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► **To cite this version:**

S.Y. Waksman, G. Giannaki, E. Todorova, Jacques Burlot, M. Daskalov, et al.. Connecting Late Roman and Early Byzantium: Investigating the technological tradition of 6th c. AD glazed wares from Northern Greece and Bulgaria. *Journal of Archaeological Science: Reports*, 2024, 60, pp.104822. 10.1016/j.jasrep.2024.104822 . hal-04761249

**HAL Id: hal-04761249**

**<https://hal.science/hal-04761249v1>**

Submitted on 31 Oct 2024

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# Connecting Late Roman and Early Byzantium: Investigating the technological tradition of 6th c. AD glazed wares from Northern Greece and Bulgaria

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## ARTICLE INFO

### Keywords:

Early Byzantine glazed pottery  
Workshop  
Bulgaria  
Northern Greece  
Chemical analysis  
Technical tradition

## ABSTRACT

Glazed wares found in Thasos (Greece) and in a pottery workshop in Sofia (Bulgaria) in 6th c. AD contexts were investigated using WD-XRF (body analysis) and SEM-EDS (glaze analysis). In both cases, they associate low-calcareous bodies and high-lead glazes, with lead compounds probably applied without the addition of silica before a single firing. This technical tradition is common to the 4th–5th c. Late Roman glazed wares studied so far, from the Balkans to Northern Italy, and to the 7th c. AD “Byzantine Glazed White Ware I”. Our corpus may thus be seen as the “missing link” between the Late Roman and the Early Byzantine glazed wares, before glazed tableware meet with a remarkable development later on in Byzantium.

## 1. Introduction

For many ceramologists, the transition between the Late Antique and the Early Byzantine pottery repertoire was defined by J.W. Hayes, in his study of the pottery excavated at the site of Saraçhane in Istanbul (Hayes, 1968, 1992). This transition in the 7th c. AD initiates the development of Byzantine glazed wares, a phenomenon which will actually not take off before the beginning of the 12th c., as emphasized by Sanders’ quantitative data in Corinth (Sanders, 1995, 2003). Glazes were known well before the 7th c. and used in the Roman and Late Roman worlds as well, but a gap seemed to persist between the Late Roman productions of the 4th–beginning of the 5th c., attested by numerous workshops from the Balkans to Northern Italy (Magrini and Sbarra, 2005; Cvjetičanin, 2006; Magrini and Sbarra, 2009; Magrini et al., 2010; Hárshgyi and Ottományi, 2013), and the Early Byzantine glazed wares of the 7th c. present in Saraçhane and in the Yassı Ada shipwreck (Hayes, 1968; Bass et al., 1982; Hayes, 1992). Trivyžadaki (Trivyžadaki, 2008, p. 22) and Petridis (Petridis, 2013, p. 187; Petridis, 2015, p. 441–442; Petridis, 2022, p. 333) suggested a clear connection between the glazed pottery discovered in Philippi and Thasos respectively and the

earlier Balkan productions and proved that glazed pottery was well in use already in the 6th c. Indeed, glazed wares excavated in Thasos (Greece) and Sofia (Bulgaria) (Fig. 1) in contexts dated back to the 6th c. may represent the missing link, and are studied by G. Giannaki in the framework of a PhD in archaeology at the universities of Athens (Greece) and Lyon (France).

The present paper investigates the provenance and technology of a sampling of the corpus studied by Giannaki, focusing on the archaeometric characterization of the bodies and glazes and the technical tradition their association may be related to.<sup>1</sup> Both Late Roman and Early Byzantine glazed wares, including the first “Glazed White Ware I” defined by Hayes in Saraçhane (Hayes, 1992), were the subject of previous archaeometric studies which provide a body of comparative data we could build upon (Walton, 2004; Walton and Tite, 2005; Waksman et al., 2007, 2008; Capelli et al., 2009, 2010a, 2010b; Walton and Tite, 2010).

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<sup>1</sup> for preliminary results on the Sofia material: [Waksman et al., 2024](#).

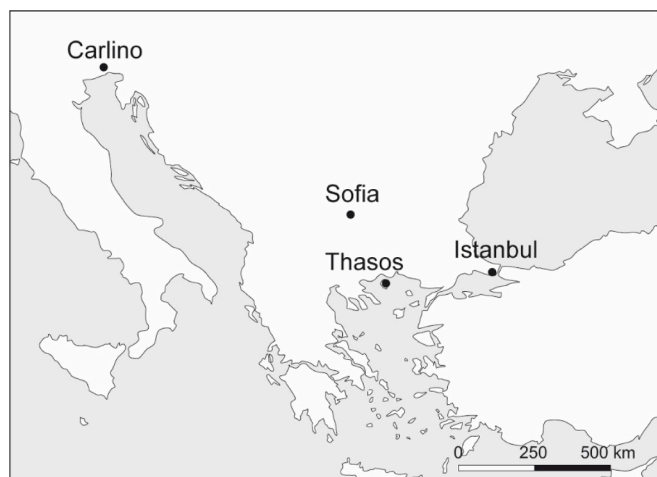


Fig. 1. Map of the main sites mentioned (base MAP O. Barge).

## 2. Material and methods

### 2.1. Corpus

The corpus of glazed wares is composed of two batches. The first one comes from a 6th c. pottery workshop excavated in the early 2000s at the site of Lozenets (Sofia, Bulgaria), by a team of the National Archaeological Institute with Museum at the Bulgarian Academy of Sciences directed by M. Daskalov and S. Goryanova (Daskalov and Goryanova, 2009; Daskalov, 2024). The detailed study of the pottery material was carried out in 2022–2023 by E. Todorova, G. Giannaki, S. Goryanova and G. Guionova, in the framework of a French-Bulgarian PHC RILA and of a Bulgarian National Science Fund program (Todorova, 2024). Besides its chronology, the status of the site as workshop was of particular interest. Both glazed and unglazed wares were manufactured there, some in the same forms, and the typological repertoire includes both table and cooking wares. A sampling of 40 sherds well identified typologically, including 23 glazed wares<sup>2</sup> and 5 wasters, was selected for analysis (Fig. 2).

The second batch came from the excavations carried out in Limenas, Thasos (Greece), by the French School at Athens, the National and Kapodistrian University of Athens, the University of Lille and the Ephorate of Byzantine Antiquities of Kavala. The presence of glazed pottery in 6th c. contexts had already been pointed out by Blondé (Blondé et al., 2003) and Petridis (Petridis, 2013, p. 187; Petridis, 2015, p. 441–442; Petridis, 2022, p. 333) before its study was developed by Giannaki (Giannaki, 2024). No evidence of glazed pottery production was found in Limenas, but the extensive corpus of chemical data on Thasos in Lyon laboratory database was expected to help identifying local wares (Picon and Garlan, 1986; Blondé and Picon, 1999; Blondé, 2007). Within the highly fragmented glazed material of Thasos, 25 sherds among the best preserved typologically were selected for analysis (Fig. 2).

### 3. Analytical methods

The sherds were first examined under the binocular microscope, to gather basic information on the fabrics, the microstructures and the firing conditions.

They were all sampled for body analysis, carried out by Wavelength-Dispersive X-Ray Fluorescence (WD-XRF) at the ceramology platform of the “Archéologie & Archéométrie” laboratory in Lyon (CNRS UMR 5138,

<sup>2</sup> these exclude sherds bearing only drops and drips of glaze, which probably dripped from a glazed ware stacked in the same kiln during firing.

Lyon University), using a Bruker S8 Tiger spectrometer. Samples were cut out with a diamond-coated saw, the glazes were removed and sub-sampled for further analyses; when absent, an external layer, whose chemical composition is more liable to be altered during burial, was removed. After heating at 950 °C (to eliminate residual water, volatile elements and organics), cooling and grinding, 800 mg of ceramic powder was mixed with 3200 mg of flux (lithium metaborate and tetraborate). The mix was heated to liquid state in a gold and platinum crucible, then cast into a bead. Analyses were carried out on these homogeneous beads, of fixed geometry, which correspond to a mean chemical composition representative of the clayey material of the sherds. Twenty-four major and trace elements are quantified, after calibration of the set-up using 40 geological standards (CRPG, USGS, NIST, British Chemical Standards...). The calibration is frequently checked using three in-house pottery standards.<sup>3</sup> Out of the 24 elements determined, 17 major (MgO, Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, K<sub>2</sub>O, CaO, TiO<sub>2</sub>, MnO, Fe<sub>2</sub>O<sub>3</sub>) and trace elements (V, Cr, Ni, Zn, Rb, Sr, Zr, Ba, Ce) are usually taken into account in subsequent multivariate statistical treatments.

A sub-sample of 14 sherds was selected for glaze analysis, based on the results of body analysis. Glaze analysis was carried out by SEM-EDS at the “Centre Technologique des Microstructures” in Lyon (CTμ, Lyon 1 University). Samples were embedded in a polyester resin, cut in a cross section in order to expose all the layers (ceramic body, slip if present, glaze), polished with a 0.25 μm diamond paste and then coated with a layer of carbon. Prior to coating with carbon, the cross-sections were observed under a binocular microscope with magnifications in the range 10x to 115x. The study of the microstructures was mainly performed using backscattered electron (BSE) images which allow differentiating the various phases according to their atomic number.

Analyses were carried out using a FEI Quanta FEG 250 coupled to an Oxford Instruments Ultim® Max 65 mm<sup>2</sup> silicon drift detector. All measurements were operated at 15 kV acceleration voltage in 60 s by setting the working distance at about 10 mm. Standardless quantification was performed using a PAP correction method of the intensities. AZtecLive software was used for data acquisition and evaluation, and the reliability of the results was checked by measuring reference glasses and geological standards (Corning Brill B, C and D, DR-N).

## 4. Results and discussion

### 4.1. Body analysis and provenance issues

As the Sofia batch is workshop material, the provenance issues concern mostly the Thasos one. In both cases, chemical analysis was intended to identify the category of clay used for these glazed productions. Fig. 3 shows the classification of the whole sampling of glazed wares by hierarchical clustering analysis (HCA), based on the concentrations of 14 major and trace elements,<sup>4</sup> using standardized data, Euclidean distances and the average linkage aggregation criterium (e.g. Picon, 1984). A general feature of all the samples is that they are made of low-calcareous clays. Different chemical groups may be distinguished according especially to the Fe, Ti, K, Mg contents. One sample (TCW 93) stands out by its high contents in Si and Al (SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> > 90 %), Ti and Zr, and low ones in alkali, alkali-earths and Mn, an association typical of kaolinitic clays. We will come back to this specific sample *infra*.

The samples from Sofia workshop form a homogeneous chemical group, with few marginal samples (BZN463, and BZN468 not represented in Fig. 3). A noticeable point is that glazed and unglazed wares have similar compositions (Table 1), indicating the use of the same

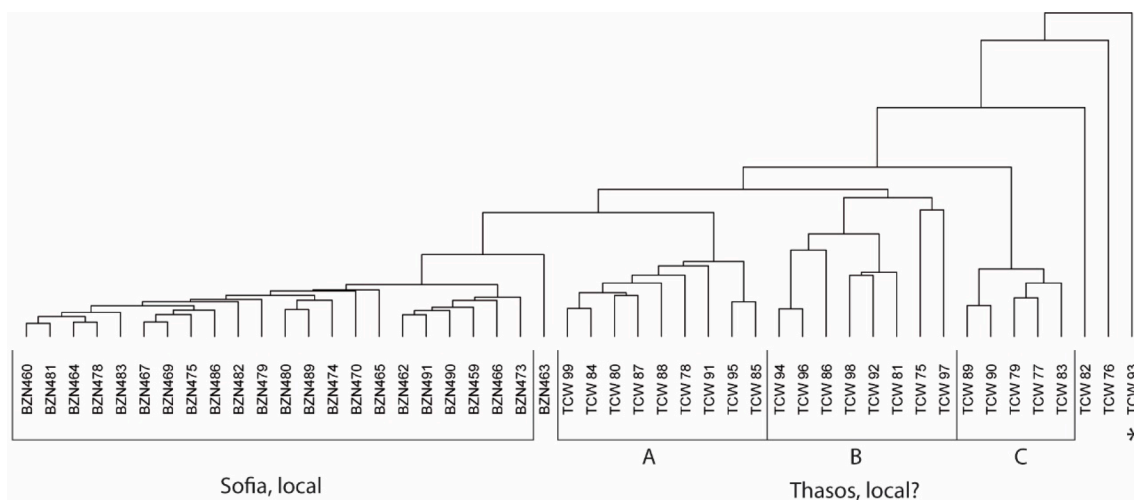
<sup>3</sup> for further details on the analytical conditions and performances: Thirion-Merle, 2024.

<sup>4</sup> In this specific case study, the concentrations in Sr, Ba and Zn were not included in the variables, as several were affected by pollutions during burial (Picon, 1991; Blondé, 2007).



**Fig. 2.** Representatives examples of the samples analyzed: Sofia workshop (above), Thasos (below), and specific cases (middle left: waster or second choice, Sofia; middle right: “Glazed White Ware I”, Thasos) (Lyon lab. ids. are indicated, photos S.Y. Waksman).





**Fig. 3.** Hierarchical clustering analysis based on the chemical composition of the bodies, whole sampling of glazed wares. The main chemical groups and sub-groups are underlined. The asterisk marks a sample (TCW 93) distinguished by a kaolinitic body.

clayey material which would have been appropriate for cooking uses too (e.g. Picon, 1995).

Thasos glazed wares are more heterogeneous. Most of them may however be gathered in a large group further sub-divided into 3 sub-groups (Fig. 3, Table 1). The most consistent sub-group (C) has higher Fe, Mg, Cr, Ni, V contents than the others, with values remaining in the low ranges. The most distinctive sub-group (A) has low Fe and Ti contents (mean values  $\sim 5\%$   $\text{Fe}_2\text{O}_3$  and  $\sim 0.45\%$   $\text{TiO}_2$ ), a rather uncommon feature in low-calcareous bodies. The investigations carried out by M. Picon on Thasos clay procurement to manufacture various categories of wares (mostly amphorae, but also black gloss, common and, to a lesser extent, cooking wares), show the chemical variability of the clay materials exploited, which he relates to the restricted availability of the clay resources and their dissemination in small-scale deposits (Picon and Garlan, 1989; Blondé and Picon, 1999). Several workshops are identified on the island, mostly for the production of amphorae. Their chemical features may be differentiated from those of the glazed wares, with the possible exception of Molos workshop, the closest to Limenas (Picon and Garlan 1989, Garlan 2004). A group of amphorae from Thasos, including several collected on the workshop site of Molos, shows some chemical similarities, although not a close match (Table 1). The same may be said of other local references, tripod stilts related to a production of glazed wares of undefined chronology,<sup>5</sup> and of cooking wares and lamps found in Limenas excavations, roughly dated to the same period as the glazed wares under study (5th–7th c.) (Petridis, 2013; Bia, 2023). Among a sampling of cooking wares and lamps<sup>6</sup> of the Early Byzantine period studied together with F. Blondé (Waksman and Blondé, 2011), a small number, including a lamp interpreted as an overfired waster, presents fairly close chemical features (Fig. 4). The chemical compositions of most of the glazed wares and of a large part of the cooking wares with a micaceous fabric actually vary in a wide range of composition, which includes Thasian local references (Fig. 4). However, we cannot consider their local status as proven at this stage of research.

Another, kaolinitic, fabric is represented in Thasos by lamps, cooking wares and glazed wares (Petridis, 2013; Bia, 2023). Only one example was part of our corpus (Fig. 2, TCW 93), and a few kaolinitic lamps were analyzed in our previous study with Blondé. These are probably related

<sup>5</sup> for a sub-contemporary production including glazed wares at Molos: Papadopoulos, 1995.

<sup>6</sup> The corpus of lamps is studied by P. Petridis and will be published as part of the final reports of the Thanar excavations in Thasos.

to another example bearing traces of glaze, found in Thasos in contexts dated to the end of the 6th – beginning of the 7th c. (Blondé et al., 2011; Petridis, 2013; Giannaki, 2024). The present study shows that sample TCW 93 is related neither to the kaolinitic lamps, nor to the kaolinitic cooking wares previously analyzed (Fig. 4). It is an import, as the histogram of distances with our reference group of glazed and unglazed “White Ware I”<sup>7</sup> shows that it is well integrated into the latter (Fig. 5).<sup>8</sup>

#### 4.2. Glaze analysis and production techniques

A sub-sample of 14 sherds was selected for glaze analysis by SEM-EDS. The Sofia samples selected (BZN467, BZN469, BZN475, BZN478) are representatives of the most common glazed forms (jugs, mortars, Fig. 2) and of the main chemical group. In addition, 2 samples were expected to bring further information on the manufacturing techniques: BZN473 considered either a waster or a second choice due to many blisters on the surface of the glaze (Fig. 2), and BZN487, where the glaze is present only as drops with a central pinhole.<sup>9</sup>

Thasos selection (TCW 75, TCW 80, TCW 84, TCW 88 to TCW 90) was taken among samples of the three chemical sub-groups (A, B, C, Figs. 3 and 4), and also included TCW 93, identified as an import of “Glazed White Ware I”.

Observation of cross-sections of the sherds under a binocular microscope already brings a range of information. In all cases, the glaze is applied directly on the body, without an intermediate slip. The bodies of most of the Sofia samples are only partly reoxidized, a few remaining completely reduced (Fig. 6).<sup>10</sup> In the former case (Fig. 6, left), the reduced part of the sherd always corresponds to the glazed side, which supports a single firing process, where reoxidation during cooling could only occur through the unglazed side. The blisters, occasional on many sherds and particularly abundant at the surface of sample BZN473, appear to be bubbles trapped at the surface (Fig. 6, right). The pinholes (Fig. 2) would be another aspect of the same phenomenon, due to

<sup>7</sup> Although not a reference group *stricto sensu* as its Constantinopolitan origin has not been proven so far, it includes the very samples from Saraçhane used by Hayes to define this ware (Hayes, 1992; Waksman, 2017, 2019).

<sup>8</sup> The chronology of this glazed sample in Thasos contexts will be discussed by Giannaki in her PhD.

<sup>9</sup> for more details on this sample, especially the high content of bismuth in inclusions present in its glaze as clue for the provenance of the lead compounds: Waksman et al., 2024.

<sup>10</sup> for the firing cycle and the reducing or oxidizing atmosphere in the kiln during this cycle, e.g. Picon, 2002.

**Table 1**  
Chemical composition of the bodies determined by WD-XRF, ranked as in Fig. 3, and comparative data (major and minor elements in oxide weight %, trace elements in ppm; m: mean,  $\sigma$ : standard deviation, n: number of samples; elements between brackets were not used in the HCA).

Lyon id.	CaO	Fe <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	K <sub>2</sub> O	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	MgO	MnO	(Na <sub>2</sub> O)	(P <sub>2</sub> O <sub>5</sub> )	Zr	(Sr)	Rb	(Zn)	Cr	Ni	La	(Ba)	V	Ce
<b>Sofia, Lozets workshop</b>																				
BZN460	1.46	5.45	0.671	2.70	65.95	20.27	1.55	0.0463	1.65	0.06	164	198	142	85	74	25	35	571	115	77
BZN481	1.48	5.42	0.670	2.68	66.20	20.17	1.50	0.0427	1.56	0.11	163	187	144	87	74	24	29	556	111	75
BZN464	1.49	5.44	0.680	2.71	65.98	20.25	1.56	0.0450	1.58	0.09	166	192	148	85	76	25	39	544	117	81
BZN478	1.44	5.31	0.681	2.64	66.29	20.22	1.54	0.0460	1.57	0.10	170	190	145	85	81	24	35	551	116	81
BZN483	1.45	5.45	0.679	2.60	66.54	19.89	1.49	0.0458	1.59	0.11	177	189	143	86	74	23	41	572	116	83
BZN467	1.42	5.56	0.680	2.59	66.59	19.95	1.46	0.0502	1.41	0.12	166	181	143	84	73	22	42	565	123	72
BZN469	1.49	5.70	0.680	2.65	66.11	20.00	1.51	0.0522	1.53	0.11	170	199	143	84	74	23	29	593	120	73
BZN475	1.65	5.55	0.672	2.63	66.21	19.87	1.47	0.0526	1.53	0.20	173	209	138	83	74	24	39	652	111	74
BZN486	1.41	5.56	0.682	2.60	65.98	20.40	1.53	0.0434	1.54	0.08	174	184	141	88	74	24	34	569	115	71
BZN482	1.37	5.70	0.646	2.69	66.55	19.86	1.41	0.0459	1.50	0.08	173	178	150	83	74	23	31	532	106	71
BZN479	1.48	5.49	0.683	2.62	66.40	19.90	1.51	0.0444	1.53	0.14	196	191	143	83	72	24	32	562	122	75
BZN480	1.43	5.67	0.670	2.71	66.02	20.13	1.50	0.0479	1.58	0.07	163	187	151	87	77	25	30	558	112	88
BZN489	1.45	5.57	0.680	2.97	65.74	20.25	1.53	0.0431	1.50	0.10	169	186	147	89	77	24	39	550	119	84
BZN474	1.51	5.45	0.692	2.64	65.95	20.27	1.56	0.0476	1.59	0.12	192	190	149	89	77	23	30	576	115	87
BZN470	1.54	5.66	0.669	3.12	65.09	20.07	1.68	0.0446	1.75	0.15	158	186	143	89	80	25	35	567	115	77
BZN465	1.48	5.36	0.630	2.64	66.91	19.69	1.44	0.0452	1.59	0.08	153	187	140	82	71	25	33	557	104	70
BZN462	1.43	5.81	0.721	2.48	65.35	20.89	1.61	0.0454	1.39	0.10	177	183	143	89	78	24	37	543	126	76
BZN491	1.43	5.83	0.732	2.45	65.16	21.03	1.64	0.0460	1.44	0.09	178	186	144	90	77	26	44	548	128	84
BZN490	1.41	5.96	0.748	2.44	64.51	21.50	1.71	0.0458	1.40	0.08	173	181	141	93	84	27	31	542	129	81
BZN459	1.49	5.77	0.707	2.59	64.63	21.36	1.59	0.0464	1.56	0.08	181	188	148	92	78	25	34	552	119	75
BZN466	1.45	5.83	0.718	2.50	65.22	20.94	1.60	0.0478	1.38	0.14	170	184	143	89	78	25	35	556	127	67
BZN473	1.99	5.64	0.696	2.52	65.07	20.42	1.51	0.0437	1.51	0.42	175	266	141	89	78	25	31	794	122	80
BZN463	2.00	5.38	0.638	3.51	65.67	19.15	1.55	0.0533	1.71	0.17	178	213	153	83	74	24	36	578	96	73
<b>Thasos, local?</b>																				
<b>sub-group A</b>																				
TCW 99	1.81	5.10	0.472	3.35	66.98	17.87	1.56	0.0490	2.08	0.44	147	317	136	102	73	38	43	893	72	79
TCW 84	1.60	4.97	0.460	3.43	67.44	17.82	1.52	0.0518	2.15	0.25	152	324	139	104	64	38	46	851	76	86
TCW 80	1.03	5.21	0.445	3.40	68.22	17.67	1.52	0.0544	2.09	0.14	152	301	142	128	64	41	40	757	77	91
TCW 87	1.17	5.34	0.487	3.49	67.11	18.15	1.54	0.0428	2.05	0.23	162	294	136	194	68	39	47	856	86	88
TCW 88	1.96	4.93	0.477	3.31	67.36	17.95	1.30	0.0354	2.15	0.20	159	346	134	103	70	37	53	957	76	90
TCW 78	1.42	5.34	0.531	3.53	66.93	18.00	1.75	0.0515	1.90	0.25	166	280	151	113	84	52	49	803	88	87
TCW 91	0.99	5.48	0.459	3.33	67.35	19.18	1.41	0.0591	1.49	0.06	163	233	153	79	62	31	34	742	86	78
TCW 95	0.90	4.99	0.444	3.43	68.18	17.99	1.57	0.0760	2.04	0.15	150	289	142	115	65	53	59	802	74	96
TCW 85	1.10	5.11	0.470	3.45	68.14	17.75	1.54	0.0685	1.99	0.14	150	275	140	157	82	57	46	756	80	91
<b>sub-group B</b>																				
TCW 94	1.16	5.19	0.590	2.97	66.61	20.56	1.32	0.0247	1.30	0.08	167	91	116	73	47	13	38	505	75	99
TCW 96	1.18	5.26	0.614	2.73	66.43	20.63	1.22	0.0228	1.47	0.21	171	89	119	71	54	17	42	498	86	98
TCW 86	1.10	4.76	0.694	2.83	67.01	19.71	1.40	0.0317	1.82	0.23	194	114	106	66	88	32	56	647	82	110
TCW 98	0.93	4.25	0.438	3.16	67.77	20.49	1.05	0.0211	1.55	0.14	158	113	139	78	38	13	57	675	53	93
TCW 92	1.44	4.33	0.453	3.07	68.44	19.26	0.95	0.0338	1.42	0.35	158	106	122	69	42	19	49	762	60	89
TCW 81	0.99	4.54	0.520	3.32	68.67	18.73	1.13	0.0246	1.62	0.21	178	109	130	74	48	16	56	724	59	103
TCW 75	1.06	4.22	0.485	3.51	69.79	17.80	0.87	0.0563	1.55	0.28	186	126	149	83	50	23	56	1019	64	116

(continued on next page)

Table 1 (continued)

	Lyon id.	CaO	Fe <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	K <sub>2</sub> O	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	MgO	MnO	(Na <sub>2</sub> O)	(P <sub>2</sub> O <sub>5</sub> )	Zr	(Sr)	Rb	(Zn)	Cr	Ni	La	(Ba)	V	Ce	
	TCW 97	1.10	4.97	0.662	3.62	67.58	19.05	1.07	0.0258	1.53	0.21	230	129	170	92	70	20	52	678	77	101	
	<b>sub-group C</b>																					
	TCW 89	1.62	6.39	0.657	3.40	64.60	18.70	2.28	0.0805	1.77	0.19	189	229	159	145	120	76	48	663	133	89	
	TCW 90	1.45	6.00	0.664	3.43	65.10	18.86	2.20	0.0748	1.81	0.18	188	232	165	144	118	72	47	675	133	89	
	TCW 79	1.93	5.92	0.667	3.38	64.26	18.96	2.36	0.0568	1.75	0.45	185	234	151	136	125	72	40	644	118	92	
	TCW 77	2.20	5.88	0.614	3.43	64.59	18.71	2.13	0.0563	1.77	0.37	177	256	160	143	114	66	42	731	121	88	
	TCW 83	2.66	5.76	0.656	3.49	63.84	18.62	2.31	0.0678	1.93	0.40	184	267	159	135	116	65	45	718	107	100	
	TCW 82	5.21	6.00	0.576	3.29	64.47	16.58	2.27	0.0581	1.20	0.14	123	226	154	82	103	71	29	584	101	73	
	TCW 76	3.12	6.45	1.013	4.27	56.98	23.31	2.18	0.0678	0.51	1.28	226	82	149	149	170	85	33	953	128	96	
	<b>Thasos, Glazed White Ware I</b>																					
	TCW 93	0.27	3.68	1.251	1.69	71.94	20.37	0.51	0.0168	0.03	0.06	316	26	82	36	89	28	52	371	92	112	
	<b>Comparative data</b>																					
	<b>Sofia, Lozenets workshop, glazed and unglazed wares (n = 38, (Waksman et al., 2024))</b>																					
	<b>m</b>	1.55	5.58	0.681	2.65	65.86	20.25	1.52	0.0461	1.53	0.15	170	201	142	87	76	25	35	610	117	77	
	<b>σ</b>	0.23	0.16	0.027	0.13	0.62	0.47	0.09	0.0034	0.08	0.13	10	31	4	3	3	1	4	112	7	6	
	<b>Thasos, Molos workshop, amphorae (n = 27)</b>																					
	<b>m</b>	2.15	4.75	0.614	3.37	64.41	21.86	1.83	0.0877	0.14	0.61	208	69	101	95	64	45	61	652	67	99	
	<b>σ</b>	1.44	0.53	0.073	0.30	1.17	1.20	0.40	0.0191	0.19	0.68	16	19	17	12	14	7	27	137	13	6	
	<b>Istanbul, Saraçhane, Glazed White Ware I (n = 16, Waksman et al. 2007)</b>																					
	<b>m</b>	0.78	5.71	1.104	1.44	69.22	20.37	0.61	0.0229	0.45	0.12	285	41	71	45	86	32	45	330	112	91	
	<b>σ</b>	0.65	0.77	0.114	0.26	2.44	2.11	0.16	0.0057	0.50	0.07	36	10	15	5	12	6	8	78	21	17	

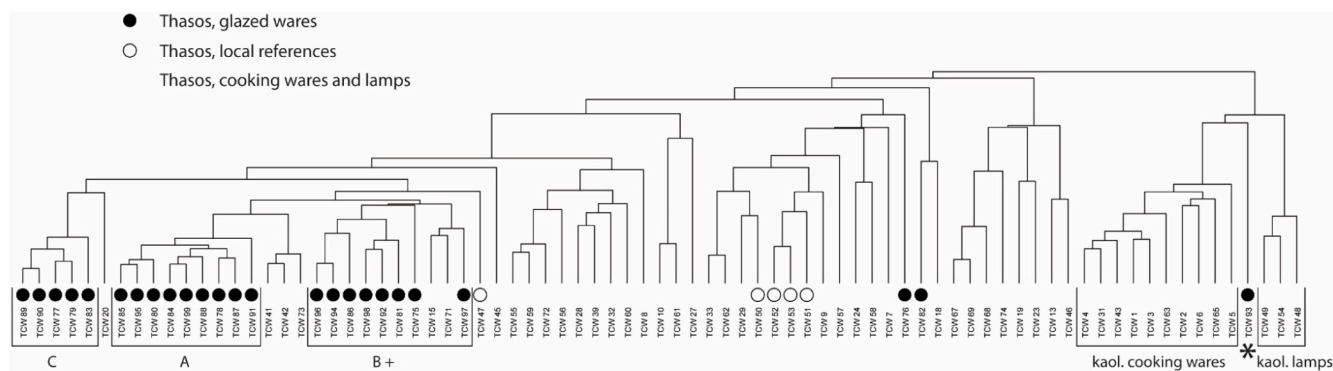


Fig. 4. Hierarchical clustering analysis based on the chemical composition of the bodies, Thasos glazed wares together with Thasos cooking wares and lamps found in Late Roman contexts, micaceous and kaolinitic fabrics (after Waksman and Blondé, 2011). The asterisk marks a glazed sample (TCW 93) distinguished by a kaolinitic body.

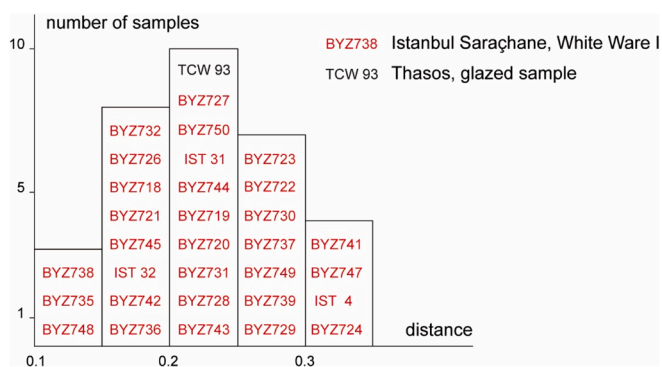


Fig. 5. Histogram of Euclidean distances between the reference group of “Byzantine White Ware I” and Thasos sample TCW 93.

bubbles of gases either trapped in the glaze (blisters) or which exploded leaving a cavity (pinholes). Both would be favoured by a single firing, as a first, biscuit firing prior to glazing and second firing would have liberated gases due e.g. to organic material contained in the clayey body, and thus avoid such glazing defects.

The firing conditions of Thasos samples are less consistent and display various aspects (bodies completely reduced, or completely re-oxidized even with both surfaces glazed, and several intermediate cases) which do not provide such a clear picture.

SEM-EDS analyses of the glazes indicate that they are high-lead ones, with  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  contents usually below 1 % (Table 2). The iron concentrations between 1.5 and 3 % FeO may account for the greenish to brown colour of the glazes, when applied on a reduced or oxidised body surface, respectively. The glaze compositions are not very homogeneous, but may be seen as variants of a similar “recipe”, with no clear pattern related either to the site (Sofia or Thasos) or to the chemical subgroup of the bodies. One sample stands out, though, the import of “Glazed White Ware I” (TCW 93), with lower lead, higher alumina and much higher silica concentrations (more than 30 %  $\text{SiO}_2$ , versus an average of c. 20 % for the other samples, Table 2). These features are in good agreement with previous data on “Glazed White Ware I” (Waksman et al., 2007). Fairly developed interfaces between the body and glaze (Fig. 7) tend to support the hypothesis of a single firing, although several other parameters should theoretically be taken into account (Molera et al., 2001; Cormier and Godet, 2022 with further literature). Most of the inclusions present at the interfaces are rich in Pb, Si, and to a lesser extent Al and K, which suggest that they may be lead feldspars, which may develop at the interface between high-lead and low-calcareous bodies (Molera et al., 2001, Cormier and Godet, 2022 with further literature).

The technical tradition our samples belong to may be better understood when compared with other Roman, Late Roman and Early Byzantine glazed wares, as seen on the binary plots presented Fig. 8.<sup>11</sup> The  $\text{CaO}/\text{SiO}_2 + \text{Al}_2\text{O}_3$  plot (left) differentiates samples having low- and high-calcareous bodies. On the right hand side of the figure, the  $\text{SiO}_2$  content of the body is plotted against the  $\text{SiO}_2$  content of the glaze, recalculated without the contribution of PbO. This diagram may be used to evaluate if a glazing mix containing an addition of silica was used ( $\text{SiO}_2$  glaze recalculated >  $\text{SiO}_2$  body), or if the lead compounds (usually sulfides or oxides) combined with the silicon of the body to form the glaze during firing (dots around the first bisector) (Hurst and Freestone, 1996; Walton, 2004; Waksman et al., 2008; Walton and Tite, 2010; see also Cormier and Godet, 2022 for details and requests for caution in the use of such diagrams). Fig. 8 (left and right) illustrates two technical traditions: on the one hand the association of calcareous bodies with a (possibly pre-fired) glazing mix containing an addition of silica, on the other hand non-calcareous bodies on which lead compounds were applied as such (or mixed with the same clay). The Late Roman batches examined, including Sofia’s and Thasos’, belong to the second tradition, as well as the Early Byzantine “Glazed White Ware I” (Waksman et al., 2007, 2008). These results are in good agreement with previous studies by Capelli et al. on Late Roman glazed wares found in Northern Italy, Hungary, and Bulgaria, and on the 5th c. production site of Carlino (Walton and Tite, 2005; Capelli et al., 2009, 2010a, 2010b).

## 5. Concluding remarks

The archaeometric study of ceramics from Bulgaria and Northern Greece provided the opportunity to investigate little known 6th c. AD glazed wares, at the transition between the Late Antique and the Early Byzantine periods. In Sofia (Bulgaria), they came from a workshop context, and are shown to be made of the same clayey material as unglazed common and cooking wares fired in the same kilns. The analyses suggest that their high-lead glazes were manufactured with lead compounds which combined with the silica of the body to form the glaze during a single firing. In Thasos, the same technical features are observed, with an association of high lead-glazes applied on low-calcareous bodies. For the majority of the glazed samples of Thasos, a local origin is possible but not demonstrated. On the other hand, the analyses clearly show the presence of an example of Byzantine “Glazed White Ware I”, which is actually the only import of this ware confirmed

<sup>11</sup> adapted from Waksman et al., 2008, where the description of the comparative material considered may be found.



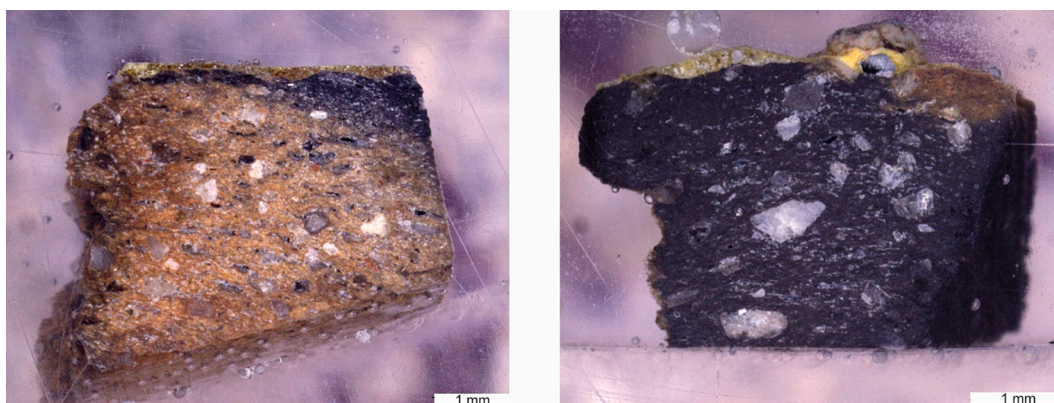


Fig. 6. Polished cross-sections under the binocular microscope, showing total reduction (right, BZN473) or partial reduction (left, BZN469) of the clayey body on the glazed side. A large bubble at the surface of the glaze covered by crusting is also visible (right). Sofia workshop samples (photos J. Burlot).

Table 2

Chemical composition of the glazes determined by SEM-EDS (in oxide weight %).

Lyon id.	Na <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	K <sub>2</sub> O	CaO	TiO <sub>2</sub>	FeO	PbO
<b>Sofia, Lozenets workshop</b>									
BZN466	0.3	0.6	7.1	20.9	0.4	0.8	0.3	2.4	67.1
BZN467	0.4	0.5	5.9	18.2	0.6	0.7	0.2	1.8	71.7
BZN469	0.2	0.5	5.8	16.3	0.4	0.9	0.2	1.8	73.9
BZN473	0.3	0.4	5.2	15.7	0.3	1.3	0.2	1.7	74.9
BZN475	0.2	0.5	5.3	17.9	0.6	0.7	0.2	2.8	71.8
BZN478	0.3	0.5	6.0	19.8	0.5	0.5	0.2	1.8	70.3
BZN487	0.6	0.7	7.5	22.4	0.7	0.9	0.3	2.4	64.6
<b>Thasos, local?</b>									
TCW75	0.3	0.5	6.4	20.4	0.6	0.7	0.3	2.1	68.7
TCW80	0.6	0.9	6.6	25.7	0.9	2.0	0.2	2.2	60.8
TCW84	0.2	0.7	5.7	19.8	0.6	1.2	0.2	2.3	69.3
TCW88	0.4	0.5	5.2	17.7	0.4	0.6	0.1	1.7	73.2
TCW89	0.4	0.9	6.2	22.5	0.7	1.0	0.3	2.0	66.0
TCW90	0.4	1.0	6.8	22.1	0.6	1.5	0.3	2.4	65.0
<b>Thasos, Glazed White Ware I</b>									
TCW93	0.2	0.2	8.6	30.8	1.0	0.5	0.6	1.6	56.5

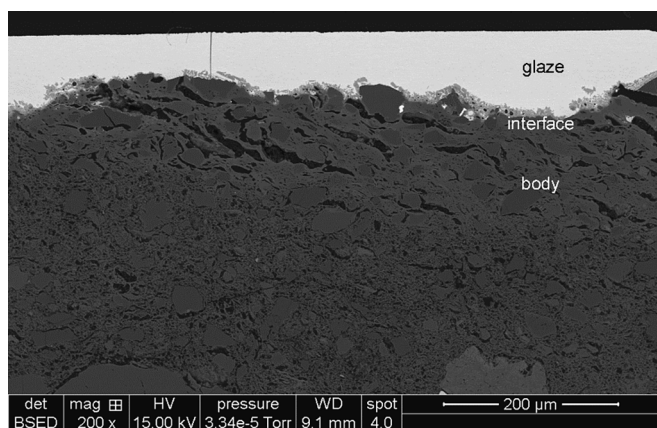
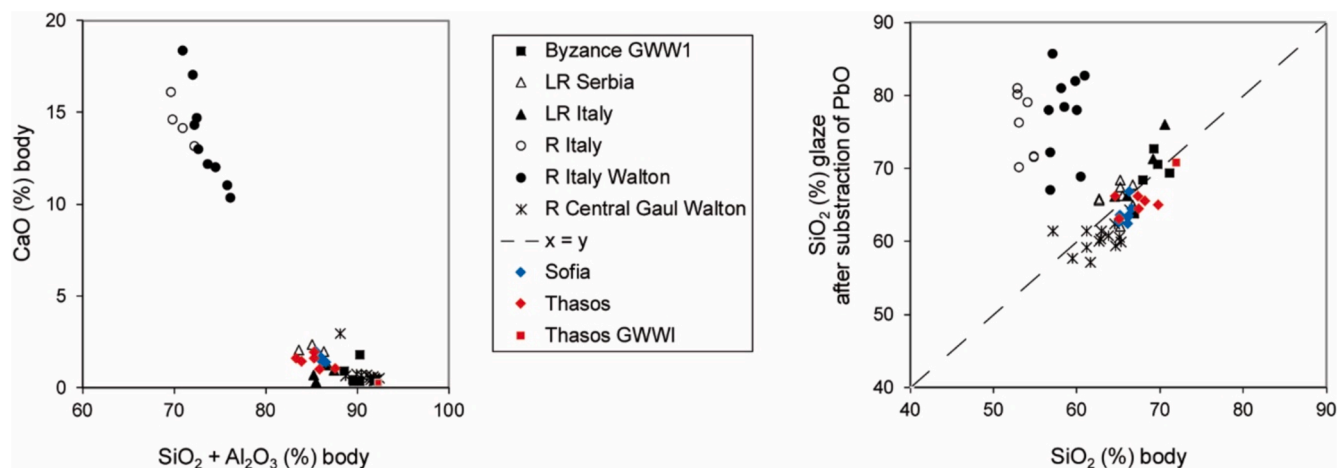


Fig. 7. Representative example of a glazed ware as seen under the SEM, BSE mode: the high-lead glaze is applied directly on the low-calcareous body, without intermediate slip; inclusions are visible at the interface between the body and the glaze (sample BZN466, Sofia) (photo L. Geay, CTU).

by chemical analyses so far.<sup>12</sup> Also noticeable in Thasos is the presence in the same contexts of other wares having a kaolinitic body, possibly including glazed lamps, which are distinct from the series of “Byzantine Glazed White Ware” attributed to Constantinople (Waksman, 2019).

Our data seem to fill what was previously seen as a gap between the 4th – early 5th c. Late Roman glazed productions, well identified archaeologically from the Balkans to Northern Italy, and the 7th c. Byzantine “Glazed White Ware I” defined in Constantinople/Istanbul and confirm Trivyzadaki’s and Petridis’ earlier suggestions. They suggest the continuity of a technical tradition which may last in the Byzantine mainlands until the short-lived emergence in the 10th c. of glazing techniques coming from the Islamic world, with the “Polychrome White Ware” (Waksman et al., 2024), and fade away at the beginning of the 12th c., with the spectacular development of glazed wares productions (Sanders, 1995, 2003) using a wide variety of clay

<sup>12</sup> For a counter example of White Ware I at Limyra (southern Turkey): Waksman and Lemaître, 2010. Also, the glazed bowl from the Yassı Ada shipwreck (Bass and von Doorninck, 1982, p.165–166, 170: P1), continuously mentioned as a “Glazed White Ware I” (e.g. François, 2017) is probably not one, although other sherds on the ship present to the naked eye the typical kaolinitic fabric of “Byzantine White Wares” (S.Y. Waksman personal observation, with thanks to J. Leidwanger, F. van Doorninck, T. Ekmekci, and especially to E. Altınanıt and Ş. Yıldız). The full study of these materials is currently underway by Leidwanger and Giannaki.



**Fig. 8.** Binary plots showing selected chemical features of the bodies and glazes of the samples, together with data from the literature; two different technical traditions are illustrated: a glazing mix mainly involving Pb and Si compounds applied on calcareous bodies, as opposed to low-calcareous bodies on which Pb compounds were applied directly or mixed with the same clay (R: Roman, LR: Late Roman, GWWI: “Glazed White Ware I”; adapted from Waksman et al., 2008).

bodies and decoration techniques enabled by the introduction of under-glaze slips.

#### CRediT authorship contribution statement

**S.Y. Waksman:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft. **G. Giannaki:** Funding acquisition, Investigation. **J. Burlot:** Investigation, Methodology. **E. Todorova:** Conceptualization, Funding acquisition, Investigation, Methodology, Writing – review & editing, Project administration. **M. Daskalov:** Investigation, Project administration. **S. Goryanova:** Investigation. **G. Guionova:** Investigation. **P. Petridis:** Conceptualization, Investigation.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Acknowledgements

This research was supported by a French-Bulgarian PHC RILA programme (project number: 48049UB), co-directed by E. Todorova and S. Y. Waksman, funded by the French Ministry for Europe and Foreign Affairs, the French Ministry for Higher Education and Research and the Bulgarian Ministry for Education and Science; by the Bulgarian National Science Fund according to contract No. КП-06-Рила-6/15.12.2021; by grants to G. Giannaki from the Hellenic Foundation for Research and Innovation (HFRI) under the 3rd call for HFRI PhD Fellowship grant (Fellowship Number: 6804) and from the French Academy (Jean Walter Zeldidja grant). Our thanks also go to the staff of the “Céramologie” (CNRS UMR 5138) and the CTμ (Lyon 1 University) platforms in Lyon, and to the MONARIS laboratory (UMR 8233) in Paris.

#### Data availability

The data are contained in the manuscript

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