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Original research article

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THE BLUES OF *ROMULIANA*

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Abstract. – The paper presents a set of glass fragments excavated at several different locations within and outside the late Roman fortified imperial residence *Felix Romuliana* (Gamzigrad, Serbia). This small group of eighteen fragments and mosaic glass *tesserae* are distinguished by their cobalt blue colour. The majority of the finds are mosaic *tesserae* (six pcs) and sheets of glass (five pcs), which could be related to architectural decoration (*sectilia* panels). Others are pieces left behind from secondary glass working (four pcs). There are also two fragments tentatively identified as window pane pieces, and only one find is a vessel sherd. The materials are dated to the 4th century. Significantly, some of the production debris and the two "window pane" fragments were found inside the destruction of a glass furnace. The analyses of the chemical glass composition of the finds confirmed that the blue colourant in all samples is cobalt, and antimony is also present at notable levels (except for one sample), likely to produce opacification of the glass. Regarding the origin of the raw glass, the data on almost all pieces suggests a Syro-Palestinian provenance, and a single sample could be related to Egyptian primary glass production. Importantly, the concentrations of the oxides added to the base glasses in order to modify the colour are positively correlated in certain samples, hinting at the makeup of the cobalt bearing ingredient and at a likely existence of particular production practices of the late Roman period.

Key words. – late Roman period, Central Balkans, cobalt blue glass, secondary glass production, *sectilia* glass sheets, glass *tesserae*, production debris, chemical glass composition, EPMA

The late Roman fortified imperial residence *Felix Romuliana* is situated in present-day Eastern Serbia, near the village of Gamzigrad. Famous for its monumental architecture, imposing mosaic floors, marble sculptures, etc.,[1] this luxurious complex was built by Emperor Galerius at the beginning of the 4th century, in the Roman province of *Dacia Ripensis* (Fig. 1). It functioned as an imperial domain during the short reign of Galerius (AD 293–311). After his death, according to the archaeological evidence, *Romuliana* continued its existence as a fortified settlement, from the end of the 4th to the end of the 6th / beginning of the 7th century.[2] The archaeological investigations at Gamzigrad have been carried out both inside the fortified complex and in the area outside the ramparts. Research has yielded impressive archaeological findings, singling out the fragmented archivolt with the inscription FELIX ROMULIANA and the monumental sculptural head of Emperor Galerius made of porphyry, which were essential for the identification of the site as *Romulianum* or *Romuliana* in Roman written sources.[3]

The glass finds excavated at the site have, so far, not received sufficient research attention. There are few publications within which groups of glass finds or individual

1 Срејовић 1983, 66–94; Живић 2010, 107–140.

2 Čanak-Medić, Stojković-Pavelka 56, 64; Petković 2011, 168.

3 Срејовић 1985, 53–61; Srejović, Vasić 1994, 124; Popović 2011, 9; Bergmann 2020, 306–308.

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Fig. 1. Location of Romuliana in the province of Dacia Ripensis

Сл. 1. Положај Ромулијане у Приобалној Дакији

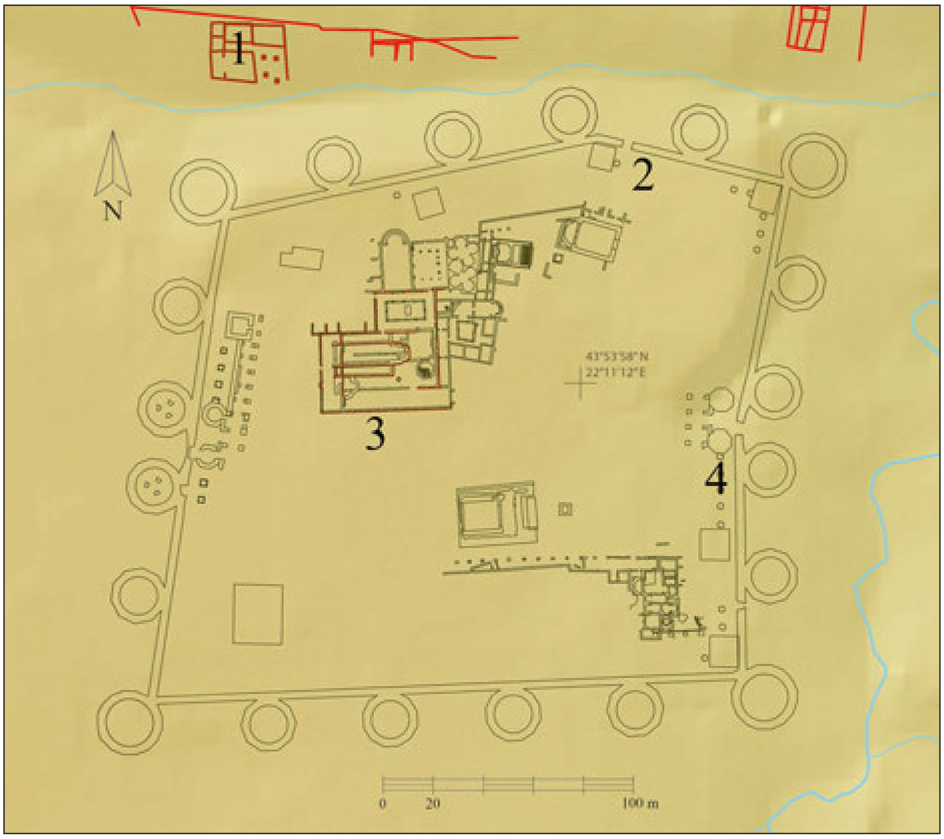

Fig. 2. Layout of Romuliana with indicated findspots of the glass finds (documentation of the Institute of Archaeology, Belgrade)

Сл. 2. План Ромулијане са назначеним местима са којих потичу стаклени налази (документација Археолошког института, Београд)

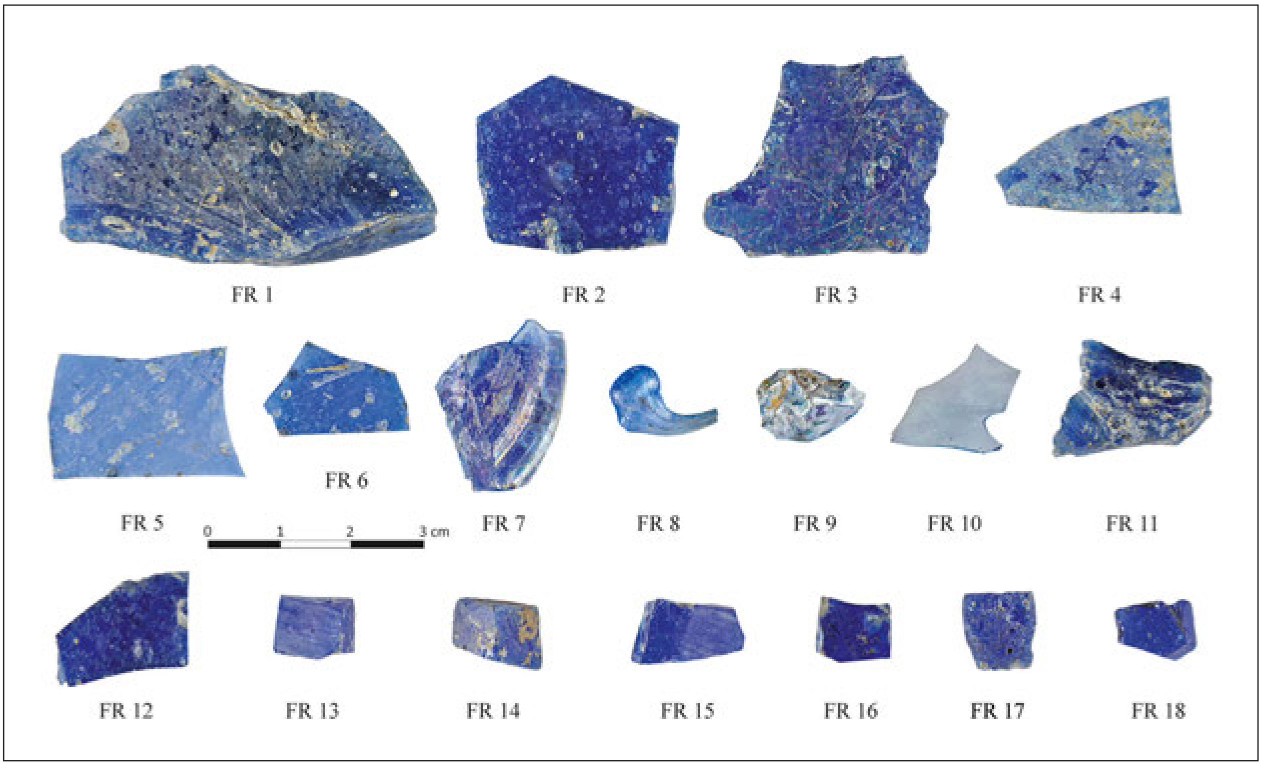

Fig. 3. The group of blue glass finds (photo V. Džikić)

Сл. 3. Груӣа налаза од ӣлавоī сӣакла (фоӣо В. Џикић)

fragments were presented in terms of their morphotypology.[4] However, this category of archaeological material from *Romuliana* remains a subject to be studied in more detail.

This paper aims to present a small group of eighteen fragments and mosaic glass *tesserae* distinguished by their cobalt blue colour (Fig. 3). Among the selected items, there are mosaic *tesserae*, *sectilia* sheets, secondary glass working waste, "window pane" fragments,[5] and a vessel sherd. For the first time, glass *sectilia* sheets have been recognised in the archaeological material from *Romuliana*. The glass production waste presents a clear indication that blue glass was locally worked there. This is confirmed, as well, by the discovery of a glass furnace, excavated in the area north of the fortified complex, in the "*villa*" *extra muros*.[6] Eight glass pieces, out of the total of 18 studied, were found in the remains of the glass furnace and in its immediate vicinity. The analysed set of blue glass pieces was selected in order to incorporate a range of categories of glass finds (i.e., architectural decorative pieces, production debris, a vessel), enabling in this way juxtapositions of the chemical make-up of different groups of finds.

The assemblage

The analysed glass fragments and mosaic *tesserae* were excavated at four different locations within and outside the fortified residence (Fig. 2, with locations numerically indicated): in the "*villa*" *extra muros* – a complex situated north of the fortified palace (1), in the area of the portico inside the northern rampart wall (2), in the area of Palace D1 (3), and in Tower 1, i.e. the southern tower of the eastern gate of the earlier fortification (4).

Among the eighteen pieces, the majority are mosaic *tesserae* (FR 13–18; Figs 3–5) and sheets of glass probably related to architectural decoration (*sectilia*

[4] Јанковић 1983, 102–103, 116, 119; Ružić 1994; Petković 2011, 193, Fig. 165; Antonaras 2013, 14, Fig. 14.

[5] The identification of the fragments as pieces of window panes is tentative since there is no evidence about the use of strongly coloured window panes in the late Roman period. At the same time, the fact that these pieces are flat and thin does not allow their recognition with certainty as vessel fragments or *sectilia* sheets, but such identifications should not be ruled out.

[6] von Bülow 2020, 251–254.

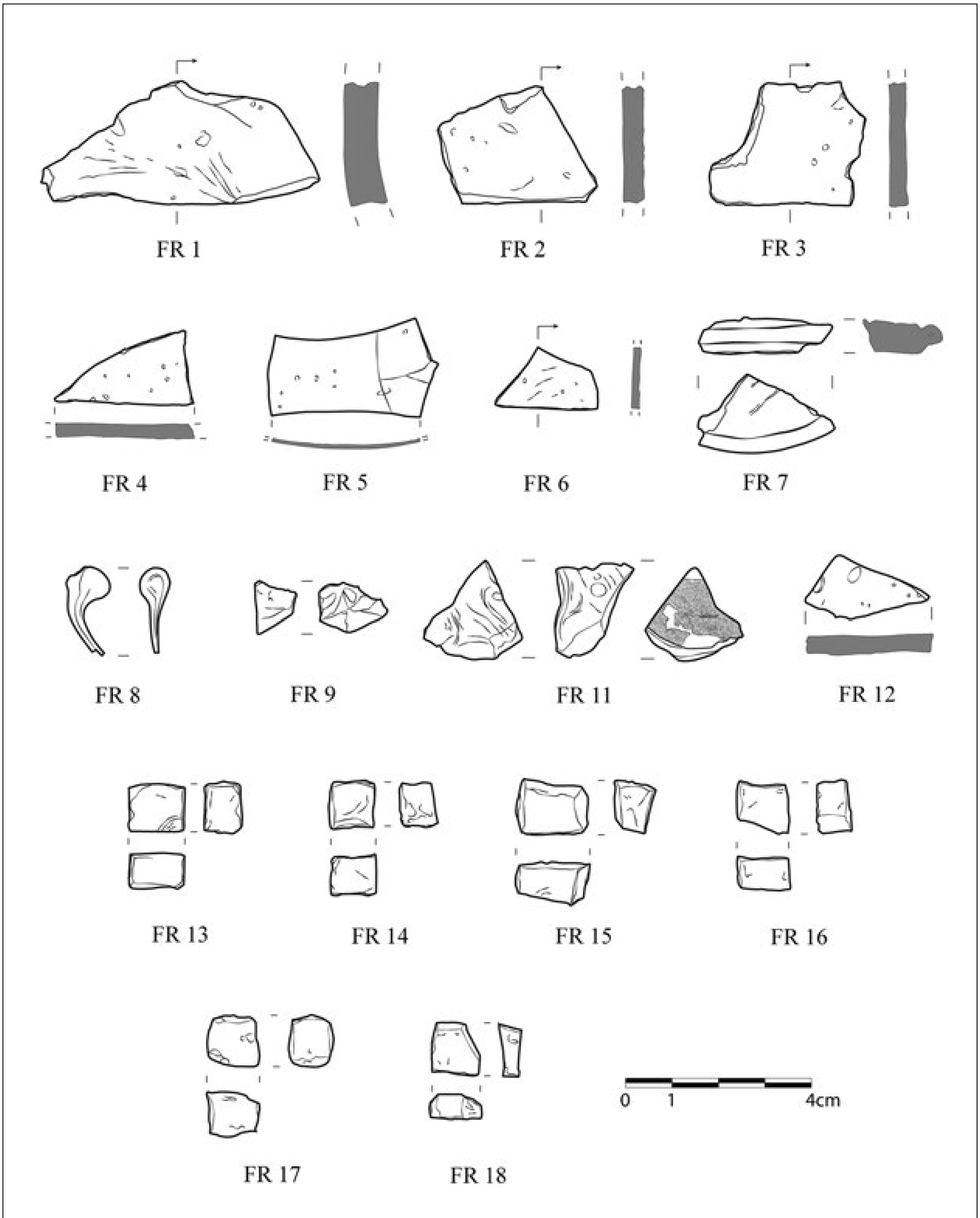

Fig. 4. The drawings of the blue glass finds; the undiagnostic sherd FR 10 is not included (authors A. Cholakova, M. Tomić)

Сл. 4. Цртежи налаза од плавог стакла; неодређени уломак посуде ФР 10 није исцртан (аутори А. Чолакова, М. Томић)

No.	Object	Location	Unit	Year	C-number
1.	*sectilia* sheet	Palace D1		1961	non-inventoried material – bag no. 1
2.	*sectilia* sheet	Palace D1		1961	non-inventoried material – bag no. 1
3.	*sectilia* sheet	Palace D1		1961	non-inventoried material – bag no. 1
4.	*sectilia* sheet	Tower 1	SW section; excavation layer XII	2009	C-210
5.	window pane	"*Villa*" *extra muros*	S 10/01, Room 1 (from glass furnace)	2010	C-1019
6.	window pane	"*Villa*" *extra muros*	S 10/01, Room 1 (from glass furnace)	2010	C-1019
7.	production waste	"*Villa*" *extra muros*	S 10/01, Room 1 (from glass furnace)	2010	C-1019
8.	production waste	"*Villa*" *extra muros*	S 10/01, Room 1 (from glass furnace)	2010	C-1019
9.	production waste	"*Villa*" *extra muros*	S 10/01, Room 1 (from glass furnace)	2010	C-1019
10.	vessel	Tower 1		2009	C-259
11.	production waste	"*Villa*" *extra muros*	S 10/6	2010	non-inventoried material – bag no. 133
12.	*sectilia* sheet	The area of the portico of the northern rampart wall		2010	non-inventoried material – bag no. 155
13.	*tessera*	The area of the portico of the northern rampart wall		2010	non-inventoried material – bag no. 155
14.	*tessera*	The area of the portico of the northern rampart wall		2010	non-inventoried material – bag no. 155
15.	*tessera*	*"Villa" extra muros*	S 10/05, Room 1	2010	C-1237
16.	*tessera*	*"Villa" extra muros*	S 10/05, Room 1	2010	C-1237
17.	*tessera*	*"Villa" extra muros*	S 10/01, outside the complex, north of Room 1	2010	C-1096
18.	*tessera*	*"Villa" extra muros*	Outside the complex, north of Room 1	2010	C-1054

Table 1. List of the analysed samples

Табела 1. Сӣисак анализираних узорака

sheets) (FR 1–4 and FR 12; Figs 3, 4, and 6). Some of the finds are fragments left behind from secondary glass working (FR 7–9 and FR 11; Figs 3, 4, and 7). There are also two pieces that could be identified, with caution, as window panes (FR 5 and 6; Figs 3, 4, and 7) and one is a vessel sherd (FR 10; Figs 3, 4, and 7). Some fragments are fully transparent, such as the fragments of "window panes" and the vessel sherd, while others seem opaque, but a closer look shows that they are rather translucent. They only differ in their thickness. Round and oval bubbles are visible in most of the fragments (FR 2–6 and FR 11; Figs 6 and 7). On some of them, tool marks are also visible.

Six mosaic *tesserae* are included in the set. Two of them were found in the area of the portico inside the northern rampart wall (FR 13 and FR 14), in the destruction layer dated to the late 4th century and the others were excavated inside and outside Room 1 in the "*villa*" *extra muros* (FR 15–18, see Table 1). They belong to the 4th century. Coins from this archaeological context mostly come from the first half of the 4th century. One coin belongs to the time of Diocletian (AD 292) and another to the reign of the emperor Valens (AD 367–375).[7] The glass furnace was situated in the north-eastern corner of Room 1.[8]

[7] von Bülow 2020, 278, 281–284.

[8] von Bülow 2020, 277, Abb. 48.

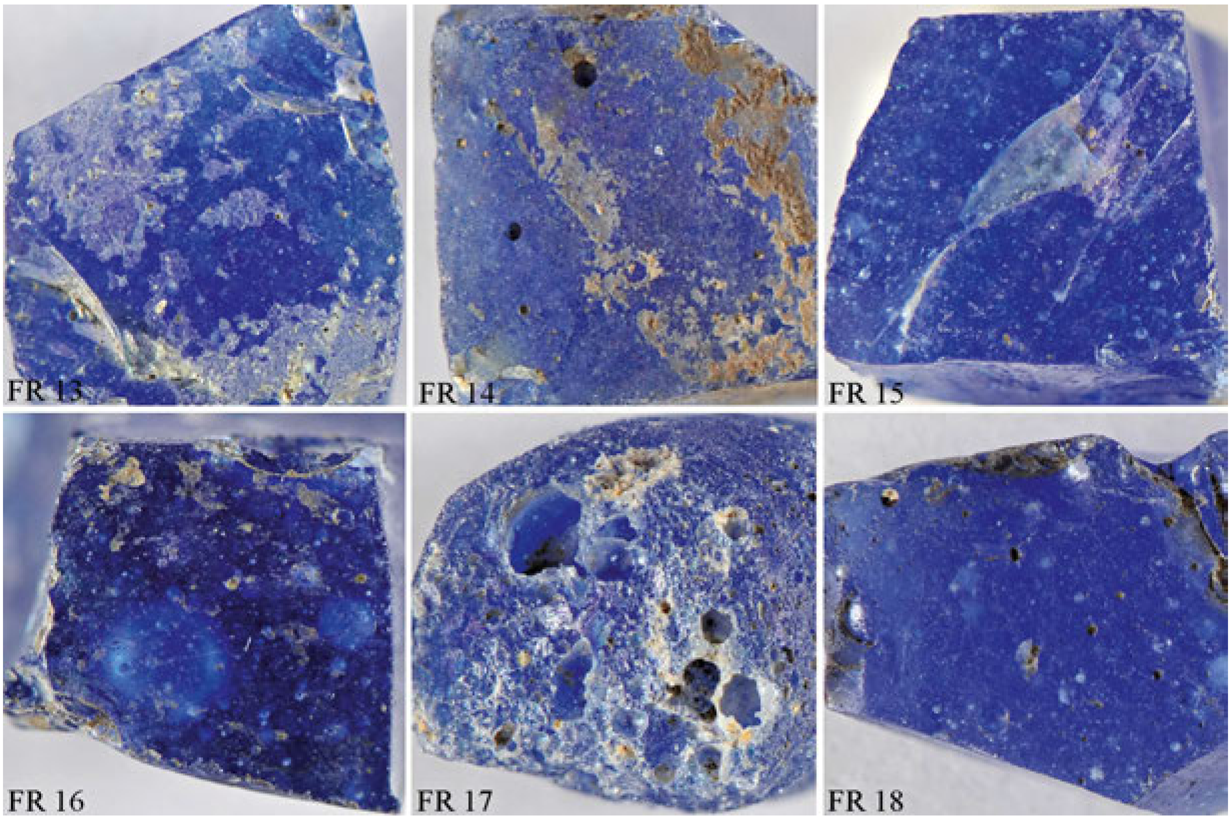

Fig. 5. Mosaic tesserae (photo V. Džikić)

Сл. 5. Коцкице мозаика (фошо В. Џикић)

Tesserae have visible cuts and tool marks on the surface. Traces of a secondary exposure to heat are evident on one piece (Fig. 5, FR 17). None of these finds was found in the context of a (preserved) mosaic floor. Four pieces were found inside Room 1 and northeast of it, outside the room. As they were discovered in the immediate proximity of the glass furnace, we may assume, with caution, their connection to secondary glass production, since *tesserae* could be used as a glass colouring material (see below).

Felix Romuliana was famous for its imposing mosaic decoration. Surfaces of the floors and walls were covered with marble cladding and mosaic *tesserae*. Geometrical, floral and figural mosaic floors are known from Palace 1, from the cross-shaped building in the south-western corner of the fortification (the so-called Romula's *triclinium*) and from the *thermae* in the south-eastern corner of the fortified complex. The most famous are the panel with Dionysus in Hall 7 of Palace 1 and the scene with *venatores* and a lion from Hall 4 in the same palace. Besides floors, walls and vaults of some buildings were also decorated with mosaics.[9]

Considering glass *tesserae*, individual finds with gold foil are also preserved. To the north of the fortified complex, in the north-eastern corner of "Gamzigrad-Nordfläche", in the so-called basilica, several finds of different coloured glass *tesserae* may indicate some depot of these finds, their storage, or even some secondary working glass activity. These pieces were found with coins issued during the reigns of Aurelian (AD 270–275), Florian (AD 275/276), Probus (AD 276–280/82) and Carinus (AD 283–285).[10]

[9] Срејовић 1983, 66–77; Живић 2010, 128–140; Jeremić 2020, 353, 355–358.

[10] Jeremić 2020, 353, 355–358; von Bülow 2020, 96–98.

[11] Сладић, Живић 2010, 210.

[12] Fig. 6, FR 2 (c), FR 3 (c), FR 4 (c) and FR 12 (c) were taken using ViTiny Pro10-3 Portable UV/IR/White Light Digital Microscope.

There are five sheets of glass (*sectilia* pieces). They were found inside the fortified complex – Palace D1 (FR 1–3), Tower 1, (FR 4) and in the area of the portico inside the northern rampart wall (FR 12). According to the stratigraphy in Tower 1,[11] FR 4 was found in a destruction layer dated to the second half of the 4th century; the other fragments probably belong to the early 4th century. The pieces are irregular in form and have traces of mortar on one side (Fig. 6). Also, bubbles are visible in their structure (Fig. 6: FR 1–4 and FR 12). Four fragments are about 0.4 cm thick, and one is 0.8 to 1 cm (Fig. 6: FR 1). Tool marks are visible on FR 1. The longer side of this piece is slightly curved. This fragment is visually slightly different from the other

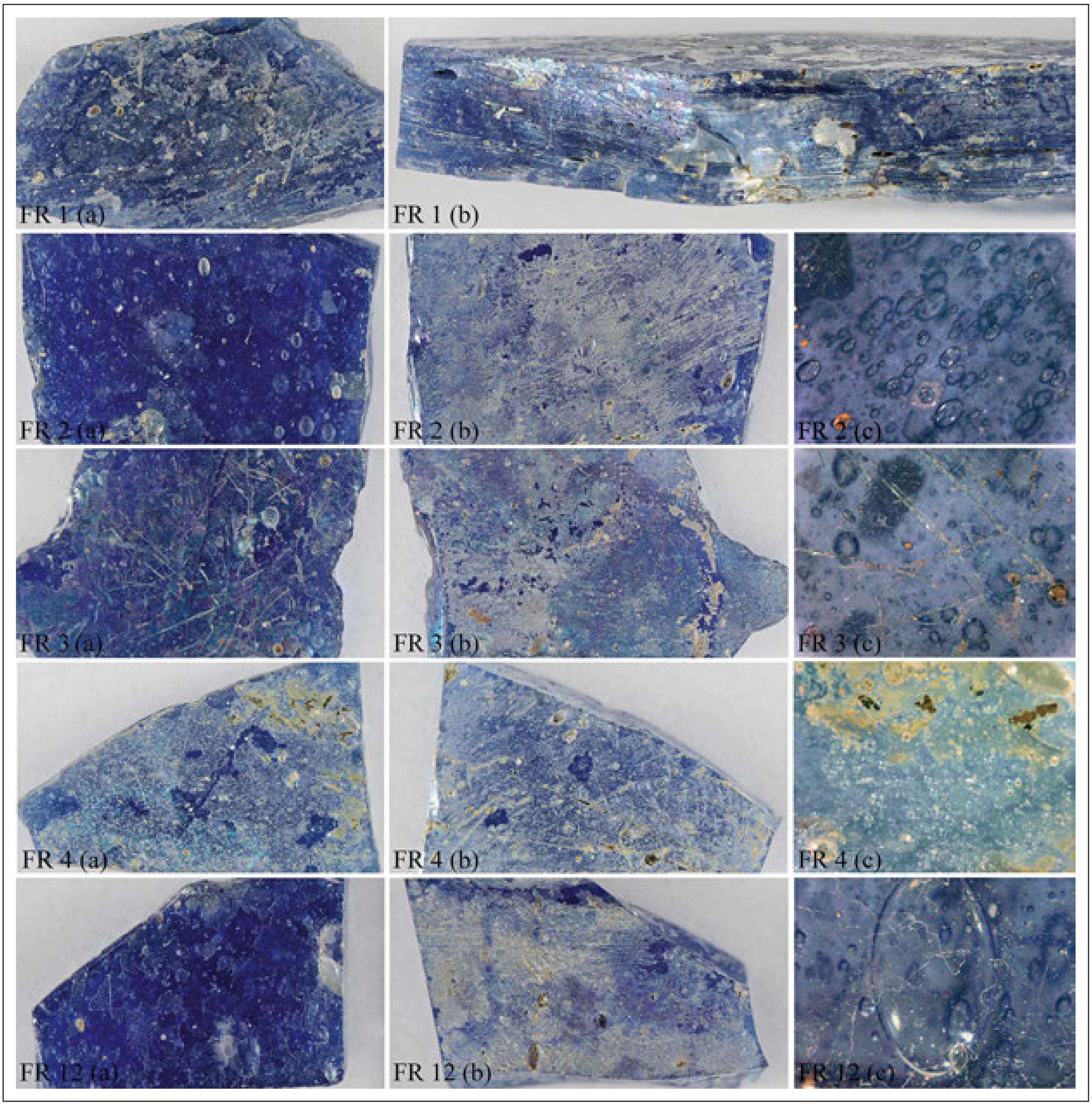

Fig. 6. Sectilia sheets (Fig. 6, FR 1 (a–b), FR 2 (a-b), FR 3 (a–b), FR 4 (a–b) and FR 12 (a–b): photo V. Džikić; Fig. 6, FR 2 (c), FR 3 (c), FR 4 (c) and FR 12 (c): photo M. Živković, S. Jovanović)[12]

Сл. 6. Фраīменūи sectilia *декорације (Сл. 6, ФР 1 (а–б), ФР 2 (а–б), ФР 3 (а–б), ФР 4 (а–б) и ФР 12 (а–б): фоūо В. Џикић; Сл. 6, ФР 2 (ц), ФР 3 (ц), ФР 4 (ц) и ФР 12 (ц): фоūо М. Живковић, С. Јовановић)*

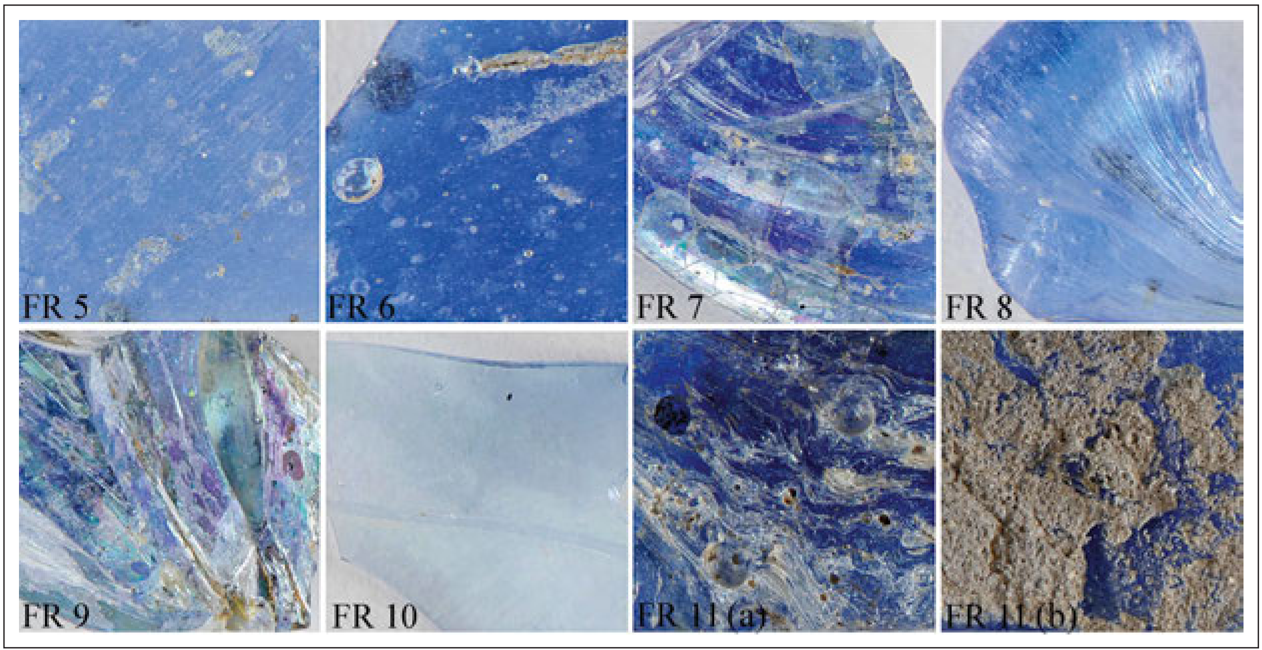

Fig. 7. Glass working waste, „window panes" and a vessel sherd (photo V. Džikić)

Сл. 7. Стаклени отпад, „прозорска окна" и фрагменти посуде (фото В. Џикић)

sectilia pieces but its chemical composition is quite similar to the composition of the others (see below). Hypothetically, it may be supposed that this piece is a reject left behind from the cutting of *sectilia* sheets.

In general, *sectilia* panels are ill-suited for floors and, thus, ideally belong to the wall revetment category.[13] They were used to decorate aristocratic or imperial residences, which were particularly luxurious.[14] Some were made exclusively of stone; others combined stone and glass, and some *sectilia* panels were entirely made of glass.[15] Sheets of glass served as a more affordable imitation of stone. Several economic and technical reasons are mentioned for this, such as the hardness of stone as a material and, thus, the difficulty of working with it, and the tendency to imitate rare types of stone. A significant feature of glass – its variation from opaque to translucent and transparent – makes it very usable for a wide range of colours and luminosity. Glass could also have been chosen to provide the colours that are almost totally absent in marble *sectilia*, such as turquoise and blue hues.[16] "The imitation should be understood as a visual play in which various materials are exploited to make unexpected effects and to show off the diligence of the artists. Their technical proficiency and virtuosity was a display of luxury and a sign of the commissioner's prosperity."[17]

Opus sectile panels, sometimes with figures, are known from a number of late Roman contexts.[18] The finest wall decorations stand in Junius Bassus' basilica in Rome (ca. AD 331), where glass was used extensively. Pieces of stone and glass there were combined in almost equal amounts. The figures in the narrative scenes are presented in light, medium and dark blue, red, orange and lemon yellow glass and gold foil.[19] Other famous

[13] Kiilerich, Torp 2018, 649.

[14] Santagostino Barbone et al. 2008, 452.

[15] Kiilerich 2014, 186. There are two ways in which glass *sectilia* panels were made. The one first implies the surface preparation, which was with raised edges and of the appropriate panel size. The earthen ware supports were laid on it and were covered with hot softened resinous substance. It served as a matrix for the glass. At the end, the pieces of glass were pressed into the matrix, which through cooling became a solid adhesive. Oppositely, the second way involved arranging glass first. Then the glass pieces had been covered with the softened adhesive, into which the artisan pressed the earthenware supports – Brill, Whitehouse 1988, 34.

[16] Kiilerich 2014, 180, 185; Kiilerich, Torp 2018, 649.

[17] Kiilerich 2014, 181, 183.

[18] It should be noted that they are also known from the earlier Roman period, for example glass *sectilia* from Gorga collection, from the imperial *villa* of Lucius Verus (AD 161–169) in Rome – Verità et al. 2013, 21–34; Bandiera et al. 2019, 2597–2611.

[19] Kiilerich 2014, 169, 179; Kiilerich, Torp 2018, 647, 649.

fragmented remains are known from Ostia, from the edifice outside Porta Marina (ca. AD 390),[20] where, in addition to the pieces of stone, a small amount of glass sheets was included for some details, such as lions' eyes, collars, belts, floral scrolls of friezes and pilasters, and the abacus of the pilaster capitals. Pieces of glass there also served for framing.[21] Furthermore, an important 4th century decoration is the glass revetment from Kenchreai (ca. AD 370), the eastern port of ancient Corinth, Greece, where panels consist only of glass.[22] Submerged remains of more than one hundred fragmentary *opus sectile* panels in glass were found, still in their shipping crates. These *sectilia* had been abandoned before they were unpacked.[23] Noteworthy are also remains from a late antique *villa* at Faragola (Ascoli Satriano), Italy.[24] The *villa* has a large dining room with a *stibadium*. It was paved with reused breccia slabs, and with three glass and stone *opus sectile* panels. It is important to point out that the *sectilia* panels were subsequently reused in a new context, for the floor decoration. This was not common, as glass *sectilia* panels are not suitable for floors.[25] Another famous example of late Roman *opus sectile* wall decoration made of glass is the Thomas Panel (second half of the 4th – early 5th century), which is believed to originate from Faiyum, Egypt.[26]

Besides *tesserae* and *sectilia* glass pieces, four fragments of production waste were also analysed (FR 7–9 and FR 11). All of them were found at the "*villa*" *extra muros*,[27] three of them (FR 7–9) in Room 1, within a glass furnace (trench S10/01).[28]According to the excavator, inside and around the furnace there were many fragments of different vessel types, as well as window pane pieces. The majority of the coin finds excavated in S10/01 came from the first half of the 4th century, and were issued from AD 312 to AD 341, during the reigns of Licinius, Constantine I, Constantius II and Constans. There is one coin from the time of Diocletian (AD 292) and another that is dated to the period of Valens' reign (AD 367–375).[29] The fourth piece of production waste was found in trench 10/06, and is also probably dated to the first half of 4th century, according to the coin finds from the same context.[30] All fragments of production debris are not clear and have numerous bubbles in their structures. Piece FR 7 could be a misshaped vessel (Figs 3, 4, and 7). Tool marks are visible on it. FR 8 is a thread from a removal of a solid impurity from the glass melt. The piece is hollow and has a drop-like shape (Figs 3, 4, and 7). FR 9 is a small piece of production waste. Fractures are visible on the surface of the fragment, as well as a large oval bubble (Fig. 7). FR 11 is almost entirely covered with an adhering of fired clay of light-greyish colour. It may have come from the surface of a furnace wall or, more likely, from a crucible. This could be a piece of glass left on the very bottom of a crucible (Figs 3, 4, and 7).

Two "window pane" fragments (FR 5 and FR 6), as already mentioned, were found in the glass furnace (trench S 10/01) together with three pieces of production waste, and are dated to the same time, most probably to the first half of the 4th century.[31] They are small, with visible bubbles and tool mark on the surface (Fig. 7).

The only vessel fragment in the set – a wall sherd (FR 10) – is not a diagnostic piece, so it is not possible to identify the vessel shape (Figs 3 and 7). It was found in Tower 1, in a destruction layer dated to the late 4th century.

The blue glasses from *Romuliana* – chemical data and interpretation

The set of eighteen glass pieces presented above was selected for chemical analysis primarily because of the visual characteristics of the finds. The range of distinct deep blue hues observed in the set suggests that cobalt is most likely the leading chromophore in all samples. The main purpose of this analytical work is to identify the base glass compositions used for the making of the blue pieces, and accordingly, to hypothesize the likely origin of the primary raw glass established in the *Romuliana* samples, and to characterise the added ingredients that impart the colour. The studied finds vary in terms of their functional identification (architectural decoration/fittings and tableware), how they relate to

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20 Kiilerich 2016, 41–58.

21 Kiilerich 2014, 179.

22 Kiilerich 2014, 185; Kiilerich, Torp 2018, 643–658; Gliozzo et al. 2010, 409.

23 Kiilerich, Torp 2018, 643.

24 Gliozzo et al. 2010, 389–415, Fig. 1.

25 Gliozzo et al. 2010, 409; Kiilerich 2014, 186; Kiilerich, Torp 2018, 648–649.

26 Brill, Whitehouse 1988, 34–50; Kiilerich, Torp 2018, 650.

27 von Bülow 2020, 281.

28 About glass furnace see von Bülow 2020, 251–254.

29 In the destruction layer of the furnace dome coins of Constantine I (AD 315–316, AD 320, AD 330–335) and Valens (AD 367–375) were found – von Bülow 2020, 278. The context was already mentioned when it came to mosaic *tesserae*.

30 von Bülow 2020, 278–279, 283–284.

31 von Bülow 2020, 283–284.

the production process (finished objects and production waste), and they also come from four different findspots within the site (Fig. 2). Accordingly, the analytical data is discussed from the perspective of possible links between compositions and object categories (glass working waste in particular), distinguishing output from single glass melting episodes, as well as regarding more general specifics of production technologies and supply of glass to the site.

Analytical techniques

The eighteen pieces from *Romuliana* were analysed in the Wolfson Archaeological Science Laboratories of the UCL Institute of Archaeology, London. Small samples were cut, the cross-sections mounted in epoxy resin blocks, polished with abrasive agents, and carbon coated. The measurements were performed by means of electron probe microanalysis (EPMA), according to established laboratory procedures.[32] Seven or ten individual measurements were taken on each sample, and the results averaged in order to obtain representative mean values (reported in Table 2 without normalisation to 100%). Twenty-four elements were routinely sought (calculated as wt% oxide values using stoichiometry to determine oxygen). Nevertheless, due to the limitations of the EPMA technique (e.g., its limits of detection), reliable quantification was not possible for all of the oxides found in the samples.[33] Corning A and B reference glasses were measured along with the archaeological glass samples; the results demonstrate an overall fair agreement with the published values of the reference materials,[34] and only occasional minimal empirical corrections were applied to bring the data in line with the standards.[35]

Results

As expected, all analysed samples are consistent with typical Roman soda-lime-silica glass (Table 2). The levels of potash (ranging from 0.47 to 0.65 wt%) and magnesia (0.45–0.71 wt%) conform with mineral soda glass ("natron") composition. Alumina and lime values vary within relatively narrow ranges (approx. 2.2–2.6 wt% Al_2O_3; approx. 7.0–8.0 wt% CaO), except for sample FR 10, which features a lower CaO concentration (5.8 wt%). Significantly, the same differentiation of sample FR 10 from the rest of the analysed glasses is also seen in the soda values: for FR 10 the content of Na_2O is 19.3 wt% while for all the other samples it is lower, ranging from 14.3 to 16.7 wt%. An identical trend is observed in the iron oxide and titania levels, which are approx. 0.55–0.75 wt% Fe_2O_3 and 0.05–0.07 wt% TiO_2 for the majority of the samples but somewhat higher in sample FR 10. Manganese values are generally below 0.5 wt%, with the lowest one found in FR 10 (0.08 wt% MnO) and the highest in FR 15 (0.61 wt%).

The EPMA data confirm the anticipated identification of the blue chromophore as cobalt for the entire set – CoO is measured at levels of 0.03–0.07 wt%, and CuO is in comparable or slightly higher concentrations (0.04–0.14 wt%), typical for Roman cobalt blue glass. All samples, again with the exception of FR 10, contain antimony mostly within the range of approx. 0.6–2.0 wt% Sb_2O_5, with samples FR 14 and FR 15 featuring respectively higher and lower concentrations (2.51 and 0.46 wt%). The EPMA measurements indicated that tin and zinc are present as trace oxides in all analysed glasses but the quantification, generally around 0.01 wt%, is considered not reliable. Finally, the samples from the studied dataset contain lead at variable levels (typically within the range of approx. 0.2–0.4 wt% PbO), with FR 14 and FR 10 standing out with the lowest and the highest values (0.06 wt% and 0.51 wt%, respectively).

Discussion

Base glass compositions

The ingredients deliberately added to the glass in order to modify its visual appearance – colour and/or texture – often distort the base chemical composition, i.e. the original makeup of the glass before the colouring (on the assumption that the colouring process is not part of the primary raw glass production). Nevertheless, in the case of the *Romuliana* blue glasses, the amount of added material is estimated at approx. $\leq$3 wt% of the

32 For details of the particular EPMA instrumental settings and the data acquisition parameters of this study see Cholakova, Rehren, Freestone 2016, 627.

33 Accordingly, certain data is not reported in Table 2; the concentrations of BaO, typically at 0.01–0.03 wt% levels, are included in the dataset but considered indicative only and not taken into account in the discussion.

34 Adlington 2017, Tabl. 3; cf. Corning A measurements in Table 2.

35 The eighteen blue samples from *Felix Romuliana* were measured in two separate analytical runs, which had a certain impact on the data (e.g. an inconsistency in the P_2O_5, Cl, SO_2 values observed across the whole set). Empirical corrections were applied selectively only (e.g., for the Sb_2O_5 values), while for some other oxides (e.g., P_2O_5) the data in Table 2 is reported without corrections.

		SiO_2	Na_2O	Al_2O_3	CaO	K_2O	MgO	Fe_2O_3	TiO_2	MnO	Sb_2O_5	P_2O_5	Cl	SO_3	CoO	CuO	PbO	BaO	total
FR14	tessera (2)	69.7	14.3	2.35	7.34	0.49	0.45	0.72	0.05	0.27	**2.51**	0.15	0.83	0.17	0.07	0.10	0.06	0.02	99.49
FR17	tessera (1)	69.5	14.5	2.61	7.31	0.65	0.50	0.65	0.05	0.24	**1.95**	0.14	0.90	0.14	0.06	0.07	0.33	0.02	99.61
FR18	tessera (1)	69.8	14.4	2.62	7.33	0.50	0.50	0.63	0.06	0.25	**1.92**	0.12	0.91	0.16	0.05	0.07	0.31	0.02	99.66
FR16	tessera (1)	69.5	14.6	2.61	7.30	0.49	0.50	0.65	0.06	0.23	**1.91**	0.14	0.91	0.15	0.05	0.07	0.30	0.02	99.43
FR13	tessera (2)	69.5	14.6	2.59	7.32	0.50	0.49	0.66	0.06	0.24	**1.86**	0.14	0.89	0.15	0.05	0.07	0.30	0.03	99.45
FR12	sheet (2)	68.8	14.8	2.57	7.47	0.54	0.58	0.72	0.06	0.33	**1.79**	0.14	0.90	0.15	0.05	0.09	0.43	0.02	99.43
FR3	sheet (3)	69.1	14.9	2.57	7.43	0.55	0.58	0.76	0.06	0.34	**1.77**	0.14	0.93	0.14	0.05	0.11	0.41	0.02	99.84
FR2	sheet (3)	69.1	14.9	2.57	7.47	0.53	0.58	0.73	0.06	0.33	**1.77**	0.14	0.89	0.14	0.05	0.10	0.38	0.02	99.73
FR1	sheet (3)	69.1	15.0	2.57	7.38	0.51	0.54	0.77	0.06	0.35	**1.66**	0.13	0.96	0.14	0.05	0.11	0.39	0.03	99.72
FR4	sheet (4)	68.9	16.0	2.48	7.10	0.50	0.57	0.66	0.06	0.28	**1.44**	0.10	1.05	0.15	0.04	0.07	0.28	0.02	99.66
FR5	"window pane" (1)	68.8	15.2	2.52	7.89	0.54	0.51	0.65	0.06	0.43	**1.39**	0.07	1.18	0.24	0.05	0.08	0.24	0.02	99.89
FR6	"window pane" (1)	69.0	15.1	2.53	7.72	0.60	0.51	0.66	0.07	0.46	**1.33**	0.14	0.99	0.14	0.04	0.08	0.28	0.03	99.63
FR11	prod. waste (1)	68.6	16.3	2.38	7.13	0.54	0.55	0.67	0.07	0.35	**1.21**	0.11	1.03	0.17	0.03	0.07	0.29	0.01	99.47
FR7	prod. waste (1)	69.2	16.6	2.28	6.98	0.48	0.54	0.56	0.06	0.25	**0.95**	0.09	1.12	0.14	0.03	0.04	0.23	0.02	99.55
FR9	prod. waste (1)	69.3	16.7	2.23	6.95	0.47	0.55	0.55	0.07	0.22	**0.83**	0.09	1.14	0.16	0.03	0.06	0.17	0.02	99.56
FR8	prod. waste (1)	69.7	15.8	2.34	7.08	0.49	0.48	0.56	0.06	0.38	**0.62**	0.06	1.30	0.18	0.03	0.04	0.21	0.03	99.42
FR15	tessera (1)	69.0	15.2	2.55	7.99	0.58	0.50	0.63	0.06	0.61	**0.46**	0.15	1.05	0.09	0.05	0.07	0.34	0.03	99.38
FR10	vessel (4)	67.4	19.3	2.28	5.79	0.53	0.71	0.84	0.11	0.08	**0.00**	0.03	1.21	0.31	0.04	0.14	0.51	0.02	99.36
Corning A measured																			
mean (n=6)		**66.74**	**14.31**	**1.02**	**4.97**	**2.87**	**2.51**	**1.05**	**0.77**	**0.96**	**1.59**	**0.12**	**0.10**	**0.06**	**0.17**	**1.08**	**0.07**	**0.47**	**98.86**
standard deviation		0.17	0.10	0.04	0.03	0.08	0.02	0.01	0.03	0.01	0.04	0.02	0.00	0.01	0.01	0.02	0.02	0.02	
Corning A published		**66.56**	**14.30**	**1.00**	**5.03**	**2.87**	**2.66**	**1.09**	**0.79**	**1.00**	**1.75**	**0.08**	**0.09**	**0.14**	**0.17**	**1.17**	**0.07**	**0.46**	
difference absolute		0.18	0.01	0.02	-0.06	0.00	-0.15	-0.04	-0.02	-0.04	-0.16	0.04	0.01	-0.08	0.00	-0.09	0.00	0.01	
difference relative		0.3%	0.1%	1.9%	-1.3%	0.1%	-5.5%	-3.8%	-2.0%	-3.8%	-8.9%	46.5%	14.8%	-57.4%	-1.2%	-7.8%	2.8%	1.3%	

Table 2. Average values of the Romuliana glass samples, as determined by EPMA, and measurements of Corning A reference glass compared to the published values; samples arranged in descending order of their Sb_2O_5 concentrations; the findspots are indicated as follows: (1) "villa" extra muros; (2) the area of the portico inside the northern rampart wall; (3) palace D1; (4) tower no. 1; highlighted in grey are the samples identified as belonging to single batches

Табела 2. Просечне вредности за узорке стакла из Ромулијане, одређене ЕРМА методом и мерењима Corning A референтног стакла у поређењу са публикованим вредностима; узорци су поређани према вредностима концентрације Sb_2O_5, од виших ка нижим; места налаза узорака назначена су на следећи начин: (1) „вила" ван бедема; (2) простор портика са унутрашње стране северног зида бедема; (3) Палата Д1; (4) Кула 1; сивом бојом су обележени узорци издвојени по смесама стакла којима припадају

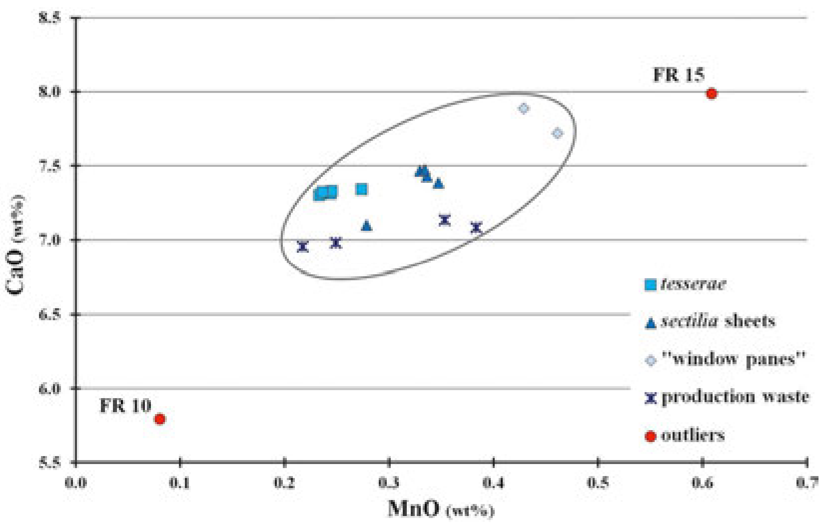

Fig. 8. Manganese and lime concentrations in the analysed samples

Сл. 8. Концентрација мангана и кречњака у анализираним узорцима

total amount of the batch,[36] and therefore it does not practically alter the base glass composition.

In terms of base glass composition, the present assemblage comprises a single, relatively uniform cluster of samples, and only two samples lie outside it (FR 10 and FR 14; Fig. 8). In the overwhelming majority of the *Romuliana* samples (17 out of 18), the ratio of the alumina to silica contents, indicative of the source of glassmaking sands, along with the relatively low soda and high lime contents, correspond to the characteristics of the primary production glass groups of Syro-Palestinian origin.[37] Their resemblance to Roman manganese containing glass, presumably produced in that region, is also evidenced by the similarities of the present dataset to the Roman Mn-decolourised glass found at 2[nd]–4[th] c. AD sites in the Northern Adriatic region and Britain.[38]

At the same time, it has to be noted that these 17 samples feature significantly lower manganese values than those found in the truly colourless "Mn-decolourised glass", mentioned above. Only the MnO content of 0.61 wt% in FR 15 (*tessera* – one of the two samples lying outside the main cluster, Fig. 8) is high enough to suggest a tentative identification of the base glass as being affiliated to Roman Mn-decolourised primary composition. Nevertheless, nothing could be stated with certainty about the original tint of the FR 15 glass, prior to colouring. This sample also features the lowest antimony content in the current dataset, possibly deriving entirely from the ingredients added to the melt during the colouring process (see below). The high lime concentration in FR 15, in fact the highest among the studied samples (Fig. 8), corroborates its association with the Mn-bearing group. A similar base glass composition is known in cobalt blue *tesserae* dated to the 2[nd] c. AD, and is interpreted as particularly suitable for the production of antimony-opacified mosaic glass.[39]

The main cluster (16 out of 17 – *tesserae*, *sectilia* sheets, window panes, production waste) of the samples assigned above to the Syro-Palestinian primary production region has MnO contents within the range of 0.22–0.46 wt%. Samples FR 5 and FR 6 (window panes) are at the higher end of this range and, significantly, they feature the highest lime values in the cluster (Fig. 8). These *Romuliana* glasses can be associated with the low MnO makeup, denoted also as weakly coloured or blue-green glass, regarded as a primary glass production group originating from the Syro-Palestinian region,[40] and most likely related in terms of production technology to the already mentioned Mn-decolourised group. Importantly, the lower manganese concentrations of the

[36] This sum includes the values of CoO, CuO, PbO and Sb_2O_5 found in the samples, still admitting that a certain amount of Sb_2O_5, at least in theory, could come from the base glass as it was prior to the colouring, instead of from the modifying ingredients added to it (see below). On the other hand, the added cobalt-rich material certainly introduced further quantities of some other oxides, e.g. Fe_2O_3 (Fig. 10; cf. Cholakova et al. 2017, Fig. 7), but estimating these quantities is not practicable in the current analytical set.

[37] Freestone 2020, Fig. 22.1, Table 22.2; cf. Freestone 2021, 249–251.

[38] Jackson 2005, Group 2b; Silvestri, Molin, Salviulo 2008, Group CL2; Foster, Jackson 2010, Colourless 2b.

[39] Paynter et al. 2015, 74; see below.

[40] Jackson, Paynter 2016, 73; Silvestri 2008, Group Ic1a and Group Ic2a; cf. Freestone et al. 2015; cf. Jackson 2005, Table 2.

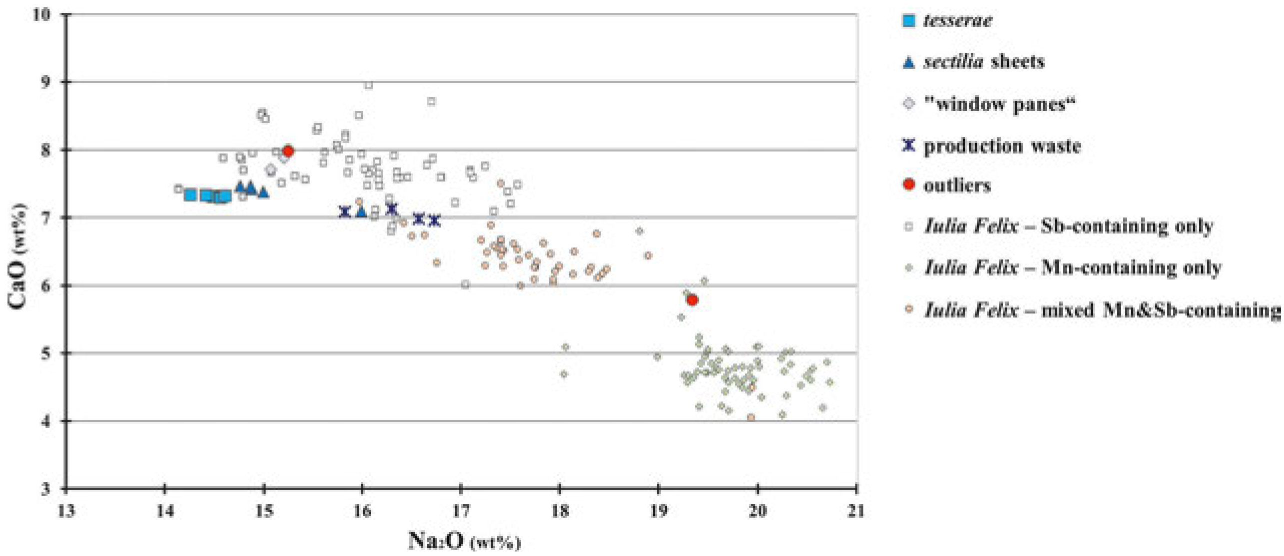

Fig. 9. Soda and lime concentrations in the analysed samples compared to the glass from Iulia Felix wreck (data from Silvestri, Molin, Salviulo 2008 and Silvestri 2008)

Сл. 9. Концентрација соде и кречњака у анализираним узорцима у поређењу са стаклом из бродолома Iulia Felix *(подаци из Silvestri, Molin, Salviulo 2008 и Silvestri 2008)*

samples in this main cluster are still above the proposed background levels of MnO caused by natural mineral impurities in the glassmaking sands (typically less than 0.05 wt%),[41] and therefore should be again regarded as resulting from addition to the melt.

Admittedly, the weakly coloured or blue-green glass composition with low MnO content often features a certain level of antimony oxide.[42] It is typically found in small amounts but still cannot be explained by the background Sb concentrations in the glassmaking sands (estimated at Sb<1.4 ppm).[43] Regarding the 16 samples from *Romuliana* with low MnO levels, it is not possible to unambiguously state whether they contained some amounts of antimony oxide in the base glass (i.e. prior to colouring), since their high Sb_2O_5 concentrations (>0.6 wt%) are clearly related to an intentional separate addition to the melt (see below).

The presence of both decolourisers – manganese and antimony oxides – in Roman glass is seen as an indication of mixed recycling of Mn-decolourised and Sb-decolourised glasses.[44] Analytical findings from sites in the Central Balkans, dated to the mid-3rd–4th c. AD and roughly contemporaneous to the *Romuliana* assemblage confirm the circulation and local secondary glassworking of mixed Mn-Sb colourless or weakly coloured glass.[45] Therefore, it could be suggested that a proportion of the Sb_2O_5 in the composition of the main *Romuliana* cluster comes from such a mixed base composition,[46] rather than from the added colouring ingredients. The use of recycled base glass may be seen as a pragmatic choice for a batch of strongly coloured glass intended for the production of architectural decoration pieces. Nevertheless, the correlation of CoO and Sb_2O_5 responsible for colouring and opacification of the *Romuliana* blue glasses implies that the overwhelming amount of antimony oxide comes from the colourant material added to the base composition (Figs 11 and 12, see below).[47] Therefore, it is unlikely that the original base glass of the samples in the main cluster was of typical mixed Mn-Sb chemical makeup; an

[41] Brems, Degryse 2014, 38; Schibille, Sterrett-Krause, Freestone 2017, 1230.

[42] Jackson 2005, Table 2.

[43] Brems, Degryse 2014, 79.

[44] Jackson 2005, 772; cf. Gratuze 2018, Fig. 6.

[45] Stamenković, Greiff, Hartmann 2017, Table 1, note the dark blue sample 16; Ivanov, Cholakova, Gratuze 2021.

[46] Cf. Jackson 2005, Group 2a; Silvestri, Molin, Salviulo 2008, Group CL1/2.

[47] In Fig. 12, the origin of the correlation trend of CoO and Sb_2O_5 is approximately at the intercept of both axes. This implies that, according to the EPMA data, the base glass before the addition of the Co colourant likely contained no substantial quantities of antimony oxide.

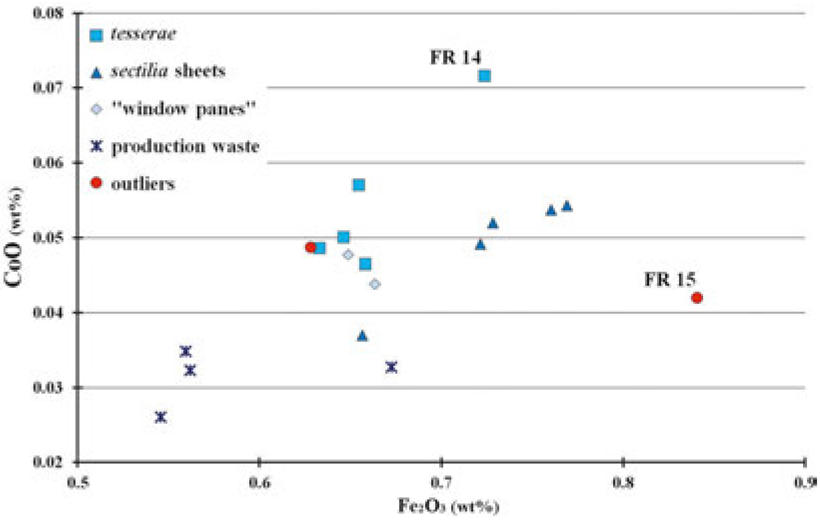

Fig. 10. Iron oxide and cobalt oxide concentrations in the analysed samples

Сл. 10. Концентрација оксида гвожђа и кобалта у анализираним узорцима

overall affiliation to the compositional range of low MnO weakly coloured group mentioned above seems more probable.

Nevertheless, the presence in some of the samples in the main *Romuliana* cluster of a certain amount of antimony oxide originating not from the added colouring material but from the base glass, should still not be definitely ruled out. The production waste pieces (FR 7–9 and FR 11) stand out with their higher soda levels, especially when compared to the *sectilia* sheets and the *tesserae* (Table 2). A comparison of the soda and lime contents in the *Romuliana* dataset to the Roman glass assemblage from the *Iulia Felix* wreck[48] – an illustrative example of Mn-containing and Sb-containing compositions and their mixing[49] – demonstrates that the production waste and a single *sectilia* sheet sample lie closer to the mixing line between the main Mn-containing and Sb-containing glass compositions and clearly away from the architectural glass samples (Fig. 9). This pattern most probably reflects the particular technology of blue glass making used by the *Romuliana* craftsmen, which likely involved a certain degree of mixing of various glasses (see below).

The remaining sample, FR 10 (the only vessel fragment in the set), was already defined as an outlier in terms of both base glass composition and added ingredients. Its low lime level and higher soda (Fig. 9), as well as elevated iron oxide and titania resemble the characteristics of the primary production groups of Egyptian origin (Fig. 10).[50] At the same time, the virtual absence of any decolourisers (no Sb_2O_5 is detected in the EPMA measurements and MnO is found at 0.08 wt% only, which may also be due to the added colourant) set this peculiar composition apart from well-known primary glass groups, such as Sb-decolourised or Mn-decolourised Foy 3.2., regarded as Egyptian production,[51] leaving the question open as to the precise affiliation of the FR 10 base glass.

To sum up, the present data allow the distinguishing of three groups of probable base glass compositions used for the production of the *Romuliana* blue glasses: Roman Mn-bearing/decolourised (FR 15) and low Mn composition (the main cluster – FR 1–9, FR 11–14, FR 16–18; some of the samples likely adulterated by some glass mixing), both originating from the Syro-Palestinian region, and a soda-rich low Ca glass (FR 10), possibly related to Egyptian primary glass production. Given the abundance of the second group (16 out of 18 analysed pieces), samples FR 10 and FR 15 are rather regarded as outliers.

Added ingredients

As already mentioned, all analysed glasses from *Romuliana* are rendered blue by the deliberate addition of cobalt-containing ingredient(s). It is known that the ores used as sources of this colourant contained certain amounts of other elements, which were also introduced in the glass melt. Gratuze and co-authors have established that during the Roman and late Roman period the

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[48] Silvestri, Molin, Salviulo 2008; Silvestri 2008.

[49] Cf. Freestone 2015, Figs 1 and 2.

[50] Freestone 2021, 250.

[51] Schibille, Sterrett-Krause, Freestone 2017, 1237–1238; Cholakova, Rehren 2018, 57.

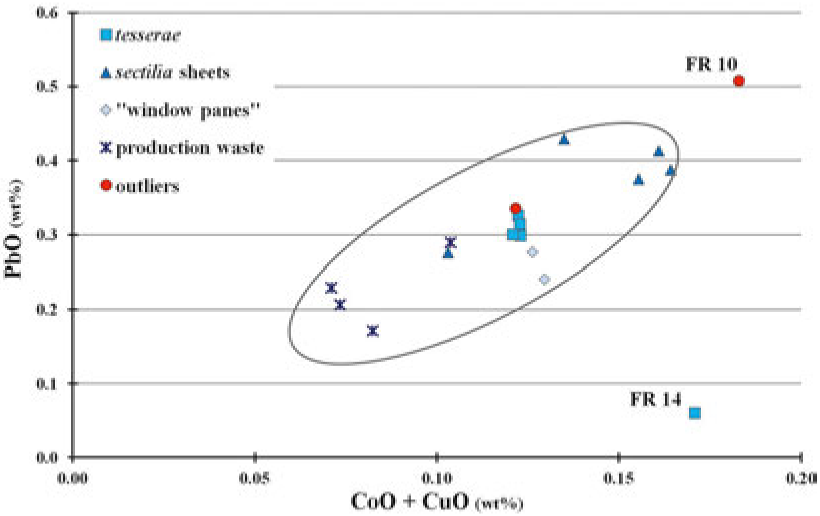

Fig. 11. Sum of cobalt and copper oxide values in the analysed samples compared to lead oxide concentrations

Сл. 11. Збирне вредности оксида кобалта и бакра у анализираним узорцима у поређењу са концентрацијама оксида олова

colourant consisted mainly of a mixture of iron, copper and cobalt oxide, with nickel recognised as a diagnostic impurity, being found consistently in low concentrations in the finds dated prior to the late 4th c. AD.[52] The present dataset is generally in line with such characteristics of the cobalt-bearing additive.[53] A general positive correlation of cobalt and iron oxide levels is seen (Fig. 10), even though the trend is not clearly pronounced, possibly because of the different Fe_2O_3 levels in the base glass compositions, and/or variable CoO/Fe_2O_3 ratio in the added colouring ingredient. An almost identical correlation is observed between CoO and CuO, although their low concentrations, close to the detection limits of EPMA, suggest that caution should be exercised.

Antimony and lead oxide are the other two components that stand out with their elevated concentrations in the analysed set. In such concentrations they can hardly be related to the natural impurities from the glassmaking sands used for the production of the discussed base glass compositions, nor to be explained as an unintentional effect of glass recycling (see above). Therefore, they are considered parts of the suite of added colouring ingredients, even though they did not contribute to the blue colour of the glasses.

Lead oxide in Roman cobalt blue glass is often associated with the CoO-containing geological material, even though the CoO/PbO ratio of the colourant seems quite variable.[54] A combined scatter graph of cobalt, copper and lead oxide concentrations in the studied set shows that their levels are positively correlated in almost all samples, regardless of the differences in their base glass compositions (Fig. 11). An exception to this trend is sample FR 14 (*tessera*), which features a significantly lower PbO content. Since the analysed selection of finds does not represent an entirely consistent technological assemblage from a single context, it is expected for the correlation in Fig. 11 not to be too distinctly outlined. At the same time, it is clear enough to suggest that the majority of the analysed glasses are rendered blue by the addition of Co-containing material of fairly comparable composition, and the main difference lies in the amount of the admixed colourant, with the lowest quantities found in the production waste pieces. As already pointed out, *tessera* FR 14, with its lower PbO content, especially relative to its highest CoO level in the set, is an outlier in terms of ratios of the main colourant components. On the other hand, the vessel fragment FR 10 (an outlier in respect of the base glass makeup), even if fitting well into the general correlation, is also somewhat atypical for the main group of samples because of its high CuO and PbO contents, relative to CoO.

Summarising, it is suggested that, in terms of the added CoO colourant and the oxides likely related to its geological source (CuO, PbO), the present dataset is relatively homogenous (i.e. a more or less uniform origin of the colouring ingredient could be proposed), with only sample FR 14 standing out as an exception.

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52 Gratuze, Pactat, Schibille 2018, 18.

53 NiO was only occasionally detected in some of the EPMA measurements at levels of around ≤0.01 wt%, indirectly confirming that the composition of the Co-containing material in the *Romuliana* blue glasses is in accordance with the conclusions of Gratuze and co-authors – Gratuze, Pactat, Schibille 2018, 5.

54 Gratuze, Pactat, Schibille. 2018, Table 3.

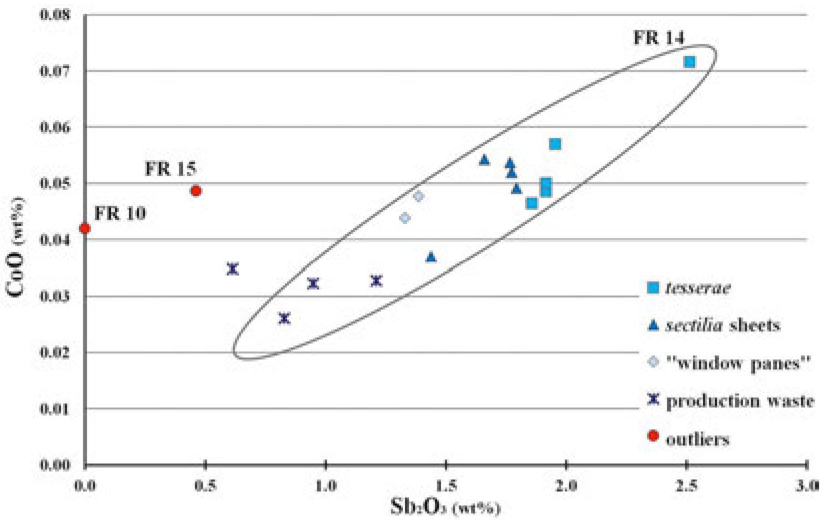

Fig. 12. Antimony oxide and cobalt oxide concentrations in the analysed samples

Сл. 12. Концентрација оксида антимона и кобалта у анализираним узорцима

Interestingly, the levels of lead oxide are also positively correlated with the antimony oxide concentrations in most of the *Romuliana* blue samples (cf. Figs 12, 13). The exceptions to this trend are again samples FR 15, FR 14, and FR 10 – the latter containing virtually no Sb_2O_5. The presence of high lead levels in Sb-rich glasses – decolourised and opacified – is a well-known phenomenon, and lead could be explained as an impurity in the geological Sb source.[55] However, recent studies suggest that lead may well be a deliberate additive to the Sb-containing glass compositions, which changes the properties of the glass by lowering the working temperature, improving the formation of opacifying particles, etc.[56] The specifics of the present dataset do not allow an unambiguous identification of the origin of the elevated PbO concentrations in the *Romuliana* blue samples (i.e., the association of PbO either with cobalt or with antimony), in particular because of the observed interdependencies in the concentrations of added oxides.

Antimony was used in the Roman glass industry as a decolouriser,[57] as well as for opacification – of strongly coloured glasses and white glass – through the formation of calcium antimonate crystals in the glass – in essence, minute particles, which do not allow light to pass through glass, thus preventing its transparency.[58]

For the majority of the *Romuliana* blue samples, it would be reasonable to assume that the elevated Sb_2O_5 concentrations do not derive from decolourising of the base glass (see above), but the purpose of this additive is opacification of the *tesserae* and *sectilia* glass, as expected for such kinds of materials. This supposition is further reinforced by the fact that the only sample without antimony oxide is a fragment of a vessel (FR 10), for which clear transparent glass was certainly preferred (Fig. 7: FR 10). Nevertheless, antimony oxide is present at the levels of approx. 0.5–1.5 wt% also in other categories of finds – window panes and production waste (Fig. 12) – which, in principle, do not require alteration of the glass texture. Furthermore, the macroscopic inspection of the studied fragments *tesserae*, *sectilia* sheets, window panes and production waste indicates that they are quite translucent, and that no proper opacification of any of the pieces has been achieved, despite the Ca- and Sb-rich composition.[59] Indeed, the translucency observed in the majority of them may well result from the gas bubbles present (Figs 5 and 6). In the absence of microstructural evidence and information about different phases in the *Romuliana* samples, it is not possible to definitely determine the effect of the antimony in the glass. The successful formation and preservation of opacifying calcium antimonate crystals in glass depends on various parameters (e.g., temperature of the melt, levels of saturation of the batch with Sb, etc.), and some other technological factors, such as remelting and mixing of opaque blue with transparent glass, may well have caused these particles to dissolve during secondary glassworking.

Probably the most pronounced correlation of the compounds added to the base glass compositions is seen

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55 Freestone, Stapleton 2015, 68.

56 Paynter, Jackson 2019; Boschetti et al. 2020, 558.

57 Cf. Paynter, Jackson 2019.

58 Neri et al. 2016, 18864; Freestone, Stapleton 2015, 67–68

59 Cf. Paynter et al. 2015.

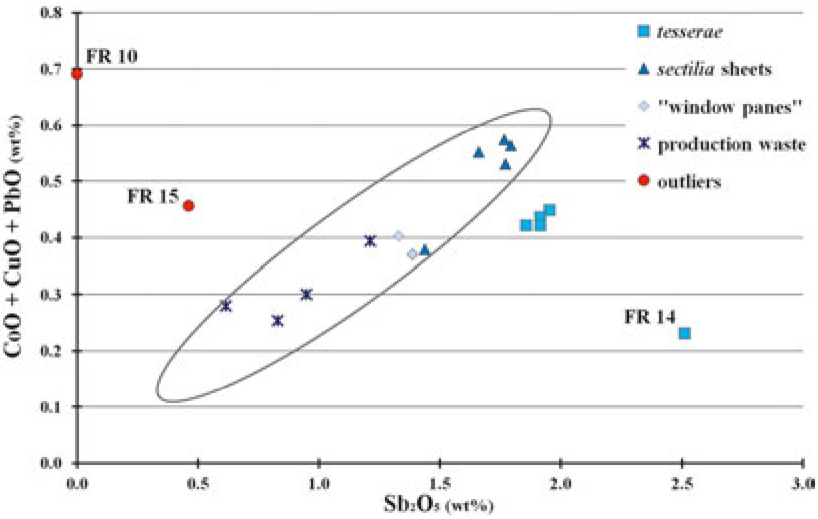

Fig. 13. Antimony oxide concentrations in the analysed samples compared to the sum of cobalt, copper and lead oxide value

Сл. 13. Концентрација оксида антимона у анализираним узорцима у поређењу са збирним вредностима оксида кобалта, бакра и олова

for antimony and cobalt oxide (Fig. 12). Only two of the samples – FR 10 with no Sb_2O_5, and FR 15 with the lowest Sb_2O_5 content – plot clearly outside this trend. Significantly, both samples are also outliers in terms of their base glass compositions. One of the production waste pieces – drop FR 8 – has a lower antimony concentration, which sets it slightly away from the correlation outline but, on the other hand, the samples of production debris seem to be generally more heterogeneous than the finished objects (see below; Figs 13 and 14). The observed link between antimony and cobalt oxide content in the majority of the samples cannot be explained by the association of the two compounds in some kind of geological material, since such a natural co-occurrence is unlikely. Nevertheless, the correlation trend leaves the impression that both components could have been incorporated into the melt from a single ingredient, similarly to the interpretation suggested for a 2nd c. AD group of cobalt blue *tesserae* from Britain.[60]

In an attempt to further explore this aspect of the *Romuliana* blue glass set, the sum of the cobalt, copper and lead oxide concentrations, presumably linked to the colouring, is plotted with antimony oxide levels (Fig. 13). As expected, an overall pattern of diversity emerges in the scatter graph: samples FR 10 and FR 15 with no/low Sb_2O_5 content are again identified as outliers, as well as FR 14, with its much higher Sb_2O_5 and low PbO levels, i.e. with a different proportion of the added colouring ingredients. Interestingly, the group of the remaining four *tesserae* also features higher antimony oxide concentrations relative to the colour-related compounds. At the same time, the *sectilia* sheets, window pane fragments and production waste pieces apparently form a consistent group of a comparable ratio of Sb_2O_5 and colourants, resembling the correlation trend in Fig. 11.

As mentioned above, a similar pattern of correlations is observed in a Roman assemblage of cobalt blue *tesserae* from Britain, which feature a strong association of their lead, copper, cobalt, nickel, arsenic and antimony levels, as well as iron and manganese.[61] Such an interdependence is interpreted by Paynter and co-authors as indicating that these colour and opacity related elements were introduced into the glass melt as a single ingredient – a concentrated form of mixed colouring substance prepared in advance.[62] The *Romuliana* samples data could be seen as further evidence for such a production technology. Nevertheless, our sample set does not represent an entirely homogeneous archaeological and technological assemblage, and even if being relatively consistent in terms of chemical glass composition, there is a variability in the detail (i.e., ratios and extent of correlation of the colour and opacity related elements). Therefore, a more nuanced interpretation of the correlation trends is preferred in the case of the *Romuliana* blue set, especially regarding the production waste pieces (see below).

Recapitulating the significance of the elevated lead and antimony oxide contents of the present samples, it is not possible to conclusively associate the PbO with either the Co-colouring ingredient, or with the Sb-opacifying additive, in the settings of this study. The only

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60 Paynter et al. 2015, Fig. 6.

61 Paynter et al. 2015, 72.

62 Paynter et al. 2015, 75.

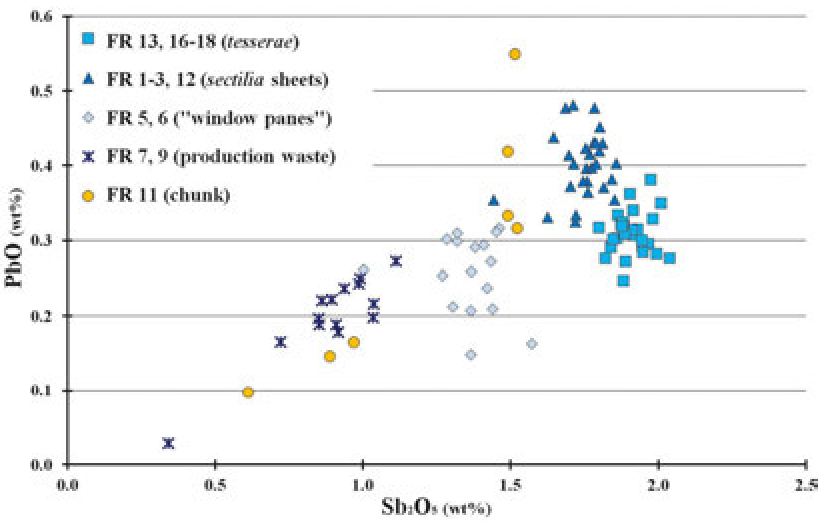

Fig. 14. Individual EPMA measurements of antimony oxide and lead oxide contents in samples identified as belonging to single production batches, and of sample FR 11 – an example of significant heterogeneity of the glass

Сл. 14. Појединачна ЕРМА мерења садржаја оксида антимона и олова у узорцима који припадају одређеним стакластим смесама, и за узорак ФР 11 – пример значајне хетерогености стакла

exception is the vessel fragment FR 10 featuring virtually no antimony but high lead oxide content, likely linked to the Co-containing raw material. The apparent lack of proper opacification in almost all the *Romuliana* pieces, despite the high Sb_2O_5 concentrations, can be explained by technological specifics and the likely remelting of the blue glasses (see below).

Production waste

The presence of blue coloured glassworking waste (FR 7–9 and 11) found in the context of a glass furnace in the "*villa*" *extra muros* area of *Romuliana*, is clear evidence that blue glass was not only supplied to the site as a readymade product but local craftsmen were also processing this material for the needs of the local consumption during the period of the active functioning of the luxurious complex. The production waste samples repeatedly at the lower end of the correlation trends discussed above (Figs 10–14) indicate that the locally worked blue glass has the lowest levels of all oxides responsible for glass colour and texture modification. The likely explanation, as discussed above, comes from the technology used by the *Romuliana* craftsmen – the observed correlation trends indicate glass mixing (i.e. these are in fact mixing lines). Most probably the local glassworkers were extending the amount of available blue glass by remelting and blending/diluting some of the strongly coloured blue pieces (e.g. *tesserae* or *sectilia* sheets) with common glass cullet. In essence, such a technology means using the blue (architectural) glass as a colouring ingredient in the local workshop, as also practiced elsewhere in late Roman and post Roman contexts.[63] As pointed out above, the position of the *Romuliana* production waste pieces in the soda and lime scatter graph (Fig. 9), away from the *sectilia* and *tesserae* and towards the area of the mixed Mn and Sb glass, implies that some mixing was involved. However, it is likely to have been a feature of the colouring process itself rather than a defining characteristic of the base glass. Quite probably, the batch of blue coloured glass blended by the local glassworkers contained some amount of Sb-decolourised cullet and/or any other available pieces intended for recycling, while the craftsmen had the skill to maintain the required blue tint of the melt. Accordingly, a remelting of this kind could have caused some decrease in the calcium antimonate particles from the blue component of the batch, and would explain the lack of proper opacification in the studied samples.

Such a reconstruction of the technology of blue glass making in the *Romuliana* workshop seems more probable than a hypothetical addition of some concen-

[63] Cf. Schibille, Freestone 2013; Boschetti, Mantovani, Leonelli 2016; Cholakova et al. 2017.

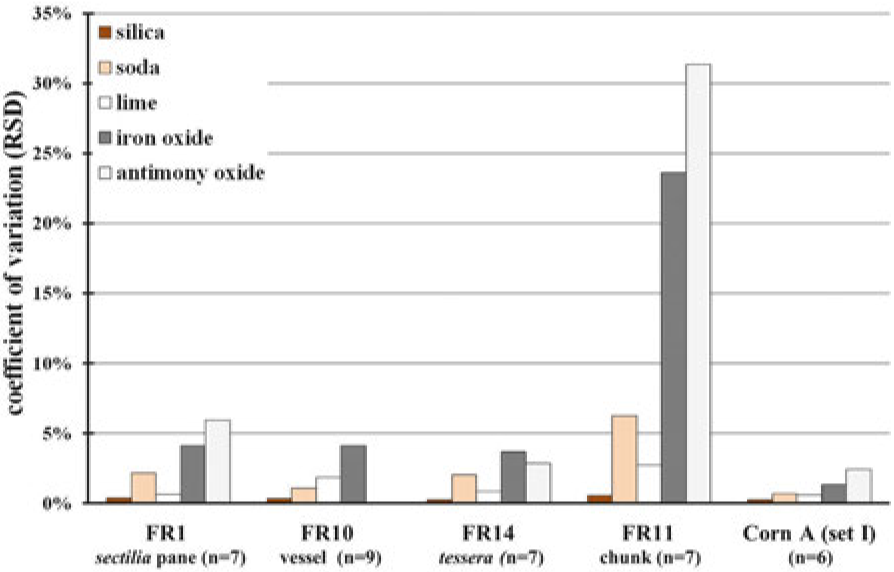

Fig. 15. Coefficient of variation of the individual EPMA measurements of selected five oxides in four of the Romuliana samples and of the reference glass Corning A.
The comparison is indicative of the degree of glass heterogeneity across different groups of finds

Сл. 15. Коефицијенти варијације индивидуалних ЕРМА мерења пет изабраних оксида у четири узорка из Ромулијане и референтног стакла Corning A.
Поређење је индикативно за степен хетерогености стакла у различитим групама налаза

trated mixture of raw colouring ingredients,[64] which would mean access to quite different sources of raw materials and relevant supply chains.

Finally, the heterogeneity of the glassworking waste samples provides further evidence about the mixed remelting carried out at *Romuliana* – the different components of the melt were not well homogenized, and this is the reason for the significant scattering of the individual EPMA measurements of these samples, specifically the calculated higher coefficient of variation (Figs 14 and 15). The most pronounced heterogeneity, also evident in the macroscopic appearance, is found in sample FR 11 – an unworked chunk with adhered fired clay from the walls of a production installation/crucible (Fig. 7), i.e. an area at the very edge of the melt where complete homogenization was not feasible.

Single production episodes

The close compositional similarity between certain samples allows identifying them as likely output from single glass melting episodes (Table 2). The recognition of the so-called single batches[65] in the *Romuliana* blue set is further reinforced by a plot of the individual EPMA measurements (Fig. 14). An overlap is seen for four out of six *tesserae* (FR 13, FR 16–18), four out of five *sectilia* sheets (FR 1–3, FR 12), the two window panes (FR 5, FR 6) and two of the four production debris pieces (FR 7, FR 9). The most tightly clustered group of the *tesserae* probably indicates that the four mosaic cubes were cut from one and the same cake, and/or that the *tessera* glass was better homogenised, compared to the other groups of finds (Fig. 15). The clusters of the *sectilia* sheets and the window panes demonstrate a more dispersed pattern, while the two glassworking waste pieces seem even more heterogeneous, as discussed above.

The significance of the single batches identified in the *Romuliana* blue set has two aspects. Firstly, and not surprisingly, pieces originating from a single production episode likely formed a single delivery to a particular area of the site and, therefore, they come from one and the same findspot – the majority of the *tesserae* were found at the "*villa*" *extra muros*; most of the *sectilia* sheets come from palace D1 (Table 2, Fig. 2). Never the

64 Cf. Paynter et al. 2015, 75.

65 Freestone, Price, Cartwright 2009.

less, *tessera* FR 13 and *sectilia* piece FR 12 from these two batches were found at a different findspot (the portico inside the northern rampart wall – Fig. 2). That would indicate that either these deliveries secured architectural glass for more than just a single building construction in *Romuliana*, or that the blue pieces were subject to secondary redistribution within the site, possibly chronologically later than the original delivery.

The second aspect of single batch samples from the present dataset concerns the production waste pieces. Two of them (FR 7 and FR 9 – a fragment of a misshaped vessel and a small unworked chunk) most probably come from a single glass melting episode, but the remaining two pieces are compositionally slightly different, which could tentatively suggest that blue glass was produced at *Romuliana* in more than just a single isolated batch.

Conclusion

The presented data and interpretations of a set of 18 blue glass pieces from the late Roman site of *Felix Romuliana* are the first attempts to explore the chemical composition of glass finds of the first half of the 4th century from this important imperial residence. The results demonstrate that glasses originating from the Syro-Palestinian region coloured blue by adding various amounts of cobalt-bearing colourant, as well as antimony, commonly used as an opacifier, and supplied to the Central Balkans, mostly for the purposes of luxurious mosaic decorations. The single vessel fragment has a different base glass origin (Egypt?), as well as a different makeup of its added ingredients. Furthermore, the analysed glassworking waste indicates that the local craftsmen were likely using available blue architectural glass pieces as a colouring material in their workshop.

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ПЛАВИ ТОНОВИ РОМУЛИЈАНЕ

Кључне речи. – Касноримски период, централни Балкан, кобалтно плаво стакло, секундарна производња стакла, плочице *sectilia* стакла, коцкице мозаика, стаклени отпад, хемијски састав стакла, *ЕРМА*

У раду је приказано 18 стаклених фрагмената и коцкица мозаика са неколико различитих локација унутар и изван утврђене касноримске царске резиденције Феликс Ромулијане (Гамзиград, Србија). Налази су опредељени у 4. век, са прецизнијим датовањем за одређене комаде. Већину чине коцкице мозаика (6 ком.), комади стаклених плочица (*sectilia sheets* – 5 фрагмената) коришћени у архитектонској декорацији, затим отпаци настали током секундарне стаклене производње (4 ком.), два фрагмента танког равног стакла, које је, са резервом, идентификовано као прозорско, и један уломак стаклене посуде неодређеног типа (Сл. 3 и 4). Фрагменти су нађени унутар и изван „виле” *extra muros*, која се налази северно од утврђене палате (1), у портику, уз северни бедем царског комплекса (2), у палати Д1 (3), и у кули 1 – јужној кули источне капије старије фортификације (4) (Сл. 2; Табела 1). Пар примерака стакленог отпада, као и два фрагмента „прозорског” стакла нађена су у стакларској пећи у Просторији 1 „виле” *extra muros*. Критеријуми за издвајање ове групе налаза представљале су њихове визуелне карактеристике – кобалтноплава боја, пре свега, и њихови морфолошко-типолошки атрибути. Примерци су хемијски испитани помоћу микроанализатора електронске сонде (*ЕРМА*) у Волфсоновим археолошким научним лабораторијама Универзитетског колеџа у Лондону.

Као што је очекивано, сви анализирани узорци уклапају се у оквирне вредности типичног састава римског стакла на бази соде, кречњака и силицијум-диоксида (Табела 2). Што се тиче основне композиције стакла, ова група састоји се од једне релативно уједначене скупине узорака, од које одступају само два налаза – фрагмент стаклене посуде и једна коцкица мозаика (ФР 10 и ФР 14; Сл. 8). У саставу 17 од 18 узорака, однос садржаја алуминијума и силицијум-диоксида, који је индикативан за утврђивање изворишта песка коришћеног у примарној производњи стакла, заједно са релативно ниским вредностима за соду и високим вредностима за кречњак, одговара карактеристикама примарних производних група сиријско-палестинског порекла, изузев за фрагмент стаклене посуде (ФР 10) који би се могао повезати са египатском примарном производњом. Сирово стакло које потиче из сиријско-палестинске области бојено је плаво додавањем различитих количина кобалта, који је коришћен као колорант, и антимона, који је обично служио да стакло учини непрозирним. Такво стакло је достављано на централни Балкан најчешће за потребе луксузних мозаичких декорација. Присуство плаво обојеног стакленог отпада (ФР 7–9 и ФР 11) у контексту стакларске пећи у „вили” *extra muros* представља јасан доказ да плаво стакло није достављано у Ромулијану само као готов производ, већ су локални мајстори (занатлије) такође обрађивали овај материјал за потребе локалне потрошње током периода активног функционисања овог луксузног комплекса. Приликом поређења нивоа садржаја оксида који се односе на боју и непрозирност стакла у узорцима из Ромулијане, констатују се њихове најниже вредности у саставу стаклених отпадака (Сл. 12 и 13). Паралелно са овим, трендови корелације ових оксида показују да су локални мајстори вероватно користили спремно и доступно интензивно бојено архитектонско стакло као колорант у својим плавим смесама, чиме су разблаживали концентрацију кобалта и антимона, а да су и даље могли одржати жељени визуелни изглед своје продукције.