Bartłomiej Sz. Szmoniewski
Institute of Archaeology and Ethnology, Polish Academy of Sciences
b.szmoniewski@iaepan.edu.pl
ORCID: 0000-0003-0737-434X

Ewelina Miśta-Jakubowska
National Centre for Nuclear Research
Institute of Archaeology, Jagiellonian University
ewelina.mista@ncbj.gov.pl
ORCID: 0000-0002-0053-8711

Dariusz Rozmus
Sztygarka City Museum, Dąbrowa-Górnicza
Humanitas University in Sosnowiec
E-mail: rozmusd@poczta.onet.pl
ORCID: 0000-0002-3264-8923

Renata Czech-Błońska
Institute of Archaeology, Jagiellonian University
renata.czech-blonska@uj.edu.pl
ORCID: 0000-0002-7043-7246

Rafał Siuda
Faculty of Geology, University of Warsaw
rsiuda@uw.edu.pl
ORCID: 0000-0003-4153-8539

Jakub Karasiński
Faculty of Chemistry, Biological and Chemical Research Centre, University of Warsaw
jkarasinski@uw.edu.pl
ORCID: 0000-0003-3143-9131

Krystian Trela
Institute of Archaeology, Jagiellonian University
krystian.trela@uj.edu.pl
ORCID: 0000-0002-7936-1428

Technological Insights into Early Medieval Slavic Lead-Glazed Pottery: Local Craftsmanship and its Broader Archaeometric Context[1]

Abstract

This study examines the technological development and material composition of glazed pottery from Lesser Poland, highlighting two distinct glazing horizons spanning the 11th to 13th centuries. Employing analytical methods, including lead isotope analysis (MC-ICP-MS), SEM-EDS, and pXRD, the research establishes a connection between early glazing practices and regional polymetallic ore deposits from Upper Silesia. The findings reveal a significant technological progression: an earlier phase (mid-11th to early 12th century) characterized by durable, lead-rich glazes, followed by a later phase (12th–13th century) marked by thinner and more refined glazing techniques. This investigation provides novel insights into the innovation, technological adaptation, and regional craftsmanship of early medieval Polish pottery, contributing to the broader understanding of interregional production networks and the diffusion of technological knowledge in medieval Europe.

Keywords: Slavic lead glaze pottery, Lesser Poland and Upper Silesia ores, lead isotope ratios, provenance study, medieval Europe

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Fig. 1. Distribution of sites in the border region between Lesser Poland and Upper Silesia with finds of lead-glazed ceramics (compiled by B. Sz. Szmoniewski).

Introduction

Glazed ceramics from the early medieval period discovered in Slavic territories represent a unique phenomenon. The earliest archaeological finds of glazed pottery, dated to the mid-11th century, sparked considerable debate regarding their origins. Initially, due to the limited number of discoveries, these finds were considered incidental and confined to a small area within Poland. However, a systematic increase in the number of sites yielding glazed ceramics has reignited the question of how this technological innovation emerged. In this context, determining the potential sources of raw materials used in glazing has become particularly significant. The present text offers a preliminary contribution to this subject, serving as an introduction to a compelling topic and laying the groundwork for further planned research.

Two principal theories have emerged in scholarly literature. The first posits that glazed ceramics were a local development, associated with the exploitation of zinc and silver ores in the Olkusz region. The second

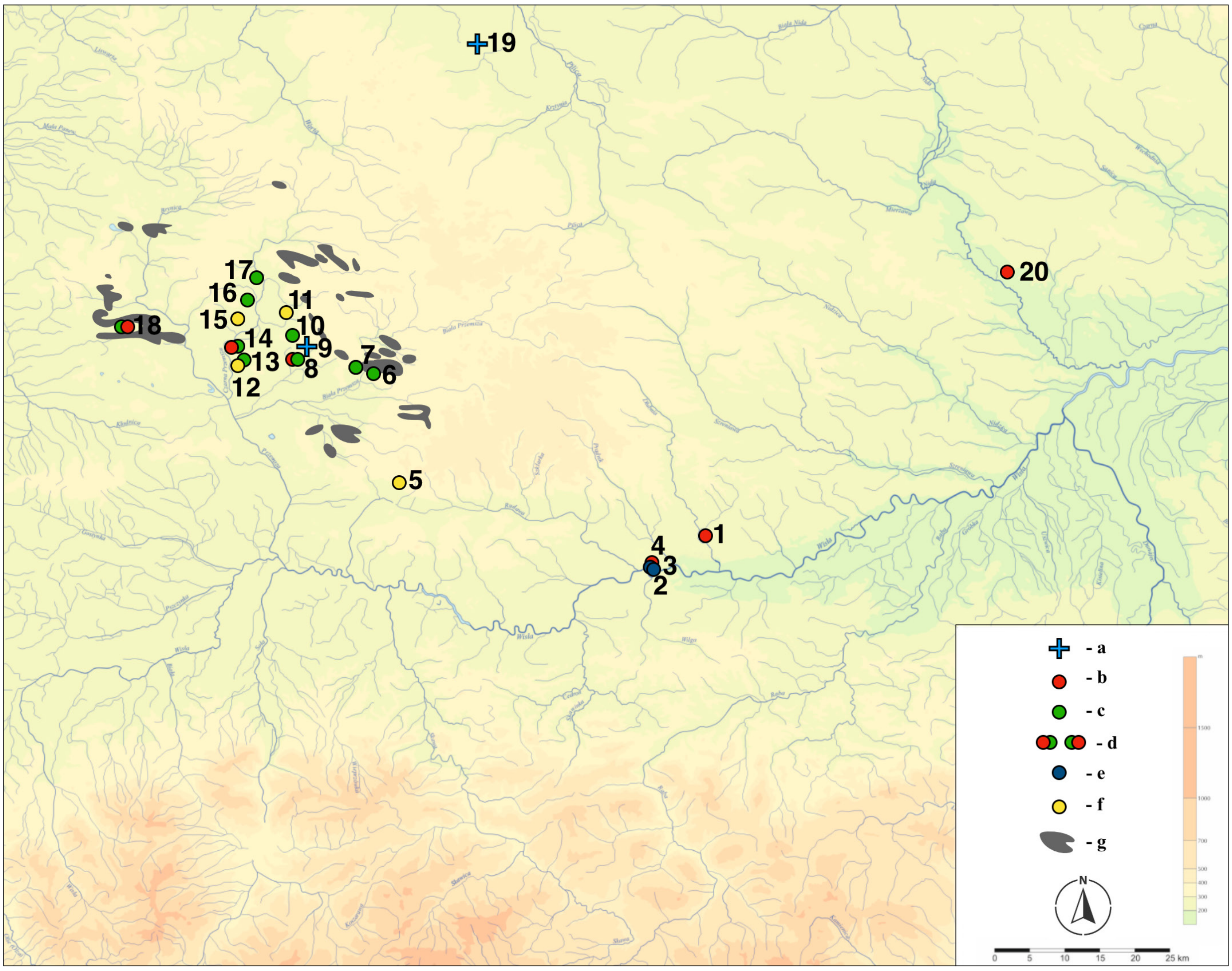

Fig. 2. Detailed map of sites with finds of lead-glazed ceramics in the western part of Kraków Land, located in the border region between Lesser Poland and Upper Silesia, in relation to Pb-Zn mineralization.
Legend: a – cemetery; b – settlement; c – settlement with production zone and kilns; d – hillfort; f – sites identified during surface prospection (source: Polish Archaeological Record); g – Pb-Zn ore deposits (after: Szmoniewski *et al.*, 2025) 1. Kraków – Zesławice, Lesser Poland Voivodeship; 2. Kraków-Wawel, Lesser Poland Voivodeship; 3. Kraków-Okół, Lesser Poland Voivodeship; 4. Kraków – Rynek, Lesser Poland Voivodeship; 5. Stare Bukowno, Lesser Poland Voivodeship; 6. Sławków, Silesian Voivodeship; 7. Bytom, Silesian Voivodeship; 8. Dąbrowa Górnicza-Strzemieszyce Wielkie, Silesian Voivodeship 9. Dąbrowa Górnicza-Strzemieszyce Wielkie, Silesian Voivodeship; 10. Dąbrowa Górnicza-Łosień, Silesian Voivodeship; 11. Dąbrowa Górnicza-Tucznawa Przymiarki, Silesian Voivodeship; 12. Sosnowiec, Park Sielecki, Silesian Voivodeship; 13. Sosnowiec-Zagórze, Silesian Voivodeship; 14. Będzin, Silesian Voivodeship; 15. Malinowcie, Silesian Voivodeship; 16. Przeczyce, Silesian Voivodeship; 17. Siewierz, Silesian Voivodeship; 18. Bytom, Silesian Voivodeship; 19. Lelów, Silesian Voivodeship; 20. Wiślica, Świętokrzyskie Voivodeship.

attributes the origins of glazing technology to cultural exchange with Kievan Rus', whose practices were themselves influenced by Byzantine traditions.[2] However, recent comparative studies have largely dismissed the latter theory, emphasizing that the ceramic traditions of Kievan Rus' were fundamentally different in terms of techniques, vessel forms, and decorative styles. Consequently, a direct influence from Kievan Rus' on Lesser Polish ceramic production appears unlikely.[3] It is worth underscoring that glazed ceramics from the Polish territories stand out within the broader landscape of Early Medieval pottery, especially when contrasted with those of the western neighbours of the Slavs. In the areas of present-day Germany, for instance, glazed pottery does not appear until the 12th century.[4] Outside of Byzantium and Kievan Rus', glazing technology was known in parts of Western Europe, with glazed ceramics being produced in 11th-century Belgium, Italy, and France.[5]

[2] Cf. Bodnar *et al.* 2006; Auch 2012.
[3] Auch 2012, 239.
[4] Höltken 2000, 17.
[5] Verhaeghe 1969, 108; Whitehouse 1980, 68–69; Husi 2003, 31; Jesset 2003, 62.

Fig. 3. Early medieval glazed pottery: 1 – Lelów, site 17, grave no. 7; 2 – Dąbrowa Górnicza-Strzemieszyce Wielkie, site 1, grave no. 80; 3 – Dąbrowa Górnicza-Strzemieszyce Wielkie, site 1, grave no. 20 (photo by B. Sz. Szmoniewski).

The first glazed ceramics in the Polish lands were uncovered during the 1930s at the exceptional cemetery site of Strzemieszyce Wielkie, dated to the mid-11th to mid-12th century (Fig. 1 and 2: 9). Among the most remarkable finds were two yellow, bucket-shaped, cylindrical vessels. They imitated a bucket. One of the specimens is decorated with a series of raised, encircling ridges featuring diagonal incisions, with bands adorned with a wavy line between them (Fig. 3:3). The second, smaller one is decorated only with closely spaced encircling ridges (Fig. 3:2). Since the post-war period, the number of glazed ceramic finds has steadily grown, with the highest concentration along the historical border between Lesser Poland and Upper Silesia – regions comprising part of Kraków Land in the early medieval period. To date, 22 archaeological sites yielding glazed ceramics have been identified in this region, along with 15 additional sites in the western part of Kraków Land that are considered part of the same tradition (Fig. 2).

Glazed ceramic vessels and fragments have been found at three main types of archaeological contexts: metallurgical settlements, settlements/hillforts/towns, and inhumation cemeteries (Fig. 1 and 2). Notably, the majority of such finds come from metallurgical sites, often interpreted as early medieval lead-smelting workshops or centres involved in lead trade, such as Siewierz, dating back to the mid- or late 11th century. The development of these sites, where glazed pottery is found in varying quantities, was made possible by the presence of near-surface lead ores with silver content. The lead ores used in these processes, primarily in the form of galena (PbS), were critical for both lead and silver production. In the case of the glazed ceramics characteristic of this region, litharge (PbO), or lead (II) oxide, served as a key intermediate in the glaze manufacturing process. It was produced through the oxidation (sintering) of galena and functioned as an essential component in obtaining both pure lead and glaze materials.[6]

This article aims to substantiate the hypothesis of local glaze production through lead isotope ratio analysis of glazes from selected early medieval vessels excavated in Poland. In addition, it presents the results of technological analyses and compares them with prior research. These findings contribute to the ongoing scholarly discussion concerning the origins and technological transmission of glazed ceramics in the Slavic cultural sphere.

[6] Rozmus, Garbacz-Klempka 2017, 267–268.

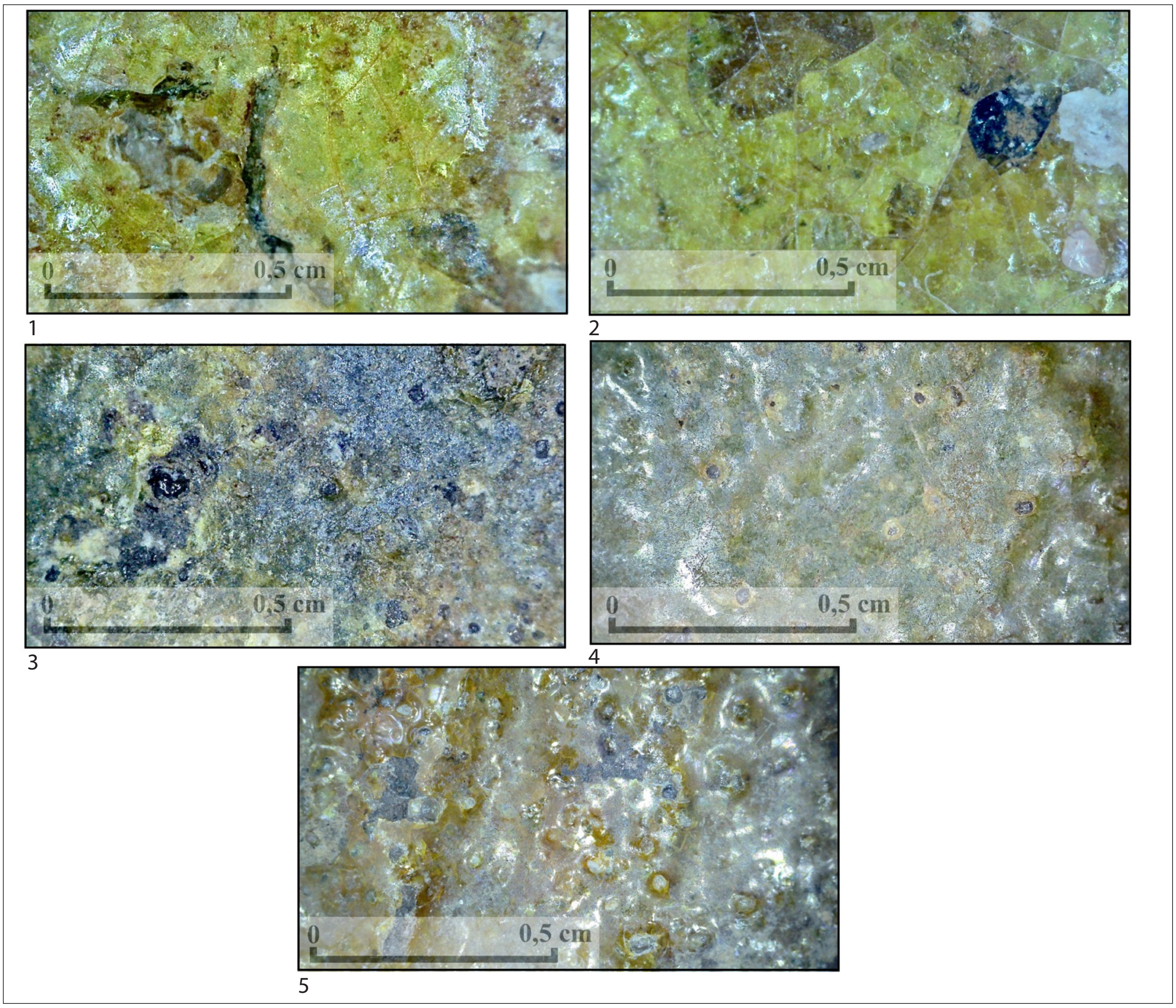

Fig. 4. Photographs of the surfaces of the analysed glazed vessels: 1, 2 – Lelów; 3 – Dąbrowa Górnicza-Łosień; 4 – Sosnowiec-Zagórze; 5 – Siewierz (photo by B. Sz. Szmoniewski).

Materials

Archaeological material

Four fragments of the pottery were subjected to technological analysis and studied for the origin of the lead used in the glazing. Three were found in the archaeological context of foundry settlements: Dąbrowa Górnicza-Łosień, site 2 (no. 1; Figs. 4:1, 6:1); Sosnowiec Zagórze (no. 2; Figs. 4:2, 6:2); Siewierz (no. 3; Figs. 4:3, 6:3), dated from the mid-11th to mid-13th century.[7] The fourth artifact was discovered in grave 7 at the inhumation cemetery in Lelów (Figs. 3:1, 4:1, 2; 5:1-4), dated to the mid-11th century.[8]

Methods, Instruments, and Analysis

Chemical composition

The technological study was conducted using Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS). The research was carried out at the Laboratory of Archaeometallurgy and Conservation of Archaeological Artifacts, Institute of Archaeology, Jagiellonian University, using a Tescan Vega 3 XMU with an Aztec X-Max 50 EDS system. Cross-sections of the samples were taken from the artifacts and coated with a thin gold layer to enhance conductivity. SEM imaging (BSE mode) was performed at

[7] Bodnar *et al.* 2005, 67.

[8] Szmoniewski *et al.* 2024.

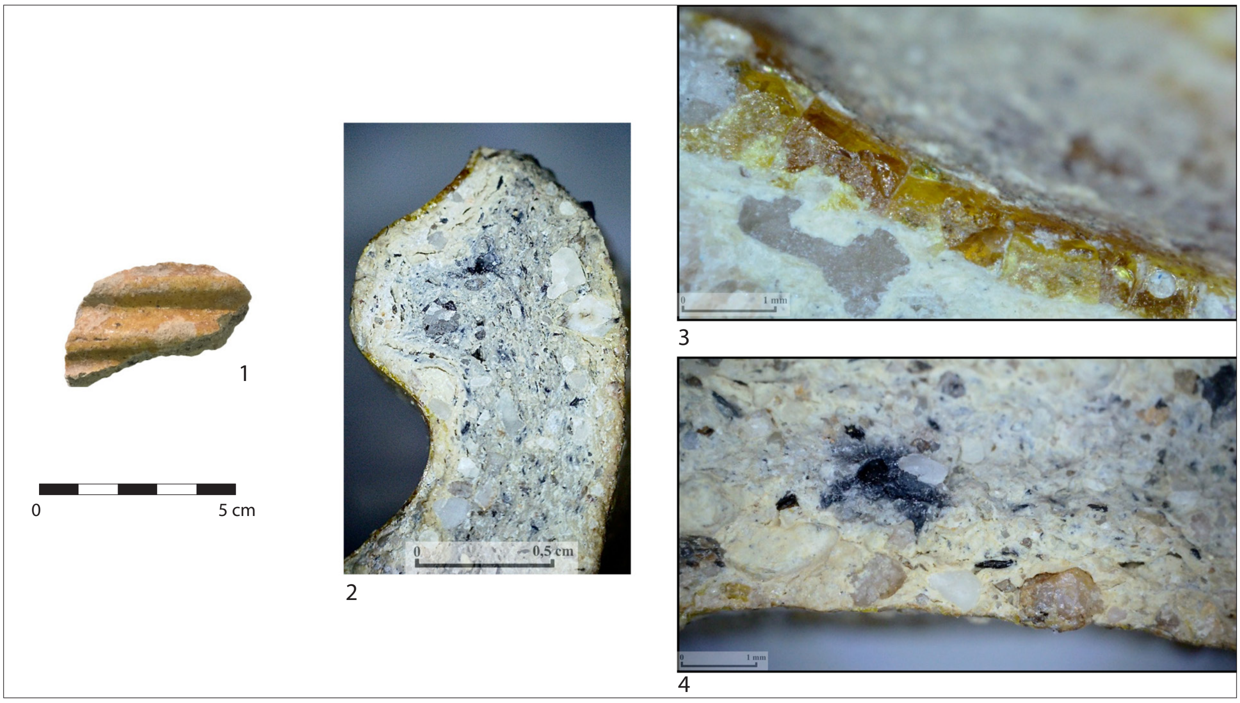

Fig. 5. 1 – Photograph of the sample taken from a glazed vessel from Lelów, grave no. 7; 2-4 –Microscopic image of the ceramic cross-section from Lelów (photo by B. Sz. Szmoniewski).

an accelerating voltage of 20 kV, and EDS measurements were conducted at a working distance of less than 15 mm. The beam current and magnification were adjusted based on the sample's surface morphology. For area analysis, the measurement time was optimized according to the sample's characteristics, with EDS maps recorded for at least 15 minutes. EDS spectra were collected with a dead time of 10% and a count rate of 8000 cps. For oxide content analysis, standardless calibration[9] was applied, with a lower limit of detection (LLD) of 0.1 wt%. The obtained EDS results for both glaze and clay areas are presented in Tables 1A and B. Chemical composition analysis focused on the technological areas, namely the clay and glazing. EDS spectra were recorded from points and areas up to 1500 × 1500 micrometers, ensuring that the measurement averages were adapted to the material's heterogeneity. This approach minimized the standard deviation (SD), ensuring statistical reliability with a minimum of three measurements (n = min. 3) (see Tables 1A and B). The phase composition of the pottery was analysed using powder X-ray diffraction (XRD) on an X'Pert Pro diffractometer at the Faculty of Geology, University of Warsaw. The analysis was conducted with the following parameters: current of 30 mA, voltage of 40 kV, CoKα anode, step size of 0.026 2θ, starting position at 4.01 2θ, and ending position at 77.98 2θ, with no monochromator used. The results were interpreted using X'Pert Plus HighScore software, referencing the ICDD PDF-2 (RDB 2008) database.

Isotopic composition

Lead isotope ratio analysis of the glaze samples was performed at the University of Warsaw Biological and Chemical Research Centre, following the methods outlined by Karasiński *et al.*[10] Samples were digested using microwave-assisted digestion (Milestone, Ethos Up), and the resulting solutions were diluted with deionized water (Millipore, MilliQ Q Pod). The levels of Tl and Hg were checked using quadrupole mass spectrometry (Perkin Elmer, NexIon 300D) to avoid problems with spectral interference of ^{204}Hg and problems with the isotopic composition of the internal standard (Tl). Due to the high lead concentration, ion exchange chromatography was not required. Lead isotope ratios were measured using multi-collector mass spectrometry (MC-ICP-MS) on a Nu Instruments Plasma III spectrometer, with 16 Faraday cups in dry plasma mode (Cetac Aridus 3 desolvation nebulizer, 100 µl/min). The sensitivity for ^{208}Pb was approximately 1.0 V per 1 µg/L Pb, so samples

[9] Trincavelli *et al.* 2014.

[10] Karasiński *et al.* 2023.

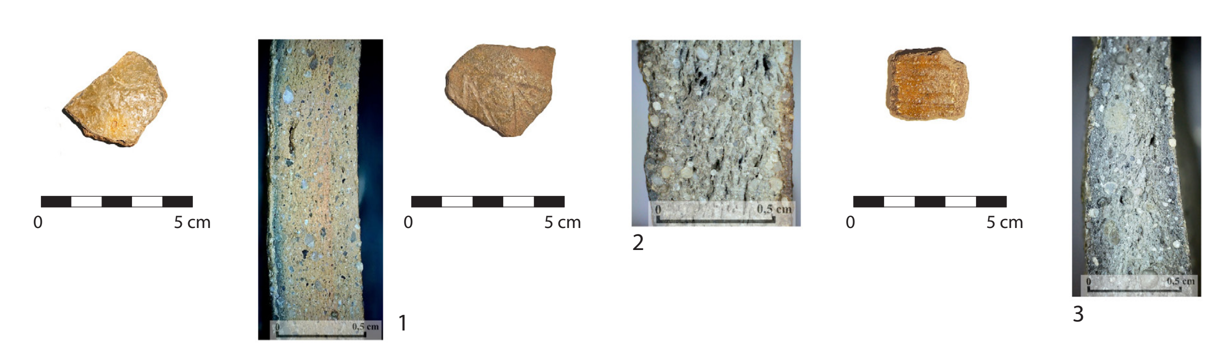

Fig. 6. Microscopic images of ceramic cross-sections: 1 – Siewierz; 2 – Dąbrowa Górnicza-Łosień; 3 – Sosnowiec-Zagórze (photo by B. Sz. Szmoniewski).

with 50 µg/L Pb were used. Samples were spiked with NIST 997 Tl solution (25-30 µg/L), and all measurements were corrected with an internal standard (Tl), following Karasiński *et al.*[11] Each measurement involved 20 integrations of 15 seconds, with background correction using 'Zero by ESA'. The ^{202}Hg isotope was monitored, and mathematical corrections were made for any interference from ^{204}Hg on ^{204}Pb. NIST SRM 981, spiked with Tl (NIST SRM 997), was analysed five times during the session. Pb isotope ratios were corrected based on the discrepancy between our recommended values[12] and the average for NIST SRM 981. The average values (n=5) and corresponding 2SD are as follows: $^{208}Pb/^{204}Pb$ 36.699±0.001; $^{207}Pb/^{204}Pb$ 15.492±0.001; $^{206}Pb/^{204}Pb$ 16.938±0.001; $^{208}Pb/^{206}Pb$ 2.16664±0.00011; $^{207}Pb/^{206}Pb$ 0.91463±0.00003. The obtained lead isotope ratios are presented in Table 2.

Results

Technology Aspects

Figure 8 presents the SEM-EDS data for two types of analysed ceramics: the older and the younger. The older phase is represented by ceramics from Lelów, while the remaining samples correspond to a younger phase, as indicated by the chemical composition analyses described below. Microscopic analyses (see also Figs. 5:2–4) show that the older ceramics, represented by artifact 4 from the Lelów cemetery, have a thicker glaze layer (approximately 200 micrometers, see Figs. 7:a, b). The remaining, younger artifacts are decorated with glaze about 100 micrometers thick (Fig. 7:d, e). All analysed vessels were made from coarse-grained ceramics with a low degree of vitrification (see Figs. 7:c, f). Tab. 1A and B pres-

Table 1A. Chemical composition (EDS) obtained for lead glaze of ceramics (in wt%±1σ, „-” - below 0.1 wt%).

No	Sampling	PbO	MgO	Al_2O_3	SiO_2	K_2O	CaO	FeO	P_2O_5	TiO_2
1 Dąbrowa-Górnicza Łosień site, greenish-brown quartz:										
1	point	70.6 ±0.4	0.4 ±0.1	5.5 ±0.2	20.2 ±0.3	0.8 ±0.1	0.8 ±0.1	1.7 ±0.2	-	-
2	area 50/50 µm	70.2±0.4	0.6±0.1	5.5±0.2	20.0±0.3	0.7±0.1	1.3±0.1	1.4±0.2	-	0.5±0.2
3	area 50/50 µm	70.6±0.3	0.7±0.1	5.6±0.2	20.1±0.3	0.8±0.1	0.8±0.1	1.5±0.1	-	-
4	area 50/50 µm	71.3±0.4	0.6±0.1	5.9±0.2	20.2±0.3	-	0.6±0.1	1.4±0.1	-	-
5	point	73.7 ±0.5	-	4.3 ±0.2	15.7 ±0.3	0.8 ±0.2	0.9 ±0.2	4.6 ±0.4	-	-
6	point	70.3±0.4	0.6±0.1	5.2±0.2	21.4±0.3	0.8±0.1	0.4±0.1	1.4±0.2	-	-
7	point	75.9±0.4	-	4.0±0.2	16.7±0.3	0.8±0.1	0.4±0.1	2.2±0.2	-	-

→

[11] Karasiński *et al.* 2023.

[12] Karasiński *et al.* 2023.

No	Sampling	PbO	MgO	Al_2O_3	SiO_2	K_2O	CaO	FeO	P_2O_5	TiO_2
8	point	71.2±0.3	0.5±0.1	5,8±0.2	21.2±0.3	-	-	1.3±0.1	-	-
9	point	72.6±0.3	0.6±0.1	4,4±0.2	20.0±0.3	0.6±0.1	0.6±0.1	1.2±0.1	-	-
10	area 50/50 µm	71.4±0.4	0.7±0.1	5.2±0.2	19.0±0.3	1.0±0.1	0.8±0.1	1.9±0.2	-	-
average ± SD		71.8±1.8	0.5±0.3	5.1±0.7	19.5±1.8	0.6±0.3	0.7±0.4	1.8±1.0	-	<0.5
2 Sosonowiec-Zagórze site, brownish quartz:										
1	point	72.8±0.3	0.8±0.1	4.1±0.1	19.6±0.3	-	-	2.1±0.2	-	0.6±0.1
2	point	73.7±0.3	0.4±0.1	4.5±0.1	19.1±0.3	-	-	2.0±0.2	-	-
3	area 50/50 µm	68.1±0.4	0.6±0.1	5.4±0.2	22.0±0.3	1.0±0.1	0.6±0.1	1.7±0.2	-	0.6±0.1
4	area 50/50 µm	71.1±0.4	0.5±0.1	4.9±0.2	21.0±0.3	0.4±0.1	-	2.0±0.2	-	-
5	area 50/50 µm	70.9±0.4	0.4±0.1	4.7±0.2	22.0±0.3	0.5±0.1	-	1.6±0.2	-	-
6	area 50/50 µm	68.7±0.4	0.4±0.1	4.5±0.2	24.5±0.3	0.5±0.1	-	1.5±0.2	-	-
7	area 50/50 µm	69.3±0.4	0.6±0.1	5.4±0.2	22.2±0.3	0.6±0.1	0.5±0.1	1.5±0.2	-	-
8	point	72.6±0.3	0.7±0.1	4.7±0.2	20.2±0.3	-	-	1.8±0.2	-	-
9	point	72.0±0.3	0.7±0.1	5.0±0.2	20.7±0.3	-	-	1.6±0.2	-	-
10	point	73.4±0.3	0.5±0.1	4.4±0.2	20.3±0.3	-	-	1.5±0.2	-	-
average ± SD		71.3±2.0	0.6±0.1	4.8±0.4	21.2±1.6	<1.0	<0.6	1.7±0.2	-	<0.6
3 Siewierz site, brownish quartz:										
1	point	64.9±0.4	0.5±0.1	6.6±0.2	18.0±0.2	0.8±0.1	2.9±0.1	3.1±0.2	3.4±0.2	-
2	point	61.1±0.4	0.6±0.1	6.5±0.2	20.0±0.3	0.9±0.1	3.2±0.1	3.7±0.2	3.0±0.1	0.5±0.1
3	point	66.6±0.4	0.5±0.1	6.1±0.2	19.0±0.2	0.6±0.1	2.1±0.1	2.6±0.2	2.2±0.1	-
average ± SD		64.2±2.8	0.5±0.1	6.4±0.2	19.2±1.3	0.8±0.1	2.7±0.6	3.2±0.6	2.9±0.6	<0.5
4 Lelów site, yellowish quartz:										
1	area 50/50 µm	81.8±0.4	-	4.4±0.2	12.3±0.2	-	0.5±0.1	1.0±0.2	-	-
2	area 50/50 µm	80.9±0.3	-	3.9±0.1	13.4±0.2	0.4±0.1	0.4±0.1	1.0±0.2	-	-
3	area 50/50 µm	77.1±0.3	-	4.9±0.1	15.6±0.2	0.4±0.1	0.6±0.1	1.4±0.2	-	-
4	area 50/50 µm	91.4±0.3	-	2.0±0.1	5.2±0.2	-	0.6±0.1	0.8±0.2	-	-
5	area 50/50 µm	73.9±0.3	0.6±0.1	6.4±0.2	17.0±0.2	0.5±0.1	0.6±0.1	1.1±0.2	-	-
6	area 50/50 µm	99.4±0.2	-	0.6±0.1	-	-	-	-	-	-
7	area 100/100 µm	93.2±0.4	-	1.6±0.1	3.8±0.2	-	1.0±0.1	0.8±0.2	-	-
8	area 100/100 µm	94.2±0.3	0.4±0.1	0.9±0.1	3.6±0.1	-	1.0±0.1	-	-	-
9	area 100/100 µm	85.7±0.3	-	3.7±0.1	8.9±0.2	-	1.0±0.1	0.9±0.2	-	-
10	area 100/100 µm	74.6±0.3	-	5.3±0.1	16.4±0.2	0.3±0.1	2.0±0.1	1.5±0.2	-	-
average ± SD		85.2±8.9	<0.5	3.4±2.0	9.6±6.1	<0.4	0.7±0.5	0.8±0.5	-	-

Table 1B. Chemical composition (EDS) obtained for clay of ceramics (in wt%±1σ, „-” - below 0.1 wt%).

No	Sampling	PbO	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	FeO	P_2O_5	TiO_2	MnO	SO_3	CuO
1 Dąbrowa-Górnicza Łosień site:														
1	area 1500/1500 µm	-	0.3±0.03	1.4±0.04	16.5±0.1	70.1±0.1	3.0±0.04	1.4±0.03	5.0±0.1	0.6±0.05	0.9±0.04	-	0.4±0.04	-
2		-	0.5±0.03	1.6±0.04	18.8±0.1	65.8±0.1	3.9±0.04	1.5±0.03	5.3±0.1	0.5±0.04	0.9±0.04	-	0.4±0.04	0.2±0.1
3		-	0.4±0.03	1.2±0.04	18.0±0.1	68.1±0.1	3.7±0.04	1.4±0.03	5.0±0.1	0.5±0.05	0.9±0.04	-	0.4±0.04	-
4		-	0.4±0.03	1.5±0.03	18.6±0.1	67.0±0.1	4.1±0.04	1.4±0.03	4.7±0.1	0.5±0.04	0.8±0.04	0.3±0.03	0.3±0.04	-
5		-	0.3±0.04	1.4±0.04	16.9±0.1	70.1±0.1	3.0±0.04	1.3±0.03	4.8±0.1	0.5±0.05	0.9±0.04	-	0.4±0.04	0.2±0.1
6		-	-	1.4±0.04	18.0±0.1	68.9±0.1	3.7±0.04	1.3±0.03	4.5±0.1	0.4±0.05	0.8±0.04	-	0.3±0.1	0.2±0.1
7		-	0.3±0.03	1.4±0.04	16.7±0.1	71.2±0.1	3.2±0.03	1.1±0.03	4.3±0.1	0.4±0.05	0.7±0.04	-	0.3±0.04	-
8	area 250/250 µm	-	0.7±0.1	1.9±0.1	21.0±0.2	63.1±0.3	4.1±0.1	1.7±0.1	6.1±0.2	-	1.1±0.1	-	-	-
9		-	0.5±0.1	1.7±0.1	19.5±0.2	66.5±0.3	3.5±0.1	1.2±0.1	5.5±0.2	-	1.3±0.1	-	-	-
10		-	0.7±0.1	1.9±0.1	19.7±0.2	64.8±0.3	3.8±0.1	1.8±0.1	5.6±0.2	-	0.7±0.1	-	0.6±0.1	-
average± SD		-	0.4±0.1	1.5±0.2	18.4±1.4	67.6±2.4	3.6±0.4	1.4±0.2	5.1±0.5	0.3±0.2	0.9±0.2	<0.3	0.3±0.2	<0.2
2 Sosonowiec-Zagórze site:														
1	area 250/250 µm	-	0.3±0.1	1.6±0.1	19.2±0.2	65.6±0.3	4.1±0.1	0.9±0.1	6.3±0.1	0.3±0.1	1.2±0.1	-	0.3±0.1	-
2		-	-	1.4±0.1	16.5±0.1	71.4±0.3	3.7±0.1	0.7±0.1	4.9±0.1	-	0.9±0.1	-	-	-
3		-	-	1.5±0.1	17.7±0.2	69.0±0.3	3.4±0.1	0.9±0.1	5.5±0.1	0.5±0.1	0.9±0.1	-	0.3±0.1	-
4		-	0.3±0.1	1.5±0.1	18.9±0.2	68.6±0.3	3.6±0.1	0.7±0.1	5.3±0.1	-	0.7±0.1	-	-	-
5		-	-	1.3±0.1	16.4±0.2	70.4±0.3	3.3±0.1	0.9±0.1	5.8±0.1	0.4±0.1	0.8±0.1	-	-	-
6		-	-	1.5±0.1	19.8±0.2	67.0±0.3	3.7±0.1	0.8±0.1	6.0±0.2	-	0.8±0.1	-	-	-
7		-	-	1.4±0.1	19.7±0.2	66.9±0.3	4.4±0.1	0.7±0.1	5.5±0.2	-	0.9±0.1	-	-	-
8		-	0.3±0.1	1.4±0.1	18.6±0.2	67.8±0.3	3.6±0.1	0.9±0.1	5.4±0.1	0.6±0.1	0.9±0.1	-	-	-
9		-	0.4±0.1	1.6±0.1	20.9±0.2	62.8±0.3	4.2±0.1	1.1±0.1	7.2±0.2	0.5±0.1	1.4±0.1	-	-	-
10		-	-	1.4±0.1	16.0±0.2	71.6±0.3	3.6±0.1	0.8±0.1	5.7±0.2	-	0.8±0.1	-	-	-

No	Sampling	PbO	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	FeO	P_2O_5	TiO_2	MnO	SO_3	CuO
average ± SD		-	<0.3	1.5±0.1	18.4±1.7	68.1±2.7	3.8±0.4	0.8±0.1	5.7±0.6	<0.5	0.9±0.2	-	<0.2	-
3 Siewierz site:														
1	area 1500/1500 µm	-	0.4±0.1	1.6 ±0.1	17.5±0.2	72.4±0.2	1.8±0.03	1.1±0.04	3.4±0.1	0.8±0.1	0.5±0.04	-	0.2±0.1	0.2±0.1
2		-	0.4±0.1	1.7±0.1	17.7±0.1	72.2±0.2	1.9±0.004	1.2±0.04	3.4±0.1	0.7±0.1	0.5±0.05	-	-	0.3±0.1
3		-	0.5±0.04	1.5±0.1	16.7±0.1	74.2±0.2	1.6±0.003	1.1±0.04	3.3±0.1	0.6±0.1	0.5±0.04	-	-	-
4		-	0.3±0.1	1.7±0.1	18.6±0.1	70.9±0.2	1.8±0.003	1.3±0.04	3.8±0.1	0.9±0.1	0.6±0.04	-	-	-
5	area 100/100 µm	-	0.3±0.1	1.7±0.1	20.5±0.2	63.4±0.3	2.6±0.1	2.3±0.1	6.4±0.2	2.0±0.1	0.9±0.1	-	-	-
6	area 200/100 µm	-	0.3±0.1	1.6±0.1	19.3±0.2	65.1±0.3	2.4±0.1	2.3±0.1	6.4±0.2	1.7±0.1	0.9±0.1	-	-	-
7	area 100/50 µm	-	1.0±0.1	1.6±0.1	20.4±0.2	64.6±0.3	3.0±0.1	2.1±0.1	5.3±0.1	1.6±0.1	0.6±0.1	-	-	-
8	point, with Pb -glaze penetration into the matrix/ contamination during sample preparation	1.1±0.2	0.3±0.1	1.7±0.1	20.9±0.2	64.0±0.3	2.0±0.1	2.1±0.1	5.2±0.1	2.1±0.1	0.5±0.1	-	-	-
9		1.2±0.2	0.4±0.1	2.1±0.1	24.1±0.2	56.7±0.3	2.3±0.1	2.5±0.1	7.4±0.2	2.8±0.1	0.6±0.1	-	-	-
10		1.5±0.2	0.4±0.1	2.3±0.1	25.5±0.2	57.2±0.3	2.1±0.1	2.2±0.1	6.1±0.2	2.2±0.1	0.5±0.1	-	-	-
average ± SD		<1.2	0.4±0.2	1.8±0.2	20.1±2.9	66.1±6.2	2.2±0.4	1.8±0.6	5.1±1.5	1.5±0.7	0.6±0.2	-	<0.2	<0.2
4 Lelów site:														
1	area 500/500 µm	1.7±0.2	1.0±0.1	1.1±0.1	28.7±0.2	59.0±0.3	2.2±0.1	2.1±0.1	3.3±0.1	-	0.9±0.1	-	-	-

→

No	Sampling	PbO	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	FeO	P_2O_5	TiO_2	MnO	SO_3	CuO
2	point, with Pb -glaze penetration into the matrix/ contamination during sample preparation	2.2±0.2	-	1.1±0.1	30.5±0.2	57.8±0.3	2.1±0.1	1.9±0.1	3.5±0.1	-	0.9±0.1	-	-	-
3		2.4±0.2	0.3±0.1	0.9±0.1	22.7±0.2	66.8±0.3	1.7±0.1	1.3±0.1	3.1±0.1	-	0.9±0.1	-	-	-
4		-	7.1±0.1	-	22.3±0.2	65.3±0.3	2.1±0.1	2.1±0.1	1.1±0.1	-	-	-	-	-
5		2.8±0.2	-	1.3±0.1	28.1±0.2	58.4±0.3	2.3±0.1	1.8±0.1	3.9±0.1	0.5±0.1	0.9±0.1	-	-	-
6		1.4±0.2	0.2±0.1	0.8±0.1	17.8±0.2	73.5±0.3	2.2±0.1	1.2±0.1	2.6±0.1	-	0.5±0.1	-	-	-
7		2.0±0.2	0.2±0.1	1.1±0.1	30.1±0.2	58.0±0.3	2.3±0.1	1.9±0.1	3.5±0.1	-	0.8±0.1	-	-	-
8		2.4±0.2	0.4±0.1	1.2±0.1	25.2±0.2	62.8±0.3	1.9±0.1	1.5±0.1	3.7±0.1	-	0.9±0.1	-	-	-
9		2.1±0.2	0.3±0.1	1.1±0.1	29.1±0.2	57.9±0.3	3.6±0.1	1.7±0.1	3.2±0.1	-	1.0±0.1	-	-	-
10		1.6±0.2	0.2±0.02	1.1±0.03	21.0±0.1	68.8±0.3	2.0±0.02	1.5±0.02	3.2±0.04	-	0.7±0.03	-	-	-
average ± SD		1.9±0.8	1.0±2.2	1.0±0.4	25.6±4.4	62.8±5.6	2.2±0.5	1.7±0.3	3.1±0.8	<0.5	0.8±0.3	-	-	-

Table 2. Description of the analyzed objects and the MC-ICP-MS lead isotope ratios obtained from lead glaze samples on pottery.

No.	Site	Description	Inv. No.	Features	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$
1	Dąbrowa-Górnicza Łosień	Foundry settlements: mid 11th c. to mid-13th c.	27/06	greenish-brown quartz	18.416 ± 0.002	15.620 ± 0.002	38.396 ± 0.004	0.8482 ± 0.0002	2.0850 ± 0.0004
2	Sosnowiec-Zagórze		-	brownish quartz	18.423 ± 0.002	15.617 ± 0.002	38.411 ± 0.004	0.8477 ± 0.0002	2.0849 ± 0.0004
3	Siewierz		S/801/W	brownish quartz	18.413 ± 0.002	15.622 ± 0.002	38.395 ± 0.004	0.8484 ± 0.0002	2.0852 ± 0.0004
4	Lelów	Inhumation cemetery, grave no 7: mid-11th c.	-	yellowish quartz	18.418 ± 0.002	15.619 ± 0.002	38.401 ± 0.004	0.8481 ± 0.0002	2.0850 ± 0.0004

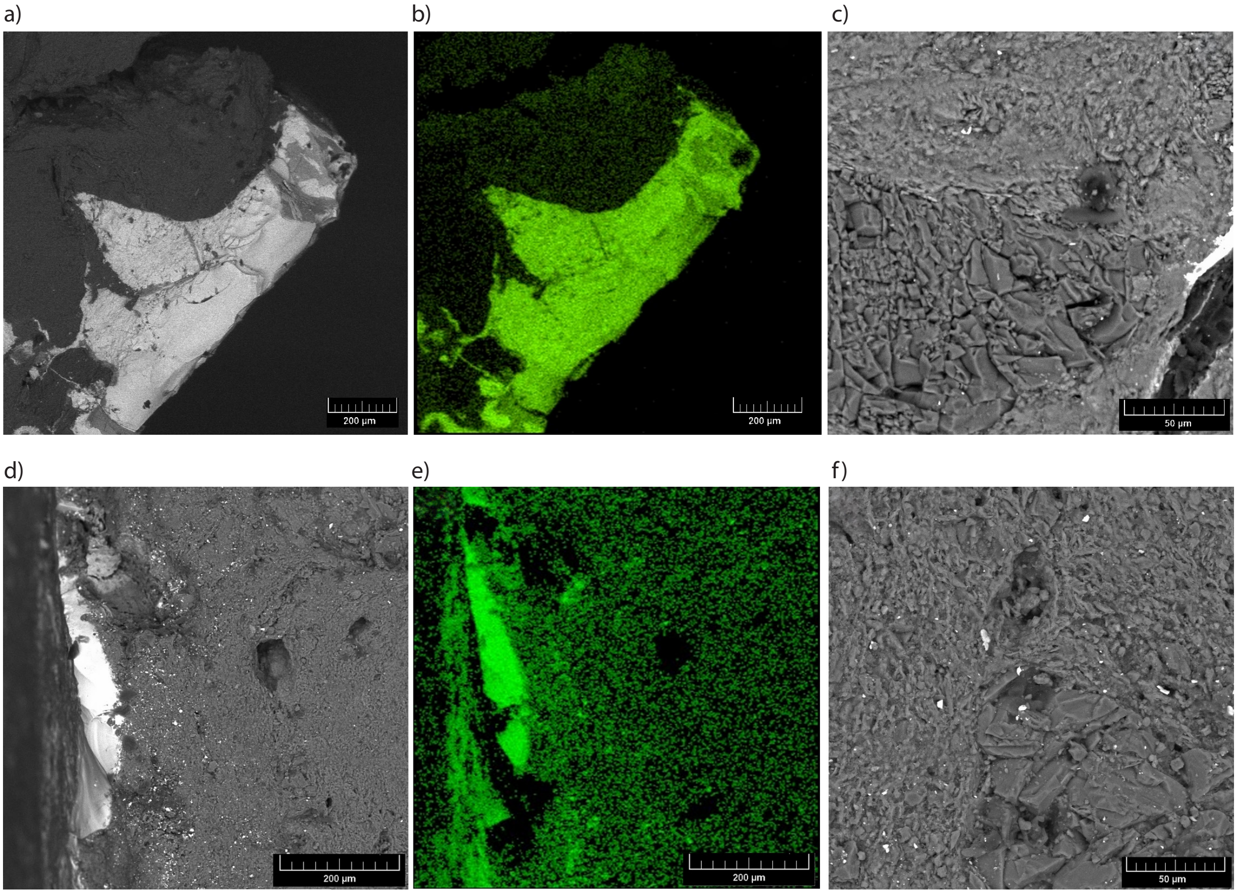

Fig. 5. 1 – Photograph of the sample taken from a glazed vessel from Lelów, grave no. 7; 2-4 –Microscopic image of the ceramic cross-section from Lelów (photo by B. Sz. Szmoniewski).

ent the EDS results for the studied lead-glazed and clay matrices. Fig. 8:a–c visualizes these chemical composition results alongside data from Auch.[13]

The glaze can be classified as high-Pb, non-alkali (Figs. 8:a, b). The Pb-oxide content (wt%) ranges from 61% to 99%, with silica content reaching up to 24% (Tab. 1A). The average PbO content across the examined artifacts follows this pattern: object 4 > object 1 = object 2 > object 3. For Lelów (sample 4), the PbO content (av. ± SD) is 85.2 ± 8.9, with SiO_2 at 10.7 ± 5.4 and K_2O at 0.4 ± 0.1. For Dąbrowa Górnicza-Łosień (sample 1), the glaze composition closely resembles that of Sosnowiec-Zagórze (sample 2), with values of (PbO, SiO_2, K_2O) 71.8 ± 1.8, 19.5 ± 1.8, 0.8 ± 0.1, and 71.3 ± 2.0, 21.2 ± 1.6, 0.6 ± 0.2, respectively. The glaze from Siewierz (sample 3) has the lowest PbO content, with 64.2 ± 2.8 PbO, 19.2 ± 1.3 SiO_2, and 0.8 ± 0.1 K_2O. These findings align with those of glazes on ceramics from Dąbrowa Górnicza-Łośień and Strzemieszyce Wielkie[14] (see Fig. 8:a and b – triangular markers). The addition of iron oxide (FeO) in the glaze reaches up to 3.7 wt%, with the highest FeO content found in the Siewierz sample and the lowest in the Lelów sample (1.5 wt%).

Chemical composition analyses of the ceramic bodies (Tab. 1B, Fig. 8:c) show that the younger ceramics (samples 1–3) are consistent with the data from Auch.[15] The ceramic body of the older Lelów ceramics is distinct, being enriched in Al_2O_3 (av. 25.6 ± 4.4 wt%). These ceramics exhibit a low degree of vitrification and contain mineral inclusions (Figs. 5:c, f).

Based on pXRD analysis, all ceramic samples exhibit very similar mineral compositions (see Fig. 8:d). Quartz, potassium feldspar, plagioclase, and phyllosilicates (10 Å illite) were present in all samples. Despite these similarities, some differences are evident in the preservation of phyllosilicates. Notably, phyllosilicates are clearly preserved in the ceramics from Lelów, while other samples show a noticeable absence of reflections characteristic

[13] Auch 2012.

[14] Auch 2012.

[15] Auch 2012.

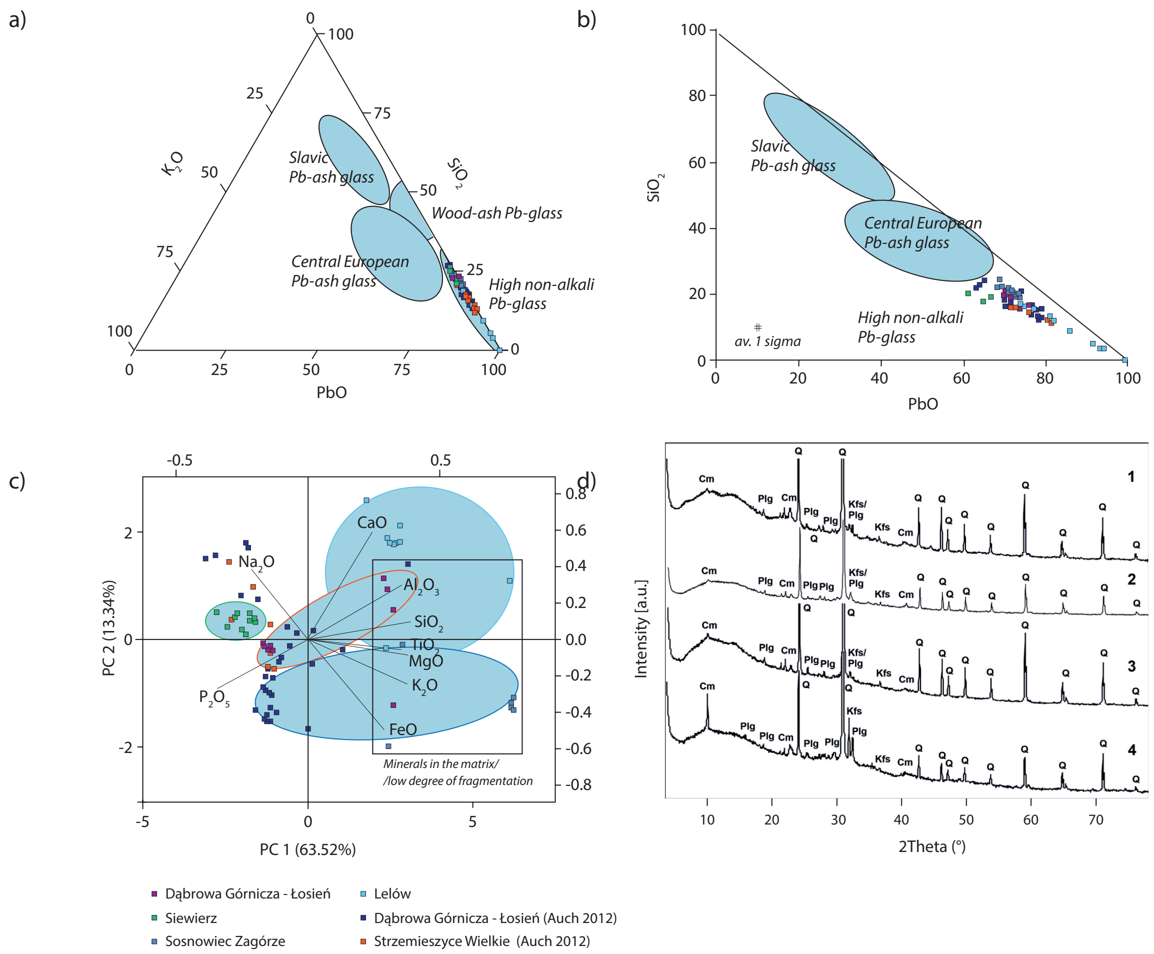

Fig. 8. SEM-EDS results (with legend on c): (a) Ternary diagram showing the PbO, SiO_2, and K_2O content in the glaze (wt%, normalized to 100%); (b) PbO vs. SiO_2 content (wt%) in the glaze. The glaze data are compared with the technological study of lead glass for early medieval glass by Mecking (2013); (c) PCA (Principal Component Analysis) correlation diagram of clay components (log-ratio transformed EDS data, after Baxter 2016, 29); (d) X-ray diffraction patterns of pottery: q – quartz, Plg – plagioclase, Kfs – K-feldspar, Cm – illite.

of this mineral phase. This loss is attributed to the decomposition of layered silicates during firing. The vessel from Lelów was fired at the lowest temperature, while higher temperatures were used for the ceramics from Sosnowiec-Zagórze.

All the studied vessels were made from a similar raw material – illite till, which is locally available. Mullite was absent from the analysed samples. This mineral typically forms from the thermal decomposition of kaolinite, suggesting that kaolinite-rich clay was not used in these ceramics. Mullite can also form by melting K-feldspar, plagioclase, and quartz, a process that occurs at temperatures between 900-1100°C.[16] At lower temperatures (900-1000°C), mullite can form from the decomposition of illite,[17] and even lower temperatures (800-900°C) can result in mullite formation in materials with high alkali and OH-group minerals.[18] The absence of mullite, the preserved reflections of illite (10 Å), and the presence of K-feldspar, plagioclase, and quartz suggest a firing temperature of approximately 800°C.

Provenance assessing

During the early medieval period in Poland (8th–12th centuries), lead likely originated from mining centres in Western and Central Europe, including Germany, Poland, and the British Isles.[19] However, archaeological evidence for early medieval silver and lead production in the Czech Republic and Slovakia remains scarce.[20]

[16] Heimann 1989.
[17] Cultrone *et al.* 2001; Cultrone *et al*, 2014.
[18] Rodriguez-Navarro *et al.* 2003.
[19] Duczko *et al.* 2022.
[20] Hrubý *et al.* 2007; Rozmus 2014, 271–276.

In present-day Germany, silver and lead mining centres in the Harz Mountains have been active since at least the 3rd century AD.[21] In the British Isles, lead production was concentrated in Derbyshire and the Mendips during the early Middle Ages.[22] While no archaeological evidence has been found for Anglo-Saxon mining in Cornwall, it is believed that these deposits were exploited during the pre-Roman and Roman periods.[23]

Radiocarbon dating of mining sites in the Upper Silesia and Kraków Uplands indicates activity from 1039 to 1211 AD, with the earliest date being 915 ± 79 BP at Dąbrowa Górnicza-Strzemieszyce.[24] Recent lead isotope analysis shows that lead usage in the Olkusz region dates back to the 6th century BC.[25]

The possibility of lead entering present-day Poland from Romania, Serbia, and Turkey exists but has not yet been definitively confirmed. Recent studies on arsenic glass from an early medieval elite cemetery in Bodzia, central Poland, suggest that the raw material originated from Romania, based on elemental composition analysis.[26] Research on the sources of tin in early medieval Poland[27] and the trade and processing of silver dirhams[28] indicates that trade routes extended southeastward.

In the Balkans, Roman-era mines were operational in regions such as Kosovo, Serbia, and Croatia, with some continuing into the Middle Ages.[29] On the Greek island of Thasos, silver and lead production dates back to prehistory and continued through the Byzantine period.[30] Isotope analysis of lead glass from the Serçe Limani shipwreck in Turkey revealed that the lead, primarily sourced from Iran and Bulgaria,[31] does not match the lead used in the glazes studied in this article.

Figure 9 presents selected deposit data matching the lead-glaze isotope ratios (Tab. 2). Reference data for archaeological artifacts are also included (see description below Fig. 9).

As shown in Fig. 5, lead isotope ratios from the British Isles (Derbyshire and Cornwall deposits) and Germany (Upper Harz ores) differ significantly from those of the lead glazes on pottery. The Pb isotope ratios of the analysed samples (represented by light green dots in Fig. 9) align closely with the isotope compositions of lead ores from Upper Silesia and the Kraków region.

Discussion

The glaze structure is heterogeneous, a result of various factors, including the suspension used, the mixture of lead compounds and colour additives, as well as chemical reactions occurring during firing. All analysed glazes can be classified as high-lead, alkali-free (see Figs. 8:a, b, Tab. 1A). The Lelów ceramic fragment stands out with a significantly higher PbO content (average 85.2 wt%) compared to the other samples, where PbO levels range from 64.2 wt% (Siewierz) to 71.3 wt% (Sosnowiec) and 71.8 wt% (Dąbrowa Górnicza-Łosień) (Tab. 1A). The higher PbO content contributes to its vivid yellow colour, which is further intensified by the bright, white-grey surface of the ceramic body.

Another technological distinction between the older and younger ceramic horizons is the FeO content. The Lelów vessel has the lowest FeO level (up to 1.5 wt%), resulting in a colour that differs from the rest (see Fig. 3:1, 4:1, 2, 5). The highest FeO content is found in the glaze of the Siewierz ceramic (average 3.2 wt%), with similar levels in the ceramics from Dąbrowa Górnicza-Łosień (Figs. 4:3, 6:1) and Sosnowiec-Zagórze (Figs. 4:4, 6:2). The higher FeO content in these glazes is reflected in their olive-brown and brownish hues.

Furthermore, the mineralogical analysis, particularly the absence of mullite and the presence of quartz, feldspars, and illite, provides insight into the firing conditions of the ceramics. The low firing temperature inferred from the mineralogical data (around 800°C) is consistent with the low vitrification observed in the ceramic bodies. The lack of mullite, a mineral typically formed at higher temperatures, suggests that these ceramics were fired at temperatures that did not exceed the threshold required for its formation. The degree of vitrification in the clay matrix further supports this, as it indicates that the firing temperature was likely insufficient to fully melt the clay and form stronger bonds.

In terms of raw material sources, the consistent use of illite-rich clays across the analysed samples suggests a local availability of suitable raw materials for ceramic production. The similarities in the ceramic bodies of the younger ceramics (samples 1–3) indicate a standardized production process, possibly reflecting the development of more sophisticated, regionally focused ceramic production techniques during this period.

21 Klappauf 1989; Rozmus 2014, 265.
22 Tylecote 1986, 70–71.
23 Tylecote 1986, 58–60.
24 Rogaczewska 2005.
25 Miśta-Jakubowska *et al.* 2024.
26 Czech-Błońska *et al.* 2023.
27 Mathur *et al.* 2024.
28 Miśta-Jakubowska *et al.* 2024a.
29 Škego 1998, 46, 92–93; Merkel 2007.
30 Hauptmann *et al.* 1988, 109; Matschke 2002, 118–119.
31 Stos-Gale 2004.
32 Auch 2012, 217.

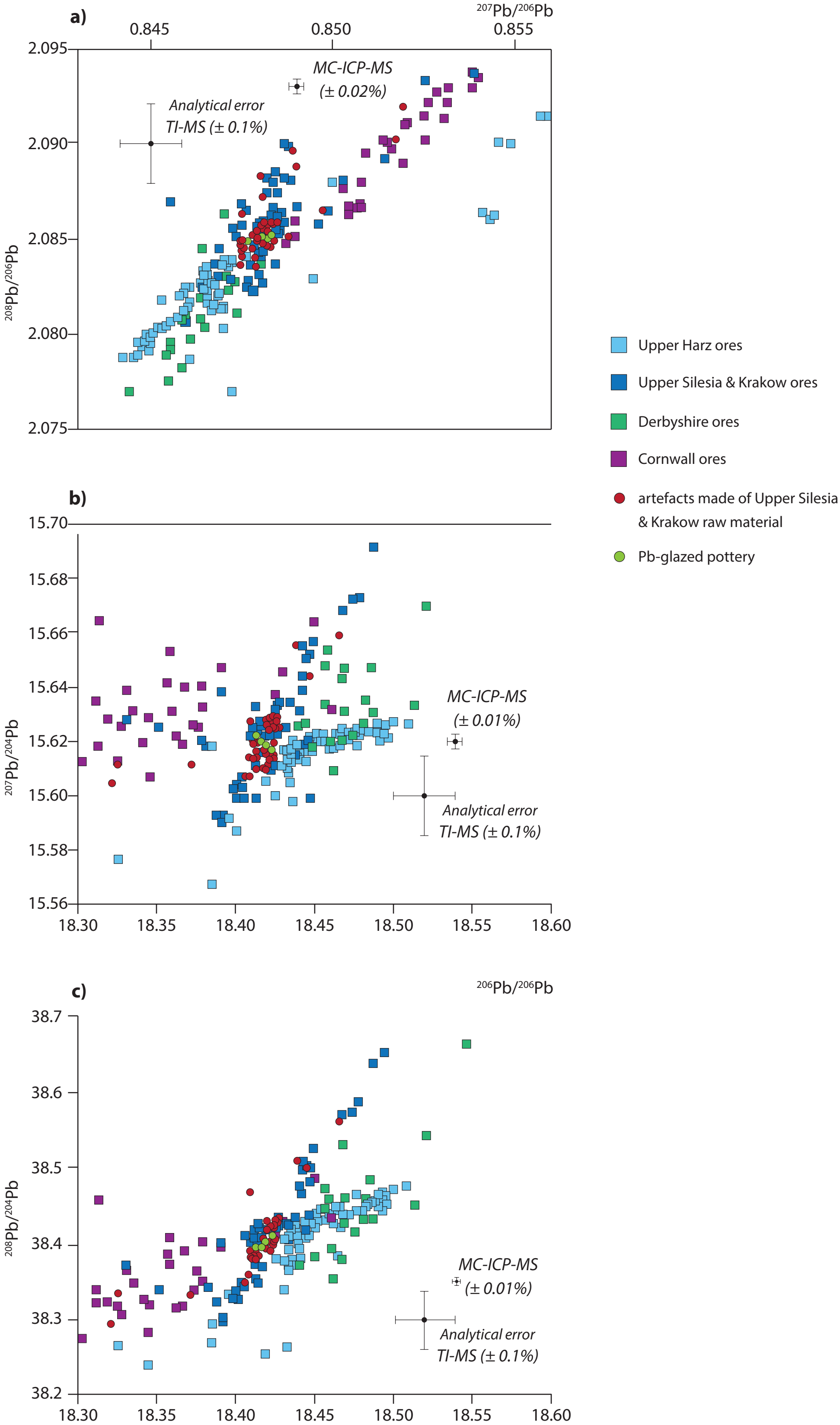

Figure 9. Lead isotope analysis (LIA) data for lead glazes on pottery compared with geological data (from http://oxalid.ox.ac.uk; Rohl 1996; Durali-Mueller *et al.* 2007; Zartman *et al.* 1979; Church & Vaughn, 1992; Lehmann, 2011). Reference archaeological artifacts, identified in the literature as using lead from Upper Silesia and the Kraków Uplands (Stos-Gale 1993; Miśta-Jakubowska *et al.* 2024; Wajda *et al.* 2023; Merkel *et al.* 2024), are marked as 1 (gray circles).

The sample from Lelów (object 4) stands out with its thicker glaze layer and higher lead content compared to the other artifacts, suggesting it may have been produced with more lead-rich materials or at a different stage of technological development. This observation might reflect regional or temporal variations in production techniques, possibly tied to the evolving technological practices in early medieval ceramic glazing.

Chemical analysis of the ceramic bodies reveals significant heterogeneity (Tab. 1B, Fig. 8:c). The Lelów sample stands out with a high Al_2O_3 content (up to 30.5 wt%) and a low FeO content, while in the other three samples, Al_2O_3, FeO, and SiO_2 levels are more consistent, ranging from 16.5 wt% to 25.5 wt%, 3.4 wt% to 7.4 wt%, and 57.2 wt% to 74.2 wt%, respectively. The observed differences, particularly in Al_2O_3 concentrations, may be related to variations in FeO content. This pattern is similar to what has been observed in ceramics from Dąbrowa Górnicza-Łosień and Strzemieszyce.[32] It can be inferred that the ceramics from these regions were likely produced from clays obtained from genetically and morphologically similar deposits.

An interesting feature of the Siewierz sample is its elevated phosphorus oxide (P_2O_5) content, both in the ceramic mass (up to 2.8 wt%) and in the glaze (up to 3.4 wt%). The higher P_2O_5 concentration in the ceramic mass may result from cooking foods of animal origin, which are rich in phosphorus, or from chemical reactions during post-depositional processes.[33] The increased presence of P_2O_5 in the glaze could be linked to glazing technology, where vessels were coated with a suspension of lead compounds after soaking in urine.[34] This process could lead to phosphorus oxide from the ceramic mass migrating into the glaze during firing.

In terms of provenance, the lead isotope ratios (Pb isotopes) of the analysed samples align closely with those of lead ores from Upper Silesia and the Kraków Uplands, as shown in Fig. 9. These ratios are consistent with other archaeological artifacts from the region.[35] Specifically, the isotope ratios of the analysed lead-glazed ceramics (represented by light green dots in Fig. 9) closely match those of lead ores from these regions, indicating that the lead used in the glazes likely came from local sources in Upper Silesia or the Kraków Uplands. This conclusion is further supported by comparison with isotopic data from the British Isles and Germany, where significant differences in Pb isotope ratios were observed. The Pb isotope ratios of ceramics from Derbyshire and Cornwall (Britain) and the Upper Harz (Germany) are inconsistent with those of the analysed Polish samples, further supporting the hypothesis that the lead used in these ceramics was locally sourced.

Although there is a possibility that lead could have been sourced from areas such as Romania, Serbia, or Turkey, this has not been conclusively established. Studies on early medieval lead-glazed artifacts from Bodzia[36] and other regions suggest trade routes extending southeast, but isotope data from those regions do not align with the lead used in the analysed Polish ceramics. Moreover, the isotopic signature of the lead-glazed pottery does not correspond with that of known lead sources in the British Isles or Germany, strengthening the assumption that the material came from local sources within Poland, particularly Upper Silesia and the Kraków Uplands.

Although the presented study is based on only four samples, it should be regarded as a preliminary stage that provides a foundation for further research. However, considering the scale of glazed pottery production in western Lesser Poland and its distinctly local character, the results align well with the known technological context of the region. When combined with the documented lead ore extraction, its range, and its use as described in the text, this allows the conclusions drawn to be considered well-justified and consistent with the historical realities of the period.

Conclusion

The glazing of vessels found in Lesser Poland, dating back to at least the mid-11th century, is one of the earliest examples in this part of Europe. This phenomenon can undoubtedly be linked to the exploitation of local polymetallic deposits in Upper Silesia and Lesser Poland, particularly for lead processing. The discovery of glazing likely occurred accidentally during experiments with litharge, rather than as a result of external influence. It is worth noting that the geographically closest workshops, where ceramics were glazed, are approximately 100 years younger than the analysed vessels

The findings from the lead isotope analysis of the glazed ceramics from four early medieval sites provide valuable insight into the sources of lead used in their production. The glaze compositions, characterized by high PbO content (ranging from 61 to 99 wt%), reveal distinct technological choices made in the preparation of the glazes, most notably the lack of alkali and the rela-

[33] Auch 2012, 217.
[34] Auch 2012, 233.
[35] Stos-Gale 1993, Miśta-Jakubowska *et al.* 2024; Wajda *et al.* 2023; Merkel *et al.* 2024.
[36] Czech-Błońska *et al.* 2023.

tively low presence of other additives such as iron oxide. The isotopic analysis suggests a clear regional provenance for the lead, specifically from the lead ores of Upper Silesia and the Kraków Uplands, which aligns with the archaeological and historical evidence of lead mining and smelting activity in these regions from the 10th to 12th centuries. The comparison of the isotope ratios from the analysed samples (Fig. 9) with geological data indicates that the lead used for the glazes is consistent with the known deposits of Upper Silesia and the Kraków Uplands. This provides strong evidence that local sources of lead were exploited during the early medieval period, likely due to proximity to mining and smelting centres. In contrast, the lead isotope ratios from the British Isles and Germany show significant differences, reinforcing the conclusion that trade routes may not have been the primary channel for sourcing the lead for these artifacts.

One of the most important results of this study is the identification of differences in the glaze and ceramic body compositions between the older and younger pottery horizons.

The first, older horizon, spans from at least the mid-11th century to the first half of the 12th century. It is characterized by vessels with a thicker glaze layer. The glaze admixture's main components were coarse and fine-grained quartz, with varying degrees of rounding, and a characteristic organic admixture in the form of burnt plant remains. The use of illite clays, which burned to a white-grey colour, provided the glaze with a luminous quality (Strzemieszyce Wielkie, Lelów). The dominant form is glazed cylindrical vessels, typically found in graves and occasionally in nearby settlements.[37] These vessels were likely of special symbolic importance. Apart from their yellow glaze, they are distinguished by their small size and a different method of decoration, featuring plastic strips with varying degrees of ornamentation. No traces of food heat treatment were found on the surfaces of the analysed vessels, suggesting that these vessels were not used for cooking. It is likely that they were placed directly in graves, symbolizing the high status of the deceased in the local community.

The second, younger horizon, which dates from the second half of the 12th century into the early Middle Ages, is characterized by the presence of classic glazed pottery forms. The glaze is thinner, and the primary admixture component is fine-grained quartz in the form of rounded grains, evenly mixed in the ceramic mass. The surface decoration typical of this period includes wavy lines (single or multiple) and grooves. In this horizon, glazed pottery is more abundant, and the variety of forms increases.

The pottery from the first, older horizon represents the initial stage of glazing knowledge. During this time, people were learning and experimenting with glazes, resulting in thicker glazes and higher lead content than in the younger horizon vessels. The latter horizon, with thinner glazes, lower lead content, and the higher temperatures required for glaze melting, indicates that the potters had gained expertise in the glazing technique. As a result, glazed vessels became more common, and typical forms like pots were more frequently glazed.

Finally, while the lead isotope analysis has provided compelling evidence for the use of local lead sources, further research, including direct dating of lead-glazed ceramics and a broader isotopic comparison with other European regions, is necessary to better understand the scope of trade networks and technological exchanges in early medieval Europe. The results of this study significantly contribute to our understanding of the origins and production techniques of lead-glazed ceramics in the Slavic regions and offer a new perspective on the role of local resources in the early medieval economy.

These findings have an international context as they contribute to our understanding of lead-glaze production in early medieval Europe, particularly the trade and technological exchange networks that spanned Central Europe. The isotopic analysis of lead sources ties local practices to broader European traditions, adding a regional dimension to the study of early medieval ceramics and trade routes. This research helps contextualize Polish production within the wider European framework, shedding light on the mobility of materials and technologies during this period.

In conclusion, the technological, chemical, and isotopic evidence collectively suggest that the lead-glazed ceramics were produced locally, with raw materials sourced from the Upper Silesia and Kraków Uplands. The variability in glaze composition and ceramic body materials highlights the diverse technological practices employed in ceramic production during the early medieval period in the Polish lands.

Bibliography

Auch M. 2012, Wczesnośredniowieczne naczynia szkliwione z terenu zachodniej Małopolski, *Archeologia Polski* 57, 199–246.

Baxter M. 2016, Multivariate Analysis of Archaeometric Data: An Introduction. Available at: https://www.academia.edu/24456912/Multivariate_Analysis_of_Archaeometric_Data_An_Introduction. Accessed 17 Oct. 2024.

[37] Auch 2012, 238.

Bodnar R., Rozmus D., Szmoniewski B. Sz. 2005, Hutnictwo srebra i ołowiu we wczesnym średniowieczu w świetle odkryć w Dąbrowie Górniczej-Łośniu (wybrane zagadnienia), in: J. Sperka, S. Witkowski (eds), *Osadnictwo nad Przemszą i Brynicą w średniowieczu*, Sosnowiec-Cieszyn, 54–74.

Bodnar R., Krudysz L., Rozmus D., Szmoniewski B. Sz. 2006, *Wczesnośredniowieczna ceramika szkliwiona z Dąbrowy Górniczej-Łośnia. Skarb hutnika*, Kraków-Dąbrowa Górnicza.

Church S. E., Vaughn R. B. 1992, Lead isotopic characteristics of the Cracow-Silesia Zn-Pb ores, southern Poland, *U.S. Department of Interior, U.S. Geological Survey Open File Report* 92-93, 1–16.

Cultrone G., Rodriguez-Navarro C., Sebastian E., Cazalla O., De La Torre M. J. 2001, Carbonate and silicate phase reactions during ceramic firing, *European Journal of Mineralogy* 13, 621–634.

Cultrone G., Molina E., Arizzi A. 2014, The combined use of petrographic, chemical and physical techniques to define the technological features of Iberian ceramics from the Canto Tortoso area (Granada, Spain), *Ceramics International* 40, 10803–10816.

Czech-Błońska R., Siuda R., Miśta-Jakubowska E., Duczko W. 2023, Chemical composition of early medieval arsenic sulphide glass beads as an indicator of the origin of the raw material. *Journal of Archaeological Science: Reports*, 52, 104291.

Duczko W., Miśta-Jakubowska E., Czech-Błońska R. 2022, *Metals – Ornaments – History. Contacts of Slavic and Scandinavian Elites in the Viking Age,* Wrocław.

Durali-Mueller S., Brey G. P., Wigg-Wolf D., Lahaye Y. 2007, Roman lead mining in Germany: its origin and development through time deduced from lead isotope provenance studies. *Journal of Archaeological Science*, 34, 1555–1567.

Hauptmann A., Pernicka E., Wagner G. A. 1988, Untersuchungen zur Prozeßtechnik und zum Alter der frühen Blei-Silbergewinnung auf Thasos, in: G. A. Wagner, G. Weisgerber (eds), *Antike Edel- und Buntmetallgewinnung auf Thasos*, Bochum, 88–112.

Heimann R. B. 1989, *Classic and Advanced Ceramics*, Weinheim.

Höltken T. 2001, *Die Keramik des Mittelalters und der Neuzeit aus dem Elsbachtal*. Dissertation, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn.

Hrubý P., Hejhal P., Malý K. 2007, Montanarchäologische Forschungen in Jihlava-Staré Hory (Iglau-Altenberg, Tschechien), *Zeitschrift für Archäologie des Mittelalters* 35, 17–60.

Husi P. 2003, Chrono-typologie de la céramique de Tours et réseaux d'approvisionnement de la ville, in: Ph. Hussi (ed.), *La céramique médiévale et moderne du Centre-Ouest de la France (11e-17e siècle)*, Tours, 23–38.

Jesett S. 2003, Chrono-typologie de la céramique d'Orléans et réseaux d'approvisionnement de la ville, in: Ph. Hussi (ed.), *La céramique médiévale et moderne du Centre-Ouest de la France (11e-17e siècle)*. Tours, 15–22.

Karasiński J., Bulska E., Halicz L., Tupys A., Wagner B. 2023, Precise determination of lead isotope ratios by MC-ICP-MS without matrix separation exemplified by unique samples of diverse origin and history, *Journal of Analytical Atomic Spectrometry,* 38, 2468-2476.

Klappauf L. 1989, Auswirkung der Grabungen im frühmittelalterlichen Herrensitz Düna bei Osterode am Harz auf die Montanforschung im Harz, *Nachrichten aus Niedersachsen Urgeschichte* 58, 171–184.

Lehmann, R. 2011, *Archäometallurgie von mittelalterlichen deutschen Silberbarren und Münzen*, Hannover.

Marciniak J. 1929–1932, Tymczasowe wyniki badań przeprowadzonych na cmentarzysku wczesnohistorycznym w Strzemieszycach Wielkich, w powiecie będzińskim, *Przegląd Archeologiczny* 4, 238–241.

Marciniak J. 1960, Cmentarzysko szkieletowe z okresu wczesnośredniowiecznego w Strzemieszycach Wielkich, pow. Będzin *Materiały Wczesnośredniowieczne* 5, 141–186.

Mathur R., Powell W., Miśta-Jakubowska E., Duczko W., Czech-Błońska R., Błoński M., Janowski A., Żołędziowski K., Jagodziński M., Gójska A., Kamenov G. 2024, Isotopic metal compositions of Viking and medieval tin artifacts from Poland reveal expansive trade network, *Journal of Archaeological Science: Reports* 53, 104296.

Merkel J. F. 2007, Imperial Roman production of lead and silver in the northern part of Upper Moesia (Mt. Kosmaj area), *Journal of the Serbian Archaeological Society* 23, 39–78.

Merkel S. W., Florkiewicz I., Jansen M., Bode M., Wołoszyn M. 2024, Evidence for Slavic lead mining and trade: Early Rus' lead seals from Czermno and Gródek on the Polish Rus' border, *Journal of Archaeological Science: Reports* 56, 104539.

Matschke K. P. 2002, Mining, in: A. E. Laiou (ed.), *The Economic History of Byzantium: From the Seventh through the Fifteenth Century, Volume 1*. Washington D.C., 115–120.

Mecking O. 2013, Medieval lead glass in Central Europe. *Archaeometry*, 55 (4), 640–662.

Miśta-Jakubowska E., Dzięgielewski K., Rozmus D., Czech-Błońska R., Szymaszkiewicz M., Michnik M., Gójska A., Karasiński J., Garbacz-Klempka A., Wagner B., Duczko W. 2024, The first isotopic evidence of Early Iron Age lead ore exploitation in the Silesian-Krakow upland, Poland: A provenance study of Lusatian culture lead ornaments, *Archaeometry* 67 (3), 1–18.

Miśta-Jakubowska E., Duczko W., Kowalska A. B., Czech-Błońska R., Mathur R., Gójska A., Rozmus D., Oleszak D., Siuda R., Klimaszewski J. 2024a, Amulets from Viking-age Baltic coast: A unique hoard from Piaski-Dramino (Poland) in the light of provenance and technological research of silvercraft art, *Journal of Archaeological Science: Reports* 53, 104356.

Tylecote, R. F. 1986, *The Prehistory of Metallurgy in the British Isles*, London.

Rohl B. M. 1996, Lead Isotope Data from the Isotrace Laboratory, Oxford: Archaeometry Data Base 2, Galena from Britain and Ireland. *Archaeometry* 38, 165–180.

Rodriguez-Navarro C., Cultrone G., Sanchez-Navas A., Sebastian E. 2003, TEM study of mullite growth after muscovite breakdown, *American Mineralogist* 88, 713–724.

Rogaczewska A. 2005, Osada wczesnośredniowieczna w Dąbrowie Górniczej – Strzemieszycach Wielkich, stanowisko 2. in: J. Sperka, S. Witkowski (eds), *Osadnictwo nad Przemszą i Brynicą w średniowieczu*. Sosnowiec-Cieszyn, 75–88.

Rozmus D. 2014, *Wczesnośredniowieczne zagłębie hutnictwa srebra i ołowiu na obszarach obecnego pogranicza Śląska i Małopolski (druga połowa XI-XII/XIII wieku)*, Kraków.

Rozmus D., Garbacz-Klempka A. 2017, Wczesnośredniowieczna ceramika szkliwiona z Dąbrowy Górniczej-Łośnia i innych stanowisk archeologicznych związanych z metalurgią srebra i ołowiu – wybrane zagadnienia, in: S. Siemianowska, P. Rzeźnik, K. Chrzan (eds), *Ceramika i szkło w archeologii i konserwacji*, Wrocław, 261–285.

Stos-Gale Z. 2004, Lead-isotope analyses of glass, glazes and some metal artifacts, in: G. F. Bass, S. D. Matthews, J. R. Steffy, F. H. van Doorninck, Jr., S. Limani (eds), *An Eleventh-Century Shipwreck, Volume I: The Ship and Its Anchorage, Crew, and Passengers*. College Station: 453–467.

Stos-Gale Z. A. 1993, The origin of copper-based metals from the Roman period settlement of Jakuszowice in Southern Poland, *Journal of European Archaeology*, 1(2), 101–131.

Szmoniewski B. Sz., Miśta-Jakubowska E., Zamelska-Monczak K., Siuda R., Kolenda J., Czech-Błońska R. 2025, Medieval Glazed Ceramics from Kraków Nowa Huta-Zesławice, Site 88, Lesser Poland Voivodeship. Their Formal and Technological Analysis, *Sprawozdania Archeologiczne* 77 (2), 475-506.

Trincavelli J., Limandri S., & Bonetto R. 2014, Standardless quantification methods in electron probe microanalysis, *Spectrochimica Acta Part B* 101, 76–85.

Wajda S., Merkel S. W., Florkiewicz I., Jansen M., Marciniak-Maliszewska B., Wagner B., Wołoszyn M. 2024, Early medieval lead glass bangles from Czermno, Poland: Results of elemental and lead isotopes analyses, *Archaeometry* 66 (2), 306–325.

Whitehouse D. B. 1980, Medieval pottery in Italy: The present state of research, in: *La céramique médiévale en Méditerranée occidentale, Xe-XVe s., Valbonne, 11-14 septembre 1978,* Paris, 65–82.

Verhaeghe F., 1969, Belgium, in: J. Hurst (ed.), *Red-painted and glazed pottery in Western Europe from the eighth to the twelfth century*, *Medieval Archaeology* 13, 106–112.

Zartman R. E., Pawlowska J., Rubinowski Z. 1979, Lead isotopic composition of ore deposits from the Silesia-Cracow mining district, in: *Research on the genesis of zinc-lead deposits of Upper Silesia, Poland. Proceedings of the Institute of Geology* 95, 133–151.