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‘A green thought in a green shade’; Compositional and typological observations concerning the production of emerald green glass vessels in the 1st century A.D.

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ABSTRACT

The results of a programme of compositional analysis on a series of emerald green glass vessels of known form and date suggest that emerald green vessels have distinct characteristics that set them apart from most contemporary glasses. These specific compositional peculiarities presented here will be evaluated in the context of the varieties of vessel forms produced in the colour. In the light of our findings we will suggest a number of ways forward in the understanding of the structure of the early Roman glass industry.

1. Introduction

The first three quarters of the 1st century A.D. witnessed by far the most widespread and adventurous use of brightly coloured glass in the history of glassmaking in the ancient world. The range of colours and the variety of forms in use across the Roman Empire are unrivalled until the modern period. Whilst vessels in the bluish-green shades of naturally coloured glass were at all times by far the most common, a vast palette of other colours was available and enthusiastically exploited. Most of these brightly coloured vessels were monochrome, but 1st-century glass workers also took advantage of the contrasts of coloured glass by creating complex polychrome vessels. Translucent dark blues, ambers, purples and emerald greens are the most common bright colours used during this time. Less common are opaque colours such as whites, reds, yellows, pale blues and glasses so dark as to appear black.

Although many hundreds of thousands of fragments of glass from 1st-century excavations have been examined, there is still only a rudimentary understanding of the organisation of the industry producing these remarkable vessels. In this paper, we present the preliminary results of a project that takes an important new methodological approach to the problem. Our research combines an in-depth understanding of the typological and chronological patterns regarding early Imperial vessel forms and manufacturing techniques, in conjunction with the results of compositional analysis of a single colour of early Roman glass, emerald green. We propose that this combination of expertise is crucial to the understanding of the processes involved in glass production during this most fascinating period in the evolution of the Roman glass industry.

1.1. Background

Emerald green is a familiar colour to glass specialists working with assemblages of the early – mid 1st century A.D. Production appears to peak in the decades leading up to the mid 1st century A.D., and the colour becomes much less common in the second half of the century, although a few vessels seem to have been produced

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after this point (Price and Cottam, 1998, 55–59). This glass was used for a wide range of vessels, both monochrome and, occasionally, polychrome. The colour was not restricted to any particular production method and was used in the three principal techniques of vessel manufacture – non-blown (cast), free-blown and mould-blown. However, a closer typological analysis reveals that in the early and mid 1st century A.D., when the use of this colour was at its height, emerald green is strikingly absent in the manufacture of some very common vessel forms. This was remarked upon by David Grose (1991, 2–11) when he surveyed early Roman glasses from Italy. Emerald green, he proposed, was essentially a Roman colour and not part of the Hellenistic glass vessel-making industry (Grose, 1991, 8). He noted that some commonly found Augustan–Flavian monochrome non-blown forms were not produced in emerald green glass. These included ribbed bowls (Fig. 1.1; Isings, 1957 form 3), as well as 'linear-cut' bowls (Fig. 1.2). Conversely, he observed that emerald green was a particularly favoured colour for producing the range of non-blown vessels often described as 'fine wares' or 'ceramic forms' (Grose, 1991, 2, Fig. 1 pl.I, IIa, IIIb). This category includes cups and bowls with a constricted convex profile (Fig. 1.4 and 1.5; Isings, 1957 form 2) bowls with vertical sides (Fig. 1.6 and 1.7; Isings, 1957 form 22) and convex sided cups and bowls on a narrow base ring (Fig. 1.8 and 1.9; Isings, 1957 forms 20 and 5). Convex bowls with no base ring and shallow flat-based bowls form a further group of non-blown bowls which are often produced in emerald green (Fig. 1.10–1.12; Isings, 1957 forms 18 and 19).

In our survey of the 1st century A.D. vessel forms produced in emerald green glass, we have also found that the peculiarities in the use of emerald green observed by Grose (1991) can also be found

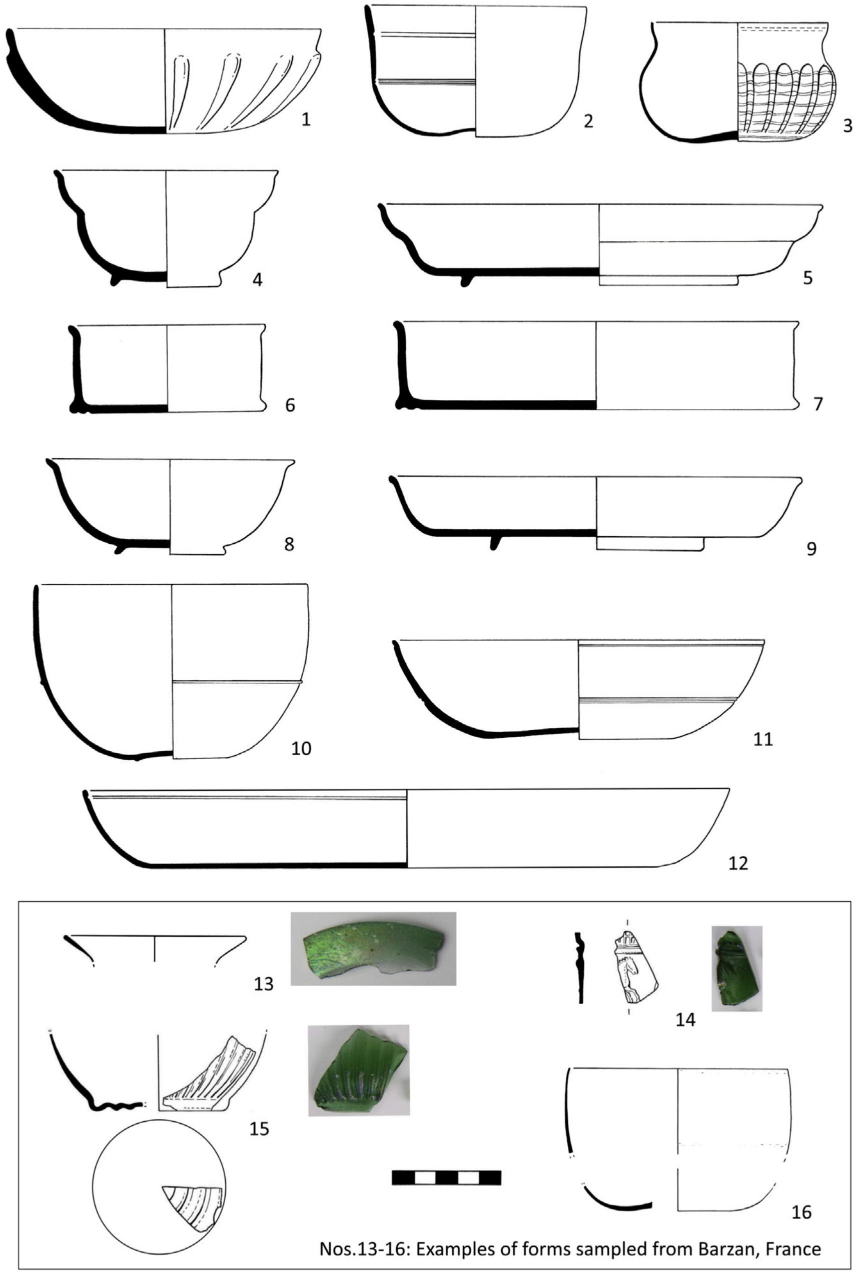

Fig. 1. Vessel forms discussed in the text.

amongst certain contemporary blown forms. For example, the distinctive blown ribbed bowl, often decorated with opaque white trails (Fig. 1.3; Isings, 1957 form 17), does not occur in emerald green, though amber, purple, dark blue, pale green and blue/green are all regularly noted. The many forms of jug produced during the 1st century are very uncommon in emerald green glass. Furthermore, emerald green is rarely used as a base colour for blown vessels decorated with contrasting trails or splashes, whilst amber, purple and dark blue are quite frequently used in this way. It does however feature in polychrome non-blown (cast) vessels, including ribbed bowls of Isings form 3.

The composition of emerald green is also atypical. Julian Henderson (1996, 190) first noted that five 1^{st}-century A.D. non-blown (cast) emerald green cups and bowls from the palace at Fishbourne (West Sussex), were compositionally unlike other contemporary Roman glasses. These green glasses were soda-lime–silica, but with potassium and magnesium above 1.5wt%, more typical of glasses produced using a plant-ash flux rather than a mineral soda (trona or 'natron'). They were coloured with copper, with higher concentrations of iron, tin and sometimes lead, which Henderson (1996, 190) attributed to the use of scrap bronze.

More recent analyses of early Roman emerald green vessel glasses show the same compositional traits (Colchester (Jackson et al. 2009), Adria region (Gallo et al. 2013), Begram (Brill, 1999, 125, sample 6226), Golfe de Fos, Ruscino (Thirion-Merle, 2005) and in green glass in 2nd century polychrome vessels from Chester (Paynter and Schibille, in press)). Furthermore, although predominantly found in emerald green, some 'copper' red glass has these compositional characteristics (Moretti and Gratuze, 2000; Nenna and Gratuze, 2009; Paynter and Kearns, 2011; Gallo et al. 2013). Very occasionally other early examples in green, brown, black and dark blue, not coloured with copper, exhibit this composition (Gallo et al., 2013; Thirion-Merle, 2005; Van der Linden et al., 2009; later 4th century examples from Egypt in Rosenow and Rehren (2014)). However, whilst this ash-based composition is not exclusively reserved for green, early Roman emerald green comprises by far the largest group consistently produced using some plant ash flux.

1.2. Aims

As part of a project to explore these typological and compositional patterns further, a set of 50 emerald green vessels of known form was analysed from early to mid 1^{st}-century sites at Fréjus and Barzan in France, Colchester in England and Ribnica and Trojane in Slovenia. The examples selected consisted of vessels of several different types, manufactured using non-blown (cast), mould-blown and blown techniques, to determine whether the unusual composition was used only for specific vessel forms. The forms include:

25 samples from non-blown (cast) forms (vessel forms are included in Table 1)

- Cups with constricted convex sides (Figs. 1.4, 1.5 and 2.1; Isings form 2)
- Small cylindrical bowls (Figs. 1.6, 1.7 and 2.2; Isings form 22)
- Small bowls with an out-turned rim (Fig. 1.13)
- Convex sided bowls with base rings (Figs. 1.8, 1.9 and 2.3; Isings form 5 and 20)
- Convex sided bowls without base rings (Fig. 1.10 and 1.11; Isings form 18)
- Shallow flat based bowls (Figs. 1.12–2.4; Isings form 19)

2 samples from mould-blown forms

- Circus cup (Fig. 1.14)
- Ribbed cup (Fig. 1.15)

23 samples from blown forms

- Convex cups (Fig. 1.16; Isings form 12)
- Shallow tubular rimmed bowls (Fig. 2.5; Isings form 45)
- Bowls with flared rims (Fig. 2.6)
- Bowls with out-turned rims (Fig. 2.7)

Other published compositional data from emerald green glasses, such as the data from Fishbourne, various sites in France and Adria, were also used to extend the dataset.

2. Methods

Major and minor elements were measured using an electron microprobe. The samples from Fréjus and Colchester were analysed using a Cambridge Microscan 9 at the Department of Earth Sciences at Sheffield University. Operating parameters, counting times and analytical protocol are given in Lemke (1998, 281–3). The remaining samples were analysed with a JEOL JXA-8200 electron microprobe housed in the Microanalysis Research Facility, at the Department of Archaeology, Nottingham University (see Meek et al., 2012, 790 for operating parameters). In both analytical sessions a Corning B soda-lime–silica glass standard was run throughout to check for accuracy and precision and to monitor any drift. The average results are presented in Table 2 and the data show good agreement with the standard data for most elements, except for antimony oxide on the Sheffield EPMA and titania at Nottingham; these elements must therefore be considered semi-quantitative.

Trace element analysis was performed using a CETAC LSX-100 laser ablation system in conjunction with an Agilent 7500c ICP-MS instrument at Imperial College, Ascot. Instrument running parameters and standard data are documented in Jackson and Nicholson (2010). Repeat measurements of SRM NIST 612 were made to assess the data (Table 3) which generally was within 10% of the standards.

3. Results of the compositional analysis

All the glasses are of a soda-lime–silica composition (Appendix 1). Soda concentrations average around 16.5wt%, lime around 6.5–7 wt%, and alumina is typically around 2.5wt%. Potash, magnesia and phosphorus pentoxide are higher than in Roman natron glasses (average 1.7wt%, 2.0wt% and 0.7wt% respectively). Lilyquist and Brill (1993) suggest concentrations of magnesia and potash above 1.5 wt% indicate manufacture using plant ash rather than solely natron. This is also reflected in the lower silica concentrations than typical Roman natron glasses, which is a consequence of the need to add greater quantities of plant ash to introduce enough alkali in order to flux the silica.

It is more difficult to determine which elements derived from which raw material in glasses produced with plant ash fluxes as they are much more complex compositionally than mineral soda fluxes such as natron. Plant ashes are also more variable and their compositions change according to the substrate on which they grow and how they concentrate specific elements into their tissues. Taking these issues into account, the data are described and interpreted tentatively in terms of the contribution of both plant ashes and sand to the glass composition.

Within this general 'plant ash' composition there is some variation between samples. For instance four 'peacock' coloured samples have an intermediate composition between natron and plant ash glasses (S757 and S1296 from Ribnica and Fréjus 156 and 158,

Table 1
Catalogue of analysed samples. References truncated for brevity; Harden (1947), Price and Cottam (1996), Cottam and Price (2009), Cool and Price (1995), Cottam (2012), Lazar unpublished.

Site	Report author	Code	Cat no	Manufacture	Form
Barzan	Cottam	25635	1	Non blown	Reticelli bowl (perhaps Isings form 1)
Barzan	Cottam	25761	18	M blown	Chariot cup
Barzan	Cottam	25814 etc	26	M blown	Convex ribbed cup
Barzan	Cottam	25111	31	Blown	Isings 12
Barzan	Cottam	26310	32	Blown	Isings 12
Barzan	Cottam	25144	33	Blown	Isings 12
Barzan	Cottam	25533	34	Blown	Isings 12
Barzan	Cottam	25533	35	Blown	Isings 12
Barzan	Cottam	25816	36	Blown	Isings 12
Barzan	Cottam	25234 etc	37	Blown	Isings 12
Barzan	Cottam	26473	174	Blown	Jug
Ribnica	Lazar	S1296		Non blown	Base ring small convex bowl, form unclear
Ribnica	Lazar	S757		Non blown	Cylindrical bowl, Isings 22
Ribnica	Lazar	S1298		Non blown	Shallow bowl without base ring (comparable with Isings 5 and 19)
Ribnica	Lazar	S1299		Non blown	Small cylindrical bowl, Isings 22
Ribnica	Lazar	S1297		Non blown	Isings 2
Ribnica	Lazar	S1270		Non blown	Bowl with convex side, exact form unknown
Ribnica	Lazar	S1186		Blown	Tubular rimmed bowl, Isings 45
Ribnica	Lazar	S1197		Non blown	Bowl with convex side, comparable with Isings 20
Ribnica	Lazar	S1161		Non blown	Shallow bowl, probably without base ring (comparable with Isings 5 and 19)
Ribnica	Lazar	S1168		?Blown	Bowl with straight side tapering in, exact form unknown
Ribnica	Lazar	S1190		Blown	Tubular rimmed bowl, Isings 45
Ribnica	Lazar	S1170		Non blown	Base ring small convex bowl, form unclear
Ribnica	Lazar	S1183		Blown	Cup/bowl without-turned rim, exact form unknown
Ribnica	Lazar	S1171		Non blown	Bowl with convex side, comparable with Isings 20
Ribnica	Lazar	S1181		Non blown	Bowl/plate with horizontal base and low base ring, form unknown but perhaps comparable with Isings 5
Ribnica	Lazar	S1210		Blown	Small bowl with conical body, comparable with Isings 41b
Ribnica	Lazar	S1222		Non blown	Small bowl with slight convex side, comparable with Isings 41a
Ribnica	Lazar	S1184		Blown	Bowl with tubular base, exact form unknown
Ribnica	Lazar	S1166		Blown	Bowl with vertical rim, change of angle on upper body, exact form unknown
Trojane	Lazar	MMK 1216		?Blown	Bowl, form unknown
Trojane	Lazar	MMK 1178		?Blown	Bowl, form unknown
Frejus	Cottam & Price	Argentiere	156	Blown	Isings 12
Frejus	Cottam & Price	Argentiere	158	Blown	Isings 12
Colchester	Cool & Price	LWC72 J951	193	Non blown	Convex bowl with handle
Colchester	Cool & Price	1.81 G3627 L3596	198	Non blown	Plate/bowl, exact form unknown
Colchester	Cool & Price	1.81 B1764 L389	199	Non blown	Rectangular tray
Colchester	Cool & Price	LWC72 J951	200	Non blown	Shallow bowl with base ring (Isings form 5)
Colchester	Cool & Price	LWC72 J944	203	Non blown	Bowl, form unknown
Colchester	Cool & Price	LWC72 J1464 F184	204	Non blown	Bowl, form unknown
Colchester	Cool & Price	LWC72 J941	208	Non blown	Unidentified
Colchester	Cool & Price	LWC72 J1536 F506	279	Blown	Isings 12
Colchester	Harden		53a	Non blown	Shallow bowl (perhaps comparable with Isings 5)
Colchester	Harden		53b	Non blown	Shallow bowl (perhaps comparable with Isings 5)
Colchester	Harden		56	Non blown	Convex bowl (comparable with Isings 18)
Colchester	Harden		56a	Non blown	Convex bowl (comparable with Isings 18)
Colchester	Harden		59	Non blown	Small convex bowl (comparable with Isings 20)
Colchester	Harden		60	Non blown	Shallow bowl with sloping side (perhaps comparable with Isings 5 and 19)
Colchester	Harden		75a	Blown	Isings 12
Colchester	Harden		75b	Blown	Isings 12

including blown and non-blown forms). These samples contain only slightly higher concentrations of potash than a natron glass, up to 1wt% MgO, and very low P_2O_5 concentrations. This may suggest the mixing of natron and plant ashes or of their respective glasses through recycling (Paynter, 2008; Freestone and Stapleton, 2015).

The concentrations of lime in emerald green glasses are worthy of comment. Calcium in glasses can derive from various sources. All plant ashes typically contain a high proportion of calcium compounds (Barkoudah and Henderson, 2006; Turner, 1956; Jackson et al. 2005), similarly the sand used to make natron glass contained calcium, derived from shells (e.g. Brems et al. 2012). If these glasses were made with plant-ash and the same sands used to manufacture Roman mineral-soda glasses, a high lime composition would have resulted, as both the sand and the ash would have contributed lime to the batch (Brill, 1999, 483). However, the plant-ash emerald green glasses here display similar, or slightly lower, concentrations of lime to the mineral-soda glasses from the same sites (unpublished data) and other mineral-soda 1st-century glasses (Jackson et al., 2009; Gallo et al., 2013). This may suggest the emerald green glass was produced with either a different (low-lime) sand source, crushed quartz or that the plant ash used was particularly low in calcium. A low lime content is also seen in high antimony Egyptian colourless natron glasses of the 1st century (Jackson and Paynter, 2015; Gallo et al., 2013) which were produced using high quality, low impurity, silica sources, and has been observed in opaque red glasses (unpublished data).

All the glasses contain copper at high concentrations, often over 2wt%. Copper in glasses in the Cu^{2+} state can produce either blue or green hues, but here the colour probably depends upon interactions of copper and iron (>1wt%), and to some extent manganese (>1wt%), antimony, tin, lead and the base glass composition

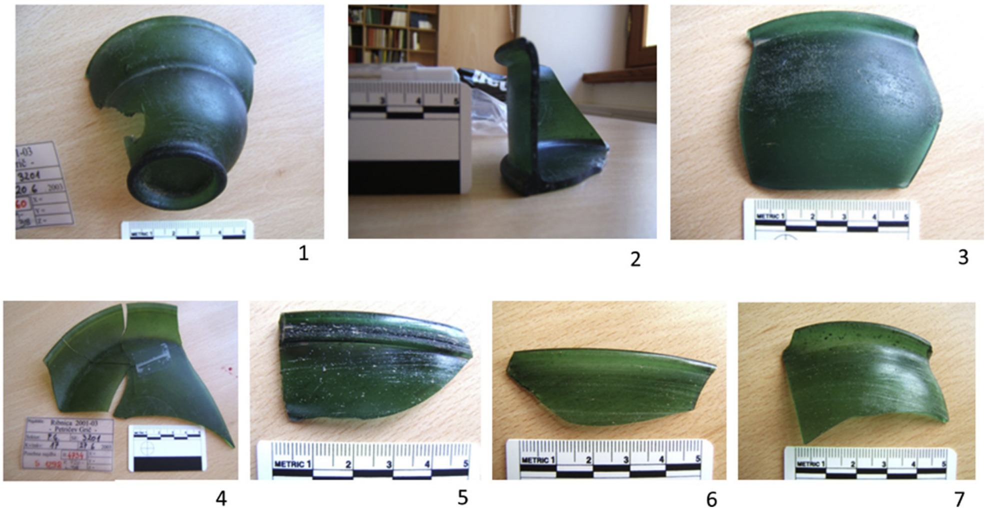

Fig. 2. Examples of vessel forms sampled from Ribnica.

which will influence the redox states of the colouring elements (Weyl, 1953, 164). The concentrations of all these elements in the glass suggest deliberate addition.

Antimony is present in all the glasses, up to 0.5wt%, which may indicate it has some influence on colour generation. Tin is also found in some samples and may be a feature of the addition of bronze. Lead, at low concentrations, may relate to the addition of copper as bronze, although in colourless glasses of the 1st century A.D. it can be linked to the addition of antimony (Paynter, 2006; Jackson and Paynter, 2015).

4. Discussion

That the glassmakers producing these glasses had a sophisticated understanding of the colouring technology and behaviour of differing additives to the glass is evident in the consistency and brilliance of the emerald green glass achieved. However the deliberate and consistent use of a plant-ash flux in the production of these vessels needs to be explained. The most obvious question is whether the use of a plant-ash alkali enabled the glassmaker to more easily achieve the emerald green colour produced by copper and iron, a colour which might perhaps not be readily produced in natron-based glasses. A further point that arises is whether this glass technology relates to a distinct method of glass production and even a particular location of production. It is possible for example that the colour could only be created by particular glassmakers, with skilled knowledge, and potentially even a monopoly on emerald green production. These questions are explored further below.

Table 2

Corning B reference data and measured values. **Note antimony oxide values are not given for Sheffield as they were corrected for interference (see Lemke, 1998, 289). n.d.; not determined.

	Consensus (Brill, 1972)	Nottingham mean values	Sheffield mean values
SiO_2	61.5	61.31	62.46
Na_2O	17.2	17.50	17.34
CaO	8.69	8.56	8.78
K_2O	1.06	1.06	1.03
MgO	1.12	1.10	1.02
Al_2O_3	4.21	4.49	4.18
FeO	0.33	0.29	0.3
TiO_2	0.13	0.07	0.11
Sb_2O_5	0.45	0.47	**
P_2O_5	0.9	0.73	0.82
MnO	0.25	0.25	0.25
CuO	2.68	2.79	2.79
V_2O_5	0.03	0.04	n.d.
SO_3	0.55	0.52	0.51
Cl	0.2	0.18	0.17

4.1. Raw materials and their sources

Plant ashes have been shown to vary between different species and within species from different locations (Barkoudah and Henderson, 2006). Differences in alkalis within the analytical group may therefore indicate different glassmaking centres. Phosphorus pentoxide and magnesia, and potash and magnesia, are strongly correlated in these glasses which suggests that the green samples analysed here as well as those from other datasets (Gallo et al., 2013; Henderson, 1996; Thirion-Merle, 2005) form a single compositional group (Fig. 3), using the same alkali type (and possibly source). The lack of a clear correlation between soda with potash, magnesia or phosphorus and the variable concentration of soda (15–19wt%) may also suggest a supplementary source of soda (natron?) was added to some of the glasses, or potentially that natron glass was being extended or mixed with a plant ash which was high in phosphorus. The occurrence of samples with low soda (<17wt%) and alumina (<1.8wt%) noted by Thirion-Merle (2005) and Gallo et al. (2013, 2597), which they suggest indicates the use of a pure silica sand, is seen in only some, but not all the emerald green glasses here.

The ratios of phosphorus pentoxide and magnesia are different to soda-ash glasses from other regions and periods (Fig. 3); Late Bronze Age Egyptian, and first millennium A.D. Sasanian and Islamic plant-ash glasses tend to have lower phosphorus pentoxide, higher magnesia and differ in their soda and potash levels compared to these Roman emerald green samples (Mirti et al., 2008; Shortland and Eremin, 2006; Freestone et al., 2000). The concentration of phosphorus pentoxide in particular is often higher in the emerald green glass than would be expected from that contributed by plant ashes, such as Salicornia or other high-soda plants analysed by Brill (1999, 482–484) and Barkoudah and Henderson (2006). None of these earlier or later glasses provide a suitable comparative compositional group so there seems to be no obvious evidence to suggest a common provenance.

Table 3
NIST612 reference standard for trace elements, all values in ppm.

NIST612	Analyte	Consensus (Pearce et al., 1997)	Average (n = 30)
Sc		41	44.1
Cr	52 Cr	36	37.3
Co	59 Co	35	39.4
Ni	60 Ni	39	43.2
Zn	68 Zn	38	43.4
Ga	71 Ga	36	40.3
Rb	85 Rb	31	36.0
B	11 B	35	48.0
Sr	88 Sr	78	74.4
Zr	90 Zr	38	35.6
Ba	137 Ba	40	36.2
La	139 La	36	36.1
Ce	140 Ce	39	32.4
Pr	141 Pr	37	35.2
Nd	146 Nd	36	34.8
Sm	147 Sm	38	36.6
Eu	151 Eu	35	35.0
Gd	157 Gd	37	33.5
Tb	159 Tb	36	35.8
Dy	163 Dy	36	33.8
Ho	165 Ho	38	36.4
Er	166 Er	38	33.9
Tm	169 Tm	38	33.8
Yb	172 Yb	39	37.4
Lu	175 Lu	37	35.0
Pb	208 Pb	39	43.2
Th	232 Th	30	35.5
U	238 U	37	40.5

4.2. *Trace elements*

Trace elements and rare earth elements (REE) are used to determine a general provenance of the raw materials used in glass manufacture. In plant-ash glasses it might be expected that both the sand, or ground quartz, and ashes will contribute to the overall compositional make-up of the glass (Ichihashi et al., 1992; Barkoudah and Henderson, 2006). Certain trace elements are thought to be associated typically with silica sources. Brems and Degryse (2014) note that in Roman natron glasses Ti, Cr, Sr, Zr and Ba are the most diagnostic for determining the silica source used.

The measured trace element concentrations in the emerald green glass are given in Appendix 2. Fig. 4 plots raw Roman natron glasses from Apollonia (Freestone et al., 2000), sand collected from the Italian coast (Brems and Degryse, 2014) and a selection of our emerald green glasses. The Apollonia glass has been chosen here as it represents a primary glass produced with a typical sand from an eastern Mediterranean coastal region and is described in documentary sources of the 1st century AD (e.g. Pliny *NH* XXXVI and Strabo *Geography* 16.2.25). All the trace elements show a distinctive pattern suggesting a similar provenance, around the eastern Mediterranean. The high Sr peak is typical of sands from the Syro-Palestinian and neighbouring regions. Only one sand from Italy shows a similar trace element pattern (IT87, Brems and Degryse, 2014), although slight differences in Nd and Dy may rule out this particular source. This trace element pattern is similar for both blown and non-blown forms.

The continuation of plant ash glass production in Mesopotamia in the Roman period (Sayre and Smith, 1961; Mirti et al., 2008), when natron glass dominated elsewhere in the Near East, has led some authors to suggest a possible link between Roman emerald green glass and Mesopotamia (e.g. Lemke, 1998, 280). Comparing the trace element ratios of chromium (Cr) and lanthanum (La) measured in Bronze Age glasses from Mesopotamia and Egypt (Fig. 5) and the glasses studied here it can be seen that the early Roman emerald green glasses have La and Cr concentrations in the same ratio as the Egyptian glasses, but higher values. These ratios are attributed predominantly to different silica sources (Shortland et al., 2007, 788). The higher concentrations of both in the Roman glasses may indicate more impure sand was used in manufacture and/or they derive from additives (see below). Our cautious interpretation is that on this basis, the emerald green Roman glasses are more likely to have been manufactured in or around Egypt or along the Mediterranean coast, rather than inland Mesopotamia. However, this hypothesis must remain tentative unless more substantial evidence can be provided.

Further examination of the pattern of trace elements Ti, Cr, Sr and Zr shows a positive correlation as might be expected if they derive from the sand, however there are broad correlations between Cu, Zr and Cr as well as groupings according to the lead levels, discussed later. Likewise, other trace element suites can be related to the use of an organic alkali source, such as Li, Cs, K and Rb. However, the potential mixing of alkalis has been suggested earlier, and so correlations between diagnostic trace elements and alkalis

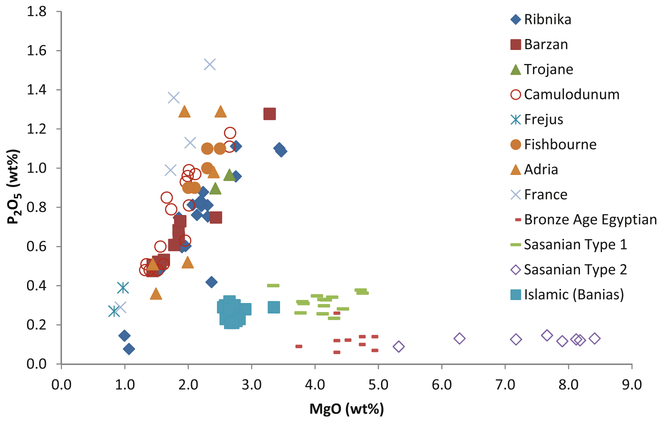

Fig. 3. Concentrations of phosphorus pentoxide and magnesia in Roman emerald green glasses (this study, Adria (Gallo et al., 2013) Fishbourne (Henderson, 1996), France (Thirion-Merle, 2005)) compared to Bronze Age Egyptian glasses (Shortland and Eremin, 2006), Sassanian glass (Mirti et al., 2008) and Islamic glass (Freestone et al., 2000).

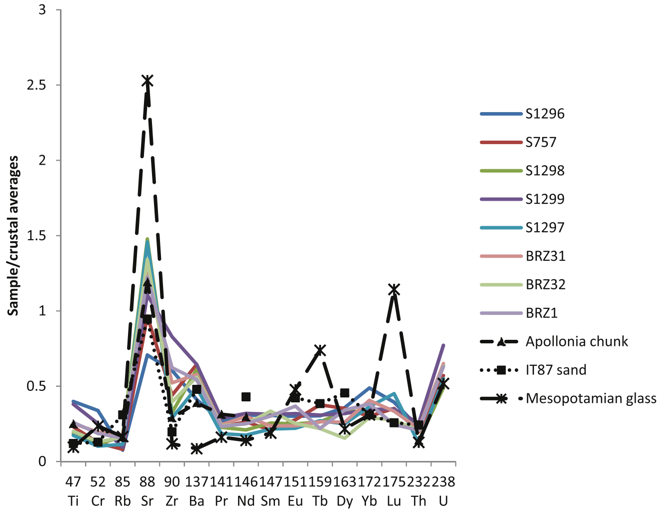

Fig. 4. Normalised values of trace and REE elements of a selection of glasses in this study, raw glass from Apollonia (Freestone et al., 2000) and sand from Italy (Brems and Degryse 2014). Mesopotamian Bronze Age plant ash glass is given for comparison (Walton et al., 2009). Data normalised to continental crust values (Wedepohl, 1995).

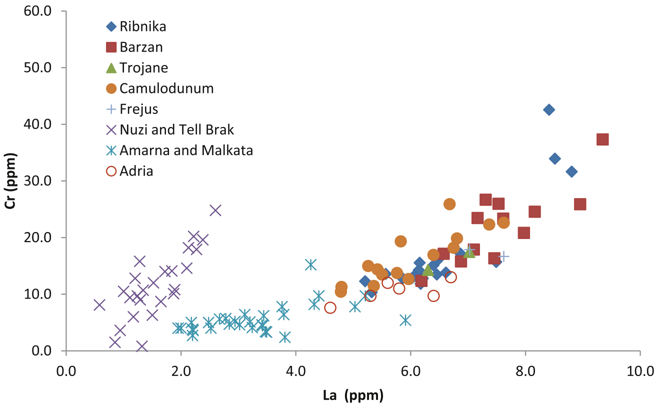

Fig. 5. Trace element concentrations of Bronze Age glasses from Egypt (Amarna and Malkata) and Mesopotamia (Nuzi and Tell Brak) showing the different trace element ratios for Cr and La in these two geologically different regions (Shortland et al., 2007), and the early Roman glasses studied here.

such as soda or potash are not clear, and other broad correlations between Rb and Pb can be observed. This suggests that the most significant variations observed in the trace elements may be related to the introduction of the colourants, so whilst it is tempting to try and attribute the fluctuations seen in the trace elements to either the flux or silica source, as with types of colourless glass, the situation with these deeply coloured glasses is actually more complex.

4.3. Factors influencing colour

Emerald green is primarily produced by the presence of copper and iron in the glass. Although the production of blues or greens in copper or iron-containing glasses is not difficult, the behaviour of both together in silicate melts is complex.

Under oxidising conditions cupric (Cu^{2+}) ions produce colours of different coordination; these include blue and green. The colour is influenced by the state of solvation of the ion which is in turn influenced by the concentration of that ion, the composition of the base glass and the melting temperature (Weyl 1953, 159). For example although still in the cupric form, a blue copper coloured glass will change to green upon heating as the number of unsaturated ions increases. Thus with all other factors the same, copper glasses melted at low temperatures are blue, whereas the same glasses melted at higher temperatures are greenish.

Iron may act as a reducing agent on copper, itself being oxidised. Under reducing conditions the ferrous ion, Fe^{2+} produces a light blue colour. The ferric ion, Fe^{3+}, produces a much less intense yellow colour (approximately 1/10 the strength of the blue ferrous ion). Therefore when iron is present, as it is here at concentrations above 1wt%, both oxidation states exist, changing the colour from blue to green. The oxidation state of iron and the equilibrium between Fe^{2+}/Fe^{3+}, is also influenced by the base glass composition and melting temperature, affecting the glass colour. The presence of iron with copper in a glass matrix will therefore help to produce the green colour.

However, the production of a glass with two colouring agents is not sufficient to produce the hue observed; other elements were deliberately introduced to produce the desired colour. Lead, antimony, tin, chlorine or even carbon monoxide in the form of charcoal causes the formation of more cuprous copper (Cu^{2+}), moving the colour from blue to green (Weyl 1953, 162). Replacing the alkali by calcium or magnesium has a similar effect, and Weyl (1953) suggests that magnesia-containing glasses provide the most suitable bases for green transmission.

Therefore the use of a plant ash, higher in magnesium, lime and potassium than natron, along with the presence of small amounts of charcoal in the ash would favour the formation of the green colour. The presence of small amounts of lead, antimony and tin would also favour a green glass as would iron in its oxidised state, itself reducing some of the copper. Taken together it may be suggested that a plant-ash glass would more readily favour the production of an emerald green colour than a mineral-soda glass.

Preliminary experiments to produce emerald green glass in both natron and plant-ash glasses, using laboratory reagents and neutral/slightly oxidising atmospheres and different temperatures have, however, been inconclusive and unsuccessful; a turquoise glass was formed in both base glasses, which was only slightly more green in the plant ash glass. It is also worth noting here that other findings suggest that this colour could be produced successfully using this combination of copper and iron in a mineral-soda glass (Cottam and Jackson, in press). Examples include some 1st-century A.D. glasses, in particular 'natron' beads (Bertini et al., 2011; Arletti et al., 2010) and emerald green raw glass (Robin, 2008, 43), as well as two green glasses here which showed compositions suggesting a mixture of alkalis was used, producing reduced potash and magnesia concentrations (S757, S1296).

Therefore the use of plant ash would facilitate the production of the green hue, but it may not be the only reason why it was used. The difficulty of producing the emerald colour experimentally and the paucity of examples of natron emerald green glasses may indicate that production was specialised, perhaps restricted to specific places or specific glassmakers.

4.4. Compositional patterns related to style

There were no significant compositional differences between non-blown and blown vessels. However, one group of blown vessels, consisting of Isings form 12 blown cups and two mould-blown cups, contain small, but significant, concentrations of lead (0.3–0.6wt%) (Fig. 6). The Isings form 12 cups are the most numerous single vessel form analysed and most come from Barzan (7/12), as do both the mould-blown vessels. The other examples are from Fréjus (2) and Colchester (3). Although all these vessels are blown or mould-blown forms, lead is not a specific feature, at least to blown vessels, as many others from a range of different vessel forms have lower lead concentrations (although higher than would be expected naturally). In these vessels there seems to be no specific typological or chronological patterning in lead content.

The higher lead concentration in these examples is intriguing and not easily explained. Recycling cannot be discounted, but the presence of lead at up to 0.5wt% would suggest it was deliberately added or that the glass was deliberately mixed with other lead-containing glasses to either aid working (making the glass 'softer') or the production of the colour (lead can act as a clarifier). However, neither of these enhancements seems particularly relevant to the vessel forms in question, and would benefit any of the forms in the sample range. An alternative suggestion is that they are a result of a failed red glass (Paynter and Kearns, 2011) which also contains high copper, iron and lead and can be of a 'soda-ash' composition. However it is unlikely here as a) red glasses generally contain much higher ratios of lead to copper (see Moretti and Gratuze, 2000) and the reverse is true here, and b) red is much less common than emerald green glass and it is unlikely so much glass failed in production.

A possible explanation may be advanced by comparison with other contemporary vessels. Similar concentrations of lead have been observed in some higher status Hellenistic and early Roman colourless glasses (Baxter et al., 2005; Paynter, 2006), and attributed to the use of an antimony–lead decolorizer. Interestingly, the

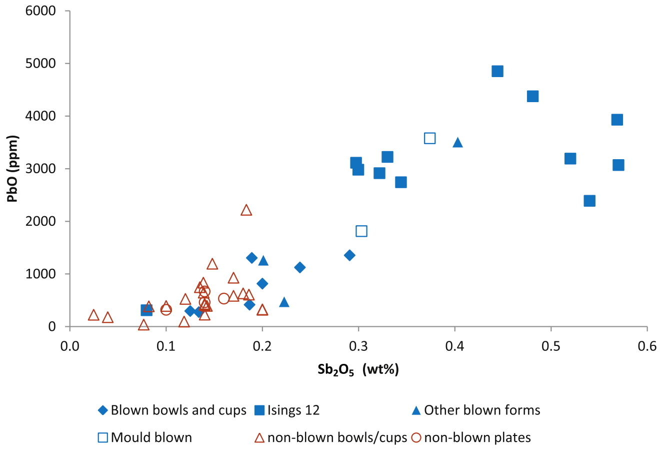

Fig. 6. Lead oxide and antimony oxide concentrations for the different forms of emerald green glasses analysed in this study.

two elements are also correlated in the emerald green glasses (Fig. 6). Similarly, both the high antimony colourless and the emerald green glasses have low concentrations of lime (and some with low alumina) which may indicate a common provenance/tradition.

4.5. *Provenance and the organisation of production*

It is now comparatively well accepted that Roman glasses were manufactured in large centres located around the eastern Mediterranean and that glass was traded as blocks to many secondary centres as Pliny intimates (Pliny *NH* XXXVI, 190–194, Foster and Jackson, 2009). The analytical basis for this model rests on the compositional homogeneity of Roman natron glasses which show few distinct compositional groups, and upon isotope and trace element analysis which gives a likely provenance for glass manufacture. For plant-ash glasses equally a tight compositional grouping would suggest a common origin; more than one distinct grouping might indicate a number of different production centres, each using slightly different raw materials. The exact provenance of the glasses is more difficult to ascertain, but the trace element data indicate the sands used to produce these glasses have characteristics common to those from the eastern Mediterranean, possibly in or near to Egypt.

Moreover, the relationship between emerald green and the plant-ash recipe makes it clear that colouring took place at the primary manufacturing location. A plant-ash based industry not linked to colour would surely reveal itself in the regular identification of this composition in vessels of other colours. However, whether colour production is the only explanation for the use of plant-ash glass certainly needs to be considered, and it may be that other factors, perhaps linked to customs of manufacture within the primary glass-making industry, also played a role.

Evidence of 1st century A.D. primary glass production is extremely scarce (Nenna, 2015) and it is at this stage difficult to establish whether the industry was centralised in a limited number of locations, or more dispersed in character; although the differences in lead concentrations may indicate more than one production location. Similarly, it is not clear whether the production of emerald green glass was integrated within the larger mineral-soda glass industries, or was a separate, perhaps specialised, enterprise. The similarity of the raw materials used to produce plant-ash and colourless mineral-soda Roman glasses, certainly in terms of the (low lime) quartz sands, might indicate that emerald green glass production was not an entirely distinct, separately located industry.

On the other hand, an examination of how emerald green glass was used in the secondary stage of the industry, vessel production, does raise questions about whether the relationship between the two glass-making methods was as close as the analytical evidence suggests, because emerald green was only used for certain forms. One of the first points to address is whether emerald green was deliberately avoided in the production of some vessel types because of certain physical properties that made the glass harder to fashion into particular forms. However, there is no evidence at this point that this is the case or that features such as ribs or handles are more difficult to form in emerald green glass than in other colours. Cultural or aesthetic concerns whilst possible, seem unlikely and are beyond the remit of this paper.

These discrepancies can now be re-examined in the light of the analytical results. If certain common 1st-century vessel forms, such as monochrome ribbed bowls of Isings form 3, or blown ribbed bowls of Isings form 17, are not being produced in emerald green glass, and no technological reason can be provided, then a possible explanation lies in the supply or use of this particular colour to the secondary workshops where these particular forms were being made. If this explanation is accepted, then the implications for the organisation of the 1st-century A.D. industry are profound. Firstly, it might suggest that there was workshop specialisation in certain forms or groups of forms and that some of these workshops were not acquiring emerald green glass, either because it was deliberately avoided, or as a result of the types of transactions which brought un-worked glass from primary to secondary workshops (an idea suggested by Thirion-Merle (2005) and Foy (2005)). Alternatively, within individual workshops glass workers were perhaps choosing, or avoiding emerald green in the production of certain forms. These ideas are presently being explored in more detail.

5. Concluding comments

As we have seen, the base glass composition, high in magnesia, potash and carbonaceous material, appears to be advantageous in the formation of a copper–iron emerald green glass. The very fact that emerald green vessels are almost exclusively produced from glass with a plant-ash component, and that vessels of other colours are almost universally natron glasses, re-enforces the theory that this composition did, or was at least perceived to, enhance or facilitate emerald green production.

Based on the results of this study, in particular the compositional distinctiveness of the green glass and its use for only certain vessel forms, we can construct more than one possible model for the production and movement of this glass in the context of 1st-century A.D. trading networks. For example, certain secondary workshops, with a given repertoire of vessels forms, may have been in a more favourable position to acquire emerald green glass, perhaps on account of their location or their commercial contacts with the primary producers. It is conceivable that emerald green glass was distributed within a set trading framework that changed little over the timespan within which certain forms were produced. A direct link between the vessel makers and the primary producers, by which green was ordered as a specific colour is possible, but might be rather improbable considering the distances involved. However, whether glass was traded freely or subject to some degree of state control is another factor to be taken into account.

There may of course be other more local explanations. A workshop receiving raw glass in many colours, and producing a range of different vessel types, may have restricted the use of emerald green to certain forms. Why this might have happened though is unclear. Emerald green does not seem to have been exclusive to vessels requiring the particular levels of workmanship or skill that might imply a higher status. The use of the colour for common and simply produced Isings form 12 cups illustrates this point.

One further and important issue that needs to be considered is the timescale within which the production of emerald green glass took place. If we are to judge by the dating associated with the various forms produced in emerald green, then the period of its use ranges from the beginning of the 1st century A.D., for forms such as Isings 2 and Isings 45, to the late 1st or even the early 2nd century for forms such as non-blown plates and bowls with wide out-turned rims (Price and Cottam, 1998, 55–9). The height of production seems to occur from around the A.D.20s to the A.D.50/60s. The colour certainly becomes very much less common after the mid 1st century, and at this point production must have been very much reduced, or have ceased entirely, with the continuing appearance of new emerald green vessels reliant on recycling. This much tighter period of production is a possibility, with individual vessels remaining in use over an extended period and broken vessels being preserved for recycling. However if production did stretch across four or more decades, then its use in only a restricted range of vessel forms is all the more curious.

What began as an investigation of a single colour has developed into a project with the potential to extend and clarify our understanding of many elements of the 1st-century glass industry. The curious link between emerald green, plant-ash glass and the vessel forms that it was used to produce provides an unexpected gateway into the world of the early Imperial glassmaker. We are in the process of extending our dataset to look at emerald green vessel forms of the later 1st century and beyond, the relationship between emerald green and vessels of similar form in other colours, as well as the influence of recycling which will form the basis of further publications, as an extension to our ‘green thoughts’.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2015.05.004.

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