Pottery technology through time : archaeometry of pottery and clayey raw material from the multi-period site in eastern Croatia

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Abstract

Consideration of multiperiod archaeological sites to understand the mechanisms of large-scale cultural changes is still a very rare research topic in Croatia. Technological traditions are of great importance, especially in the context of considering continuity, innovation, and change. In this paper, we used an archaeometric approach to investigate pottery technology. Therefore, this article presents an analysis of petrography and mineralogy of archaeological ceramics and potential raw materials collected in the vicinity of the multi-period archaeological site (the Neolithic through the Medieval period) Jagodnjak-Krčevine located in eastern Croatia, i.e. the south-western part of the Pannonian Basin. The primary goal is to determine what kind of clay recipe (clay and temper) potters used to make vessels in order to better understand their variability in the context of techno-functional features. The additional objective is to examine the availability and quality of clays for pottery production and to study their distribution in the local landscape. The analytical methods applied in the research are optical microscopy, X-ray diffraction, and grain size analysis. The comparison of archaeological ceramics with clayey materials established that ancient potters used locally available clays, and the selection of temper material added to the clay represents a strong element of techno-tradition, which is more pronounced for prehistoric communities. Furthermore, these results represent the first research in Croatia focused on a discussion about distances that potters travelled to obtain their resources in the different periods of the past, which can contribute to the study of a regional system of production and landscape use.

Keywords:

archaeometry; Baranja; clayey raw material; field sampling; pottery technology

1. Introduction

Raw materials are an essential component of every production process and natural materials represented the only raw materials available in ancient times. In the context of the production process, pottery-making was an integral part of the evolution of human culture since the Neolithic and is considered one of the most important components of tradition and technological development. While manufacturing techniques have not changed significantly, especially for prehistory, diversity in morphology and style in archaeology represent a very significant and usually the main indicator of chronology and cultural determination. However, subtle changes and shifts in technology (or just techniques) affect the appearance and performance of the final product, and the reasons for such changes can be triggered by various factors, such as social or, for example, environmental changes. Therefore, investigating past technologies throughout the reconstruction of that process necessarily implies looking at each step in the operational sequence (**van der Leeuw, 1984; Sillar and Tite, 2000; Albero Santacreu, 2014: 53–59**) from procurement of the raw material, paste preparation, shaping, drying, and firing (**Hunt, 2016; Roux, 2019**) in order to not only reconstruct that process, but also to try to understand what is in the background of such changes. To investigate these processes, archaeometry has been increasingly considered as the best starting point for study (**Tite, 1999**), especially the choices of potter raw material used diachronically over a long period of time.

To obtain a reliable dataset of potential clayey sources, it is necessary to conduct field sampling near the location of the ancient settlement. Although in most studies it is assumed that the raw material is of local origin (**Arnold, 1978; Gosselain et al., 2005; Albero Santacreu and Mateu Vicens, 2012; Michelaki et al., 2012;**

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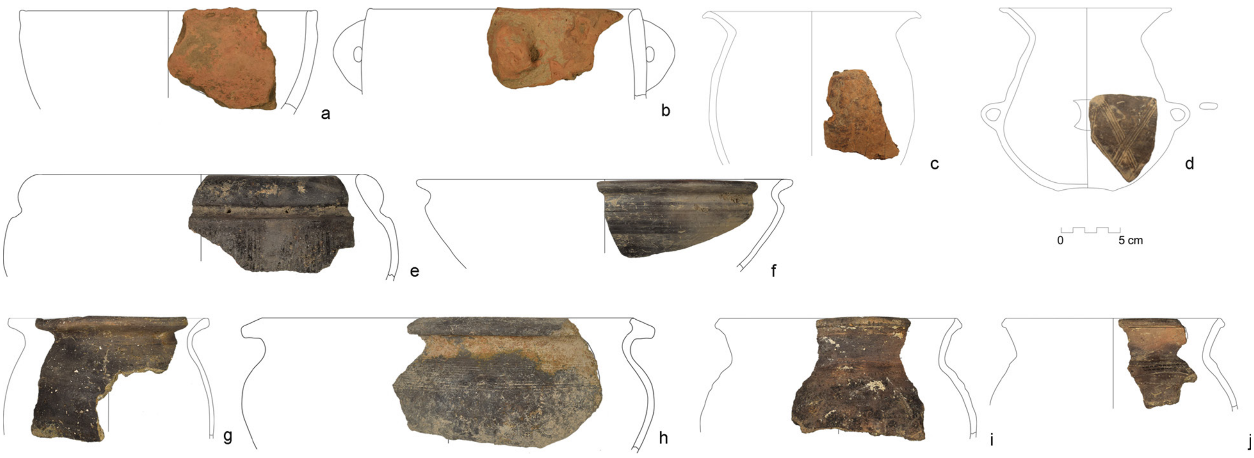

Figure 1: A selection of pottery chosen for analysis from the archaeological site Jagodnjak-Krčevine: a, b (Neolithic, samples 8987, 8988); c, d (Bronze Age samples 9459, 9460); e, f (Late Iron Age, samples 8991, 9000); g, h (Roman period, samples 8997, 9001); i, j (Medieval, samples 8996, 8752)

De Bonis et al., 2013; Žibrat Gašparič and Dolenec, 2015; Kudelić et al., 2018), the field sampling will give answers to the questions regarding which part of the landscape the potters either preferred or did not prefer for raw material exploitation, but also how the people oriented themselves in that landscape (**Michelaki, 2014**). Furthermore, it is assumed that the raw material preparation and the choice of tempering material (clay paste recipes) also reflect temporal and cultural differences in pottery practices.

This paper presents the first study on the continuity and variability of pottery technologies over more than 7000 years in Croatia according to the archaeological records from a multi-period (Neolithic, Bronze Age, Late Iron Age, Roman, and Mediaeval period) site of Jagodnjak-Krčevine located in the Baranja region. The objective is to examine the characteristics of raw materials used in the past, to determine ceramic technological features, and to study the availability and distribution of pottery raw materials in the local landscape. The aim of the study is to answer the questions of whether the ceramics from the Jagodnjak site were produced using locally available clays and whether potters from different periods had preferences for particular clay sources or clay characteristics. Moreover, the aim is to uncover the clay recipes and temper material used to make the vessels in order to understand the variability and preferences of ancient potters. To methodically address all research questions, the study focuses on the petrographic and mineralogical analyses using several analytical techniques: optical microscopy, X-ray diffraction (XRD), and additionally grain size analysis and physical properties of the collected sediments.

2. Archaeological setting

Baranja is a historical and geographical region in eastern Slavonia bordered by the Drava River in the southwest, the Danube River in the east, and the Croatian-Hungarian border in the north. Geomorphologically, it is a lowland with a slightly raised ridge that has always been suitable for settlement. Therefore, numerous archaeological sites with valuable remains dating from the Neolithic to Medieval are known in this area. The site of Jagodnjak-Krčevine represents one of these archaeological settling places located 10 kilometres northeast of the Drava River and 18 kilometres west of the Danube at 91 meters above sea level on the slope of a loess plateau along the Gmajna Stream. The site was excavated in 2014 and 2015 due to the construction of the highway route, revealing the remains of settlements and cemeteries from different periods of the past (**Tresić Pavičić, 2015**).

The oldest traces of human activities found on the site belong to Early Neolithic communities (6th millennium BC). Discovered pottery (see **Figure 1**) has the stylistic characteristics of the Starčevo culture i.e. the Starčevo-Körös-Criş cultural group (**Balen et al., 2014**) and was found inside the remains of a settlement with a system of circular ditches, indicating a permanent settlement. The vessels were hand-made, of simple shape, mainly bowls and pots of thick walls. Most of the archaeological records belong to the Bronze Age, i.e. to the communities of Pannonian Encrusted Pottery (20th – 17th century BC, **Kiss, 2012**). Bronze Age records consist of the peripheral part of the settlement and the cemetery with biritual burials. Graves were accompanied by extremely rich grave goods, such as metal jewellery (gold, bronze), bronze parts of costumes, and numerous ceramic vessels. The pottery style is very distinctive, especially fine ware with a dark surface decorated with white paste inlay that fills incised motive compositions. The excavation also discovered traces of a settlement complex dated to the Late Iron Age with characteristic dark grey (graphite) pots and wheel-made bowls which present the *La Tène* culture i.e. Celtic pottery tradition (3rd – 1st century BC). The pottery style corresponds to vessel types found in numerous settlement remains of Eastern Slavonia, produced and used by Scordisci communities. (**Dizdar, 2001**).

Additionally, the site was occupied shortly after, in the Roman Imperial Period (1st – 4th century AD). The utilitarian ceramics of local production from Jagodnjak correspond to vessel repertoire in the area (**Jelinčić Vučković, 2015; Ožanić Roguljić, 2016**).

This position was again occupied during the Early Middle Ages – with an excavated larger cemetery. Later, during the Medieval (12th – 15th century), a settlement was again built on the site. A small part of the settlement consists of predominantly ceramic material, i.e. simple-shaped pots, most often cooking pots. A similar vessel shape was frequently used during the High Middle Ages, and such vessels can be found on archaeological sites in the area of eastern Slavonia and Baranja (**Tkalčec et al., 2017**). According to the excavation results, and the evidence of well-organized communities that chose this location for permanent settling, it seems that the site was an important strategic place, probably chosen because of the good geostrategic features, particularly significant for certain periods of the past (Neolithic, Bronze Age, Late Iron Age, Roman period, Early Middle Ages and Mediaeval). Since the settlements were of a long-term character, and according to the easy availability of raw materials, it is assumed that the pottery production was organized locally.

3. Geological setting

The Baranja region tectonically belongs to the North Croatian Basin as a part of the south-western Pannonian basin system (**Horváth et al., 2006; Pavelić and Kovačić, 2018**). The formation of the Pannonian basin system occurred in the Early Miocene due to the continental collision and subduction of the Adriatic microplate beneath the Pannonian tectonic segment of the Euroasian Plate (**Šumanovac et al., 2017; Pavelić and Kovačić, 2018**). The area is characterized by a long emersion phase that lasted until the Early Miocene. It is a period of continental environments that were replaced by lacustrine and then marine sedimentation during the Middle Miocene (**Kováč et al., 2007; Mandic et al., 2012; Pavelić and Kovačić, 2018**).

According to **Bognar** (**1990**), three morphographic types represent the relief of Baranja; lowlands, plains, and hilly relief. The lowland relief accounts for almost 90% of the area and geomorphologically consists mainly of marshes and fluvial lowlands. The most widespread is the fluvial lowland of the Drava River in the central and southwestern part of Baranja, and the Danube River, in the eastern part of this area (**Bognar, 1990**). The formation of the rivers dates back to the Early Pleistocene while a significantly warmer period during the Early Holocene caused the extensive melting of Alpine glaciers and the downstream deposition of clayey, silty, and sandy sediments (**Oreščanin et al., 2005; Lóczy et al., 2014**). The lowland is covered by the Southern and Northern Baranja loess plateau composed of loess and loess-like deposits of aeolian origin (**Bognar, 1990; Galović, 2016**). These well-preserved successions have an excellent preservation potential for traces of climate change and are therefore continuously the subject of numerous studies (**Marković et al., 2009; Galović et al., 2009; 2011; Banak et al., 2012; Galović 2016; Galović and Peh, 2016**). Loess-paleosol successions can reach a thickness of up to 40 m and are commonly intercalated with alluvial deposits composed of loess-derived sediments eroded from the rivers catchments (**Galović, 2016; Galović and Peh, 2016**). During the Late Pleistocene, strong winds formed in a cold glacial climate led to the deposition of loess and loess-like sediments in lakes, ponds, shallow marshes, and on the mild elevations (**Bačani et al., 1999**). Conversely, the formation of paleosols and alluvial sediments indicates warmer periods and fluvial activity (**Galović, 2016**). Different types of loess-like sediments are also prevalent on Bansko brdo, the only elevation in the area. Tectonically, it is an asymmetric horst in the NE-SW direction (**Banak et al., 2012**). The oldest exposed rocks belong to the Miocene volcano-sedimentary complex with basalt-andesite and pyroclastic rocks (**Pamić and Pécskay, 1996; Banak et al., 2012**). The formation of this complex is probably related to continental rifting processes during the Pannonian Basin extension (**Horváth, 1995; Pavelić, 2001; Banak et al., 2012; Mandic et al., 2012**).

The multi-period archaeological site Jagodnjak-Krčevine is located in the central Baranja region, near the village of Jagodnjak. In contrast to the very well studied loess-paleosol sequences, there are few investigations explaining the geological background of the study area. Geomorphologically, the most prominent feature in the area is the meandering Drava River with its alluvial terrace. The predominant deposits are represented by sandy and silty sediments, while oxbows and ridges were recorded in the southern part (**Bognar, 1990; Pikija et al., 1991; Pikija et al., 2015**). The river channel migration together with changes in flood level resulted in the formation of oxbows with a predominant deposition of silty, sandy, and sandy clayey sediments (**Pikija et al., 1991**).

4. Sampling and methods

4.1. Field sampling

According to ethnoarchaeological research, the distance between the raw material source and the place of pottery production ranges from 1 to 10 kilometres (**Rice, 1987**). However, raw materials were most often exploited within a radius of 1 km from the settlement where production took place (**Arnold, 2000**). Therefore, field

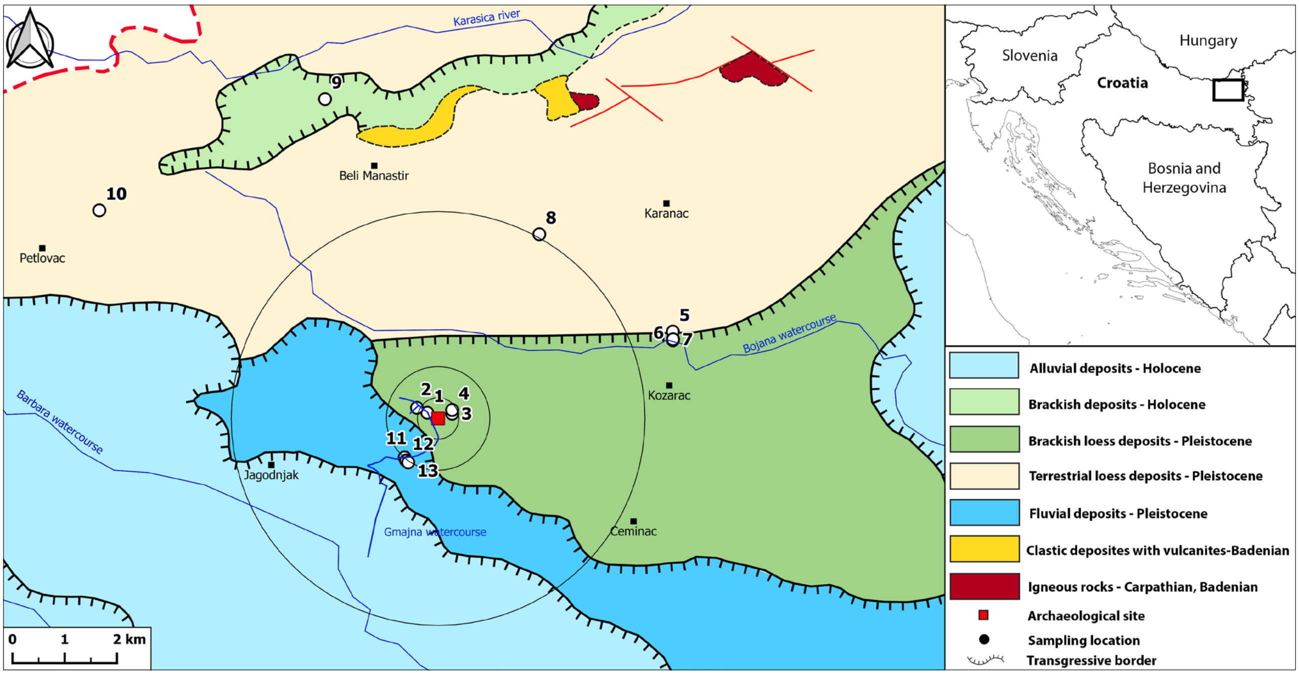

Figure 2: Geological map with sampling locations within a different radius distance from the archaeological site Jagodnjak-Krčevine. Gmajna watercourse – location 1 (samples 9095, 9096, 9097), location 2 (sample 9098), location 11 (sample 9108), location 12 (sample 9109) and location 13 (sample 9110); immediate vicinity of the archaeological site – location 3 (sample 9099) and location 4 (sample 9100); Kozarac old clay pit – location 5 (9101); Bojana watercourse – location 6 (sample 9102) and location 7 (samples 9103, 9104); Karanac old clay pit – location 8 (sample 9105); Beli Manastir old clay pit – location 9 (sample 9106); Petlovac old clay pit – location 10 (sample 9107) (modified after **Croatian Geological Survey, 2009**).

sampling was concentrated in the vicinity of the archaeological site, near the present small watercourses, which are a potentially good location for collecting fine-grained clay sediments. Several locations of recently exploited clay pits (**Pikija et al., 1991**) in the study area were chosen as the first sampling sites. After that, samples were collected in several zones: near the archaeological site (400-meter radius from the archaeological site), and in zones within 1, 4, and 10 km radius (see **Figure 2**). During the fieldwork, samples of clay sediments were collected using a hand auger from 0.3 and max 1.7 m depth. A total of 16 samples were collected from 13 locations and subsequently prepared for physical (plasticity and shrinkage), granulometric, mineralogical, and petrographic analyses. Plasticity was measured on-site, by simulating actual processing conditions and by manual modelling a clay roller and observing deformation due to bending force (plasticity range: no plasticity, low, moderate, and high plasticity).

4.2. *Analytical Methods*

Two types of samples were analysed: archaeological and geological. Archaeological samples include 31 ceramic sherds dated to five different periods. The archaeological data and main physical characteristics of sherds are presented in **Table 1**. Geological samples are represented by 16 samples of clayey sediments collected in the vicinity of the archaeological site. Analyses present in this study were conducted at the University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering and at the Institute of Archaeology in Zagreb.

4.2.1. Clay briquettes and test rollers - firing and shrinkage

In order to examine the clayey material consistency and microtexture after firing, and enable correlation with archaeological ceramic sherds, experimental clay briquettes were made from the collected clayey materials, i.e. from the samples with moderate and high plasticity observed on site (12 out of 16 samples). By simulating the actual processing conditions, the samples were freed from coarser fractions and plant inclusions, and each was kneaded until it reached the optimal workable condition. Despite the same storage conditions, a very wide range of processability was found for the different samples. Few samples were already in a plastic state that allowed the clay to be modeled – mostly without the presence of coarse mineral inclusions or plant remains that had to be removed. Extremely dry samples, where it was not possible to achieve optimal workability, were soaked in water for several days and after removing the excess water, the samples were dried until they became workable. The samples were molded in 4 x 6 x 1.5 cm briquettes and dried at room temperature for several days. They were fired in a laboratory kiln at 650°C under controlled conditions for one hour with a 30-minute soaking period (holding the kiln at final firing temperature) and then allowed to cool overnight. Short firing

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Table 1: Archaeological data and main physical characteristics of the vessels from the Jagodnjak-Krčevine site (PEP – Pannonian Encrusted pottery, SM – smoothed, UN – untreated, ROU – roughed)

Sample number	Archaeol. Context	Vessel type	Period	Style / Culture	Manufacturing technique	Wall thickness (cm)	External Surface Treatment	Inner Surface Treatment	Firing methods
8987	Settlement	unknown	Neolithic	Starčevo	Coiling / Slab tech.	0.9	SM	SM	Open fire
8988	Settlement	pot	Neolithic	Starčevo	Coiling / Slab tech.	1	SM	SM	Open fire
8989	Settlement	bowl	Neolithic	Starčevo	Coiling / Slab tech.	1	UN	SM	Open fire
8990	Settlement	pot	Neolithic	Starčevo	Coiling / Slab tech.	0.5	SM	SM	Open fire
8992	Settlement	pot	Neolithic	Starčevo	Coiling / Slab tech.	0.5	SM	SM	Open fire
8998	Settlement	pot	Neolithic	Starčevo	Coiling / Slab tech.	0.5	SM	SM	Open fire
9456	Grave 056	fine pot	Bronze Age	PEP	Coiling / Slab tech.	0.6	SM	SM	Open fire/Kiln
9432	Grave 060	fine pot	Bronze Age	PEP	Coiling / Slab tech.	0.4	SM/ROU	SM	Open fire/Kiln
9457	Grave 056	fine pot	Bronze Age	PEP	Coiling / Slab tech.	0.5	SM/ROU	SM	Open fire/Kiln
9458	Grave 060	fine pot	Bronze Age	PEP	Coiling / Slab tech.	0.6	SM/ROU	SM	Open fire/Kiln
9459	Grave 059	fine pot	Bronze Age	PEP	Coiling / Slab tech.	0.4	SM/ROU	SM	Open fire/Kiln
9433	Grave 056	fine pot	Bronze Age	PEP	Coiling / Slab tech.	0.3	SM/ROU	SM	Open fire/Kiln
9460	Grave 002	coarse pot	Bronze Age	PEP	Coiling / Slab tech. / Beating	0.6	SM/ROU	SM	Open fire
9461	Grave 006	coarse pot	Bronze Age	PEP	Coiling / Slab tech. / Beating	0.8	SM/ROU	SM	Open fire
9462	Grave 059	coarse pot	Bronze Age	PEP	Coiling / Slab tech. / Beating	0.6	SM/ROU	SM	Open fire
9434	Grave 027	coarse pot	Bronze Age	PEP	Coiling / Slab tech. / Beating	0.7	SM/ROU	SM	Open fire
9435	Grave 061	coarse pot	Bronze Age	PEP	Coiling / Slab tech. / Beating	1.0	SM/ROU	SM	Open fire
8991	Settlement	graphite pot	Late Iron Age	La Tène	Coiling / Slab tech.	0.6	SM	UN	Kiln
8995	Settlement	graphite pot	Late Iron Age	La Tène	Coiling / Slab tech.	0.6	SM	SM	Kiln
9000	Settlement	fine bowl	Late Iron Age	La Tène	Wheel-thrown	0.5	SM	SM	Kiln
8753	Settlement	graphite pot	Late Iron Age	La Tène	Coiling / Slab tech.	0.8	SM	SM	Kiln
8986	Settlement	lid	Roman period	Roman	Wheel-coiling	0.5	SM	SM	Kiln
8993	Settlement	pot	Roman period	Roman	Wheel-coiling	0.6	SM	SM	Kiln
8994	Settlement	pot	Roman period	Roman	Wheel-coiling	0.3	UN	UN	Kiln
8997	Settlement	pot	Roman period	Roman	Wheel-coiling	0.4	SM	SM	Kiln
9001	Settlement	bowl	Roman period	Roman	Wheel-thrown	0.6	SM	UN	Kiln
8996	Settlement	pot	Medieval	Medieval	Wheel-coiling	0.5	SM	SM	Open fire/Kiln
8999	Settlement	pot	Medieval	Medieval	Wheel-coiling	0.6	SM	SM	Open fire/Kiln
9002	Settlement	pot	Medieval	Medieval	Wheel-coiling	0.7	SM	SM	Open fire/Kiln
9003	Settlement	pot	Medieval	Medieval	Wheel-coiling	0.5	SM	UN	Open fire/Kiln
8752	Settlement	pot	Medieval	Medieval	Wheel-coiling	0.7	SM	SM	Open fire/Kiln

time and low temperatures are assumed for most archaeological ceramics, especially for prehistoric pottery. Therefore, the aim was to mimic prehistoric firing conditions to obtain conditions for more relevant comparisons of briquettes and archaeological ceramics. The briquettes were prepared without the addition of temper to reveal the differences in composition of the potential raw materials and, if possible, enable the correlation with ceramic material matrix. In addition, the remaining parts of these samples were used for examination of the physical property (shrinkage). 50 g of each sample was modelled in a roller of 7 x 2.5 cm size. The length and diameter of each roller was measured after 24, 48, 72, and 96 hours, respectively, until they were dry. Relative shrinkage was assessed by the difference between the original and dried volumes of each sample.

4.2.2. Grain size anaylsis

Grain size analysis was conducted on 16 sediments collected on-site. Before analyzing, samples were soaked in distilled water for several hours and then put in an ultrasonic bath to achieve better disintegration. Grain size analysis was conducted using Malvern Panalytical Mastersizer 3000 Particle Size Analyzer with Hydro EV unit and < 5% obscuration.

4.2.3. Petrography

Thin sections of the pottery sherds (31 samples) and the fired clay briquettes (12 samples) were examined under a polarizing microscope Zeiss Axiolab 5 in transmitted light. The petrographic analysis of ceramics includes the determination of the colour of the matrix, its texture, matrix birefringence, mineral composition, the presence of natural and anthropogenic inclusions, voids, and pores. During the macroscopic description and the petrographic analysis, the inclusion density, size, sorting, and roundness of the grains were determined according to the instructions of the Prehistoric Ceramic Research Group (**PCRG, 2010**). Petrography of ceramics enables determination of ceramic fabric groups which indicate the compositional differences among the clay paste. The definition of tempering material is based on the type, size, shape, and bimodal grain size distribution in the matrix.

4.2.4. Mineralogical analyses

Mineralogical analysis by XRD was performed on ceramics (24 samples from all the determined fabric groups and ceramics from all studied periods), as well as clayey material samples (16 samples). Bulk samples (of both types) have been crushed to a powder fraction using a Retsch vibratory disc mill RS 200. In order to better define clay minerals within clayey material, <2 micrometers fraction, as well as oriented films of the separated clay fraction were subjected to various treatments (glycolated, dimethyl sulfoxide intercalated, heated 550°C) and analysed. A clay fraction was analysed on samples with "moderate" and "high" plasticity observed on site. Interpretation of clay mineral content was done according to **Moore and Reynolds (1997)**.

The mineralogical composition was determined using a Panalytical Empyrean diffractometer equipped with a graphite monochromator and Cu-Kα radiation. Scan settings were 3–70 °2θ on the rotating sample stage, 0.013 °2θ step size, 1 s count time per step. Mineral identification of samples was conducted using PANalytical X'Pert HighScore software with standardized Powder Diffraction Files (PDF) of the International Centre for Diffraction Data (ICDD) (NewtonSquare, PA, USA).

5. Results

For better understanding, the overall results of this study are divided into two categories: archaeological and geological samples. The results of each analysis conducted on both ceramic and clayey samples are presented below.

5.1. Archaeological ceramic

5.1.1. Petrography

The mineral composition of ceramic clay matrix determined by optical microscopy is mainly composed of very fine (< 0.1 mm) quartz and mica crystalloclast inclusions (see **Table 2**). K-feldspar is identified in most of the samples while plagioclase is less common. Mineral phases such as biotite, pyroxene, and zircon are very rarely present. Larger quartz grains sometimes contain cracks. By observing the density and size of mineral inclusions in the matrix, ten main fabric groups have been determined (see **Table 2**, **Figure 3**). In general, the density of very fine crystalloclasts varies from moderate (15%) to abundant (50%) while only one sample stands out with less than 5% (8994) of crystalloclast inclusions. Mineral inclusions are well to very well distributed in the matrix in all samples. Besides very fine crystalloclast inclusion, some samples also contain fine (0.1 – 0.25 mm) crystalloclasts whose density varies from rare (2%) to moderate (15%).

According to the mineral composition of the clay matrix, two general groups of raw materials were observed. The first one is dominated by quartz, while the second is dominated by mica. Quartz-rich matrix is determined in seven fabric groups, representing 80% of all samples and characterized by angular-subangular mono-crystalline quartz grains. The matrix colour varies from orange to dark brown while the birefringence is low to high but mainly medium high. Micaceous matrix is less common, determined in three fabric groups, and therefore present in 20% of all samples. It is dominated by a large number of mainly elongated very fine to fine mica minerals. The colour of the matrix is light brown to brown with the birefringence varying from medium-high to high.

Along with crystalloclasts, rock fragments (lithoclasts) are present in 12 samples (39% of total samples). They are mainly represented by metamorphic rocks, quartzite, and less common schist. Among sedimentary rocks, the most common is limestone while sandstones and chert are present in smaller amounts. Igneous rocks are rarely present. The characteristic lithoclasts are subrounded and sub-angular, fine to coarse in size (0.1-3 mm) with moderate to very common amounts (10 – 30%). Lithoclasts are generally poorly to moderately sorted in the matrix, although there are several samples with well sorted grains. The amount and bimodal grain size distribution suggest that medium and coarse lithoclasts were added to the clay intentionally as temper.

Moreover, grog (ceramoclasts) is determined in seven samples (23%). Grog grains are sub-angular to subrounded with the majority having sub-rounded shapes. The grog size varies from medium to coarse and is medium to poorly sorted in the matrix. The composition of grog grains is usually very similar to the composition of the ceramic matrix and the main difference is in the colour and sometimes in the amount of very fine crystalloclasts. Clay pellets/ARF (argillaceous rock fragments) were recorded in negligible quantity. The majority of them are transparent, with some being opaque, having sharp, clear, or diffuse edges. The amount and size of the pores are variable from sample to sample but in general,

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they vary from 2% to 15% (average: 6.3 %). Three samples or 10% of all analysed samples have no visible pores (less than 1%). They are mostly elongated, parallel to the vessel walls while rounded and irregular pores are present but less common. In five samples, organic material is recorded in mostly elongated and curved voids. Moreover, fragments of shells, medium to coarse in size are recorded in four samples in mostly elongated and slightly curved shapes. Fragments are present in sparse amounts (<5%) and are therefore probably naturally present, with clearly visible inner structure. By observing the type, size, shape, and bimodal grain size distribution in the clay matrix 19 fabric subgroups have been determined (see **Table 2**).

Fabric 1.1: The main naturally present crystalloclast inclusions are very fine (< 0.1 mm) and fine (0.1 – 0.25 mm) monocrystalline quartz with the occurrence of mica minerals. Grains are sub-angular and very well distributed in the clay. The amount of very fine crystalloclasts in the matrix is moderate to common (15 – 20%) while the density of fine crystalloclasts is sparse to moderate (5 – 10%). Moreover, slightly curved, and mostly elongated shell fragments are present in sparse amounts (<5%).

Fabric 1.2: The main characteristic of this subgroup is grog tempering. This fabric contains between 7 and 15% of grog. The grains are medium to coarse (0.25 – 3 mm), sub-angular to sub-rounded, and generally moderately sorted with one sample showing well sorted grains. Grog has a similar mineral composition and brownish colour as a clay matrix with sporadically vitrificated grains. The main naturally present crystalloclast inclusions are very fine and fine monocrystalline quartz with the occurrence of mica minerals and the rare presence of K-feldspar. Grains are sub-angular and very well distributed in the clay. The characteristics of naturally present crystalloclast inclusions correspond to the subgroup 1.1.

Fabric 1.3: Grog and lithoclast tempering is characteristic for this group. This fabric contains around 15% of grog and 10% of lithoclasts. Grog grains are medium in size, sub-rounded, and moderately sorted in the clay. Grog grains contain slightly greater amount of fine crystalloclast inclusions than the matrix and are darker in colour. Lithoclasts are composed of metamorphic rocks, mainly quartzite. These are fine to medium in size, subangular and sub-rounded, moderately sorted in the clay. The characteristics of naturally present crystalloclast inclusions correspond to the subgroup 1.1.

Fabric 2.1: This subgroup is characterized by lithoclast tempering. Lithoclasts are composed of metamorphic rocks, mostly quartzite with the sporadic occurrence of igneous rocks. The grains are sub-angular, present in a common amount (25%), and poorly sorted. Naturally present crystalloclast inclusions are composed of very fine monocrystalline quartz and mica minerals. The density of very fine crystalloclasts in the matrix is common (20%) and the grains are sub-angular and very well distributed in the clay.

Fabric 2.2: Unimodal grain size distribution in this subgroup suggests no added tempering material. However, elongated shell fragments with visible inner structure are present in sparse amounts (<5%). The characteristics of the clay matrix are the same as in subgroup 2.1.

Fabric 2.3: This subgroup is characterized by grog and lithoclast tempering. Grog is present in sparse amounts (5%) and the grains are coarse, sub-rounded, and moderately sorted in the matrix. When compared with the clay matrix, grog grains possess similar mineral composition and are slightly darker colour. Lithoclasts are composed of metamorphic (quartzite) and less common sedimentary rocks (sandstone). The grains are fine to medium in size, moderately sorted with sub-angular and sub-rounded shapes. Sandstone inclusions seem to be more rounded. Naturally present crystalloclast inclusions are very fine monocrystalline quartz and mica minerals with the occurrence of K-feldspar. The characteristics of the clay matrix inclusions are the same as in subgroup 2.1.

Fabric 3.1: The main characteristic of this subgroup is the presence of elongated and curved voids in amounts between 10 and 15%. It is assumed that the voids retained the form of plant material added to the paste before firing. In several samples, black carbonized remains of plant inclusions occur within curved voids. The main naturally present crystalloclast inclusions are very fine and fine monocrystalline quartz with the occurrence of mica minerals and the rare presence of K-feldspar. Grains are sub-angular and very well distributed in the clay. The amount of very fine crystalloclasts in the matrix is abundant (40%) with sparse occurrence (5%) of fine crystalloclast inclusions.

Fabric 3.2: Regarding the absence of medium and coarse inclusions in the matrix, this fabric subgroup has no tempering material. The main naturally present crystalloclast inclusions in this subgroup are very fine and fine monocrystalline quartz with the occurrence of mica minerals and K-feldspar. Plagioclase, biotite, and zircon are determined in some samples. The density of naturally present crystalloclast inclusions in the matrix corresponds to the subgroup 3.1.

Fabric 3.3: This subgroup is characterized by grog tempering in the amount between 7 and 10 %. The grains are medium to coarse, sub-rounded, and moderately sorted. Grog grains tend to have the same colour and mineral composition as the matrix and are therefore sometimes hard to recognize. The characteristics and mineral composition of clay matrix correspond to the subgroup 3.1.

Fabric 4.1: This group is characterized by both lithoclasts and graphite tempering. Prevailing lithoclasts are metamorphic (quartzite) with a rare occurrence of sedimentary rocks (chert). The density of lithoclasts is moderate (15%), grains are medium to coarse, sub-angular and moderately sorted in the matrix. The significant characteristic of this group is the presence of opaque

Table 2: Ceramic petrography analysis of pottery sherds from Jagodnjak-Krčevine site (L – low, MH – medium high, H – high; F – fine, M – medium, C – coarse; PS – poorly sorted, MS – medium sorted, WS – well sorted, SA – sub-angular, SR – sub-rounded; OM – organic material, ** – plant material, * – shell fragments)

Sample number	Birefringence	Very fine crystalloclasts	Fine crystalloclasts	Quartz	K-feldspar	Plagioclase	Muscovite	Biotite	Pyroxene	Zircon	Lithoclasts density	Lithoclasts size	Lithoclasts sorting	Lithoclasts shape	Metamorphic	Igneous	Sedimentary	Graphite	Grog density	Grog size	Grog sorting	Grog shape	OM	Fabric groups	Type of raw material
8999	MH			+			+																*	**1.1**	Quartz-rich
9435	MH			+	+		+												15%	M/C	MS	SR		**1.2**	
9457	MH	15-20%	5-10%	+	+		+												7%	M	MS	SR		**1.2**	
9461	MH			+	+		+												15%	M/C	MS	SR		**1.2**	
9432	H			+	+		+				10%	F/M	MS	SA/SR	+				15%	M	MS	SR		**1.3**	
8993	H			+			+				25%	F/C	PS	SA	+	+								**2.1**	
8997	H	15-20%		+	+		+																*	**2.2**	
9460	H			+	+		+				10%	F/M	MS	SA/SR	+		+		5%	C	MS	SR		**2.3**	
8987	MH			+			+																**	**3.1**	
8988	MH			+	+		+																**	**3.1**	
8998	MH			+			+																**	**3.1**	
9000	MH			+	+		+																	**3.2**	
9456	MH	40-50%	5%	+	+		+																	**3.2**	
9458	MH			+	+	+	+																	**3.2**	
9459	H			+	+		+	+		+														3.2	
9433	MH			+	+		+	+																**3.2**	
9462	MH			+	+	+	+												7%	M/C	MS	SR		**3.3**	
9434	H			+	+	+	+												10%	M/C	MS	SR		**3.3**	
8991	L	20-25%	10%	+		+	+	+	+		15%	M/C	MS	SA	+			+						**4.1**	
8753	L			+	+	+	+	+	+		15%	M/C	MS	SA	+		+	+						**4.1**	
8994	MH	<5%		+			+	+			30%	F/C	PS	SA	+	+								**5.1**	
8989	MH	35-40%		+	+		+																	**6.1**	
8990	H			+	+		+																**	**6.2**	
8995	L	25%		+	+		+				15%	F/C	MS	SA	+	+		+						**7.1**	
9003	MH			+	+		+				30%	M/C	WS	SA	+									7.2	
8996	H			+	+		+				20%	M/C	MS	SA	+	+	+							8.1	Micaceous
9002	MH	25%		+	+		+				25%	M/C	PS	SA	+		+						*	**8.1**	
8752	H			+	+	+	+				20%	M/C	MS	SA	+									**8.1**	
8986	H	40%		+	+		+	+															*	**9.1**	
9001	H			+	+		+	+			30%	M	WS	SA	+		+							**9.2**	
8992	MH	40%	5%	+	+		+																**	**10.1**	

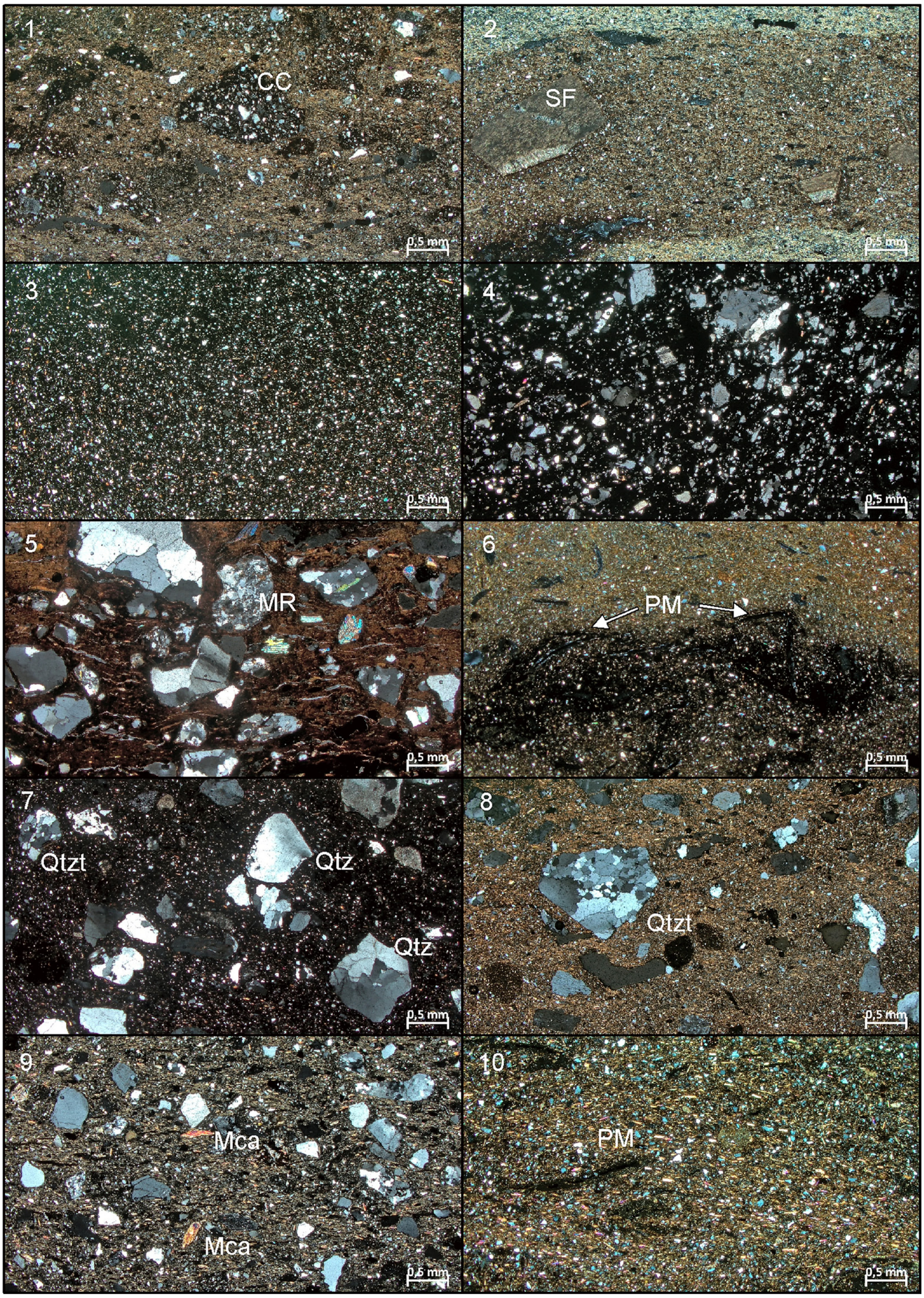

Figure 3: Thin section microphotographs of different fabric groups (XP).
Fabric group 1 – sample 9432; Fabric group 2 – sample 8997; Fabric group 3 – sample 9000; Fabric group 4 – sample 8991; Fabric group 5 – sample 8994; Fabric group 6 – sample 8990; Fabric group 7 – sample 9003; Fabric group 8 – sample 8752; Fabric group 9 – sample 9001; Fabric group 10 – sample 8992; (Mca – mica, Qtz – quartz, Qtzt – quartzite, MR – metamorphic rock, SF – shell fragment, PM – plant material, CC-ceramoclast/grog).

graphite grains which cause the extremely dark matrix colour and low birefringence. These grains are present in very common amounts (30%), fine to coarse in size and angular to subangular in shape. The main naturally present crystalloclast inclusions are composed of very fine and fine monocrystalline quartz. Mica minerals, K-feldspar, and plagioclase are also present in the samples. The density of very fine crystalloclasts in the matrix is common (20%) and the grains are sub-angular and very well distributed in the clay. Fine crystalloclast inclusions are present in moderate (10%) amounts.

Fabric 5.1: This group is also characterized by lithoclast tempering. Lithoclasts are very common (30%), composed of metamorphic (quartzite and less common schist) and igneous rocks. They are mainly sub-angular, fine to coarse in size and poorly sorted in the matrix. Naturally present crystalloclast inclusions are composed of very fine monocrystalline quartz and mica minerals present in sparse amounts (<5%). These are sub-angular and very well distributed in the clay.

Fabric 6.1: According to unimodal grain size distribution, this subgroup has no added temper material in the paste. Naturally present crystalloclast inclusions are composed of very fine monocrystalline quartz and less common K-feldspar and mica minerals present in very common amounts (35%). Grains are sub-angular and well distributed in the clay.

Fabric 6.2: This subgroup is characterized by the presence of elongated and curved voids in amount around 15% that retained the form of plant material added to the paste before firing. As in the subgroup 3.1, sometimes black carbonized remains of plant occur within curved voids. The characteristics and mineral composition of clay matrix correspond to the subgroup 6.2.

Fabric 7.1: Like in Fabric 4.1, the characteristics of this subgroup are both lithoclast and graphite tempering. Characteristic lithoclasts are metamorphic rocks, mostly quartzite and less common schist while igneous rocks are rarely present. These grains are sub-angular, present in moderate amounts (15%) and moderately sorted in the matrix. The graphite grains are opaque, present in common amount (20%), with sub-angular shape and medium to coarse in size. Naturally present crystalloclast inclusions are composed of very fine monocrystalline quartz with the occurrence of K-feldspar and mica minerals. These are sub-angular, well distributed and common in the clay (25%).

Fabric 7.2: The main characteristic of this subgroup is lithoclast tempering. Characteristic lithoclasts are metamorphic rocks, mostly quartzite and less common schist while igneous rocks are rarely present. Grains are sub-angular, present in common amounts (30%) and are well sorted in the matrix. The characteristics and mineral composition of clay matrix correspond to the subgroup 7.1.

Fabric 8.1: Similar to previous one, this group is also characterized by lithoclast tempering. Among lithoclasts, all three rock types are determined in the samples but metamorphic lithoclasts prevail (quartzite). Sedimentary lithoclasts are mostly determined as limestone. The grains are medium to coarse, sub-angular and poorly to moderately sorted in the matrix. The lithoclast density varies between 20 and 25%. The main naturally present crystalloclast inclusions are very fine elongated mica minerals with the occurrence of quartz, K-feldspar and plagioclase minerals. Grains are sub-angular and well distributed in the clay with contents up to 25%.

Fabric 9.1: The main naturally present crystalloclast inclusions are composed of very fine elongated mica minerals with the common presence of quartz and K-feldspar. Biotite and plagioclase are rarely present. Grains are sub-angular and well distributed in the clay. Very fine crystalloclast inclusions are present in abundant (40%) amounts. The only coarse inclusions recorded in this subgroup are slightly curved and elongated shell fragments present in sparse amounts (<5%) and probably naturally present.

Fabric 9.2: The main characteristic of this group is lithoclast tempering. Lithoclasts are mostly composed of metamorphic rocks (quartzite and schist) while sedimentary rocks (limestone) are present in smaller amounts. Lithoclasts are very common (30%), sub-angular, medium in size and well sorted in the matrix. The characteristics and mineral composition of clay matrix correspond to the subgroup 9.1.

Fabric 10.1: This group is characterized by elongated and curved voids present in sparse amounts (7%). The occurrence of black carbonized remains of plant material within curved voids is very common. The main natu-

Table 3: Qualitative mineralogical composition of pottery samples determined by X-ray diffraction analysis (Qtz – quartz, Pl – plagioclase, Kfs – K-feldspar, Mca – micaceous minerals, Cal – calcite, Dol – dolomite, Amph – amphibole, Grph – graphite, Hem – hematite, Crs – cristobalite, + – present, n.d. – not detected)

Sample number	Qtz	Pl	Kfs	Mca	Cal	Dol	Amph	Grph	Hem	Crs
8986	+	+	+	+	+	+	+	n.d.	n.d.	n.d.
8989	+	+	+	+	+	+	+	n.d.	n.d.	n.d.
8994	+	+	+	+	n.d.	n.d.	+	n.d.	n.d.	n.d.
8995	+	+	+	+	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
8997	+	+	+	+	+	n.d.	+	n.d.	n.d.	n.d.
8998	+	+	n.d.	+	n.d.	n.d.	+	n.d.	n.d.	n.d.
8999	+	+	+	+	+	n.d.	n.d.	n.d.	n.d.	n.d.
9000	+	+	+	+	n.d.	n.d.	+	n.d.	+	n.d.
9001	+	+	+	+	+	n.d.	n.d.	n.d.	n.d.	n.d.
9002	+	+	+	+	+	+	n.d.	n.d.	n.d.	n.d.
9003	+	+	+	+	+	n.d.	+	n.d.	n.d.	n.d.
8752	+	+	+	+	+	n.d.	n.d.	n.d.	n.d.	n.d.
8753	+	+	+	+	n.d.	n.d.	n.d.	+	n.d.	n.d.
9432	+	+	+	+	n.d.	n.d.	+	n.d.	n.d.	n.d.
9433	+	+	+	+	+	n.d.	+	n.d.	n.d.	n.d.
9434	+	+	+	+	n.d.	n.d.	+	n.d.	n.d.	+
9435	+	+	+	+	+	n.d.	+	n.d.	n.d.	+
9456	+	+	+	+	n.d.	n.d.	+	n.d.	n.d.	n.d.
9457	+	+	+	+	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
9458	+	+	+	+	n.d.	n.d.	+	n.d.	n.d.	n.d.
9459	+	+	+	+	n.d.	n.d.	+	n.d.	n.d.	n.d.
9460	+	+	+	+	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
9461	+	+	+	+	+	n.d.	+	n.d.	n.d.	n.d.
9462	+	+	+	+	+	n.d.	n.d.	n.d.	n.d.	n.d.

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rally present crystalloclast inclusions are composed of very fine elongated mica minerals with quartz and K-feldspar occurrence. The amount of very fine crystalloclasts in the matrix is very common (40%), the grains are sub-angular and very well distributed in the clay. Besides that, the subgroup contains fine crystalloclast inclusions present in sparse amounts (5%).

5.1.2. Mineralogy

The mineralogical composition of the archaeological ceramic determined by XRD generally confirmed the optical microscopy observations (**Table 3**). The presence of quartz and plagioclase is characteristic for all samples while K-feldspar and amphiboles are practically ubiquitous. Calcite is frequently documented and may be accompanied by a sporadic occurrence of dolomite, which are assigned here as primary phases since no secondary calcite was detected by optical microscopy. The common feature of all the analysed samples is the distinct reflex at 10Å interpreted as the first basal peak of the micaceous phyllosilicate. Micaceous material determined by XRD analysis is in accordance with optical microscopy results, classified as muscovite and biotite. Graphite and hematite are recorded in only one sample (8753 and 9000, respectively), while cristobalite was detected in two samples (9434 and 9435).

5.2. Clayey sediments

5.2.1. Physical properties

According to the macroscopic description observed while sampling, most of the collected samples were classified as clayey sediments with brown to grey colour (see **Table 4**). Some of them, especially those collected near the Gmajna watercourse, contain shell fragments whereas those from old clay pits generally did not have any coarse inclusions. Despite generally similar macroscopic descriptions, they possess significantly different plasticity ranges according to the initial examination observed. Among all of the studied samples, those with “high plasticity” were collected in the immediate vicinity of the archaeological site (Gmajna watercourse) and in an abandoned Petlovac clay pit. The plasticity range of other samples varies from “low” to “moderate” while “no plasticity” was observed in three samples (see **Table 4**). The relative shrinkage of samples varies from approximately 6 to 33% (see **Table 4**). The high plasticity samples generally possess greater shrinkage values (>20%). The samples with the lowest shrinkage values are those collected near the Gmajna (sample 9097 and 9098) and Bojana watercourse (sample 9103).

5.2.2. Grain size analysis

The grain size distribution analysis suggests three different sediment types (see **Figure 4**). The majority of the samples contain more than 75 vol. % of silty fraction and less than 23% of clay fraction and are therefore classified as silt. Four samples with a lower silt proportion (65 – 74 vol. %) and a greater amount of clay (25 – 33 vol. %) are determined as clayey silt. Besides that, only two samples stand out showing a significantly different grain size distribution. They are characterized by a higher amount of sandy fraction (around 50 vol. %) and a

Table 4: List of potential raw materials with sampling location and depth, plasticity range, colour (according to the Munsell colour chart), coarse inclusions and shrinkage (/ - not measured). *The clay samples were collected from the exploitation pits where the actual depth was generally greater than 4m.

Sample number	Sampling location	Depth (cm)	Plasticity	Munsell colour	Colour	Coarser inclusions	Shrinkage (%)
9095	1	60–70	high	10YR 2/1	black	shells	28
9096	1	90–100	high	2.5Y 2.5/1	dark grey	shells	33
9097	1	110–120	moderate	2.5Y 4/1	black	shells	10
9098	2	80–90	high	2.5Y 6/4	light yellowish brown	shells	6
9099	3	160–170	no plasticity	5Y 5/2	olive grey		/
9100	4	90–100	moderate	10YR 5/4	yellowish brown		19
9101	5	20–30	no plasticity	2.5Y 5/4	Light olive brown		/
9102	6	*	moderate	2.5Y 4/2	dark greyish brown		17
9103	7	70–80	moderate	2.5Y 4/1	dark grey		9
9104	7	40–50	moderate	2.5Y 3/1	very dark grey		17
9105	8	30–40	moderate	2.5Y 4/4	olive brown		16
9106	9	70–80	moderate	2.5Y 4/2	dark greyish brown		21
9107	10	*	high	2.5Y 5/2	greyish brown		37
9108	11	90–100	high	2.5Y 4/2	dark greyish brown	shells	17
9109	12	*	no plasticity	5Y 4/1	dark grey		/
9110	13	40–50	low	10YR 4/3	brown		/

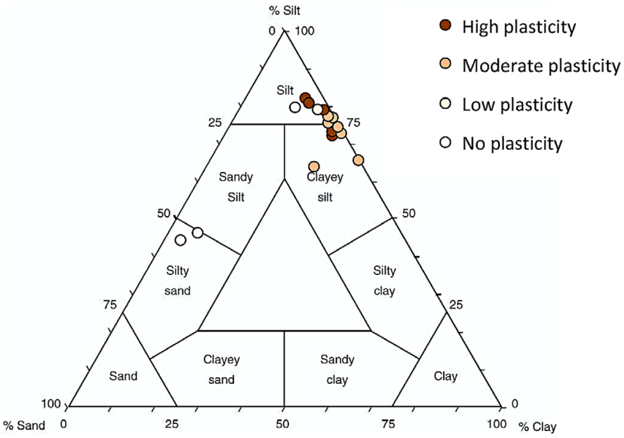

Figure 4: Grain size distribution of clayey sediments collected in the vicinity of the archaeological site correlated with the plasticity range measured on-site

very low clay content, ranging from 4 to 9 vol. %, and are therefore classified as silty sands.

5.2.3. Petrography

The mineral composition of fired clay briquettes is dominantly composed of angular-subangular monocrystalline quartz inclusions with the sporadic occurrence of mica (see **Table 5**). K-feldspar and plagioclase are rarely noticeable. By observing the density and size of mineral inclusions in the matrix of fired clay briquettes, nine fabric groups have been determined (see **Figure 5**). The size and density of inclusions vary among samples. Very fine crystalloclasts inclusions are present in all the studied samples with density varying from moderate (15%) to abundant (40%). The majority of samples also contain fine crystalloclasts inclusions but in a lower amount, generally up to 7%. Nevertheless, two samples stand out possessing a significantly higher (15 – 20%) amount of fine crystalloclasts inclusions (9106 and 9108). Optical microscopy revealed the presence of shell fragments in eight samples collected along the Gmajna and Bojana watercourse (sampling locations

Table 5: Petrography analysis of potential raw materials collected near the archaeological site (L – low, MH – medium high; + – present)

Sample number	Birefringence	Very fine crystallo-clasts	Fine crystallo-clasts	Quartz	Feldspar	Muscovite	Biotite	Shells	Fabric group
9095	L	20%	5%	+	+	+		+	1
9097	L			+	+	+		+	
9096	L	15%	3%	+		+		+	2
9098	MH			+	+	+			
9100	MH	35%	5%	+	+	+			3
9102	MH	15%	7%	+	+	+		+	4
9103	MH	30%	5%	+	+	+		+	5
9104	MH			+	+	+		+	
9105	MH	40%		+	+	+			6
9106	MH	30%	15%	+	+	+	+	+	7
9107	MH	25%		+	+	+			8
9108	MH	20%	15%	+	+	+	+	+	9

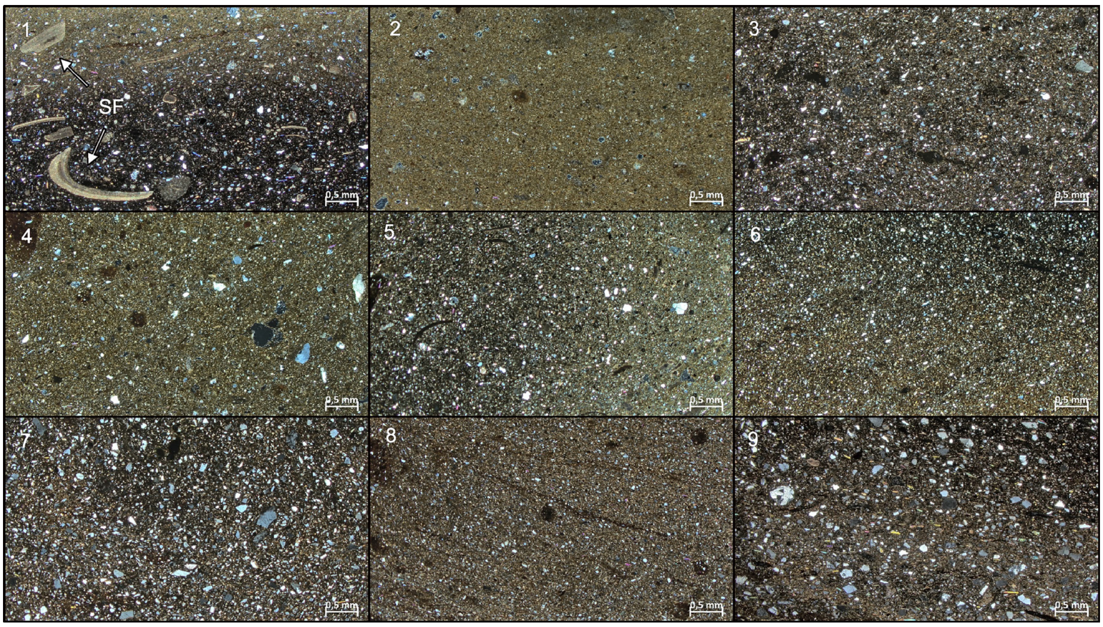

Figure 5: Microphotographs of nine fabric groups of fired clay briquettes determined according to matrix microtexture (XP). Fabric group 1 – samples 9095 and 9097; Fabric group 2 – samples 9096 and 9098; Fabric group 3 – sample 9100; Fabric group 4 – sample 9102; Fabric group 5 – samples 9103 and 9104; Fabric group 6 – sample 9105; Fabric group 7 – sample 9106; Fabric group 8 – sample 9107; Fabric group 9 – sample 9108 (SF – shell fragment).

Table 6: Semi-quantitative mineralogical composition of clayey samples determined by X-ray diffraction analysis (Qtz – quartz, Pl - plagioclase, Kfs – K-feldspar, Mca – micaceous material; including mica, illite and illite/smectite, Cal – calcite, Dol – dolomite, Arg – aragonite, Amph – amphibole, Gt – goethite, Kln – Kaolinite, Chl – chlorite, Sw. clay – swelling clay, n.d. – not detected, * - traces, + - minor, ++ - intermediate, +++ - major, ++++ - dominant)

<table>
<tr><th rowspan="2">Sample number</th><th rowspan="2">Qtz</th><th rowspan="2">Pl</th><th rowspan="2">Kfs</th><th rowspan="2">Mca</th><th rowspan="2">Cal</th><th rowspan="2">Dol</th><th rowspan="2">Arg</th><th rowspan="2">Amph</th><th rowspan="2">Gt</th><th colspan="3">Clay minerals</th></tr>
<tr><th>Kln</th><th>Chl</th><th>Sw. clay</th></tr>
<tr><td>**9095**</td><td>+</td><td>+</td><td>*</td><td>+</td><td>++</td><td>+</td><td>+</td><td>+</td><td>n.d.</td><td rowspan="3">+</td><td rowspan="3">+</td><td rowspan="3">+</td></tr>
<tr><td>**9096**</td><td>+</td><td>+</td><td>n.d.</td><td>+</td><td>+++</td><td>+</td><td>+</td><td>+</td><td>n.d.</td></tr>
<tr><td>**9097**</td><td>+</td><td>+</td><td>n.d.</td><td>+</td><td>++++</td><td>+</td><td>n.d.</td><td>+</td><td>n.d.</td></tr>
<tr><td>**9098**</td><td>+</td><td>+</td><td>*</td><td>+</td><td>++</td><td>+</td><td>n.d.</td><td>+</td><td>+</td><td colspan="3">+</td></tr>
<tr><td>**9099**</td><td>+</td><td>+</td><td>+</td><td>++</td><td>+</td><td>+</td><td>n.d.</td><td>+</td><td>n.d.</td><td colspan="3">+</td></tr>
<tr><td>**9100**</td><td>+</td><td>+</td><td>+</td><td>++</td><td>*</td><td>n.d.</td><td>n.d.</td><td>+</td><td>n.d.</td><td>+</td><td>+</td><td>+</td></tr>
<tr><td>**9101**</td><td>+</td><td>+</td><td>+</td><td>++</td><td>+</td><td>+</td><td>n.d.</td><td>+</td><td>n.d.</td><td colspan="3">+</td></tr>
<tr><td>**9102**</td><td>+</td><td>+</td><td>+</td><td>++</td><td>+</td><td>+</td><td>n.d.</td><td>+</td><td>n.d.</td><td>+</td><td>+</td><td>*</td></tr>
<tr><td>**9103**</td><td>+</td><td>+</td><td>+</td><td>++</td><td>+</td><td>+</td><td>n.d.</td><td>+</td><td>n.d.</td><td rowspan="2">+</td><td rowspan="2">+</td><td rowspan="2">*</td></tr>
<tr><td>**9104**</td><td>+</td><td>+</td><td>+</td><td>+</td><td>+</td><td>+</td><td>n.d.</td><td>+</td><td>n.d.</td></tr>
<tr><td>**9105**</td><td>+</td><td>+</td><td>+</td><td>+</td><td>*</td><td>n.d.</td><td>n.d.</td><td>+</td><td>n.d.</td><td>+</td><td>+</td><td>+</td></tr>
<tr><td>**9106**</td><td>++</td><td>+</td><td>+</td><td>+</td><td>*</td><td>n.d.</td><td>n.d.</td><td>+</td><td>n.d.</td><td>+</td><td>+</td><td>+</td></tr>
<tr><td>**9107**</td><td>+</td><td>+</td><td>+</td><td>+</td><td>+</td><td>n.d.</td><td>n.d.</td><td>+</td><td>n.d.</td><td>+</td><td>+</td><td>+</td></tr>
<tr><td>**9108**</td><td>+</td><td>+</td><td>+</td><td>++</td><td>+</td><td>+</td><td>n.d.</td><td>+</td><td>n.d.</td><td>+</td><td>+</td><td>+</td></tr>
<tr><td>**9109**</td><td>++</td><td>++</td><td>+</td><td>++</td><td>+</td><td>+</td><td>n.d.</td><td>+</td><td>n.d.</td><td colspan="3">+</td></tr>
<tr><td>**9110**</td><td>+</td><td>+</td><td>+</td><td>++</td><td>n.d.</td><td>n.d.</td><td>n.d.</td><td>+</td><td>n.d.</td><td colspan="3">+</td></tr>
</table>

1, 2, 6, 7, and 11) and in an old clay pit near Beli Manastir (location 9) while iron nodules are present in four samples (9096, 9101, 9102 and 9107). The birefringence of samples is low to medium-high while the matrix colour is mainly brown with occasional orange and light brown shading. Fired clay briquettes are mainly orange to light brown in colour with dark brown and grey core in several samples, caused by a short firing process.

5.2.4. Mineralogy

The semi-quantitative mineralogical composition of the sediments determined by XRD analysis is presented in **Table 6**. The common feature of all analysed samples is the presence of quartz, plagioclase, micaceous material and amphiboles whereas K-feldspar is almost ubiquitous. Calcite is determined in almost all samples (except 9110) but its presence varies considerably and it is mostly followed by a minor presence of dolomite. Therefore, samples 9095-9098 collected at locations 1 and 2 are distinguished from the others by their high carbonate content and minor aragonite presence. The presence of clay minerals is characteristic of all samples. More specifically, the treatments conducted on the <2μm fraction of samples with “moderate” and “high” plasticity revealed generally uniform clay mineral composition. Kaolinite, chlorite and swelling clays are present in all samples whereas some mixed layer clay minerals are probably present in the samples 9095, 9096, 9097, 9106, 9107 and 9108. Lower swelling clay mineral content is present in samples 9102, 9103 and 9104. Phyllosilicates at 7 and 14Å are characteristic of all samples with “low” and “no” plasticity evaluated on-site but detailed clay mineral composition on the <2μm fraction has not been determined for those samples.

6. Discussion

The most challenging task in this study is the appropriate identification of raw material sources used in the past. To resolve this issue, it was necessary to properly analyse both the archaeological ceramic samples and potential raw clayey material. The discussion is therefore focused on the raw clayey material, archaeological ceramic samples and consequently their comparison and insight into the sources and distribution of pottery raw materials used in the past.

6.1. Characteristics of clayey material

The clayey sediments collected in the Baranja region are mainly located in a flood plain of the Drava River where channel migration and changes in flood levels lead to the deposition of silty and clayey sediments (**Pikija et al., 1991**). The similar origin and sedimentary environment of these clays are reflected in their generally uniform mineralogical composition. However, the samples collected near the Gmajna watercourse differ from the others and may be identified as “calcareous clays” due to their high calcite content which is consistent with previous investigations of clayey sediments in the area (**Bognar, 1990**). Four samples (9100, 9105, 9106, and 9110) are determined as "non-calcareous clays" due to the absence of carbonate phases. Shell fragments in samples 9095 and 9096 are determined by optical microscopy and additionally confirmed by aragonite presence with XRD analysis. Samples can be classified into different categories based on their physical properties.

Measuring the plasticity of clay is not an easy task. The assessment of plasticity depends on the subjective perception of the potter. Therefore, it is often defined descriptively as the optimal condition of the raw material for vessel making or the "workability" of the material based on the potter's experience and feeling, without a defined quantitative value (**Rice, 1987**). Accordingly, observation of the plasticity ranges on-site provided an insight into the physical characteristics of the potential raw material sources. Among all the studied samples, those with the highest plasticity were generally found within a radius of 1 km from the site whereas one was collected in abandoned Petlovac clay pit. The high plasticity of these samples generally corresponds to high shrinkage values probably caused by the higher swelling clay mineral content. These clays sometimes need to be mixed with non-plastic inclusions because the high shrinkage affects the vessel causing the breakage during drying and firing (**Rye, 1981; Velde and Druc, 1999).** Although the observed plasticity varies significantly among samples, grain size analysis revealed two sediment types (**Shepard, 1954**). The dominant sediments are silt and silty sands–with no samples classified as "clay". In particular, the samples with the highest observed plasticity, according to grain size analysis, are generally determined as silt or clayey silt which strongly suggests the underestimation of the clay fraction also observed by **Fedotov et al.** (**2007**). More specifically, the non-spherical shape of the clay particles, as well as optical properties and measurement limits, led to a different evaluation and increase of silt fraction (**Fedotov et al., 2007; Polakowski et al., 2014; Mako et al., 2017**). The comparison of these results, together with the geology in the study area, proves that the clayey raw material is easily accessible and available in significant amounts in the vicinity of the settlement, especially near the Gmajna watercourse, making the ancient landscape suitable for the unhindered production of pottery.

6.2. Technological features

This research shows that ancient potters preferred sandy clay throughout all periods of the past. The quartz-rich raw material was used mainly in the Bronze and Late Iron age, while the use of micaceous raw material was less common, and it was used by the potters from the Neolithic, Mediaeval, and especially the Roman period. A higher proportion of non-plastic inclusions of fine-grained crystalloclasts tends to improve the workability of the clay, resulting in the reduced plasticity and shrinkage and a shorter drying process (**Orton and Hughes, 2013; Rice, 1987**). Therefore, it was not necessary to add temper material to this clay. Also, the field research has shown that this raw material is present at shallow depths below the soil surface and that ancient potters probably did not need to refine the clay beyond removing unwanted materials such as roots. In this sense, but also technologically, the potters had a high-quality raw material at their disposal.

However, despite the availability of optimal quality clays, ancient potters made extensive use of tempering material or non-plastic inclusions added to the clay. Temper is usually added to a very fine, plastic clay that is highly sticky (**Quinn, 2013**) to improve the workability of the clay paste but also to reduce shrinkage, resulting in a better-quality product (**Rice, 1987; Velde and Druc, 1999**). Among the potters from Jagodnjak, the selection of tempering material was not only related to the knowledge about their influence on the production process, but the choice of temper was also subject to tradition (**Stark, 1998; Gosselain et al., 2005**). The results of this study show that temper selection was distinctive exclusively by a particular social group, i.e. by different periods of the past. For example, the Neolithic potter added plant material to the clay in order to produce different types of vessels. The curvature of the voids present in the matrix shows that the potter tempered the clay with agricultural by-products caled chaff. According to the results of numerous archaeometric analyses of Early Neolithic ceramics throughout the Pannonian Plain and the Balkans (**Kreiter et al., 2013b; Spataro and Meadows, 2013; Spataro et al., 2021**), it was established that the potters from Jagodnjak used a clay recipe by following a practice characteristic of a very wide geographical area. The reasons for using this type of temper material can be related to techno-functional performance. It is known that the vegetal temper increases plasticity and it may also increase the dry strength of very sandy clays (**Rice, 1987**). Also, research has shown that vegetal tempering provides lighter vessels, ensures resistance to breakage but meanwhile causes reduced heating effectiveness and less abrasion resistance (**Skibo et al., 1989**). Despite certain positive effects, the use of chaff was not strictly functional, and according to researchers of early Neolithic pottery, the interpretations are more socially oriented (**Kreiter et al., 2013b; Dzhanfezova, 2021; Papadakou et al., 2021**). In that sense, ceramic production shows a direct relationship with agricultural activities, throughout agricultural by-products incorporated into ceramics. While the technological tradition of plant tempering is widespread and extremely stable for early Neolithic communities, during the Bronze Age in the Pannonian Plain, the same can be said for grog-tempered ceramics. For example, grog (ceramoclasts) is present in the Bronze age pottery from the Jagodnjak site in various quantities (between 7 and 15%) with sizes between 0.25 and 3 mm. As mineralogical composition and grain size distribution of grog do not vary significantly from the samples' matrix, it can be presumed that grog was made from the same materials as pottery. According to numerous studies on pottery production and use, it has been established that the use of grog is very common among the Bronze age communities across the Pannonian Plain (**Kreiter, 2007; Michelaki, 2008; Sofaer et al., 2012; Žibrat Gašparič and Dolenc, 2015; Kudelić et al., 2018**). Some authors emphasize the functional basis of grog tempering which improves the physical and thermal properties of the vessel (**Rice, 1987; Velde and Druc, 1999**). On the other hand, a smaller amount of grog tempering (less than 15%), as recorded in studied samples, can be an indication of pottery recycling as a part of cultural tradition (**De Boer, 1974; Smith, 1989; Chapman, 2000; Brück, 2006; Kreiter, 2007**). Moreover, it can be noted that Bronze age potters sometimes combined grog tempering along with smaller amounts of lithoclasts, used for making cooking pots and pots for processing or storing food or drink. Small-sized and thin walled vessels (cups and jugs) were made of non-tempered mostly fine-grained sandy clay. Late Iron age pots selected for this study mainly represent a widespread, distinctive type of pottery, found in most parts of the Central European Celtic world. This group of vessels was graphite tempered, presumably cooking pots (**Kreiter et al., 2009; Kreiter et al., 2013a; Žibrat Gašparič and Dolenc, 2015**) of dark grey colour with a silver shine. These can be easily recognized by the extremely dark matrix colour caused by the presence of graphite grains but also the medium and coarse rock tempering material. The extensive use of graphite during the Late Iron Age is interpreted exclusively as part of the Celtic cultural tradition. However, published research on the use of graphite also implies functional reasons, for example, graphite improves the vessel's resistance to thermal and mechanical stress, increases thermal conductivity and vessels are more resistant to chemical attack (**Kreiter et al., 2013a:173** and references therein). On the other hand, the cultural, as well as the economic role of such raw material should be assumed, since graphite sources in the area of the Pannonian Plain are very rare (**Kreiter et al., 2013a**), indicating a long-distance trade. Lithoclast-tempering tradition is present in all studied periods except the Neolithic, but it is especially common among pottery from the Mediaeval times, and to a lesser extent in Roman ceramics. Bimodal fabrics and angularity of rock fragments with mainly moderately or poorly sorted grains indicate the intentional addition of crushed rocks to clay. Various amounts of rock fragments are usually added to the clay to improve the physical and especially thermal properties of the vessel (**Rice, 1987; Velde and Druc, 1999**). In our case, such a recipe was used to make pots that are assumed to have been used for the thermal processing of food. The choice of such tempering, during the Roman times, was also observed in the Medieval times, which indicates a tradition that seems to be predominantly based on functionality, unlike in prehistoric periods.

The firing method represents one of the crucial moments in the production process, and it is the final test for a potter. Diagnostic features of firing techniques are the surface colour and the colours of the radial section of the walls (**Rye, 1981; Rice, 1987; Roux, 2019**). Prehistoric pottery was fired together with the fuel mainly on open fires or in shallow pits. Studied pottery from the Neolithic was fired in the atmosphere of incomplete or complete oxidation indicating uncontrolled firing conditions probably on an open fire. During the Bronze Age, it can be seen that the firing regime depends on the vessel's shape (see **Table 1**) and it is presumed that pottery was fired on an open fire although kiln firing for fine vessels is not excluded. From the Late Iron Age, onward, kiln firing became the main firing method. Birefringence of the matrix is relatively high for all the studied ceramics, indicating firing temperatures lower than 800-850°C (**Quinn, 2013**) which is consistent with the firing temperatures usually evaluated for prehistoric pottery. Despite the low birefringence, similar firing temperatures can be assumed for graphite-tempered pottery since the firing temperatures of these wares had to be kept below 850°C in order to avoid accidental oxidation and the loss of graphite (**Gebhard et al., 2004**). The assessment of firing temperature can also be related to the mineral phases present in a specific temperature range. The presence of calcite and dolomite together with 10Å phyllosilicates, which corresponds to a dehydroxylated illite-like phase, additionally confirms firing temperatures lower than 800°C (**Gruver, 1950; Guggenheim et al., 1987; Cultrone et al., 2001; Rodriguez-Navarro et al., 2009; Šegvić et al., 2012; Cultrone and Carrillo-Rosúa, 2020**). The lowest firing temperatures can be estimated at around 550-600°C, assumed by recorded cracked quartz grains attributed to the quartz inversion at 573°C (Žibrat Gašparič **and Dolenc, 2015** and reference therein). Since the occurrence of cristobalite, as high temperature SiO_2 polymorph, suggest firing temperatures generally above 1200°C, certain peaks present in some samples are more likely the result of SiO_2 glass decomposition, which occurs at lower temperatures (**Pagliari et al., 2013**).

Technological features, especially those related to the selection of tempering material in prehistory, above all, represent a social signature characteristic of an individual community. On the other hand, the choice of exclusively mineral tempering is characteristic of later, Roman, and Mediaeval communities with interpretations emphasizing function, not the social implications of potters' choices.

6.3. Availability of pottery raw materials

XRD analysis is commonly used and very useful in determining the mineralogical composition of the samples. However, in this research, the XRD analysis did not point to different types of clayey material present in ceramic samples. The possible reason is that tempering material when mixed with the clay matrix, strongly affect the entire mineralogical composition, and neglect the differences among the clayey materials. Applying the petrological studies is therefore necessary to emphasize the difference between the compositions of clay matrix and tempering material to identify the raw material preferences related to a specific technology, i.e. social group (**Rice, 1987; Wallis et al., 2015**). The study results point to several potential raw material sources exploited by ancient potters. While collected clays are generally uniform in their mineralogical composition, two general types of raw materials (quartz-rich and micaceous) were determined in the archaeological ceramic samples. In particular, all of the clayey samples collected on site can be approximately correlated with quartz-rich fabric groups (see **Figure 6**) while three micaceous fabrics remain separated. Despite their similar mineralogical composition, samples can be more precisely separated and correlated with each other by observing the matrix microtexture with the help of optical microscopy. Thus, by comparing the collected clay with the archaeological ceramic matrix, four sources of pottery raw material were located. Even though good quality clayey material is easily accessible near the archaeological site (locations 1, 2, and 4), it is not classified as the raw material used during the studied periods. In contrast, it is assumed that clayey material found at more distant locations, around 4km from the site was more commonly used (locations 6, 7, 8, and 10). The correlation between pottery made by different social groups and the collected potential raw material indicates several important issues. It seems that most raw material sources do not correspond with a specific pottery tradition but were exploited by different communities from the past. These indicate the intentional choice of quartz-rich raw material throughout all the studied periods. Moreover, the Bronze age and the Neolithic communities used raw material with very common to abundant (35–50%) crystalloclast inclusions in the matrix, which correlate with the clayey material from locations 6, 7, and 8. These can suggest the preferred exploitation of specific raw material sources with a higher amount of crystalloclast inclusions in the matrix. It seems that the clay source location in Petlovac (location 10) with a distance of more than 4 km was less commonly used in prehistory and can be related especially to the Roman period community. Moreover, since all of the clayey sediments collected on site belong to the quartz-rich raw material, the field sampling did not reveal a source of micaceous and inclusion-poor clay (<5% of crystalloclast inclusions) present in the fabrics 8, 9, 10 and 5, respectively. According to the previous investigations of the area (**Bognar, 1990**), the micaceous clay is probably of local origin but located at specific, still unknown locations. Conversely, the inclusion-poor clay determined as Fabric 5 can be an indication of a long distant transport present among Roman period communities. If excluding this sample, according to the mineral composition and matrix microtexture, the local origin of pottery can be assumed for all studied samples. Moreover, the frequent occurrence of lithoclasts, predominantly composed of metamorphic rocks which are present at the pre-Neogene Drava basement (**Pikija et al., 1991**), additionally indicate the local origin of pottery. In the case of graphite tempered pottery from the Late Iron age, a long-distance trade is presumed. Since the sources of graphite in the area of the Pannonian Plain are very rare, it is assumed that such raw material was acquired through trade or exchange (**Kreiter et al., 2013a**). However, in the case of potters from Jagodnjak, the use of regional graphite is assumed, since the nearest source is located in the Papuk and Psunj mountains (Šinkovec and Krkalo, 1994; Drnić and Mileusnić, 2012), located around 90 km from the settlement where pottery production probably took place.

So where did the potters collect the raw material and how did they use their landscape in terms of pottery production? The use of local clay and easily available tempering materials through all the studied periods is undeniable. However, it is a bit surprising that the potters did not use the clay available at the watercourse, immediately western of the settlement. A discovery of this kind may reflect environmental dynamics, where erosion and alluviation can easily alter the landscape. Therefore, although currently available, these locations may not have been accessible in the past. In addition, the reasons may be hidden in the fact that the area along today's Gmajna Stream represented a kind of boundary or restricted use zone. For instance, according to many ethnographic studies, the resource area in which potters obtain their resources to make pottery may depend on the distribution of their political relationships or it can depend on the social and community boundaries, rather than the geographical distribution of the resources (**Livingstone Smith et al., 2005**).

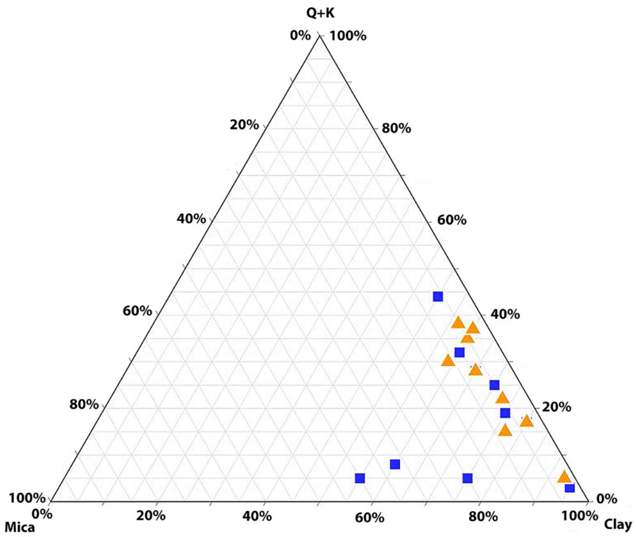

Figure 6: Mineral composition of archaeological ceramic (squares) and clayey material (triangles) fabric groups

7. Conclusion

This paper presents an analysis of the petrography and mineralogy of archaeological ceramics and potential raw materials collected in the vicinity of the multi-period archaeological site (Neolithic, Bronze Age, Late Iron Age, Roman and Medieval period) Jagodnjak-Krčevine located in the lowland region of Baranja. The research objective was to examine the availability and quality of clays for pottery production and to study their distribution in the local landscape. The compositional analysis of archaeological ceramics and the comparison with the clay samples, within the framework of the applied analytical methods (optical microscopy, XRD, grain size analysis), suggests that the pottery raw material (clay and added tempering material) used in the past was of local origin. High quality and diverse clay material is easily available and widely distributed in the local landscape, and interestingly, ancient potters preferred sandy clay in all periods of the past. In this sense, the research showed that the nearest source of quality raw material is only a hundred meters away, but it was not used as a pottery raw material in the past. Also, the study showed that the most likely clay sources used were located to the south and east of the settlement, at a maximum distance of 4 km from the settlement. Moreover, quartz-rich raw material was mainly used during the Bronze and Late Iron Age, while the use of micaceous raw material was less common, and it can be related to the Neolithic, Mediaeval, and especially the Roman period. According to these results, it seems that most ceramics can be associated with sources within a 4 km radius, which is a preferred source especially for Bronze Age potters, but also for Neolithic potters. This indicates patterns in the choice of spatial zones for the procurement of raw materials characteristic of a certain period of the past. On the other hand, the selection of a particular type of tempering material, which has a positive technological effect on shaping, drying, and firing, was preferred by a particular social group and represents a characteristic feature of that community. Thus, Neolithic potters added plant material (chaff) to clay, following a practice that was widespread over a very large geographic area, while tempering with grog is characteristic of the Bronze Age. Celtic potters (Late Iron Age) preferred graphite tempering, suggesting the trade of raw material over long distances, while rock tempering was common in the Roman and Medieval periods for the production of cooking pots. These results represent the first research in Croatia focused on a discussion about distances that potters travelled to obtain their resources in different periods of the past, which, in general, can contribute to the study of a regional system of production and landscape use.

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SAŽETAK

Lončarska tehnologija kroz vrijeme: Arheometrija keramike i lončarske sirovine s višeperiodnog arheološkog nalazišta istočne Hrvatske

Razmatranje višeperiodnih arheoloških nalazišta s ciljem razumijevanja mehanizama kulturnih promjena velikih razmjera još je uvijek vrlo rijetka tema istraživanja u Hrvatskoj. Tehnološke tradicije od velike su važnosti, posebice u kontekstu razmatranja kontinuiteta, inovacija i promjena. U ovom radu upotrijebili smo arheometrijski pristup za istraživanje lončarske tehnologije. Stoga ovaj članak predstavlja analizu petrografije i mineralogije arheološke keramike i potencijalnih sirovina prikupljenih u blizini višeperiodnog arheološkog nalazišta (od neolitika do srednjeg vijeka) Jagodnjak-Krčevine smještenog u istočnoj Slavoniji, tj. jugozapadnom dijelu Panonskog bazena. Primarni cilj je utvrditi kakvu su recepturu lončarske smjese (glina i primjese) koristili lončari za izradu posuda, radi boljeg razumijevanja njihove varijabilnosti u kontekstu tehno-funkcionalnih značajki. Dodatni cilj je ispitati dostupnost i kvalitetu gline za proizvodnju posuda te proučiti njihovu rasprostranjenost u lokalnom krajoliku. Analitičke metode primijenjene u istraživanju su optička mikroskopija, rendgenska difrakcija i granulometrijska analiza. Usporedbom arheološke keramike s glinama utvrđeno je da su drevni lončari vjerojatno koristili lokalno dostupne gline, a odabir primjesa koja se glini dodavala predstavlja snažan element tehno-tradicije, koji je izraženiji kod prapovijesnih zajednica. Nadalje, ovi rezultati predstavljaju prvo istraživanje u Hrvatskoj usmjereno na raspravu o udaljenostima koje su lončari prelazili kako bi došli do svojih resursa u različitim razdobljima prošlosti, što općenito može pridonijeti proučavanju regionalnog sustava proizvodnje i korištenja krajolika.

Ključne riječi:
arheometrija; Baranja; terensko uzorkovanje; lončarska sirovina; lončarska tehnologija

Author’s contribution

Natali Neral (Doctoral Student – Assistant, geologist) participated in field research, conducted laboratory and data analyses, and interpreted and presented the results. **Andreja Kudelić** (Research Associate, archaeologist) designed and organized the research, conducted sampling, and performed the interpretation and presentation of the results. **Ana Maričić** (Associate Professor, geologist) participated in the field research and assisted in the presentation of the results. **Marta Mileusnić** (Full professor, geologist) participated in the interpretation of the results.