An offprint from

GLASS OF THE ROMAN WORLD

Hardcover Edition ISBN 978-1-78297-774-2
Digital Edition ISBN 978-1-78297-775-9

Edited by

JUSTINE BAYLEY, IAN FREESTONE AND CAROLINE JACKSON

Oxford & Philadelphia

www.oxbowbooks.com

Published in the United Kingdom in 2015 by
OXBOWBOOKS
10 Hythe Bridge Street, Oxford OX1 2EW

and in the United States by
OXBOWBOOKS
908 Darny Road, Havertown, PA 19083

in association with THE ASSOCIATION FOR THE HISTORY OF GLASS

Hardcover Edition ISBN 978-1-78297-774-2
Digital Edition ISBN 978-1-78297-775-9

A CIP record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data

Glass of the Roman world / edited by Justine Bayley, Ian Freestone, and Caroline Jackson.
pages cm
Summary: "These 18 papers by renowned international scholars include studies of glass from Europe and the Near East. The authors write on a variety of topics where their work is at the forefront of new approaches to the subject. They both extend and consolidate aspects of our understanding of how glass was produced, traded and used throughout the Empire and the wider world drawing on chronology, typology, patterns of distribution, and other methodologies, including the incorporation of new scientific methods. Though focusing on a single material the papers are firmly based in its archaeological context in the wider economy of the Roman world, and consider glass as part of a complex material culture controlled by the expansion and contraction of the Empire"
Includes bibliographical references.
ISBN 978-1-78297-774-2 (hardcover edition) -- ISBN 978-1-78297-775-9 (digital)
1. Glass--Rome--History. 2. Glass manufacture--Rome--History. 3. Glassware, Roman. 4. Glassware industry--Rome--History. 5. Material culture--Rome--History. 6. Rome--Antiquities. 7. Rome--Social life and customs. 8. Rome--Commerce--History. 9. Rome--Economic conditions. I. Bayley, J. (Justine) II. Freestone, Ian. III. Jackson, Caroline M.
TP850.G55 2015
666'.10937--dc23
2015001452

Typeset by M.C. Bishop at The Armatura Press
Printed in Malta by Gutenberg Press

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Front Cover: top left, bowl from excavations at Usk ©Amgueddfa Cymru – National Museum Wales, bottom left circus cup from excavations at Colchester (1870,0224.3) and bottom right ribbed bowl from Hartford Heath (1958,0704.724), both © Trustees of the British Museum, top right Cameo vase (see Newby this volume) © Bonhams, London.
Back cover: far right and left, images from excavations at Argentière (Fréjus) photograph taken by Jeff Veitch © Department of Archaeology, Durham University, image, second left, painted cup (possibly Bacchus) from excavations at Catterick (published Jennifer Price, Antiquaries Journal 1990).

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COMPOSITION, TECHNOLOGY AND PRODUCTION OF COLOURED GLASSES FROM ROMAN MOSAIC VESSELS

Ian C. Freestone and Colleen P. Stapleton

Introduction

Profound changes occurred in the early Roman glass industry, which included a major increase in the scale of production along with the widespread adoption of shaping by blowing a gather of hot glass on a blowpipe (*e.g.* Grose 1986). However, our understanding of the detail of these changes remains limited. It might be expected that the substantial reorganisation of the industry that occurred at that time would have had ramifications for the technologies used to produce the glass materials used in vessel production and by implication their compositions. However, the number of published datasets of compositions of early Roman glass is surprisingly small and although we have a general understanding of the colourants used in Roman glass, we have limited understanding of any variations in craft practice that may have occurred with time and place.

The subject of the present paper is the opaque and strongly coloured glass used to manufacture polychrome mosaic glass vessels in the early imperial period, from the 1st century BC to the 1st century AD (Fig. 6.1). The forms of these early Roman vessels are in general very similar to those of the Hellenistic world, and it seems likely that Hellenistic glassworking skills were transmitted to the Roman glass industry (Grose 1989). There is little direct archaeological evidence for the location of the workshops involved in the production of these vessels, but literary evidence suggests that a major source of coloured glass vessels at this time was Rome itself (Grose 1986; 1989) and the distribution of the objects from archaeological contexts supports this view (Nenna 2002).

Mosaic glass vessels are generally believed to have been made using a technique known as slumping, whereby a disc formed from slices of coloured canes was slumped over a domed form to produce an open vessel, typically a bowl (Figs 6.2, 6.3; Grose 1986; Gudenrath 1991; Taylor and Hill 2003). The complex *chaîne opératoire* and high level of skill that would have been required to produce the bowls suggest that they were relatively expensive items and a number of writers of the mid-1st century AD comment that, by that time, glass had recently become much less expensive, implying that the earlier vessels of the type under discussion here were costly (Grose 1986).

The use of strongly-coloured vessel glass declined dramatically in the 1st century AD, with the adoption of glass-blowing as a means of fabrication, which favoured the adoption of transparent colourless and naturally coloured glass for utilitarian purposes. Colourless glass resembling rock crystal had, according to Pliny (*Natural History* books 34–37: Eicholz 1962), become the most expensive variety of glass. This change in the use of colour in glass vessels did not necessarily mean a decline in the production of strongly coloured glass, however. Although it became far less frequent in vessels, the use of coloured and opaque glass continued as an important element of the wall mosaics which decorated the houses of the wealthy. Thus while glass as a material became accessible to a much wider stratum of society than had previously been the case, strongly coloured glass is likely to have continued to occupy a niche at the upper end of the market, a necessity as its production is likely to have been a relatively expensive affair, in terms of both time and raw materials.

In this paper, analyses of a range of colours from two types of early Imperial Roman mosaic vessels are presented and used to interpret the colourant technology. These are compared to the compositions of other Roman glassware to identify any variations in technology that may have taken

Fig. 6.1: Mosaic glass bowl with applied foot. 25 BC–25 AD. Victoria and Albert Museum 969–1868.

place. A major wide-ranging analytical survey of mosaic vessel glass by Nenna and Gratuze (2009) is underway. However, as will be shown here and has been argued elsewhere, detailed examination of closely related groups of material can yield information which complements that of more general surveys (cf. Price *et al*. 2005; Freestone *et al.* 2009).

Analysed vessels

The origins of the mosaic glass fragments of this study are described by Stapleton (2003). The fragments are divided into two stylistic groups based on colour patterns. Three fragments derived from ribbed bowls on tall foot rings in the collections of the British Museum (BM), consist of marbled white opaque with blue transparent or amber (brown) transparent glasses (vessel nos. 11–13; Fig.6.4). The second group, from the collections of the Victoria and Albert Museum (VA), are formed of short strips of coloured canes from unidentified vessel forms (vessels 2–9; *e.g.* Fig. 6.5). The colours of these vessels include those found in the marbled fragments as well as opaque red and yellow, and translucent pale blue, purple and colourless. In these fragments, glass that appears to be translucent green in fact comprises a transparent pale blue glass overlying an opaque yellow glass. Table 6.1 shows the concordance between the analysis numbers and the museum registration numbers.

Analytical Methods

Forty-nine individual samples of coloured and colourless glass, less than 2mm^3, were removed from 10 vessel fragments, representing nine colours overall. The elemental compositions of the samples were analysed in a JEOL JSM

Fig. 6.2: Stages in the production of mosaic glass vessels, produced by Mark Taylor and David Hill – canes, sliced canes, disc ready for slumping, former and glass bowls.

Fig. 6.3: Slumping of a glass disc over a bowl-shaped former. Replication by Mark Taylor and David Hill.

Fig. 6.4: The marbled fragments investigated, British Museum (see text). Photo: British Museum

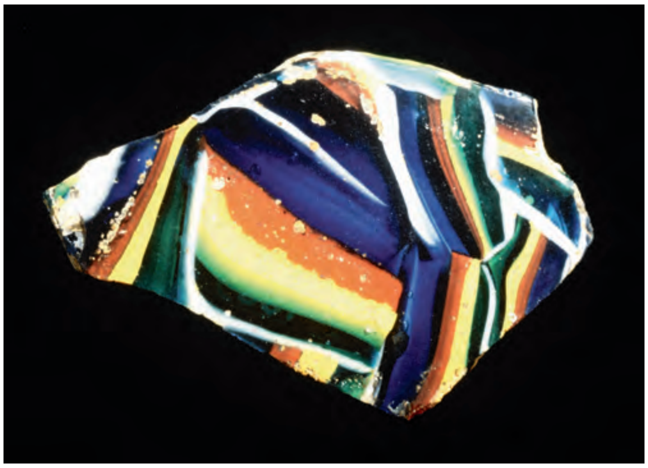

Fig. 6.5: A fragment from a bowl composed of coloured strips. Victoria and Albert Museum (see text). Photo: British Museum

Vessel no.	*Museum reg. no.*
3	VA ^{63}/1 ^{63}/20 ^{63}/2 - 1883
4	none (VA)
5	VA ^{63}/12:16 - 1885
6	VA ^{63}/1 ^{63}/20 ^{63}/12 - 1885
7	VA ^{63}/1 ^{63}/20 ^{63}/12 - 1885
8	VA ^{63}/1 ^{63}/20 ^{63}/12 - 1885
9	VA ^{63}/1 ^{63}/20 ^{63}/12 - 1885
11	BM GR 1886,11-17,203
12	BM GR 1886,11-17,252
13	BM GR 1886,11-17,252

Table 6.1: Concordance of Museum number and analytical number.

840 scanning electron microscope (SEM) using an Oxford Instruments Link ISIS energy dispersive X-ray analyser (EDXA) with a GEM germanium detector. The glasses were analysed at 15 kV accelerating voltage, and 1.7 nA beam current measured in a Faraday cup, for 200 seconds. The electron beam was rastered over as large an area as possible that avoided weathered or otherwise altered glass. In this way the area analysed represented as closely as possible the relative proportions of opacifier and glass matrix. All analyses are presented as weight percent. Detection limits are around 0.1% for each oxide, except for SnO_2 and Sb_2O_3 which are around 0.4%. Pure oxides, elements and minerals were used as primary standards. Corning Glass standards A, B, C, and D (Brill 1999) as well as commercially available glass standards were used as secondary standards and were routinely analysed. On this basis, the accuracy relative to the standards for elements present in concentrations above 10% is around 1%; for elements present between 1% and 10% is better than 5%; and better than 20% for components present between 0.3% and 1%, except for sulphur, which has a relative accuracy of about 100%.

In addition, using the approach of Verità *et al.* (1994), transparent pale blue, transparent medium to dark blue, opaque medium blue and purple, and colourless glasses, were analysed a second time at 40 kV with 0.6 nA current for 200 seconds. The increased sensitivity offered by the higher excitation potential allowed improved detection limits of 0.05% for cobalt and zinc, 0.07% for copper, and 0.2% for tin and antimony. Relative accuracies for these elements are the same as for those analysed at 15 kV. Elements present in the opacifying phases in the glass were identified by spot analysis.

Results

SEM-EDXA results are listed by colour in Table 6.2. In addition to the absolute compositions given in the Table, the compositions of the glasses were also considered as reduced compositions (Brill 1999) including only SiO_2, Al_2O_3, MgO, CaO, Na_2O, K_2O, P_2O_5, SO_3, and Cl, components brought into the glass mainly through the batch raw materials rather than as colourants. This allows comparison of the base glasses without the diluting effects of added colourants and opacifiers, which range up to 35% in the case of lead oxide, for example.

The base glasses are all soda-lime-silica glasses. The majority have characteristic “Roman” compositions insofar as they have magnesia and potash below 1.5%, indicating that they were made using natron as a source of soda, rather than plant ash (Brill 1970; Lilyquist and Brill 1993). In the reduced compositions, lime is typically around 8% in most glasses, while soda is around 18%. Alumina is typically 2.5% and is substantially higher only in some opaque yellow and red glasses. Except in the opaque yellow, red and dark blue glasses, iron oxide is typically 0.3–0.4% and these values are considered typical of the sand from which the glass was made, as similar values are also characteristic of later Roman-type glass from primary glassmaking furnaces (*e.g.* Freestone *et al.* 2000). Manganese, well known as a decolourant in Roman glass (Sayre 1963; Jackson 2005), was detected in most glasses except the ambers, its concentration varying typically between 0.2 and 1.4%. These characteristics are not exceptional in a Roman context. We therefore infer that all of the coloured glasses presently analysed, with the possible exception of some of the opaque reds, were made from a natron-type soda-lime-silica base glass with about 0.4% FeO, which in most cases had already been decoloured by variable amounts of manganese oxide. The various colouring and opacifying agents are likely to have been added to such a base glass.

Colourless, purple and amber glasses

The colours of these transparent to translucent glasses depend largely upon the behaviours and interactions of the elements iron, manganese and antimony. Their influence upon the colour of Roman glass has been usefully discussed by Schreurs and Brill (1984) and more recently by Bingham and Jackson (2008). Without a deliberately-added colourant, such as copper or cobalt (see below), the colour of glass depends largely upon the amount and oxidation state of any iron present. The ferrous ion, Fe^{2+}, formed under reducing conditions, is responsible for a distinctive bluish colouration, while the oxidised ferric ion, Fe^{3+}, is responsible for a much less intense yellow. Most glasses contain iron in both oxidation states, generating a range of greens, bluish greens and blues.

Sayre (1963), in a seminal study, recognised that manganese and antimony oxides were added deliberately to some ancient glass as decolourants, to convert the relatively strong blue-green colour of Fe^{2+} to the weak yellow of Fe^{3+} and change a relatively intense bluish tint to a hardly noticeable yellow. The detailed mechanisms involved are complex; the initial role of the compounds MnO_2 and Sb_2O_5 was probably to add oxygen to the melt but, once dissolved, the manganese and antimony cations form redox couples with iron, helping to maintain its oxidised condition (Schreiber *et al.*, 1999; Pollard and Heron 2008). There is some

Vessel no.	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cl	SO_3	CoO	CuO	ZnO	SnO_2	Sb_2O_3	PbO	Total
translucent pale blue																			
4	66.62	<0.10	2.40	0.39	0.18	0.44	7.65	18.17	0.56	0.17	0.91	0.78	<0.04	1.41	<0.05	<0.20	<0.20	0.17	99.85
5	68.32	<0.10	2.25	0.23	0.49	0.43	7.19	18.16	0.79	<0.10	0.42	1.00	<0.04	1.59	<0.05	0.29	<0.20	0.25	101.41
6	66.99	<0.10	2.51	0.36	0.54	0.52	7.26	17.49	0.74	0.16	1.00	0.57	<0.04	1.53	<0.05	0.33	0.25	0.28	100.53
8	64.38	<0.10	2.01	0.28	0.82	0.59	8.01	18.38	0.56	<0.10	1.00	0.41	<0.04	1.77	<0.05	0.29	0.30	0.43	99.23
9	65.26	<0.10	2.16	0.29	0.41	0.65	8.07	17.98	0.68	0.12	0.81	0.43	<0.04	1.86	<0.05	0.32	0.34	0.25	99.63
translucent medium to dark blue																			
3	65.84	<0.10	2.42	1.12	1.22	0.67	8.26	18.09	0.82	0.23	0.80	0.42	0.09	0.14	<0.05	<0.20	<0.20	<0.10	100.12
4	66.87	<0.10	2.60	1.39	0.32	0.56	7.85	18.31	0.81	0.11	0.58	0.48	0.15	0.17	0.33	<0.20	<0.20	<0.10	100.53
6	66.61	<0.10	2.44	1.33	1.03	0.63	7.88	17.67	0.83	0.16	0.88	0.39	<0.04	0.12	<0.05	<0.20	0.34	<0.10	100.31
7	66.45	<0.10	2.40	1.30	0.99	0.68	7.81	17.82	0.83	0.17	0.80	0.41	0.07	0.11	<0.05	<0.20	0.39	<0.10	100.23
8	67.17	0.16	2.42	1.67	0.38	0.63	8.89	18.79	0.81	0.27	0.70	0.42	0.11	0.13	<0.05	<0.20	0.33	<0.10	102.88
9	65.29	<0.10	2.34	1.39	0.99	0.59	8.69	17.84	0.85	0.15	0.63	0.47	0.11	0.53	0.53	<0.20	0.42	<0.10	100.82
11	67.78	<0.10	2.48	0.91	0.45	0.48	7.60	17.54	0.77	<0.10	0.88	0.44	<0.04	0.05	<0.05	<0.20	<0.20	<0.10	99.38
12	67.66	<0.10	2.34	0.87	0.28	0.59	9.18	16.80	0.57	0.14	0.60	0.67	0.05	0.19	<0.05	<0.20	<0.20	<0.10	99.94
opaque medium blue																			
13	60.42	<0.10	2.21	1.77	0.92	0.54	7.71	15.00	0.68	0.16	0.53	0.80	0.91	0.44	<0.10	<0.40	6.80	<0.10	98.89
colourless																			
3	65.56	<0.10	2.33	0.28	2.66	0.69	7.44	18.81	0.59	0.12	1.05	0.50	<0.10	<0.10	<0.10	<0.40	<0.30	<0.10	100.03
5	67.24	<0.10	2.60	0.34	1.33	0.60	7.96	18.81	0.80	0.11	1.00	0.41	<0.10	<0.10	<0.10	<0.40	<0.20	<0.10	101.20
6	66.52	<0.10	2.73	0.37	1.42	0.66	7.62	18.43	0.84	0.15	1.00	0.35	<0.10	<0.10	<0.10	<0.40	<0.20	<0.10	100.09
7	68.51	<0.10	2.24	0.23	1.07	0.56	7.29	17.73	0.75	<0.10	0.76	0.48	<0.10	<0.10	<0.10	<0.40	<0.30	<0.10	99.62
8	68.30	<0.10	2.40	0.33	1.24	0.63	8.83	18.76	0.69	0.18	0.90	0.48	<0.10	<0.10	<0.10	<0.40	<0.20	<0.10	102.74
9	66.55	<0.10	2.29	0.35	1.18	0.60	7.42	19.13	0.70	<0.10	0.76	0.60	<0.10	<0.10	<0.10	<0.40	<0.40	<0.10	99.58
translucent purple																			
4	64.18	<0.10	2.54	1.10	3.05	0.78	8.66	17.54	0.77	<0.10	0.61	0.47	<0.04	0.22	<0.05	<0.20	0.25	<0.10	100.17
8	68.71	<0.10	2.16	0.34	1.41	0.62	8.03	19.08	0.65	0.11	1.09	0.39	<0.04	<0.06	<0.05	<0.20	0.26	<0.10	102.85
9	67.61	<0.10	2.10	0.30	1.61	0.57	7.89	18.64	0.64	<0.10	1.04	0.33	<0.04	<0.06	<0.05	<0.20	0.37	<0.10	101.10
translucent amber																			
8	70.13	<0.10	2.36	0.26	<0.10	0.45	7.35	19.20	0.73	<0.10	1.08	0.37	<0.10	<0.10	<0.10	<0.40	<0.20	<0.10	101.93
11	66.98	<0.10	2.32	0.19	<0.10	0.40	7.03	16.43	0.77	<0.10	0.95	0.56	<0.10	<0.10	<0.10	<0.40	<0.40	<0.10	95.63
12	70.51	<0.10	2.49	0.26	<0.10	0.39	7.23	17.06	0.64	<0.10	1.22	0.35	<0.10	<0.10	<0.10	<0.40	<0.40	<0.10	100.15
13	69.40	<0.10	2.58	0.26	<0.10	0.52	7.49	17.31	0.81	<0.10	1.17	0.27	<0.10	<0.10	<0.10	<0.40	<0.40	<0.10	99.81
translucent black																			
12	68.33	<0.10	2.69	0.76	0.27	0.54	9.29	10.55	0.64	0.29	1.17	1.21	<0.10	1.56	<0.10	<0.40	<0.40	<0.10	97.30
opaque white																			
3	62.26	<0.10	2.27	0.34	1.27	0.69	7.54	15.83	0.83	0.20	0.45	0.89	<0.10	<0.10	<0.10	<0.40	7.68	<0.10	100.25
4	65.03	<0.10	2.42	0.37	0.36	0.58	7.82	16.87	0.81	0.16	0.54	0.73	<0.10	<0.10	<0.10	<0.40	4.22	<0.10	99.91
4	57.14	<0.10	2.05	0.39	0.79	0.66	6.81	13.88	0.71	<0.10	0.45	0.58	<0.10	<0.10	<0.10	<0.40	3.86	12.05	99.37
5	64.75	<0.10	2.24	0.33	0.40	0.50	7.12	16.66	0.74	<0.10	0.45	0.93	<0.10	0.34	<0.10	<0.40	6.49	<0.10	100.95
6	62.97	<0.10	2.30	0.35	1.17	0.74	7.79	16.55	0.74	0.12	0.50	0.85	<0.10	<0.10	<0.10	<0.40	6.11	<0.10	100.19
7	63.90	<0.10	2.20	0.35	0.80	0.74	6.99	15.57	0.85	0.14	0.46	0.67	<0.10	<0.10	<0.10	<0.40	6.85	<0.10	99.52
8	65.30	0.15	2.40	0.35	0.53	0.56	8.39	17.34	0.77	0.12	0.51	0.77	<0.10	<0.10	<0.10	<0.40	5.03	<0.10	102.22
9	53.45	<0.10	1.85	0.37	0.93	0.59	6.32	12.64	0.57	<0.10	0.29	0.63	<0.10	<0.10	<0.10	<0.40	6.61	15.51	99.76
11	64.02	<0.10	2.40	0.38	0.37	0.58	7.57	14.82	0.72	0.11	0.50	0.85	<0.10	<0.10	<0.10	<0.40	6.14	<0.10	98.46
12	64.24	<0.10	2.38	0.28	0.66	0.54	6.72	15.75	0.64	0.15	0.42	0.79	<0.10	<0.10	<0.10	<0.40	7.37	<0.10	99.94
13	61.94	<0.10	2.50	0.53	1.07	0.68	7.08	15.74	0.80	<0.10	0.50	0.95	<0.10	<0.10	<0.10	<0.40	7.35	<0.10	99.14
opaque yellow																			
3	45.76	<0.10	1.93	1.63	0.44	0.48	3.76	9.73	0.46	<0.10	0.55	0.35	<0.10	<0.10	<0.10	<0.40	2.98	31.98	100.05
5	47.17	<0.10	1.70	1.41	<0.10	0.41	4.66	9.79	0.50	<0.10	0.58	0.80	<0.10	<0.10	<0.10	<0.40	2.16	30.25	99.43
6	42.64	<0.10	1.81	1.30	<0.10	0.33	3.47	11.23	0.43	<0.10	0.57	0.56	<0.10	0.37	<0.10	<0.40	3.58	33.40	99.69
7	47.58	0.15	1.88	1.36	0.38	0.46	3.67	11.88	0.60	<0.10	0.62	<0.20	<0.10	0.28	<0.10	<0.40	2.41	26.51	97.78
8	53.92	<0.10	1.88	1.11	<0.10	0.43	6.51	14.08	0.56	0.13	0.76	0.37	<0.10	0.46	<0.10	<0.40	1.75	18.42	100.38
9	46.53	<0.10	1.60	1.63	0.28	0.48	5.18	11.14	0.48	<0.10	0.60	<0.20	<0.10	0.62	<0.10	<0.40	1.74	27.31	97.59
opaque red																			
3	57.35	<0.10	2.53	1.96	0.12	0.74	6.83	16.32	0.71	0.16	0.84	0.53	<0.10	1.45	<0.10	3.99	<0.40	5.86	99.39
5	54.19	0.14	2.56	1.35	0.59	0.72	6.81	14.50	1.11	0.18	0.71	0.56	<0.10	2.27	0.33	<0.40	0.74	13.74	100.50
6	53.07	0.15	2.55	1.34	0.49	0.80	6.56	14.47	0.83	0.20	0.67	0.31	<0.10	1.37	<0.10	0.50	0.69	15.77	99.77
7	58.43	0.27	2.35	2.10	0.52	1.92	8.04	16.80	1.17	0.63	0.66	0.35	<0.10	1.26	<0.10	1.12	<0.40	3.87	99.49

Table 6.2: Compositions of glasses determined by SEM-EDXA (see text).

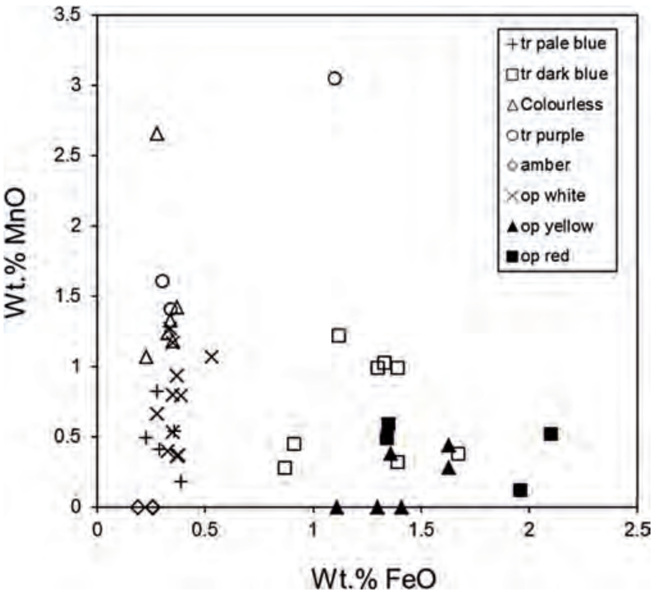

Fig. 6.6: Contents of manganese oxide and iron oxide in the various glass colours analysed.

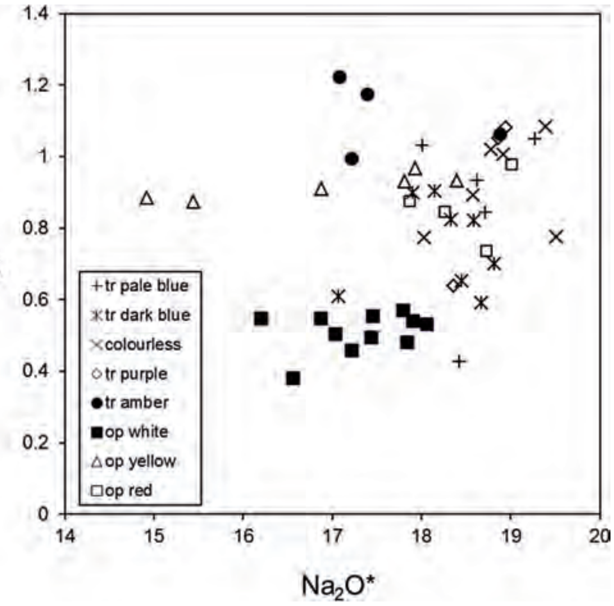

Fig. 6.7: Chlorine versus soda in the various glass colours analysed (indicates reduced weight per cent compositions).*

confusion in the literature over the level of manganese in a glass which indicates a deliberate addition. However, in natron glasses, negligible manganese will have entered the glass with the alkali, and any levels above those natural to sand are likely to reflect a deliberate addition at some point in the glassmaking process. The ratio iron:manganese in the earth's crust is around 10:1 (Wedepohl 1995; Kamber *et al.* 2005) and appears not to depart significantly from this in most glassmaking sands. Iron concentrations in most vessel glass are around 0.5% (5000 ppm), implying that manganese below 500 ppm is derived from the sand but that higher levels reflect additions by the glassmakers. This view is supported by the analysis of raw glass from the Byzantine and early Islamic primary tank furnaces where manganese concentrations are typically a few hundred ppm (Freestone *et al.* 2000 and unpublished data). Similarly, antimony levels in sand are typically at the ppm (or sub-ppm) level, and greater concentrations will indicate the addition of an antimony-bearing ingredient. Hence antimony and manganese oxides detectable by the SEM-EDXA techniques used in the present study are likely to represent deliberate additions at some stage in the production process, with the proviso that in some cases they may have been incorporated by the recycling of old glass.

Amber glasses analysed here are simple soda-lime-silica types with no added colourants or opacifiers (Table 6.2). They have the lowest manganese contents of all the translucent glasses analysed (Fig. 6.6) and it appears that manganese was not intentionally added at any stage. The amber colour is likely to be due to the presence of the ferri-sulphide chromophore, a complex which forms in the glass under strongly reducing conditions. These result in the presence of reduced sulphide, S^- ions, in the coordination polyhedron of Fe^{3+} and this complex generates the amber colour (*e.g.* Schreurs and Brill 1984; Pollard and Heron *op. cit.*). Low manganese is a typical feature of amber glass (Sayre 1963) because the oxidising conditions it promotes favour the higher oxidation states of sulphur, inhibiting the generation of the amber colour.

The need to maintain strongly reducing conditions would have made it desirable to minimise the length of time that amber glass was reheated in air, after its initial manufacture. The chlorine content of the glass can provide an indication of the extent to which it has been held at high temperature. Chlorine is likely to be present in soda-lime-silica glass as NaCl complexes, as indicated by the presence of very small exsolved particles of NaCl in glasses which have been heat-treated (Barber and Freestone 1990; Barber *et al.* 2009). The amount of chlorine in the glass is therefore likely to be related to the sodium content, but is also dependent upon the duration and temperature of heating, as chlorine is a volatile phase which will be lost from the surface of the molten glass. The amber glasses have the highest chlorine contents of all of the glasses analysed in this project, as shown in Fig. 6.7. This is likely to reflect a shorter period at high temperatures than the other glasses, or fewer episodes of melting, so that less chlorine was volatilised. Amber glass is therefore likely to represent material used directly from the primary glassmaking furnaces without intermediate phases of melting.

The colourless glasses analysed are all decolourised by manganese, containing over 1% MnO. No other additives were detected and they are compositionally similar in most respects to the amber glasses. The purple glasses are compositionally similar to the colourless glasses and colourless and purple glasses have the highest manganese contents of all the glasses analysed (Fig. 6.6). Manganese is typically present in glass as Mn^{2+}, while the purple colour is likely to be due to the Mn^{3+} ion, which has a very high absorption coefficient so that only very small amounts are needed to generate an intense purple (Schreurs and Brill 1984; Sanderson and Hutchings 1987; Schofield *et al.* 1995). Strongly oxidising conditions are required to oxidise the manganese to Mn^{3+}. Small amounts of antimony oxide, detected in all of the purple samples, but not in the colourless samples (Table 6.2) may have served to oxidise the manganese via the interaction: $2Mn^{2+} + Sb^{5+} = 2Mn^{3+} + Sb^{3+}$, as suggested by Sanderson and Hutchings (1987) for a piece of Anglo-Saxon glass. In the present context, it is observed that the manganese contents of the colourless and the purple glasses are more-or-less the same (Fig. 6.6), suggesting that the antimony content was indeed a critical factor in generating the colour.

Two of the purples contain FeO at about 0.3% and MnO at about 1.5%. The third, from vessel no. 4, contains higher concentrations of these oxides (1.1 and 3.05% respectively) and is a dark purple glass that appears almost black. No cobalt was detected in the dark purple glass above the detection limit of about 0.04% CoO. The very dark nature of this glass is probably mainly due to a greater concentration of oxidised manganese, Mn^{3+}, due to the higher total concentration of MnO, perhaps with a small contribution from the iron.

Opaque white glasses

The opaque white glasses owe their opacity and colour to the presence of abundant crystals of calcium antimonate precipitated in the glass matrix. Antimony concentrations in the range 3–8% seem to have been added to a standard soda-lime-silica glass base. The lime contents of the reduced compositions of the opaque whites are essentially the same as those of the colourless glasses, indicating that the antimony was added as antimony oxide or possibly sulphide rather than as calcium antimonate (Bimson and Freestone 1983; Foster and Jackson 2005).

As is well known, calcium antimonate crystallises or "strikes" in opaque white glass as it is cooled. The precise mechanism responsible for this is rarely discussed, but it may be explained by a consideration of the oxidation states of antimony in the glass melt, which have been measured for example by Claes and Decelle (2001) and by Krol and Rommers (1984). Antimony occurs in two oxidation states, the oxidised form Sb^{5+} and the reduced form Sb^{3+}. The ratio Sb^{3+}/Sb^{5+}decreases as temperatures fall and Krol and Rommers (1984) found that, in a glass they studied, $Sb^{3+}/(Sb^{3+} + Sb^{5+})$ varied from <0.1 to >0.9 between 900 and 1500^{o}C. The form of antimony in the opacifier $Ca_2Sb_2O_7$ is the oxidised variety. Thus, as a glass melt with dissolved antimony is cooled, the antimony oxidises and, given suitable concentrations of antimony and calcium oxides, calcium antimonate precipitates. In order for this reaction to take place, free oxygen must be present in the glass:

$$Sb_2O_3 + O_2 \rightarrow Sb_2O_5$$

In modern glass technology, this oxidation-reduction reaction is exploited in the use of antimony as a fining agent – during melting large amounts of oxygen are released causing the formation of large bubbles which move easily though the melt and remove the smaller bubbles ("seeds"). To produce opaque glass, the oxygen content of the glass should be high, to maximise the formation of the oxidised calcium antimonate phase. The chlorine contents of the glasses investigated here provide evidence that procedures were adopted by the glassworkers to maximise the oxygen content of the glass and the formation of calcium antimonate. Opaque white glasses have lower chlorine contents than all the other colours (Fig. 6.7). This is likely to represent melting for a prolonged period or at higher temperatures. If antimony had been added to the batch as the sulphide mineral, stibnite (Sb_2S_3), or partially oxidised stibnite, a more extreme melting process would have driven off the sulphur and oxidised the antimony, promoting the formation of calcium antimonate. In addition it would also have helped homogenise the antimony in the melt so that the calcium antimonate opacifier was homogeneously dispersed in the glass upon striking.

The estimated accuracy of our sulphur measurements at the lowest concentrations is unfortunately poor, but precision is fair. The whites tend to have higher sulphur contents than most other colours and there is a loose positive correlation between sulphur and antimony (Fig. 6.8). A similar positive correlation between the antimony and sulphur in Roman glass was observed by Fredrickx *et al.* (2004). This suggests that the antimony was originally derived from stibnite but it does not prove that it was added

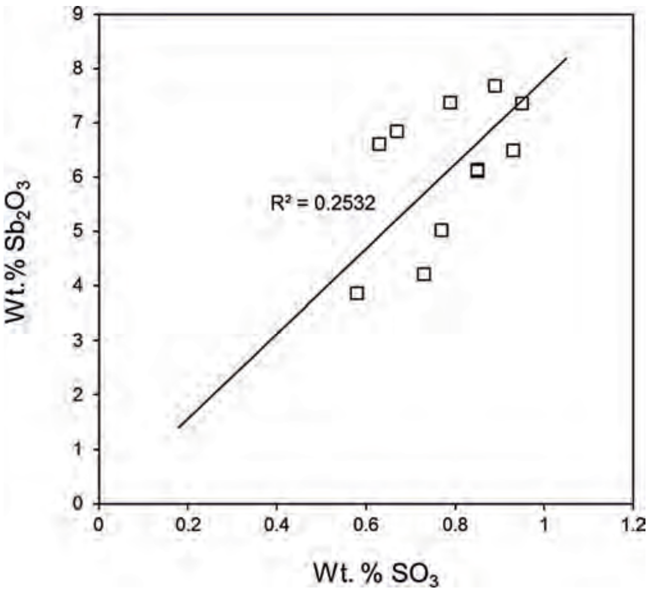

Fig. 6.8: Antimony oxide versus sulphur trioxide in the opaque white glasses.

to the glass in mineral form. Foster and Jackson (2005) have demonstrated that it would have been possible to produce an opaque white glass by adding either oxide or sulphide. The sulphur contents of the glasses could be explained by the addition of imperfectly roasted stibnite to the glass (Foster and Jackson, *op. cit.*), coupled with a dependency of sulphur solubility upon antimony content.

Two of the white glasses are rich in lead oxide, with around 12% and 15% respectively. This is a characteristic shared by many of the white overlay glasses on cameo vessels from approximately the same period, such as the Portland Vase (Bimson and Freestone 1983; Mommsen *et al.* 1997). These previous investigators speculated that the lead in cameo vessel glass was added to make it softer and hence to improve its cutting properties, or to lower its melting temperature. However, these characteristics would not offer advantages in the production of mosaic vessels. It is therefore possible that an ore rich in lead and antimony was being exploited so that high levels of lead entered some glasses with the antimony. The possibility that there was some technical advantage which has not yet been recognised seems unlikely given the inconsistent presence of lead. One analysed vessel, no. 4, includes both high-lead and low-lead white glass (Table 6.2), so the presence or absence of lead is unlikely to be related to differences between workshops, unless the craftsmen who made the vessels did not make their own colours but received them from specialist colouring workshops.

Blue glasses

Pale blue glasses are coloured with 1–2% CuO. This glass appears bright green when it overlies an opaque yellow, otherwise its appearance is blue or “limpid light blue” (Sayre 1964), which is emphasized when it overlies opaque white. The arrangements of the blue and apparently green glasses in the mosaic patterns are regular, suggesting that the green effect was intentionally produced. Low levels of lead, typically in the range 0.2% to 0.4% PbO, occur in each glass. Tin was measured in four samples at around 0.3% SnO_2, while antimony was detected at similar levels in three. The proportions of copper, tin, and lead are similar to those found in some Roman bronzes, suggesting that copper alloy metal, alloy scale or dross (the oxide-rich scum formed on top of a crucible of molten copper alloy) may have been the source of copper for these glasses (see Brill *et al.* 1988; Sayre 1964).

Eight fragments sampled had a strong blue colour, which is deep enough in some samples to appear opaque. A deep blue colour in glass is typically due to cobalt and quantities of only a few hundred parts per million may impart a strong colouration, while just 5ppm may impart a noticeable tint according to Preston and Turner (1941). Cobalt was measured in four of the glasses at levels of around 0.1%, and was tentatively detected in two more. It is therefore likely to be present in all of them. The iron oxide content of the dark blue glasses is higher than in most other colours (Fig. 6.6), ranging between about 0.9% and 1.7% FeO suggesting that iron oxide was added with the cobalt colourant. Manganese ranges from about 0.3% to 1.2% MnO and concentrations in this range are not exceptional within the overall assemblage and are typical of the base glass (Fig. 6.6), so it is unlikely that large quantities of MnO were added with the cobalt. Copper was present in all samples at levels between 0.05 and 0.5% CuO, and is likely to have entered the glass with the cobalt. Arsenic, frequently associated with cobalt ores in nature, was sought but not detected. One of the cobalt-coloured blues in a short strip mosaic fragment (vessel no. 4) contains about 0.3% ZnO, which may reflect the cobalt source.

In marbled vessel no. 12, very thin streaks of black glass, observed only with the use of a low-powered binocular microscope, occur within the cobalt-coloured blue. Present in the black are sulphur and copper-rich particles, less than 0.001mm diameter, probably a copper sulphide which is responsible for the black appearance. These particles are likely to have precipitated due to the elevated S and Cu in the black region, analysed as around 1% SO_3 and 2% CuO (Table 6.2). Sulphide compounds have been found to be responsible for the black appearance of some other ancient glasses (*e.g.* Stapleton and Swanson 2002). However, in the present case the inclusion of these very fine black streaks in the host blue glass are likely to be related to the manufacture of the cobalt colourant rather than to the intentional manufacture of a black glass. Cobalt ore commonly occurs in the form of sulphides and is frequently associated with copper mineralisation so it is possible that these streaks represent the use of imperfectly oxidised ore.

The single example of *opaque* blue analysed shows similarities in composition to the translucent cobalt-blues, containing about 1.8% FeO and 0.9% MnO, as well as 0.4% CuO. This glass is opacified by crystals of calcium antimonate, due to the presence of around 7% Sb_2O_3. The cobalt content of this glass, about 0.9% CoO, is much higher that in the translucent cobalt blues, due to the need to counteract the white of the calcium antimonate. This opaque blue appears to have been made by adding the cobalt pigment to an opaque white glass similar to the low-lead opaque whites in the vessels; it is noted that the chlorine content of the opaque blue glass is low, similar to those of the opaque whites.

Opaque yellow glass

Yellow glasses are coloured and opacified by yellow lead antimonate crystals, probably $Pb_2Sb_2O_7$ (Rooksby 1962). Antimony is present at in the range 1.8% to 3.6% Sb_2O_3, while lead occurs between about 18% and 32% PbO (Table 6.2). Thus, the PbO:Sb_2O_3 ratios of the yellows are much higher than those of the two lead-bearing opaque white glasses. In fact, for each yellow, assuming that all of the antimony present is in the $Pb_2Sb_2O_7$ crystals, there is an excess of lead of the order of 15% to 30% PbO over the amount required to combine with all of the antimony. In the early modern period, yellow glass was made by producing a precursor lead-antimony-silicate, known as *anime*, which would be mixed with a soda-lime-silica glass to colour it (Moretti and Hreglich 1984). A similar practice is likely to have occurred in the production of yellow glass in Late Bronze Age Egypt (Shortland 2002) and it was also the practice in the production of the tin-based equivalent opacifier, lead tin yellow, where Heck *et al.* (2003) report early medieval crucibles in which the precursor appears to have been made. For the present glasses, lime is plotted against silica in Fig. 6.9. It is observed that the yellow glasses have elevated silica relative to the other colours suggesting that the yellow colourant was indeed added in the form of a silica-containing precursor. The reduced compositions of the yellow glasses also have relatively low potash and magnesia (Fig. 6.10) supporting the addition of a diluting siliceous material.

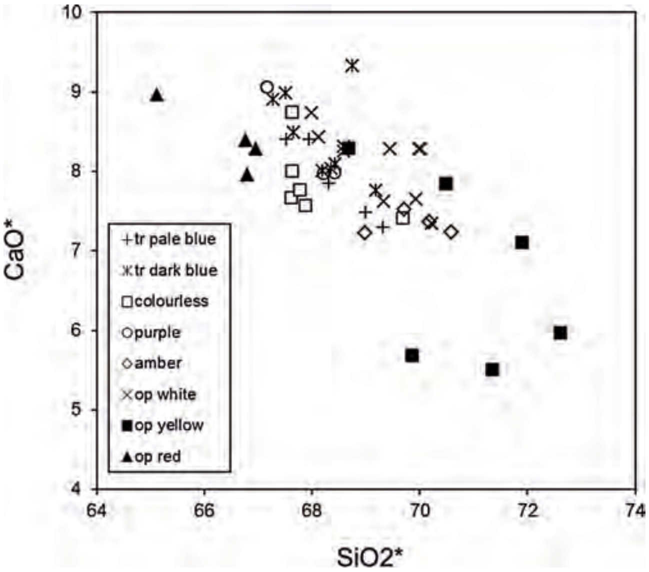

Fig. 6.9: Reduced lime versus silica for the glasses analysed. Note the occurrence of the red and yellow glasses at opposite ends of the distribution.

A lead-antimony-silica pigment was probably used because lead antimonate is a relatively unstable pigment and fades when held at high temperatures, as has been demonstrated experimentally (Shortland 2002). The excess lead is likely to have reduced the melting temperature needed to make the antimonate pigment and a high-lead glassy matrix is likely to have helped stabilise the lead antimonate phase. Lead antimonate does not appear to "strike" (to form during cooling) in the same way as calcium antimonate white. This explains why glasses such as those here and on some cameo vessels may contain high antimony and high lead but still appear opaque white, rather than opaque yellow. It reflects the very different technologies used to produce the two colours. As the colour of lead antimonate is relatively unstable, the glassmakers would have minimised the time that yellow glass was held at high temperature during the colouration process. The chlorine content of opaque yellow is therefore typically high relative to opaque white glass and many other glasses analysed (Fig. 6.7).

The diluting effect of the high lead values make most of the remaining oxides in the yellow glass compositions appear unusually low. Even so, iron oxide is elevated to between about 1% and 1.6% and is higher than in most other colours, except for blues and reds (Fig. 6.6). In all of these colours an iron-rich compound is likely to have been

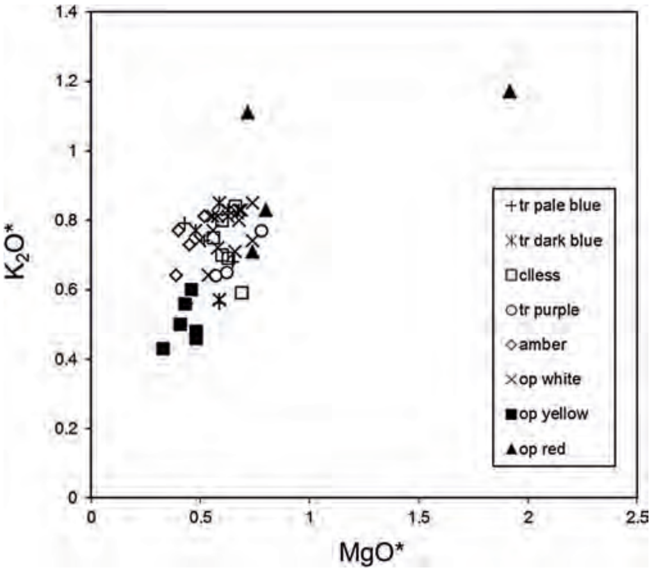

Fig. 6.10: Reduced magnesia and potash in the colours analysed, showing elevated concentrations in the red glasses. Note also the relatively low concentrations in the opaque yellows.

added to the glass as part of the colouration process. In the case of yellow glass we may speculate that iron additions tend to stabilise the lead antimonate and hence make a stronger yellow. Moretti and Hreglich (1984) found that the lead antimonate colours they obtained were stronger in the presence of iron (more orange or brownish yellows).

A green opaque glass may be formed by combining a lead antimonate opacifier with a copper blue coloured glass matrix. However, in the mosaic glasses analysed here green was produced by overlaying a translucent copper blue glass on an opaque yellow background. This may be a reflection of the difficulties in controlling the colours of glasses opacified with lead antimonate outlined above or possibly the challenge of manufacturing opaque green. Dissolution of copper oxide in a pre-existing opaque yellow glass is the most obvious route to green, but the high temperatures needed to dissolve the copper are likely to cause the lead antimonate to dissolve. Addition of lead antimonate pigment to a pre-existing copper blue glass would appear to be more likely to produce a successful glass but would have been a more complex and time consuming process than overlying translucent blue over yellow. Interestingly, in ancient glass cobalt is rarely, if ever, seen in combination with lead antimonate yellow to manufacture a green, presumably as cobalt is too strong a colourant and absorbs too much light to be used successfully in this way.

Opaque red glass

Minute particles of a copper-rich phase, probably metallic copper (Barber *et al.* 2009; Brun *et al.* 1991), of the order of 1µm or less in diameter, colour and opacify the opaque red glasses. 1–2% copper, reported as CuO, is present (Table 6.2) and lead is present between about 4% and 16% PbO. The two reds with the highest lead also have detectable levels of about 0.7% Sb_2O_3. Small amounts of tin and zinc in several of the samples are likely to represent the use of copper alloy scrap as a source of colourant.

Iron oxide is also high in the red glasses (Fig. 6.6), and is likely to have been added as a reducing agent to facilitate the formation of the copper particles (Freestone 1987; Freestone *et al.* 2003). An examination of the potash and magnesia contents indicates that in the opaque reds these are highest of the mosaic glasses investigated (Fig. 6.10). High magnesia opaque reds have been reported in other studies of mosaic glasses (Nenna and Gratuze 2009) and Roman opaque red glasses in general (Henderson 1991a; 1991b). In some cases it has been suggested that they represent plant ash based glass, an alternative source of glass, implying a trade in a material which is inferred to have been more difficult to produce than other colours, and which was more difficult to obtain. However, this is unlikely to be the case for the present glasses. As is indicated by Fig. 6.10, while all four red glasses have relatively high MgO and K_2O, these are only slightly elevated compared to the other (natron-based) glasses analysed. The standard criterion used to distinguish between plant ash and natron based glass is typically around 1.5% each of K_2O and MgO (*e.g.* Lilyquist and Brill 1993). Only one of these red glasses exceeds 1.5% in either of these oxides and this is vessel 7, with 2.1% MgO in its reduced composition, but only slightly elevated K_2O at 1.2% (Fig. 6.10). Relative to (colourless) soda-lime-silica glasses produced using plant ash from any period, Bronze Age to medieval (*e.g.* Brill 1999; Freestone 2006, fig.1) these values remain low, and for this reason the suggestion that they represent "plant ash glasses" must be treated with scepticism. However, there is clearly a plant ash signature, as emphasised by the particularly high P_2O_5, another characteristic indicator of plant ash, in vessel no. 7 (0.6%; Table 6.2). The position of these compositions, intermediate between plant ash and natron, suggests that they represent a mixture of either plant ash and natron based glasses, or natron-based glass and plant ash. When reduced lime and silica for all mosaic glasses are plotted, it is observed that silica is lowest while lime is relatively high in the red glasses (Fig. 6.9), which favours the addition of ash, with high lime and low silica, rather than a mixture of two glasses, as soda plant ash and natron glasses typically have broadly similar lime and silica contents. The addition of ash to red glass is explicable in terms of the colouration process. Fuel ash frequently contains finely divided charcoal and its addition to the glass would therefore have served as a reducing agent, favouring the formation of reduced forms of copper and the precipitation of copper metal particles to give the colour.

Discussion

The results presented reflect a highly complex glass colouration technology in the early imperial period, underpinned by a sophisticated empirical knowledge of material behaviour. To produce the range of colours seen in the vessels analysed, the addition of a single colouring agent with minimal preparation was not sufficient. In the case of cobalt blue or antimony-opacified glasses, it was necessary to thoroughly burn and oxidise any sulphide ore used; for lead antimonate yellow a lead antimony silicate precursor compound was produced and iron added to stabilise the colour. Furthermore, the durations of the melting processes were controlled as indicated by the chlorine contents of the white, colourless, yellow and amber glasses. Internal oxidation states of opaque reds were manipulated by adding both iron compounds and carbon (in ash), and in the manganese purples by the addition of small quantities of antimony. These characteristics suggest a well-established and mature colourant technology.

The lime and alumina contents of natron-based glass can be used to evaluate potential sand sources and origins of the base glass (Freestone *et al.* 2000; 2006). Roman vessel glass of the later 1st–4th centuries falls into several compositional groups: (1) common green-blue glass; (2) colourless glass, in which the colour due to iron oxide was removed by additions of antimony; (3) almost colourless glass, decoloured by manganese and similar in other respects to green-blue (Sayre 1963; Jackson 2005). Typical antimony-decoloured glass and green-blue glass may be readily differentiated using major elements such as lime and alumina, which suggests the use of different sands (Fig. 6.11; Freestone 2008). Elemental and isotopic studies suggest that many of these glasses originated in the south-eastern Mediterranean (Nenna *et al* 1997; Picon and Vichy 2003; Degryse and Schneider 2008) and the use of eastern Mediterranean sands continued into the middle of the 1st millennium A.D., in the form of the “Levantine I” blue-green glass of late Roman/early Byzantine times (Freestone *et al.*, 2000).

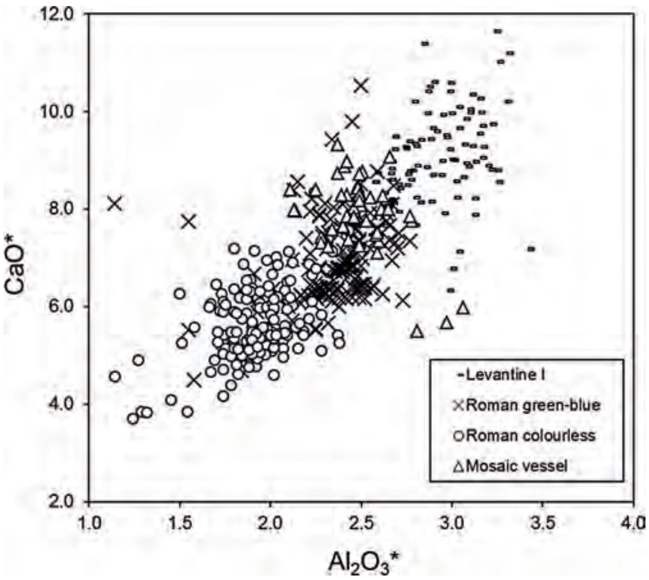

Fig. 6.11: Reduced lime and alumina contents for mosaic glasses analysed here versus Roman weakly coloured (green-blue) and antimony-decolourised colourless glass of 1st–3rd centuries and Levantine I type glass of the early Byzantine period (for sources of data, see Freestone 2008). The small cluster of mosaic glass lying below the main group comprises opaque yellow.

Fig. 6.11 compares the reduced composition of the glass from mosaic vessels analysed in the present study with the Roman colourless, green-blue and Levantine I groups (for sources of data see Freestone 2008). It is observed that the mosaic vessels form a coherent compositional group, apart from three samples which lie below the main cluster. These outliers are opaque yellow glasses and, as discussed above, their deviation is likely to be due to the addition of silicate components with the lead antimonate opacifier. The base glass of the mosaic vessels is very similar to the compositions determined for 1st–3rd century green-blue glass. This is not surprising as Pliny, writing around 70AD, indicates that glass was traditionally made from the sand of the beach near the mouth of the River Belus, which flows into the Bay of Haifa (Freestone 2008). However, it is noted that the mosaic vessels do not fully overlap the Roman green-blue glasses, but are concentrated at higher lime and slightly higher alumina contents (Fig. 6.11). Rather than a change in the glassmaking sand used, this may reflect changes in production practices in the 1st century AD. The low-lime antimony-decolourised colourless glass does not appear to have become common until after the middle of the 1st century AD, well after the present vessels were

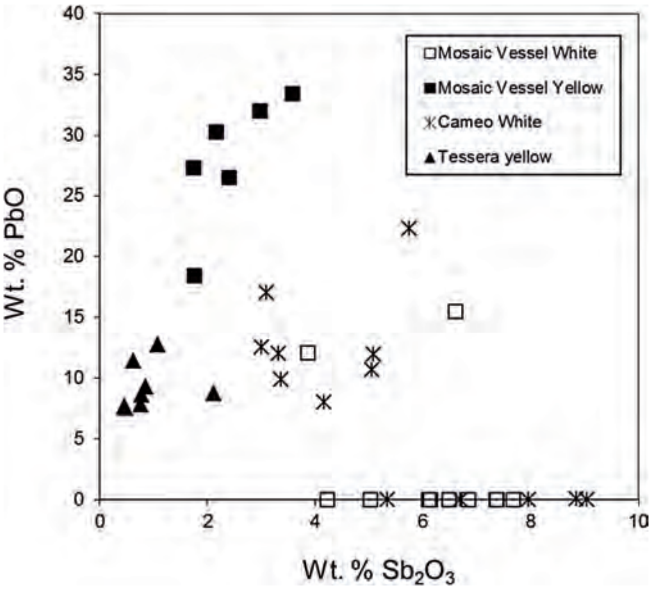

Fig. 6.12: Lead versus antimony oxide in opaque yellow and white glasses analysed, plus white glasses from cameo glass and yellow glass tesserae from wall mosaics of the 1st–3rd centuries.

produced. The green-blue glasses with lower lime and alumina than the mosaic glasses (Fig. 6.11) may be interpreted as resulting from mixing of this colourless glass with blue-green glass due to glass recycling. The base glass of the mosaic vessels is therefore likely to be representative of Roman glass made from the Belus sand source and use of this sand appears to have continued through to the 4th century.

The fact that the mosaic glasses were made from the standard source of sand for Roman glass, and one which continued in use for some centuries, means that it is not possible to use the sand composition to determine their provenance. Hence it does not help to determine if the colours were made in a single workshop or a number of different workshops. However, this result does suggest that the major expansion of the Roman glass industry which occurred with the widespread adoption of blowing was possible using the traditional raw material source, and did not depend upon the introduction of new sources of sand. Even so, the coherent and explicable patterns of compositional variation within the mosaic glasses, particularly with respect to components such as chlorine, are consistent with the view that these colours were made in a single workshop or closely related workshops.

Jackson *et al.* (2009) tend to favour a hypothesis whereby *coloured* glasses used to make vessels of the 1st century AD were produced in primary workshops where glass was made from its raw materials and transported to glass workshops around the Roman world. Part of the evidence for this is a type of copper-coloured green glass which has high magnesia, potash and phosphate, interpreted as a plant ash base glass made from different raw materials and hence in a different locality to the natron-based glasses. This green glass was not present in the vessels studied here. A plant ash component is detected in the opaque red glass but it is considered to indicate an addition of ash, rather than manufacture of a primary plant ash glass as such (see above). In contrast to our interpretation, however, we should note that opaque red glasses with elevated magnesia and potash are considered plant ash glasses by Nenna and Gratuze (2009).

There is evidence that some of the amber glasses in our sample shared a primary production campaign as these have a very narrow range of CaO and lower MgO than other colours, particularly if they are compared with reduced, base glass compositions. This distinctive base glass composition is likely to reflect the derivation of the amber for vessels 11, 12 and 13 (British Museum vessels) from a single primary tank of glass. The amber glass in vessel no. 8 (one of the V&A group) has higher soda and is likely to have originated in a different batch. This is not surprising given the different typologies of the vessels. Amber is likely to have been an incidental colour which developed when conditions in the primary furnace were exceptionally reducing. The glass would have been distributed for its colour and care would have been taken not to disrupt the reduced state of the glass by adding oxidants or by melting it with other glass.

There appear to be few significant differences between the compositions of the early imperial opaque glasses analysed here and those in Hellenistic and early imperial mosaic fragments analysed by Gedzeviciute *et al.* (2009). Indeed, there appear to be relatively few differences between the colourant technology used in the mosaic vessels and that seen in later Roman coloured glass, for example in glass tesserae from wall mosaics. The absence of manganese from amber glass, which owes its colour to a very reducing environment, is also a feature of 1st century AD amber vessel glasses surveyed by Lemke (1998) and further considered by Jackson *et al.* (2009). Similarly the manganese and iron contents of the purples match those reported by Jackson *et al.* (2009) and indicate a manganese source which incorporates a subordinate quantity of iron oxide which becomes apparent when higher concentrations of MnO (*c.* 3%) are present. The dark blue glasses analysed have only iron as an elevated component and generally lack the elevated Ni, As and Zn values associated with cobalt sources used at later dates (Gratuze *et al.* 1995); furthermore the manganese values are typical of the colours as a whole and are not correlated with the cobalt. These dark blues have high iron:cobalt ratios and are typical of Roman and late pre-Roman coloured glass in Europe (Bimson and Freestone 1983; Henderson 1992; Jackson *et al.* 2009).

There are significant compositional differences between the yellows and whites analysed here and some later glasses of these colours. Comparison of the yellows analysed here with a number of 1st to 3rd-century mosaic tesserae analysed by Stege and Freestone (unpublished) indicates that the later tesserae have lower iron oxide contents. Furthermore, Fig. 6.12 illustrates that the yellows of the mosaic vessels analysed here have higher lead. While these conclusions are based on a relatively small number of samples, the data of Gedzeviciute *et al.* (2009) support this view for early imperial and Hellenistic mosaic vessels but also suggest that mosaic glass that they attribute to Egypt on stylistic grounds was of the lower-lead type. There is a tentative indication here of two technological traditions in the production of lead antimonate yellow glasses which merits further investigation. The absence of antimony opacified greens in the present study also suggests that the lead antimonate technology may not have been uniformly mastered, perhaps reflecting the challenging nature of this colour.

The variable lead content in opaque white glasses of the early imperial period remains difficult to explain. As is seen in Fig. 6.12, the lead contents of the whites from cameo glasses of the period, such as the Portland Vase, fall into similar compositional ranges to those of the mosaic glasses (Bimson and Freestone 1983; Weiß and Schüssler 2000), and it is clear from the differences in lead/antimony ratios of the different colours that the leaded whites are not directly related to the production of opaque yellow, for example as failed attempts to make lead antimonate-coloured glass. Rather, they must represent some characteristic of the white production technology. This appears to be restricted to the early Roman period, as antimony-opacified white glasses with high lead do not appear to be common in later assemblages. While use of a mixed ore is possible, the total weight of lead plus antimony oxide is much higher in the leaded glasses, suggesting that lead was not incidentally incorporated with the antimony. Furthermore, there is a compositional gap rather than a gradation between white glasses with lead and those without (Fig. 6.12), which suggests that the addition of lead was a distinctive step in the production process, and was carried out only in specific cases. More work is required to elucidate the role of lead oxide in early Roman glass technology.

Conclusions

This paper presents a substantial addition to the corpus of published analyses of Roman coloured glasses, in particular those from the early imperial period. It suggests that, while the principle colourants and opacifiers of Roman glass were well established by the 1st century AD, there were variations in technology which can be elucidated by careful analysis of carefully defined groups of glass. The concentrations of components typically associated with the base glass such as silica, lime and chlorine can yield important insights into the colouration processes used, while analysis of a significant sample of the same colour from well contextualised samples may allow technological variations with time and place to be discerned. However, the conclusions attainable are not restricted to the details of glass technology. For example, the tight compositional grouping of the amber glasses, suggesting a single batch of primary glass, implies that production of vessels 11–13 was from a single workshop, over a relatively short period. Variations in opaque yellow glass composition suggest that there may have been two traditions of producing this colour, one characterised by higher lead than the other, suggesting that it may be possible to identify different regions of origin, or groups of workshops. Comparison with published data suggests that they may represent Egyptian and Italian production.

As has been shown in a number of other contexts, Roman glass may superficially appear tediously homogeneous in composition, but carefully selected groups of closely related objects, analysed by quantitative methods, may reveal significant compositional groupings that improve our understanding of its technology and production.

Acknowledgements

We are delighted to include this paper in a volume dedicated to Jenny Price who has inspired and encouraged so many of us. We thank Justine Bayley for her very helpful comments on a draft of this paper. The analytical work was carried out while the authors were staff of the British Museum and we are very grateful to the late Veronica Tatton-Brown who initiated and encouraged this study and provided samples from the British Museum collections. Reino Liefkes kindly allowed access to samples from the collections of the Victoria and Albert Museum.

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