3.09	2.41	4.00	2.70	0.00	0.02	98.00	1.98	10.16	12.85
		IPG	86.60	3.55	2.43	0.53	0.34	1.41	1.29	3.46	0.38	0.00	0.00	96.72	1.46	6.74	10.46
Amarna																	
5033/1	18th D	GLZ	68.30	16.16	3.62	0.82	0.09	0.29	0.14	0.02	10.53	0.00	0.03	96.39	4.47	19.60	176.89
		IAL	74.12	12.55	3.03	1.64	0.17	0.50	0.69	0.01	6.97	0.29	0.01	97.33	4.14	7.68	72.17
		IPG	67.76	15.23	3.68	3.98	0.04	0.08	0.14	0.00	8.96	0.12	0.02	95.87	4.14	3.82	423.09
5033/2	18th D	IAL	71.46	13.06	2.94	5.64	0.14	0.25	0.30	0.02	6.10	0.10	0.00	99.34	4.44	2.32	93.55
		IPG	82.94	5.62	1.72	5.17	0.14	0.22	0.17	0.02	3.93	0.07	0.00	98.85	3.26	1.09	39.60
5033/3 Segmented	18th D	IAL	74.18	10.67	3.00	0.79	0.20	0.21	0.29	0.10	10.11	0.44	0.01	97.07	3.56	13.46	52.42
5033/4 Segmented	18th D	IAL	69.19	13.35	4.14	0.95	0.17	0.10	0.16	0.08	11.65	0.21	0.00	99.38	3.23	14.03	79.36
		IPG	74.12	10.90	3.53	0.77	0.20	0.17	0.21	0.17	9.61	0.33	0.00	99.97	3.09	14.24	55.41
5033/5	18th D	IAL	80.09	10.04	2.54	1.48	0.37	0.88	0.50	0.02	3.90	0.18	0.00	99.11	3.96	6.78	27.26
		IPG	78.72	10.18	2.86	2.35	1.07	0.76	0.47	0.00	3.49	0.09	0.01	98.33	3.56	4.33	9.48
5032/1 Cobalt	18th D	IAL(O)	74.59	11.99	3.12	1.73	1.72	4.80	0.56	0.50	0.70	0.02	0.27	99.70	3.84	6.93	6.97
		IAL(I)	77.30	11.10	2.78	1.34	1.50	4.25	0.39	0.42	0.68	0.02	0.22	99.80	4.00	8.26	7.43
5033/6 Cobalt	18th D	IAL(O)	70.39	14.97	2.86	1.46	1.60	3.18	0.65	0.83	3.64	0.18	0.24	94.69	5.23	10.26	9.35
		IAL(I)	80.52	8.88	2.17	1.18	1.06	2.79	0.93	0.74	1.40	0.15	0.19	95.12	4.09	7.50	8.35

[a] MK − Middle Kingdom; SIP − Second Intermediate Period.

[b] GLZ − glaze layer; IAL − interaction layer glass phase; IAL(O) and IAL(I) refer to outer and inner regions of more-or-less continuous glass matrix (CGM); IPG − body interparticle glass.
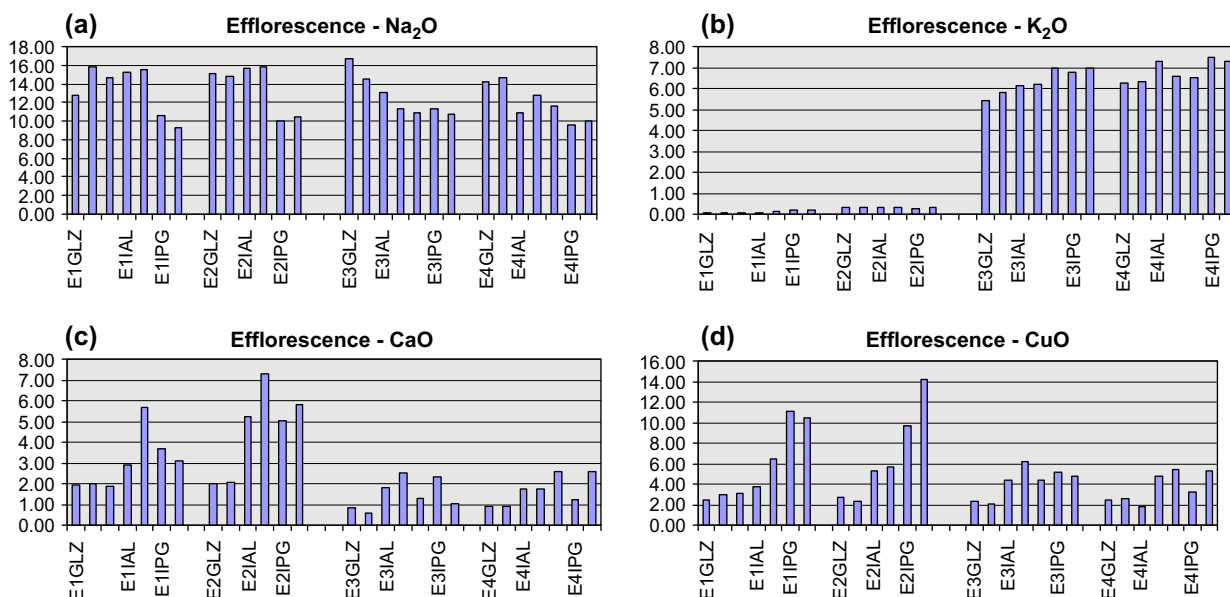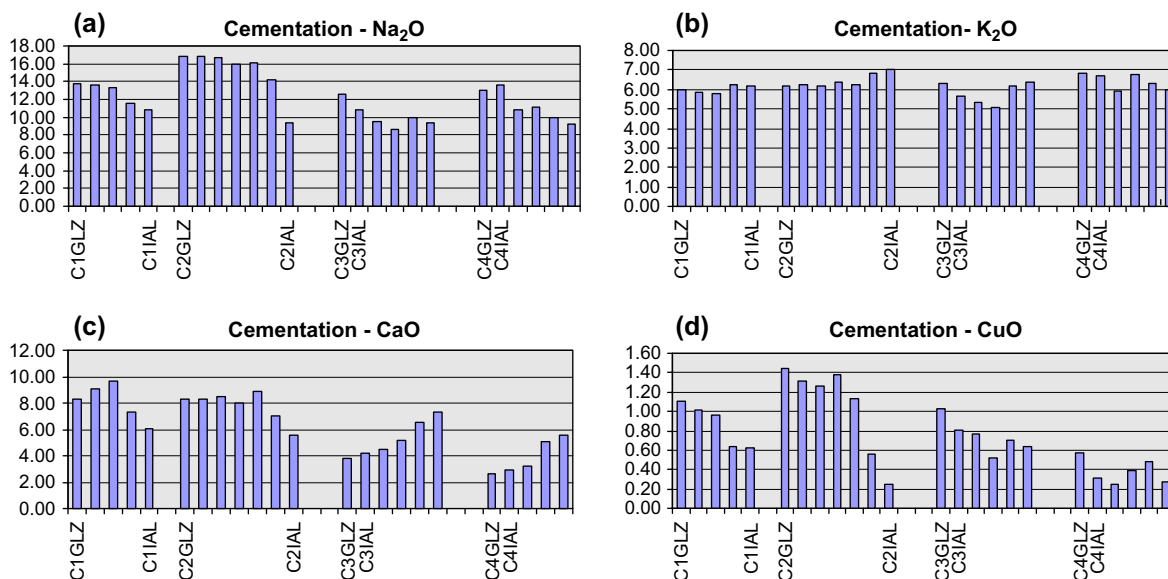
Fig. 3. Soda, potash, lime and copper oxide concentration profiles from the glaze (GLZ), through the interaction layer glass phase (IAL), to the body interparticle glass (IPG) for replicate efflorescence faience samples E1–E4.

the 22nd dynasty Abydos faience with the highest ratios (majority in the range 8–13) (Tables 4–6, Fig. 8). These ratios are comparable with those for the glass phase in Egyptian blue and turquoise frits from New Kingdom Amarna, the majority of which fall in the range 2–6 (Hatton, 2005). However, with the exception of the 22nd dynasty Abydos faience, the faience glass phase ratios are all lower than those for New Kingdom, copper blue glass from Amarna and Malkata (average 7.9) (Shortland, 2000; Shortland and Eremin, 2006). The differences in the Na_2O/CaO and Na_2O/MgO ratios in the faience interaction layer and interparticle glass (majority in the ranges 3–20 and 10–80, respectively) between these four groups are

less clear cut. However, the ratios are all significantly higher than those observed for the New Kingdom glass (averages 2.1 and 4.2, respectively).

The question that therefore needs to be considered is whether the differences in composition between the faience glazes and glass phases, and New Kingdom glass is the result of using plant ashes of different compositions, or whether it is due to the different processes involved in faience and glass production.

Because of the observed differential efflorescence of soda, potash, lime and magnesia, and differential diffusion of soda and potash from the cementation glazing mixture, the ratios

Fig. 4. Soda, potash, lime and copper oxide concentration profiles from the glaze (GLZ), through the interaction layer glass phase (IAL) for replicate cementation faience samples C1–C4.
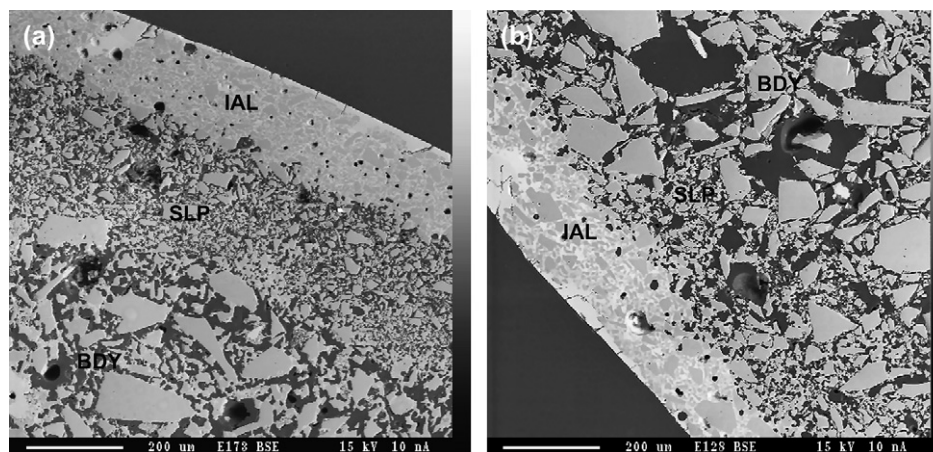
Fig. 5. SEM photomicrographs of sections through outer glaze (small areas visible at surface), interaction layer (IAL), fine textured slip (SLP) and coarse textured body (BDY) of Abydos bowls (a) E173 and (b) E129. [Quartz particles are darker grey and glass phase lighter grey; pores are black.]

observed in the faience glaze and glass phases can differ from those of the original plant ashes used in the glazing mixtures. However, for efflorescence glazing, it can be seen from the composition profiles for the replicates (Table 3) that the ratios for the added plant ash should match those for the faience glass phase somewhere within the interaction layer. In contrast, for cementation glazing, it can be seen from the compositions of the replicates that the Na_2O/K_2O ratios for the plant ash in the glazing mixture could be some 5 times higher than the ratio in the resulting glaze and glass phase (Table 3). However, although the Na_2O/CaO and Na_2O/MgO ratios in the cementation glazing mixture are sometimes lower than those in the glaze and glass phase, the differences are less pronounced than for the Na_2O/K_2O ratio, particularly with respect to the interaction layer glass phase (Table 3).

Similarly, in glass production, the components of the plant ash could be partitioned in some not readily predictable way between the glass itself and the waste products so that the original composition of the plant ash is again not necessarily preserved in the glass.

A further possible explanation for the very high Na_2O/CaO and Na_2O/MgO ratios (i.e. low lime and magnesia contents) in the faience is that the plant ashes were purified prior to use by dissolution to leave insoluble calcium and magnesium carbonates, and subsequent evaporation of the solution. Alternatively, it is possible that not all the lime and magnesia present in New Kingdom glass comes from plant ash, but that a proportion is due to the inclusion of limestone or a lime bearing sand in the mixture of raw materials from which the glass is produced.

In summary, therefore, it is not entirely clear whether or not the differences in composition between the faience glazes and glass phases and New Kingdom glass are due to the use of plant ashes with different compositions.

4.2.3. Colorants

With the exception of the Middle Kingdom-Second Intermediate Period Abydos bowls, ring and beads, all the copper coloured faience analysed, including the Second Intermediate Period Esna beads, contains a small amount of tin oxide.
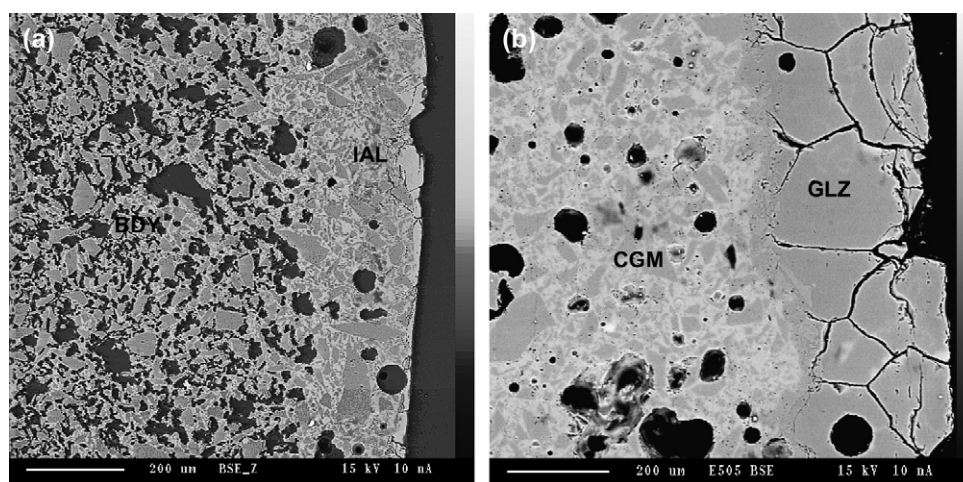

Fig. 6. SEM photomicrographs of sections through (a) copper coloured Amarna ring (5053/4) showing small areas of glaze visible at surface, interaction layer (IAL) and body (BDY) containing extensive interparticle glass; and (b) cobalt coloured Amarna ring (5053/1) showing glaze (GLZ) and quartz in a more-or-less continuous glass matrix (CGM) extending throughout ring. [Quartz particles are darker grey and glass phase lighter grey; pores are black.]
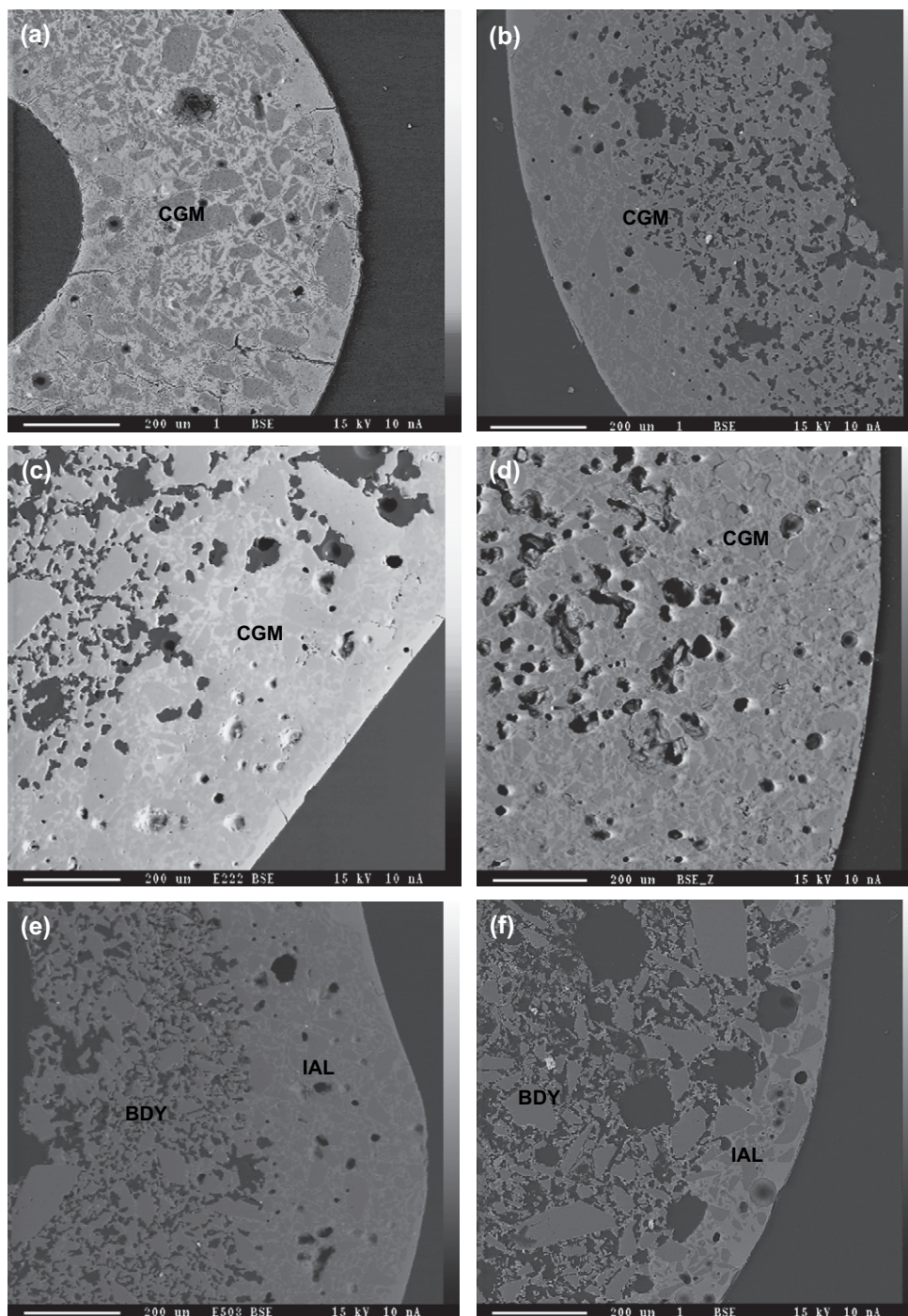
Fig. 7. SEM photomicrographs of sections through (a) Esna bead (2011/2) (b) Abydos bead (2335/2), (c) Abydos bead (2221/4) − cobalt coloured, (d) Amarna bead (5032/1) − cobalt coloured, (e) Amarna bead (5033/1), and (f) Abydos bead (2335/4) − black. Small areas of glaze are visible at the surfaces of all the beads. (a) − (d) show quartz in a more-or-less continuous glass matrix (CGM) extending throughout each bead, with increasing porosity away from the outer surface except for (a). (e) and (f) show interaction layer (IAL) and body (BDY) containing varying amounts of interparticle glass. [Quartz particles are darker grey and glass phase lighter grey; pores are black.]

Therefore, the source of the copper colorant for this group was almost certainly the scale resulting from the oxidation of bronze metal, bronzes containing typically between 5 and 10% tin being used (Sayre and Smith, 1974). In the case of the Middle Kingdom-Second Intermediate Period Abydos faience, produced at a period when bronze was not available in Egypt, the possible sources of the copper would have

been either the scale from the oxidation of copper metal, or a relatively pure copper ore such as malachite.

As previously discussed (Tite and Shortland, 2003), the cobalt coloured Amarna faience is characterised by high alumina, magnesia and manganese oxide contents. Therefore, the source of the cobalt was almost certainly the cobaltiferous alum that is found in the Kharga and Dakhla Oases in the
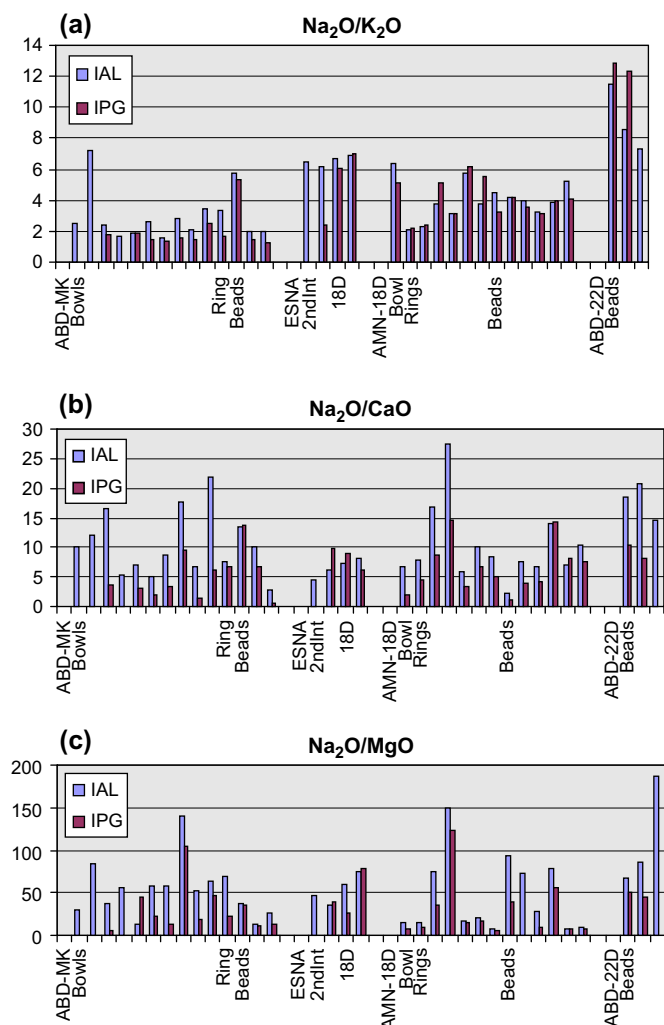
Fig. 8. Na_2O/K_2O, Na_2O/CaO and Na_2O/MgO ratios in interaction layer glass phase (IAL) and body interparticle glass (IPG) for Middle Kingdom Abydos (ABD-MK) bowls, ring and beads, Second Intermediate Period (2ndInt) and 18th dynasty (18D) Esna beads, 18th dynasty Amarna (AMN-18D) bowl, rings and beads, and 22nd dynasty Abydos (ABD-22D) beads.

Western Desert of Egypt (Kaczmarczyk, 1986; Shortland et al., 2006a). In contrast, the single 22nd dynasty cobalt coloured bead from Abydos does not have the high alumina and magnesia contents associated with the use of cobaltiferous alum, and was therefore instead coloured using a cobalt ore with a high manganese content.

4.3. Methods of glazing

Examination with a low-power binocular microscope to identify, for example, drips of glaze, drying or firing marks, and variations in glaze thickness across an object, can be a valuable first step in determining which of the possible glazing methods were used (Vandiver, 1983, 1998). However, with the present group of faience, significant macroscopic evidence was not detected on the fragments that were available for examination. Therefore, the microstructural and compositional evidence obtained using scanning electron microscopy was of primary importance.

First, on the basis of laboratory replications, Tite and Bimson (1986) proposed that the different methods used to glaze faience could be distinguished on the basis of differences in glaze and interaction layer thicknesses, the nature of the boundary between the interaction layer and the body, and presence or absence of interparticle glass bonding together the quartz particles in the body. In particular, they proposed that efflorescence glazing could be distinguished from cementation and application glazing on the basis of the presence or absence, respectively, of interparticle glass in the body.

However, Vandiver (1998) has subsequently argued convincingly that these microstructural criteria must be used with caution. For example, with both cementation and application glazing, some glazing mixture would normally have been added to the quartz body in order to facilitate forming the object, and to increase its strength both before and after firing. This would result in the formation of interparticle glass within the body, and depending on the amount of glazing mixture added, a less well defined boundary between the interaction layer and the body. The overall microstructure would not then differ significantly from that associated with efflorescence glazing. Furthermore, both the present replication experiments and those reported by Vandiver (1998) have shown that, depending in part on the firing temperature and time, the interaction layer associated with cementation glazing can penetrate to depths of up to 1000 μm. Therefore, for objects with thin cross-sections, such as the tubular beads examined in the present paper, cementation glazing could result in quartz particles in a more-or-less continuous glass matrix throughout the body of the object.

Second, in terms of compositional profiles, the current replication experiments suggest that cementation and efflorescence glazing differ in that the copper oxide content decreases from the glaze into the interaction layer for the former, and increases from the glaze through the interaction layer into the body interparticle glass for the latter (Tables 2 and 3).

Finally, in trying to identify the method of glazing used, it is also important to consider which glazing method is most appropriate for the type of object being studied. For example, cementation glazing has the advantage that a large number of small objects (less than about a centimetre across) can be glazed *en masse* without leaving drying or firing marks on their surfaces. However, it is less appropriate for bigger objects because of the large quantities of glazing mixture that would be required. Efflorescence glazing has the advantage that, in combination with moulding to shape, it provides an efficient method for the large scale production of objects up to some 20−30 cm across. Again, application glazing is particularly appropriate for objects such as tiles and inlays that only need glazing on one side.

4.3.1. Bowls

The interparticle glass observed in the Abydos and Amarna bowls indicates that a glazing mixture was added to both the coarse quartz body and to the fine quartz slip. In addition the boundary between the interaction layer and the underlying quartz slip is reasonably well defined. Therefore, the overall

microstructure is consistent with the glaze being the result of efflorescence from a glazing mixture incorporated into the slip. However, the significant decreases in the copper oxide contents from the interaction layer into the slip interparticle glass (typically by a factor in the range 2–4) are inconsistent with efflorescence glazing and instead suggest either cementation or application glazing. Cementation glazing would have been less appropriate both because of the size of the bowls (about 15 cm in diameter) and their black decoration, but application glazing, in combination with the addition of glazing mixture to both the fine quartz slip and coarse quartz bodies, is a strong possibility.

4.3.2. Rings

The microstructure of the rings from Abydos and Amarna differs from the bowls in that their interaction layers are less readily distinguished from the underlying quartz bodies that now contain extensive interparticle glass. Therefore, efflorescence glazing could again have been used with a higher proportion of glazing mixture being added to the quartz than in the case of the bowls. The more-or-less continuous glass matrix associated with the cobalt coloured ring is probably due to a combination of an even higher proportion of glazing mixture added to the quartz, and the lower mobility of cobalt as compared to the copper colorant (Vandiver, 1998, p. 137). However, for the copper coloured rings, the decreases in the copper oxide contents from the interaction layer into the body interparticle glass, although less than for the bowls (typically by a factor in the range 1–2), again appear to be inconsistent with efflorescence glazing. Therefore, both cementation and application glazing, in combination with the addition of glazing mixture to the body prior to glazing, remain as possible alternatives.

4.3.3. Beads

The microstructures observed for the beads span the full range from a reasonably well-defined interaction layers (Abydos black beads), through interaction layers that are difficult to distinguish from the extensive interparticle glass in the underlying bodies (Amarna copper coloured beads), to a more-or-less continuous glass matrix (Amarna cobalt-blue beads, Abydos and Esna beads). With the exception of the Abydos black beads and Amarna cobalt coloured beads, the overall glass phase increases with decreasing bead wall thickness. Therefore, the microstructures could again all be the result of efflorescence glazing with the increasing glass phase being due to increasing proportions of glazing mixture being added to the quartz, possibly in order to increase the strength as the bead wall thickness decreases.

However, in the case of the two Abydos black beads, the very large decreases in the copper oxide contents from the glaze into the interaction layer and the further decreases into the body interparticle glass (overall by factors of 16 and 38) are strong evidence for the use of cementation or application glazing. In view of the small size of the beads, cementation glazing using a glazing mixture containing plant ash, and with manganese oxide but no or minimal copper oxide being

added to the quartz body prior to glazing, seems the more likely method. The presence of copper oxide in the glaze of these black beads does not contribute significantly to their colour. Therefore, it seems probable that black beads were glazed together with turquoise beads for which the copper oxide in the glazing mixture was essential as the colorant.

Similarly, for the other beads, because of the tendency for decreasing copper oxide contents from the interaction layer into the body interparticle glass (typically by factors in the range 1–2), cementation glazing again remains a possibility. In the case of the thicker walled Amarna beads (up to 2000 μm), some glazing mixture would again have needed to be added to the quartz body prior to glazing, but this would not have been necessary for the thinner walled Abydos and Esna beads (up to 1200 μm).

5. Conclusions

The composition profiles for the replicate efflorescence and cementation faience have provided new data on the differential efflorescence and differential take up into the glaze, respectively, of the components of the glazing mixtures used. Thus, there appears to be preferential efflorescence of sodium carbonate over potassium carbonate, probably as a result of the significantly lower solubility of the former. Conversely, in cementation glazing, there appears to be preferential take up into the glaze of potash over soda, probably because potash is more effective than soda as a flux of silica.

The glaze and glass phases associated with ancient Egyptian faience are generally significantly richer in potash and poorer in lime and magnesia than New Kingdom glass. However, it is not clear whether these differences in composition are due to the use of plant ashes with different compositions, or to the different processes involved in faience and glass production. Regarding the other raw materials, it seems probable that, with one exception (Amarna bowl E5048), the source of the quartz was crushed quartz pebbles rather than quartz sand. Bronze scale probably provided the copper colorant, except for the Middle Kingdom-Second Intermediate Period Abydos faience, and cobaltiferous alum from the Western Desert in Egypt provided the cobalt colorant, except for the 22nd dynasty Abydos faience in which a cobalt ore was probably used.

As a result of the loss of crucial information through weathering together with the use of hybrid methods, in which the addition of glazing mixture to the quartz body is combined with either cementation or application glazing, it is only rarely possible to determine with certainly the method used to glaze ancient faience from microstructural and compositional evidence. Thus, with the exception of the Abydos black beads which were almost certainly glazed using the cementation method, it is not impossible that all the faience examined was glazed by the efflorescence method. However, because of the decreasing copper oxide contents from the interaction layer into the body interparticle glass, it is possible that application glazing was used for the bowls, that cementation or application glazing was used for the rings, and that cementation glazing was used for all the beads. If either cementation or application glazing was used,

then some glazing mixture would certainly have been added to the quartz bodies as a preliminary to glazing, and as a result, some prior efflorescence would probably have occurred.

Because of these difficulties, it is recommended that, in future studies of ancient faience, as much emphasis is placed on the performance characteristics resulting from the observed microstructures as on trying to determine the details of the glazing method by which they were achieved. In this context it is worth noting that, perhaps in order to maintain the necessary strength, the glazing methods employed for the ancient faience currently under investigation normally appear to have been such as to achieve an increase in the amount of interparticle glass within the body as the thickness/size of the object decreased. Thus the glass content of the bodies increases from low levels in the Abydos bowls, to higher levels in the Amarna rings and beads, to more-or-less continuous glass matrices in the Abydos and Esna beads.

Finally, it is perhaps worth highlighting the fact that a conservatism appears to be inherent in the production technology of Egyptian faience. Thus, a plant ash producing glaze and glass phases with distinctively high potash and low lime and magnesia contents was used from the Middle Kingdom through until at least the 18th dynasty, and there was no obvious change with the beginning of glass production. Again, the methods of glazing were such as to produce beads with similar microstructures, and therefore similar mechanical performance characteristics in use, from the Middle Kingdom through until the 22nd dynasty.

Acknowledgements

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