Journal of Archaeological Science: Reports 49 (2023) 103920

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

The dating and provenance of glass fragments from the site of Serabit el-Khâdim, Sinai

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ARTICLE INFO

Keywords:
Glass
New Kingdom
Ramesside
Late Bronze Age
Serabit el-Khâdim
Sinai
LA-ICP-MS
Composition

ABSTRACT

Serabit el-Khâdim, located on the western coast of the Sinai Peninsula, is the site of an ancient turquoise mine established in the early 12th Dynasty (c. 1985 BCE) and active between the 18th and 20th Dynasties (c. 1550–1136 BCE). The temple dedicated to Hathor at Serabit detail the number of offerings made, thereby recording the level of activity at Serabit during each reign. The last offerings were made by Rameses VI (1143–1136 BCE) corresponding with the collapse of the Late Bronze Age before the site was abandoned. 976 glass fragments were given to the Ashmolean Museum by Flinders Petrie following his 1905–6 excavations. 41 fragments from the collection were selected for LA-ICP-MS analysis with the aim of provenancing and dating an unknown collection of glass using composition and available stylistic features to further narrow the date of manufacture and therefore indicate the possible workshop of origin. The analysis showed that all 41 fragments are of Egyptian provenance and of standard Late Bronze Age high magnesia plant ash glass, except one fragment which is a unique example of natron blue glass applied as decoration to a white plant ash vessel body. Subtle compositional differences show that 18th Dynasty plant ash glass, plant ash Ramesside glass and natron Ramesside glass are all present, therefore corresponding with the known Egyptian activity at Serabit.

1. Introduction

Serabit el-Khâdim, or Serabit, is an ancient mining development located approximately 7 km east of the modern port of Abu Zenima, halfway down the western coast of the Sinai Peninsula. Due to the inhospitable environment, ancient Sinai was regarded as little more than a land bridge connecting Egypt and the Levant until the discovery of turquoise in the early dynastic period (c. 3150 BCE) (Mumford, 1999, p722). Strongly associated with ancient Egyptian jewellery, turquoise is a relatively rare stone and compounded with religious significance (Aldred, 1971, p34), therefore it was a highly prized, luxury item and used extensively for amulets and jewellery (Aston, Harrell and Shaw, 2000, p62). Despite the extraction of turquoise being exceedingly labour-intensive (Aldred, 1971, p128), the ancient Egyptian market was particularly lucrative, and private Egyptian workers, military forces and ranking officials were dispatched to ensure the successful recovery of the stone (Redford, 1992, p79). Thus, Serabit became what was arguably-one of the most significant centres of Egyptian enterprise in the Sinai-peninsula (Wilkinson, 2017, p239).

In the early 12th Dynasty (c. 1985 BCE), a temple dedicated to the Goddess Hathor, also named “the Mistress of Turquoise” and the “Lady of Malachite” was constructed; Hathor was the deity responsible for foreign expeditions and was believed to be the patron goddess of turquoise miners (Giveon, 1978, p54-62). Serabit was also a popular pilgrimage site with many gifts and offerings being placed at the temple as tribute, making evident the ancient Egyptian belief that mining expeditions would only be successful if the proper religious respects were paid (New, 1932; Mumford, 2006; Caelen, 2013). The temple itself contains numerous inscriptions denoting the increasing number of turquoise mining expeditions undertaken from the reign of Amenemhat I (1985–1956 BCE), the first king of the 12th Dynasty, to Amenemhat IV (1786–1777 BCE). Mining activities ceased at the end of the 12th Dynasty (c. 1785 BCE) following the immigration of the Canaanites and invasion of the Hyksos (Barrois, 1932; Grimal, 1992, p391), and only resumed when political stability returned following the formation of the New Kingdom (Mumford, 1999, p724). After 12 years of peace under Amenhotep I (1525–1504 BCE), mining was re-established along with the tradition of monument building; repairs, extensions and embellishments were made to the temple between the reigns of Hatshepsut (1473–1458 BCE) and Amenhotep III (1390–1352 BCE) (Mumford,

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https://doi.org/10.1016/j.jasrep.2023.103920
Received 23 January 2023; Received in revised form 18 February 2023; Accepted 25 February 2023
Available online 21 March 2023
2352-409X/

1999a, p725; Wilkinson, 2017, p239). It is from the mid-18th Dynasty (c. 1550 BCE) that glass vessels and objects were included as part of the temple offerings. Strictly administered and regulated by the Egyptian royal court, glass became one of the highest symbols of elite status in the New Kingdom (Shortland, Nicholson and Jackson, 2001, p153), therefore the presence of glass core formed vessels at the temple demonstrates the high value of offerings made to Hathor and confirms the importance of turquoise mining activities at Serabit.

According to the temple inscriptions, 71 votive offerings were placed at Serabit between the reigns of Tuthmosis III and Ay (1327–1323 BCE) (Mumford, 2006) and an estimated 329 votives were placed between the reigns of Rameses 1 (1295–1294 BCE) and Tawosret (1188–1186 BCE), with 66 votives offered during the Iron Age (IA) reigns of Sethnakht (1186–1184 BCE) onwards (Mumford, 2006). Further building work, offerings and inscriptions were made between the reigns of Rameses IV (1153–1147 BCE) and Rameses VI (1143–1136 BCE), which were the last recorded activities, with the mines subsequently being abandoned, corresponding with the collapse of the Late Bronze Age (LBA) (Eckenstein, 1921, p63). Periods of mining activity at Serabit and political and social stability in Egypt and the Near East are therefore analogous, indicating that even highly profitable endeavours were abandoned during times of political crisis (Giveon, 1978, p51).

1.1. The excavation at Serabit

The temple at Serabit was re-discovered in 1762 by Carsten Niebuhr and revisited by several scholars, whose work was largely limited to making copies of inscriptions (Eckenstein, 1921, p17). The first extensive excavation was undertaken by Petrie in the winter of 1905–6, which resulted in the first complete plan of the temple with over 300 photographs taken of the site (Petrie, 1904).

According to Petrie's excavation notes, the temple offerings were mainly of "glazed ware", such as vases, bowls and cups, as well as other offerings such as *menats*, bracelets, sistra and wands. The damage to the offerings was so extensive that no item was observed intact, with the remains forming a layer on the temple floor "two or three inches thick" (Petrie, 1906, p138). After attempting some reconstruction work, Petrie concluded that a large portion of the fragments were missing, likely scattered outside the temple and left to disintegrate in the severe atmospheric conditions (Petrie, 1906, p122).

1.2. Samples

The Serabit expedition finds were divided between several museums, including the Cairo Museum, the British Museum, London, and the Ashmolean Museum, Oxford (Petrie, 1906, p123). 976 glass fragments from Serabit (Accession number E.4486) reside at the Ashmolean Museum (Simpson, 1990). Most fragments are on average between 1 and 4 cm, and are coated with a white, salt deposit or the distinctive red-brown deposit that reflects the red Nubian sandstone geology of Serabit. Although heavily coated with deposits, some fragments that have sustained recent breakage show good preservation. The colours are remarkably vibrant; turquoise, light and dark blue hues, black, brown, green and white are included in the collection. Also visible on some fragments are fine examples of feather and garland patterns applied in white and yellow, as well as rims created from thin, twisted coloured glass rods. Handles and other defining features allows the inference of the vessel type, therefore it can be speculated that pots, amphora, spherical vessels, pomegranate vessels and *kratiskeros* were among those presented to the temple (Nolte, 1968), in addition to items with glass inlays.

Forty-two fragments which exhibited good preservation, glass matrix uniformity and clarity of colour were selected for laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) analysis. Description of the fragments are included in Table 1. All fragments included in the study are relatively small, therefore the pattern

Table 1
Description of fragments from Serabit selected for analysis by LA-ICP-MS.

Acc. #	Main body colour	Opaque/ Translucent	Fragment description	Shape and approximate size in centimetres
OX122	Black	Semi translucent	Vessel fragment with feather, garland or arcade dragged pattern applied in two colours: white and apparent yellow/ brown. Transecting thicker white band bordering the pattern.	3.0 × 2.5
OX144	Black	Semi translucent	Vessel fragment with straight white band applied transecting the fragment.	2.5 × 1.5
OX299	Black	Translucent	Vessel fragment with straight white band applied transecting the fragment.	3.0 × 2.0
OX358	Amber/ brown	Translucent	Vessel fragment with decorative threads of yellow/ white visible on the cross section. Pattern imperceptible.	2.5 × 1.5
OX420	Brown	Translucent	Vessel fragment with garland pattern applied in at least two different colours.	4.0 × 4.0
OX561	Brown	Translucent	Vessel fragment with possible decoration applied in yellow.	Oblong fragment 2.0 × 2.5
OX189	Mid Blue	Translucent	Vessel fragment with flat arcade/ garland pattern applied with three colour thread combination. Pattern appears to be applied in the pattern form rather than using an implement to drag over the surface, forming the pattern.	3.5 × 3.0
OX193	Dark blue	Translucent	Vessel fragment with elaborate feather pattern applied in apparent white and yellow threads.	Roughly triangular 1.5 × 3.0
OX414	Dark blue	Opaque	Unknown object. No perceptible pattern, prominent white thread transecting the fragment.	3.5 × 1.5
OX433	Dark blue	Translucent	Vessel fragment with possible garland pattern applied in lighter colour.	3.0 × 2.0
OX437	Dark Blue	Translucent		

(*continued on next page*)

Table 1 (*continued*)

Acc. #	Main body colour	Opaque/ Translucent	Fragment description	Shape and approximate size in centimetres
			Vessel fragment with possible garland pattern applied in at least two different colours. Rim made from twisted threads.	2 fragments, both 2.0 × 1.5
OX669	Dark blue	Translucent	Vessel fragment with regular white garland/arcade pattern applied in lighter colour.	Triangular fragment 2.5 × 1.5
OX84	Dark blue	Translucent	Vessel fragment with possible feather pattern and two white transecting bands.	2.5 × 3.0
OX107	Dark blue	Semi translucent	Possible vessel fragment with no perceptible pattern.	1.5 × 2.0
OX183	Dark blue	Translucent	Vessel fragment with elaborate pattern (possibly feather) applied in at least three colours	Triangular 3.5 × 2.0
OX200	Dark blue	Translucent	Vessel fragment with pattern applied with yellow, white and light blue threads.	Roughly triangular fragment approx. 3.2 × 1.7 at widest point
OX481	Black/dark blue	Semi translucent	Vessel fragment with white thread present in rim section.	Triangular fragment 2.0 × 2.0
OX501	Dark blue/ black	Semi translucent	Unknown object type with no perceptible pattern.	Oblong fragment 3.0 × 2.0
OX70	Light blue	Translucent	Vessel fragment with yellow and dark blue thread applied in a straight design.	1.5 × 2.5
OX103	Turquoise	Translucent	Unknown object type with no perceptible pattern.	3.0 × 2.5
OX127	Mid blue	Translucent	Unknown object type with no perceptible pattern. Semi translucent.	2.0 × 3.5
OX195	Blue	Semi translucent	Vessel fragment with consistent, even feather pattern applied in three (?) colours.	3.5 × 2.0
OX198	Light blue	Translucent	Vessel fragment with apparent feather pattern applied in yellow and white threads, thicker white band transecting the fragment.	Triangular fragment 2.5 × 3.0
OX235	Light blue	Semi translucent	Vessel fragment with possible feather pattern	2.0 × 2.0

Table 1 (*continued*)

Acc. #	Main body colour	Opaque/ Translucent	Fragment description	Shape and approximate size in centimetres
			applied in yellow and white threads.	
OX429	Turquoise blue	Translucent	Vessel fragment with no perceptible pattern. Rim contains merged yellow and blue glass.	4.0 × 4.0
OX442	Light blue	Translucent	Vessel fragment with possible garland or feather pattern applied. Rim applied with at least two colours of twisted glass of apparent white and dark blue.	2.5 × 2.0
OX472	Turquoise blue	Translucent	Vessel fragment with feather pattern applied in two other colours, one possibly yellow.	2.5 × 2.0
OX482	Blueish green	Translucent	Vessel fragment with garland pattern applied with at least two different colours, one being yellow. Rim applied in solid opaque yellow.	Triangular fragment 2.0 × 2.0
OX488	Mid blue	Translucent	Vessel fragment with no perceptible pattern, rim applied in darker blue and white twisted glass.	Square fragment 1.0 × 1.0
OX897	Light blue	Translucent	Vessel fragment with no perceptible pattern.	Square fragment 1.7 × 1.5
E.4486	Green	Opaque	Unknown object type. Fragment is flat with no perceptible pattern applied	Irregular shaped fragment 2.5 × 2.0
E.4486.1	Green	Semi translucent	Unknown object type with no perceptible pattern.	Irregular shaped fragment 2.5 × 2.0
OX140	Green	Opaque	Unknown object type with no perceptible pattern.	1.5 × 2.0
OX484	Green/ blue	Translucent	Rounded fragment - "leaf" from a pomegranate vessel? Yellow rim applied to the edge of rounded section.	Rounded fragment 2.0 × 1.5
OX77	Black/ Purple	Translucent	Vessel fragment with pattern applied in at least two different coloured threads.	3.0 × 2.0
OX85	Purple/ brown	Translucent	Unknown object type with no	6.0 × 3.0

(continued on next page)

Table 1 (*continued*)

Acc. #	Main body colour	Opaque/ Translucent	Fragment description	Shape and approximate size in centimetres
			perceptible pattern.	
OX641	White	Opaque	Vessel fragment with dark blue/ black band visible under red deposit, white prominent thread transecting fragment	Oblong fragment 3.2 × 1.7
OX264	Yellow	Semi translucent	Vessel fragment with no perceptible pattern.	Roughly triangular fragment 3.0 × 1.7 at widest point
OX444	Yellow	Opaque	Vessel fragment with no perceptible pattern. Rim applied in white and black/dark brown coloured glass.	2.5 × 2.5
OX334	Dark red	Semi translucent	Unknown object type with no perceptible pattern.	2.0 × 2.0
OX226	Amber/ brown	Translucent	Vessel fragment with undetermined pattern applied in two lighter colours, possible yellow and white.	3.0 × 2.0

described per fragment cannot be considered as descriptive of the complete object. Small samples were taken from the fragments with a pair of wire cutters and then mounted in resin blocks and polished.

2. Methodology

The analyses were carried out with an Agilent 8900 triple quadrupole ICP-MS coupled with an ESI New Wave Research NWR 193 ArF excimer laser. The operating conditions for the laser ablation system were set at 7 J/cm^2 with a frequency of 15 Hz and a spot size of 70 µm. The ICP-MS was operated with a RF power set at 1380 W, a plasma gas flow of 15 L min^{-1} and an auxiliary gas flow of 0.90 L min^{-1}. Helium was used as carrier gas (800 mL min^{-1}) in single MS mode with no cell gas. The ICP-MS was tuned before each session on the glass SRM NIST612 to achieve high sensitivity and stability (RSD < 5 %). The plasma condition was monitored with U/Th ratio (0.9–1.1) and ThO/Th ratio was used to assess a low oxide level (ThO/Th < 0.01). The ICP-MS was setup in full-quant mode for the acquisition of 42 masses. Gas blanks were recorded during the 15 *sec* warm-up time and 15 *sec* washout time. Each sample was analysed in triplicate with 60 *sec* of ablation per spot. The first 20 *sec* of ablation were considered as pre-ablation and were not used in the calculation of the concentration. Quantitative data were obtained using the calibration protocol described by Van Elteren et al. (Van Elteren, Tennent and Šelih, 2009) using linear combination of a set of four glass SRMs as external standards (NIST 612, NIST 610, Corning B and Corning D) and SiO_2 as the internal standard. The full set of SRMs used as external standards were regularly measured in the batches and the results were comparable to the accepted values (Vicenzi et al., 2002; Jochum et al., 2011; Wagner et al., 2012).

3. Results

The glasses contain between 16.0 % and 22.8 % Na_2O (Table 2) therefore represent the expected values for un-weathered Egyptian LBA glass. All samples contain an average of 4.2 % MgO and 1.7 % K_2O, thus compare with standard Egyptian LBA plant ash glasses produced in the 18th Dynasty (Sayre and Smith, 1961; Lilyquist et al., 1993; Shortland and Eremin, 2006) The exception is the Co + Cu blue glass from fragment OX641 which is discussed separately.

3.1. Provenance

Shortland et al. demonstrated that by using a covariant plot of Cr/La vs 1000Zr/Ti, glasses of Egyptian and Mesopotamian origin can be distinguished (Shortland, Rogers and Eremin, 2007). The trace elements from the Serabit study group (Table 3) were plotted against the glasses of known Egyptian and Mesopotamian origin, showing that all Serabit glasses are of Egyptian provenance (Fig. 1).(SeeTable 4.).

4. Discussion

4.1. Style and workshops

Vessels produced between the reigns of Amenhotep III and Akhenaten are considered to represent the "golden era" of Ancient Egyptian glassmaking due to the fine artistry and high quality of production. New Kingdom vessels are typified by the *amphoriskos* and *krateriskos* shape, created primarily in blue hues, with yellow and white threads applied in feather and garland patterns. Ramesside vessels by comparison show a diversity in colour and shape (such as the introduction of pomegranate and pilgrim flasks) often with no or basic patterns applied. Ramesside glasses are notably less sophisticated, both in glass quality and artistry following the decline of the glass industry after the end of the 18th Dynasty (c. 1295 BCE) (Nolte, 1968).

Two significant Ramesside glass workshops are known: debris from Qantir indicates that this was a primary glassmaking site between c. 1300–1270 BCE (Pusch and Rehren, 2007, p131) for the mass manufacture of red glass (and some cobalt glasses) in the form of ingots rather than objects (Rehren, Pusch and Herold, 2001; Rehren and Pusch, 2005; Rademakers, Rehren and Pernicka, 2017). The later site of Lisht is known to have produced vessels and other items, such as inlays, in a range of colours including Cu-blue, yellow, white, black, purple, brown and green dated to between 1295 and 1070 BCE (Keller, 1983). Notably, evidence of cobalt blue glass production at Lisht has not been confirmed, however, evidence of recycling is present at this site (Keller, 1983; Brill, 1999; Mass, Wypyski and Stone, 2002). Research indicates that glasses produced at Lisht have a distinctive chemical signature, characterised by low levels of lime, alumina and iron oxide in addition to relatively high concentrations of soda compared with other Egyptian glasses (Smirniou, Rehren and Gratuze, 2018). Also, Lisht Cu-blue glasses generally contain very little, if no, tin; therefore, both factors can indicate later Lisht glasses, or be used as exclusion criteria when comparing unknown samples.

Gurob has been identified as a lesser Ramesside glassworking site (Brunton and Engelbach, 1927 Shaw, 2007) and the available analyses suggest that white, black, Cu-blue (with elevated tin) and Co + Cu-blue glasses were worked at the site, the latter containing the "Type R" cobalt source, used exclusively in Ramesside glasses and characterised by low Zn, elevated Ni and lower Al compared with New Kingdom Co-glasses (Abe et al., 2012; Lankton, Pulak and Gratuze, 2022).

4.2. Cobalt blue

All six glasses in the Co blue group contain between 0.84 % and 1.2 % K_2O with an elevated average content of 2.43 % Al_2O_3, therefore comparable to standard CoO Egyptian LBA glasses, which are well published

Table 2
Average results for the LA-ICP-MS analyses showing major and minor elements of the samples from Serabit (wt%).

			Major and minor elements [wt %]												
High Magnesia High Potash															
As. Number	**Colour group**	**Translucent/ Opaque**	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**K_2O**	**CaO**	**MnO**	**Fe_2O_3**	**CoO**	**CuO**	**Sb2O3**	**PbO**
OX122	Black	Opaque	16.01	4.64	0.73	67.89	0.11	1.31	7.47	0.02	0.43	0.00	0.01	0.00	0.00
OX144	Black	Opaque	17.75	4.93	0.66	61.72	0.10	1.89	8.11	0.02	0.67	0.00	0.12	0.38	2.42
OX299	Black	Semi-translucent	18.47	4.65	0.76	62.75	0.13	1.76	9.40	0.02	0.43	0.00	0.00	0.00	0.00
Black average			**17.41**	**4.74**	**0.72**	**64.12**	**0.11**	**1.65**	**8.33**	**0.02**	**0.51**	**0.00**	**0.04**	**0.13**	**0.81**
OX358	Brown	Opaque	17.80	4.09	0.65	64.21	0.15	1.61	6.52	0.03	0.45	0.00	1.84	0.15	0.92
OX420	Brown	Opaque	18.34	3.50	0.41	64.99	0.16	1.53	5.81	0.02	0.28	0.00	2.02	0.19	0.88
OX561	Brown	Translucent	18.15	5.33	0.44	63.56	0.16	2.06	6.94	0.03	0.37	0.00	0.87	0.05	0.53
Brown average			**18.10**	**4.30**	**0.50**	**64.25**	**0.16**	**1.73**	**6.42**	**0.02**	**0.37**	**0.00**	**1.58**	**0.13**	**0.78**
OX189	Co blue	Translucent	20.79	5.33	3.17	59.25	0.11	0.98	7.99	0.21	0.44	0.07	0.02	0.03	0.00
OX193	Co blue	Translucent	18.77	3.50	1.10	65.90	0.10	0.93	7.08	0.08	0.52	0.13	0.03	0.01	0.01
OX414	Co blue	Opaque	19.66	3.36	2.12	62.33	0.18	1.20	8.22	0.18	0.33	0.18	0.01	0.29	0.00
OX433	Co blue	Translucent	20.66	4.94	2.25	58.74	0.09	0.84	9.73	0.11	0.47	0.10	0.01	0.07	0.00
OX437	Co blue	Translucent	20.35	5.41	3.01	59.88	0.12	0.93	7.74	0.16	0.50	0.08	0.02	0.00	0.00
OX669	Co blue	Translucent	20.30	5.10	2.96	60.19	0.13	0.99	7.85	0.15	0.47	0.07	0.02	0.00	0.00
Co Blue average			**20.09**	**4.61**	**2.43**	**61.05**	**0.12**	**0.98**	**8.10**	**0.15**	**0.45**	**0.10**	**0.02**	**0.07**	**0.00**
OX84	Co + Cu blue	Translucent	20.13	3.57	1.54	64.62	0.09	0.60	6.06	0.18	0.71	0.10	0.35	0.09	0.03
OX107	Co + Cu blue	Opaque	20.67	3.98	1.37	63.29	0.15	1.21	6.25	0.09	0.43	0.19	0.15	0.28	0.00
OX183	Co + Cu blue	Translucent	19.27	4.64	1.56	61.05	0.16	1.51	8.26	0.11	0.49	0.06	0.97	0.07	0.00
OX200	Co + Cu blue	Translucent	22.27	3.51	2.95	61.04	0.09	0.90	6.24	0.20	0.52	0.10	0.22	0.00	0.00
OX481	Co + Cu blue	Opaque	19.05	3.80	1.33	66.23	0.15	1.12	5.61	0.08	0.40	0.16	0.13	0.25	0.00
OX501	Co + Cu blue	Opaque	21.67	3.90	1.39	58.89	0.15	1.07	8.79	0.14	0.90	0.07	0.18	0.50	0.16
Co + Cu blue average			**20.51**	**3.90**	**1.69**	**62.52**	**0.13**	**1.07**	**6.87**	**0.13**	**0.58**	**0.11**	**0.33**	**0.20**	**0.04**
OX70	Cu blue	Translucent	16.69	3.98	0.83	67.27	0.17	1.46	7.29	0.02	0.46	0.00	0.45	0.02	0.05
OX103	Cu blue	Translucent	18.35	4.28	0.37	62.97	0.16	2.27	9.16	0.01	0.22	0.00	0.49	0.04	0.28
OX127	Cu blue	Translucent	18.58	3.44	0.55	64.88	0.16	1.74	7.57	0.02	0.33	0.00	0.97	0.01	0.00
OX195	Cu blue	Opaque	19.31	3.23	0.35	64.37	0.23	2.52	6.21	0.02	0.28	0.00	0.42	1.28	0.00
OX198	Cu blue	Semi-translucent	18.15	4.28	0.83	63.95	0.17	1.51	7.59	0.02	0.46	0.00	1.05	0.26	0.01
			Major and minor elements [wt %]												
High Magnesia High Potash															
As. Number	**Colour Group**	**Translucent/ Opaque**	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**K_2O**	**CaO**	**MnO**	**Fe_2O_3**	**CoO**	**CuO**	**Sb2O3**	**PbO**
OX235	Cu blue	Translucent	18.09	4.49	0.53	66.08	0.21	1.41	6.57	0.02	0.33	0.00	0.71	0.02	0.00
OX429	Cu blue	Translucent	18.69	4.80	0.73	62.77	0.21	2.44	7.75	0.02	0.41	0.00	0.76	0.00	0.00
OX442	Cu blue	Opaque	22.81	3.33	0.36	60.72	0.22	2.57	6.80	0.02	0.31	0.00	0.58	0.44	0.00
OX472	Cu blue	Opaque	19.44	4.46	0.63	61.17	0.18	1.87	8.18	0.02	0.39	0.00	1.24	0.60	0.02
OX482	Cu blue	Translucent	16.69	3.66	0.78	67.58	0.15	1.22	7.41	0.02	0.48	0.00	0.38	0.07	0.14
OX488	Cu blue	translucent	20.48	4.16	0.51	63.00	0.18	1.76	6.32	0.03	0.31	0.01	1.65	0.02	0.00
OX897	Cu blue	Translucent	18.05	4.42	1.10	65.83	0.19	1.45	6.48	0.02	0.33	0.00	0.69	0.02	0.00
Cu blue average			**18.78**	**4.04**	**0.63**	**64.22**	**0.19**	**1.85**	**7.28**	**0.02**	**0.36**	**0.00**	**0.78**	**0.23**	**0.04**
E.4486	Green	Opaque	18.54	4.72	0.39	61.34	0.20	2.42	9.07	0.01	0.28	0.00	0.01	0.16	1.46
E.4486.1	Green	Semi-translucent	20.01	3.88	0.49	65.32	0.16	1.87	6.22	0.02	0.32	0.00	0.01	0.00	0.00
OX140	Green	Semi-translucent	18.82	4.87	0.47	63.20	0.11	1.65	8.97	0.02	0.28	0.00	0.01	0.00	0.00
OX484	Green	Opaque	17.22	4.33	0.48	61.41	0.15	2.07	9.20	0.02	0.42	0.00	0.01	0.50	2.81
Green average			**18.65**	**4.45**	**0.46**	**62.82**	**0.16**	**2.00**	**8.37**	**0.02**	**0.33**	**0.00**	**0.01**	**0.16**	**1.07**
OX77	Purple	Translucent	18.28	3.65	0.57	65.04	0.20	2.26	6.98	0.75	0.71	0.00	0.05	0.00	0.00
OX85	Purple	Translucent	19.69	3.79	0.58	63.08	0.18	1.94	8.50	0.27	0.34	0.00	0.01	0.00	0.00
OX444	Purple	Translucent	19.43	3.39	0.80	63.90	0.17	1.83	7.58	0.21	0.80	0.09	0.00	0.00	0.00
Purple average			**19.13**	**3.61**	**0.65**	**64.01**	**0.18**	**2.01**	**7.69**	**0.41**	**0.62**	**0.03**	**0.02**	**0.00**	**0.00**
OX122	White	Opaque	18.43	4.01	0.48	64.60	0.21	2.34	6.70	0.03	0.28	0.00	0.18	0.85	0.01
OX641	White	Opaque	21.75	3.35	0.54	61.49	0.17	1.71	6.27	0.02	0.31	0.00	0.16	2.26	0.00
White Average			**20.09**	**3.68**	**0.51**	**63.05**	**0.19**	**2.02**	**6.48**	**0.02**	**0.30**	**0.00**	**0.17**	**1.56**	**0.01**
OX264	Yellow	Opaque	19.71	4.79	0.40	59.00	0.22	2.47	9.56	0.01	0.29	0.00	0.09	0.20	1.51
OX444	Yellow	Opaque	17.07	4.65	0.65	56.34	0.10	1.76	7.75	0.02	1.31	0.00	0.10	1.40	7.36
OX561	Yellow	Opaque	18.04	4.40	0.49	58.99	0.16	2.05	9.32	0.02	0.46	0.00	0.08	0.72	3.35
Yellow average			**18.27**	**4.61**	**0.51**	**58.11**	**0.16**	**2.09**	**8.88**	**0.02**	**0.69**	**0.00**	**0.09**	**0.77**	**4.07**
OX334	Red	Opaque	20.55	3.79	0.41	63.91	0.24	2.20	5.45	0.02	0.26	0.00	1.20	0.14	0.01
OX226	Amber	Translucent	19.91	4.23	0.38	64.74	0.26	2.80	5.43	0.03	0.25	0.00	0.01	0.00	0.00
Low Magnesia Low Potash															
OX641	Co+Cu blue	Opaque	21.80	0.49	1.00	64.94	0.03	0.91	2.69	0.01	0.69	0.08	1.33	1.08	2.76

(Shortland and Eremin, 2006; Shortland, Rogers and Eremin, 2007; Kemp, Brownscombe and Shortland, 2021). The glasses in this group are coloured with an average of 0.1 % CoO and exhibit elevated levels of associated elements Mn, Ni, and Zn and with an average of 0.15 %, 677 ppm, and 725 ppm respectively. Therefore all glasses in the Serabit CoO group are coloured with the characteristic cobaltiferous alum used exclusively in the Egyptian 18th Dynasty, known as “Type A”, hence were likely manufactured between the reigns of Tuthmosis III (1479–1425 BCE) and Akhenaten (1352–1336 BCE (Kaczmarczyk, 1986; Abe et al., 2012).

4.3. *Co + Cu blue*

The six glasses contain between 0.06 and 0.19 % CoO and 0.13–0.97 % CuO, therefore conform to the definition of Co + Cu glasses (Shortland and Eremin, 2006; Smirniou and Rehren, 2013). All Serabit Co + Cu blue glasses contain an average concentration of 1.69 % Al_2O_3 with elevated Ni, Zn, and Mn, hence characteristic of the Type A cobalt source used

Table 3
Average results for the LA-ICP-MS trace elements analyses of the samples from Serabit (ppm).

			Trace elements (ppm)																												
High Magnesia High Potash																															
As. Number	**Colour group**	**Translucent/Opaque**	**Li**	**Be**	**B**	**Ti**	**V**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Rb**	**Sr**	**Zr**	**Nb**	**Ag**	**Sn**	**Sb**	**Cs**	**Ba**	**La**	**Ce**	**Au**	**Pb**	**Th**	**U**
OX122	Black	Opaque	5.9	0.1	54	427	7.5	5.3	186	3012	6.7	7.6	46.4	10.8	1.3	7.3	670	22.5	1.5	0.1	2.2	26.1	0.2	49.5	3.2	6.1	0.0	13.4	0.6	0.2
OX144	Black	Opaque	5.2	0.2	65	338	6.7	5.3	148	4665	1.9	4.7	926	15.1	8.5	8.1	710	29.2	1.3	6.1	7.4	3174	0.1	37.7	2.3	4.7	0.0	20991	0.6	0.2
OX299	Black	Semi-translucent	4.9	0.1	70	446	8.3	6.6	170	3010	1.9	4.1	24.8	12.6	1.2	8.8	1075	38.4	1.6	0.4	0.6	21.0	0.2	39.2	2.9	5.7	0.0	2.7	0.7	0.3
Black average			**5.3**	**0.2**	**63**	**403**	**7.5**	**5.8**	**168**	**3562**	**3.5**	**5.4**	**332**	**12.8**	**3.7**	**8.0**	**819**	**30.0**	**1.4**	**2.2**	**3.4**	**1074**	**0.2**	**42.1**	**2.8**	**5.5**	**0.0**	**7002**	**0.6**	**0.3**
OX358	Brown	Opaque	6.8	0.1	88	372	6.6	5.8	215	3165	10.9	13.6	14727	24.8	26.8	6.9	507	33.3	1.2	4.1	746	1211	0.1	42.4	2.4	4.6	0.7	7927	0.5	0.3
OX420	Brown	Opaque	4.1	0.1	72	240	5.0	4.9	128	1946	2.9	9.7	16155	223	40.4	7.2	524	27.0	0.8	4.5	1517	1574	0.1	48.5	1.8	3.4	3.7	7648	0.4	0.3
OX561	Brown	Translucent	7.2	0.1	74	237	5.5	3.9	231	2571	3.9	6.8	6972	758	37.8	6.6	593	16.8	1.0	1.6	343	423	0.1	37.9	2.3	4.4	0.4	4599	0.4	0.2
Brown average			**6.0**	**0.1**	**78**	**283**	**5.7**	**4.9**	**191**	**2561**	**5.9**	**10.0**	**12618**	**335**	**35.0**	**6.9**	**541**	**25.7**	**1.0**	**3.4**	**869**	**1070**	**0.1**	**42.9**	**2.1**	**4.2**	**1.6**	**6725**	**0.5**	**0.2**
OX189	Co blue	Translucent	9.1	2.6	84	328	6.2	4.1	1607	3059	562	369	141	698	2.3	5.0	703	32.1	1.2	0.0	6.4	217	0.1	29.4	3.0	8.2	0.0	6.9	41.9	41.9
OX193	Co blue	Translucent	7.0	0.8	148	434	7.4	4.4	646	3614	1060	1260	250	279	2.3	3.9	495	38.1	1.3	0.1	15.7	85.5	0.0	32.6	2.5	5.3	0.0	47.9	0.4	0.2
OX414	Co blue	Opaque	5.6	0.6	106	311	4.9	3.2	1398	2291	1391	820	52.4	1600	6.0	6.0	1328	29.3	1.0	0.1	1.4	2463	0.1	31.1	2.2	6.1	0.0	19.2	0.4	0.2
OX433	Co blue	Translucent	10.3	2.2	133	457	7.6	7.1	861	3262	787	877	89.6	462	3.1	5.2	1084	58.5	1.6	0.2	5.9	558	0.1	45.0	3.3	7.5	0.0	10.6	0.6	0.3
OX437	Co blue	Translucent	9.6	1.7	132	407	7.1	3.7	1274	3473	638	423	648	762	2.5	4.7	725	37.9	1.4	0.1	7.4	8.4	0.1	33.3	3.6	9.5	0.0	5.2	1.1	0.7
OX669	Co blue	Translucent	9.9	1.5	128	377	6.9	4.1	1158	3286	515	310	128	547	2.2	4.9	736	38.9	1.4	0.1	4.3	9.2	0.0	34.2	3.4	8.3	0.0	5.2	0.7	0.3
Co Blue average			**8.6**	**1.6**	**122**	**386**	**6.7**	**4.4**	**1157**	**3164**	**826**	**677**	**218**	**725**	**3.1**	**4.9**	**845**	**39.1**	**1.3**	**0.1**	**6.9**	**557**	**0.0**	**34.3**	**3.0**	**7.5**	**0.0**	**15.8**	**7.5**	**7.3**
OX84	Co+Cu blue	Translucent	10.9	0.9	134	678	11.3	8.0	1383	4967	788	634	2776	250	10.0	4.7	418	49.1	2.4	0.3	209	714	0.1	49.4	4.9	10.1	0.1	299	1.1	0.7
OX107	Co+Cu blue	Opaque	8.4	0.4	120	473	8.4	6.5	704	3015	1476	1331	1209	358	11.1	5.9	517	46.8	1.6	0.3	68.4	2346	0.1	40.3	3.2	6.6	0.2	29.0	0.4	0.9
OX183	Co+Cu blue	Translucent	7.1	0.5	98	476	8.7	6.1	857	3405	482	259	7748	664	30.7	9.4	807	38.5	1.8	1.1	789	552	0.2	42.5	3.5	7.7	0.2	43.1	0.8	0.4
OX200	Co+Cu blue	Translucent	9.9	1.8	132	474	7.2	5.8	1547	3644	781	570	1742	821	5.6	5.3	701	46.0	1.5	0.3	100	16.9	0.1	40.1	3.1	7.4	0.2	13.4	0.7	0.3
OX481	Co+Cu blue	Opaque	6.2	0.4	123	452	6.9	5.4	646	2822	1256	1186	1061	291	8.6	4.9	427	39.2	1.4	0.2	59.9	2122	0.1	36.5	2.7	5.4	0.2	26.8	0.6	0.3
OX501	Co+Cu blue	Opaque	10.6	0.7	73	585	12.4	9.9	1087	6292	527	343	1474	221	17.5	4.1	757	39.6	1.7	0.4	186	4175	0.1	46.2	3.2	7.0	0.3	1427	1.1	0.8
Co+Cu blue average			**8.9**	**0.8**	**114**	**523**	**9.1**	**6.9**	**1037**	**4024**	**885**	**721**	**2668**	**434**	**13.9**	**5.7**	**604**	**43.2**	**1.7**	**0.4**	**235**	**1654**	**0.1**	**42.5**	**3.4**	**7.3**	**0.2**	**306**	**0.8**	**0.5**
OX70	Cu blue	Translucent	5.3	0.2	75	480	8.2	6.5	164	3241	5.7	7.0	3591	20.4	13.2	7.0	479	30.6	1.6	0.3	179	208	0.1	41.7	3.2	6.2	0.1	413	0.7	0.3
OX103	Cu blue	Translucent	6.3	0.1	83	198	3.9	2.7	82	1507	2.2	3.6	3896	149	7.5	6.5	1092	17.9	0.7	0.6	201	301	0.1	25.9	1.4	2.6	0.4	2442	0.3	0.1
OX127	Cu blue	Translucent	5.8	0.1	78	335	6.5	3.0	135	2340	3.6	7.0	7747	13.8	22.4	7.4	569	29.9	1.1	0.6	536	91.7	0.1	29.1	2.1	4.2	0.5	24.7	0.5	0.2
OX195	Cu blue	Opaque	6.2	0.1	87	194	5.5	3.7	193	1974	4.0	4.3	3352	52.2	30.2	6.6	552	12.9	0.7	1.4	104	10715	0.1	44.9	1.8	3.4	0.1	28.3	0.3	0.6
OX198	Cu blue	Semi-translucent	7.3	0.0	62	452	8.7	5.3	186	3223	7.9	10.7	8363	24.1	32.6	8.0	630	30.3	1.6	0.4	330	2188	0.1	43.0	3.3	6.4	0.2	45.8	0.7	0.3
OX235	Cu blue	Translucent	4.7	0.1	79	278	5.7	4.0	177	2297	3.6	5.9	5641	13.2	19.4	5.5	532	15.5	1.0	0.3	330	184	0.1	28.9	2.1	4.2	0.1	38.3	0.4	0.2
OX429	Cu blue	Translucent	6.3	0.1	72	459	7.6	5.4	173	2899	2.4	5.7	6089	17.6	18.8	8.5	920	41.0	1.5	0.9	414	5.5	0.1	38.4	2.7	5.3	0.9	16.7	0.6	0.3
OX442	Cu blue	Opaque	6.7	0.1	64	189	6.3	3.6	146	2141	1.8	3.1	4658	41.6	23.1	7.1	602	14.9	0.7	0.7	160	3640	0.1	42.8	2.0	3.8	0.1	16.2	0.4	0.9
			Trace elements (ppm)																												
High Magnesia High Potash																															
As. Number	**Colour group**	**Translucent/ Opaque**	**Li**	**Be**	**B**	**Ti**	**V**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Rb**	**Sr**	**Zr**	**Nb**	**Ag**	**Sn**	**Sb**	**Cs**	**Ba**	**La**	**Ce**	**Au**	**Pb**	**Th**	**U**
OX472	Cu blue	Opaque	7.9	0.1	73	379	7.6	4.8	177	2700	6.7	8.9	9879	21.2	63.2	6.5	737	30.4	1.3	0.7	366	5016	0.1	38.7	2.7	5.3	0.2	132	0.6	0.3
OX482	Cu blue	Translucent	4.1	0.2	84	485	8.1	6.5	168	3340	20.9	18.2	3049	21.1	8.8	4.4	667	26.0	1.3	0.4	269	548	0.1	44.8	2.7	5.4	0.1	1181	0.6	0.3
OX488	Cu blue	translucent	5.2	0.1	77	302	5.7	3.4	225	2159	57.4	48.1	13206	61.6	32.5	5.9	497	16.0	1.0	1.0	913	179	0.1	33.8	1.9	3.7	0.3	26.0	0.4	0.2
OX897	Cu blue	Translucent	4.2	0.1	77	272	5.5	3.9	177	2282	3.6	5.6	5527	13.0	18.7	5.6	514	14.8	0.9	0.4	322	205	0.1	28.4	2.0	4.0	0.1	40.5	0.4	0.2
Cu blue average			**5.8**	**0.1**	**76**	**335**	**6.6**	**4.4**	**167**	**2509**	**10.0**	**10.7**	**6250**	**37.4**	**24.2**	**6.6**	**649**	**23.4**	**1.1**	**0.6**	**344**	**1940**	**0.1**	**36.7**	**2.3**	**4.5**	**0.3**	**367**	**0.5**	**0.3**
E.4486	Green	Opaque	5.7	0.1	75	219	4.3	3.3	106	1980	1.4	2.5	58.1	710	2.6	11.0	1314	24.3	0.8	0.3	1.4	1322	0.1	72.4	1.7	3.3	0.0	12641	0.4	0.2
E.4486.1	Green	Semi-translucent	4.2	0.1	72	292	5.7	4.6	158	2243	1.6	3.2	43.8	12.4	1.0	8.3	535	21.2	1.0	0.1	1.1	13.0	0.1	29.4	1.7	3.3	0.0	2.4	0.4	0.2
OX140	Green	Semi-translucent	6.5	0.1	62	270	5.2	5.2	128	1948	2.1	3.3	98.2	19.8	1.2	33.1	1232	28.7	1.0	0.1	2.1	7.2	0.6	24.0	1.9	3.9	0.0	12.7	0.4	0.2
OX484	Green	Opaque	5.5	0.1	69	288	5.5	4.8	125	2966	1.8	3.5	54.2	1067	4.5	9.6	1397	36.0	1.0	0.5	2.9	4155	0.1	89.7	2.1	4.2	0.0	24358	0.5	0.4
Green average			**5.5**	**0.1**	**70**	**267**	**5.2**	**4.5**	**129**	**2284**	**1.7**	**3.1**	**63.6**	**452**	**2.3**	**15.5**	**1120**	**27.6**	**1.0**	**0.3**	**1.9**	**1374**	**0.2**	**53.9**	**1.8**	**3.7**	**0.0**	**9254**	**0.4**	**0.2**
OX77	Purple	Translucent	9.1	1.0	65	341	8.9	4.3	5795	4948	9.7	12.3	386	157	3.6	8.5	552	23.5	1.3	0.4	11.3	33.7	0.1	50.4	3.0	5.8	0.0	26.9	0.6	0.6
OX85	Purple	Translucent	6.2	0.1	58	384	7.8	5.8	2080	2389	2.2	3.3	51.6	22.9	1.7	8.2	897	37.2	1.3	0.1	3.1	0.9	0.1	57.1	2.3	4.5	0.0	4.2	0.5	0.3
OX444	Purple	Translucent	6.3	0.4	84	491	8.0	7.1	1651	5606	717	281	30.8	132	1.1	5.9	787	29.7	1.5	0.0	1.4	11.7	0.1	45.8	2.6	6.2	0.0	8.8	0.7	0.3
Purple average			**7.2**	**0.5**	**69**	**405**	**8.2**	**5.7**	**3175**	**4314**	**243**	**99**	**156**	**104**	**2.1**	**7.5**	**746**	**30.1**	**1.3**	**0.2**	**5.2**	**15.4**	**0.1**	**51.1**	**2.7**	**5.5**	**0.0**	**13.3**	**0.6**	**0.4**
OX122	White	Opaque	8.6	0.1	100	315	5.4	3.3	205	1981	1.4	2.6	1401	12.6	23.3	4.9	576	21.8	0.9	0.1	1977	7137	0.1	37.3	1.9	3.6	0.0	63.4	0.4	0.2
OX641	White	Opaque	4.5	0.1	71	335	6.7	3.3	169	2173	1.9	2.9	1304	15.1	30.5	4.9	555	13.3	1.0	0.3	1.2	18899	0.1	30.2	1.9	3.7	0.3	27.1	0.5	0.4
White Average			**6.6**	**0.1**	**86**	**325**	**6.1**	**3.3**	**187**	**2077**	**1.6**	**2.7**	**1353**	**13.9**	**26.9**	**4.9**	**565**	**17.5**	**1.0**	**0.2**	**989**	**13018**	**0.1**	**33.8**	**1.9**	**3.7**	**0.2**	**45.2**	**0.4**	**0.3**

(*continued on next page*)

Table 3 (*continued*)

High Magnesia High Potash			Trace elements (ppm)																											
As. Number	**Colour group**	**Translucent/ Opaque**	**Li**	**Be**	**B**	**Ti**	**V**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Rb**	**Sr**	**Zr**	**Nb**	**Ag**	**Sn**	**Sb**	**Cs**	**Ba**	**La**	**Ce**	**Au**	**Pb**	**Th**	**U**
OX264	Yellow	Opaque	6.1	0.1	74	237	4.6	3.6	108	2058	1.4	2.7	700	914	3.0	10.9	1371	24.6	0.8	0.4	12.5	1672	0.1	72.0	1.8	3.5	0.0	13053	0.4	0.2
OX444	Yellow	Opaque	5.3	0.4	59	341	6.8	5.4	146	9148	2.0	4.7	827	23.5	23.2	7.4	687	27.3	1.2	11.3	1.6	11654	0.1	38.4	2.3	4.5	0.0	63781	0.6	0.3
OX561	Yellow	Opaque	5.7	0.1	67	295	5.6	5.3	127	3247	1.8	3.7	669	1426	5.8	9.4	1542	36.5	1.0	0.6	3.0	6037	0.1	107.7	2.2	4.2	0.0	29053	0.7	0.4
Yellow average			**5.7**	**0.2**	**67**	**291**	**5.7**	**4.7**	**127**	**4818**	**1.7**	**3.7**	**732**	**788**	**10.7**	**9.2**	**1200**	**29.4**	**1.0**	**4.1**	**5.7**	**6454**	**0.1**	**72.7**	**2.1**	**4.1**	**0.0**	**35295**	**0.6**	**0.3**
OX334	Red	Opaque	5.3	0.1	85	263	5.6	4.0	167	1853	4.2	8.0	9584	17.1	41.5	6.6	424	13.1	0.8	0.9	952	1140	0.1	32.0	1.7	3.3	0.1	45.8	0.4	0.2
OX226	Amber	Translucent	5.3	0.1	91	300	4.2	4.1	255	1719	0.8	1.6	41.9	9.3	0.8	3.9	391	19.1	1.0	0.0	0.4	3.2	0.1	32.5	1.8	3.4	0.0	1.1	0.4	0.1
Low Magnesia Low Potash																														
OX641	Co+Cu blue	Opaque	7.7	0.2	102	591	9.3	6.9	83	4819	667	12.0	10662	92.6	88.3	5.3	222	50.0	1.8	1.1	31.4	8998	0.1	42.4	3.0	6.0	1.6	23930	0.7	0.8

exclusively in the 18th Dynasty (Kaczmarczyk, 1986; Abe et al., 2012). Therefore, all six Co + Cu glasses were likely produced in the 18th Dynasty. In addition, several fragments from both the Co– and Co + Cu-blue groups exhibit finely applied patterns in several colours and styles, supporting the evidence that these were produced in the 18th Dynasty, likely by expert craftsmen at Malkata or Amarna (Shortland, 2012, p62).

4.4. *Copper blue*

All 12 Cu-blue glasses in this group are within known LBA Egyptian Cu-blue composition ranges, coloured with an average of 0.78 % CuO and contain associated elevated levels of Sn of between 104 ppm and 913 ppm, indicative of a bronze copper source (Kaczmarczyk and Hedges, 1983; Shortland and Eremin, 2006; Shortland, Rogers and Eremin, 2007). Cu-blue glasses are one of the most prevalent types of glass in the Egyptian LBA and outliers of indicative elements can make dating difficult. One dating indicator for later Cu-blue glasses is the use of lead-rich bronze used in the Ramesside period (Rademakers, Rehren and Pernicka, 2017). However, this presents challenges as atypically high lead contents are observed in several studies examining Egyptian Cu blue glasses which are firmly dated to the 18th Dynasty (Shortland and Eremin, 2006; Shortland, Rogers and Eremin, 2007; Lankton, Pulak and Gratuze, 2022).

OX195, OX198 and OX235 exhibit fine examples of feather patterns in yellow and white, therefore are stylistically typical of 18th Dynasty vessels (Nolte, 1968). Two of the Serabit Pb-rich glasses, OX70 and OX482, have basic yellow patterns applied, therefore the high lead may be due to contaminated crucibles or represent less skilful vessels produced at a later workshop using a lead rich bronze. Stylistic elements on the remaining fragments are either obscured by thick surface deposits or do not have a perceivable pattern, therefore cannot be used to further narrow the production epoch.

4.5. *Yellow*

Although variations are observed in Egyptian LBA yellow glasses, notably in the concentrations of Sb and Pb, the three yellow glasses are comparable with published Egyptian LBA compositions (Shortland and Eremin, 2006; Shortland, 2012; Kemp, Brownscombe and Shortland, 2021). In the 18th Dynasty, yellow glass is more commonly used for decorative elements but became more common for ground colour after the Amarna period (Nolte, 1968). OX264 and OX561 are similar in composition, but different formats; OX264 is a yellow monochrome fragment with no distinguishable pattern whereas OX561 is a brown glass fragment with an undetermined yellow pattern (possibly uneven feather?) applied. Only seven yellow vessels are described in *Die Glassgefässe im alten Ägypte,* all of which are broadly dated to between the reigns of Tutankhamen (1336–1327 BCE) to Pinodjem II (990–969 BCE) the latter whose reign stands at the end of the 21st Dynasty, therefore it is likely that OX264 is a vessel produced after the Amarna period. OX561 is described in the brown glass section.

OX444 is a rounded, opaque, yellow core formed vessel fragment with a dark and white glass twisted decoration. Two opaque yellow pilgrim flasks, described in *Die Glassgefässe im alten Ägypten*, dated between the 19th and 20th Dynasty, show strong stylistic similarities (Nolte, 1968, p75). OX444 also contains the highest Sb_2O_3, PbO, and Fe_2O_3 content of the group and exhibits significantly higher concentrations of As and Ag with significantly lower concentrations of Zn and Sr, which indicates that the lead source may have been derived from a by-product of silver production, litharge (Mass, Wypyski and Stone, 2002). This would account for the higher Ag content and the low Zn content, which would be considerably depleted during this process. The processing of litharge is a later practice, and therefore supports the proposition that this vessel was likely produced between the 19th and 20th Dynasty (Nolte, 1968). The purple glass from the same fragment (described in the later section) also provides strong evidence for

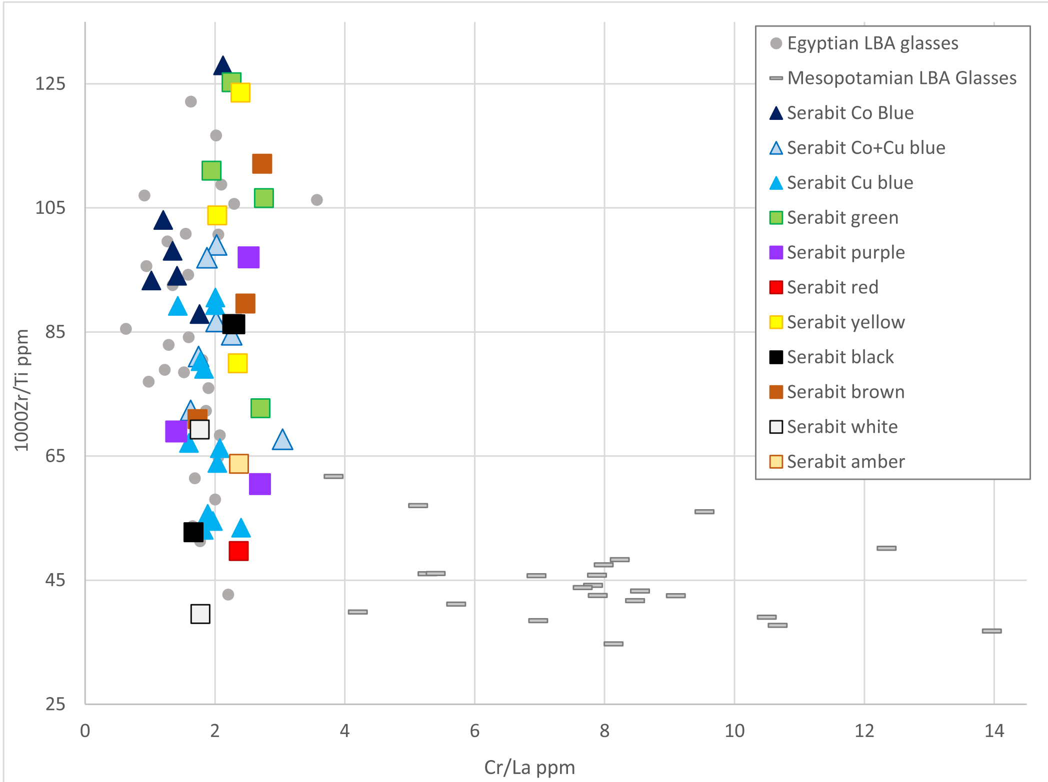

Fig. 1. Covariant plot of Cr/La vs 1000Zr/Ti comparing the glasses from Serabit. Samples are plotted against the Egyptian and Mesopotamian glasses of known origin (Shortland, Rogers and Eremin, 2007).

classification of OX444 as a Ramesside glass.

4.6. Black

The three black Serabit glasses have the highest average MgO of all the colour groups at 4.74 % and the highest Al_2O_3 concentration at 0.72 % in the study group, excluding those glasses containing significant cobalt. The Serabit black glasses contain very low levels of Co, Cu and Mn and therefore reflect the colouring strategy that achieves a dark/black hue without the apparent deliberate addition of colourants (Turner, 1956; Sayre and Smith, 1974). OX122 and OX299 are similar in composition and both appear closer to LBA Egyptian colourless glasses (Shortland, Rogers and Eremin, 2007) compared with early black glasses from the reigns of Tuthmosis III and Amenhotep II, that achieved black hues by colouring the glass a very deep blue or purple using copper, cobalt, manganese or a combination of colourants (Lilyquist et al., 1993, p36; Jackson and Nicholson, 2007, p107). Interestingly, the composition of OX144 is comparable with green samples E.4486 and OX484, which also contain trace levels of CuO and elevated Sb_2O_3 and PbO with lower concentrations of Fe_2O_3 and Al_2O_3, indicating that both glasses were manufactured according to an exacting process, possibly at the same workshop.

The Fe-black colouring strategy is identified in other black glasses from Amarna and in later glasses from Lisht, Gurob and Timna (Brill, 1999; Shortland and Eremin, 2006; Lankton, Pulak and Gratuze, 2022). Therefore, the black Serabit glasses represent later Fe-black glasses, which appear from the reign of Akhenaten. A particularly skilful feather pattern is applied to OX122 which could indicate that this was an early Fe-black glass vessel produced at Amarna.

4.7. Green

The four Serabit green glasses fall into two distinct groups: The first group, E.4486 and OX484, contain 0.16 % and 0.5 % Sb_2O_3, high concentrations of 1.46 % and 2.81 % PbO respectively, and notably elevated zinc which suggests that they were opacified with lead antimonate (Shortland, 2002). The second group, E.4486.1 and OX140, contain below 50 ppm of Zn, Sb_2O_3 and Pb. All four glasses contain trace CuO, therefore the green hue is likely achieved from natural impurities in the raw materials (Schreurs and Brill, 1984; Varberg, Gratuze and Kaul, 2015).

Remarkably, SEM-WDS analysis of 15 green glasses (working debris, rods and vessel fragments) from the LBA Egyptian sites of Malkata and Amarna (Shortland and Eremin, 2006), and LA-ICP-MS analysis of 10 green glasses from Amarna (Lankton, Pulak and Gratuze, 2022) showed that all 25 samples were coloured using CuO, 24 of which were opacified using lead antimonate. Research undertaken by Varberg et al. identified green glass rods from Amarna that showed three distinct compositions and were of both Egyptian and Mesopotamian origin, confirming not only the exchange of glass between the two regions, but also that both Cu and non-Cu green colouring strategies were worked contemporaneously at Amarna (Varberg et al., 2016). E.4486.1 and OX140 specifically are comparable with a green glass rod from the Varberg study, 7412, which is of Egyptian provenance and exhibits similar low concentrations of Sb, Pb, and Zn all below 50 ppm with low levels of CuO (Varberg et al., 2016).

Therefore, the four green Serabit glasses are likely produced from the Amarna period onwards, however, one of the green fragments, OX484, has a distinctive rounded edge with a yellow rim, likely a “leaf” from the neck of a pomegranate vessel. A green pomegranate vessel with a yellow rim is described in *Die Glassgefässe im alten Ägypten* (Accession Number AF 1571, p133, plate number XXVII) and a virtually identical vessel is currently held at the Metropolitan Museum of Art, New York (Accession Number 44.4.52). Pomegranate vessels are broadly dated between the reigns of Tutankhamen (1336–1327 BCE) to Pinodjem II (990–969 BCE) (Nolte, 1968), therefore OX484 represents a later non-Cu green glass

Table 4
Summary of Serabit glass production periods.

As. Number	Proposed production date
High Magnesia High Potash glass fragments	
Black	
OX122 OX144 OX299	Amarna period onwards, from the reign of Akhenaten (1352–1336 BCE) to Rameses VI (1143–1136 BCE).
Brown	
OX358 OX420 OX561	Amarna period onwards, from the reign of Akhenaten (1352–1336 BCE) to Rameses VI (1143–1136 BCE).
Co blue	
OX189 OX193 OX414 OX433 OX437 OX669	18th Dynasty, between the reigns of Tuthmosis III (1479–1425 BCE) and Akhenaten (1352–1336 BCE).
Co + Cu blue	
OX107 OX183 OX200 OX481 OX501 OX84	18th Dynasty, between the reigns of Tuthmosis III (1479–1425 BCE) and Akhenaten (1352–1336 BCE).
Cu blue	
OX195 OX198 OX235	Stylistically dated to 18th Dynasty between the reigns of Tuthmosis III (1479–1425 BCE) and Akhenaten (1352–1336 BCE) owing to the fine examples of pattern application.
OX70 OX482	Composition potentially indicates post-Amarna production due to high lead content and basic pattern application. From the reign of Akhenaten (1352–1336 BCE) to Rameses VI (1143–1136 BCE).
OX103 OX127 OX429 OX442 OX472 OX488 OX897	Dated to between the reigns of Tuthmosis III (1479–1425 BCE) and Rameses VI (1143–1136 BCE).
Green	
E.4486 E.4486.1 OX140	Amarna period onwards, from the reign of Akhenaten (1352–1336 BCE) to Rameses VI (1143–1136 BCE).
OX484	Pomegranate vessel produced between the reigns of Tutankhamen (1336–1327 BCE) and Rameses VI (1151–1143 BCE).
Purple	
OX77 OX85	Dated to between the reigns of Tuthmosis III (1479–1425 BCE) and Rameses VI (1143–1136 BCE).
OX444	19th-20th Dynasty - Rameses I (1295–1294 BCE) and Rameses VI (1143–1136 BCE).
White	
OX122	Amarna period onwards, from the reign of Akhenaten (1352–1336 BCE) to Rameses VI (1143–1136 BCE).
Yellow	
OX264 OX561	Amarna period onwards, from the reign of Akhenaten (1352–1336 BCE) to Rameses VI (1143–1136 BCE).
OX444	19th-20th Dynasty - Rameses I (1295–1294 BCE) and Rameses VI (1143–1136 BCE).
Red	
OX334	Dated to between the reigns of Tuthmosis III (1479–1425 BCE) and Rameses VI (1143–1136 BCE).
Amber	
OX226	Dated to between the reigns of Tuthmosis III (1479–1425 BCE) and Rameses VI (1143–1136 BCE).
Low Magnesia Low Potash Co + Cu blue and white glass fragment	
OX641	Likely represents one of the last glass offerings made to the temple, therefore (later) 20st Dynasty.

produced after the Amarna period (Nolte, 1968).

4.8. Brown

The three brown Serabit glasses are compositionally similar and follow the same colouring strategy, containing between 0.87 % and 2.02 % CuO and likely opacified using lead antimonate. They contain the associated high levels of Sn and As at 867 ppm and 33 ppm respectively, indicating a bronze Cu source was used. The Serabit brown glasses are therefore compositionally different to brown glasses analysed in the 2006 Shortland et al. study which include an early glass, twelve glasses from Malkata and Amarna, and two glasses from Lisht, all of which have no deliberately added colourant (Shortland and Eremin, 2006). Brown vessels are rare and are broadly dated from the reign of Tutankhamun to Pinodjem II (Nolte, 1968), although some brown glasses are known from Amarna (Jackson and Nicholson, 2007). OX561 has a yellow glass applied which appears to be a later composition from the by-product of litharge practiced in the Ramesside period (Mass, Wypyski and Stone, 2002). Therefore, the three Cu-brown glasses may represent a new colouring strategy at a specialist workshop.

4.9. Amber

OX226 is a pale amber hue with no apparent colourant deliberately added, therefore this glass is comparable with published amber/colourless glasses from the LBA (Shortland and Eremin, 2006; Shortland, 2012, p104). Notably, this glass falls within the Lisht compositional criteria.

4.10. Purple

The Serabit purple glasses show some variation between the colouring strategies, however all three are comparable with known Egyptian LBA manganese-purple glass compositions (Shortland and Eremin, 2006; Kemp, Brownscombe and Shortland, 2021). Both OX77 and OX444 exhibit a visibly deeper hue than OX85, which contains 0.27 % MnO with no additional colourants added. OX77 contains 0.75 % MnO, the highest concentration in the Serabit glasses, in addition to an elevated Fe_2O_3 concentration of 0.71 %.

OX444 contains 0.21 % MnO, 0.80 % Fe_2O_3, and interestingly 0.09 % CoO which likely contributes to the darker hue. Purple glasses enhanced with cobalt and/or elevated concentrations of Fe have been observed in the LBA, therefore OX444 exhibits a known colouring strategy (Shortland and Eremin, 2006). OX444 contains significantly lower alumina than New Kingdom glasses containing cobalt and has depleted Zn with elevated Ni, therefore comparable with the “Type R” source used during the 19th-20th Dynasty (Abe et al., 2012). This date is consistent with the yellow glass from the same fragment described earlier, and therefore can be confidently dated to the Ramesside period.

4.11. Red

OX334, the only red glass from the selected Serabit material, is a standard high magnesia LBA Egyptian red glass coloured with 1.2 % CuO and opacified with 0.14 % Sb_2O_3 with an associated elevated concentration of Sn (952 ppm), As (42 ppm) but notably very low lead (46 ppm). Red is one of the rarest Egyptian LBA glasses and published compositions from the 18th Dynasty show wide variations in base composition and colouring strategy (Lilyquist et al., 1993; Shortland and Eremin, 2006; Pusch and Rehren, 2007; Kemp, Brownscombe and Shortland, 2021; Lankton, Pulak and Gratuze, 2022). The red glass from Serabit also falls within the Lisht compositional criteria.

4.12. White

OX122 is a standard white LBA glass opacified with antimony (Shortland and Eremin, 2006; Kemp, Brownscombe and Shortland, 2021) and applied to a Fe-black vessel, the composition of which indicates a later glass as discussed.

4.13. Ox641

OX641 is a white core-formed vessel fragment, with a dark blue (possibly garland) pattern applied. The white glass is of standard LBA composition but contains notably high soda, and is low in lime, alumina, and iron oxide, consistent with glasses produced at Lisht (Smirniou, Rehren and Gratuze, 2018). The blue Co + Cu decoration from the same fragment contains 0.49 % MgO and 0.91 % K_2O, therefore consistent with natron glasses produced in the IA which are characterised by MgO and K_2O concentrations between 0.5 and 1.5 % (Lilyquist et al., 1993, p56). The blue glass contains 2.7 % CaO which is significantly lower than the lime content of the other Serabit glasses in addition to containing a high concentration of CuO with low Sn, indicating the use of a pure copper source. The blue OX641 glass also contains 1.0 % Al_2O_3 and low levels of nickel, zinc and manganese, therefore compares with "Type N1" cobalt, characterised as having "lack of nickel and depletion of zinc" with low MnO, and used in natron glasses during the Late Period (Abe et al., 2012). Therefore, OX641 represents the first identified example of a vessel composed of a plant ash body with a natron glass decoration.

The OX641 Co + Cu blue glass is similar in composition to those from the tomb of Nesikhons, containing between 0.3 and 1.2 % MgO, 0.4–0.9 % K_2O and 1.3–4.8 % CaO (Schlick-Nolte and Werthmann, 2003). These glasses are considered to be among the last glass vessels produced in Pharaonic Egypt, manufactured in the early 10th century BCE. OX641, therefore, was the last glass offering made to the temple in the study group and likely corresponds with the culmination of Egyptian presence at Serabit in the 20st Dynasty.

5. Conclusion

All glasses in the Serabit study group, excluding fragment OX641, are high magnesia plant ash glasses of Egyptian provenance. Excluding OX641, the 12 blue glasses containing cobalt can be confidently dated to the 18th Dynasty by the characteristic cobaltiferous alum, therefore likely produced in the workshops of Malkata and Amarna. Fragment OX444, containing both purple and yellow glass, can also be confidently dated to the 19th-20th Dynasty by the distinctive Type R cobalt signature and likely use of litharge for the lead source. Unlike early compositions of green and black glasses, the Serabit green and black glasses appear to have no deliberate colourant added and therefore compare with later glasses made during the Amarna period and after. The Serabit glass group exhibit differing strategies for producing 'rarer' ground colours, which became more commonly used in the Ramesside period, therefore reflective of the increase in activity at Serabit during this time. Where present, the stylistic features of vessel types provided production period 'milestones' and were used in conjunction with compositional information to narrow the dates of production; this is exemplified by the green fragment OX484 which is likely a leaf from a pomegranate vessel.

OX641 is a unique example of a vessel using early natron Co + Cu blue glass, coloured with the later N1 cobalt source, to decorate a white vessel made of high magnesia plant ash glass, with both glasses falling clearly within the Egyptian provenance range. That the Co + Cu natron blue glass is applied to a white glass body of standard LBA plant ash glass confirms that the two glass technologies were worked contemporaneously.

Three periods of Egyptian core-formed vessel glassmaking are therefore represented at Serabit: 18th Dynasty plant ash glass, plant ash Ramesside glass and natron Ramesside glass, which corresponds with the known periods of Egyptian activity at Serabit.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgments

We are extremely grateful to Dr Kelly Domoney and Dr Liam McNamara of the Ashmolean Museum for providing access to the Serabit materials, for assisting with the sampling process and for supporting this research.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2023.103920.

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