

Glass Coloring Technologies of Late Roman Cage Cups: Two Examples from Bulgaria

Anastasia Cholakova, Thilo Rehren, Bernard Gratuze, and James Lankton

Cage cups, also known as *vasa diatreta*, are widely recognized as being among the finest glass vessels of the late Roman period. This distinctive and highly specialized production group covers a chronological framework of approximately a century, starting from around A.D. 250 (with a few early Roman exceptions), although most cage cups are datable to the fourth century A.D. In cases where findspots are known, they belong to late Roman provincial contexts.¹ Their delicate and fragile appearance continues to fascinate scholars and to attract the interest of wider audiences, with a major focus on creating comprehensive catalogs of the finds, as well as on discussing the mechanics of the elaborate openwork decoration.

Nevertheless, little attention has so far been given to the chemical composition of the colored parts of the vessels made of non-dichroic glass,² and only limited information is

Acknowledgments. The authors gratefully acknowledge the support of the following colleagues and institutions: Mario Ivanov and Georgi Mavrov for giving permission for the analyses of the Serdica fragments and for helpful discussions; the Regional Museums of History in Sofia and Yambol for providing access to the finds; the Ministry of Culture of the Republic of Bulgaria for granting export permits that allowed the fragments to be analyzed at the Institut de Recherche sur les Archéomatériaux (IRAMAT); Robert Brill for affording access to the samples of the Benaki Museum and Corning Museum of Glass cage cup fragments, and for his pioneering work in the chemical analysis of cage cup glasses; various readers for constructive feedback and helpful advice that improved the manuscript; and the Qatar National Research Fund for the support of the analyses (NPRP No. 7-776-6-024 research project). Part of this research was conducted while AC was a fellow of the New Archaeological Research Network for Integrating Approaches to Ancient Material Studies (NARNIA ITN), funded by the Seventh Framework Programme for Research and Technological Development (FP7) (Grant agreement no. 265010), and a doctoral candidate at the Institute of Archaeology of University College London.

¹ Hallie Meredith, *World Becomes Image: Openwork Vessels as a Reflection of Late Antique Transformation*, Oxford, U.K.: Archaeopress Archaeology, 2015, map on p. 57; C[onstanze] Höpken, “Diatretglas-Fragmente vom Dülük Baba Tepesi: Funde der Jahre 2006 und 2011,” in *Kult und Herrschaft am Euphrat*, ed. Engelbert Winter, Asia Minor Studien, v. 73, and Dolichener und Komagenische Forschungen, v. 6, Bonn: Habelt, 2014, pp. 107–126, colorplate 10; David Whitehouse, with the assistance of William Gudenrath and Paul Roberts, *Cage Cups: Late Roman Luxury Glasses*, Corning: The Corning Museum of Glass, 2015, p. 50, fig. 26a.

² Dichroic glass represents a special case of raw material for openwork vessels. See Ian Freestone and others, “The Lycurgus Cup—A Roman Nanotechnology,” *Gold Bulletin*, v. 40, no. 4, 2007, pp. 270–277; its discussion is beyond the scope of this article.

available on the colorless glass of cage cups. Despite the recent surge of scientific studies on archaeological glass, there are not many publications of compositional data on the combinations of colorless and colored glasses used in a single cage cup. This is probably because of the rarity of these finds and their exceptional value as museum objects.³ The majority of the existing research emphasizes the use of antimony-decolorized glass for the production of these high-status items.⁴ However, no substantial attempts have been made to explore how instructive the compositional data might be with respect to the organization of such extremely complex and specialized glass vessel manufacture.

This article attempts to demonstrate the unique potential of archaeometric approaches to archaeological materials for opening new directions in the research on cage cups, based on the interpretation of the various chemical compositions as combined in two cage cups found in present-day Bulgaria: a figured beaker found near Serdica, and a beaker with an inscription found in Yambol. The aim of this study is to go beyond the conventional descriptive research and to examine the compositions of these two vessels as deliberately formed “technological assemblages,” and as products of the conscious skills of the artisans, rooted in their empirical knowledge and understanding of material properties. Accordingly, inferences need to be sought about the choices and working practices of the craftsmen who produced the cage cup blanks, and about the importance of the analytical data for the reconstruction of various craft traditions that probably existed at this elite level of the late Roman glass industry.

The Cage Cups from Serdica and Yambol and Their Scientific Analysis

Rescue excavations of a mausoleum in the vicinity of the ancient town of Serdica, modern Sofia, yielded an exceptional figural cage cup (Fig. 1) with a colorless inner vessel body

³. Robert H. Brill, *Chemical Analyses of Early Glasses*, v. 1, *Catalogue of Samples*, and v. 2, *Tables of Analyses*, Corning: The Corning Museum of Glass, 1999; Robert H. Brill and Colleen P. Stapleton, *Chemical Analyses of Early Glasses*, v. 3, *The Years 2000–2011, Reports and Essays*, Corning: The Corning Museum of Glass, 2012.

⁴. Edward V. Sayre, “The Intentional Use of Antimony and Manganese in Ancient Glasses,” in *Advances in Glass Technology*, v. 2, ed. Frederick R. Matson and Guy E. Rindone, New York: Plenum Press, 1963, pp. 263–282; Harriet E. Foster and Caroline M. Jackson, “The Composition of Late Romano–British Colourless Vessel Glass: Glass Production and Consumption,” *Journal of Archaeological Science*, v. 37, no. 12, December 2010, pp. 3068–3080.

and transparent blue openwork decoration. The beaker was discovered in a stone sarcophagus, and was in a highly fragmentary state, with numerous pieces missing because of an evident robbing of the mausoleum during antiquity.⁵ Despite the poor preservation and complicated vessel reconstruction, most of the openwork decoration was restored. It consists of combined geometric patterns (circular meshes) in the lower part of the beaker and a figural composition with Dionisiac imagery in the upper part. The find is dated by Mario Ivanov to the second half of the fourth century on the basis of its stylistic characteristics.

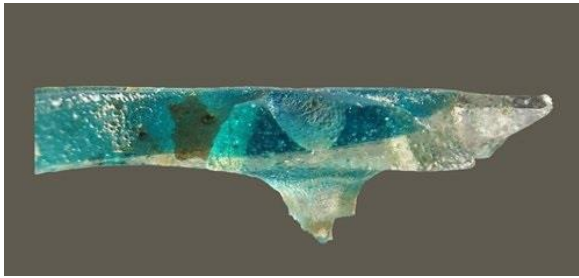
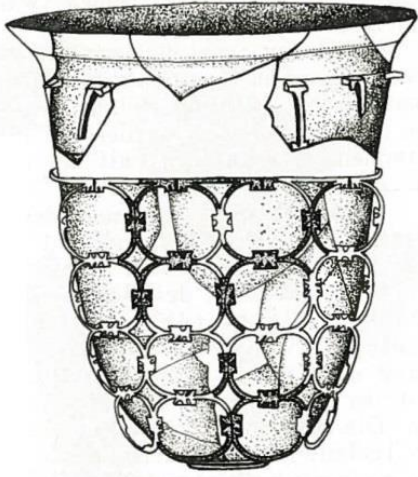
Another fragmentary cage cup was found accidentally during construction works near Yambol in southeastern Bulgaria (Fig. 2.). This beaker is multicolored, with colorless walls and openwork decoration in four different colored glasses arranged in horizontal bands.⁶ The decoration consists of an inscription (translucent blue glass) below the rim, with the rest of the vessel covered by a network of circular meshes in transparent bands of green-blue, light

⁵. Mario Ivanov, "A *Vas Diatretum* from Serdica," *Archaeologia Bulgarica*, v. 8, no. 1, 2004, pp. 51–57; Whitehouse [note 1], pp. 170–171, cat. no. A-3. The vessel is housed in the collection of the Regional Museum of History in Sofia.

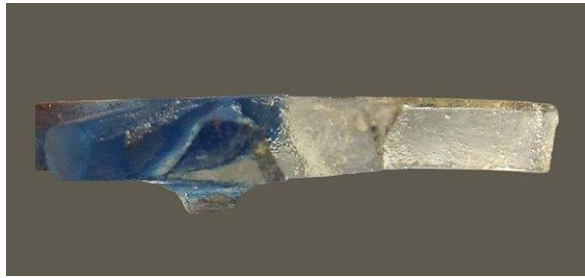
⁶. Aleksandra Dimitrova, "A *Vas Diatretum* from Thrace," *Journal of Glass Studies*, v. 16, 1974, pp. 14–17; Alexandra Dimitrova and Živko Popov, "Zwei Begräbnisse aus der ersten Hälfte des 4. Jh. aus Jambol," *Thracia*, v. 4, 1977, pp. 235–257; Whitehouse [note 1], pp. 102–103, cat. no. 21. The vessel is part of in the collection of the Regional Museum of History in Yambol. Its detailed documentation, restoration, and study are currently in progress in the framework of a joint project of the Römisch-Germanisches Zentralmuseum, Leibniz-Forschungsinstitut für Archäologie in Mainz (RGZM); the National Institute of Archaeology with Museum – Bulgarian Academy of Sciences in Sofia; and the Regional Museum of History in Yambol. The results of its reconstruction will be published by Katja Broschat.



FIG. 1. *Figural cage cup from Serdica (drawing after Ivanov [note 5]). (Photos: Anastasia Cholakova)*



Fragment YAM 4



Fragment YAM 6



Fragment YAM 7



Fragment YAM 2



Fragment YAM 1

FIG. 2. *Cage cup from Yambol (drawing after Dimitrova [note 6]). (Photos: Anastasia Cholakova and Krasimir Georgiev)*

blue, and purple glasses, separated by colorless areas. The Yambol cage cup is dated to the first half of the fourth century, according to the general date of the burial and the rest of the grave goods found there.

The incomplete and highly fragmentary state of these two cage cups is not beneficial for their reconstruction, or for determining the precise dimensions and shapes of the vessels. On the other hand, the fact that such remarkable examples of late Roman glassworking were found in small pieces provided an exceptional opportunity to closely inspect the finds and, before they were restored, to conduct nondestructive scientific compositional analysis of loose small fragments, without needing any sampling or sample preparation procedures, and without leaving any traces visible to the naked eye on the fragments' surfaces.

The measurements of 12 fragments—three from the Serdica cup (SER 26, represented by two minute pieces, and SER 27) and nine from the Yambol cup (YAM 1–YAM 9)—were carried out by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Institute de Recherche sur les Archéomatériaux (IRAMAT), Centre Ernest Babelon, Centre National de la Recherche Scientifique (CNRS), in Orléans, France. The chemical composition of the samples was determined using an Element XR mass spectrometer, Thermofisher Instruments, combined with an Nd:YAG pulsed laser beam (for the Serdica samples)⁷ and with a Resonetics RESOLUTION M50e laser probe ablation device (for the Yambol samples).⁸ Data for 58 elements were sought. Fragments SER 26 (colorless) and SER 27 (blue) were analyzed by two or three individual spot analyses only because of their small size, and the data is discussed here as averaged values. The analytical strategy for the Yambol samples was more elaborate, with 4

⁷. For details of the analytical protocol, calibration procedures, and accuracy, see Bernard Gratuze, “Glass Characterisation Using Laser Ablation Inductively Coupled Plasma Mass Spectrometry Methods,” in *Modern Methods for Analysing Archaeological and Historical Glass*, v. 1, ed. Koen Janssens, Chichester, U.K.: Wiley, 2013, pp. 201–234; Matt Phelps and others, “Natron Glass Production and Supply in the Late Antique and Early Medieval Near East: The Effect of the Byzantine–Islamic Transition,” *Journal of Archaeological Science*, v. 75, November 2016, pp. 56–71.

⁸. For details of the analytical protocol, calibration procedures, and accuracy, see Bernard Gratuze, “Glass Characterisation Using Laser Ablation Inductively Coupled Plasma Mass Spectrometry Methods,” in *Recent Advances in Laser Ablation ICP-MS for Archaeology*, ed. Laure Dussubieux, Mark Golitko, and Bernard Gratuze, Natural Science in Archaeology, Berlin: Springer, [2016], pp. 179–196; and Nadine Schibille and others, “Comprehensive Chemical Characterisation of Byzantine Glass Weights,” *PLoS ONE*, v. 11, no. 12, December 2016, doi:10.1371/journal.pone.0168289.

over 50 individual spot analyses in total, characterizing the colorless glass (25 spots across all nine fragments), the translucent blue glass (six spots on fragments YAM 1 and YAM 2), the green-blue glass (seven spots on fragments YAM 3 and YAM 4), the light blue glass (10 spots on samples YAM 5 and YAM 6), and the purple glass (six spots on fragments YAM 7 and YAM 8). The averaged results for selected oxides measured on the Serdica and Yambol fragments are presented in Table 1. As expected, the chemical compositions are generally consistent with that of typical Roman natron glass, with antimony and manganese used as decolorizers, a range of various transition metals (cobalt, copper, manganese, iron, and lead) involved in glass coloring, and antimony imparting the opacifying effect in the translucent blue glass.

The new data provide an opportunity to investigate the relationship between the colorless main body and the colored external layers of the cage cup blanks. The interpretation of the compositions of the Serdica and Yambol cup samples aims to outline answers to the following main questions: What is the nature of the added decolorizers and colorants? Is it possible to identify specific patterns in the colored glass compositions in comparison to the colorless ones? Are the colored glasses based on the respective colorless glasses of the blanks, or was a different base glass used for the openwork decoration? Can we recognize particular technologies of glass coloring, and what would their significance be with respect to the working practices of the producers of the cage cup blanks and the raw material procurement for this highly specialized craft?

The Colorless Glass Compositions

Previous research tends to link the “exceptional artistic merit” of the cage cups to the “superior decoloration obtainable through the use of antimony.”⁹ Such an understanding would imply that the glassworkers who produced the cage cup blanks may have had particular preferences and privileged access to exclusive supplies of raw materials. However, the new data are not fully consistent with this notion. Indeed, the level of antimony oxide in sample SER 26 (nearly 0.60 wt % Sb_2O_3) can define this composition as antimony decolorized. At the same

⁹. Quotation after Sayre [note 4], p. 280; see also Foster and Jackson [note 4]; Brill and Stapleton [note 3], p. 395, fig. 6.

time, the presence of manganese oxide (around 0.16 wt % MnO), well above the supposed background levels that would derive from the glassmaking sand,¹⁰

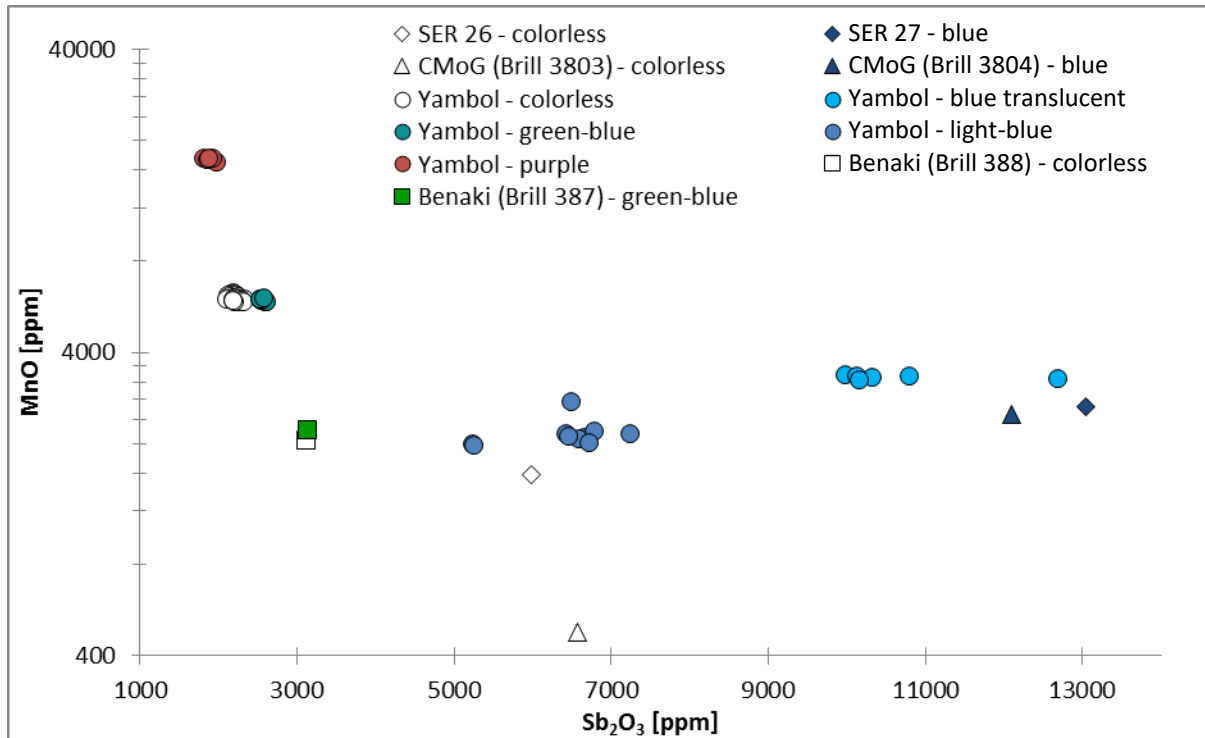


FIG. 3. Antimony oxide and manganese contents in present data set. The scatter graph shows the use of mixed decolorizers in the Serdica, Yambol, and Benaki Museum cups (data for the colorless Benaki Museum sample are after Brill [note 3] and Brill and Stapleton [note 3]; note the logarithmic scale for MnO). [Note to designer: In the legend, here and elsewhere, change “blue transparent” to “transparent blue,” and change “light-blue” to “light blue.”]

but still not reaching the concentrations of intentional additions of MnO to the melt,¹¹ indicates that the colorless glass of the Serdica cup probably came from a batch of mixed antimony- and

¹⁰. Dieter Brems and others, “Western Mediterranean Sand Deposits as a Raw Material for Roman Glass Production,” *Journal of Archaeological Science*, v. 39, no. 9, September 2012, pp. 2897–2907, esp. p. 2905; Khaled Al-Bashaireh and others, “Composition of Byzantine Glasses from Umm el-Jimal, Northeast Jordan: Insights into Glass Origins and Recycling,” *Journal of Cultural Heritage*, v. 21, September/October 2016, pp. 809–818. An example of virtually uncontaminated antimony-decolorized glass used in cage cup production is plotted in Figure 3 – a *patera* handle in The Corning Museum of Glass (acc. no. 55.1.143); see Whitehouse [note 1], pp. 70–71, cat. no. 1; and Brill [note 3], sample nos. 3803 and 3804, with MnO concentration of about 0.05 wt %. New LA-ICP-MS analyses of these samples were performed at IRAMAT (results given in Table 1).

¹¹. C[aroline] M. Jackson, “Making Colourless Glass in the Roman Period,” *Archaeometry*, v. 47, no. 4, November 2005, pp. 763–780.

manganese-decolorized glass (Fig. 3). Such mixing is explained by recent research as the result of remelting (mixed recycling) colorless cullet and/or raw glass having a diverse chemical composition (low alumina and lime antimony-decolorized glass, together with manganese-decolorized glass with higher levels of impurities),¹² as opposed to secondary glassworking carried out using unblended supplies of pristine raw chunks of glass only.

The same interpretation is valid for the colorless glass of the Yambol cup, even though the significant prevalence of manganese oxide (0.60 wt % MnO) over the concentration of antimony oxide (0.22 wt % Sb₂O₃) marks this composition as manganese decolorized rather than antimony decolorized (see Figure 3).¹³

Interestingly, there are not many examples of cage cup analyses that demonstrate the same mixing of different colorless glass types or the predominance of manganese decolorizing.¹⁴ Nevertheless, the likely pragmatic choice by the glassworkers to use mixed glass melts (with some selected cullet?), without affecting its colorless appearance, suggests that at least some of them were flexible in their decisions and apparently not bound to using specialized supplies of unadulterated—and presumably higher-quality—raw glass.

The Blue Glass Compositions

The analyzed data set contains three instances of blue-colored glasses—transparent blue (SER 27), translucent blue (YAM 1 and YAM 2), and transparent light blue (YAM 5 and YAM 6). All three compositions contain comparable levels of cobalt oxide, within the range of about

¹² Ian C. Freestone, “The Recycling and Reuse of Roman Glass: Analytical Approaches,” *Journal of Glass Studies*, v. 57, 2015, pp. 29–40; C[aroline] M. Jackson and S[arah] Paynter, “A Great Big Melting Pot: Exploring Patterns of Glass Supply, Consumption and Recycling in Roman Coppergate, York,” *Archaeometry*, v. 58, no. 1, 2016, pp. 68–95.

¹³ The opportunity to analyze multiple points of this glass throughout the vessel shows that several mixing lines can still be identified (e.g., negative correlations Sb₂O₃–MnO, Sb₂O₃–CaO), despite the good homogenizing of the mixed melt. The detailed analytical data of all of the measured spots of the Yambol and Serdica cup will be published elsewhere.

¹⁴ The colorless glass of an unfinished cage cup fragment in the Benaki Museum collection (see Whitehouse [note 1], pp. 162–163, cat. no. 67), plotted in Figure 3, contains approximately equal amounts of both decolorizers; see Brill [note 3], sample 388. A new LA-ICP-MS analysis of this sample was performed at IRAMAT (results given in Table 1).

380–540 ppm, which likely acted as the main glass colorant (Fig. 4). Nevertheless, the three compositions differ in their visual appearance, combination of additives (Fig. 5), and the geochemical characteristics of the base glass.

The translucent blue glass of the inscription band of the Yambol cup is very close, both compositionally and visually, to some published cobalt-blue glasses opacified with antimony, such as colored glass cakes or mosaic tesserae.¹⁵ It can be stated with certainty that the contrast between the translucent, almost opaque glass of the inscription and the transparent glasses of the meshes is a deliberately sought effect of the vessel decoration. At the same time, the translucent blue glass differs from the colorless glass of the cage cup in its lower titania and magnesia levels (Fig. 6), and in the concentrations of some of the trace oxides not related to the colorant (e.g. ZrO_2 , Y_2O_3 , CeO_2 – see Table 1. Therefore, the composition of the translucent blue glass is unrelated to that of the colorless glass of the Yambol vessel, at least because the glasses are likely of different geographical origins. At the same time, the similarities between the translucent blue glass of the Yambol cup and known antimony opacified cobalt-blue compositions confirm that the technological link between the manufacture of colored glass cakes and mosaic tesserae¹⁶ and the raw material supply and production of cage cups, suggested in the literature, cannot be doubted.¹⁷ Thus, the use of pre-existing opaque colored glass was most likely part of the working practices of the cage cup craftsmen.

¹⁵. See, for example, Sarah Paynter and others, “Roman Coloured Glass in the Western Provinces: The Glass Cakes and Tesserae from West Clacton in England,” *Journal of Archaeological Science*, v. 62, October 2015, pp. 66–81.

¹⁶. *Ibid.*, p. 67, fig. 2 – an example of such colored glass cakes.

¹⁷. As suggested by Freestone and others [note 2], p. 274.

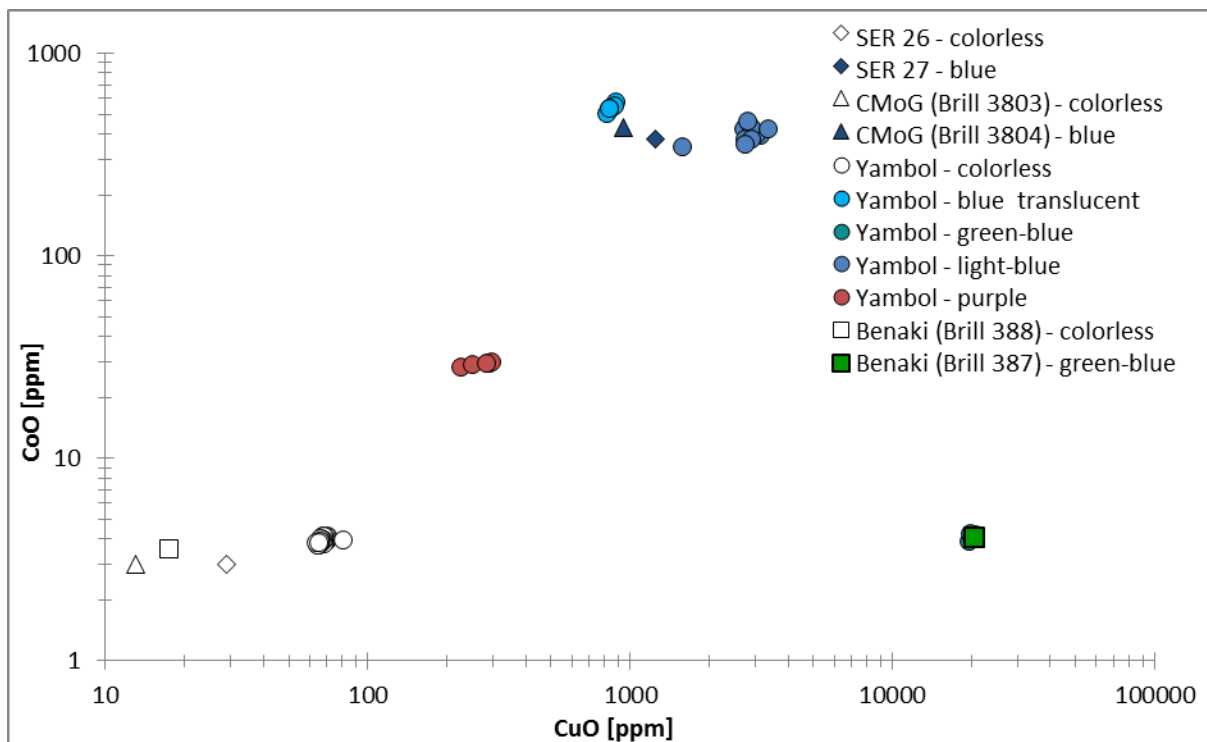


FIG. 4. Copper oxide and cobalt oxide contents in the present data set. The scatter graph shows the distinction between colorless and colored glasses (data for the colorless Benaki Museum sample are after Brill [note 3] and Brill and Stapleton [note 3]; note the logarithmic scale of both axes). The Benaki Museum green-blue sample and the Yambol green-blue glass almost fully overlap here, but the two compositions differ in their iron oxide levels (see Figure 9).

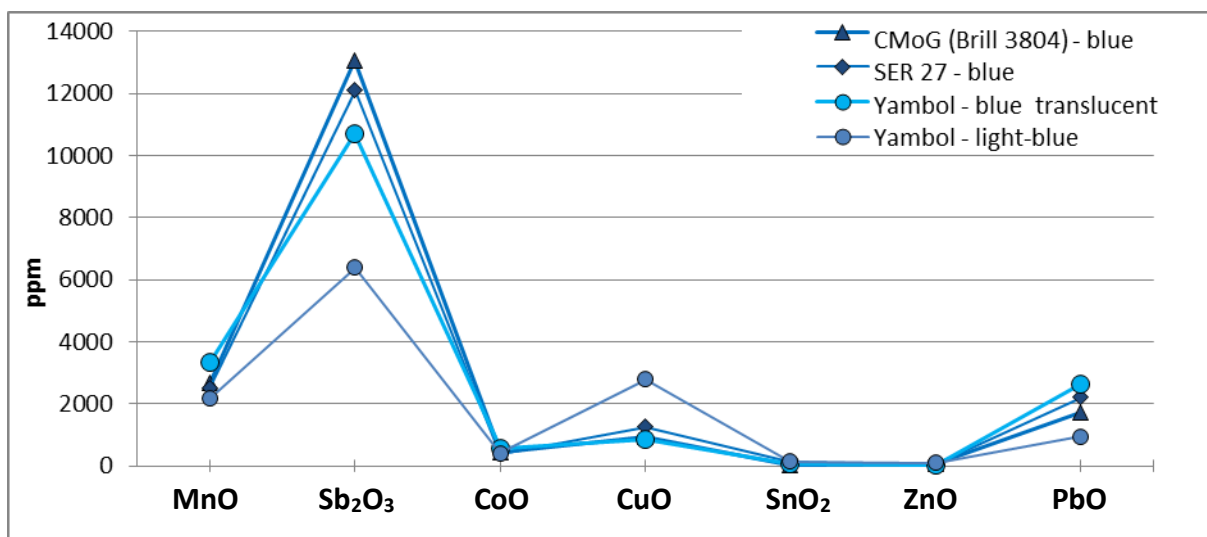


FIG. 5. Colorant compositions of the three blue glasses of the Serdica and Yambol cage cups and the Corning Museum of Glass patera fragment. The line graph shows the close similarity of SER 27 and the Corning Museum fragment.

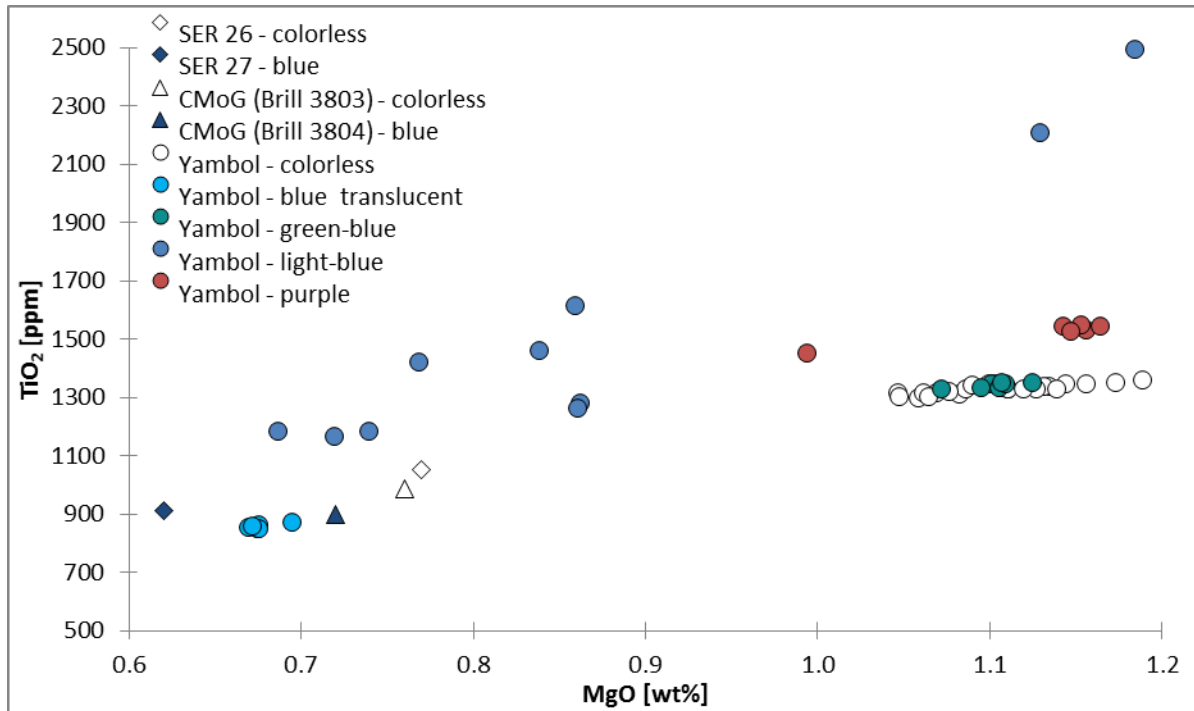


FIG. 6. Magnesia and titania contents in the present data set. The heterogeneity of the light blue glass of the Yambol cup is evident.

Nevertheless, further evidence would be necessary to determine whether this practice consisted of the straight reuse of opportunistically collected loose tesserae (i.e., the general model of commonplace recycling technology of moderate/lower quality, which is not likely here),¹⁸ or of purposely produced supplies of unworked cobalt-blue opacified glass, for instance in the form of cakes, delivered as raw material for the cage cup workshops.

The composition of the transparent blue overlay of the Serdica cup is very similar to that of the translucent blue glass of the Yambol cup in regard to the oxides introduced with the colorant (see Figure 5). However, despite its even higher level of antimony oxide (about 1.3 wt % Sb₂O₃), no visible opacifying effect is present in SER 27. The same puzzling elevated

¹⁸. For examples of such a technological practice, see Cristina Boschetti, Valentina Mantovani, and Cristina Leonelli, “Glass Coloring and Recycling in Late Antiquity: A New Case Study from Aquileia (Italy),” *Journal of Glass Studies*, v. 58, 2016, pp. 69–86; Nadine Schibille and Ian C. Freestone, “Composition, Production and Procurement of Glass at San Vincenzo al Volturno: An Early Medieval Monastic Complex in Southern Italy,” *PLoS ONE*, v. 8, no. 10, 2013, doi:10.1371/journal.pone.0076479; and J[ustine] Bayley and R[oger] Doonan, *High-Lead Glassworking and Alkali Glass Bead Making at 16–22 Coppergate and 22 Piccadilly, York*, Ancient Monuments Laboratory Report, no. 74, London: English Heritage, 1999.

antimony concentration and no opacity is seen in the cobalt-blue layer of a cage cup fragment (a patera handle) in The Corning Museum of Glass, which is also dated to the fourth century.¹⁹ Both vessels are rather exceptional among the cage cups because of their unusual shapes and decorative models. Moreover, the compositional resemblance of their cobalt-blue openwork overlays could potentially indicate the use of identical colorants – that is opacified blue pre-existing glass – which in turn could indicate that both vessels were produced in the same workshop. At the same time, it is important to stress the differences between the compositions of the colorless glasses of the two vessels (see Figure 3).

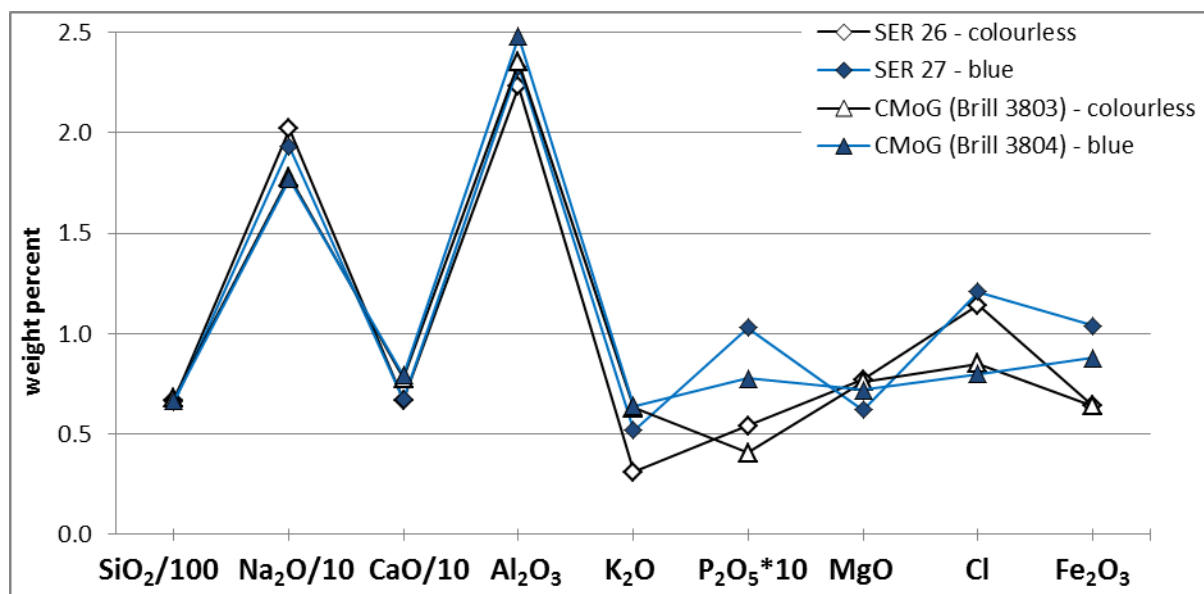


FIG. 7. Comparison of the major and minor oxides in the compositions of the Serdica cage cup and the Corning Museum of Glass patera fragment. Silica, soda, lime and phosphate are scaled in order to visualize clearer the data in the minor oxide range; full data is given in Table 1. [Note to designer: From this point on, in the legend, please also change “colourless” to “colorless.”]

A closer comparison between the pairs of colorless and blue-colored compositions of the Serdica cup and the Corning Museum fragment points to some systematic patterns (Figs. 7 and

¹⁹. See note 10.

8). The close similarity between the basic characteristics of the two kinds of glass within each pair (colorants excluded) is disrupted only by different levels

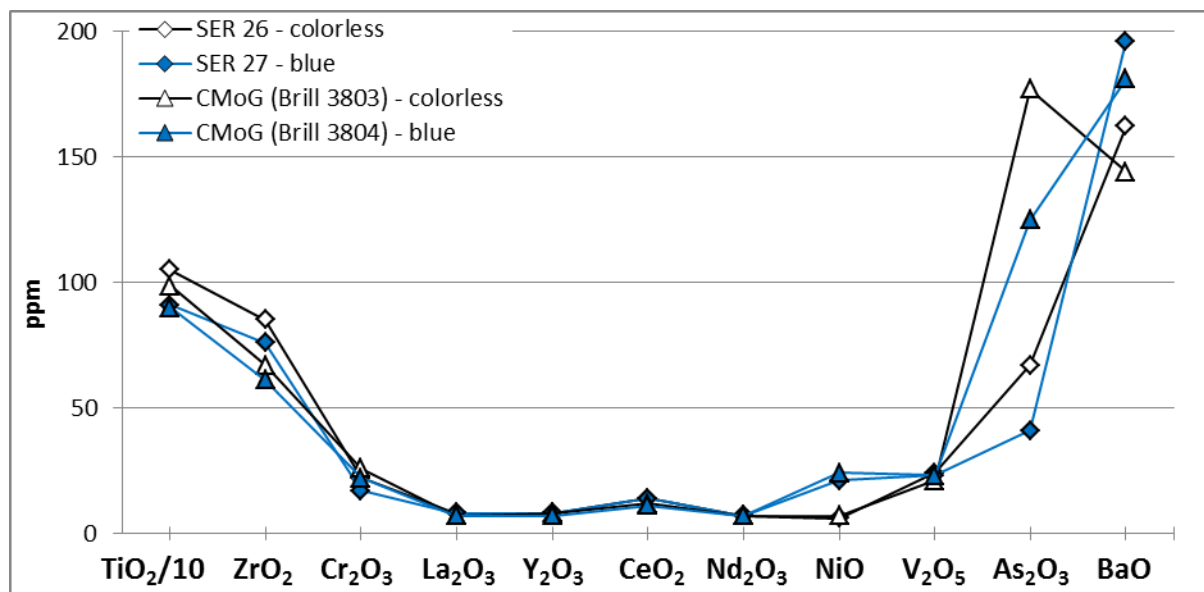


FIG. 8. Comparison of selected trace oxides, colorants excluded, in the compositions of the Serdica cage cup and the Corning Museum of Glass patera fragment. Note the identical patterns of variation of the blue glasses relative to the respective colorless compositions of the vessels.

of potassium, phosphorus, magnesium, sodium, and aluminum (for Serdica), and calcium, aluminum, phosphorus (and not potassium) (for the Corning Museum) in the blue glasses. Such a pattern of increase in these oxides has recently been widely recognized as being due to fuel vapor/ash contamination that resulted from prolonged heating of the glass melt during the coloring process.²⁰ Natural impurities, such as iron and nickel oxides introduced with the original cobalt-bearing material-i.e., are increased in the blue glasses and also account for compositional variance.²¹ These observations give rise to a tentative reconstruction of a

²⁰. Sarah Paynter, "Experiments in the Reconstruction of Roman Wood-Fired Glassworking Furnaces: Waste Products and Their Formation Processes," *Journal of Glass Studies*, v. 50, 2008, pp. 271–290; Thilo Rehren and Marion Brüggler, "Composition and Production of Late Antique Glass Bowls Type Helle," *Journal of Archaeological Science Reports*, v. 3, September 2015, pp. 171–180; Al-Bashaireh and others [note 10].

²¹. A similar pattern of correlated increase of these trace oxides is found in cobalt-blue mosaic tesserae, and is explained as related to the cobalt-bearing minerals; see Paynter and others [note 15], p. 72,

production technology that involves mixing some of the colorless base glass employed for the cage cup blanks with the colored material used to create the transparent blue overlays. Recalling the close similarity between the translucent blue glass of the Yambol cup and the transparent blue glasses of SER 27 and the Corning Museum fragment (see Figure 5), as well as their collective resemblance to late Roman opacified blue glass, we can hypothesize mixing, in a certain ratio, of the respective colorless base glasses of the Serdica cup and the Corning Museum fragment with some kind of antimony-opacified cobalt-blue glass that is compositionally related to the translucent glass used for the production of the Yambol cage cup's letters. During this process of coloring, the obtained transparent blue glasses would be contaminated by some fuel vapor/ash, while at the same time the opacifying effect of the high antimony content would be intentionally eliminated by dissolving the crystals of calcium antimonate in it through a deliberate control of the heating process. We admit the speculative nature of such a reconstruction of technology, but it still seems to us to be the most likely explanation of the overall resemblance of the glasses within the pairs of colorless – blue-colored glasses and the unusually elevated antimony oxide concentrations in the transparent blue compositions.²²

The hypothesis of mixing various glasses in order to obtain the desired color, degree of transparency, and, quite probably, glassworking properties necessary for the successful cutting of the thick multicolored blanks may be indirectly corroborated by the composition of the third blue glass in the current data set: the light blue glass of the Yambol cup, analyzed on fragments YAM 5 and YAM 6. Despite their similar cobalt concentrations, this composition differs from that of the other two blue glasses (namely, the translucent blue glass of the Yambol cup and SER 27) by its much higher copper oxide and iron oxide levels (see Figures 4 and 9) and the overall quite significant glass heterogeneity seen in all of the scatter graphs of the individual spot measurements (see, e.g., Figures 6 and 12).

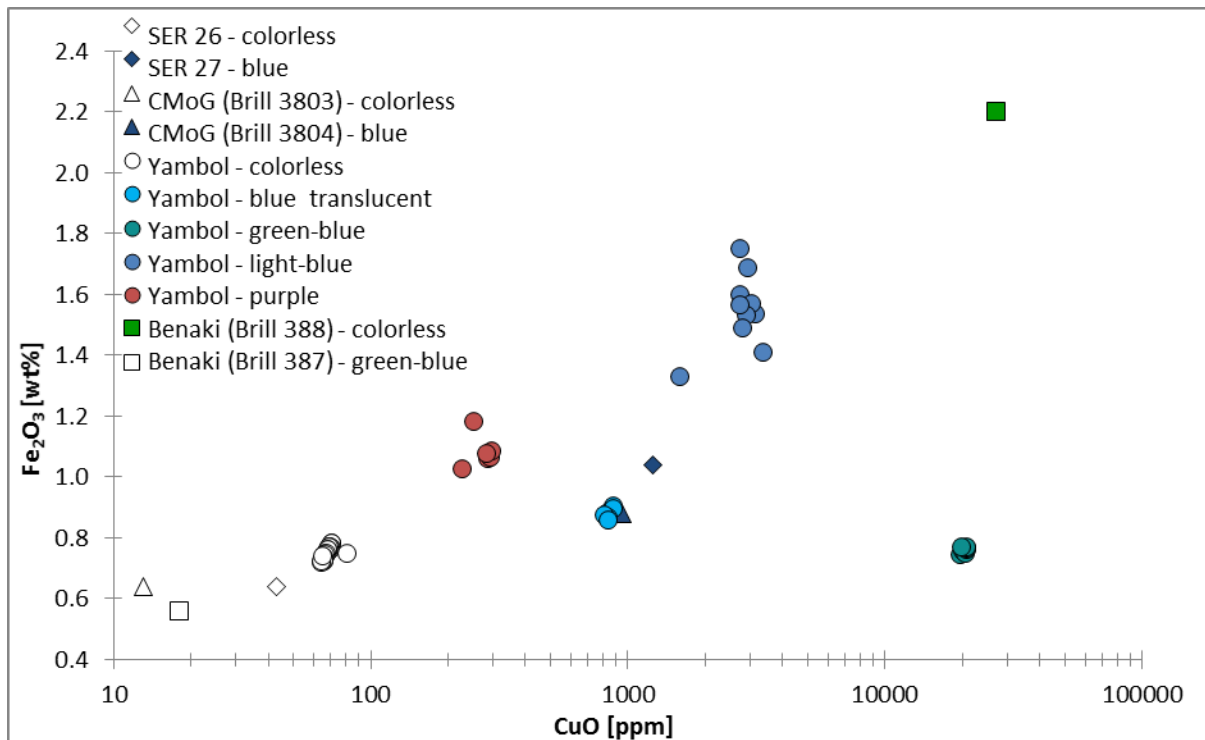
fig. 6. The relatively high As_2O_3 content of the two colorless glasses is unusual, and appears diluted by the added blue glass with normal arsenic concentrations.

²². An alternative possibility would be to interpret the use of antimony as a fining agent in the blue glasses, but this technology is typical for modern glassworking and presumably requires heating the glass to temperatures that were not achievable in the secondary glass workshops in antiquity. See, for example, Koji Fujita, Yoshihiro Takahara, and Yoshinori Chikaura, "Influence of Refining Agent in Soda Lime Glass for Ultraviolet Ray Transmittance," *Materials Transactions*, v. 49, no. 2, 2008, pp. 372–375.

In a manner similar to that of the translucent blue glass, the light blue composition features a relatively high content of antimony oxide, which is also much higher than the levels found in the colorless glass of the Yambol cup (see Figure 3). In contrast to the hypothetical explanation of mixing pre-existing colored glass, with the colorless base glass of the blank, the light blue composition could have resulted from incomplete mixing (hence the glass heterogeneity) of two different colored/opacified glasses, unrelated to the base glass.²³

The Green-Blue Glass Composition

The green-blue glass found in the Yambol cup, fragments YAM 3 and YAM 4, is characterized by a high level of copper oxide, exceeding 2 wt % CuO, and cobalt oxide concentrations of less than 5 ppm (see Figure 4). The content of copper oxide, a widely used glass colorant, is responsible for the peculiar green-blue color of the glass, possibly in combination with a slightly elevated amount of lead oxide. The juxtaposition of the colorless base glass of the Yambol



²³ Such a supposition could help to explain, for example, the quite unusual combination of high antimony oxide (almost 0.65 wt % Sb₂O₃) and high iron oxide (1.55 wt % Fe₂O₃) found in the light blue glass, which has not so far been attested in any primary glass composition of antiquity.

FIG. 9. *Copper and iron oxide contents in the present data set. The scatter graph shows the distinction between colorless and colored glasses (data for the colorless Benaki Museum sample are after Brill [note 3] and Brill and Stapleton [note 3]; note the logarithmic scale for CuO).*

cup and the green-blue glass of fragments YAM 3 and YAM 4 clearly shows that they overlap compositionally when colorant-related oxides are not considered (see, for example, Figures 6 and 11). Subtraction of the copper additive and of a few other oxides related to it, followed by normalization of the base composition to 100 percent,²⁴ confirms that the green-blue appearance resulted from mixing the colorless base glass of the blank with almost pure copper oxide. This copper-rich substance introduced additional minor amounts of lead, antimony, tin, and iron oxides to the melt, comparable to the levels of natural impurities in copper metal, which may point to the use of unalloyed copper for making copper scale as colorant through burning or calcination of the metal. Interestingly, no significant increase in potash and phosphate is found in the green-blue composition, in comparison with the colorless base glass, which is unlike the pattern observed in SER 27 (see Figure 7).

This technology of coloring glass is mirrored by another example of copper green-blue glass used for cage cup decoration: a fragment from the Benaki Museum collection.²⁵ This unfinished piece features an identical overlap between the composition of the colorless body and that of the colored overlay, as is seen in the Yambol cup. Nevertheless, the colorant used to produce the green-blue decoration of the Benaki Museum fragment contains not only copper oxide but also a significant amount of iron oxide (see Figures 9 and 10), and this can hardly be explained by the original composition of the copper-bearing material used for coloring. Instead, it appears that an additional amount of iron scale was added to the copper-based colorant.²⁶ The cage cup craftsmen could also have used a copper–iron-colored glass. The addition of iron to a

²⁴. The full data will be published elsewhere.

²⁵. See note 14.

²⁶. The use of iron hammer-scale for glass coloring is directly attested in two instances of glass working debris from the Balkans. See Thilo Rehren, A. Cholakova, and Miloš Živanović, “The Making of Black Glass in Late Roman Doclea, Montenegro,” *New Antique Doclea*, v. 3, 2012, pp. 75–90; and Anastasia Cholakova and Thilo Rehren, “Producing Black Glass during the Roman Period – Notes on a Crucible Fragment from *Serdica*, Bulgaria,” in *Proceedings of the 39th International Symposium on Archaeometry, 28 May–1 June 2012, Leuven, Belgium*, ed. Rebecca and others, Leuven: Centre for Archaeological Sciences, KU Leuven, 2014, pp. 261–276.

Cu-colored turquoise glass to deplace color toward green hues is commonly found in Roman glasses. The use of iron scale to color glass is not unique to the Balkans.

The Purple Glass Composition

The final color to be discussed here is the purple glass of the Yambol cup, which was analyzed on fragments YAM 7 and YAM 8. The coloration of this composition was obtained by manganese, with a

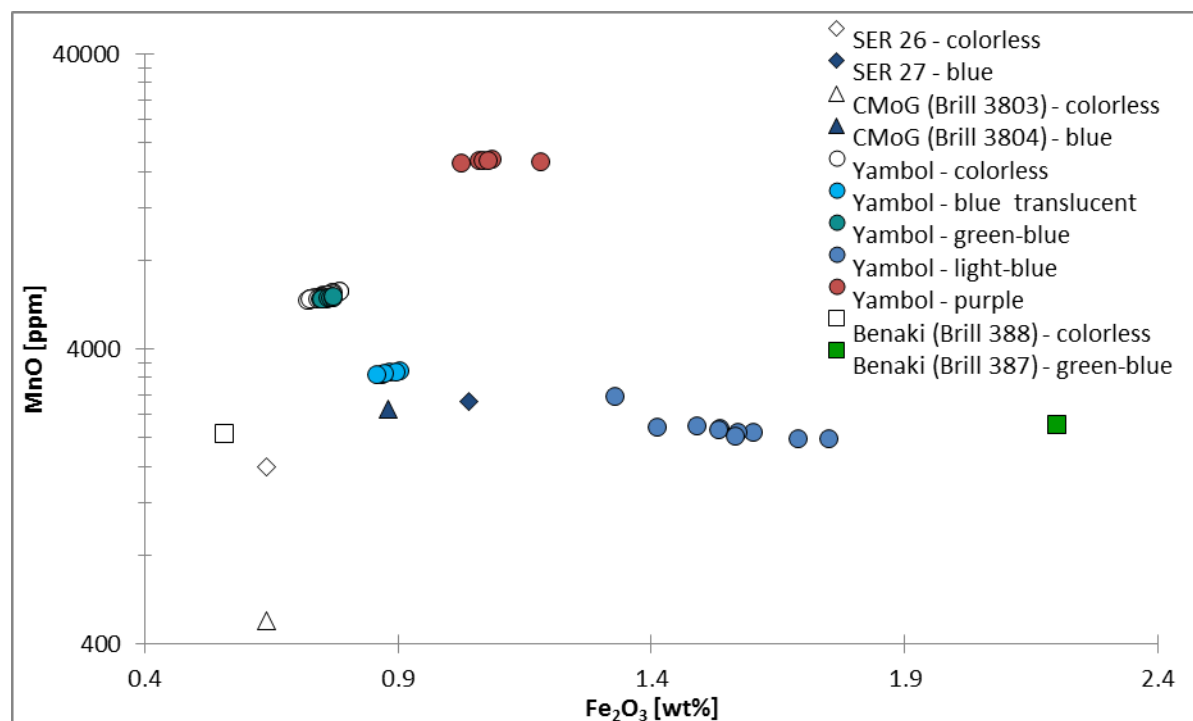


FIG. 10. Iron oxide and manganese contents in the present data set. The scatter graph shows the differences in the blue glass compositions (data for the colorless Benaki Museum sample are after Brill [note 3] and Brill and Stapleton [note 3]; note the logarithmic scale for MnO).

concentration of MnO of about 1.75 wt % (see Figure 10). Various manganese minerals were used as colorants or decolorizers in the Roman glass industry,²⁷ and their tentative identification is generally based on correlations between the manganese content and certain trace elements (e.g., barium and strontium). However, little is known about the actual geological sources of the manganese-bearing minerals employed for glass production. Furthermore, there is no reason to

²⁷. Jackson [note 11], p. 764.

suspect that pure minerals would have been used instead of the much more common natural combinations of various minerals that contain manganese in different oxidation states and also have a range of trace impurities.

A compositional comparison of the purple glass and the colorless base glass of the Yambol cup demonstrates that a small amount of concentrated colorant was added to the base glass to obtain the coloration. This follows the same technological approach as with the green-blue composition. Accordingly (and interestingly), no difference is seen in the basic geochemical characteristics of the colorless, green-blue, and purple glasses, while the other glasses have different trace-element patterns (Fig. 11). However, unlike the green-blue composition, in which copper scale is easily recognizable as the coloring agent in the glass, the identification of the manganese-bearing colorant in the purple glass is more complicated. The levels of several minor and trace oxides in the purple

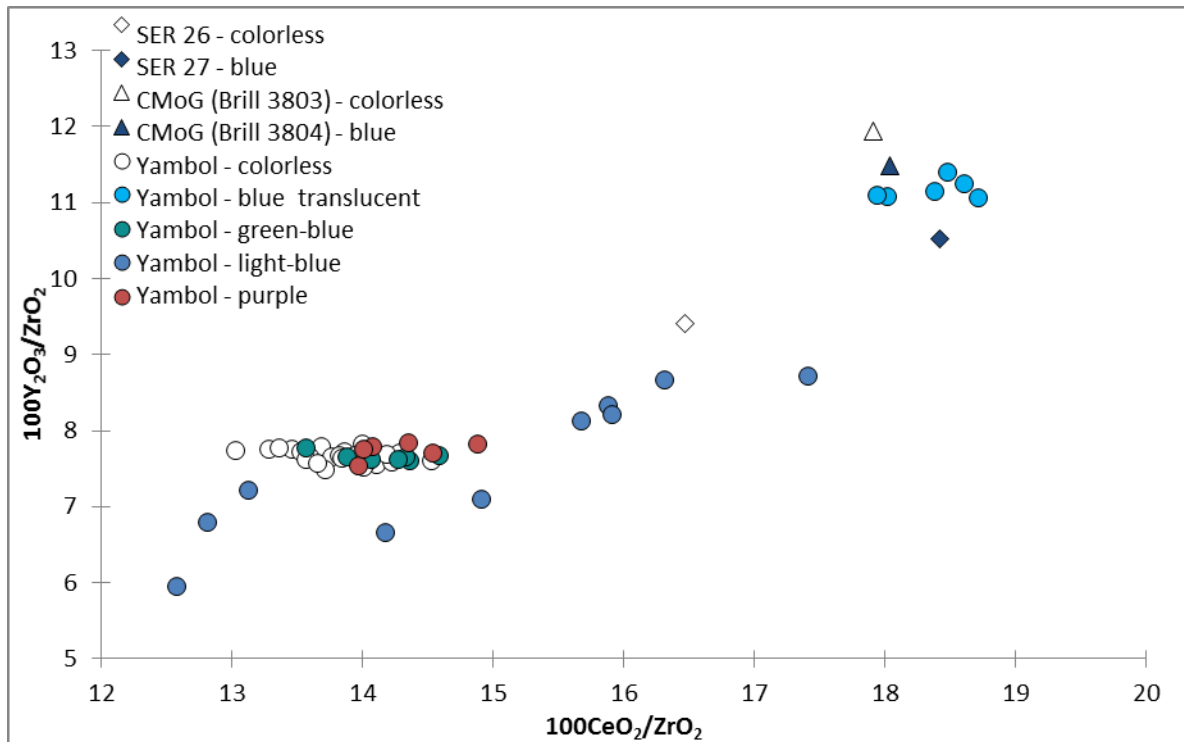


FIG. 11. Ratios of selected trace oxides in the present data set, indicative of the characteristics of different glassmaking sands. The scatter graph shows the overlap of the colorless, green-blue, and purple glasses of the Yambol cup.

glass are higher than in the colorless glass, including titanium and vanadium (Fig. 12), cobalt and copper (see Figure 4), and barium oxide. Furthermore, the purple glass features higher quantities of iron oxide, potash, and lime (see Figure 10 and Table 1), and certain positive correlations—such as BaO–MnO, K₂O–MnO, and Fe₂O₃–MnO—can be clearly recognized when the measurements of the individual spots are closely inspected. All of this strongly suggests that a mixture of various manganese-bearing minerals (e.g., psilomelane, cryptomelane,²⁸ and certain kinds of high-manganese iron minerals) was likely used as a colorant,²⁹ some of these minerals introducing additional impurities at the level of minor and trace elements. The natural variability of such a composite ore may have been easily reduced or even eliminated by a simple pre-treatment (such as mechanical crushing and grinding), which would have helped to obtain a relatively homogeneous colorant, well suited for adding to and dissolving into the glass melt in a secondary workshop.

²⁸. A[liberta] Silvestri, “The Coloured Glass of *Iulia Felix*,” *Journal of Archaeological Science*, v. 35, no. 6, June 2008, pp. 1489–1501; Filomena Gallo, Alberta Silvestri, and Gianmario Molin, “Glass from the Archaeological Museum of Adria (North-East Italy): New Insights into Early Roman Production Technologies,” *Journal of Archaeological Science*, v. 40, no. 6, June 2013, pp. 2589–2605, fig. 8a.

²⁹. Hassan M. Baioumy, Mohamed Z. Khedr, and Ahmed H. Ahmed, “Mineralogy, Geochemistry and Origin of Mn in the High-Mn Iron Ores, Bahariya Oasis, Egypt,” *Ore Geology Reviews*, v. 53, no. 1, 2013, pp. 63–76.

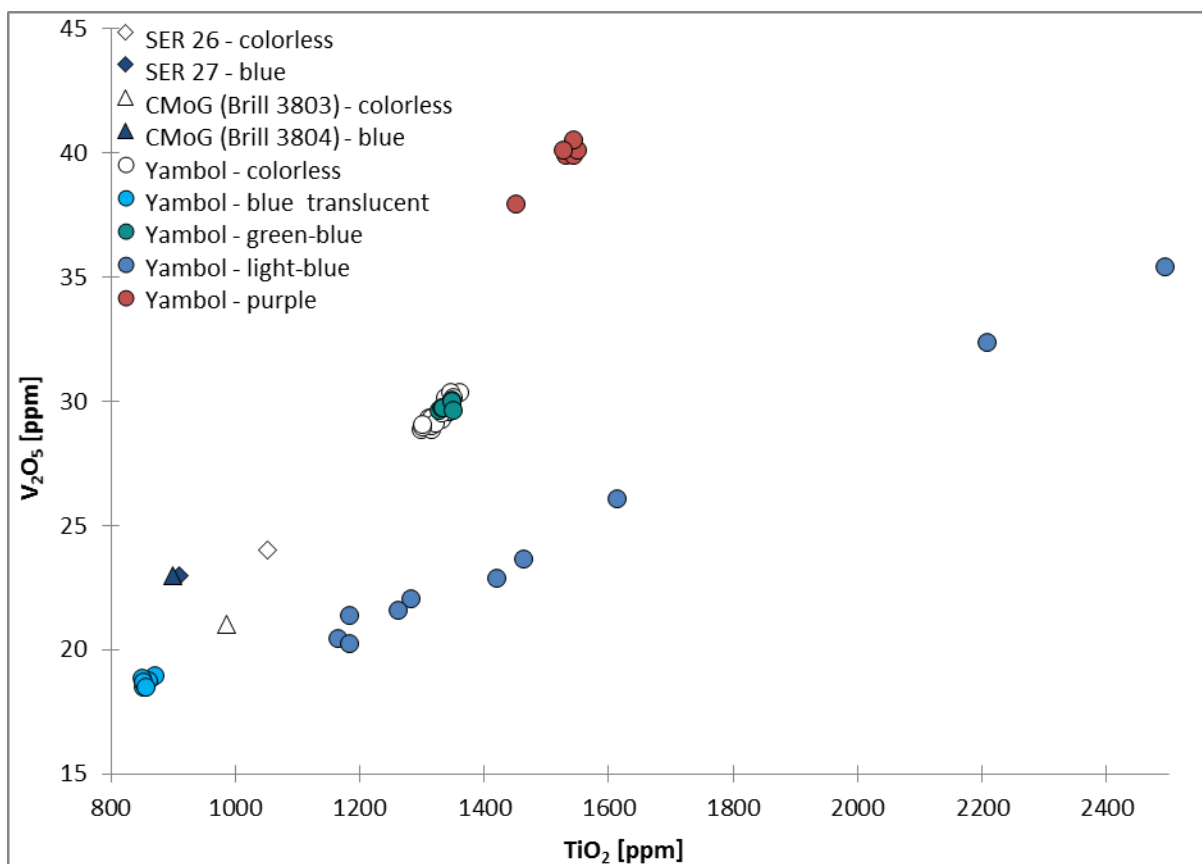


FIG. 12. Titania and vanadium oxide contents in the present data set. The increase of both in the purple glass of the Yambol cup is due to the added manganese-bearing colorant.

Technologies of Coloring in Cage Cup Production

The interpretation of the compositional data from the Serdica and Yambol fragments provides hitherto unsuspected insights into the making of blanks for cage cups and the technological choices involved in this elaborate process. First, it is clear that, despite the prevalence of uncontaminated antimony-decolorized glass for most of the cage cups analyzed to date,³⁰ mixed antimony- and manganese-decolorized (partially cullet?) glass was also used.

Furthermore, two main technological groups of colored glass are identified in the present data set: (1) for the translucent lettering and the transparent light blue decoration of the Yambol cup, the craftsmen simply used pre-existing, strongly colored glass, different in its base

³⁰. See note 9.

composition from that of the colorless body; and (2) for the other colors, the craftsmen made the colored glass using the colorless glass of the blank's body. Two contrasting approaches to the technology of coloring can be reconstructed: the introduction of small amounts of a relatively pure colorant (seen in the green-blue and purple glasses of the Yambol Cup),³¹ and the blending of the colorless base glass with another, strongly colored glass (e.g., SER 27, which probably included opacified blue glass)³² to obtain a transparent blue. The proposed multiple ways of creating the colored glass are not unique to the two cage cups found in Bulgaria, as is shown by the transparent blue glass of the Corning Museum's patera fragment (Brill's sample no. 3804), which was produced in the same way as SER 27, and by the unfinished Benaki Museum fragment (Brill's sample no. 387), whose overlay was colored by adding copper and iron scale to the base glass, similarly to the green-blue and purple glass of the Yambol cup.

Several implications regarding the organization of cage cup production follow from these observations. In the first place, the glassworkers involved in the making of blanks for cage cups certainly had access to a wide range of raw materials: unadulterated colorless glass, mixed colorless cullet, pure colorants, and precolored and opacified glasses. Moreover, these craftsmen were not using their glass supplies simply as fixed and "ready-made." Instead, as part of the blank-making process in their workshops, they were apparently able to skillfully combine all of these raw materials, both to create new glass colors and to retain or eliminate opacity.

These intricate working practices were dictated by the artisans' aesthetic preferences and possibly by the particular demands of their customers, but, most importantly, they served a crucial technological purpose. The production of thick-walled cage cup blanks required special attention to reducing the residual stress in the glass and to securing physical compatibility when different colors and compositions were combined within a single blank.³³ Such careful

³¹. Tentative calculations of the amounts of colorants show that, in both cases, the added materials—copper scale and manganese-containing minerals—were approximately 2 wt % of the whole batch.

³². A quantification of the two components of the melt (modeling of the compositional alterations on the basis of CoO concentration) suggests that they may have been combined in approximately equal amounts.

³³. Charles Bray, *Dictionary of Glass: Materials and Techniques*, 2nd ed., London: A & C Black, and Philadelphia: University of Pennsylvania Press, 2001, pp. 27 and 81.

preparation of the blank (together with adequate annealing) would ensure that the glass was well suited for cutting and not susceptible to cracks.

It is known that special attention was paid in Roman law to the arrangements of risk and legal responsibility which resulted from breakage of the materials during cutting and carving – the glass- and stone-cutters were liable in case the damage was caused by their incompetence, and the providers of the material – in case the blank was originally defective.³⁴ Such detailed juridical assignment certainly must have involved assessment of the blank quality before the cutting process began. Considering the highly specialized nature of cage cup production, it should be assumed that the craftsmen, whose work was subject to liability, were well aware of the different ways to control the expansion, annealing, and shrinkage of the thick-walled blanks, as well as of compatibility when several compositionally different glasses were fused in a single blank.³⁵ The use of only one colorless base glass, unaltered in the main body and colored with added material in the decoration layer, probably provided the closest possible compatibility in the two layers of the blank.

The present data suggest that the different coloring techniques outlined above were not chosen at random, but were likely linked to the structure of the blank. The Serdica cup consists of a blank of colorless base glass entirely covered by a single, continuous blue overlay. Such a complete covering, with its significant size of the contact area between the two glasses, required more attention to compatibility and annealing to prevent internal stress building up,³⁶ and thus

³⁴. John Humphrey, John Oleson and Andrew Sherwood, *Greek and Roman Technology: a Sourcebook: Annotated Translations of Greek and Latin Texts and Documents*, London and New York: Routledge, 1998, p. 380; Andreas Wacke, “Si Artifex Calicem Diatretum Faciendum Imperitia Fregit: Danni Derivanti dalla Rottura di Gemme e di Bicchieri Preziosi: Le Clausole di sopportazione del rischio nell’artigianato romano,” *Studia et Documenta Historiae et Iuris*, no. 69, 2003, pp. 573–586; Susan D. Martin, “Imperitia: The Responsibility of Skilled Workers in Classical Roman Law,” *The American Journal of Philology*, v. 122, No. 1 (Spring, 2001), pp. 107–129, in particular pp. 117-120.

³⁵. Lack of compatibility is reported as the main reason for the failure of modern attempts to produce replicas of multicolored cage cups; see George Scott, “Producing Cage Cup Replicas,” *Journal of Glass Studies*, v. 33, 1991, pp. 93–95. However, glass compatibility results from a complex combination of different factors, which may not necessarily be related to the match of the chemical glass compositions; see Daniel W. Schwoerer, “Compatibility of Glasses: COE Does Not Equal Compatibility,” *Technotes*, January 2013, www.bullseyeglass.com/images/stories/bullseye/PDF/TechNotes/technotes_03.pdf (accessed January 30, 2017).

³⁶. See note 33 and note 35.

the same base glass was blended with saturated blue glass to produce the overlay. In addition, this process eliminated the effect of opacity in the initial blue composition, and could indicate that no “pure” cobalt colorant was available to be added to the base glass, in the same way as copper scale or manganese ore. By contrast, the Yambol cup was cut from a blank of colorless base glass with four horizontal bands of different colors, each of which was relatively narrow and not connected to the other bands); these bands were probably marvered flush with the surface of the main body of the blank (see Figure 2).³⁷ It is probable that, in this case, fewer compatibility problems were encountered during annealing and cutting due to a significantly smaller contact area between the colorless body and the colored bands, leading to less accumulated stress from differential thermal behavior; therefore the use of different, unrelated compositions was less risky.

This study of the cage cups from Serdica and Yambol has demonstrated that these vessels do not represent simply chance combinations of glass compositions, nor were they based on pristine high-quality glass alone. Instead, their production was based on deep empirical knowledge, considerable skill, flexibility in the choices of raw materials, intentional and attentive use and combination of various glasses, and a clear perception of the colors and opacity/transparency within the overall planning of the vessels’ decoration. Considering the reconstructions of the operational sequences of this craft leads to new and promising interpretive directions for further analytical research, which may reveal patterns, chronological developments, and regional features, and may even help to identify various workshop-specific methods of manufacture in the production of late Roman cage cups. By fully employing the scientific data and their practical interpretation, researchers should be able to gain new insights by approaching cage cup production from the perspective of the craftsmen, instead of being limited to that of the fascinated customers who were able to view only the finished product.

³⁷. Such a technique of decoration is possible only if the thick-walled blank is blown; marvered trails of colored glass are not compatible with the so-called pressed blank theory. Cf. Rosmarie Lierke, “On the Manufacture of Cage Cups in Whitehouse, ‘Cage Cups – Late Roman Luxury Glasses,’ Corning, New York 2015,” *Pressglas-Korrespondenz*, no. 2, 2016, www.pressglas-korrespondenz.de/aktuelles/pdf/pk-2016-2w-lierke-whitehouse-cage-cups-diatret-2015-engl.pdf (accessed January 30, 2017).

Anatasia Cholakova – Research Fellow, National Institute of Archaeology with Museum – Bulgarian Academy of Sciences, Sofia; sia_cholakova@hotmail.com

Thilo Rehren – Professor for Archaeological Materials and Technologies, UCL Institute of Archaeology, London; th.rehren@ucl.ac.uk

Bernard Gratuze – Director of Research, IRAMAT-CEB, UMR5060, CNRS/Univ. Orleans, gratuze@cnrs-orleans.fr

James Lankton – Honorary Senior Research Associate, UCL Qatar, Doha; jamesyuri@gmail.com