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At the edge of the Empire, at the turn of the millennium: glass supply and glassworking practices on the periphery of Byzantium (a case study of window glass from Veseloye, northwestern Caucasus)☆

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ABSTRACT

The late 1st millennium AD was a period of fundamental transformations in glass production, consumption, and supply in the Mediterranean region and beyond. The data shedding light on these processes at the periphery of Byzantium are very limited so far. A church of the 10th century CE was excavated in Veseloye, in the northwestern Caucasus – the region which was under the strong cultural, economic, and religious influence of the Byzantine Empire. The chemical composition of window panes found here provides data on glass circulation and glassworking practices on the north periphery of the Byzantine world. Most of the colourless windows found here were made using plant ash glass of Levantine origin. The strongly coloured glass is of the high-boron type; it likely originated from Western Anatolia. Its compositional variability points to the complex nature of the fluxing agent, which melted with sand originating from different locations. The data obtained support the idea of several glassmaking workshops operating in parallel in Asia Minor. All the glass found in Veseloye should have been supplied to the north Caucasus through the Byzantine Empire. The peculiarities of its composition reflect the model of manufacturing window panes for the church by commission, probably in the Caucasian region. It is likely that allochthonous craftsmen worked here using imported glass. The evidence for extensive recycling has been attested for some series of high-boron glass.

1. Introduction

The later 1st millennium AD is a period of fundamental transformations taking place in glass production, consumption, and supply in the Mediterranean basin and beyond. For the early Islamic glassmaking centres in the Eastern Mediterranean, it was a time of transition from natron to plant ash glass production (Sayre and Smith, 1974; Gratuze and Barrandon, 1990; Whitehouse, 2002; Henderson, 1999; 2002; Henderson et al., 2004; Phelps et al., 2016; Schibille, 2022 with the references therein). In Western and Central Europe, due to the lack of imported raw glass from the east in the last quarter of the 1st millennium, craftsmen recycled Roman and late antique glass in the period before the transition to wood ash receipt. In Asia Minor and other regions within or neighboring the Byzantine Empire in the Early and Middle Byzantine periods, the production of probably western Anatolian glassmaking centres with elevated boron, alumina, and lithium contents has been identified (Schibille, 2011; Rehren et al., 2015; Swan et al., 2018). By the late 10th century, the Levantine plant ash glass was also imported to the Byzantine Empire and, to a lesser extent, to Europe, from the 9th-10th to the 11th centuries (Siu et al., 2019; Schibille, 2022).

The data published thus far originate mainly from the sites of the Eastern Mediterranean, Western and Central Europe, and Asia Minor. This article aims to introduce the data on the chemical composition of glass from a site of the Middle Byzantine period, studied in the North Caucasus, a region that was under the strong cultural, economic, and religious influence of the Byzantine Empire. Thus, the glass assemblage from Veseloye reflects the model of glass supply to the North Caucasus, the northern periphery of the Byzantine world.

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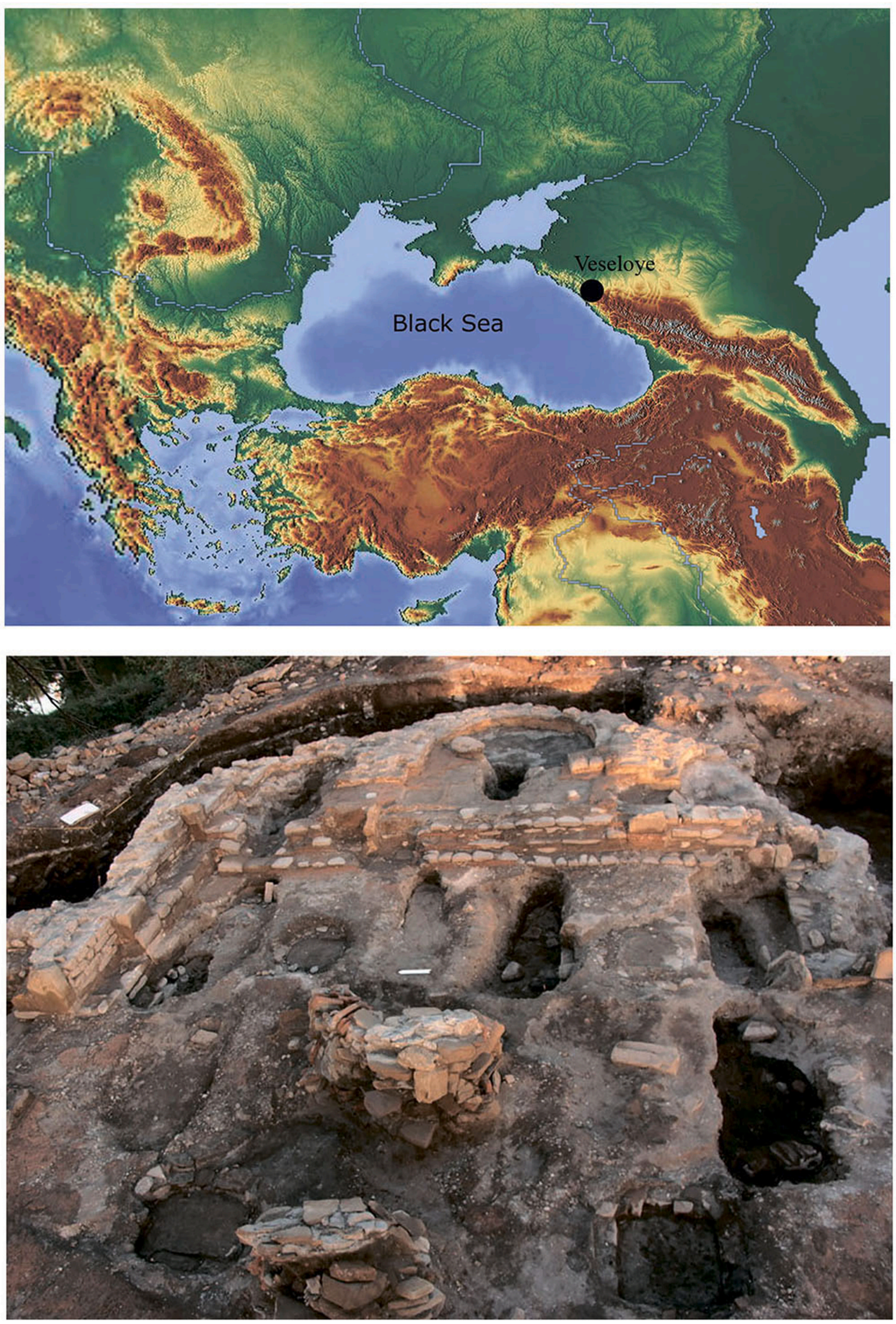
2. The site and material

The church of the Middle Byzantine period was excavated in 2010–2011 by the expedition of the Institute of Archaeology of the Russian Academy of Sciences near the village of Veseloye in the vicinity of the city of Sochi (Russia) in the North Eastern Black Sea region (Fig. 1A). It was built in the 10th century CE and could have been active till the mid-11th century at the latest. From the 8th to the 11th century this territory was part of the Abkhasian and then of the Abkhasian-Kartli Kingdoms, being under the strong influence of the Byzantine Empire. The Christian churches known in the region could have been erected here by Byzantine builders, possibly from Trapezund, or by their apprentices (Armarchuk et al., 2012; Armarchuk and Kuzina, 2024).

The church belongs to the group of monuments that are typical of the Abkhazian kingdom and shares some common features with the churches of Alania, a mediaeval kingdom in the foothills of the North Caucasus. It is a rather large edifice of the cross-in-square type with three apses, a narthex, and three porches (Fig. 1B and 2). Among the original features are the vaulted crypt under the narthex and a well near the south-western corner of the church. The domes appear to have been supported by columns, not piers, which is not typical of other churches in the region (Armarchuk et al., 2012).

Nearly 1100 fragments of blown window panes, *oculi,* were found mainly near the north, western and south walls of the church, first of all, around and within the porches (Fig. 2), above which the window openings should have been situated (Armarchuk and Kuzina, 2024). The



A
B

Fig. 1. (A) Map of the Black Sea region showing the location of Veseloye and (B) a view of the church ruins (after Armarchuk and Kuzina, 2024).

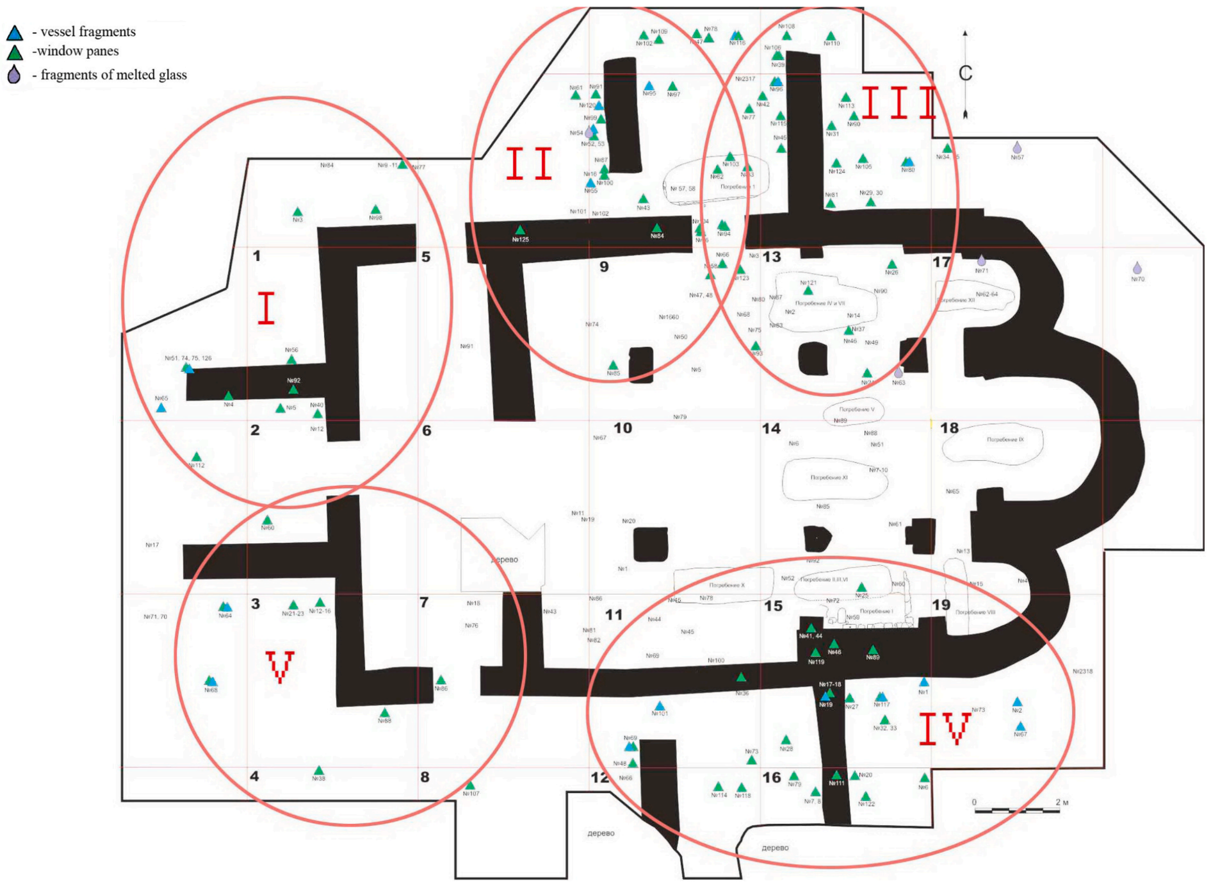


Fig. 2. The location of the finds of window panes near the church. The sector numbers I-V correspond to those in the table 1.

stratigraphy of the finds does not reveal evidence of glazing renovation of the church during its existence.

Nearly half of the window pane fragments are made of colorless and naturally coloured glass, while the others are strongly coloured glass of purple, cobalt blue, emerald green, light blue, and olive colours (Fig. 3; Ibid.). The colour palette of the finds is approximately identical in all sectors.

Some of the coloured window panes were blown using a dip mould; they had relief, the so-called 'optic' decoration (Fig. 3B). Their parallels are well known in the Caucasus south of the region under discussion, in Abkhazia, and primarily in Georgia, where they are believed to have been manufactured (Ibid.).

3. Materials and methods

The first study on the chemical composition of a small series of glass from Veseloe was undertaken earlier using optical emission spectroscopy (Kuzina, 2013; Armarchuk and Kuzina, 2024). In 2023, a new project dedicated to the composition and origin of window glass from sites in the Northern Pontic region was launched. Within the framework of this project, the chemical composition of 63 window glass samples from Veseloe was studied using SEM-EDS and LA-ICP-MS techniques. The sample set includes a series of glasses of each color found at the site, taken from five locations near the church, where they were concentrated (Fig. 2).

3.1. SEM-EDS

Sixty-three samples were mounted in epoxy resin, polished on the cross-sections to a 1 μm diamond suspension finish, and coated with carbon. Major and some minor elements were analyzed using a Tescan Mira LMU scanning electron microscope with an attached energy dispersive spectrometer X-Max 50 (Oxford Instruments) in the Scientific research centre "Wear Resistance" of the National research University "Moscow Power Engineering Institute" (Moscow). The samples were analyzed at an electron beam current of 1.7nA, and an accelerating voltage of 20 kV for a counting live time of 140 s. The EDS data were quantified using INCA Oxford Instruments software. The accuracy and precision of the results were checked by analyzing the Corning Museum of glass A, B, and NIST 620 standards at the beginning of every analytical run (Table S1). For each sample, random areas of approximately 0.1 mm^2 were analysed. The results totalled between 98 and 102 %; they are reported as original analytical totals without normalization. The mean values of four or five separate measurements (excluding strongly deviating data points) are reported. The results are presented as weight oxides, with oxygen calculated by stoichiometry (Table 1). The analytical precision as indicated by the relative standard deviation (SD) is better than 4 % for elements in concentration from 1 wt% and better than 10 % for the majority of elements in concentration between 0.1 and 1 wt%; the accuracy was generally better than 5 % for the former (for CuO and Fe_2O_3 it was 7–8 %) and 10 % for the latter. Due to the SEM-EDS limitations, the data demonstrate poor precision and accuracy for phosphorus (CMG A), sulphur (CMG A, B), titanium (CMG B), tin (CMG A, B), and lead oxides (CMG B), and poor accuracy for antimony oxide (CMG B) at low concentrations. For these oxides, as well as for all elements at concentrations up to 0.1 wt%, only LA-ICP-MS data will be considered (see below)

3.2. LA-ICP-MS

The trace and minor element concentrations were measured using the LA-ICP-MS technique performed with a Perkin Elmer NexION 300S

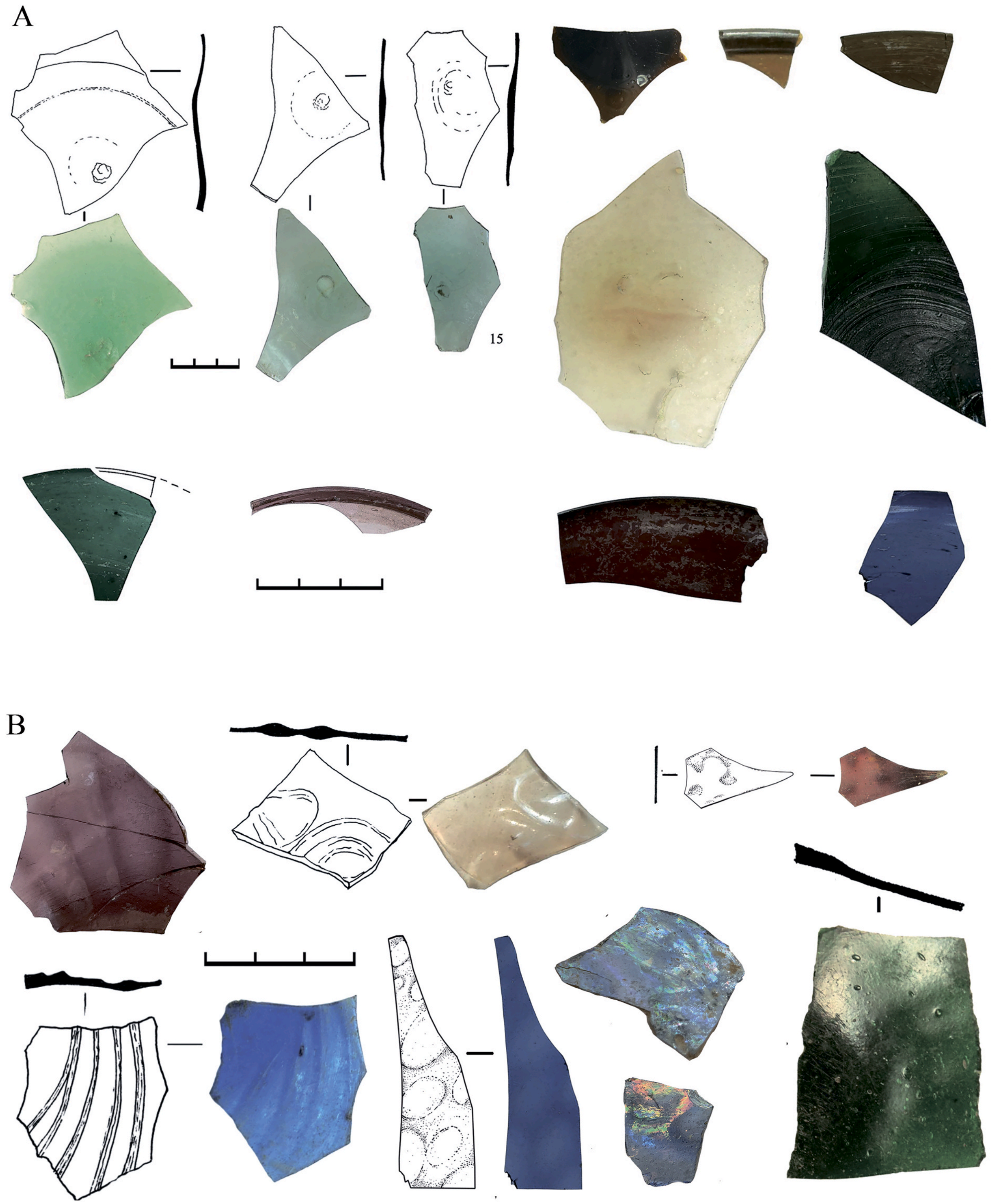


Fig. 3. Selection of window pane fragments from Veseloye, representing different colours. (A) plain; (B) with dip-mould blown décor.

Inductively Coupled Plasma Mass Spectrometer, equipped with an ESI NWR 213 laser ablation sampling device, in the Common Use Centre "Geoanalyst," Institute of Geology and Geochemistry of the Ural Branch of RAS (Ekaterinburg). For LA-ICP-MS measurements, the same samples mounted in epoxy resin as those used for SEM-EDS were used. The laser ablation system parameters: laser beam energy – 10.5–11.5 J/cm^2, the repetition rate of the laser – 10 Hz, laser beam diameter – 50 μm, carrier gas: He (400 ml/min), the analytical time – 50 s, and the blank time – 20 s. The ICP-MS parameters were as follows: the sample was flushed by 1,1–1,2 l/min of argon carrier gas, ICP RF power – 1500 W, dwell time – 10 ms per isotope element, the number of scan cycles – 1, and the number of replicates – 250. The length of the connecting tube between the mass spectrometer and laser ablation system was 1.5 m. The data were quantified using GLITTER V4.4. software. SiO_2 was used as an internal standard; NIST 610 – for the calibration procedure, and NIST SRM 612 – as an external standard to calculate the reproducibility and accuracy. NIST 610 and 612 were measured after every 10–12 sample measurements (the average values and standard deviations were calculated for 19 measurements) (Table S2). The mean values for 3–4 measurements for each studied sample, excluding deviating data points,

Table 1
SEM-EDS data for the glass of window panes from Veseloye, in wt%.

Group	Series	Sample	glass colour	relief décor	sector*	Na_2O	MgO	Al2O3	SiO_2	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	CuO	PbO
GROUP I		Ves-1	colourless	–	V	14.23	3.65	1.66	64.63	0.25	0.78	2.16	11.01	<0,10	0.91	0.38	<0,10	<0,10
Plant ash glass		Ves-10	colourless	+	V	13.21	3.49	1.77	65.33	0.21	0.80	2.35	9.86	<0,10	0.89	0.40	<0,10	<0,10
		Ves-30	colourless	–	IV	12.62	3.34	1.67	65.76	0.21	0.74	2.12	10.27	<0,10	1.41	0.39	<0,10	<0,10
		Ves-34	colourless	–	II	13.37	3.29	1.84	65.30	0.23	0.72	2.32	10.21	<0,10	1.14	0.42	<0,10	<0,10
		Ves-35	colourless	–	II	14.06	3.60	1.63	63.65	0.25	0.76	2.11	10.84	<0,10	0.86	0.36	<0,10	<0,10
		Ves-36	colourless	–	IV	14.22	2.90	1.55	66.66	0.21	0.78	2.13	8.80	<0,10	0.62	0.31	<0,10	<0,10
		Ves-37	colourless	+	I	12.35	3.31	1.73	65.96	0.20	0.72	2.15	10.51	<0,10	1.41	0.42	<0,10	<0,10
		Ves-43	colourless	–	IV	14.07	3.61	1.66	64.16	0.25	0.75	2.12	10.88	<0,10	0.90	0.39	<0,10	<0,10
		Ves-47	colourless	–	IV	14.14	2.88	1.60	68.27	0.22	0.77	2.13	8.80	<0,10	0.63	0.31	<0,10	<0,10
		Ves-54	colourless	–	III	13.85	3.00	1.58	67.42	0.25	0.74	2.05	9.13	<0,10	0.66	0.29	<0,10	<0,10
		Ves-56	colourless	–	V	13.33	3.54	1.73	66.02	0.22	0.68	2.42	9.64	<0,10	0.84	0.45	<0,10	<0,10
		Ves-58	colourless	–	I	14.21	3.64	1.68	64.17	0.24	0.74	2.11	10.79	<0,10	0.91	0.37	<0,10	<0,10
		Ves-61	colourless	+	II	13.37	3.47	1.80	65.85	0.22	0.77	2.34	9.86	<0,10	0.94	0.39	<0,10	<0,10
		Ves-31	colourless with light greenish hue	–	V	14.36	2.87	1.70	66.23	0.23	0.69	1.97	9.12	<0,10	0.65	0.45	<0,10	<0,10
		Ves-33	colourless with light bluish hue	–	IV	14.20	2.89	1.77	66.38	0.21	0.68	1.98	9.11	<0,10	0.65	0.46	<0,10	<0,10
		Ves-24	purple	–	IV	13.38	3.39	1.83	64.83	0.22	0.60	2.22	9.11	<0,10	1.79	0.52	<0,10	<0,10
		Group I, mean				**13.69**	**3.30**	**1.70**	**65.66**	**0.23**	**0.73**	**2.17**	**9.87**	**<0,10**	**0.95**	**0.39**	**<0,10**	**<0,10**
GROUP II	Series II.1	Ves-14	aqua bluish	–	V	15.77	2.31	2.51	64.52	0.42	0.15	1.77	10.32	0.12	<0,10	1.21	<0,10	<0,10
High B, high Li glass (HBLi)		Ves-15	aqua bluish	–	V	15.40	2.39	2.60	64.47	0.38	0.15	1.89	10.51	0.13	<0,10	1.25	<0,10	<0,10
		Ves-16	aqua bluish	–	IV	15.22	2.43	2.57	64.37	0.35	0.14	1.93	10.65	0.14	<0,10	1.25	<0,10	<0,10
		Ves-63	blue-green	–	II	16.05	2.39	2.57	63.83	0.39	0.13	1.77	10.03	0.12	<0,10	1.22	<0,10	<0,10
		Series II.1, mean				**15.61**	**2.38**	**2.56**	**64.30**	**0.39**	**0.14**	**1.84**	**10.38**	**0.13**	**<0,10**	**1.23**	**<0,10**	**<0,10**
	Series II.2	Ves-2	aqua bluish	–	V	22.15	0.84	1.86	64.38	0.20	0.59	0.70	7.29	0.10	0.23	0.70	<0,10	0.49
		Ves-3	aqua bluish	–	V	21.96	0.85	1.86	64.40	0.19	0.62	0.70	7.18	<0,10	0.24	0.71	<0,10	0.53
		Ves-7	aqua bluish	–	V	22.17	0.84	1.90	64.45	0.21	0.54	0.71	7.31	<0,10	0.21	0.71	<0,10	0.44
		Ves-11	aqua bluish	–	V	22.42	0.81	1.78	63.83	0.20	0.58	0.69	7.23	<0,10	0.21	0.70	<0,10	0.39
		Ves-20	aqua bluish	–	IV	21.93	0.84	1.86	63.96	0.20	0.62	0.72	7.17	0.11	0.24	0.71	<0,10	0.52
		Series II.2, mean				**22.13**	**0.84**	**1.85**	**64.20**	**0.20**	**0.59**	**0.70**	**7.24**	–	**0.23**	**0.71**	**<0,10**	**0.47**
	Series II.3	Ves-4	dark blue	–	V	17.70	1.25	2.56	64.10	0.21	0.57	1.10	7.42	0.14	0.58	2.87	0.56	0.24
		Ves-12	dark blue	–	V	17.63	1.23	2.59	63.81	0.21	0.58	1.09	7.34	0.15	0.59	2.89	0.58	0.24
		Ves-13	dark blue	–	IV	17.59	1.24	2.56	63.61	0.20	0.56	1.11	7.29	0.15	0.57	2.70	0.52	0.28
		Ves-28	dark blue	–	V	17.87	1.28	2.59	63.60	0.23	0.57	1.11	7.31	0.16	0.58	2.84	0.53	0.26
		Ves-40	dark blue	–	IV	17.79	1.24	2.59	63.94	0.22	0.58	1.10	7.34	0.15	0.59	2.80	0.50	0.24
		Ves-52	dark blue	–	III	17.88	1.26	2.58	63.93	0.22	0.56	1.11	7.28	0.15	0.56	2.81	0.53	0.22
		Ves-57	dark blue	+	V	17.80	1.23	2.58	63.72	0.22	0.56	1.12	7.26	0.13	0.58	2.79	0.52	0.27
		Series II.3, dark blue, mean				*17.75*	*1.25*	*2.58*	*63.82*	*0.22*	*0.57*	*1.11*	*7.32*	*0.15*	*0.58*	*2.81*	*0.53*	*0.25*
		Ves-6	emerald green	–	V	17.53	1.28	2.38	62.45	0.22	0.61	1.08	7.41	0.12	0.42	1.13	4.68	0.28
		Ves-18	emerald green	+	–	17.46	1.32	2.36	62.04	0.21	0.60	1.10	7.41	0.13	0.44	1.14	4.62	0.25
		Ves-41	emerald green	–	IV	17.67	1.32	2.38	62.35	0.22	0.61	1.09	7.37	0.13	0.43	1.14	4.40	0.31
		Ves-51	emerald green	–	III	17.68	1.32	2.38	62.31	0.21	0.60	1.09	7.43	0.14	0.43	1.11	4.56	0.29
		Series II.3, emerald green, mean				*17.59*	*1.31*	*2.38*	*62.29*	*0.22*	*0.61*	*1.09*	*7.41*	*0.13*	*0.43*	*1.13*	*4.57*	*0.28*
		Ves-8	purple	–	V	17.84	1.33	2.45	63.49	0.18	0.52	1.10	7.69	0.14	2.90	1.23	<0,10	0.25
		Ves-9	purple	+	V	18.08	1.32	2.50	63.51	0.21	0.56	1.14	7.75	0.13	2.05	1.21	<0,10	0.23
		Ves-26	purple	–	–	17.69	1.34	2.45	63.07	0.18	0.50	1.12	7.69	0.15	2.88	1.23	<0,10	0.28
		Ves-53	purple	–	III	17.98	1.33	2.47	63.23	0.18	0.51	1.09	7.63	0.13	2.77	1.19	<0,10	0.36

(*continued on next page*)

Table 1 (*continued*)

Group	Series	Sample	glass colour	relief décor	sector*	Na_2O	MgO	Al2O_3	SiO_2	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	CuO	PbO
		Ves-60	purple	–	II	17.91	1.32	2.45	63.06	0.17	0.50	1.09	7.58	0.14	2.83	1.21	<0,10	0.31
		Series II.3, purple, mean				*17.90*	*1.33*	*2.46*	*63.27*	*0.18*	*0.52*	*1.11*	*7.67*	*0.14*	*2.69*	*1.21*	<0,10	*0.29*
		Ves-5	olive green	–	V	16.80	1.37	3.53	65.49	0.17	0.73	1.24	8.04	0.24	0.34	1.65	<0,10	0.15
		Ves-23	olive green	–	IV	17.02	1.39	3.43	64.25	0.17	0.69	1.21	7.81	0.23	0.33	1.54	<0,10	0.19
		Ves-29	olive green	–	III	16.94	1.37	3.49	64.26	0.17	0.71	1.21	7.86	0.23	0.34	1.59	<0,10	0.20
		Ves-49	olive green	–	IV	17.05	1.38	3.45	64.72	0.19	0.72	1.22	7.83	0.22	0.34	1.54	<0,10	0.19
		Ves-62	olive green	–	II	16.29	1.39	4.02	65.45	0.15	0.50	1.33	7.41	0.29	0.32	1.86	<0,10	0.14
		Series II.3, olive green, mean				*16.82*	*1.38*	*3.58*	*64.83*	*0.17*	*0.67*	*1.24*	*7.79*	*0.24*	*0.33*	*1.64*	<0,10	*0.17*
		Ves-46	blue-green	–	IV	18.82	1.31	2.43	65.28	0.20	0.65	1.08	7.52	0.13	0.44	1.05	<0,10	0.28
		Series II.3, mean				**17.53**	**1.31**	**2.75**	**63.64**	**0.20**	**0.59**	**1.14**	**7.53**	**0.16**	**0.99**	**1.83**	–	**0.25**
	Series II.4	Ves-19	light blue	+	IV	19.63	3.63	2.84	65.63	0.16	0.48	1.83	3.91	0.18	0.10	0.90	0.06	0.08
		Ves-22	light blue	+	IV	19.57	3.59	2.83	65.73	0.15	0.48	1.85	3.83	0.19	0.10	0.91	0.07	0.06
		Ves-38	light blue	+	IV	21.24	2.88	2.88	64.46	0.16	0.49	1.92	3.33	0.17	<0,10	0.93	0.06	0.03
		Ves-44	light blue	+	IV	21.07	2.74	2.92	66.26	0.15	0.50	2.01	2.98	0.19	<0,10	0.93	0.07	0.04
		Series II.4, mean				**20.38**	**3.21**	**2.87**	**65.52**	**0.16**	**0.49**	**1.90**	**3.51**	**0.18**	–	**0.92**	**0.07**	**0.05**
	Series II.5	Ves-17	emerald green	–	III	17.42	0.85	2.87	62.35	0.18	0.70	0.81	6.47	0.17	0.64	1.27	5.62	0.46
		Ves-21	emerald green	–	IV	17.39	0.85	2.81	61.56	0.20	0.70	0.80	6.38	0.17	0.62	1.23	5.54	0.38
		Ves-25	emerald green	–	–	17.29	0.84	2.81	61.64	0.19	0.70	0.79	6.40	0.16	0.62	1.23	5.38	0.40
		Ves-55	emerald green	–	V	17.59	0.86	2.86	62.10	0.21	0.69	0.80	6.36	0.18	0.62	1.25	5.57	0.40
		Series II.5, mean				**17.42**	**0.85**	**2.84**	**61.91**	**0.20**	**0.70**	**0.80**	**6.40**	**0.17**	**0.63**	**1.25**	**5.53**	**0.41**
	Outliers	Ves-59	olive green	–	I	18.92	3.32	3.58	63.09	0.18	0.48	1.91	6.15	0.20	0.19	1.03	<0,10	<0,10
		Ves-50	blue-green	–	III	20.05	1.18	2.20	65.85	0.29	0.49	0.98	6.92	0.12	0.24	0.89	<0,10	<0,10
GROUP III	Series III.1	Ves-39_mean	purple	–	–	19.50	0.47	0.97	65.84	<0,10	0.36	0.29	8.92	<0,10	2.06	0.91	<0,10	<0,10
Elevated B, low Li glass		Ves-42_mean	purple	+	IV	18.69	0.63	1.13	68.61	<0,10	1.13	0.22	6.97	<0,10	0.97	0.41	<0,10	<0,10
		Ves-45_mean	colourless	–	IV	19.57	0.43	1.06	71.24	<0,10	0.93	0.26	5.47	<0,10	<0,10	0.36	<0,10	<0,10
		Series III.1, mean				**19.25**	**0.51**	**1.05**	**68.56**	<0,10	**0.81**	**0.26**	**7.12**	**<0,10**	–	**0.56**	<0,10	<0,10
	Series III.2	Ves-27_mean	blue-green	–	V	18.11	0.86	3.50	65.90	0.15	0.81	0.81	6.98	0.22	0.56	1.14	<0,10	0.23
		Ves-32_mean	bluish	–	IV	17.48	0.89	3.42	64.75	0.19	0.81	0.85	7.22	0.24	0.70	1.34	<0,10	0.36
		Ves-48_mean	blue-green	–	IV	18.02	0.89	3.50	65.71	0.19	0.81	0.79	7.28	0.22	0.66	1.54	<0,10	0.35
		Series III.2, mean				**17.87**	**0.88**	**3.47**	**65.45**	**0.18**	**0.81**	**0.82**	**7.16**	**0.23**	**0.64**	**1.34**	<0,10	**0.31**

are given as the results (Table 2).

Results and discussion

4.1. Base glass composition

All the studied samples are of the soda-lime-silica type, with low or elevated content of magnesium and potassium oxides, which are positively correlated with one another as well as with lithium and, to a lesser extent, boron (Fig. 4A, 4B). The sample set comprised three basic compositional groups (Tables 1-3). One of them (the group I) is a group of colourless plant ash glass, which is compositionally homogenous. Group II is a low-alumina glass with high concentrations of boron and lithium. It contains samples of naturally and strongly coloured glass of various colours, which are exceptionally variable in composition. The group III includes low-alumina glass with low lithium and slightly elevated boron concentration – colourless, purple, and naturally coloured.

Group I. Plant ash glass (16 samples).

Colourless window panes represent a chemically homogenous group

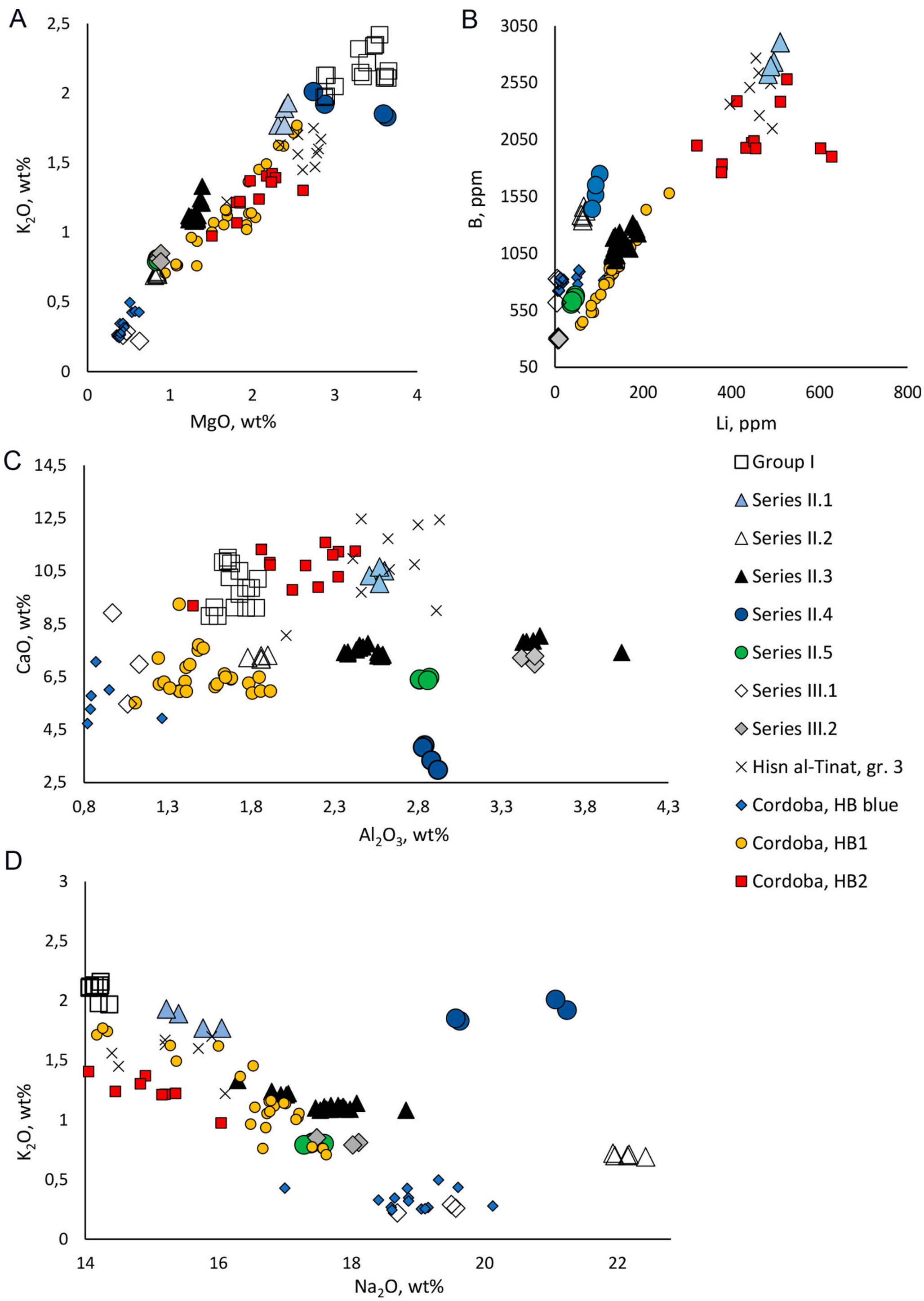


Fig. 4. Glass from Veseloye compared to high-boron samples from Ḥiṣn al-Tīnāt (Swan et al., 2018) and Córdoba (Gómez-Morón et al., 2021). Flux-related elements content and ratios.

Table 3
Average chemical compositions of the glass groups identified in Veseloye (SEM-EDS, LA-ICP-MS data).

Groups	Type, origin	Series	Colour	Level of recycling markers		wt% Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	ppm Li	B	As	Sr	Zr	Ba
Group I	Levantine plan ash	–	colourless, n = 15	very low	Mean	13.69	3.30	1.70	65.66	0.16	0.73	2.17	9.87	0.07	0.95	0.39	6.95	102	3,59 (2,91*)	642	39.2	244
(n = 16)			purple, n = 1	moderate	Stdev	0.61	0.30	0.09	1.23	0.01	0.05	0.13	0.79	0.00	0.33	0.06	1.06	51.1	4,90 (2,55*)	90.6	5.5	35.9
Group II	HBLi Asia Minor (Western Anatolia)	Series II.1	naturally coloured	very low	Mean	15.61	2.38	2.56	64.30	0.07	0.14	1.84	10.38	0.12	0.03	1.23	495	2742	38.2	2737	35.4	87.9
(n = 41)	mineral soda	n = 4			Stdev	0.37	0.05	0.04	0.32	0.002	0.01	0.08	0.27	0.01	0.001	0.02	11.7	117.7	1.96	250.0	2.6	1.2
		Series II.2	naturally coloured	high	Mean	22.13	0.84	1.85	64.20	0.11	0.59	0.70	7.24	0.10	0.23	0.71	64	1399	39.2	330	54.1	123
		n = 5			Stdev	0.20	0.02	0.04	0.29	0.01	0.03	0.01	0.06	0.01	0.02	0.01	3.8	46.4	2.0	17.3	4.9	4.6
		Series II.3	strongly coloured, n = 21	high**	Mean	17.53	1.31	2.75	63.64	0.11	0.59	1.14	7.53	0.16	0.99	1.83	152	1160	59.5	875	71.6	328 (183*)
		n = 22	naturally coloured, n = 1	high	Stdev	0.52	0.05	0.49	0.97	0.01	0.07	0.07	0.22	0.04	0.97	0.74	18.9	90.5	40.2	85.3	7.6	271,7 (22,2*)
		Series II.4	coloured	very low or moderate	Mean	20.38	3.21	2.87	65.52	0.18	0.49	1.90	3.51	0.20	0.08	0.92	92.4	1603	6.1	179	226	102
		n = 4	light blue, n = 4	(selective recycling?)	Stdev	0.90	0.47	0.04	0.76	0.02	0.01	0.08	0.44	0.02	0.02	0.02	6.8	130.6	1.2	18.9	21.0	8.6
		Series II.5	emerald green, n = 5	?	Mean	17.42	0.85	2.84	61.91	0.12	0.70	0.80	6.40	0.19	0.63	1.25	41.9	643	122	440	107	248
		n = 5			Stdev	0.12	0.01	0.03	0.38	0.01	0.01	0.01	0.05	0.01	0.01	0.02	4.4	30.4	10.7	26.5	8.2	8.4
Group III	Asia Minor (Western Anatolia) mineral soda	Series III.1	colourless, n = 1	very low	Mean	19.25	0.51	1.05	68.56	0.07	0.81	0.26	7.12	0.06	0,01*; 1,52***	0.56	5.93	754	29.9	73	29.5	66,8*; 225***
(n = 6)		n = 3	purple, n = 2	moderate	Stdev	0.49	0.11	0.08	2.70	0.02	0.40	0.04	1.73	0.01	–	0.30	1.99	117.3	12	28.4	3.8	–
		Series III.2	naturally coloured	high	Mean	17.87	0.88	3.47	65.45	0.11	0.81	0.82	7.16	0.22	0.64	1.34	7.67	302	32.7	408	125	263
		n = 3		(recycled HBLi + natron glass?)	Stdev	0.34	0.02	0.05	0.62	0.001	0.00	0.03	0.16	0.003	0.07	0.20	0.96	6.5	1.4	48.9	2.3	20.5

* – except for the purple glass.
** – definable for purple and olive glass.
*** – purple glass.

of high-quality plant ash glass that is perfectly decolourised with manganese (Fig. 4A, C, D). Only two samples have a very slight natural greenish or bluish hue. One sample of purple glass is coloured with Mn (see below). The concentration of silica-related elements (titanium, iron, zirconium, etc.), along with the content of magnesium, potassium, and phosphorus moderate for plant ash glass, as well as a rather high concentration of lime, suggest its Levantine origin (Freestone, 2002; Phelps et al., 2016; Schibille, 2022 with references therein). The thorium to zirconium (1000/(Th/Zr) – 19.2–24.5, mean 21.5) and lanthanium to titanium ratios (La/TiO_2 – 58–80, mean 72.5) correspond to Tyre-type plant ash glass (Schibille, 2022, 116-118, Fig. 36).

Levantine plant ash glass was imported into the Byzantine Empire and regions under its control, likely by the 10th century CE. It has been identified among window panes of the Pantocrator church (Zeyrek Camii) in Constantinople (11th–12th centuries AD), suggesting that the Byzantines acquired the glass from the Levant to produce window panes for the major religious buildings commissioned by the Komnenoi family; it was also imported for architectural decorations and personal adornment throughout the 10th–13th centuries (Siu et al., 2019, 2645–2646, with the references therein). A large cargo from the Serçe Limani shipwreck, which sank off the coast of Bodrum in southwest Turkey, included raw glass of Levantine origin; it is dated to the 11th century (Bass et al., 2009; Schibille, 2022, 122-123). It is likely that the glass of the group I was imported to the North Caucasus through the Byzantine Empire, more precisely, through Asia Minor.

Groups II and III: high boron glass.

Rehren et al. (2015) have indicated the threshold of boron content for high boron glass as 500 ppm. High-boron glass from the Mosque of Córdoba contains more than 400 ppm B (Gómez-Morón et al., 2021). The boron concentrations in the glass of group II from Veseloye are higher, ranging from 619 to 2906 ppm. The Li content ranges from 37 to 511 ppm and is generally comparable with its values in glass tesserae from Córdoba (more than 60 ppm), with the exception of one series. In all the cases these concentrations significantly exceed Li content in "typical" Eastern Mediterranean soda-lime-silica glass melted with natron or plant ash, and they are comparable with those in high-B glass from Ḥiṣn al-Tīnāt in western-central Anatolia (Swan et al., 2018). Further, we label this group as HBLi (high boron, high lithium).

The glass of the group III features low (up to 8 ppm) lithium content and slightly elevated boron (297–828 ppm); the latter is marginally higher than in "typical" soda-lime-silica glass.

The glass with high concentrations of boron and lithium of the early and middle Byzantine period likely originated from Western Anatolia, and all the finds are connected to territories within or immediately neighboring the Byzantine world (Schibille, 2011; Rehren et al., 2015; Swan et al., 2018). The largest known dataset of high-boron glasses originates from the Mosque of Córdoba, which received the mosaic tesserae from Byzantine emperors in the 10th century as a diplomatic gift (Gómez-Morón et al., 2021). Brill (2002, 17) suggested that high boron levels possibly derive from plants harvested in Western Turkey; Schibille (2011) proposed that the high boron is due to evaporitic mineral soda sources rich in boron, lithium and strontium, probably Western Anatolian borate deposits, which were used as flux (Swan et al., 2018, with the references therein). A significant part of published glass of high B, high Li composition features also very high alumina content (> 5 wt% of Al_2O_3 – Schibille, 2011; Rehren et al., 2015; Swan et al., 2018, Table 2).

High boron glass from Veseloye is very heterogeneous compositionally, which is generally typical of glass of this type (Gómez-Morón et al., 2021). Alumina concentration, often high in the glass of such composition, does not exceed 4 wt% and is lower on average.

Based on lithium, boron, magnesium, and potassium, as well as other flux- and, to a lesser extent, silica-related element concentrations and ratios, seven tight clusters (*series*) (five for group II and two for group III) can be distinguished (Fig. 4; Tables 1, 3).

Exceptionally variable content of magnesium and potassium oxides (0.43–3.63 wt% MgO, 0.22–2.01 wt% K_2O) in the glass with high B concentrations is especially worth noting. The "natural" threshold between their low and high content seems to correspond to the same 1.5 wt % determined for natron and plant ash glass (Sayre and Smith, 1961; Brill, 1970). Although its nature in high-boron glass is still unclear, we use this value as a reference for low and high levels of potassium and magnesium.

Group II. Glass with high lithium and boron concentrations (41 sample).

This group includes five glass series. Two of them, series 1 and 2, contain naturally coloured translucent glass with bluish or greenish hues. They differ considerably in terms of base and trace element composition as well as recycling markers. The series 3–5 mostly include strongly coloured glass.

Series II.1 (4 samples).

This series features the highest in the sample set content of Li and B (495 and 2742 ppm on average), as well as very high Sr content (2737 ppm) and elevated concentrations of arsenic, rubidium, caesium, germanium, and chromium. Magnesium and potassium oxides' concentrations are also high (2.38 and 1.84 wt%). Nevertheless, in the glass they are hardly related to a possible ash component, while they are accompanied by low phosphorus content (0.07 wt% P_2O_5). The soda and chlorine levels are the lowest in group II.

Among high-boron glass, this compositional group is best determined. The series II.1 is close to group 3 from Ḥiṣn al-Tīnāt in south-central Turkey, dated to the 10th-12th centuries (Swan et al., 2018), in terms of the majority of base and trace element concentrations, with the exception of iron and titanium. A group of samples featuring a close trace element pattern but differing in average concentration of alumina, chlorine, magnesium, and iron values also originate from the Mosque of Córdoba. Such composition has been identified there among the tesserae – a diplomatic gift of the Byzantine emperor to the caliph of Córdoba, dating to the first half/mid-10th century CE (samples with low Ba values in the group HB2 – Gómez-Morón et al., 2021). The difference between the glass from Veseloye, Ḥiṣn al-Tīnāt and Córdoba could be due to the generally extremely variable composition of the high-boron glass, as well as to different sources of raw materials (first of all, alkali sources). Close compositions have also been identified in Aphrodisias, Hagia Sophia and Sardis (Gómez-Morón et al., 2021, with references therein). Elevated Sr and Rb concentrations have also been observed in HBAL glass from Pergamon, as well as a very low concentration of chlorine (Rehren et al., 2015), attested also in Veseloye.

Series II.2 (5 samples).

This series of naturally coloured glass significantly differs compositionally from the series II.1. Li and B concentrations are much lower (64 and 1399 ppm), as are the levels of Sr, Cr, Rb, Ge, and Cs. At the same time, As content is still high. As regards the base composition, the glass of the series II.2 is also lower in magnesium and potassium content, which is below 1 wt%, as well as in silica-related elements – alumina, calcium and iron – but higher in soda, chlorine and slightly higher in phosphorus.

Among three series of coloured HBLi glass, the most numerous one contains glass of deep blue, emerald green and purple colours, as well as a number of samples with an olive tinge, and only one naturally coloured window pane. Two "monochrome" series consist of light blue and emerald green glass.

Series II.3 (22 samples).

The glass of this series, the most numerous in Veseloye, features moderately elevated concentrations of Li (132–188 ppm) and B (991–1313 ppm). MgO and K_2O are below 1.5 wt%, P_2O_5 content is low. Alumina and titanium concentrations are higher in the olive glass compared to their concentrations in the glass of other colours, which is due to a colouring agent. The iron concentration is variable and also depends on colour (see below).

Among the glass of this series are 21 samples of strongly coloured glass, plain and mould blown, and one of naturally coloured (aqua blue) glass.

Series II.4 (4 samples).

This series consists only of light blue glass with dip-mould blown décor. It is high in soda (20.4 wt%), magnesium (3.21 wt%), and potassium (1.90 wt%), differing considerably by the lowest in the sample set content of calcium (3.51 wt%), as well as low strontium (179 ppm) and barium (101 ppm) content, along with a high concentration of zirconium (226 ppm) and titanium (0.20 wt% TiO_2), suggesting a primary origin differing from that of all other HBLi groups. Thorium content (3.19 ppm) is the highest in Veseloye. Its base and trace element pattern resembles those of glass melted using Egyptian sands. For different periods, soda-lime-silica – first of all, natron glass with high sodium, titanium and zirconium as well as low lime, strontium and barium in different combinations – was associated with the Egyptian glass making (Freestone et al., 2003; Nenna et al., 2000; Nenna and Gratuze, 2009; Panighello et al., 2012; Rolland and Venclová, 2021 and many others). Nevertheless, the composition of the series II.4 finds no parallels among the synchronous Egyptian plant ash groups E1-E4 (Schibille, 2022). Low Sr content points to the use of inland sand with limestone rather than the coastal sand containing seashells as a source of lime (Freestone et al., 2003). Dip-mould blown glass of other colours differs compositionally from the light blue.

Series II.5 (4 samples).

This series contains only emerald green glass, differing from the glass of the series II.3 (also including emerald green) by a lower content of lithium (37–46 ppm) and boron (609–677 ppm), elements related to them (Sr, Rb, Cs, Ge), as well as a slightly lower level of magnesium and potassium oxides, along with a higher level of titanium, zirconium and barium. It suggests another primary origin or, at least, another glass batch.

Outliers.

Two samples of HBLi glass (group II) cannot be associated with one of the series. One of them (Li 80 ppm, B 1410 ppm) features high MgO (3.31) and K_2O (1.91 wt%) content, typical for the Eastern Mediterranean glass of this period, with a rather high phosphorus concentration (near 0.26 wt%). A rather high content of copper (179 ppm) in the glass of olive colour suggests that it contains recycled glass. Possibly it's the result of a mixture of plant ash and HBLi material. The second one, of naturally coloured glass (Li – 184 ppm, B – 1849 ppm), with low content of MgO and K_2O (1.18 and 0.98 wt%), also containing elevated levels of recycling markers (Cu and Pb), might be a mixture of natron and HBLi glass.

Group III. Low Li, elevated B glass (6 samples).

This group includes six samples of glass with low (up to 8 ppm) lithium and slightly elevated boron (up to 828 ppm) content, rather heterogenous compositionally. Low magnesium, potassium and phosphorus concentrations bring it closer to natron glass; nevertheless, these samples have no parallels among primary compositional groups widespread in the Mediterranean basin in the 1st millennium AD.

Series III.1 consists of three samples – one of colourless and two of purple glass. It features high soda (19.25 wt% Na_2O), very low magnesium (0.51 wt% MgO) and potassium (0.26 wt% K_2O) and variable lime (5.47–8.92 wt%) content. Low concentrations of silica-related elements (alumina, iron, titanium, barium, zirconium and others) in the glass of this series point to the use of a very pure silica source, suggesting the source of the stabilizer other than molluscan shells occurring in the beach sand (Freestone et al., 2003). Manganese in the colourless glass (81 ppm) has not been added intentionally; nevertheless, the glass has no natural hue. Low levels of recycling markers in two samples of three suggest that it is rather a primary than a "mixed" group containing much recycled material.

Close compositional parallel of this glass originates from the Mosque of Córdoba. It is the group of high boron blue tesserae featuring almost identical base and trace element patterns, with the exception of an averagely higher lithium value (32.5 ppm) (Gómez-Morón et al., 2021).

Series III.2 includes three samples of naturally coloured glass with a bluish aqua hue. Boron concentration (near 300 ppm) is slightly higher than the upper threshold of 250 ppm determined for "typical" European and Near Eastern glass (Rehren et al. 2015: 275). It represents another primary group, being much higher in alumina, iron, titanium, strontium, zirconium, and barium than the glass of the series III.1. The Mn content of 0.64 wt% on average suggests its intentional addition; nevertheless, it's not enough for decolourising. Moderate level of magnesium, potassium and phosphorus oxides, along with the highest in the sample set average chlorine content and spectacular signs of recycling (see below), suggest the possibility of mixing recycled HBLi and natron glass.

The series of HBLi and elevated-boron glass (groups II and III) could be interpreted as glass of different primary origin, or related to different glazing campaigns, or simply to different glass batches melted during the same production event (see below). The contents and ratios of the base and trace elements allowed distinguishing three main components in the glass composition. High sodium content, reaching in some series 19–22 wt%, supports the hypothesis of the mineral nature of one of them – probably, fluxing agents from soda-rich evaporites characterised by elevated boron levels (Schibille, 2011; Swan et al., 2018; Gómez-Morón et al., 2021). At the same time, a high content of magnesium and potassium in some series of the group II (as well as in some published data) and a strong correlation between them could indicate the presence of an "ash component" in the batch (Gómez-Morón et al., 2021). The "natural" threshold for high- and low-magnesium and –potassium glass of about 1.5 wt% corresponds to the one between natron and plant ash glass, likely supporting this suggestion. Nevertheless, low phosphorus values and the lack of correlation between it and positively intercorrelated magnesium and potassium are not typical of glass containing plant ash. In the glass of the groups II and III (except for the series II.4, which is separate and its origin is certainly related to a distinct glassmaking centre), magnesium, potassium, sulphur, lime, lithium, boron, strontium, rubidium, chromium, germanium, and caesium are strongly intercorrelated ($R^2 = 0.62$–0.99), although their ratios slightly differ for different series (Fig. 4). These elements were introduced into the glass with a fluxing agent. At the same time, they are negatively correlated with soda and chlorine (which are not correlated between them, with the exception of the series II.4), suggesting the presence of a second source of sodium in the glass batch. Potassium and magnesium also negatively correlate with In, Sn, Pb, and U. A negative correlation between sodium and positively correlated magnesium and potassium oxides has been previously attested for the group HB1 (Gómez-Morón et al., 2021), and this tendency generally characterises high boron glasses of different groups – from Veseloye as well as for published materials (Fig. 4). Na/B ratios of the glass from Veseloye, which could indicate the source of the fluxing agent (Swan et al., 2018, p. 227-228), are extremely variable: for glass without recycling markers in the composition, they vary between 40 and 220. It could suggest that the HB glass from Veseloye represents a mixture of glass of different compositions (see Freestone et al., 2005), although the end members are not evident (Figs. 4 and 5). It could have been high boron glass of different groups, containing flux-related elements in a different proportion. Among the tesserae from the Mosque of Córdoba, a group with a positive correlation between Na and U, with elevated content of Mg and K oxides, has been identified (HB 1 – Gómez-Morón et al., 2021). The glass with close compositional features seems to suit well to the role of one of the components. The different order of the glass series from Veseloye in the diagrams (from low to high concentrations), as well as slightly different Li/B, Na_2O/B, and Na_2O/K_2O ratios, support the idea of two (or more) components based on different fluxing agents in the resulting composition of glass.

It might also be suggested that a second fluxing agent was added to the batch at a certain stage of the melting process. This feature could also be influenced by recycling practices attested for the glass of most series from Veseloye (see below).

Among the recycled glass influencing sodium to magnesium and potassium ratios could have been natron glass cullet, especially strongly

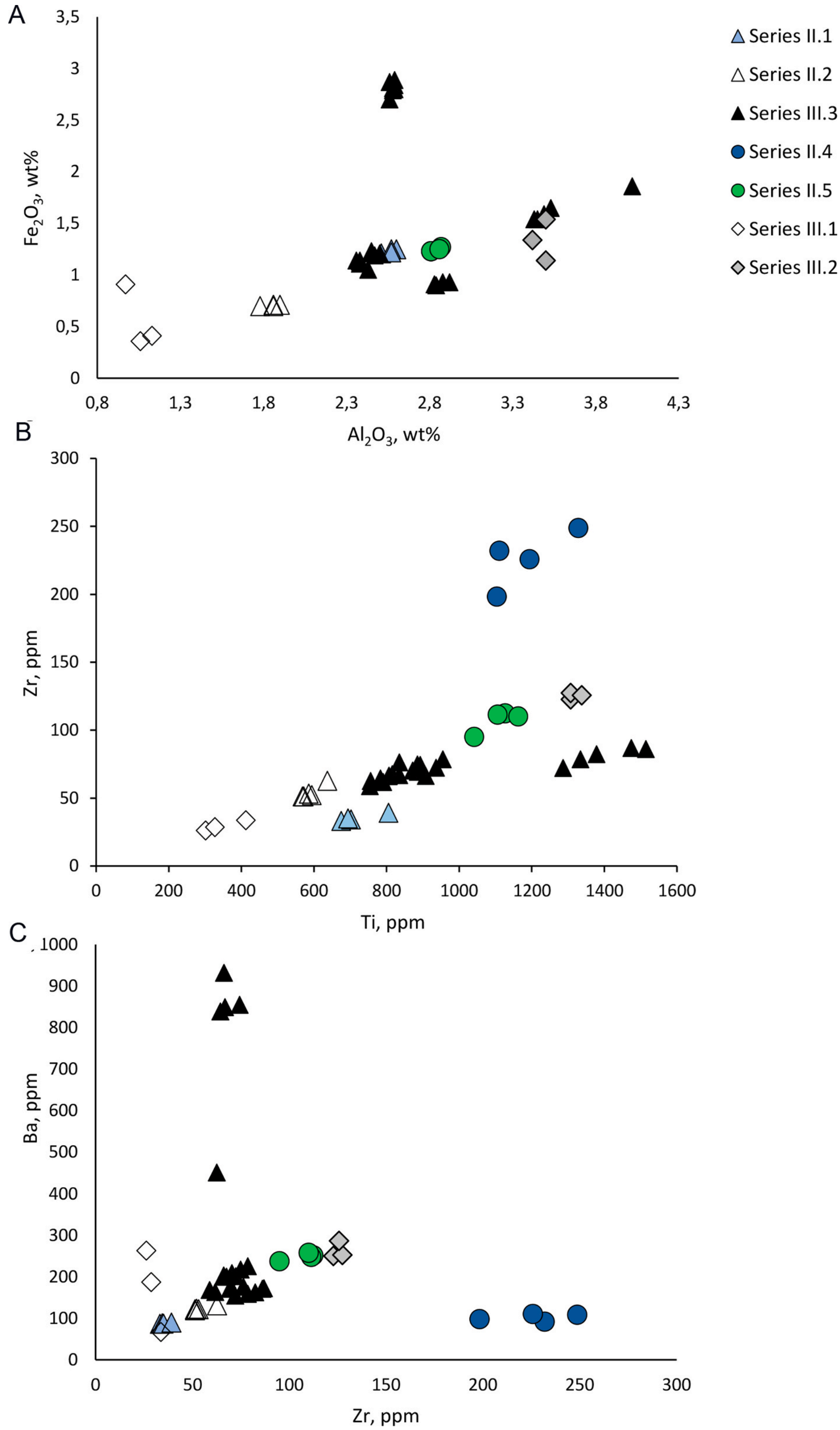


Fig. 5. High-boron glass from Veseloye. Silica-related elements' content and ratios.

coloured, which was extensively recycled in Europe in the later first millennium AD (Henderson, 1995; Jackson, 1996; Foy et al., 2003; Silvestri and Marcante, 2011: 2513; Schibille and Freestone, 2013; Zori et al., 2023). Indeed, some series of glass from Veseloye feature pronounced signs of recycling (see below). At the same time, the lack of correlation between Na_2O and Cl suggests that its influence (if there was one at all) on the resulting composition was limited. Moreover, the highest sodium content in the HBLi glass from Veseloye (22.13 wt%) exceeds its concentration in the series of natron glass widespread in the Mediterranean region (below 20 wt% – Foy et al., 2003, 2004; Cholakova and Rehren, 2018; Gratuze, 2018; see also Schibille, 2022, 35). It means that the addition of natron glass (with low Mg and K values) has not resulted in a higher concentration of sodium.

The third group of elements is related to silica and includes iron, alumina, titanium, zirconium, hafnium and barium (Fig. 5), which are also strongly intercorrelated as well as correlated with Nb, Ta, and Th (with the exception of the series II.4 and samples with Mn-bearing Ba). This similarity of sand characteristics strongly suggests that in spite of different fluxing agents, all high boron glass, excluding series II.4 was melted using glassmaking sand from neighbouring (if not the same) regions (see Freestone et al., 2018).

The compositional variability of high boron glass in terms of components related to fluxing agents, along with the features characterising the glassmaking sand, supports the idea that several primary workshops producing high boron glass operated in parallel on a relatively small scale (Gómez-Morón et al., 2021).

4.2. Glass decolouriser and colourants

Group I.

Only plant ash glass of the Levantine origin from Veseloye (the group I) was intentionally decolourised with manganese. The concentration of Mn is moderate; nevertheless, in all absolutely colourless glass, the MnO/Fe_2O_3 ratio is 1.87 and higher (in most cases – 2.3–2.4), generally corresponding well to the criteria developed by Silvestri et al. (2005), Schibille et al. (2017), and Gratuze (2018). In two samples with a very light aqua hue, the ratio is 1.4; nevertheless, they seem to be intentionally decolourised. Manganese is strongly correlated with the elements occurring in Mn-bearing minerals – Mo, Ba, and V (R^2 = 0.70–0.95) – and, to a lesser extent, with Co, Ni, and W (R^2 = 0.50–0.52) (see Freestone et al., 2023). One sample of purple glass of this group is coloured with Mn in concentration 1.79 wt%. Manganese in the purple glass could have originated from another source than in the colourless samples, considering the slightly lower Mn/Ba ratio (Fig. 6); the arsenic level is slightly elevated. It could be related to some *chaîne operatoire* peculiarities: glass was decolourizing in the course of primary production and could have been coloured during the secondary production stage (Freestone et al., 2023).

Group II.

Most samples of purple glass make part of the series II.3. They are coloured with Mn in a concentration near 1.2 wt%. They also feature a much higher level of barium than the Levantine glass of group I, characterising the source of manganese, as well as slightly elevated V, Co, Ni, Zn and Mo concentrations. Mn, Ba, V, Zn, Mo and W are intercorrelated (R^2 = 0.73–0.89), originating from the manganese-bearing minerals (Freestone et al., 2023). At the same time, Mn is in a moderate negative correlation with Co and Ni, possibly resulting from the recycling practices (see below).

Dark blue glass is present in the series II.3. It is coloured with cobalt, accompanied with elevated concentrations of iron, which is the highest in the series II.3 and likely related to the cobalt colorant (Fig. 7), as well as copper, nickel and zinc. Manganese content is also slightly elevated compared to the glass of this series of the other colours (Fig. 7). Rather high concentrations of tin and lead are generally typical for the glass of this series. Gratuze et al. (2018) identified two major changes in the cobalt sources in the 1st millennium AD, based on the ratios of Co, Ni, Zn and other elements occurring in the cobalt-bearing ores. In terms of Co, Ni, Cu, Sn, Pb, Zn, As and In concentrations and ratios, the glass from Veseloye is the closest in composition to the late antique glass of the 6th-7th centuries (Gratuze et al., 2018: Table 4), although the Co/Ni ratio (from 9.4 to 10.1) is near its upper threshold and is typical for the synchronous Islamic glass. At the same time, the Co/Zn ratio is much higher than in the latter, and Co and Zn are not correlated, as was attested for the Islamic blue glass (Gratuze et al., 2018). High boron glass from Córdoba of the 10th century features considerably lower Co concentration as well as higher Co/Ni ratios, more typical for the Roman glass (Gómez-Morón et al., 2021). The same features are characteristic of high alumina HBLi glass from Ḥiṣn al-Tīnāt of the 10th-12th centuries (the group 2 after Swan et al., 2018). This variability could mean different nature and origin of the cobalt colourant in the high-boron glass, including the secondary use of glass of earlier periods. At the same time, the high concentration of cobalt (near 1200 ppm) in the blue glass from Veseloye, well exceeding its level in the glass from Córdoba (near 500 ppm) and Ḥiṣn al-Tīnāt (up to 657 ppm) and comparable with the Co content in late Antique and early Islamic glass (Gratuze et al., 2018), points rather to the use of a mineral colourant than of blue glass cullet as such. It does not exclude that the latter could have been additionally introduced to the batch.

Emerald green glass, present in the series II.3 and II.5, is coloured with copper in high concentration (4.6 wt% in the series II.3 and 5.5 wt% in the series II.5), positively correlated with antimony, tin, lead, and zinc (R^2 = 0.88–0.98). Within each of the series these elements also correlate with As, Ag and Bi, the concentration of which is the highest in the emerald green glass; at the same time, their ratios differ for the series II.3 and II.5, possibly suggesting slightly differing sources of a colourant (Fig. 7). The content of Sn and Sb is also slightly elevated, compared to the uncoloured glass. Strong positive correlation between the listed elements, as well as a very high Cu/Sn ratio (averagely 135 in the series II.3 and 87 in the series II.5), excluding the use of metal scrap as a source of colourant, points to its origin from the copper ore or metallurgical waste. The most likely source of antimony-rich copper colourant, containing also trace concentrations of Sn, Zn, As, Ag, Pb and Bi, are the ore

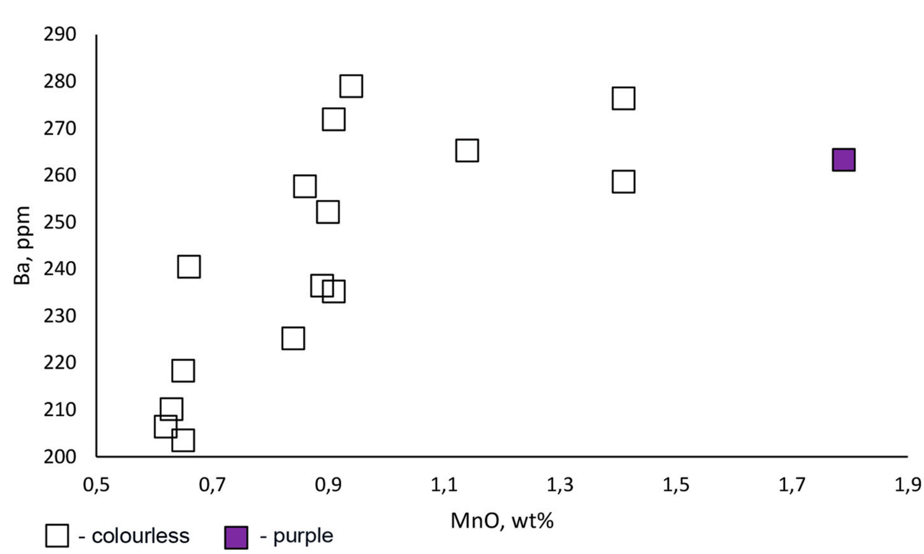


Fig. 6. Mn/Ba ratio in the plant ash glass of the Levantine origin (group I).

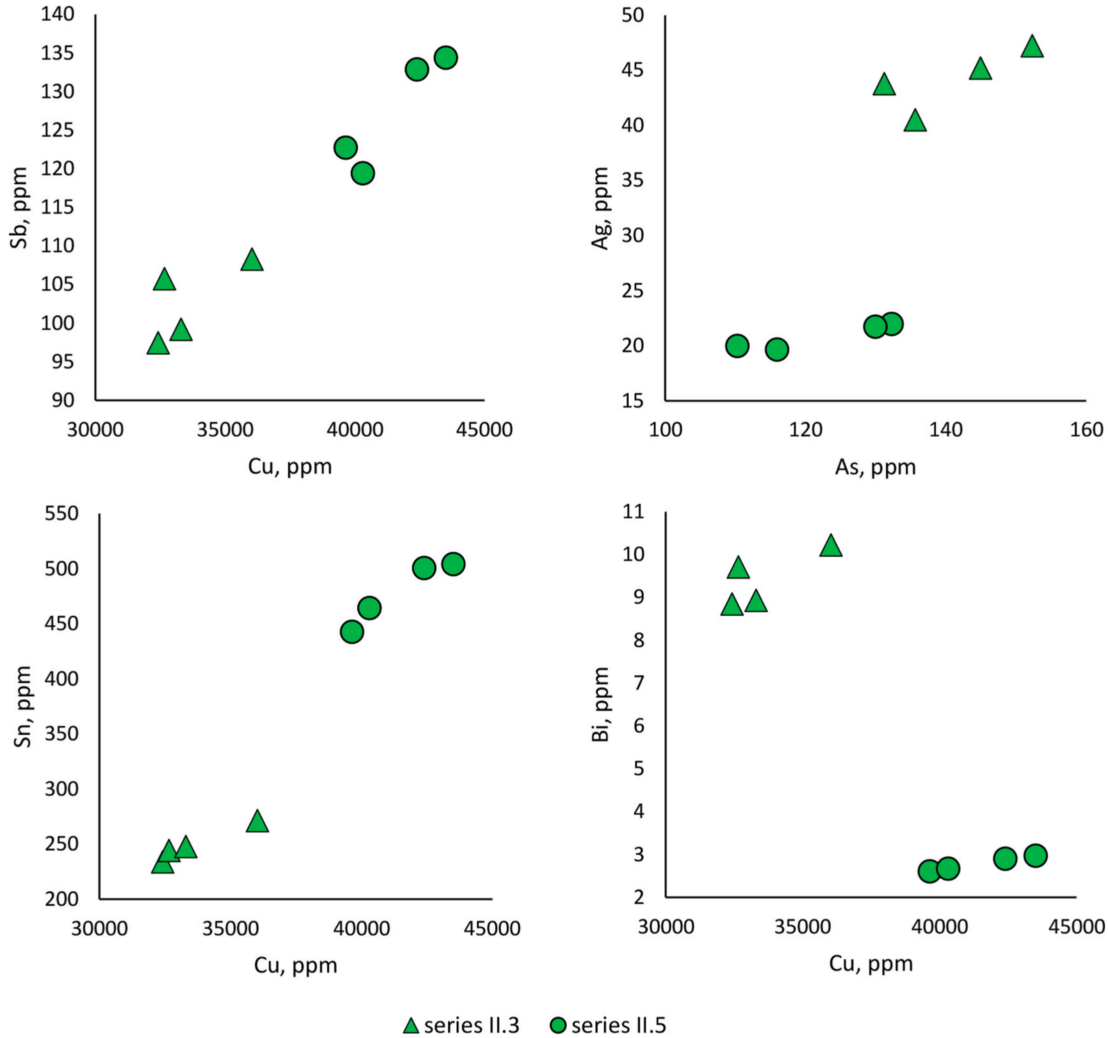


Fig. 7. Emerald green glass of the series II.3 and II.5. Copper, tin, antimony, arsenic, and silver content and ratios.

deposits of the Caucasian region (most likely the South Caucasus / Transcaucasia or Greater Caucasus) or Eastern Anatolia (Chernykh, 1966; Dillis and Degryse, 2022, with the references therein), which corroborates perfectly with either the eventual glassmaking region of high-boron glass or a possible place of its secondary production where the glass could have been remelted and coloured.

Iron content, which was sometimes used for the colouring of emerald green glass along with copper (Jackson and Cottam, 2015) does not exceed its concentration in the glass of the other colours.

Glass of olive green colour is mostly related to the series II.3. Its colour, usually due to the predominance of Fe^{3+} ions, likely was achieved intentionally by an addition of iron, positively correlated with alumina and titanium; the concentration of these elements is higher in olive glass, compared to purple and green samples of the same series (Fig. 8). It allows the suggestion that olive glass of the series II.3 was coloured by metallurgical by-products (probably slag) as a source of iron (Peake and Freestone, 2012). An outlier of olive glass (Ves-49) features lower iron content (near 1 wt% Fe_2O_3); it could have been either naturally or intentionally coloured.

The light blue colour of the glass of the series II.4 is due to the presence of minor concentrations of cobalt (223 ppm) and copper (596 ppm on average). Co/Ni and Co/Zn ratios (8.6 and 3.9) are close to those in dark blue glass.

Group III.

Two samples of purple glass of the series III.1 are coloured with Mn; barium content (187–262 ppm), compared to its level in the colourless glass of the same series (66 ppm), suggests its presence in Mn-bearing materials.

4.3. Recycling practices

Glass recycling practices can be evaluated, first of all, for naturally coloured and colourless glass upon elevated concentrations of high transition metals (Co, Cu, Sn, Pb and some others) as well as upon the content of decolourisers, manganese and antimony, in ancient glass (Freestone, 2015 with references therein). Sometimes it is also possible to suggest the application of this practice for the coloured glass from Veseloye.

The colourless samples of group I, identified as plant ash glass of Levantine origin, feature very low content of the recycling markers (Co – up to 5 ppm, Cu – up to 57 ppm, Sn $<$ 3 ppm, Sb up to 1.4 ppm, Pb up to 45 ppm), suggesting the use of pristine raw glass or at least very careful selective recycling. In the sample of purple glass of this group, it is slightly higher: copper and lead concentrations exceed 100 ppm. Evidently for the coloured glass, recycling was a more inoffensive and consequently more frequent practice. Worth noting that in two samples with a very light natural hue, the boron content is the highest in this group (171 and 195 ppm), possibly suggesting a moderate use of high-boron “Byzantine” cullet.

Naturally coloured glass of the series II.1, II.2, and III.2 features different levels of recycling markers.

In the series I.1, it is very low, suggesting the use of pristine raw

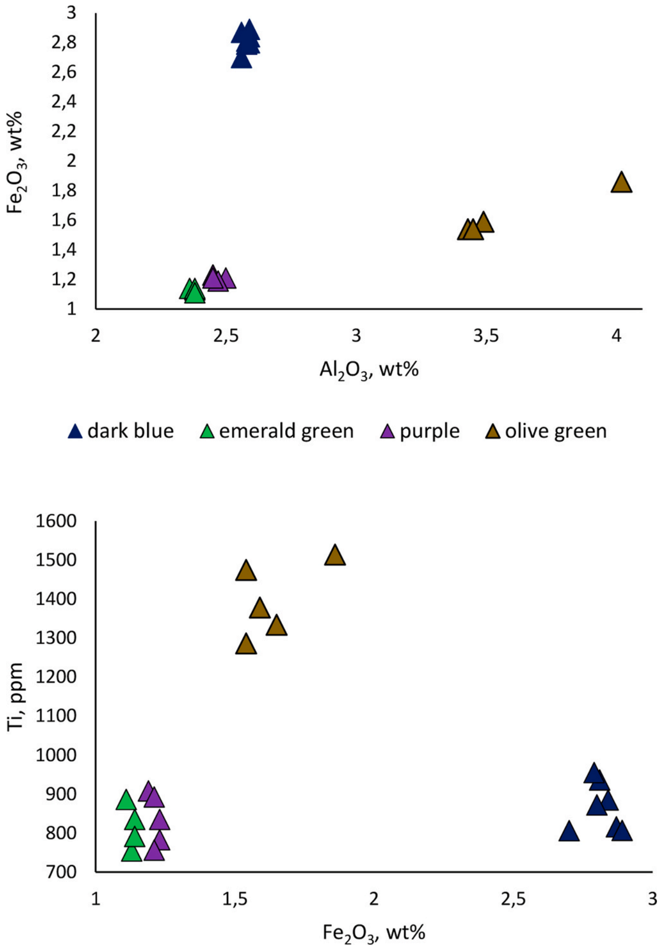


Fig. 8. Alumina, iron and titanium content and ratios in the strongly coloured glass of the series II.3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

glass. Only the antimony content is rather high (57 ppm). For the natron glass based on sand from the European Mediterranean shore, the Sb content does not exceed 30 ppm (in the sand suitable for glassmaking – 1.4 ppm) (Degryse, 2014), but possibly for western Anatolian sources it is higher – the low content of other recycling markers in the glass under discussion strongly suggests it, as well as the elevated Sb level in some other series of HBLi glass from Veseloye. Sb content is also rather high in the previously published high Li-B glass (Swan et al., 2018, the group 3; Gómez-Morón et al., 2021). Mn content (up to 221 ppm) does not exceed its natural level in glassmaking raw materials (Gratuze, 2018).

In contrast to the series II.1, two other series of naturally coloured glass (II.2 and III.2) feature the elevated level of high transition metals (Cu – up to 740 ppm, Sn – up to 315 ppm, Pb – up to 4426 ppm), suggesting extensive addition of cullet to the batch. In the glass of the series II.2 manganese content (0.23 wt%) is typical for the naturally coloured glass containing decolourised cullet (Schibille et al., 2017; Gratuze, 2018). In the series III.2 it is higher (0.56–0.70 wt%, MnO); nevertheless, it is also too low for decolourising glass containing an average of 1.34 wt% of iron oxide. Elevated concentration of antimony, attested in the series III.2 (82–134 ppm, compared to less than 60 ppm in naturally coloured glass of the series II.1 and II.2), allows assuming the recycling of glass cullet of the Roman time, while the use of antimony in glass making ceased in the late 4th/early 5th century CE at the latest (Cholakova and Rehren, 2018). There are numerous examples of secondary use of Roman glass in the last quarter of the 1st millennium AD (see, for example, Schibille and Freestone, 2013, and many others).

Light blue dip-mould blown window panes (series II.4) feature very low content of Sn (near 2 ppm), Sb (less than 1 ppm) and Pb (up to 16.5 ppm), suggesting the use of pristine raw glass. Nevertheless, the Mn concentration is higher than its natural level in the glassmaking sand (Gratuze 2018), and it seems to be negatively correlated with Co, excluding the possibility that Mn is related to the cobalt colourant. It is likely that the colorants were added to the glass containing small amounts of manganese, possibly due to the selective recycling of the naturally coloured base glass.

For the series II.3, the evaluation of the recycling practices is possible for purple and olive-green glass. Elevated concentrations of copper and tin (exceeding 300 and 80 ppm, respectively) and lead (surpassing 1000 ppm in all the cases) suggest extensive recycling of the glass of this series. Elevated content of cobalt and nickel in the purple samples, compared to the glass of the other colours, negatively correlated with Mn, supports this assumption.

In the glass of the series III.1, two samples, of purple and of colourless glass (Ves-42 and 45), feature very low content of recycling markers, suggesting the use of "fresh" raw glass; the sample Ves-39 contains elevated copper (90 ppm) and lead (177 ppm) and thus should contain a portion of cullet. Extremely high Zn content (408 ppm) is difficult to explain.

The assemblage of window panes from Veseloye represents a combination of "fresh" raw glass of four series (Levantine; HBLi naturally coloured (II.1); light blue dip-mould blown (II.4); high B low Li colourless + purple III.1) and at least three series of recycled glass (naturally coloured HBLi series II.2 and high B III.2; strongly coloured HBLi II.3). In some cases, it can be explained by difference in the handling of coloured or colourless glass. In the case of naturally coloured glass, this difference possibly allows us to associate the series with different glazing campaigns. Worth noting that the levels of B and Li in pristine glass of the groups II and III, the composition of which is not affected by recycling practices, can vary from several ppm up to almost 500 ppm for Li and from 600 to more than 2700 ppm for B.

4.4. *Identification of a single batch*

Tight compositional clusters of glass similar to those in Veseloye have been previously noted for a settlement of the Roman period in Stonea; each of them corresponded to a specific vessel type. Freestone et al. (2009) interpreted them as vessels made of a single batch of glass – a working pot or a small tank furnace, representing a single acquisition made at the same time and for a specific purpose. The application of this method allows identifying such glass batches for Veseloye: coefficients of variation for each element of the single batch glass should be within a standard deviation for the glass standards (Ibid.).

Window panes made using a single batch are identified among two of the series of naturally coloured glass ('fresh' II.1 (all four samples, found in the sectors II, IV and V – Fig. 2) and recycled II.2 (all five samples, sectors IV and V). Each of them could have been related to an independent production event.

Among the strongly coloured window panes of the series II.3, found in all five sectors, most samples of each colour can also be related to a single batch: all seven samples of blue and all four samples of emerald green glass, including mould-blown window panes; four of five samples of purple glass, with the exclusion of one dip-mould blown, the composition of which is close, but not identical, to the others; and four of five samples of olive-green glass. Emerald green glass of the series II.5 (four samples from the sectors III-V, where the glass of series II.3 of the same colour was also found) also belongs to a single batch.

The composition of the Levantine plant ash glass (the group I) found in all five locations near the church is homogenous; nevertheless, window panes made from a single batch of glass cannot be distinguished among them.

Four window panes of the series II.4, identical in colour and dip-mould blown décor, found at the same location IV, do not seem to be made using the same glass batch; they could belong to two or even three different batches (only the samples Ves-19 and 22 could be assigned to the same batch).

For the samples of the series III.1 and III.2 found in the sectors IV and V, single batches cannot be distinguished, although the series III.2 is very homogenous compositionally.

4.5. Dip-mould blown window panes

Oculi with a relief mould-blown décor, thought to be related to the Georgian or Abkhasian production (Armarchuk and Kuzina, 2024, with the references therein), are present in the group I (plant ash Levantine glass) and in the series II.3 (HBLi coloured glass – deep blue, purple and emerald green). All the samples of light blue glass of the series II.4 are also mould-blown. They originate from different sectors (I, II, IV, V). Their compositional variability suggests that raw glass of different origins (Levantine and possibly western Anatolian) could have been supplied to the Caucasus region, where it was transformed into window panes according to local demands and aesthetic preferences. Of course, it does not imply the local origin of the glassworkers. A significant number of churches erected in the Abkhazian Kingdom in the late 9th – 10th centuries AD (Armarchuk et al., 2012; Vinogradov and Beletskiy, 2015) could suggest the presence in the region not only of the Byzantine builders but also glass workers, although there is no direct evidence for glass production here.

4.6. Possible place and number of production events

Although an attempt to determine the number of episodes of church glazing in Veseloye is very tentative, it is tempting to make it.

The most numerous series, identified in all sectors near the church, are the Levantine group I and the HBLi series II.3 of coloured glass. They could have been related to the initial glazing of the church. This idea is supported by the presence in both series of dip-mould blown window panes. Moreover, in some cases, coloured glass of the objects with relief decoration is related to the same batch that was used for blowing plain windows.

Emerald green glass of the series II.5 is compositionally close to the series II.3. As regards the base glass composition, it could have been associated with the same glazing campaign, representing another glass batch. At the same time, the emerald green glass of both series is repeated in the same sectors III, IV and V; most likely it suggests different glazing events when some of green window panes have been replaced. Slightly differing ratios of copper-related elements in these series likely support their relation with different glazing campaigns, although the accidental distribution of windows of both series over three porches during a single glazing cannot be excluded.

Light blue dip-mould blown window panes of a peculiar composition identified in sector IV could have been related either to the same (probably initial) glazing campaign as the other dip-mould blown window panes or to one of the later renovations, regarding its concentration only in one sector.

The base composition of naturally coloured glass of the series II.1, II.2 and III.2 differs significantly, and it also differs from that of the series II.3 (which includes a naturally coloured sample). These samples belong to the windows found south and southwest of the church; all of them are without relief décor. Given the difference in base composition and in the concentration of recycling markers (one of the series is free of them), they likely represent different episodes of glazing renovation – at least of the west and south porches where they have been found. The isolated samples of high B, low Li, colourless and purple glass (series III.1) that originated from the same location IV also seem to be related to a particular glazing episode, while the glass colours of this series double those of the Levantine origin and HBLi series II.3, which are much more numerous.

Worth noting that window panes made of a single batch of glass are distinguished only for high boron (probably western Anatolian "Byzantine") glass. At the same time, dip-mould blown window panes thought to be a peculiarity of the local Caucasian ecclesiastic architecture are attested among both Levantine and high-boron glass. It suggests that the production place of all the windows could have been the same. Different glassworking practices that have affected the variability of glass composition (allowing the distinguishing of single batches or not) may have been due to the colour and quality of glass. Colourless glass could have been used without any 'local' modifications, while colouring and recycling took place in the course of making windows specially commissioned for the church in Veseloye – possibly, regionally.

Conclusion

The glass for the window panes of the church in Veseloe originates from the Levantine region (colourless) and probably from Asia Minor (mostly strongly and naturally coloured). The latter, with elevated boron (and more often also lithium) content, is very variable compositionally due to its complex nature, not fully understood so far, and sometimes extensive recycling practices.

The clusters of glass evidently related to separate glass batches likely reflect the manufacturing of window panes for the church by commission. Probably they were produced locally in the Caucasian region using the imported glass. The evidence for extensive recycling is attested only for high boron glass. The colourless glass of Levantine origin was treated more carefully; it bears no evidence of recycling. Even if cullet was added to the batch, it was done very selectively.

We can tentatively assume that the windows made of colourless Levantine and strongly coloured HBLi glass are related to the initial glazing of the church. Four series of naturally coloured high boron glass, as well as single colourless and purple panes, probably have been used in the course of glazing renovation. Unfortunately, we cannot rank them chronologically.

There is little doubt that the glass used for the window panes in Veseloye has been supplied to the Caucasus from Byzantium. After the return of the Abkhazian Kingdom to the union with the Byzantine Empire in the 880s, active church construction starts on its territory. The Abkhazian church was subordinate to the Patriarch of Constantinople (Vinogradov and Beletskiy, 2015: 370–371; Khrushkova, 2020). An impressive number of churches were erected here in the late 9th – 10th centuries AD, as well as in the adjacent regions of the North Caucasus. The original architectural style, dominating in the kingdom, emerged here in this period. Most probably its founders originated from Trapesund or another centre of Pontus – the north-eastern part of Asia Minor (Vinogradov and Beletskiy, 2015:315–317; 371). Window panes could have been supplied to the region as finished products. Nevertheless, a transfer not only of glass but also of glass workers from Asia Minor as a part of construction artels seems more likely despite the absence of any glassworking evidence in the Caucasus closer than in Georgia (Armarchuk and Kuzina, 2024; Chkhatarishvili, 2007).

Materials from Veseloye compared to the datasets from Ḥiṣn al-Tīnāt (western central Anatolia), Córdoba (Spain), and some other sites allow more detailed definition of low alumina high boron glass groups of the 10th century and somewhat later. They provide additional information on the composition, nature, and colouring agents of HBLi glass, further strengthening the hypothesis of its origin from Asia Minor and shedding new light on its distributional pattern outside of the Empire. Gómez-Morón et al. (2021) convincingly presented evidence of long-distance transfer not only of glass goods but also likely of skilled craftsmen together with them. The mosaic tesserae investigated there, a royal gift of the Byzantine Emperor, were aimed at developing diplomatic relations with the Caliphate of Córdoba. Glass supply to the Caucasus, probably also with the transfer of glass workers, was destined for the church construction as a part of the religious politics of Byzantium in the region. To date, only the distribution of the HBLi glass within the Empire and its transfer related to its political and religious purposes are attested undoubtedly, at least for the middle Byzantine period. There is no evidence of the long-distance trade by high boron raw glass, which was well documented for the production of the Eastern Mediterranean glassmaking centres in different periods. It could reflect, *inter alia*, the scale of Western Anatolian glass production, which was not as important as, for example, in the Levant and Egypt. Possibly, further accumulation of data on high boron glass will correct this assumption with time.

Different models of glass supply are documented in various parts of the North Pontic region to date. At the same period the southwestern and central Crimea also was under the strong influence of Byzantium – its southwestern region was a part of Thema Hersonos. However, in the later 1st millennium AD and probably slightly later, by the 11th century, the model of glass consumption here is closer to that attested in Western and Southern Europe (Henderson, 1995; Jackson, 1996; Schibille and Freestone 2013 and many others). The recycled glass of the early Byzantine period was used for glazing the churches in this region (series Foy-2.2, Rumyantseva and Mastykova, 2023; Rumyantseva et al., 2023a). Window panes made of low alumina HBLi glass are known in the southwestern Crimea later, in the 11th-13th centuries (Rumyantseva et al., 2023b). The difference in glass consumption between the north-eastern Caucasus and the Crimea can be explained by different availability of old glass for recycling. From the mid-6th to the mid-7th century CE, there was a period of intensive construction campaigns led here by Byzantium. In Chersonesos and the southwestern Crimea generally, they encompassed not only residential structures but also ecclesiastical ones. Glass from the buildings of this particular horizon was obviously used later as a “secondary” raw material.

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Olga S. Rumyantseva: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Ekaterina A. Armarchuk:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Inna N. Kuzina:** Writing – review & editing, Writing – original draft, Visualization, Data curation. **Anna V. Mastykova:** Writing – review & editing, Funding acquisition, Conceptualization. **Maria V. Chervyakovskaya:** Writing – review & editing, Formal analysis, Data curation. **Vasiliy S. Chervyakovskiy:** Writing – review & editing, Formal analysis, Data curation.

Declaration of AI application in the writing process

During the preparation of this work the authors used Quillbot grammar checker in order to edit and improve English language. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105381.

Data availability

The data is provided in the publication.

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