RESEARCH ARTICLE – VÝZKUMNÝ ČLÁNEK

# Technological and provenance insights into La Tène pottery: An analysis of the settlement assemblage from Křinec (Czech Republic)

## Vhled do technologie výroby a provenience laténské keramiky: Analýza sídlištního souboru z Křince (Česká republika)

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*During the Late La Tène period in the first century BC, Central Europe witnessed significant shifts in settlement structures and material culture. Understanding these changes necessitates an examination of LT D1b phase settlements, particularly in Bohemia, where such sites are rare. This study extends beyond conventional stylistic analysis of pottery, incorporating material and manufacturing perspectives to reveal production organisation, distribution, and community interactions. Through a comprehensive examination of the settlement pottery from the feature 27/1986 from Křinec using X-ray fluorescence, thin section analysis, and computed tomography, we have gained a better understanding of the settlement's position in the regional socio-economic network within which ceramic vessels or raw materials were transported over distances of more than 20 km. The presented approach offers a deeper comprehension of the La Tène period's end in Bohemia and underscores the value of multifaceted pottery research in archaeological studies.*

Late La Tène period – production of pottery – socio-economic network – X-ray fluorescence – ceramic petrography – computed tomography

*Během pozdní doby laténské v prvním století před Kristem došlo ve střední Evropě k zásadní proměně sídlištní struktury a materiální kultury. Pochopení této transformace vyžaduje studium sídlištních souborů z fáze LT D1b předcházející této proměně, a to obzvláště v Čechách, kde jsou takovéto soubory vzácné. Tato studie jde nad rámec konvenční stylistické analýzy tvarů a výzdoby keramiky a zahrnuje rozbor použitého materiálu a technologie výroby s cílem poodhalit organizaci výroby, distribuci a interakce mezi komunitami. Komplexní zkoumání sídlištní keramiky z objektu 27/1986 z Křince pomocí rentgen-fluorescenční analýzy, analýzy výbrusů a výpočetní tomografie dovolilo lépe porozumět pozici, kterou toto sídliště zaujímalo v regionální socio-ekonomické struktuře, uvnitř níž byly transportovány nádoby nebo suroviny k jejich výrobě na vzdálenosti větší než 20 km. Představený přístup umožňuje získat hlubší vhled do závěru doby laténské a ukazuje potenciál vícefázové analýzy keramiky jako součásti archeologického výzkumu.*

pozdní doba laténská – výroba keramiky – socioekonomická síť – rentgenová fluorescence – keramická petrografie – počítačová tomografie

## Introduction

Analyses of the properties of pottery enable to study not only its manufacturing process but also the contacts between the regions and past societies that produced and used these vessels. The production chain of ceramic vessels was influenced by multiple factors, such as the raw material used, their function in society, organisation of their manufacturing, and cultural conventions (*Orton – Hughes 2013*, 23–35; *Hunt 2017*, 135–136; *Eramo 2020*, 2, 4; *Montana 2020*, 2). In general, forms of ceramic production resulted from interactions

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between people and their environment (*Hunt 2017*, 135–136). Pottery was also a part of the everyday reality of past communities, as it was essential for multiple activities, and therefore factors influencing its properties and production included customs and traditions (*Santacreu 2017*).

The social role of pottery was reinforced by relations between generations of potters who shared conceptions of correct manufacturing procedures and ideal final products (*Nicklin 1971*; *Arnold 2005*; *Spataro – Meadows 2013*, 60; *Roux et al. 2017*; *Berg 2018*, 97). Consequently, potters could disregard manufacturing techniques of other communities with distinct pottery production traditions (*Roux et al. 2017*; *Spataro – Meadows 2013*, 72). In addition, the pottery production process was often adapted to certain types of raw materials (*Nicklin 1971*). The spread and preservation of the same pottery tradition between different communities required a stable system of contacts and the sharing of information about manufacturing practices among potters (*Jeffra 2011*, 27–28, 207–208; *Santacreu 2017*).

In individual communities, all households could manufacture pottery solely for their own use. Alternatively, some households might have produced pottery for other households as a secondary means of subsistence. Investments in production, including time and resources, grew with the importance of pottery production for a household's subsistence (*Peacock 1982*, 8–9, 13–24; *Rice 2015*, 189; *Thér et al. 2015*, 40–41). In general, specialisation of the production of any commodity increases with the lower availability of necessary resources, the higher complexity of the manufacturing process, or the demand of consumers for products with certain attributes (*Thér et al. 2015*, 38–40). Higher specialisation of production may be likewise connected to the demographic development of society (*Thér – Mangel 2014*, 5) and is not necessarily related to sociopolitical complexity (*Hunt 2017*, 117). Thus, the transportation of products (including pottery) between regions primarily depends on suitable conditions, such as the proximity of travelling routes (*Nicklin 1971*; *Peacock 1982*, 79–80; *Clark – Parry 1990*, 297).

The characteristics of pottery manufacturing often varied between regions. Likewise, in such cases, the attributes of ceramic vessels also differed. Therefore, it is possible to study contacts between regions with distinct pottery production traditions (*Orton – Hughes 2013*, 23–35). Contacts could involve the transportation of vessels, imitation of the visual properties of pottery from other areas, or the spread of different manufacturing techniques. Forms of contact may be investigated by comparing styles, ceramic fabrics, and manufacturing processes of the vessels (*Meyer 2013*; *Stapfer 2017*). An examination of ceramic fabrics includes analyses of their elemental and mineralogical composition (*Orton – Hughes 2013*, 140–146; *Rice 2015*, 379–382, 393–400; *Gliozzo 2020a*; *Repka 2020*, 22–23).

The manufacturing process can be reconstructed by examining the attributes of pottery. It consists of multiple stages, including the collection of a raw material and its modifications, the shaping of a vessel, adjustments to its appearance, and firing (*Hunt 2017*, 102–105). The choice of raw material is limited by available resources (*Rice 2015*, 52). In the case of pre-industrial societies, potters usually gather raw material (both clay and inclusions) within one kilometres of the household. Only rarely inclusions are collected from a distance greater than seven kilometres (*Arnold 2005*; *Hein – Kilikoglou 2020*, 10). However, some materials may be more suitable for the manufacture of specific products, such as wheel-made pottery (*Hunt 2017*, 95–98), or vessels with distinct functions (*Orton – Hughes 2013*, 117). In addition, potters might prefer a certain source of clay or type of inclusions based on their traditions (*Schiffer – Skibo 1987*).

The shaping of a vessel involves various operations, which can be divided into primary (forming of a roughout) and secondary techniques (*Thér et al. 2015*, 47; *Hunt 2017*, 104). A vessel may be shaped completely with the hands or with the help of a rotational device. Its rotational energy might be used to create a primary shape, to finish a shape made with the hands (for example by coiling), or during another part of ceramic manufacturing. An advantage of the first possible application of rotational energy is the speed of shaping. However, this method requires a longer learning period than the rest of the techniques (*Thér et al. 2015*, 28–29; *Běhounková 2018*, 8; *Thér 2020*, 7). Individual shaping techniques leave specific traces (*Jeffra 2011*, 56, 115–123, 126–128; *Thér et al. 2015*, 47, 63; *Thér 2020*, 2, 8–10). Pottery featuring a surface without irregularities, with uniformly thick walls, and parallel striations on the inner wall can be classified as wheel-made. When rotational energy is applied only to finish a vessel, it may also be possible to observe traces characteristic of hand-made pottery (*Jeffra 2011*, 56, 122–123, 148–149; *Choleva 2012*; *Běhounková 2018*, 13–17, 20–21), such as irregularly oriented striations, relicts left from joints of coils or separate parts, and unevenly thick walls (*Jeffra 2011*, 116–128; *Běhounková 2018*, 8, 13–15, 18).

Most of the visible traces are removed by potters before firing. Nevertheless, the shaping of a vessel can also be studied based on the orientation of particles in a ceramic fabric, which can be examined, for instance, by micro-petrographic analysis or computed tomography (*Thér et al. 2015*, 47, 63; *Hunt 2017*, 544–549). The attention to surface treatment then potentially indicates the importance of the pottery's visual attributes and other functions. For example, the surfaces of vessels may vary in the level of polishing. In addition to specific appearance, polishing also leads to the lower permeability of fluids and deposition of dirt (*Jeffra 2011*, 56, 137; *Corina Ionescu – Hoeck 2020*). Alternatively, the outer surface might be roughened, often to facilitate the manipulation and transportation of a vessel (*Rice 2015*, 138, 140).

Structures used to fire pottery can be divided into open and closed variants. Additionally, the structures differ in whether the fuel is in contact with the pottery or not. However, all structures allow potters to adjust the process of firing (*Mangel 2016*, 48–49; *Roux 2019*, 111–116). The specifics of firing affect the colours of the final products. Their colouring depends on a combination of temperature, level of oxidation and composition of the fabric. In this regard, the colouring of pottery can be influenced by a potter (*Thér et al. 2015*, 47, 66–72; *Roux 2019*, 111; *Gliozzo 2020b*; *Repka 2020*, 24) and may differ even between vessels made of the same material (*Hunt 2017*, 203). Depending on the firing process, cross-sections of fired vessels will have homogeneous colouring or colouring composed of more than one layer (*Orton – Hughes 2013*, 133–135). For instance, a potter can create thin light or dark surface layers by adjusting the final phase of firing (*Thér et al. 2015*, 71; *Roux 2019*, 101).

In this paper, the research on pottery production serves as a source of information about society at the end of the La Tène period (1st century BC) in Central Europe. At this time, material culture and the settlement network underwent a significant transformation associated with social changes (*Venclová 2008a*; 147; *Salač 2010*). The end of the La Tène period in Bohemia can be defined by stage LT D1 (130/100 – ca. 50 BC) and LT D2, which is synchronous with stage A of the Roman period (*Kysela 2013*, 131). In the phase LT D1a (130/100–80/70 BC), the social, economic, and settlement development of the Late La Tène period reached its peak. However, in phase LT D1b (80/70–50/40 BC), the population began to decrease, and settlements started to be abandoned. This process ended with the collapse of the settlement network and gradual replacement of existing material culture by new elements (*Waldhauser 1983*; *2001*, 41, 130–132; *Beneš et al. 2018*, 89–90; *Danielisová 2020*, 136–145). The transformation included fundamental changes in pottery production, such as the end of the use of potter's wheels and double chamber kilns, and alterations in the shapes and decoration of the vessels (*Thér et al. 2015*, 16; *Beneš et al. 2017*). Analogous changes can also be observed in other regions of Central Europe (*Beneš et al. 2018*, 90), for example, in Central Germany (*Daszkiewicz – Meyer 2003*; *Meyer 2013*) or Bavaria (*Tappert 2005*).

Pottery production of the La Tène period in Bohemia reached its peak in the stages LT C2–D1 (*Beneš et al. 2018*, 208). Coarse and fine ware were clearly separated, both in terms of their properties and in regional variability/homogeneity. Attributes of coarse pottery varied between regions, while fine pottery was highly uniform (*Venclová et al. 1998*, 150–151, 166–167; *2008a*, 98–101). During the research of pottery production in Eastern Bohemia, fine and coarse ware did not differ in clay sources, but in the subsequent preparation of material (*Thér et al. 2015*, 103). The preparation of material for the production of coarse pottery, including types of inclusions, was related to regional traditions (*Venclová et al. 1998*, 150–151; *2008b*, 186–187; *Danielisová 2010*, 67; *Thér et al. 2015*, 133; *Joštová 2020*, 57–58).

Depending on the region, fine and coarse ware also frequently differed in terms of the shaping process. In Central and Eastern Bohemia, fine ware was always formed with the help of a wheel. Likewise, rotational energy was sometimes used during the shaping of graphite pottery and, especially in Central Bohemia, other coarse pottery. The rest of the coarse pottery was most often shaped by coiling (*Mangel et al. 2013*, 103; *Thér et al. 2015*, 101–102, 120; *Thér – Mangel 2024*, 16, 22). In Western and Northwestern Bohemia, differences between fine and coarse pottery were less pronounced and their shaping process was more variable (*Thér – Mangel 2024*, 16, 22, 15–16). The frequency of wheel-made fine ware varied between regions and even between individual settlements (*Motyková et al. 1990*, 351–362; *Venclová 2008a*, 98; *2008b*, 186–187, 191; *Salač – Kubálek 2015*, 90; *Danielisová 2010*, 65–66).

A smooth or polished surface was characteristic for fine ware in all regions of Bohemia. The types of roughened surfaces of coarse pottery then varied across regions (*Venclová 2008a*, 98–100). For example, grated surfaces predominated in Central and Eastern Bohemia (*Venclová et al. 1998*, 151; *2008b*, 188, Tab. 33; *Danielisová 2010*, 76; *Joštová 2020*, 78–82), while the most common variants of the roughened surface in Northwestern Bohemia were 'marble' and 'crumb' types (*Salač – Kubálek 2015*, 62).

Pottery was fired in various open and closed structures including double chamber kilns, which were used to fire wheel-made ceramics (*Mangel 2016*, 69, 272; *Beneš et al. 2018*, 204–205). Simultaneously, wheel-made fine ware mostly had uniform colouring, while the colouring of coarse pottery made by hand varied. Wheel-made coarse pottery differed in colouring (to some extent) from both previous groups (*Thér et al. 2015*, 120–121).

The high uniformity of fine ware indicates that it could be produced by specialised potters (*Venclová 2008a*, 58–59, 81–82; *2008b*, 185). These producers used potter's wheels and firing kilns to intensify ceramic production or to create specific types of pottery (*Thér – Mangel 2014*, 12). Especially in Central Bohemia, specialised potters also produced wheel-made coarse pottery. On the other hand, coarse pottery in Eastern Bohemia was usually made by hand in individual households (*Thér et al. 2015*, 14, 132). The specialised

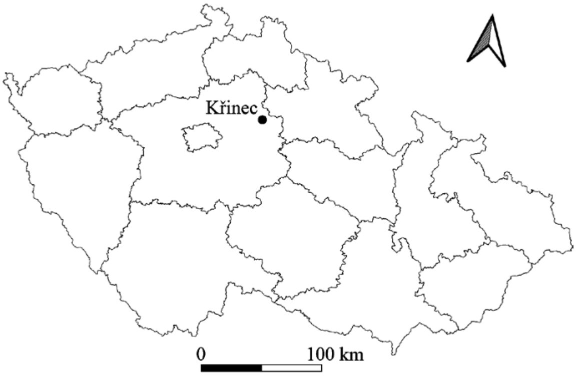

Fig. 1. Position of the Křinec site at the map of the Czech Republic.

production of wheel-made pottery was conducted by numerous independent workshops with a short range of distribution (*Thér – Mangel 2024*, 24–25).

Understanding the changes in pottery production during the Late La Tène period in Bohemia is, however, complicated by the fact that the analysed pottery often comes from oppida or settlements that were abandoned before the phase LT D1b. One of the sporadic examples of the LT D1b assemblage represents pottery from the settlement in Křinec (*Fig. 1*) in the eastern part of Central Bohemia (*Beneš et al. 2018*, 302; *Danielisová et al. 2018*, 164). The La Tène settlement in this part of Bohemia was primarily concentrated around the rivers Labe (Elbe), Jizera, Cidlina, and Mrlina (*Venclová 2008a*, 26). Křinec is located about 10 km northeast of the Labe. In its cadastral territory, three settlement areas from the stages LT B–D could be recognised around the river Mrlina. The settlement was formed by small groups of houses or individual unfenced homesteads (*Motyková-Šneidrová 1957*; *Rybová 1968*, 22; *Waldhauser 2001*, 284). This form of settlement was also common in other parts of Bohemia during the LT B–D period (*Venclová 2008a*, 31; *2008b*, 176).

In the eastern part of Central Bohemia, the most prominent settlements in the Late La Tène period were situated at the sites of Žehuň and Týnec nad Labem and a settlement agglomeration also most likely existed near Kolín (*Fig. 2*). All these sites were connected to other regions by the communication route along the Labe (*Mangel et al. 2013*, 92–93; *Beneš et al. 2018*, 86; *Thér – Mangel 2024*, 7). The site of Týnec nad Labem is located 28 km southeast of Křinec (*Fig. 2*: 1) on the hill Kolo (225 m.a.s.l.) overlooking the Labe (*Fig. 2*: 2). It was inhabited in the Hallstatt period and also in the Late La Tène period. The site has been known to archaeologists since the first half of the 20th century and was partially excavated between 1974 and 1977. A metal detector survey was then conducted south of the site between the hill and the river. Finds included fragments of metal vessels, mirrors, rings, and 68 coins dated to stages LT D1–D2 having origin in Bohemia as well as in other regions of Europe (*Beneš 2015*; *2020*).

The site of Žehuň takes position between Křinec and Týnec nad Labem (*Fig. 2*: 3). It was inhabited in the Bronze Age as well as in the La Tène and Roman periods. Finds from the La Tène period include 143 coins (74 from LT C1–C2, 56 from phase LT D1a and 13 from phase LT D1b), 164 other metal artefacts, and pottery fragments. Pottery was typical for the eastern part of Central Bohemia, while types of metal artefacts pointed to the contacts with other regions, for example with the central Danube area. The La Tène settlement in Žehuň was probably abandoned in phase LT D1b, and therefore it was contemporary with the Křinec settlement (*Danielisová et al. 2018*).

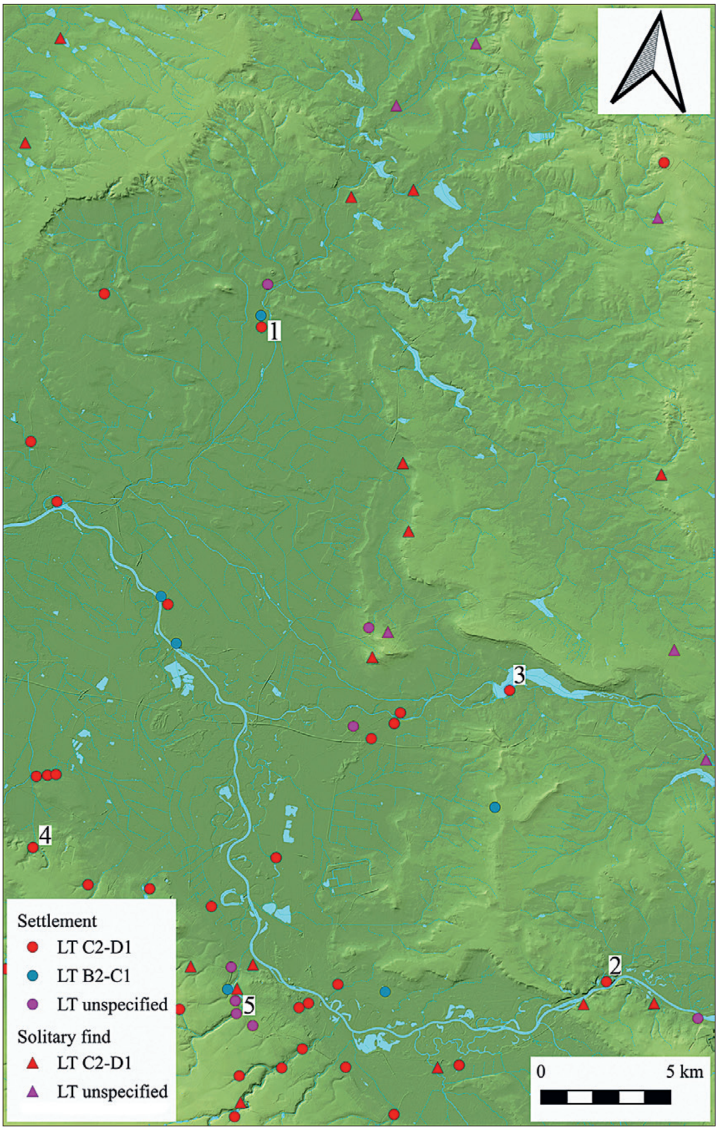

Fig. 2. La Tène settlement structure in the vicinity of Křinec: 1 – Křinec, 2 – Týnec nad Labem, 3 – Žehuň, 4 – Cerhýnky, 5 – Štítary u Kolína.

The assemblage from Křinec can be used as an example of pottery from the end of the La Tène period before subsequent changes of the stage LT D2 appeared. Its attributes can be compared with characteristics of pottery from the previous phases of the Late La Tène period in order to determine whether it has a similar character or whether it differs. Chemical composition analysis and thin section analysis also allow to study ceramic fabrics. Their distinctions might point to the choice of a specific material for the production of certain categories of ceramic vessels or to a different provenance of pottery. Based on this, we can obtain new data regarding the organisation of pottery production and distribution and contacts between local settlements at the end of the La Tène period.

## Geological setting

Křinec is located on the fluvial deposits of the Mrlina River, primarily consisting of loam, sand, and gravel, which are part of the southern Bohemian Cretaceous Basin, notably the Teplice formation. The Teplice formation, dated from the Upper Turonian to Lower Coniacian, ranges from 30–110 m in thickness. It often begins with the 'Upper Turonian transgressive horizon' overlaying siltstone with glauconite and nodules of phosphates, including phosphatised fauna relics and coprolites. In the Křinec vicinity, these marine sediments mainly include calcareous claystone, marlite, and siltstone with clay limestone. Downstream, near the Březno formation, sediment composition shifts to primarily marlite and limestone (*Fig. 3*).

The Mrlina River, which is situated about 300 m east of the site of Křinec, originates around 20 km north in Příchvoj and flows mostly through the Březno formation of calcic claystone, marlite, and calcic siltstone. Approaching Křinec, it traverses the Rohatec layers of the Teplice formation, which is characterised by silicified calcic claystone and marlite.

The broader region encompasses geological units from the Teplá-Barrandien area, Moldanubian Zone, Kutná Hora – Svratka area, and the Permocarbon of the Blanice furrow. The Moldanubian Zone, situated to the southwest, features the two-mica, medium- to coarse-grained porphyritic Říčany granite of the Central Bohemian pluton. Nearby, the Barrandien area presents Neoproterozoic slate, greywackes, and conglomerates, along with Ordovician rocks including slate, siltstone, sandstone, and quartzite.

Southeast from Křinec, the area of the Podhořany Crystalline Complex in the Iron Mountains is predominantly composed of fine-grained paragneiss and mica schist, with the Chvaletice-Sovolusky Proterozoic and Chrudim Paleozoic not far away. The Chvaletice Group includes phyllitised clay shale and greywacke schist, tuffitic rocks, volcanic basic rocks, and bodies of amphibole to amphibole-pyroxene gabbro, while the Sovolusky Group contains clayey shale and spilitic rocks. The Chvaletice massif is located between the Podhořany Crystalline Complex and the Chvaletice-Sovolusky Proterozoic and consists of two-mica granite, granodiorites, and amphibolic gabbro to metagabbro with a transition to amphibolites.

Southwards, the Kutná Hora Crystalline Complex is delineated into Šternberk-Čáslav, Kutná Hora, and Malín Groups featuring a diverse array of rocks including two-mica gneiss, amphibolite, and quartzite. The metamorphosis took place in kyanite-staurolite, or sillimanite-almandine subfacies with muscovite (*Mísař et al. 1983*).

## Material

The assemblage analysed in the article comes from feature no. 27/1986 in Křinec. The site is situated on a small elevation over the left bank of the river Mrlina (197 m.a.s.l.) in the south part of the cadastral area of Křinec. During the excavation in 1986 and 1987, around 60 archaeological features were found, including nine from the La Tène period. However, only the sunken feature 27/1986 could be dated to stage LT D1b. Its chronology is based particularly on the find of an iron spoon-type brooch. The feature had a size of 550×330×40 cm and was oriented to east-west axis. It contained two rows of cone-shaped loom weights in the western corners and three rows of loom weights in the northeast

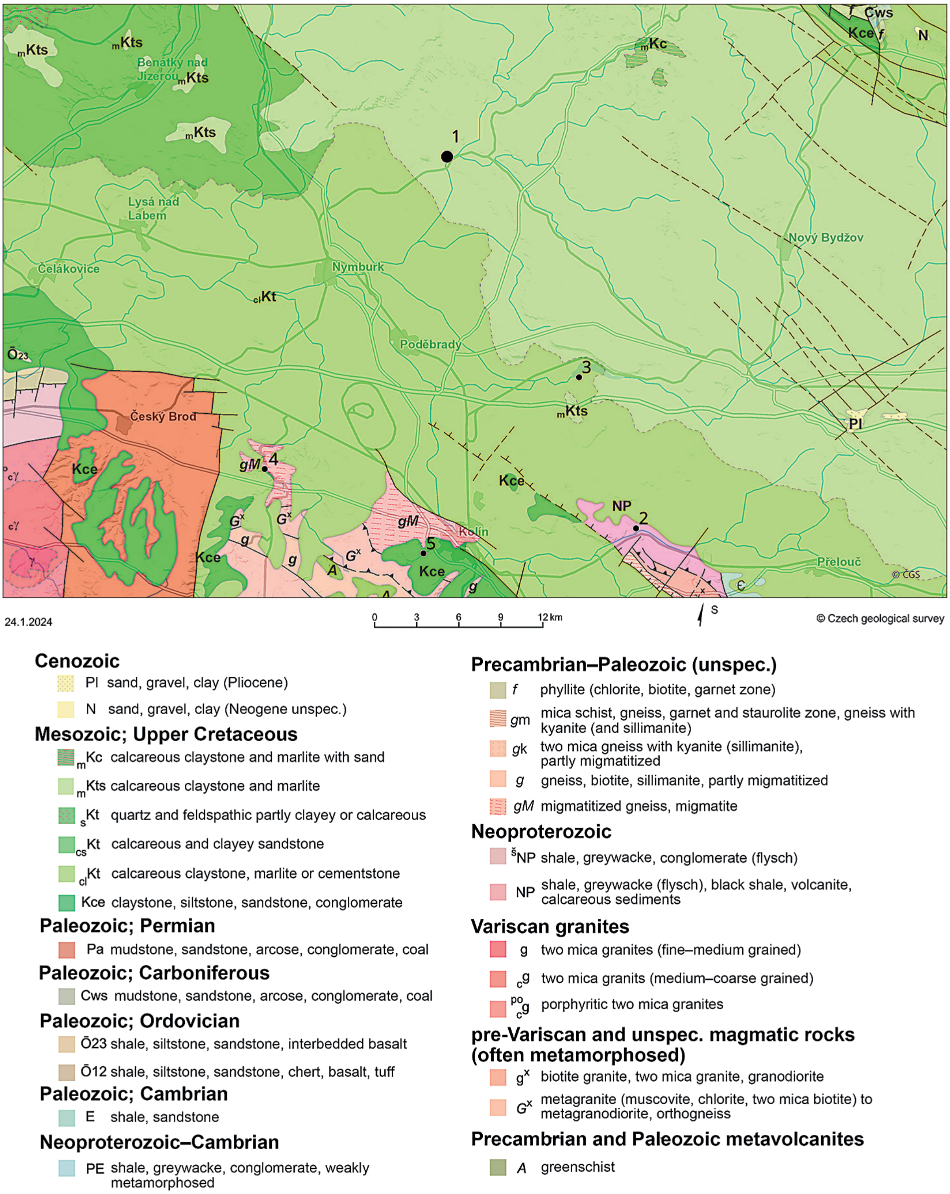

Fig. 3. Geological map of the region: 1 – Křinec, 2 – Týnec nad Labem, 3 – Žehuň, 4 – Cerhýnky, 5 – Štítary u Kolína (after Czech geological survey 2024, modified).

corner. In addition, a shallow hole with a layer of ash interpreted as a hearth was found in the western part. Other finds from the feature included eight spindle whorls, an iron hook, part of an iron chain, a fragment of a bracelet from a silver sheet, and pottery fragments. The finds are deposited in the Polabské Museum in Poděbrady (P 34158–34197, 34232–34434, 34474–34509).

Tab. 1. Values of the variables Po, Mat, Vy, and traces left from the shaping process.

| Surface treatment (Po) | |
|---|---|
| Po1 | polished |
| Po2 | smoothed |
| Po3 | roughly smoothed |
| Po4 | matt |
| Po5 | grainy |
| Po6 | grated |
| Po7 | uneven coating of fine clay, so-called ‘marble’ type |
| Po8 | coarse coating, so-called ‘crumb’ type |
| Po9 | combing |
| **Material category (Mat)** | |
| Mat1 | size of inclusions up to one mm, sorting high |
| Mat2 | size of inclusions up to one mm, sorting medium |
| Mat3 | size of inclusions up to three mm, sorting medium |
| Mat4 | size of inclusions up to three mm, sorting low |
| Mat5 | size of inclusions above three mm |
| **Colouring of a cross-section (Vy)** | |
| Vy1 | homogeneous dark |
| Vy2 | homogeneous light |
| Vy3 | light–dark |
| Vy4 | dark–light |
| Vy5 | dark–light–dark or dark–light–dark–light–dark |
| Vy6 | light–dark– light or light–dark–light–dark–light |
| Vy7 | asymmetrical multicolored |
| **Traces left from the shaping process** | |
| Hand | traces associated with hand-made pottery |
| Wheel | traces associated with wheel-made pottery |
| Comb | traces associated with a combination of both methods |

The majority of pottery from the feature was identified as being wheel-made and created from similar material (*Sedláčková 1991*). Based on the stylistic assessment, the assemblage does not contain pottery from the Roman period or from other regions (*Droberjar 2006*, 16). In terms of vessel shapes, the assemblage is very uniform and can be dated to the stage LT D. It is supported by the dating of the silver bracelet, which comes from the same period. The studied assemblage of pottery consists of 541 ceramic specimens, of which 30 were selected for archaeometric analyses (*Fig. 4–5*; *Tab. 2*) based on their attributes.

## Methods

### Macroscopic analysis

As an initial step, the assemblage was analysed macroscopically to gather data about its main characteristics and to select representative samples for further analyses. Examined attributes of pottery included weight, wall thickness, level of fragmentation, preserved part, shape, surface treatment (Po), material category (Mat), proportion of inclusions (InMn), variability of inclusions (InVar), traces left from the shaping process (*Tab. 1*), and the colouring of a cross-section (Vy).

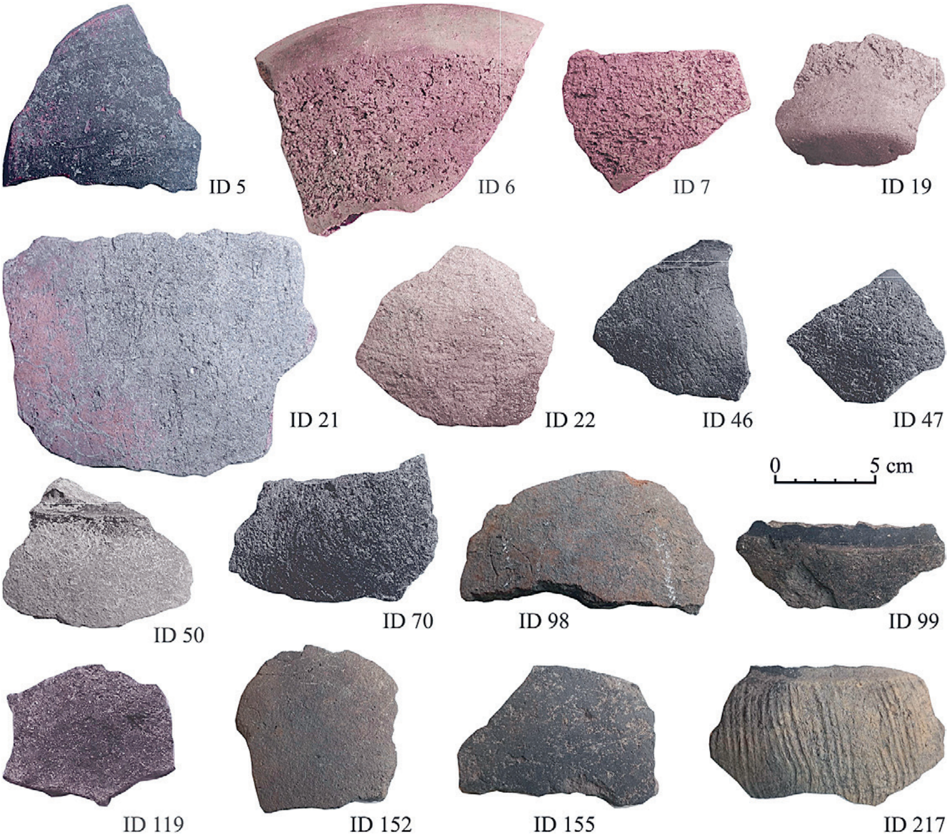

Fig. 4. Samples selected for X-ray fluorescence spectrometry (ID 5–217).

| ID | Fabric | XRF | OM |
|---|---|---|---|
| **5** | A1 | + | |
| **6** | C | + | + |
| **7** | C | + | |
| **19** | A4 | + | |
| **21** | A3 | + | |
| **22** | A2 | + | |
| **46** | B | + | |
| **47** | A4 | + | + |
| **50** | A3 | + | + |
| **70** | A4 | + | |
| **98** | D | + | + |
| **99** | A2 | + | + |
| **119** | A1 | + | |
| **152** | D | + | |
| **155** | B | + | + |
| **217** | B | + | + |
| **228** | A2 | + | |
| **257** | C | + | + |
| **258** | C | + | |
| **313** | A3 | + | + |
| **339** | B | + | |
| **416** | A1 | + | |
| **493** | A3 | + | |
| **494** | A3 | + | |
| **534** | C | + | |
| **536** | A4 | + | |
| **576** | A1 | + | + |
| **577** | A3 | + | |
| **587** | B | + | |
| **594** | A1 | + | |

Tab. 2. List of samples, fabrics, and analytical methods (XRF – energy-dispersive X-ray fluorescence spectrometry, OM – optical microscopy).

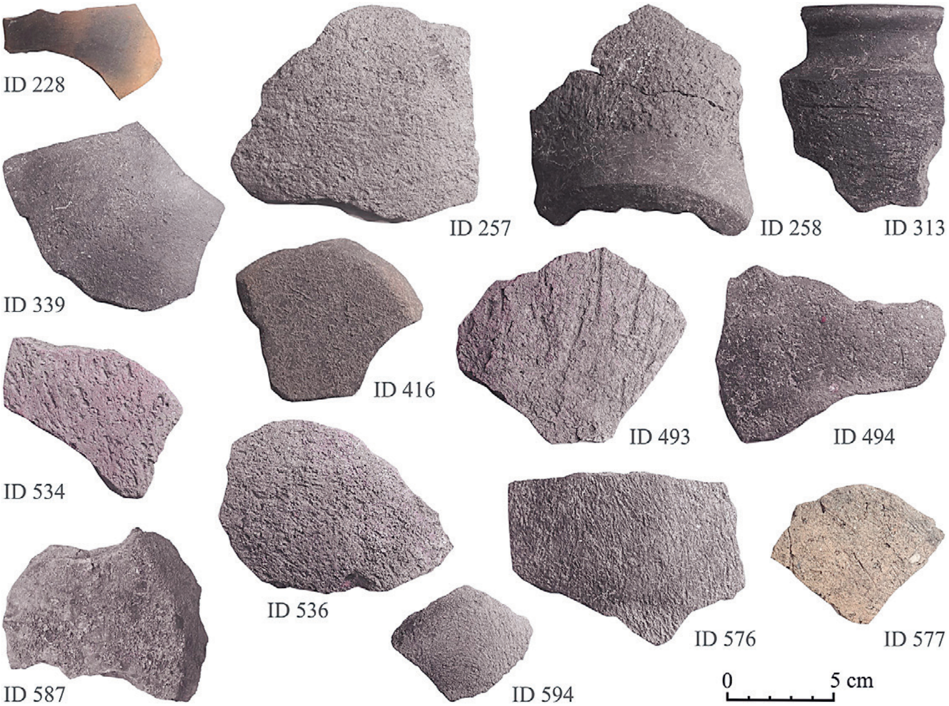

Fig. 5. Samples selected for X-ray fluorescence spectrometry (ID 257–594).

Surface treatment (Po) was divided into nine potential variants based on the typology created by *Venclová* (*1998*, 90–91; *2008a*, Fig. 50) for the La Tène pottery in Bohemia. The five subcategories of ceramic material (Mat1–Mat5) were defined according to size and the sorting of inclusions. The proportion of inclusions (InMn) was categorised into three groups: less than 5 % (InMn1), 5–20 % (InMn2) or more than 20 % (InMn3) (after *Orton – Hughes 2013*, 238–240). Inclusions in the ceramic fabric also differed in their shapes, colours, and other attributes. For this reason, the descriptor for variability of inclusions (InVar) was defined. Ceramic fabric might have contained one type or none (InVar1), two types (InVar2), or more types (InVar3) of the visually determinable inclusion.

Finally, seven variants of colouring visible on the cross-section (Vy) were distinguished based on the alternation of light and dark layers. Colours were described from the outer wall to the inner one and determined using the Munsell Book of Soil Colour Charts. The assessment of layers also involved an examination of their thickness and regularity (see *Orton – Hughes 2013*, 133–135, Fig. 11.1).

## Computed tomography

Computed tomography (CT) was used as a non-destructive alternative to petrographic analysis. It helped to investigate the microstructure of the ceramic fabric and identify the forming process of six ceramic vessels (ID 135, 258, 313, 328, and 567; *Fig. 6*). Samples were selected during the macroscopic analysis based on traces linked with different forming

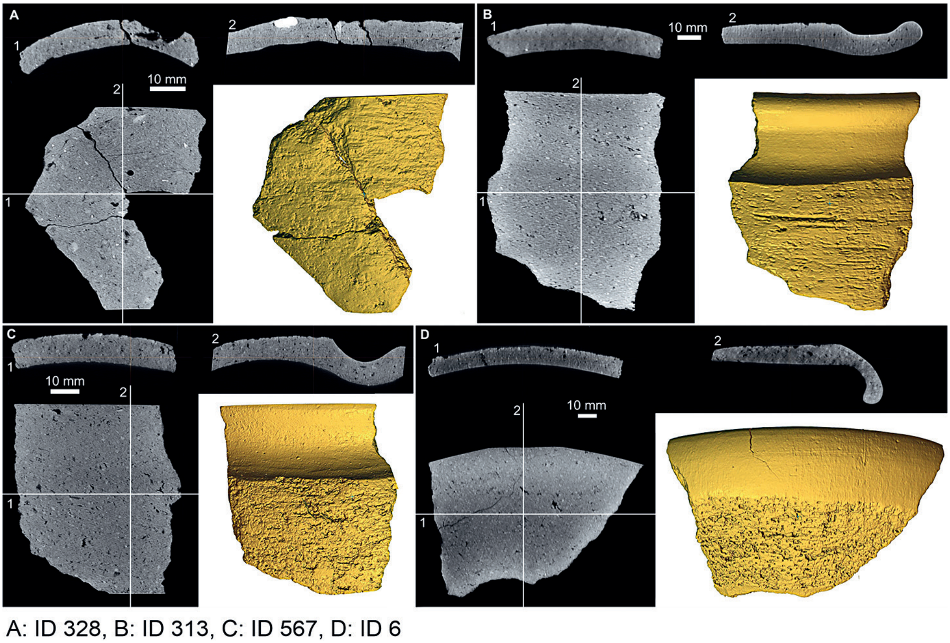

Fig. 6. Samples ID 6, 313, 328, and 567 selected for computed tomography.

methods. Three samples (ID 6, 313, 567) had traces characteristic for wheel-made pottery and two samples (ID 135, 328) had traces typical both for hand-made and wheel-made pottery. During the CT, the shaping process of the vessels was determined based on the orientation of components in the ceramic fabric and discontinuities in the structure of the walls. The main factor affecting the orientation of components is the direction of a force applied during the forming. The forming forces cause compressive and shear stress in the material. The compression rotates elongated particles and deforms the shape of voids. Deformation by compression stress results in the diagonal orientation of particles relative to the forming force. In the case of shear stress, the particles are aligned along the direction of the forming force (*Rye 1981*; *Vyalov 1986*; *Carr 1990*; *Courty – Roux 1995*; *Middleton 2005*; *Livingstone Smith 2007*; *Berg 2008*).

X-ray images were acquired by an X-ray generator using a lamp with a focal spot of 0.05 mm at a voltage of 120 kV and a current of 160 µA (obtained on the Explorer X test 200-120/400 X-ray device by Testima). Each CT reconstruction was based on 400 RTG images acquired with the same settings as single X-ray images. CT reconstructions were created using LometomArk software equipped with the X-ray device mentioned above. The resolution of the resulting CT reconstructions varied depending on the size (ranging between 55 and 120 µm).

In the next step of the analysis, radial, tangential, and horizontal sections were extracted from the 3D reconstructions. Components identified in the 3D reconstructions were classified based on their orientation, shape, and position. Structures of tangential, radial, and horizontal sections were also evaluated. The evaluation recognised regulated, omnidirectional, and fluid structures of components (*Thér 2020*). The interpretation of collected data was based on theoretical assumptions regarding the connection between applied shaping techniques as well as the resulting structures of the ceramic fabric and on the reference pottery assemblage.

## Ceramic petrography

Chemical composition analysis was conducted using a Rigaku NexCG energy dispersive fluorescence spectrometer (ED-XRF) equipped with a 50 W Pd tube and a silicon drift detector (SDD) with a resolution capability of up to 145 eV. Element quantification errors due to matrix-based discrepancies were mitigated through the application of a calibration library, which was specifically designed for ceramics and soils using standard reference materials of the National Institute of Standards and Technology (NIST), the China National Analysis Centre for Iron and Steel, the National Research Centre for Certified Reference Materials in China, the National Institute of Advanced Industrial Science and Technology in Japan, and MINTEK. The 30 samples were analysed in the form of pressed powder pellets.

Concentrations of selected elements (Al, Si, K, Ca, Ti, V, Mn, Fe, Ni, Cu, As, Rb, Sr, Ba, Pb) were statistically analysed. Hierarchical clustering of the first four components of PCA yielded a classification of samples, allowing for the selection of 10 samples for thin section analysis. Standard thin sections (30 µm) were examined by an Olympus BX 51 polarising optical microscope. The methodology of thin section analysis followed the procedures described by *Quinn* (*2013*). Inclusion abundance was expressed as a semiquantitative score using the adjusted guidelines of *Sauer* and *Waksman* (*2005*).

## Statistical data analysis

Data collected during macroscopic analysis were evaluated using RStudio statistical software (R version 4.2.2). An initial exploratory data analysis examined the distribution of individual variables and their potential relationships, which were visualised by bar plots and boxplots. Subsequently, the contingency tables were created to study relationships between categorical variables, and the Kendall rank correlation coefficient was applied to estimate the association between numeric variables. The first part of the data analysis in RStudio used dplyr packages for the organisation (*Wickham et al. 2023*), skimr for the summarisation (*Waring et al. 2022*), and ggplot2 for the visualisation of data (*Wickham 2016*).

In the next step, relationships between categorical variables were further examined using the chi-square test of independence, Cramér's *V*, and correspondence analysis (CA). The chi-square test was used to confirm whether categorical variables in the contingency tables were independent or associated in some way (*Baxter 2015*, 203; *Carlson 2017*, 190–193). Values of Cramér's *V* obtained through the rstatix package (*Kassambara 2023*) helped to estimate the strength of the associations (*Carlson 2017*, 195–198). CA was performed in RStudio through the FactoMineR package (*Lê et al. 2008*) to summarise and visualise the relationships between categorical variables (*Carlson 2017*, 279). The conclusions of macroscopic analysis were compared with the results of interdisciplinary analyses. The comparison made it possible to investigate, for example, whether pottery made from ceramic fabrics of different compositions also varied similarly in other attributes.

# Results

## Macroscopic analysis

The most numerous material category (Mat) was represented by Mat3 (47.1 %), followed by Mat1 (32.4 %), Mat5 (14 %), Mat2 (3.7 %), and Mat4 (2.8 %). The proportion of inclusions (InMn) in ceramic fabrics ranged between 5–20 % (InMn2) in 57 % of the assemblage; it was higher than 20 % (InMn3) in 29.5 %, and lower than 5 % (InMn1) in 13.5 % of the assemblage. The fabric contained two types of visually distinguishable inclusions (InVar2) in 46.4 % of the assemblage, one or none (InVar1) in 45.5 %, and more than two (InVar3) in 8.1 %. Fabric did not contain visible inclusions in 2.4 % of the assemblage.

The variable Mat was positively correlated ($r^2 = 0.456$) with the variable InVar. Between Mat1 and Mat5, the frequency of the value InVar1 decreased, while the frequency of the values InVar2 and InVar3 increased (*Tab. 3*). The correlation between variables Mat and InMn was less significant ($r^2 = 0.297$). All material categories regularly appeared together with the value InMn2. In contrast, the value InMn1 occurred predominantly with values Mat1 and Mat2, while the value InMn3 was most characteristic of Mat5. The variables InMn and InVar were positively correlated ($r^2 = 0.368$). Frequency of the value InVar1 decreased with a higher proportion of inclusions, while the frequency of values InVar2 and InVar3 increased (*Tab. 4*). Based on the chi-square test and Cramér's *V* (*Tab. 5*), relatively strong relationships existed between the variables Mat, InMn, and InVar. Similarities and differences between material categories were confirmed by CA, particularly the distinction between Mat1 (mainly associated with the variables InMn1, Po1, and Po2) and Mat5 (InVar3). CA dimensions were also defined by the opposition of wheel-made and hand-made pottery (*Fig. 7*).

Wall thickness mostly varied between five and eight mm (46 %). Less frequently, pottery had walls thinner than five mm (22 %) or thicker than 10 mm (6 %). Wall thickness was not significantly correlated with material category ($r^2 = 0.194$) or with proportion ($r^2 = 0.208$) and variability of inclusions ($r^2 = 0.18$). Nevertheless, the value InMn1 was characteristic mainly of pottery with walls thinner than 6 mm.

Traces characteristic of hand-made or wheel-made pottery did not occur on 58 % of samples. The rest of the assemblage featured traces specific for hand-made (22.9 %) and wheel-made pottery (15 %) or traces linked with a combination of both methods (4.1 %). Pottery in all three groups was predominantly made from Mat3 but differed in the ratio of Mat1 and Mat5. The value Mat1 occurred more frequently in the second group and the value Mat5 in the first group. In the third group, the ratio was balanced (*Tab. 3*). Pottery in all three groups also usually contained 5–20 % of inclusions (InMn2). However, compared to the other two groups, the value InMn1 appeared less frequently in the first group (*Tab. 6*). The group of pottery with traces specific for wheel-made pottery then varied from the other two groups by higher frequency of the value InVar1 and lesser frequency of the values InVar2 and InVar3. Simultaneously, pottery with walls thinner than 6 mm belonged almost exclusively to the group of pottery with these traces.

The chi-square test and Cramér's *V* confirmed the existence of relationships between the pottery-forming traces and other variables. However, the general strength of the associations was only minimal (*Tab. 5*). Based on CA, the group of pottery with traces typical

Tab. 3. Relations between material categories and the variables InMn, InVar, Po, Vy, and traces left from the shaping process.

| | Mat1 | Mat2 | Mat3 | Mat4 | Mat5 | Total |
|---|---|---|---|---|---|---|
| InMn1 | 58 | 3 | 8 | 0 | 4 | **73** |
| InMn2 | 85 | 11 | 165 | 11 | 35 | **307** |
| InMn3 | 32 | 5 | 81 | 4 | 37 | **159** |
| InVar1 | 124 | 13 | 108 | 0 | 1 | **246** |
| InVar2 | 50 | 7 | 130 | 13 | 51 | **251** |
| InVar3 | 1 | 0 | 17 | 2 | 24 | **44** |
| Comb | 6 | 0 | 9 | 1 | 6 | **22** |
| Wheel | 35 | 1 | 38 | 2 | 5 | **81** |
| Hand | 24 | 2 | 66 | 1 | 31 | **124** |
| Po1 | 11 | 0 | 2 | 1 | 0 | **14** |
| Po2 | 33 | 2 | 11 | 2 | 5 | **53** |
| Po3 | 39 | 6 | 66 | 4 | 19 | **134** |
| Po4 | 37 | 3 | 65 | 3 | 25 | **133** |
| Po5 | 7 | 0 | 8 | 0 | 5 | **20** |
| Po6 | 26 | 8 | 57 | 3 | 9 | **103** |
| Po7 | 4 | 0 | 16 | 0 | 5 | **25** |
| Po8 | 12 | 1 | 19 | 2 | 7 | **41** |
| Po9 | 2 | 0 | 4 | 0 | 0 | **6** |
| Vy1 | 78 | 7 | 118 | 6 | 24 | **233** |
| Vy2 | 10 | 1 | 11 | 0 | 10 | **32** |
| Vy3 | 32 | 5 | 63 | 6 | 22 | **128** |
| Vy4 | 8 | 0 | 7 | 0 | 1 | **16** |
| Vy5 | 34 | 6 | 40 | 2 | 12 | **94** |
| Vy6 | 8 | 1 | 10 | 1 | 6 | **26** |
| Vy7 | 1 | 0 | 1 | 0 | 1 | **3** |

Tab. 4. Relations between the variables InMn and InVar.

| | InMn1 | InMn2 | InMn3 | Total |
|---|---|---|---|---|
| InVar1 | 64 | 145 | 35 | **244** |
| InVar2 | 9 | 141 | 101 | **251** |
| InVar3 | 0 | 21 | 23 | **44** |
| **Total** | **73** | **307** | **159** | **539** |

Tab. 5. Chi-square test: Relations between properties of pottery.

| Variables | χ2 | df | p-value | Cramér's V |
|---|---|---|---|---|
| Mat-InMn | 100.7 | 8 | <0.001 | 0.3056347 |
| Mat-InVar | 158.87 | 8 | <0.001 | 0.3831842 |
| InMn-InVar | 90.823 | 4 | <0.001 | 0.2902614 |
| Traces-Mat | 23.144 | 8 | 0.003184 | 0.2257826 |
| Traces-InMn | 15.355 | 4 | 0.004019 | 0.1839069 |
| Traces-InVar | 10.864 | 4 | 0.02814 | 0.1546903 |
| Po-Mat | 65.645 | 32 | 0.0004165 | 0.1761339 |
| Po-InMn | 132.54 | 16 | <0.001 | 0.3546179 |
| Po-InVar | 28.525 | 16 | 0.02734 | 0.1641997 |
| Po-Traces | 49.616 | 16 | <0.001 | 0.3335376 |
| Vy-Mat | 25.042 | 20 | **0.1998** | 0.1087862 |
| Vy-InMn | 20.028 | 10 | 0.02899 | 0.1378462 |
| Vy-InVar | 12.127 | 10 | **0.2767** | 0.1070598 |
| Vy-Traces | 13.895 | 10 | **0.1778** | 0.1757228 |
| Vy-Po | 62.594 | 40 | 0.01269 | 0.155309 |

|  | Comb | Wheel | Hand | Total |
|---|---|---|---|---|
| InMn1 | 4 | 19 | 7 | **30** |
| InMn2 | 14 | 43 | 76 | **133** |
| InMn3 | 4 | 19 | 41 | **64** |
| InVar1 | 5 | 43 | 42 | **90** |
| InVar2 | 15 | 34 | 70 | **119** |
| InVar3 | 2 | 4 | 12 | **18** |
| Po1 | 1 | 11 | 0 | **12** |
| Po2 | 2 | 19 | 7 | **28** |
| Po3 | 5 | 12 | 37 | **54** |
| Po4 | 4 | 12 | 38 | **54** |
| Po5 | 2 | 3 | 4 | **9** |
| Po6 | 5 | 17 | 17 | **39** |
| Po7 | 0 | 2 | 7 | **9** |
| Po8 | 3 | 3 | 9 | **15** |
| Po9 | 0 | 2 | 1 | **3** |
| Vy1 | 6 | 36 | 50 | **92** |
| Vy2 | 4 | 4 | 5 | **13** |
| Vy3 | 6 | 11 | 30 | **47** |
| Vy4 | 0 | 2 | 2 | **4** |
| Vy5 | 3 | 21 | 29 | **53** |
| Vy6 | 2 | 7 | 7 | **16** |
| Vy7 | 1 | 0 | 1 | **2** |

Tab. 6. Relations between traces left from the shaping process and the variables InMn, InVar, Po, and Vy.

for hand-made pottery differed significantly from the group with traces characteristic of wheel-made vessels both in material and surface treatment (*Fig. 7*). The group of pottery with traces linked with a combination of both methods varied from the other two groups as it was associated most prominently with the value Vy2. Dimensions were defined primarily by the opposition of the values Mat5, InMn3, InVar3, Po3, and Po4 (hand-made pottery), and the values Mat1, InMn1, InVar1, Po1, and Po2 (wheel-made pottery).

Types of surface treatment (Po) occurred in the following order: Po3 (25.3 %), Po4 (25.1 %), Po6 (19.5 %), Po2 (10 %), Po8 (7.8 %), Po7 (4.7 %), Po5 (3.9 %), Po1 (2.6 %) and Po9 (1.1 %). Only three ceramic fragments featured a surface coated with graphite. The surface Po1 appeared almost exclusively on pottery from Mat1. The type Po2 was also most characteristic for ceramics from Mat1 but occurred on pottery from other materials as well, including Mat5. In comparison, types Po3 and Po4 represented common surface treatments of pottery from all material categories. Likewise, types Po5 and Po6 were not specific for a single material category, while types Po7 and Po8 appeared slightly more often on pottery from Mat3–Mat5 (*Tab. 3*). The frequency of surfaces Po1 and Po2 significantly decreased with a higher proportion of inclusions. In contrast, the occurrence of type Po3 changed only minimally, and the frequency of type Po4 increased. Other types of surface treatment were mostly identified on pottery containing more than 5 % of inclusions. Pottery with distinct types of surface treatment did not differ significantly in the variability of inclusions (*Tab. 7*).

Pottery with traces specific for wheel-made vessels predominantly featured surface treatments Po2, Po6, Po3, Po4, and Po1. Pottery identified as hand-made typically had surface treatments Po4, Po3, Po6, and Po8. In the case of the last defined group, the most

| | Po1 | Po2 | Po3 | Po4 | Po5 | Po6 | Po7 | Po8 | Po9 | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| InMn1 | 9 | 26 | 21 | 9 | 1 | 1 | 0 | 2 | 1 | **70** |
| InMn2 | 5 | 15 | 80 | 76 | 7 | 69 | 16 | 28 | 4 | **300** |
| InMn3 | 0 | 11 | 32 | 48 | 12 | 33 | 9 | 11 | 1 | **157** |
| InVar1 | 10 | 34 | 62 | 49 | 6 | 45 | 9 | 18 | 6 | **239** |
| InVar2 | 3 | 17 | 62 | 72 | 13 | 46 | 14 | 20 | 0 | **247** |
| InVar3 | 1 | 2 | 10 | 12 | 1 | 12 | 2 | 3 | 0 | **43** |
| Vy1 | 6 | 19 | 61 | 54 | 9 | 54 | 12 | 13 | 0 | **228** |
| Vy2 | 1 | 1 | 9 | 7 | 3 | 3 | 1 | 6 | 0 | **31** |
| Vy3 | 0 | 10 | 33 | 39 | 2 | 19 | 7 | 16 | 2 | **128** |
| Vy4 | 0 | 1 | 2 | 3 | 1 | 6 | 0 | 0 | 1 | **14** |
| Vy5 | 6 | 16 | 20 | 21 | 4 | 14 | 5 | 4 | 3 | **93** |
| Vy6 | 1 | 3 | 8 | 6 | 1 | 5 | 0 | 1 | 0 | **25** |
| Vy7 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | **3** |

Tab. 7. Relations between surface treatment and the variables InMn, InVar, and Vy.

frequent surface treatments were represented by types Po3, Po6, Po4, and Po8 (*Tab. 6*). In comparison, the wall thickness of pottery with distinct types of surface treatments did not vary significantly, with the exception of type Po1, which was characteristic of vessels with walls thinner than 5 mm. The chi-square test and Cramér's *V* confirmed an association between the variable Po and other variables, particularly InMn and traces connectable with a shaping process (*Tab. 5*). During CA, types of surfaces Po7, Po4, Po8, Po5, and (less notably) Po3 were associated with different values than types Po2 and Po1. The type Po6 then varied from other types of surface treatment. In the first two dimensions, both groups were defined (in addition to properties of inclusions) by the opposition of hand-made and wheel-made pottery. This opposition was visible even on the biplot of the second and third dimension (*Fig. 8*).

Variants of the cross-section colouring (Vy) occurred in the following order: Vy1 (43.8 %), Vy3 (24.1 %), Vy5 (17.7 %), Vy2 (6 %), Vy6 (4.9 %), Vy4 (3 %), and Vy7 (0.6 %). Homogeneous types (Vy1 and Vy2) represented 49.9 % of the assemblage, double layered types (Vy3 and Vy4) 26.7 %, and multilayered symmetrical types (Vy5 and Vy6) 22.6 %. Simultaneously, types with a dark surface (Vy1, Vy4, and Vy5) were more frequent (64.5 %) than types with a light surface layer (Vy2, Vy4, and Vy6). The uneven transition of layers was visible on more than a third (33.6 % – 38.5 %) of pottery with colouring types Vy3, Vy5, and Vy6 and half of ceramics with the type Vy4. In comparison, uniformly thick layers were most characteristic of the type Vy3 (46.1 %), less for the types Vy6 (26.9 %) and Vy4 (25 %), and the least for the type Vy5 (16 %). At the same time, thick core and thin surface layers occurred more frequently with the type Vy5 (46.8 %) than the type Vy6 (23.1 %).

Frequency of colouring types with a dark surface (Vy1, Vy4, and Vy5) slightly decreased with higher material categories (*Tab. 3*). Differences in occurrence of these types (*Tab. 6*) were also found between pottery with traces connectable with wheel-made ceramics (72.8 %), hand-made ones (65.3 %), and a combination of both methods (40,9 %). In the case of surface treatments (*Tab. 7*), the frequency of types with a dark surface was as follows: 85.8 % (Po1), 72.5 % (Po6), 70.7 % (Po2), 70 % (Po5), 68 % (Po7), 66.7 % (Po9), 61.9 % (Po3), 60 % (Po4), and 42.5 % (Po8). Multilayered symmetrical types were then

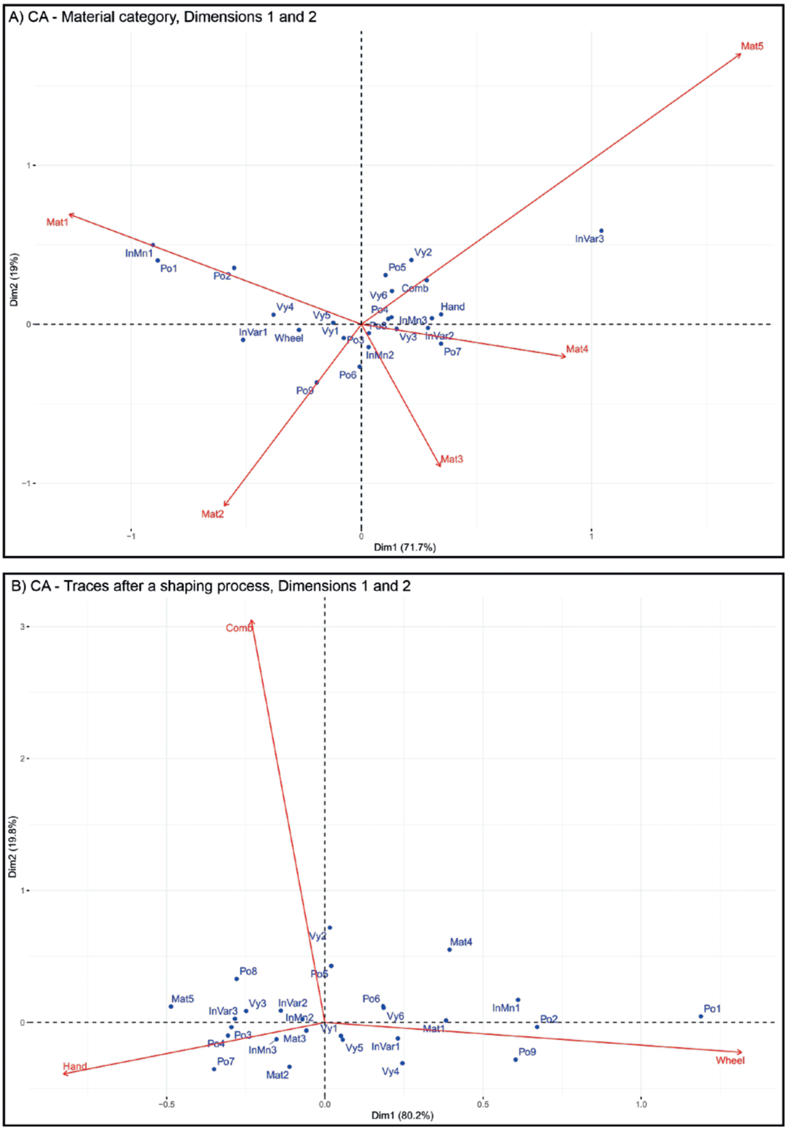

Fig. 7. Correspondence analysis: A – Relations between material categories and other attributes of pottery; B – Relations between traces of shaping process and other attributes of pottery.

characteristic for pottery with surfaces Po1 (50.3 %) and Po9 (50 %) and occurred only rarely together with type Po8 (12.5 %). Based on the chi-square test, the null hypothesis of independence between the variable Vy and other variables could be rejected only in the case of InMn and Po. The values of Cramér's *V* did not indicate strong relationships between the variables (*Tab. 5*). CA showed that differences primarily existed between groups of colouring with dark (Vy1, Vy4, Vy5) and light surfaces (Vy2, Vy3, Vy6). On the biplot of the second and third dimension, it was possible to observe differences between symmetrical multilayered types of colouring (Vy5, Vy6) and the type Vy3. Simultaneously, there was a similarity between homogeneous types of colouring (Vy1 and Vy2). (*Fig. 9*).

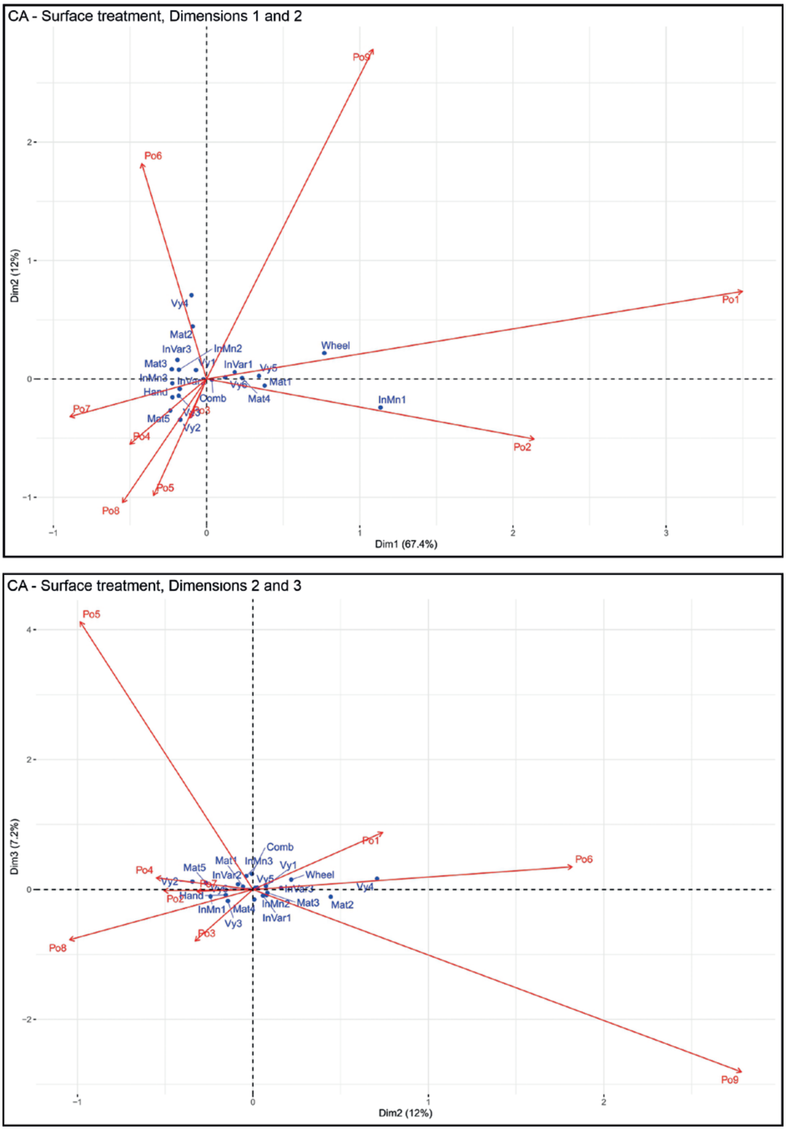

Fig. 8. Correspondence analysis: Relations between surface treatment and other attributes of pottery.

## Attributes of fabric groups

Four groups of fabrics could be identified based on the chemical composition and thin section analysis (*Online Supplementary Material 1*). Pottery in group A was made from fabric with a high content of mica and could be divided into four subgroups. The subgroup A1 (ID 5, 119, 416, 576, 594) was represented by pottery from different materials and with various surface treatments (Po2, Po7, Po9). Samples in the subgroup A2 varied in most of the attributes (ID 22, 99, 228). The subgroup A3 (ID 21, 50, 313, 493, 494, 577) consisted, with one exception (ID 313), of pottery made from the material category Mat5 with

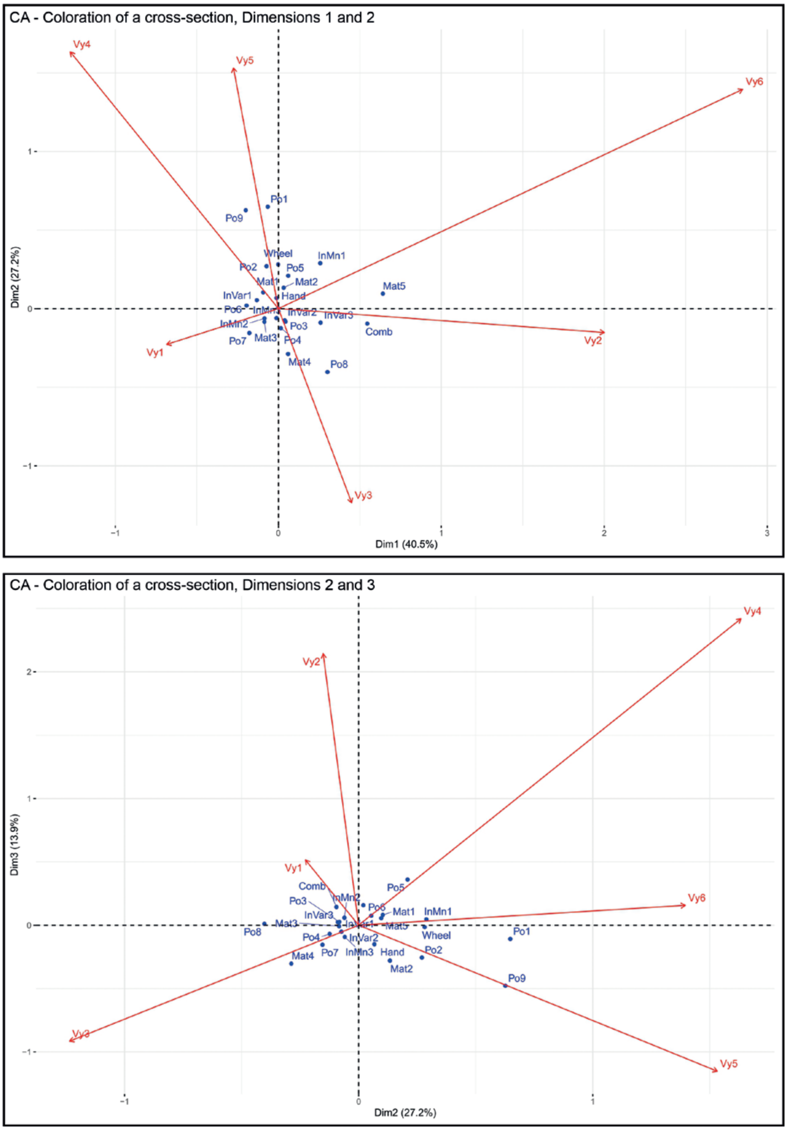

Fig. 9. Correspondence analysis: Relations between the colouration of a cross-section and other attributes of pottery.

surface treatments Po3, Po4, and Po8. The subgroup A4 (ID 19, 47, 70, 536) then contained only pottery with surface treatments Po6 (3x) and Po7 (1x). The group B (ID 46, 155, 217, 339, 587) was less variable than other groups and included one ceramic fragment with a surface coated with graphite (ID 339). Most pottery in the group featured surface treatments Po3 and Po4. Pottery in the group C (ID 6, 7, 257, 258, 534) had the identical surface treatment (Po6) but differed in other attributes. The group D (ID 98, 152) consisted of pottery with a high content of inclusions (InMn3), traces typical for hand-made pottery, and with the surface Po7. The chi-square test confirmed the existence of an association between fabric groups and the variable Po ($\chi^2 = 72.231$, df = 42, p = 0.002553, $V = 0.6443008$).

## Computed tomography

*Sample ID 6*

The sample comes from the torso of a bowl. On the tangential section, the orientation of the components was omnidirectional with irregularly shaped voids. On the radial section, the structure was oriented obliquely, rising from the inner to the outer surface. The vessel was probably constructed from thick coils transformed in the wall by pinching and drawing, which were attached asymmetrically to the outer upper edge of the constructed vessel.

*Sample ID 135*

The rim, neck, and upper body parts were preserved. On the tangential section, horizontal orientation in the neck area and omnidirectional in the body area were observed. On the radial section, the structure was oriented obliquely, rising from the inner to the outer surface. The neck of the vessel was made from a separate segment. The segment terminating the vessel body could be either a slab or a thicker coil transformed in the vessel wall. Oblique orientation on the radial section corresponded to asymmetric segment placement. Segments were joined to the outer part of the upper edge of the constructed vessel.

*Sample ID 258*

The lower body part of the vessel was preserved. Irregular voids prevailed in the tangential section. The segments could be a slab or a transformed thick coil. Omnidirectional irregular pores corresponded to the drawing technique. Drawing exerts shear stress on the wall and the intended consequence of this stress is plastic deformation. However, if this stress is excessive, it can cause the formation of cracks manifested as irregular voids, especially around aplastic inclusions.

*Sample ID 313*

The rim, neck, and upper body parts were preserved. The tangential section showed an alternation of omnidirectional and horizontally directed voids. The radial section showed an omnidirectional structure. Alternation of omnidirectional and horizontally directed structures corresponded to the use of thick transformed coils. A horizontal structure marked the area where the coils were joined. The omnidirectional structure represented the cores of the coils transformed by pinching and drawing.

*Sample ID 328*

The rim, neck, and body of the vessel were preserved. In both sections, a fluid structure with predominantly horizontal orientation on the TR could be observed. Joints between segments were detected and the vertical distance between them was about 15–20 mm.

*Sample ID 567*

The rim, neck, and upper body parts were preserved. Alternating horizontal and omnidirectional orientation on tangential sections and omnidirectional orientation on radial sections were observed along with the remnants of horizontal joints of perpendicularly attached segments. This undoubtedly pointed to the use of transformed thick coils; in this case, however, the coils were attached perpendicularly to the edge of the formed vessel.

## Ceramic petrography

Statistical analysis allowed to categorise the ceramics into four fabrics, labelled A–D (*Fig. 10*). Fabric A was the most extensive, and its chemical composition did not exhibit any significant specificity within the dataset. Fabric B exhibited the highest concentrations of Si and Ca. Fabric C was characterised by elevated levels of Al, K, Rb, Sr, As, and Pb. Fabric D displayed the highest metal contents, specifically Ti, Mn, Fe, and Ni. Subsequently, we presented petrographic descriptions of selected representatives for each fabric (*Online Supplementary Material 2*).

### *Fabric A*

It was characterised based on five samples (ID 47, 50, 99, 313, 576). This type of ceramic featured a very fine matrix (with aleuritic particle content ranging from 1 to 5 %). The matrix exhibited a lenticular microstructure. Non-plastic inclusions were very poorly sorted, with a bimodal size distribution. Larger inclusions accounted for 20–30 % of the volume and were typically single or double-spaced. Their predominant shape was elongated-equant and mostly subangular. In sample 313, some sandy grains were even round. The average porosity reached 5 % in all samples, with pores primarily taking the form of vughs.

Petrographically, fabric A was distinguished by its high content of mica flakes (*Fig. 11*: A). Muscovite was frequently to abundantly present, while biotite was common to abundant. The most prevalent mineral after mica was quartz (common to abundant). Feldspars occur occasionally, with both plagioclase and alkali feldspars having equal representation. Calcite was rare in samples 47 and 50. All samples contained trace amounts of amphibole and tourmaline. Other accessory minerals identified include glauconite (present in varying amounts from rare to common in samples 99, 313, 50, 47), garnet (traces in samples 99, 576; *Fig. 12*: A), pyroxene (traces in samples 50, 576), kyanite (rare in sample 576; *Fig. 12*: B), and epidote (traces in sample 99). Sample 50 contained trace amounts of microfossils.

Fragments of rocks were predominantly composed of gneiss and, except for sample 576, all samples included frequent to dominant two-mica gneiss grains (*Fig. 12*: C). This specific sample was distinctive for its inclusion of metaquartzite instead of gneiss, although these may represent quartz-rich portions of gneiss. Some gneiss fragments in other samples contained sillimanite (sample 99; *Fig. 12*: D) and kyanite (sample 576). Two samples (47, 50) contained occasional mica schist grains, which could be attributed to mica-rich portions of gneiss. Sample 47 included graphite metaquartzite in rare volume, and chert was identified in trace to scarce amount in two samples (samples 313, 50).

### *Fabric B*

It has been characterised based on two samples (ID 155, 217). Similar to fabric A, this group represented ceramics with a notably clay-rich matrix. The microstructure was unparallel. Non-plastic inclusions were very poorly sorted, exhibiting a bimodal size distribution. The psamitic fraction was less abundant, ranging from 10 to 20 % and resulting in the double or open spacing of grains. The predominant shape of these grains was nearly exclusively equant and varies from subrounded to rounded (*Fig. 11*: B). Pores appeared as vughs and planar features with varying volumes (5–15 %). The firing temperature was

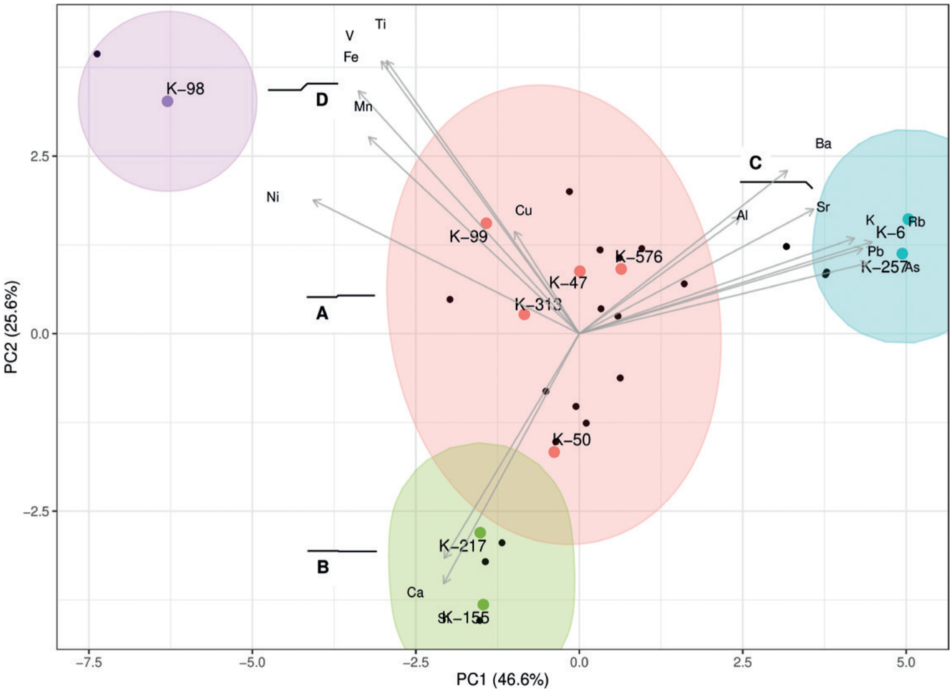

Fig. 10. Principal component analysis showing the relation of fabrics based on their chemical composition.

similar to fabric A, i.e., lower than 700 °C. However, in sample 217, green amphiboles were light brown-green, indicating a slightly higher temperature, possibly around 750 °C. It is considered a threshold after which green amphiboles start transitioning to brown and red hues (*Kiriatzi et al. 2011*; *Quinn 2013*). The matrix of sample 155 contained foraminifera microfossils.

Among the present mineral grains, quartz predominated as frequent to abundant, followed by common muscovite. Muscovite was significantly more abundant than biotite, which was found only in rare amounts. Calcite occurred in occasional to common volumes. Feldspars, both alkali and plagioclases, were present only in rare amounts. However, sample 155 contained common alkali feldspars. Accessory minerals were represented by amphiboles in trace amounts, as well as tourmaline and chlorite (*Fig. 12*: E). Fragments of rocks were not very common. Both samples contained metamorphic rocks in the form of gneiss (occasional in 155, rare in 217) and mica schist (rare in 155). Sample 217 contained chert in rare amounts.

### *Fabric C*

It was represented by samples ID 6 and 257. The group was characterised by a comparable representation of alkali feldspars to quartz, with both minerals being frequent to abundant (*Fig. 11*: C). Another distinctive feature was the presence of frequent biotite flakes. Plagioclases were occasional to common, while muscovite was rare to occasional. In sample 257, common amphibole grains were present, while sample 6 contained only

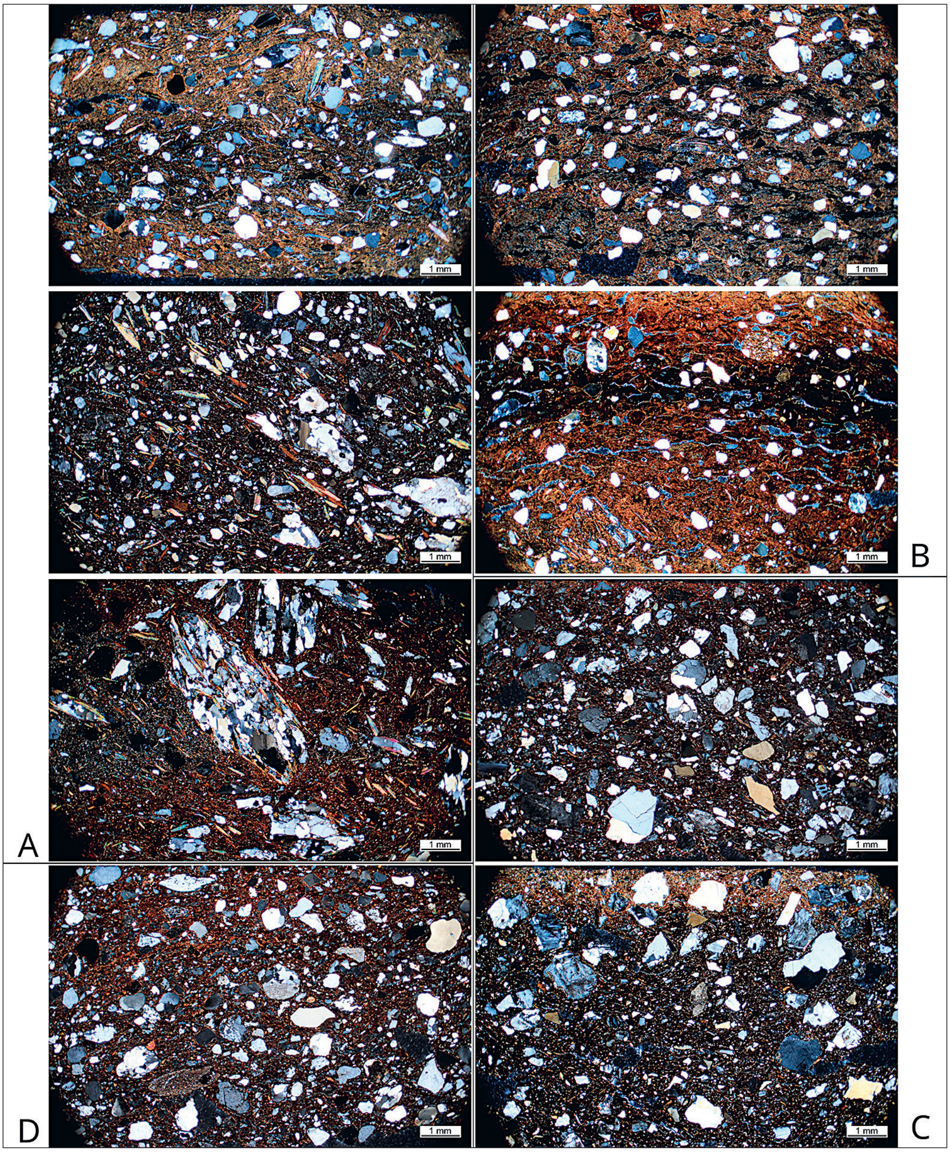

Fig. 11. Photomicrographs of samples demonstrating basic characteristics of each fabric: A – abundance of mica flakes and large fragments of metamorphic rocks in fabric A (IDs from top to bottom: 50, 313, 99); B – rounded quartz grains in fine-grained matrix of fabric B (155, 217); C – alkali-feldspar and quartz dominated temper in fabric C (257, 6); D – sand-tempered (quartz, feldspars among other various rock types) fabric D (98).

rare amounts. Pyroxene was identified in rare quantities only in sample 257 along with trace amounts of tourmaline.

Another specific attribute of this fabric was the abundance of granitoid rock fragments (*Fig. 12*: F). In sample 257, the predominant minerals in these granitoids were quartz,

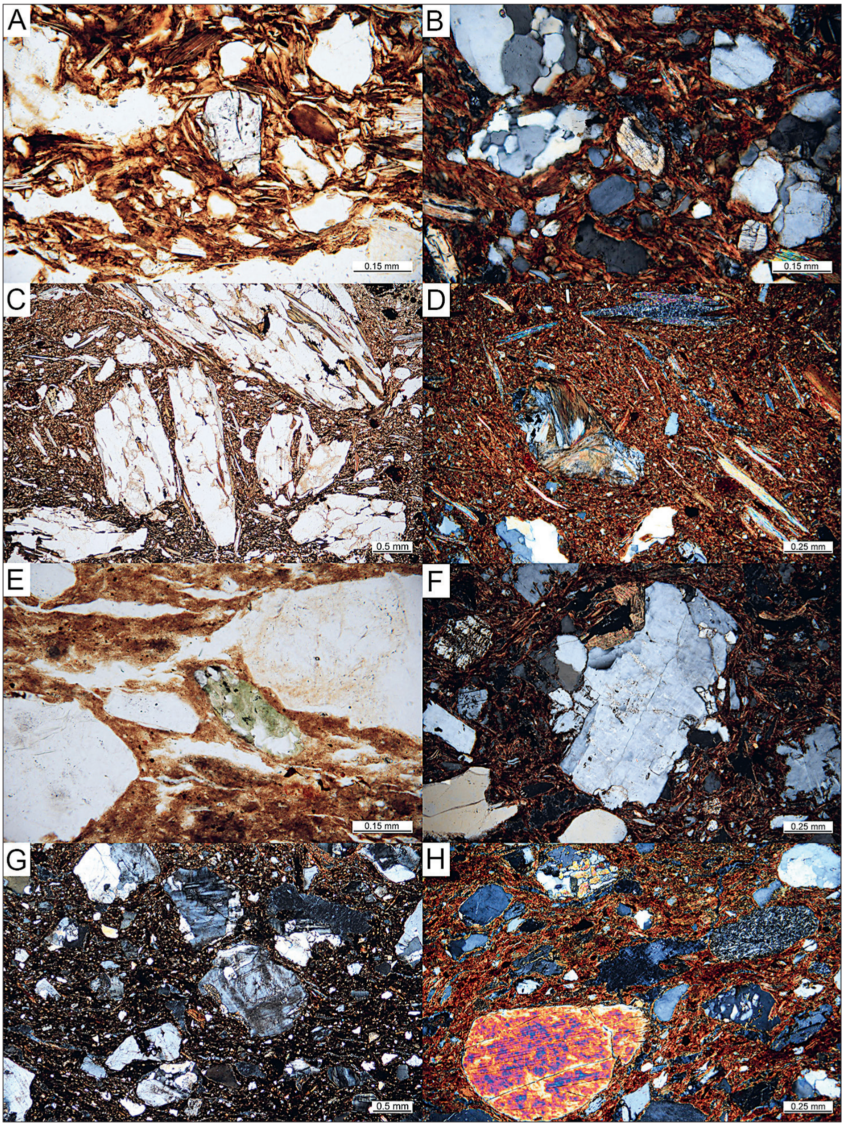

Fig. 12. Photomicrographs of important inclusions: A – colourless garnet grain in mica-rich matrix (ID 576, fabric A); B – kyanite next to polycrystalline quartz, alkali feldspars, and micas (ID 576, fabric A); C – large fragments of two mica gneiss (ID 99, fabric A); D – sillimanite gneiss next to muscovite and biotite flakes (ID 99, fabric A); E – detail of chlorite (ID 155, fabric B); F – biotite granite fragment (ID 6, fabric C); G – alkali feldspar grains (ID 6, fabric C); H – amphibole grain (bottom left) next to accumulation of epidotes (top) and an elongated fragment of unspecified volcanic rock (top right; ID 98, fabric D).

followed by alkali feldspars (*Fig. 12*: G), biotite, and plagioclases in order of their abundance. In contrast, in sample 6, alkali feldspars predominated in these fragments, with quartz being less common, and muscovite was also present. Sample 257 also contained unspecified weathered grain of clastic sedimentary rock.

*Fabric D*

It was described based on a single sample (ID 98). This sample exhibited a weakly parallel microstructure. Non-plastic inclusions were very poorly sorted, with a bimodal grain size distribution. Aleuritic particles made up 5 % of the volume, while psamitic grains constituted 20 %. These grains were spaced at double intervals and were elongated to equant with a subrounded shape. Pores were predominantly vughs and planar, accounting for 10 % of the sample. Biotite flakes exhibited a medium degree of pleochroism. Green amphibole pleochroism ranged from light green to brownish-green, thus the estimated firing temperature is in the range of 700–800 °C.

The minerals present in the sample included abundant quartz grains, frequent alkali feldspars, common biotite, and rare muscovite (*Fig. 11*: D). Accessory minerals were represented by common amphiboles, occasional epidote, and trace amounts of tourmaline (*Fig. 12*: H). Fragments of various rock types were present in the sample, including clastic sediments, granitoids, metamorphic rocks, and volcanic rocks. Clastic sediments were represented by sandstone with iron-rich cement in occasional amounts. Occasional granitoid fragments consisted of granite, with minerals quartz, alkali feldspars, and plagioclases being the most abundant. Occasional metamorphic rocks included phyllites and an unspecified rock composed of amphiboles, quartz, and pyroxenes. Fragments of unspecified volcanic rocks were rare in the sample.

## Discussion

Ceramic fabrics identified in the assemblage varied in percentage and the sorting of inclusions. Certain types of materials were preferred for the production of pottery with traces typical for wheel-made or hand-made ceramics, while other types could be seen as universal variants. Likewise, these categories of pottery differed in surface treatment. For example, wheel-made pottery from fine material often had a highly smoothed (Po2) or polished surface (Po1), while the surface of hand-made pottery was usually just unevenly smoothed (Po3) or roughened. Pottery formed by a combination of both methods evinced similar surface treatment to hand-made pottery but varied in properties of material. The variability of the firing process was also connected with the properties of pottery, including surface treatment.

One of the ceramic categories was particularly pronounced: pottery made from Mat1 with a low proportion (InMn1) and variability of inclusions (InVar1) and with traces typical for wheel-made ceramics, walls thinner than 6 mm, and a dark surface. Its surface was often polished (Po1) or smoothed (Po2). However, none of these attributes were specific only for this group. Furthermore, the assemblage also contained solitary fragments of pottery with traits which were otherwise mutually exclusive. An example of the high variability of the assemblage could be found in the firing process. Certain types of pottery featured the dark surface more frequently and differed in the occurrence of homogeneous, two-layered, and multilayered variants of colouring. However, even the firing of wheel-made pottery from fine material and with a polished or smoothed surface was not completely identical. Likewise, variability existed in the transition of layers of individual colouring types (Vy). This could point to differences in the process of firing.

Results of the macroscopic analysis showed preferences for certain ceramic fabrics and techniques for the production of specific groups of vessels, but it was possible to observe various irregularities. Based on this, we may conclude that the production of pottery was not completely consistent and not always uniformly repeated; not only samples with traces typical for hand-made pottery, but also samples with traces characteristic of wheel-made pottery varied in its attributes. A relatively uniform group was represented by pottery without visible inclusions, which always had a wall thickness up to 6 mm and evinced only traces linked with wheel-made pottery. Still, ceramic specimens in this group differed in surface treatment (4x Po1, 5x Po2, 2x Po3, 2x Po4) and also in the firing process (5x Vy1, 1x Vy2, 1x Vy3, 1x Vy4, 2x Vy5, 2x Vy6).

Compared to ceramics from the previous phases of the Late La Tène period (*Venclová et al. 1998*, 150–151, 166–167; *2008a*, 98–101), fine pottery from Křinec was not uniform in its attributes. Simultaneously, the frequency of pottery made of material without visible inclusions was significantly lower (2.4 %) than, for example, in the assemblage from the oppidum in České Lhotice (32 %) or the settlement in Slepotice (14.8 %) in Eastern Bohemia (*Danielisová 2010*, 67; *Joštová 2020*, 57). The occurrence of pottery with traces characteristic of wheel-made vessels in Křinec did not differ from other settlements from the Late La Tène period in Bohemia (*Venclová 2008b*, 186–187; *Danielisová 2010*, 65–66; *Salač – Kubálek 2015*, 90). However, in the assemblage from Křinec, traces linked with hand-made vessels could be found even on pottery from Mat1 and Mat2. This contrasts with other assemblages from Central and Eastern Bohemia, including the assemblage from Týnec nad Labem, which did not contain hand-made fine pottery (*Thér et al. 2015*, 14; *Thér – Mangel 2024*, 16, 22).

Additional information regarding shaping techniques was obtained by computed tomography. During the macroscopic analysis, three (ID 6, 313, 567) out of six samples had traces typical for wheel-made pottery and two samples (ID 135, 328) had traces linked to a combination of both methods. Nevertheless, computed tomography showed that all six samples were formed by hand, mostly from thick coils transformed by pinching and drawing. This conclusion was supported by optical microscopy as none of the samples exhibited features typical for wheel-thrown pottery and the microstructure was mostly unparallel or lenticular. Also, the mica flakes, a good indicator of particle orientation, showed no systematic orientation. Consequently, it could be assumed that the majority of pottery from Křinec was formed by hand. In general, the computed tomography revealed that macroscopic analysis has only indicative information value for the reconstruction of the shaping process. Nevertheless, statistical analysis showed differences between groups of pottery with distinct traces, which can still be considered as signs of differences in the shaping process.

Similar to various other ceramic assemblages from the Late La Tène period in Central and Eastern Bohemia, the most common type of roughened surface of pottery from Křinec was the grated surface (Po6). Unlike these assemblages, Křinec revealed mainly the pottery with a minimally treated surface (Po3 and Po4), while the polished surface (Po1) was almost absent (*Venclová et al. 1998*, 151, 153; *2008b*, 188, 190; *Danielisová 2010*, 76). In terms of the high frequency of the untreated and low frequency of the polished surface, the assemblage from Křinec was similar to, for example, the pottery from the settlement in Slepotice (*Joštová 2020*, 78–82). Compared to other sites from the Late La Tène period in Central and Eastern Bohemia, pottery from Křinec also differed in the variability of its colouring. Even the group of fine pottery (Mat1, Mat2) did not feature identical colouring (*Beneš et al. 2018*, 204–205; *Thér et al. 2015*, 120; *Joštová 2020*, 58–61).

Comparison of the results of macroscopic analysis and X-ray fluorescence analysis did not show a significant connection between the chemical composition of the ceramic fabric and other attributes of pottery. Differently formed and fired vessels did not necessarily vary in the sources of clay used. The clay source did not differ even between fine (Mat1–Mat2) and coarse pottery (Mat3–Mat5). A similar situation was observed in Eastern Bohemia. However, unlike there, the clay of the pottery from Křinec came from multiple sources (*Thér et al. 2015*, 102–103). Fabric groups varied mainly in the occurrences of surface treatments, specifically the roughened types Po6 and Po7. Observed variance might be related to the distinct provenance of pottery (*Venclová 2008a*, 99–102). Likewise, characteristics of inclusions could be connected with local traditions of pottery production (*Thér et al. 2015*, 133). Fabric groups did not differ in estimated firing temperature. In comparison, pottery from the settlement from the stages LT B2/C1 – D2 in Nitra – Mikov Dvor in Slovakia varied in the firing temperature independently on fabric groups (*Gregor – Březinová 2012*).

## Provenance

None of the identified fabrics appear to correspond to the geological setting of the Křinec site located in the Bohemian Cretaceous Basin. The expected petrographic composition of locally produced pottery would primarily include sandstone, siltstone, or marlite grains with quartz as the dominant mineral. Other minerals would be less common, with a significant presence of glauconite among the accessory minerals. It is worth noting that glauconite was exclusively identified in fabric A, but the rest of the petrographic description does not align with local origin. The bimodal distribution of non-plastic components suggests intentional tampering of the ceramic clay. The presence of subrounded grains (except for fabric B, where grains are equant and subrounded-rounded) indicates some degree of transport by natural agents. This could potentially be associated with alluvial sediments.

The samples of fabric A were found to be rich in micas and contained fragments of gneiss, some of which included minerals like kyanite and sillimanite. These minerals are not common and can be diagnostic in terms of provenance. Glauconite, calcite, and microfossils contained in the pottery do not provide any additional aid in the search for material provenance given the fact that they occur naturally in the large region of the Bohemian Cretaceous Basin. However, kyanite and sillimanite are minerals typical for metamorphosed aluminum-rich pelitic rocks such as gneiss. They can also occur in pegmatites. Regarding the possible sources of these rocks, the two closest regions can be considered. The first is the Kutná Hora Crystalline Complex situated 25 km to the south and southwest. The second are the metamorphosed Proterozoic rocks of the Iron Mountains approximately 30 km to the southeast.

The Kutná Hora Crystalline Complex forms the bedrock in the strip from Plaňany in the northwest to Kolín in the southeast. Migmatites belonging to this complex contain muscovite, biotite, sillimanite, garnet, and kyanite. Unconsolidated sediments of river terraces in the form of sand and gravel from the lower Pleistocene in the vicinity of Dobřichov and Cerhenice and it has been confirmed that they contain a significant proportion of gneiss, phyllites, and granitoids. The heavy mineral fraction in these sediments includes not only common minerals but also garnet and green amphiboles (*Adamovič et al. 1993*). Several settlements from the Late La Tène period are known from this area and its surroundings, including the site in Cerhýnky (*Fig. 2*: 4; *Fig. 3*: 4), where a pottery kiln was found

(*Rybová 1968*, 9–10; *Waldhauser 2001*, 173). La Tène pottery kilns were also excavated west of Kolín (*Malyková 2014*) in Štítary u Kolína (*Fig. 2*: 5; *Fig. 3*: 5).

As mentioned above, the second possible source could be the metamorphosed rocks of the Chvaletice Proterozoic in the Iron Mountains region. These rocks have a similar mica content, and they also include garnet and kyanite (*Fediuk 1981*). However, there is no documented occurrence of sillimanite in them. Sillimanite could have been part of the fluvial sands of the Doubrava River and its tributaries. The site of Týnec nad Labem represents a prominent settlement within the area (*Fig. 2*: 2; *Fig. 3*: 2).

The petrography of fabric B is less specific compared to the previous group, but it can be generally characterised as similar to fabric A in terms of the increased content of muscovite and the presence of metamorphic rocks. Additionally, it contains chlorite and slightly more calcite. Nevertheless, the origin of the raw material, especially the temper, could be associated with the suggested sources.

Fabric C is defined by a significant content of alkali feldspars and biotite, which are derived from granitoids where these two rock-forming minerals (along with quartz) prevail over others. This description aligns with the granites of the Chvaletice Massif, which constitute the magmatic core of the Iron Mountains region (*Beneš et al. 1963*). The nearest occurrence of these granites is located less than 30 km southeast of the studied site. Another possible source could be the Říčany Granite of the Central Bohemian Pluton, which is situated 35 km to the southeast (*Janoušek et al. 2014*).

Fabric D differs from the others in its higher content of epidote and amphiboles. It is characterised by a notable frequency of alkali feldspar grains and an increased portion of plagioclases. Biotite predominates over muscovite. This mineral assemblage could also correspond to the magmatic rocks of the Chvaletice Massif, which include not only granites but also gabbro. The presence of epidote indicates a certain degree of metamorphism. Therefore, the source rocks for this fabric could combine gabbro, possibly granites, and metamorphic rocks of the Chvaletice Proterozoic.

Distribution of materials used as a temper over greater distances was also documented in Eastern Bohemia (*Thér et al. 2015*, 103–111). In comparison, the ceramic clay used in Nitra – Mikov Dvor mostly originated in the area surrounding the settlement (*Gregor – Březinová 2012*).

## Conclusions

In general, pottery from Křinec was partially similar (for example in surface treatment) to assemblages from the previous phases of the Late La Tène period in Central and Eastern Bohemia. However, it differed in the higher variability of its properties. Even the group of pottery made from fine material was not homogeneous and varied, for example, in the process of firing. Considering these results, pottery in the assemblage from Křinec could originate from several sites, which differed in the production of pottery. Simultaneously, none of the fabrics were specific only for a certain category of ceramic vessels. The acquired data point to the possibility that at the end of the La Tène period contacts between settlements in the region included the transportation of ceramic vessels or raw material, but potters from different communities did not share knowledge about pottery production. However, to confirm or reject this hypothesis, it would be necessary to examine more local assemblages from the Late La Tène period.

The ceramic materials from the Křinec settlement, embedded in the Bohemian Cretaceous Basin, show no geological alignment with the local setting, hinting at a non-local origin. The study reveals distinct characteristics in the ceramic fabrics (A, B, C, and D). Fabric A, with gneiss containing kyanite and sillimanite, likely originates from the Kutná Hora Crystalline Complex or the metamorphosed Proterozoic rocks of the Iron Mountains. Fabric B is similar to A but varies in mineral mix. Fabric C is composed of alkali feldspars and biotite, which suggests a source in the granites of the Chvaletice Massif or the Říčany Granite. Fabric D, with content of epidote and amphibole, points to a composite origin from gabbro, granites, and metamorphic rocks of the Chvaletice Proterozoic. All proposed sources located no closer than 25 km from the studied site are indicators of a socio-economic network with a potential centre in Týnec nad Labem or near Kolín.

The pottery from Křinec should be compared with Late La Tène assemblages from other parts of Bohemia in order to obtain data on regional differences in production and distribution of pottery during this period.

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