Pottery firing in the Early Iron Age in western Slovenia

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ABSTRACT – *The article discusses the possible use of kilns for the firing of pottery in western Slovenia during the Early Iron Age. In the absence of archaeologically attested kilns, their use in this area is studied based on indirect factors,* i.e. *the analysis of the vessel firing technique, and with the help of experiments from the field of experimental archaeology. The article strives to determine the reasons for the poor state of preservation of the kilns in the area in question. Samples from archaeological experiments and archaeological pottery were subjected to AMS measurements, petrographic and mineralogical analyses (X-ray diffraction), which revealed the importance of considering the soaking time as a criterion for observing the firing processes and use of single-chamber kilns for the firing of pottery, even if they have not yet been discovered.*

KEY WORDS – *pottery; firing process; experimental archaeology; pottery kiln; ceramic technology; apparent magnetic susceptibility AMS; X-ray diffraction XRD; Early Iron Age; Kras; Slovenia*

Žganje lončenine v starejši železni dobi v zahodni Sloveniji

IZVLEČEK – *V članku obravnavamo potencialno rabo peči za žganje keramike v zahodni Sloveniji v starejši železni dobi. Ker arheološko še niso bile izkopane, je njihova uporaba predvidena na podlagi posrednih kazalnikov, kot so način žganja in poskusi s področja arheologije poskusov. Namen raziskave je prepoznati razloge za slabo ohranjenost peči na tem območju. Na vzorcih, ki smo jih pridobili iz arheoloških poskusov in na arheološki keramiki, smo merili navidezno magnetno susceptibilnost, izvedli petrografske in mineraloške (rentgenska difrakcija) analize. Rezultati teh analiz so pokazali na pomembnost upoštevanja časa žganja kot merila pri opazovanju žgalnega procesa in uporabi enoprostornih peči za žganje keramike, čeprav še niso bile odkrite.*

KLJUČNE BESEDE – *keramika; proces žganja; arheologija poskusov; peč za žganje keramike; tehnologija; navidezna magnetna susceptibilnost; rentgenska difrakcija XRD, starejša železna doba; Kras; Slovenija*

Introduction

How was pottery fired in the Early Iron Age in what is today western Slovenia? Can we assume the use of kilns despite their absence? On the territory of present-day Italy, two-part updraft kilns with a separate fireplace and firing chamber were known in this period, while on the territory of Slovenia they appear no sooner than in the Late Iron Age. We assume that the preservation of such structures in the discussed areas depends on various factors, so we will show the possible reasons for the poor preservation of these based on the results of experimental archaeology. Through macro- and microscopic analyses of

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the pottery and samples from archaeological experiments, we will try to reveal the features of the pottery associated with the firing process, which will indirectly help us identify structures for the firing of pottery.

Firing is one of the most important steps in pottery production, as it involves the transformation of clay into ceramics. Due to the complexity of the production process of pottery vessels, from the raw material to the final product, the concept of the ceramic *chaîne opératoire* has recently developed in ceramic analysis (*Lemonnier 1993; Roux 2016.104–107*). Based on such observations, we try to identify technological traditions and patterns of certain technical traits (*cf. Roux 2016.104, 112*). By including the ceramic *chaîne opératoire* approach, ceramic experimental archaeology has gained a more solid methodology (*Jeffra 2015. 141*), but only if when the principle of so-called controlled comparison is considered (*Roux 2016. 7*). Until the advent of experimental archaeology and scientific analyses, the process of pottery firing was actually the least known technological process in the ceramic *chaîne opératoire* (*Rado 1988.92*). We will attempt to answer the question of what type of structures were used for firing pottery in western Slovenia in the Early Iron Age by integrating data from the macroscopic and microscopic analyses of the pottery mass and firing technology. The data will be acquired from experimental archaeology, measurements of apparent magnetic susceptibility (AMS), and with the results of mineralogical analyses (X-ray diffraction).

The firing process

In the past, people had to rely on personal experience with firing, which in practice probably meant conducting numerous successful and unsuccessful experiments, as evidenced by the considerable overfired vessel waste at archaeological sites (*Cuomo di Caprio 1985.130*). Today, laboratory and archaeological experiments are carried out, adding significantly to the knowledge and, above all, to the understanding of technological processes, which are usually different under controlled laboratory conditions (*cf. Thér 2014.96*).

After clay transforms into ceramics during the firing process (*Cuomo di Caprio 1985.125*), a series of chemical and physical reactions occur affecting the hardness, permeability, porosity, and mineral composition of the final product. The products become impermeable, change colour, and lustre (*Heimann 1978–1979.79, 82*), and become hard and resistant to decay (*Rice 2005.55, 80*). The colour change is related to the presence or absence of iron minerals (chlorites, micas, Fe-oxides/hydroxides, sulphides) in the clay. In the are discussed in this study the clays are very rich in iron, which usually causes the vessels to turn red (oxidation atmosphere) or grey and black (reduction atmosphere) (*cf. Maritan 2018. 206*). The colour can also be affected by the presence of organic material, which converts to carbon and oxidizes into CO_2 in the presence of sufficient oxygen. This change occurs at a temperature of about 800°C and can be recognized by a change in colour (grey/dark grey when carbon is present and cream/reddish when carbon is oxidized) (*Gliozzo 2020.26*).

During firing, structural changes also occur in the minerals in the clay (*Cuomo di Caprio 1985.130; Levi 2010.112*). The thermal stability of the mineral phase and the changes induced by heat depend on numerous factors, such as grain size, the mineralogical and chemical composition of inclusions and temper, presence of aplastic inclusions, presence of organic material, position in the vessel, the position of the vessel in the kiln, the soaking time, and cooling (*Gliozzo 2020.5*).

What changes occur during the firing process and which of them are relevant for the pottery of the discussed area? Hydration begins at different temperatures, depending on the heating and the type of clay minerals (*e.g.*, illite 300–600°C), but the mixing of clays can lower it (*Rice 2005.87–88*). Carbon oxidation of carbon starts at 200°C and burns out completely between 600 and 750°C or at least just below 800°C (*Cuomo di Caprio 1985.131; Levi 2010. 121; Gliozzo 2020.26*). Experiments showed that the main loss of organic material (the use of barley straw) in daub and kilns occurs between 200 and 300°C, with the final loss at about 400°C (*Macphail, Goldberg 2018.235*). Between 675 and 870°C, calcite decomposes completely into calcium oxide, with cell volume decreasing and crystal size increasing (*Gliozzo 2020.6*). Above 800°C, complex aluminosilicates form and the phase of sintering begins (*Levi 2010.121*), which is lower for carbonate clay (around 800°C). Hence, we cannot develop a unified phase diagram for the firing process (*Gliozzo 2020.5*). The presence of calcium carbonate contributes to a lower sintering temperature because lime acts as a flux, causing vessels with admixed calcium carbonate to sinter faster (*Maggetti* et al. *1984; Shoval 2016.12*). In highly processed deposits, a fired mineral is present as rubefied mineral inclusions ranging in size from silt to sand-size. The presence of these materials provides increased magnetic susceptibility, whereas iron-free minerals are not rubefied and therefore magnetic susceptibility is naturally high (*Macphail, Goldberg 2018.235*).

Iron oxides were frequently used for coatings, especially for the so-called *ceramica zonata*, which is typical for the Early Iron Age in a large area, ranging from northern Italy (Este, Padua) to Slovenia. Examples of so-called ceramic *situlae* from Slovenia are mostly considered imports (*cf. Grahek 2018. 315*). Red slips are also typical of other vessel types (*e.g.*, Dolenjska region in south-eastern Slovenia; *Dular 1982.90*). Iron oxide haematite (Fe_2O_3) provides a red or reddish colour, while magnetite (Fe_3O_4) provides grey, blue, green, and grey-brown colours, and in the reduction, black (*Heimann 1978–1979. 86; Rice 2005.334–336*).

The firing atmosphere controls the partial pressure of oxygen, which is higher in the oxidizing atmosphere. By leading the firing, we change the firing phases (*Heimann 1978–1979.86*). In an oxidizing atmosphere, complete firing occurs. We need dry firewood and an air supply to achieve the combustion of organic matter and the decomposition of sulfides if the latter is present. In a reduction atmosphere, incomplete firing happens. We close the air supply and pile organic material into the kiln (*e.g.*, horse hooves, straw, *etc.*), which may be slightly moist (*Cuomo di Caprio 1985.126, 131*).

In prehistory, different structures for firing pottery were known. The basic division is into firing in the open (bonfire) and firing in a kiln. In a bonfire, the maximum temperature is reached quickly (approx. 10–50 minutes, usually 20–30 minutes), while firing in a kiln takes longer (approx. 60 minutes to 11–12 hours). In a bonfire, the soaking time at maximum temperature is shorter (a few minutes) than in a kiln (up to 30 minutes). Oxidative and reductive atmospheres can be achieved in both, yet the latter is much more controlled in two-chamber kilns with a perforated floor, especially the exchange. Cooling takes less time in a bonfire (a few minutes to 1 hour), while it is slower in the kiln (1–4 days), and firing in a bonfire also takes less time than firing in the kiln (*Gliozzo 2020.2–3*).

Any natural clay type can be fired at low temperatures, *i.e.* below 800°C, but the lowest possible temperature for firing pottery is 500°C (*Rye 1981. 16, 96*). The data shows that prehistoric pottery was mostly fired between 550 and 650°C or at the most up to 750–850°C. Analyses from the field of experimental archaeology generally reveal that temperatures of 950°C and even 1100°C could be reached in the kilns known in the Neolithic (*Kovárník 1999. 315–317*). Nevertheless, it was found that the soaking time is of greater importance than the maximum firing temperature (*Gosselain 1992.244, Fig. 1*). Furthermore, it was also found that the temperature of the core of the vessel burned in a bonfire is not unified and that a temperature difference occurs between the outer surface and the fracture up to 220°C. The latter was also confirmed in the example of vessels fired in a kiln (*Maggetti* et al. *2011; Gliozzo 2020.4*). Consequently, it is necessary to examine the question of which part of the pottery production is associated with a particular firing structure (*Thér 2014.78*) or which forms or types of vessels were fired in which structure (*Gliozzo 2020. 27*). Based on 72 archaeological experiments, Richard Thér (*2014*) showed that there are no differences between firing structures at temperatures up to 1050°C when thermal profiles are observed and that the firing method is more important than the firing structure (*Thér 2014.79–80, 93*). Later, he tried to find out if it was possible to distinguish between products fired in a bonfire and those fired in a kiln by observing the thermal gradient of maximum temperature (XRD analyses) in the core of the vessel and in the outer and inner surfaces. He discovered that the difference between the maximum temperature between the outer surface and the core was 100–200°C when fired in a bonfire, and between 0 and 50°C when fired in a kiln (*Thér* et al. *2018.1144–1145, 1169*). This means that we have finally found a way to distinguish firing in bonfire from firing in a kiln.

Archaeological background

In general, only a few pottery firing structures from the Bronze and Iron Ages have been found in the area of present-day Slovenia. Until the end of the Early Iron Age, only single-chamber kilns are known (*e.g.*, Oloris near Dolnji Lakoš from the Late Bronze Age, Dobrava near Otočec (*Horvat Šavel 1988–1989. 130–131; Dular* et al. *2002.37, T. 24–25; Josipović* et al. *2015.16, Figs. 11–12*). While a two-chamber kiln with a perforated floor was found at the Late Iron Age site Hajdina at Ptuj (*Tomanič Jevremov, Guštin 1996.271, Fig. 4*). Generally, two-chamber kilns were used much earlier, as they appear individually in Italy no later than in the Middle Bronze Age (*Bronzo recente*), while their use increases in the Early Iron Age[1] (*Levi 2010.117*). To date, no firing structures have been found in western Slovenia. All the consumptions in the literature are still based on indirect data, on the macroscopic analysis of the technology of pottery firing from three hillforts in the Kras, Tabor near Vrabče, Tomaj, and Štanjel (Fig. 1). In addition to stratigraphic data, also radiocarbon dates are also available (*Vinazza 2021.430–433, Fig. 5*). The Tabor site near Vrabče belongs to the transition from Late Bronze to Early Iron Age (Phase 1; 11.–10. cent. BC) and Early Iron Age (Phase 2; 8.–7. cent. BC). The Tomaj site belongs to the Early Iron Age (6.–5. cent. BC) and Štanjel belongs to the end of Early Iron Age (6th and 5th cent. BC). The macroscopic analysis indicated that at the end of the Late Bronze Age (Ha A2/B1) the majority of pottery was fired in a reduction atmosphere (*e.g.*, Tabor near Vrabče 38.2%). In the 8th and 7th cent. BC (Ha C0–C2) the ratio begins to change as less and less reductive firing take place, only 4.8% at Tabor near Vrabče and 25% at Tomaj. This trend continues until the end of the Early Iron Age, as shown by the analysis of pottery from Štanjel (7.1–23.9%). It should be emphasized that incomplete oxidation firing predominates throughout at all the sites, with the proportion of oxidation firing increasing only at the end of the Early Iron Age in the case of Štanjel (38.7%) (*ibid*. Tab. 3). Changes are also observed in the preparation of the pottery paste. The macroscopic analysis of pottery mass confirms the findings in the wider area of north-eastern Italy and western Slovenia, as a temper of calcite prevails at the end of the Early Iron Age, while pottery is more frequently fired in oxidation atmosphere (*Saracino 2014.104–122, 131–132; Grahek 2018.311; cf. Vinazza 2021.433, Fig. 1*).

Certain sites in Kras and in the Posočje region[2] revealed individual examples of the so-called red-black painted pottery (Este style, Ita. *ceramica zonata*). Case analyses from Posočje region, from Most na Soči, showed the presence of iron and manganese to achieve the red and black colour of coating on the pottery (*Grahek 2018.313–314*). This final colour effect is the result of the so-called *three-stage firing* (ORO), in which oxidation and reduction firing

Fig. 1. Sites mentioned in the text (© Google Earth Pro).

1 Ponte San Marco (*Poggiani Keller 1994.76*), Forcello di Bagnolo S. Vito (*Rapi* et al. *2019.107*), Montedoro di Scapezzano, Matelica (Macerata), Marche, Cesena, Foro Annonario (*Gasparini, Miari 2017.24*), Padova, Ex Brolo (*Iaia, Moroni Lanfredini 2009.65, 68, 70*).

2 Repentabor (7th and 6th cent. BC) (*Maselli Scotti 1978–1981.Fig. 9.1*); Repnič from the 7th and 6th cent. BC (*Maselli Scotti 1983.T. 54, 214*), Štanjel (*Vinazza 2011.T. 9.103*), and Most na Soči (*Grahek, Košir 2018.315*).

atmospheres exchange (*cf. Aloupi-Siotis 2020.3, 5*). This is made possible by the two-chamber kilns with a separated fireplace and firing parts, which have been already mentioned several times before. One of the most important parts of such kilns is the perforated floor. When determining this type of kilns based on the perforated floor, we need to be careful since such perforated floors were also used in, for example, salt extraction in the area under study in this work.[3] Such a ceramic *situla* was also found at the Štanjel site (*Vinazza 2011.T. 9. 103*), and is part of the present study.

Methods and sampling

For the present study, which is first of this kind in the studied area, we analysed 18 samples. The archaeological pottery comes from two hillforts, Tabor near Vrabče and Štanjel (for more details, see *Vinazza 2021.422–425*). Other samples were produced during archaeological experiments. Besides experimental archaeology, we also carried out additional analysis, such as AMS measurements, ceramic petrography analysis, and X-ray diffraction analysis (see Tab. 1).

We conducted experiments on the construction and use of a single-chamber kiln in order to better understand why the remains of kilns are so poorly preserved in the archaeological record in the studied area, and to get samples for observing changes in material under different temperatures. The kiln was built on the model of a Late Bronze Age kiln from the Oloris site near Dolnji Lakoš (*Horvat Šavel 1988–1989.130–131*). We were thus able to observe its manufacture, material, construction, and use during firing, as well as its decay.

Clay,[4] straw, and hazel branches were used for the construction of the kiln (16.6.2020). We prepared the mixture of clay, water, and straw (40%). The bottom of the 10cm deep pit was first covered with a clay mixture. After that, a construction from hazel branches, which was covered on the outside with clay strips of 20x15x5cm, was built. Seven people built the kiln in 5 hours (the preparation of the material and the construction). After 4 days, the kiln was dried by burning spruce chips (we used up 12kg), which took 6 hours and 30 minutes. After that, the kiln was ready for pottery firing.

The firing of the pottery took place after two months (28.8.2020). The kiln was loaded with 57 vessels that we formed from different local clays.[5] Two thermoelements[6] were installed onto the kiln, one along the kiln wall and the other in the centre, just below the vessels. We wanted to understand if there was any change in temperature in the kiln during firing.

To obtain different types of data and their possible application to the archaeological remains, we measured the AMS of the kiln.[7]

The magnetic susceptibility of the ground[8] or sediment is determined by the amount of magnetic minerals present. During burning, the magnetic susceptibility increases because iron minerals are bound. If the ground or the sediment does not contain iron minerals, the magnetic susceptibility is not high. The iron content depends on the geological background (*Goldberg, Macphail 2006.350–351*; see also *Mušič 1999.363*). If magnetite is present in the clay, magnetic susceptibility is naturally high (*Macphail, Goldberg 2018.236*). Measurements were taken in the laboratory on soaked clay (the Renče clay) (mixed with water and straw: 0.850) from which the kiln was built, on samples from the kiln after drying, and on samples from the kiln after firing (Fig. 3). The values given are average values.[9]

Clay from Renče that was used for building the kiln was also fired in a controlled atmosphere. We have

3 A perforated floor from the Ellerji hillfort has been interpreted several times before as the remains of salt production (*Lonza 1981. T. 44–45; Zendron 2018*), while the remains of a perforated floor from the Monkodonja site in Istria were among the earliest in the wider area (Early and Middle Bronze Age) (*Mihovilić 2020.36–39, Fig. 31*). This means that they appear significantly earlier than in the entire Italic peninsula, which indicates the supra-regional role of Monkodonja.

4 The Renče deposit: GKY 396454, GKX 83339.

5 Griže: GKY 417619, GKX 69497; Veliki Dul: GKY 411812, GKX 70871; Lukovica: GKY 476504, GKX 112322, and Renče: GKY 396454, GKX 83339.

6 Thermoelement type MTC500 with a Ni-Kr-Ni tip.

7 The Kappameter KT-7 (GF Instruments) instrument was used.

8 Values of AMS were measured on various samples of clays and present the results that do not enable simplified conclusions, since the values range from 0.1 to $8\cdot10^{-3}$SI. Location near Tupelče (GKY 407902, GKX 73627): clay to $6–8\cdot10^{-3}$SI; Vrabče (GKY 409555, GKX 77491): clay $0.063–0.207\cdot10^{-3}$SI; Veliki Dul (GKY 409555, GKX 77491): $0.532–0.666\cdot10^{-3}$SI; Ostri vrh (GKY 409555, GKX 77491): $0.766–0.966\cdot10^{-3}$SI.

9 Three measurements were taken for every point and the average value was calculated.

Sample ID	Petrolab ID	Source	Description	Clay	Add informations	Manipulation	Firing	Method
Sample 1	2020-6	Archaeological pottery, site Štanjel	Neck of the pot	Unknown	US 52	0	0	Macroscopic technological analysis; XRD analysis
Sample 2		Experiment	Rim of the bowl	Renče		Added water	670 °C	Arch. experiment; ceramic petrography analysis; XRD analysis
Sample 3	2022-3	Experiment	Bottom of the kiln	Renče		Added water and straw	670 °C	Arch. experiment macroscopic technological analysis; XRD
Sample 4	2021-24	Experiment	Wall of the kiln	Renče		Added water and straw	670 °C	Arch. experiment; ceramic petrography analysis; XRD analysis
Sample 5		Experiment	Chimney of the kiln	Renče		Added water and straw	670 °C	Arch. experiment; macroscopic technological analysis; XRD
Sample 6		Experiment	cube	Renče		Added water	600 °C	Arch. experiment; macroscopic technologigcal analysis; XRD
Sample 7		Experiment	cube	Renče		Added water	800 °C	Arch. experiment; macroscopic technologigcal analysis; XRD
Sample 8		Clay	No manipulation	Renče		0	0	Arch. experiment; macroscopic technological analysis; XRD
Sample 9	2020-10	Archaeological pottery, site Štanjel	Neck of the pot	Unknown	US 52	0	0	Macroscopic technological analysis; XRD analysis
Sample 10	2020-10	Archaeological pottery, site Štanjel	Neck of the pot	Unknown	US 52	0	0	Macroscopic technological analysis; XRD analysis
Sample 11	2020-10	Archaeological pottery, site Štanjel	Neck of the pot	Unknown	US 52	0	0	Macroscopic technological analysis; XRD analysis
Sample 12	2022-2	Experiment	Rim of the bowl	Renče		Added water and calcite	670 °C	Arch. experiment; macroscopic technological analysis; XRD
Sample 13		Experiment	No manipulation	Renče		Added water and straw	670 °C	Arch. experiment; macroscopic technological analysis; XRD
Sample 14	2022-1	Archaeological pottery, site Štanjel	Bottom of ceramic situla	Unknown	US 28	0	0	Macroscopic technological analysis; ceramic petrography analysis
Sample 15	2022-4	Archaeological pottery, site Štanjel	Silos	Unknown	US 28	0	0	Macroscopic technological analysis; ceramic petrography analysis
Sample 16	2020-18	Clay	No manipulation	Štanjel		0		Macroscopic technological analysis; ceramic petrography analysis
Sample 17	2020-1	Archaeological pottery, siteTabor near Vrabče	Rim of the pot	Tabor near Vrabče	US 18	0	0	Macroscopic technological analysis; ceramic petrography analysis
Sample 18	2020-12	Archaeological pottery, siteTabor near Vrabče	Rim of the pot	Tabor near Vrabče	US 9	0	0	Macroscopic technological analysis; ceramic petrography analysis

Tab. 1. Samples 1–12 are part of the present study.

prepared two samples (Tab. 1.6, 7) by adding water to the clay and firing them at the temperatures of 600 and 800°C in an electrically operated kiln (70kW, with Shimaden FP93 programme controller).

For ceramic petrography analysis, we chose samples on the basis on the results from the macroscopic technology analysis. We chose this method for various reasons. We wanted to observe changes in pottery recipes between Late Bronze and Early Iron Ages at the sites Tabor near Vrabče and Štanjel, changes during different temperature stages comparing archaeological material and material from our archaeological experiments (see *Cultrone* et al. *2001.629*), and compare pottery paste with local clays (*Quinn 2015*) in the case of the Štanjel site. The selected samples (Tab. 1) were prepared as polished thin sections, 30 microns thick, mounted on glass slides and analysed under the polarizing light microscope, Zeiss Axiocam 305 colour, using standardized descriptions (*Quinn 2015; 2022. 98–124*).

X-ray diffraction is used to characterize archaeological pottery in terms of the minerals present and their relative abundance and allows the characterization of minerals that cannot be recognized in thin-section petrography, such as clay minerals or new phases formed during firing. The XRD analysis of minerals present in pottery can help identify the temperature interval at which pottery was fired, as certain minerals are indicators of changes that occur during the firing process – examples include haematite, magnetite, cristobalite, mullite, calcite, montmorillonite, illite, vermiculite, and feldspars (*Quinn, Benzonelli 2018.2; Amicone* et al. *2020.526–527*).

The mineral composition of the pottery samples was determined using a Philips PW3710 X-ray diffractometer. It was recorded at a voltage of 40kV and a current of 30mA in the range from 3° to 70° 2θ at a speed of 3°/min. The wavelength of the Cu Kα X-ray wavelength was 1.5460Å. A secondary graphite monochromator and a proportional counter were used. The detection limit for minerals was between 0.5 and 3%. The Rietveld method was used to quantify the mineral phases. Diffractograms of the recorded samples were processed using the computer program X'Pert HighScore Plus 4.8v and the PAN-ICSD database.

Results

In carrying out the archaeological experiments, firing in the kiln took a total of 10 hours. First, we started heating slowly at the entrance and only began to increase the temperatures after four hours (Fig. 2). Initially, the temperature along the kiln wall increased more rapidly than in the centre, while from 500°C onward the temperature in the centre started rising more rapidly than along the wall. We were burning fuel in the front and to the left and right of the vessels. The drop in the temperature along the kiln wall (Fig. 2.15, 35) is the result of clearing the charcoal from the kiln. During firing up to 0.75m^3 of beech wood was burned and a temperature of 670°C was reached. The soaking time at this temperature lasted 30 minutes. The total time of the firing process was 10 hours. After this time, we did not measure the temperature further. On the third day (31.8.2020), we opened the kiln and took out 56 vessels (98% of them were successfully fired, unbroken). To date, some of the vessels have been used for cooking over an open fire seven times and are still undamaged.

The AMS measurement results show that temperatures that would affect the increased AMS are not reached during drying. The change occurs at higher temperatures, but mainly at the areas where the kiln surface was in direct contact with the fire. We thus have the highest values at locations where the fire was burning ($9.524 \cdot 10^{-3}$SI, $12.54 \cdot 10^{-3}$SI, and $17.91 \cdot 10^{-3}$SI), and on the inside of the chimney ($15.21 \cdot 10^{-3}$SI) where the fire directly touched the kiln. High values were also recorded on the inner wall of the kiln ($5.852 \cdot 10^{-3}$SI) and on the outer side in the centre of the kiln ($7.316 \cdot 10^{-3}$SI), where the kiln wall was thin. From this part towards the ground, the values decrease, while at the same time the kiln walls were significantly thicker towards the bottom.

The next goal of our study was the observation of the kiln's decay. The kiln was covered over a month after firing and then we left it in the open air, under the sun, rain, and snow. The dome collapsed half a year later, on 9.12.2020. The floor of the kiln was still as hard as when the firing was finished and covered with the ruins of the dome. Pieces of the dome and kiln walls were still very compact. The kiln walls were preserved only at the edge of the kiln. Over the next six months (Fig. 4.A), the most compact parts of the kiln softened and gradually began to merge into the depositional matrix. On 31.1.2022 (Fig. 4.B), parts of the kiln wall were still standing, but softened, while the kiln floor was still equally as hard as it had been six months earlier. Major visible changes occurred over the next five months (Fig. 4.C). The preserved walls weakened,

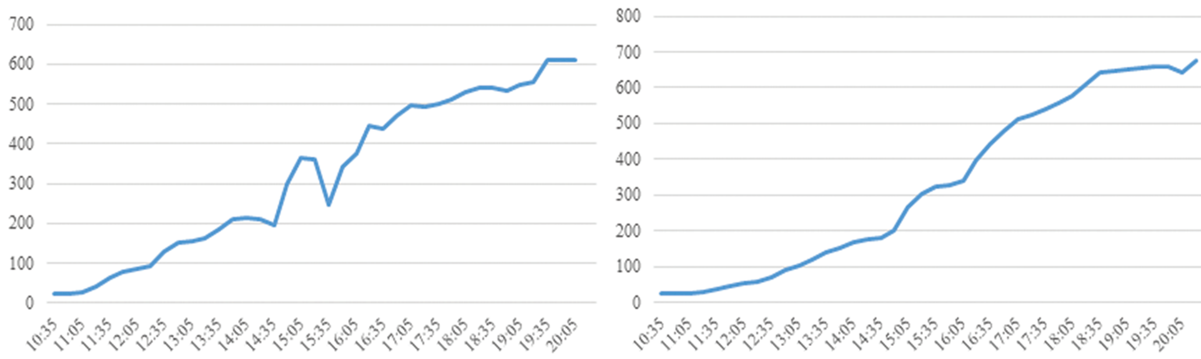


Fig. 2. Measurements of temperature in the kiln during firing. Left: along the wall, right: at the bottom of the kiln, under the vessels.

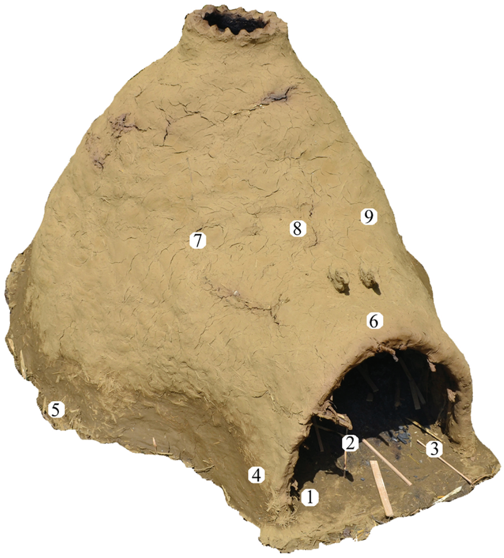
and the outer and inner edges were only sporadically preserved. Most of the dome turned into the depositional matrix, while the underlying slab was also preserved, being protected by the material. Today (October 2022) more and the more depositional matrix is forming, and the kiln floor is still hard as it was before.

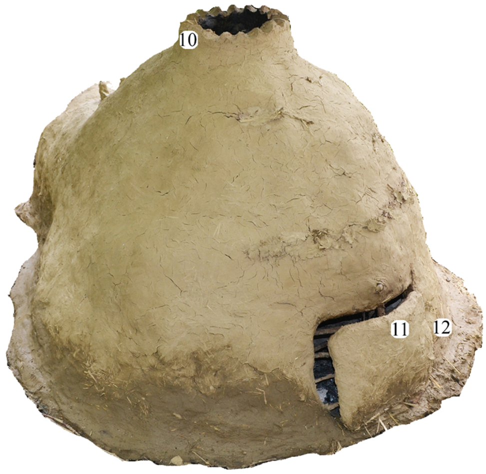
The analysis of pottery thin sections from Tabor near Vrabče shows that at the transition to the Late Bronze Age grog (20%) predominates as a temper. We could detect different types of grog in one vessel (20%); there is some organic temper (2%) and some planar voids. Individual calcite (1%) and quartz (5%) grains we understand as inclusions (Fig. 6.1; Tab. 1.17). Slightly later, in the 8th and 7th cent. BC (Phase 2), the pottery paste changes (Fig. 6.2; Tab. 1.18) and calcite predominates as the only temper (30%). There are a lot of visible voids and some small parts of organic matter (>1%). Sharp calcite edges (rhombohedral cleavage) indicate intentional crushing (Fig. 6.2–3). Calcite also predominates as a temper in the final stage of the Early Iron Age, in the 6th and 5th cent. BC (40%), as pottery from Štanjel shows (Tab. 1.1). The difference is visible in the size of the calcite temper. The grains are bigger in pastes from the 8th and 7th cent. BC than in those from the 6th and 5th cent. BC. In the later period there is a finer temper of calcite. The temper is still poorly sorted, but in comparison with older material there are no voids.

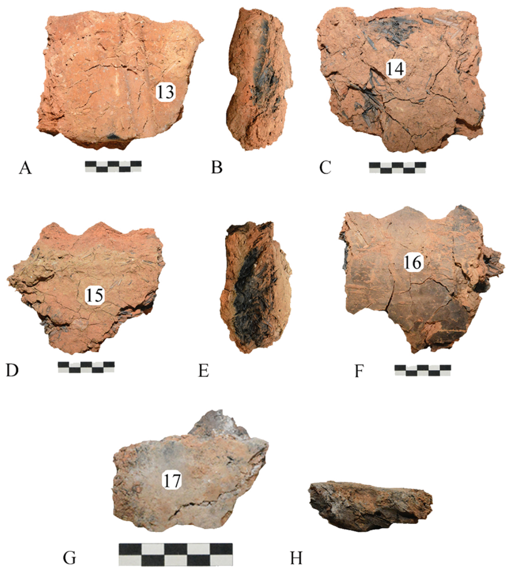
The kiln wall pottery thin section (Fig. 5) corresponds to the basic characteristics of such objects found at archaeological sites. Here we have in mind the main micromorphological features of mudbricks, such as the presence of organic elongated fragments and randomly oriented channels and voids, reflecting the addition of straw into the otherwise very compact structure during the preparation (*cf. Friesem* et al. *2018.99–100*). In our case (Sample 4) the are many planar voids and channels, indicating that straw is the only temper used for kiln paste. Other features are inclusions, such as Fe-oxides, clay pellets, quartz grains, and some other opaque minerals.

In order to determine the origin of the classic *situla* from Štanjel and thus the possibility of the presence of the two-chamber kilns, we conducted a comparative study of the pottery masses using pottery thin sections. We took samples of local clay (Fig. 7B; Tab. 1.16), *silos*[10] (Fig. 7.D; Tab. 1.15), and pottery from the Štanjel site. One from the local form (Fig. 7.A; Tab. 1.1) and one from a presumably imported ceramic *situla* (Fig. 7.C; Tab. 1.14). *Silos*, such as ceramic rings, loam weights, and house plaster, are generally made from the clay closest to the site, making them a good comparison for determining local/imported products. Even a quick look at the pottery thin section of a *silo* (Fig. 2.4) and the ceramic *situla* (Fig. 7.3) shows that we are dealing with different clays. The *silo* contains muscovite/illite (up to 20%) and polycrystalline and monocrystalline quartz (25%), while the muscovite/illite is not present in the ceramic *situla*. The latter also did not include clasts of trachyte, which is typical of such forms from the Euganean area (see *Saracino 2014.120, 144*). The clay matrixes of the local vessels, the *silo*, and the local clay, sampled near Štanjel are very close in composition, while the ceramic *situla* stands out.

10 A *silo* petrographic thin section (Fig. 2.4) indicates the presence of certain carbonates, which are unchanged, meaning that firing took place at a temperature from 675 to 870°C. The same is true for the pottery from Renče (Sample 2), fired at 670°C. The *silos* as such is also solid (7 according to the Mohs scale), which reflects firing at a high enough temperature and at the same time changes the idea that such pottery forms were fired at low temperatures (*Vinazza 2016.7*).







Position of measurement	Description	After firing	Before firing
1	Bottom of the kiln (entrance)	12.54	
2	Bottom of the kiln (entrance)	9.524	0.338
3	Bottom of the kiln (entrance)	17.91	
4	Kiln`s wall (external surface)	3.181	
5	Kiln`s wall (external surface)	0.351	
6	Kiln`s wall (external surface)	1.426	0.069
7	Kiln`s wall (external surface)	7.316	0.178
8	Kiln`s wall (external surface)	2.893	
9	Kiln`s wall (external surface)	3.683	
10	Chimney (external surface)	3.181	0.149
11	Closing	3.117	0.357
12	Kiln`s wall (external surface)	5.852	0.647
13	Kiln`s wall (external surface)	1.831	
14	Kiln`s wall (external surface)	5.606	
15	Chimney (external surface)	20.059	
16	Chimney (internal surface)	18.323	
17	Bottom of the kiln (in the middle of the kiln)	13.96	

Fig. 3. The AMS measurement points were chosen on various parts of the kiln (in the centre) and of the individual parts (kiln wall (A–C), chimney (D–F), and kiln floor (G–H)).

The XRD analyses were performed on 12 samples (Tab. 1.1–13). The objective of the analysis was to determine the comparison of the XRD analysis results with the firing temperature in the kiln, which was measured with thermoelements during firing. We also tried to show that the firing temperatures of individual kiln parts do not reflect the temperature of the pottery firing, which consequently cannot be applied to the archaeological material. Third, following the lead of Thèr (*2020*), we sought to determine whether we could detect differences between the results of XRD analysis at the fracture and on the outer surface of the pottery, and thus determine the use of a bonfire and/or kiln at the site. The analyses were carried out on the samples of the kiln from the Renče clay, which is of the illite-chlorite type (*Rokavec 2014.35*), and on the pottery from the Štanjel site, which belongs to the end of the Early Iron Age (Tab. 1; Fig. 8).

Renče clay (Samples 2–8, 12)

Clay from Renče (Sample 8) has a higher amount of kaolinite (Fig. 8) which is not present in the other samples (Samples 2–5), meaning that the latter were fired at over 550°C. Comparing the parts of the kiln (floor/walls/chimney), most kaolinite is found in the kiln walls (Sample 4), less in the floor (Sample 3), while no kaolinite is present in the sample from the chimney (Sample 5). It is therefore understandable that most of it is in the wall where the temperature in the kiln was the lowest. Sample 6 (firing at 600°C) contains very little kaolinite, while Sample 7 (firing at 800°C) and Sample 12 (firing at 670°C) contain no kaolinite. Illite, which begins to decompose at 900°C, is present in all samples, while only Sample 7 contains less because it was fired at 800°C. Quartz is also present in all samples. Calcite is also present in Samples 6 and 8, which we attribute to its natural occurrence in the clay. Sample 12 (Fig. 8) has an elevated calcite value, which we attribute to the intentional addition of the temper of calcite to the clay, which is also confirmed from pottery thin sections. It is no longer present in Sample 7, as it begins to decompose above 670°C. Dolomite is found in Samples 6 and 8, but in small amounts and is no longer present in Sample 12.

Štanjel pottery (Samples 1, 9–11)

Calcite is present in all samples indicating that the pottery was fired at temperatures below 870°C, at which calcite decomposes completely. Sample 1 (Fig. 8) has an increased value of calcite, which we attribute to the intentional admixture of the temper of the calcite to the clay (Fig. 8), which is also confirmed by pottery thin sections. At the same time, kaolinite is no longer present, indicating that the pottery was fired at over 550°C. The samples from Štanjel contain very little illite, which is due to the mineralogical composition of the clay. A comparison of the calcite in the vessel's core (Sample 10) and in the outer (Sample 9) and inner surfaces (Sample 11) shows that the vessel's core contains more calcite.

Discussion

Archaeological finds that would indicate the firing of the pottery in Kras and the Posočje region in the Bronze and Iron Ages are not known for either a bonfire or a kiln. There are at least two possible reasons for this. First, slow sedimentation at Kras is very problematic from a stratigraphical point of view. In most cases, the sites have very thin archaeological layers and only rarely do we discover a longer stratigraphic sequence (*cf.* Monkodonja in Istria; *Hänsel* et al. *2015.75*). The soil at Kras is characterized by the bedrock, various limestones and dolomites, their decomposition and dissolution, and the leaching of debris into relief depressions. On karstified hills and in higher areas there is less soil, while in depressions, *e.g.*, dolinas (*Habič 1979.150*), there are uniform and thicker layers. The discussed pottery originates from the hillfort sites of Tabor near Vrabče and Štanjel (*Vinazza 2021*), where there is in both cases less soil.

The second reason is connected with the firing structures and the question of how to recognize them in order to understand the firing process. Structures

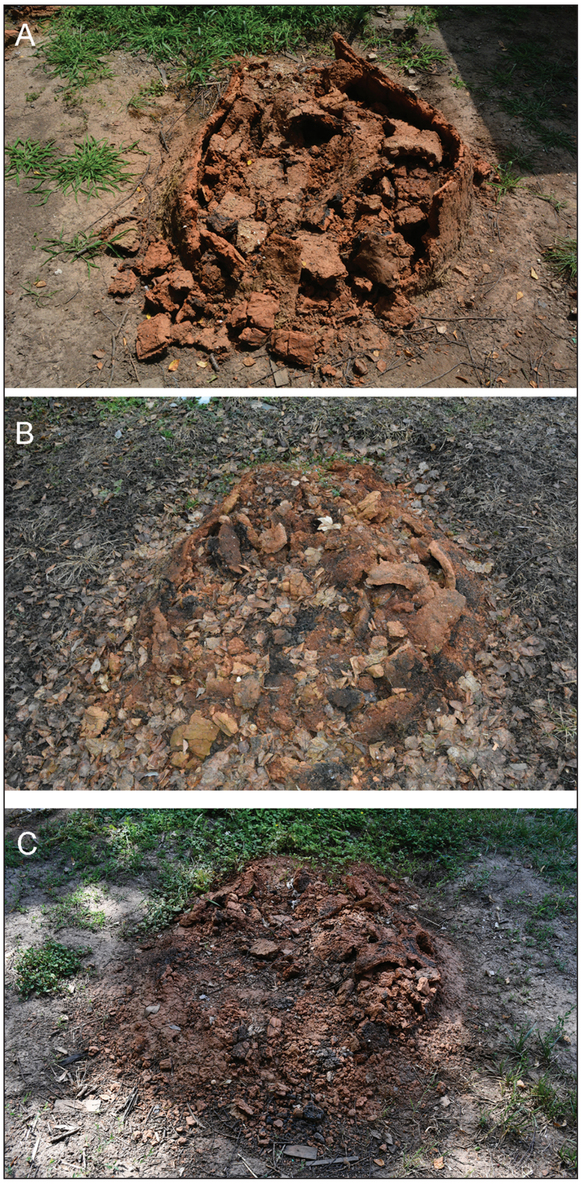


Fig. 4. A year's decay of the kiln. **A** ***27.07.2021,*** **B** ***31.01.2022,*** **C** ***16.06.2022.***

such as bonfires do not leave any significant traces behind, and are thus difficult to discern. If we consider a burned layer of soil, a large pile of plant charcoal, wooden charcoal, burned-through soil, and burned lumps of soil as the key indicators of the remains of a bonfire for firing pottery (*Guo 2017. 184*), then some of the structures found at several sites from Eneolithic to the Early Iron Age in central and north-eastern Slovenia could be interpreted as bonfires.[11] We are still missing this kind of data for the Kras area.

11 The Eneolithic: Kalinovjek, SE 171, 174, 176, 178, 257, 259 (*Kerman 2013.58, 59, 62*); the Early Bronze Age; Nova tabla, PO 29, PZ 24 (*Guštin* et al. *2017.112, 115*); the Middle and Late Bronze Ages: Nedelica pri Turnišču SU 344/343, 372, 381 (*Šavel, Sanković 2013.78*), Svetje, SU 41/42 (*Leghissa 2011.86*); the Late Bronze Age: Pod Kotom – sever pri Krogu, SU 347 (*Kerman 2011. 71*); Orehova vas, SU 160M, 191A, 81R (*Grahek 2015.53, 59, 88*)); the Early Iron Age: Nova tabla, PO 223 (*Guštin* et al. *2017. 127*); Hotinja vas near Maribor, SU 271/272 (*Gerbec 2015.43*).

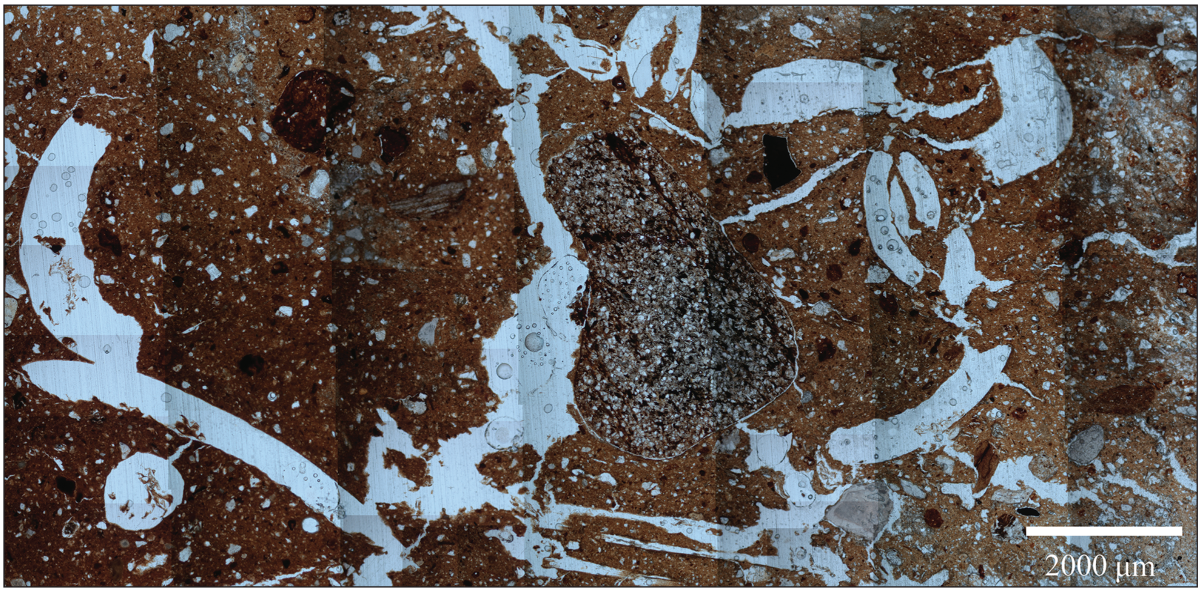


Fig. 5. Panoramic view of a pottery thin section of the kiln wall. The voids are the result of the burned-out organic material, straw. Photos taken under plain polarized light.

The situation is a different matter with kilns. They decay in a certain phase, but their remains depend on different situations. Today's climate in the discussed area is too dry, and poorly fired structures decompose into the matrix of the archaeological deposit (*Amicone* et al. *2020.522*), and it is also possible that the space is reused at a later date.

We believe one of the reasons why these kilns have not been preserved is also due to the use of these structures. Our archaeological experiments have shown that different parts of kilns are exposed to different temperatures, which is consistent with the results of the AMS. The most exposed parts were the kiln floor and the chimney. Higher values of the AMS mean that these parts were fired better, which affects the degree of preservation of these parts of the kiln. In the exposure to different temperatures, we see the reason for the poor preservation of the kilns, which can be applied to the wider area.[12] From this, we can say that we can mistake the remains of the kiln floor with, for example, a hearth. Hence we believe that we should focus our attention on possible remains of an interlacement that could have belonged to the former dome,[13] which will significantly contribute to the final interpretation of whether it is a kiln or a hearth.

Consequently, we believe that the firing temperatures of vessels cannot be determined by analysing the temperature of the parts of kilns. As already mentioned, different values of AMS indicated different temperatures of the firing of different kiln parts. Since kiln parts are usually randomly preserved, it means we do not necessarily obtain the best-fired part when sampling. Moreover, in the case of kilns the soaking time plays an important role, since bricks, for example, are fired for several days before they are properly fired. When macroscopically observing the core of cubes made of Renče clay (App. 1: Samples 6 and 7) it can be seen that the core is still grey at 600°C, while at 800°C the grey part shrinks.

Evidence of this is the results of the XRD analysis of vessels and kiln parts from the Krašnja site in Slovenia, which showed that the vessels were fired at about 800°C, while samples of the wall and bottom of the kiln indicate a temperature of no more than 500°C (*Žibrat Gašparič* et al. *2014.232, 234*).

We can also apply these results to pottery firing. As Thér *et al.* (*2018*) have already shown, the soaking time needs to be considered when comparing firing in a bonfire with firing in a kiln.

12 Here we always need to compare AMS measurements of the local clays, since the values may depend on the natural composition and the presence of, for example, magnetite.

13 We have found five pottery kilns at the roman site Otok pri Metliki in southeastern Slovenia. Above the perforated floor there was a red layer full of small pieces of burned clay. There were no visible marks of the construction made with branches (see *Udovč, Vinazza 2018.147–149*).

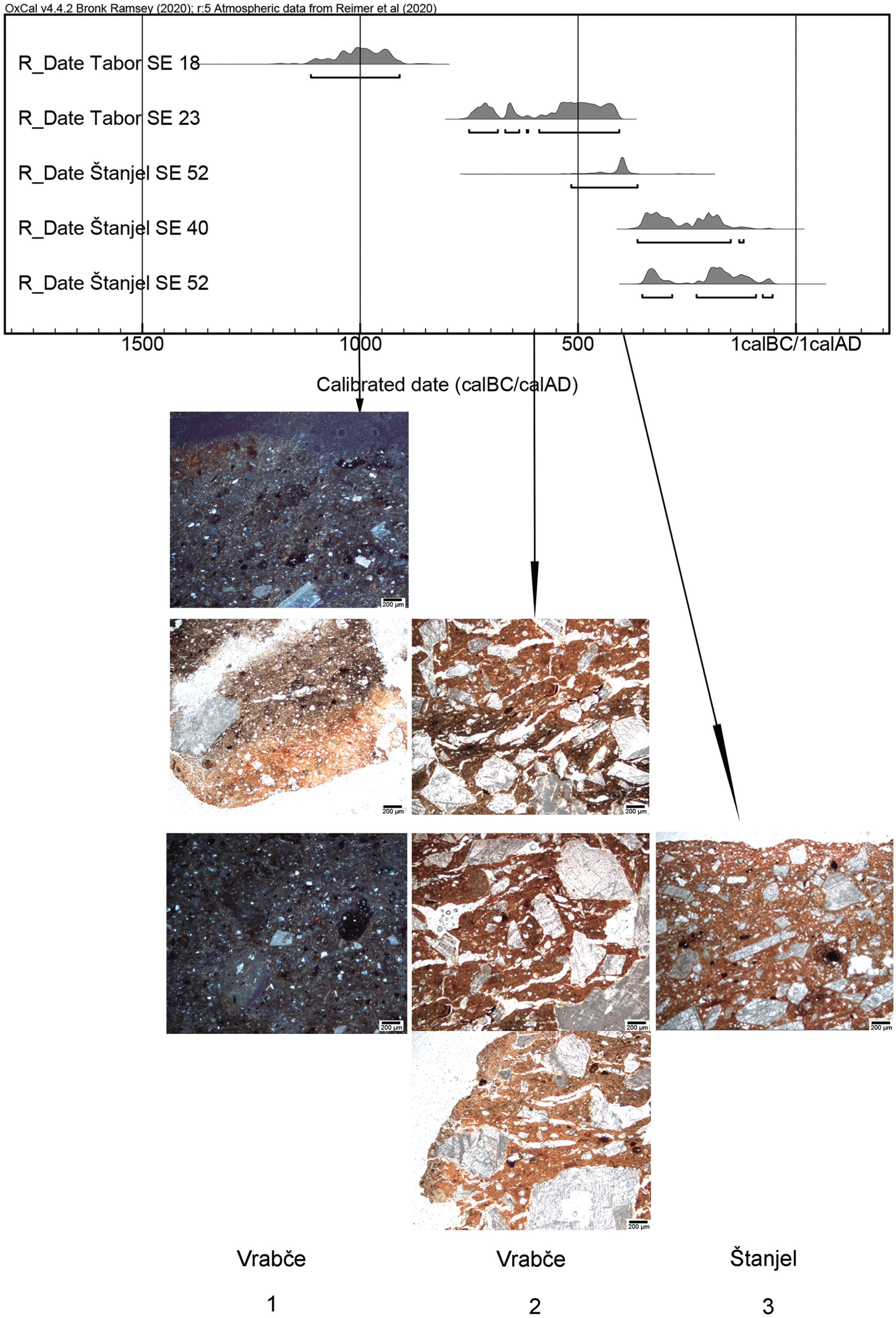


Fig. 6. Changes in the pottery recipes (petrographic thin sections and site phases (1 Late Bronze Age; 2 Early Iron Age; 3 end of Early Iron Age)) in combination with radiocarbon dates from the sites of Tabor near Vrabče and Štanjel. Photos taken under plain polarized and cross polarized light.

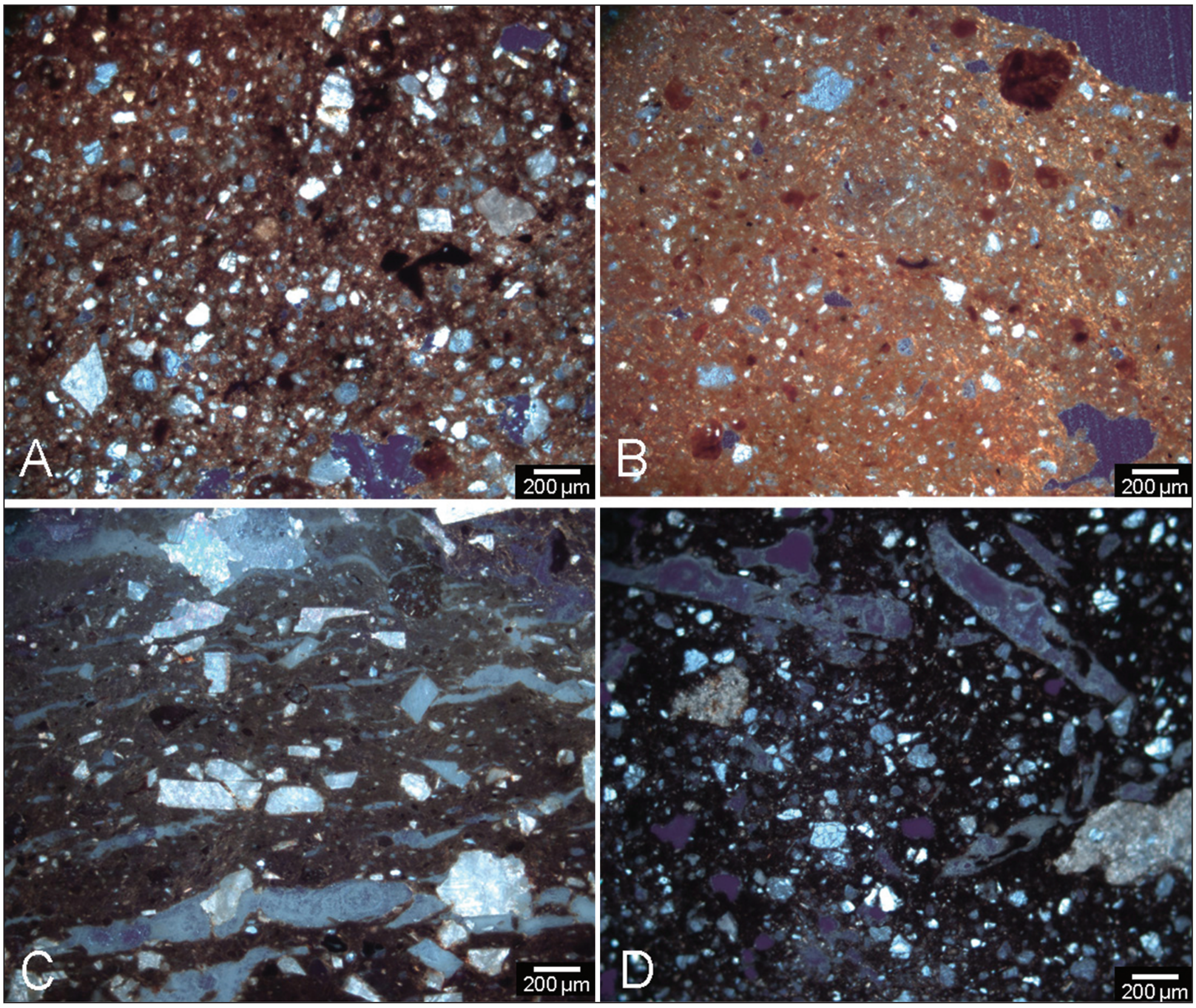


Fig. 7. A comparison of clay-matrix archaeological pottery – vessels (1, 3), with a silo (4) and clay from the vicinity of Štanjel (2). Photos taken under plain polarized and cross polarized light.

There are no differences in the mineralogical composition of the Štanjel pottery when comparing the vessel's core and inner and outer surfaces (Samples 9–11). We take the lack of variation in these values as evidence that the pottery was fired in a kiln. The calcite values have not changed, which means that the decomposition of the calcite has not started at a temperature that has not exceeded 850°C.

Here, we would like to point out that the increase of calcite that was already shown by macroscopic technological analysis (*Vinazza 2021*) and confirmed with pottery thin sections in this study, in pottery from sites Tabor near Vrabče and Štanjel is not linked to a particular vessel type, but is noted in various forms, such as pots, dishes, and lids. This means the reason for the addition of calcite is not only related to the functional properties, which increases the resistance to thermal shock (*Bronitsky, Hamer 1986.95–99*), but also to the firing process, since calcite acts as a flux that allows carbonate clays to be fired at lower temperatures (*Shoval 2016.12*). Since calcite decomposes at a temperature of up to 870°C and since the XRD results for Štanjel pottery show that the temperature did not exceed 870°C, we assume that the use of kilns makes it easier to control the temperature and thus the use of such an amount of calcite.[14]

Finally, we analysed ceramic *situla* from Štanjel in order to find confirmation of ORO firing of this type of vessel and consequently the potential use of two-chamber kilns with a perforated floor in the Kras area. As the ceramic *situla* from Štanjel was not made from the same clay, as the other samples show, we see it as an imported vessel. Samples from Most na Soči from Posočje (*Grahek, Košir 2018.309–311, 314–315*; sample MNS D or Most 4) suggest the pos-

14 This material is ubiquitous in the discussed area (see *Jurkovšek 2013*).

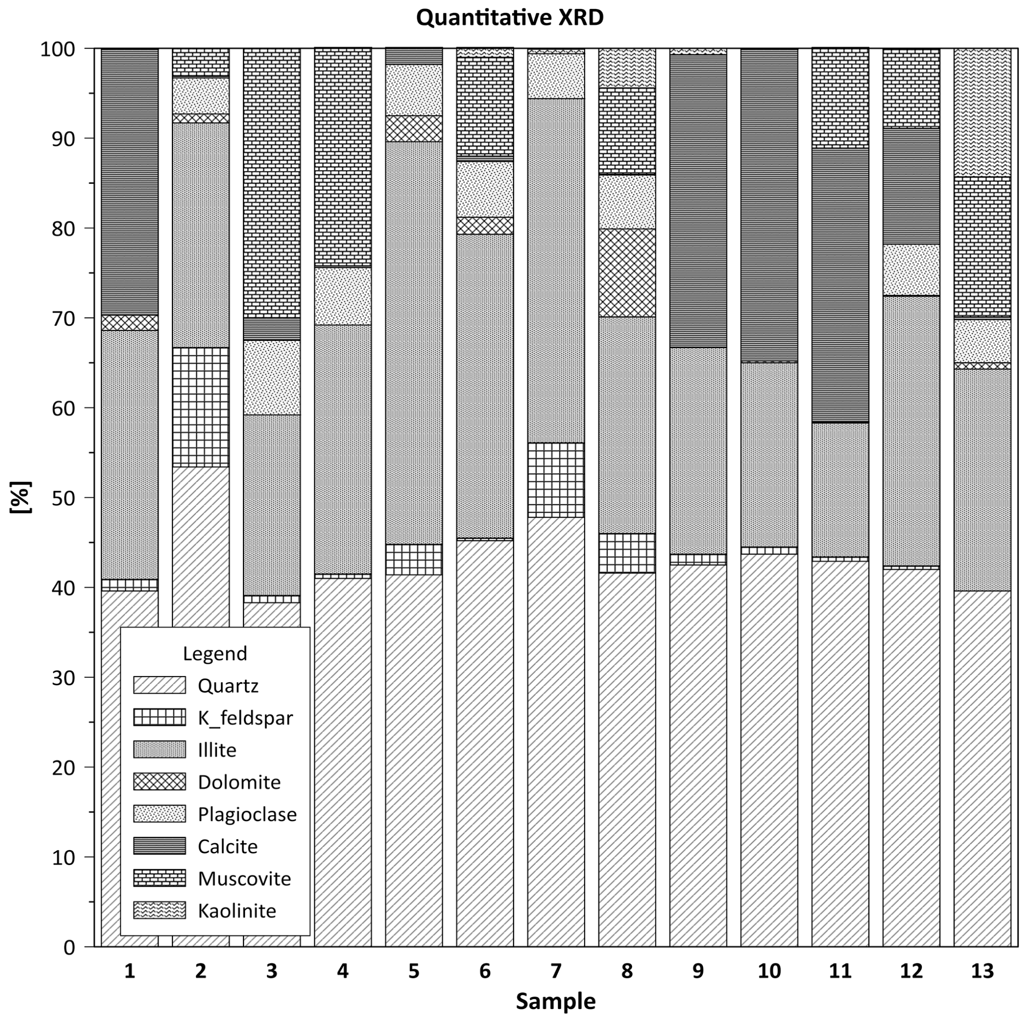


Fig. 8. Mineralogy distribution (XRD results).

sibility that some of the pieces were imported from workshops in the Este area, while others are probably the product of local workshops. In our case, no pieces of trachyte were found in the pottery mass, which is typical for the Euganean area (see *Saracino 2014.144*). We believe that the area of origin of the ceramic *situla* from Štanjel is elsewhere and the possibility of local workshops is still open to discussion, since the XRD results also show no or a very small amount of muscovite in pottery from Štanjel (Fig. 8.samples 9, 10).

Conclusion

With the help of various research methods and scientific analyses, we have tried to determine whether the use of kilns for pottery firing can be expected in the Early Iron Age in western Slovenia. The pottery-manufacture technology of this period suggests this possibility, and the same is true for the results of XRD analysis, which do not reveal major temperature deviations between the outer surface and core of the vessel, which means that the soaking time was long enough to allow gradual and uniform firing of the vessels. The XRD analyses of the pottery from Štanjel show that the temperature did not exceed 870°C, while the addition of calcite as a temper, which did not decompose, suggests that the firing took place under controlled conditions, which can be better controlled in a kiln (*e.g.*, no sudden temperature rise due to the wind blowing). The prevalence of oxidative firing, which is much more controlled in a kiln, is also supported by the macroscopic analysis of pottery in western Slovenia at the end of the Early Iron Age. Based on the above, we assume that in western Slovenia at the end of the Early Iron Age (the 6th and 5th cent. BC) only single-chamber kilns for the firing of pottery were known, even though archaeological excavations have not (yet) brought them to light. We need to point out that a single-chamber kiln from the Early Iron Age was found in the Dolenjska region (site Dobrava near Otočec), as mentioned above, but for the area of Friuli Plain in Italy we still have no evidence. In the future, we will have to pay more attention to the excavations of such structures, and in the Kras area there is a lack of scientific research. Only with such an approach will we be able to understand more about pottery technological practices in the Early Iron Age.

However, the non-local origin of the ceramic *situla* from Štanjel does not suggest the use of two-chamber kilns with a perforated floor for the firing of the pottery at the end of the Early Iron Age in the Kras area. Since the clay for ceramic *situla* does not originate from the Eugaeum area, we still need to find a closer production area for this type of vessel. Some additional local clay sampling in a broader area close to key Early Iron Age sites (*e.g.*, Tomaj, Most na Soči, Gradisca di Spilimbergo in Italy) thus needs to be done.

Finally, we would like to point out that the level of technological knowledge was also determined by the properties of the raw material available in a certain area. Thus, the final results must also be understood in light of the natural resources (*e.g.*, clay quality) of the area and not only in terms of the level of technological development, as is often the case in archaeological studies.

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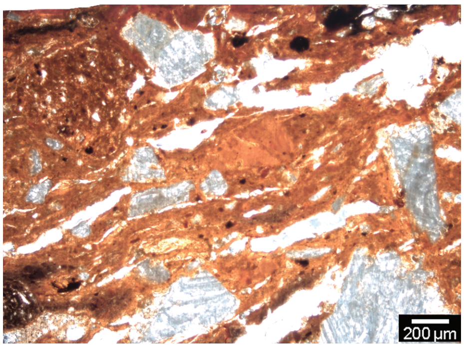
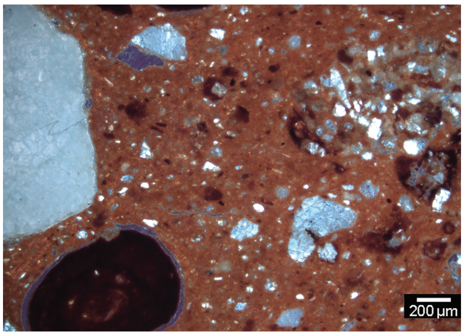
Appendix

1. Štanjel, red slip coating on the situla, outer surface. 8x magnification Leica Stereomicroscope EZ4.



2. Štanjel, coating thin section, a fracture (orange colour). 40x magnification. PPL with Zeiss Axiocam 305 color.

3. A thin section of a vessel fired in a kiln at 670°C. 8x magnification Leica Stereomicroscope EZ4.



4. A thin section of Sample 2. XPL with Zeiss Axiocam 305 color.

5. Renče clay, fired at 600°C, Sample 6. 8x magnification Leica Stereomicroscope EZ4.

6. Renče clay, fired at 800°C, Sample 7. 8x magnification Leica Stereomicroscope EZ4.

7. Štanjel, Samples 9 (outer surface), 10 (fracture), 11 (inner surface). 8x magnification with Leica Stereomicroscope EZ4.

8. Renče clay with admixed calcite, Sample 12. 8x magnification Leica Stereomicroscope EZ4.