DE GRUYTER Open Archaeology 2021; 7: 1160–1175

Research Article

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A Multidisciplinary Approach to the Study of Early Neolithic Pyrotechnological Structures. The Case Study of Portonovo (Marche, Italy)

https://doi.org/10.1515/opar-2020-0198
received December 30, 2020; accepted August 15, 2021

Abstract: The introduction of agricultural practices fostered the development of specific technologies for the new subsistence practices and the production of new artefacts. Pyrotechnological structures such as ovens are part of the Neolithic equipment and accompanied the spread of agriculture from the Near East across Europe and the Mediterranean Sea. Ovens located within settlements – mainly domed, above-ground structures – have been traditionally linked to cooking and baking. The function is usually deduced from techno-morphological traits, although experimental approaches or ethnoarchaeological observations have often been used. This article aims to demonstrate the effectiveness of the multidisciplinary approach to understand the function of fire structures. An integrated methodology that combines archaeological analysis, archaeometry, and experimental archaeology has been applied to study the underground ovens of the Early Neolithic site of Portonovo (Marche, Italy) dated to the sixth millennium BCE. Samples of hardened sediment of archaeological ovens' inner surface and selected pottery fragments were analysed through X-ray powder diffraction to estimate the temperature reached. A life-size replica of an underground oven was then created to perform firing experiments, including pottery firing. Samples of the oven's walls and experimental vessels were analysed with the same method, and the values were compared. Our results indicate that the Portonovo ovens are potentially multifunctional structures, built for about 700 years, always with the same technique exploiting the natural soil's insulating properties.

Keywords: Early Neolithic, pyrotechnology, ovens, experimental firing, X-ray powder diffraction

1 Introduction

Innovations in fire-related technology contributed to change in human physiology, social interactions, and human–environment relationship. It is assumed that the control of fire fostered the evolution of

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Special Issue: THE EARLY NEOLITHIC OF EUROPE, edited by F. Borrell, I. Clemente, M. Cubas, J. J. Ibáñez, N. Mazzucco, A. Nieto-Espinet, M. Portillo, S. Valenzuela-Lamas, & X. Terradas

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cooperation (Twomey, 2014) and facilitated brain evolution thanks to the invention of cooking food (Wrangham, 2009). The Agricultural Revolution introduced later an extensive set of new technologies connected to farming, food processing, and pottery production, an innovative tool for changing needs. Pyrotechnological structures are among the facilities that were improved or created to serve the new subsistence practices, and some of them, such as ovens, became common features within Neolithic settlements.

Ovens are found as part of the Neolithic house's standard equipment since the eighth millennium BCE in Anatolia and the Levant and as a usual component of the Neolithic package following the spread of agriculture across Greece and the Balkans (Fuller & Gonzalez Carretero, 2018). In Central Mediterranean, these structures frequently occur within Neolithic settlements as above-ground features built inside the houses or located in open areas outside dwellings, as attested in numerous sites in Greece, Anatolia, Bulgaria, Serbia, and Italy. Clay-built domed ovens are the most common type, and they are often found in association with other fire-related structures such as hearths and clay platforms (Cattani, Debandi, & Peinetti, 2015; Frère-Sautot, 2003; Gimbutas, Winn, & Shimabuku, 1989; Kalogiropoulou, 2013; Prévost-Dermarkar, 2003) or with accessories such as clay andiron and portable hearths (Mallory, 1984/1987).

Because of their tight connections with domestic activities and household organisation, ovens embody utilitarian as well as social functions. Shape, size, and construction techniques are strictly related to their primary function and the raw materials at disposal. Moreover, the location of ovens is crucial to understand if the use and function are related to a single household – this is the case of the ovens placed inside a dwelling or a room of the house – or if ovens were communal structures located in open areas within settlements. Therefore, ovens located inside houses are traditionally viewed as domestic facilities for cooking food, baking bread, and toasting cereals, while structures placed outside dwellings have been interpreted for food processing and craft activities carried out in public spaces (Hastorf, 2012; Kalogiropoulou, 2013; Parker, 2011).

However, morphological and spatial parameters did not suffice alone to understand the oven's function. In the last few decades, the increasing application of multidisciplinary methods ranging from micromorphology (Germain-Vallée, Prévost-Dermarkar, & Lespez, 2011; Mentzer, 2014) to organic residues analyses (Gur-Arieh et al., 2014; Thoms, Laurence, Short, & Kamiya, 2015), from experimental archaeology (Costa, Cavulli, & Pedrotti, 2017, 2019; Đuričić, 2014; Eiland, Luning, & Williams, 2003; March, 1992; Mulder-Heymans, 2002; Pfaffinger & Pleyer, 1990; Thér et al., 2019; Werner, 1991) to ethnoarchaeology (Orliac & Orliac, 1980; Parker, 2011; Ramseyer, 2003), and from petrological (Eramo, 2005; Eramo & Maggetti, 2013) to computational approaches to heat transfer (Hein & Kilikoglou, 2007) indicates that ovens – and pyrotechnological structures in general – require an integrated and multiparametric approach to understand their original functions.

We applied an integrated methodology, which combines archaeological observation, experimental replication, and archaeometric analyses, to verify the archaeological interpretative model of new Italian evidence of underground ovens, frequently attested in Neolithic settlements of central Europe from France to Hungary (Cheben & Hajndova, 1997; Lüning, 2004; Pechtl, 2008; Petrasch, 1986). These underground structures are generally associated with baking and food processing although their use for pottery drying has not been excluded (Staššiková-Štukovkhá, 2002).

2 The Early Neolithic Underground Ovens of Portonovo (Marche, Italy)

The Early Neolithic site of Portonovo is located on a hilly slope at 120 m a.s.l., less than 1 km as the crow flies from the Adriatic sea (Figure 1). The geological substratum of the Early Neolithic site of Portonovo Fosso Fontanaccia is constituted by marls, alternated with marly limestones and marly clays (Schlier Fm., Cello & Tondi, 2011). The 23 ovens unearthed over an explored area of 600 m^2 (Figure 2) were made by digging a large pit into eluvial-colluvial sediment and then by excavating one or two hemispherical cavities. The

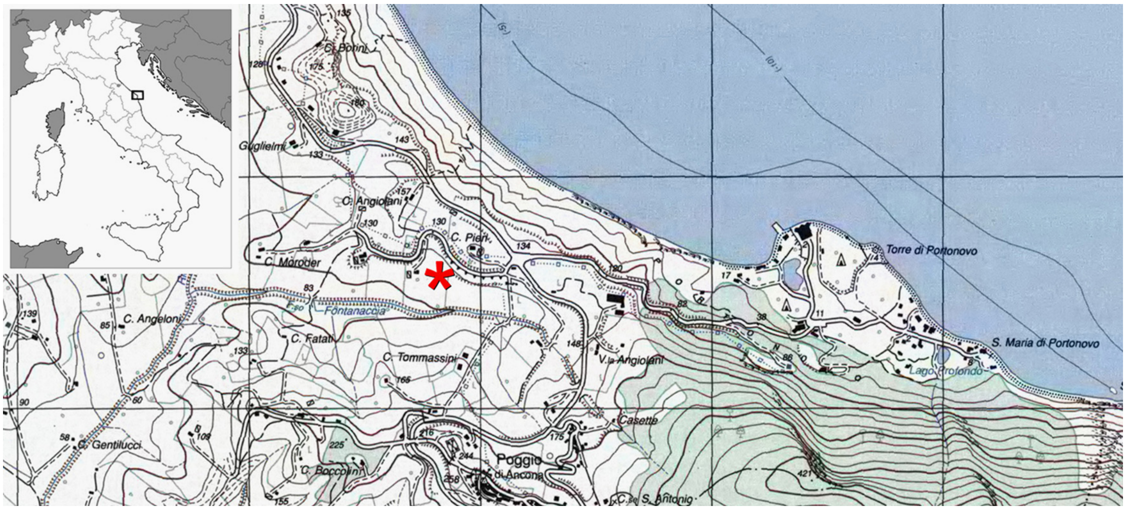

Figure 1: Localisation of the archaeological site of Portonovo (Marche, Italy). IGM Map 1:25.000, 118 – IV.

function of the pit was first to allow the construction of the ovens and second to facilitate the oven's use, loading the fuel and the materials or foodstuffs to be cooked. The access pits were large in size: for example, the one in front of oven 23 was 5 m × 4 m wide and 1 m deep, although the actual depth was at least 1.5 m considering the severe erosion of the area (Figure 3).

The ovens have a circular base of 1.8–2 m in diameter, a maximum height of about 0.5 m, and a single opening of 0.5 m. The floors were smoothed and, in some cases, covered with a light coating of clay. Finally, the ovens were consolidated by fire and repeated use (Conati Barbaro, 2013, 2019; Conati Barbaro et al., 2019). The floor and interior walls of the ovens are yellow to reddish in colour. Seven ovens were found entirely preserved, as a thicker superficial deposit protected them. No evidence of vents was found so far. Although only 7 of 23 ovens are entirely preserved, based on dimensional and formal parameters, it is assumed that only one construction model was used, which did not include a vent.

No residential structures or other settlement facilities settlement areas were identified during the excavation. Therefore, the area where the ovens are located could be seen as a place dedicated to performing specific activities related to one or more nearby settlements. Indeed, Neolithic surface materials collected during non-systematic surveys during the 1990s (Barbone, Barbone, Carlini, Pignocchi, & Silvestrini, 2005) suggest the presence of other Neolithic sites along the valley is no longer visible due to marked slope erosion.

Radiocarbon and archaeomagnetic dates indicate a long-term occupation of the site from 5900 to 5200 cal. BCE (Conati Barbaro, 2019; Tema et al., 2016). According to ^{14}C dates (Conati Barbaro, 2019), ovens were not all contemporarily in use. Each oven was possibly made and used for a few years and then abandoned as there is no evidence of maintenance to extend its functional life. Moreover, when a new oven was built, the position of the previous ones was probably known because there are only two cases of overlapping.

Two ovens were reused for funerary purposes in a later phase of the site occupation (last centuries of the sixth millennium BCE). Two individuals were buried inside oven 1, while oven 5 contains the remains of an adult male (Catalano & Di Giannantonio, 2013; Conati Barbaro, 2013, 2019).

Based on the evidence of charred cereal caryopses found in large numbers inside five ovens, it has been assumed that ovens were used for toasting or drying cereals before storage or consumption. Moreover, the abundant faunal remains, mainly pigs and ovicaprids (Antonino, 2020), contained in the large pits in front of the ovens also suggest their use for food processing. Also, most of the archaeological material comes from the filling of the access pits, while inside the ovens, it is scarce, suggesting the possible existence of a closure. Pottery shows a predominant use of fine and coarse pastes ranging from red to brown in colour, while the yellow to pinkish yellow figulina pottery is rarely attested (La Marca, Eramo, Muntoni, & Conati Barbaro, 2017). Large bowls and jars are the most represented vessels, although articulated shapes are also present.

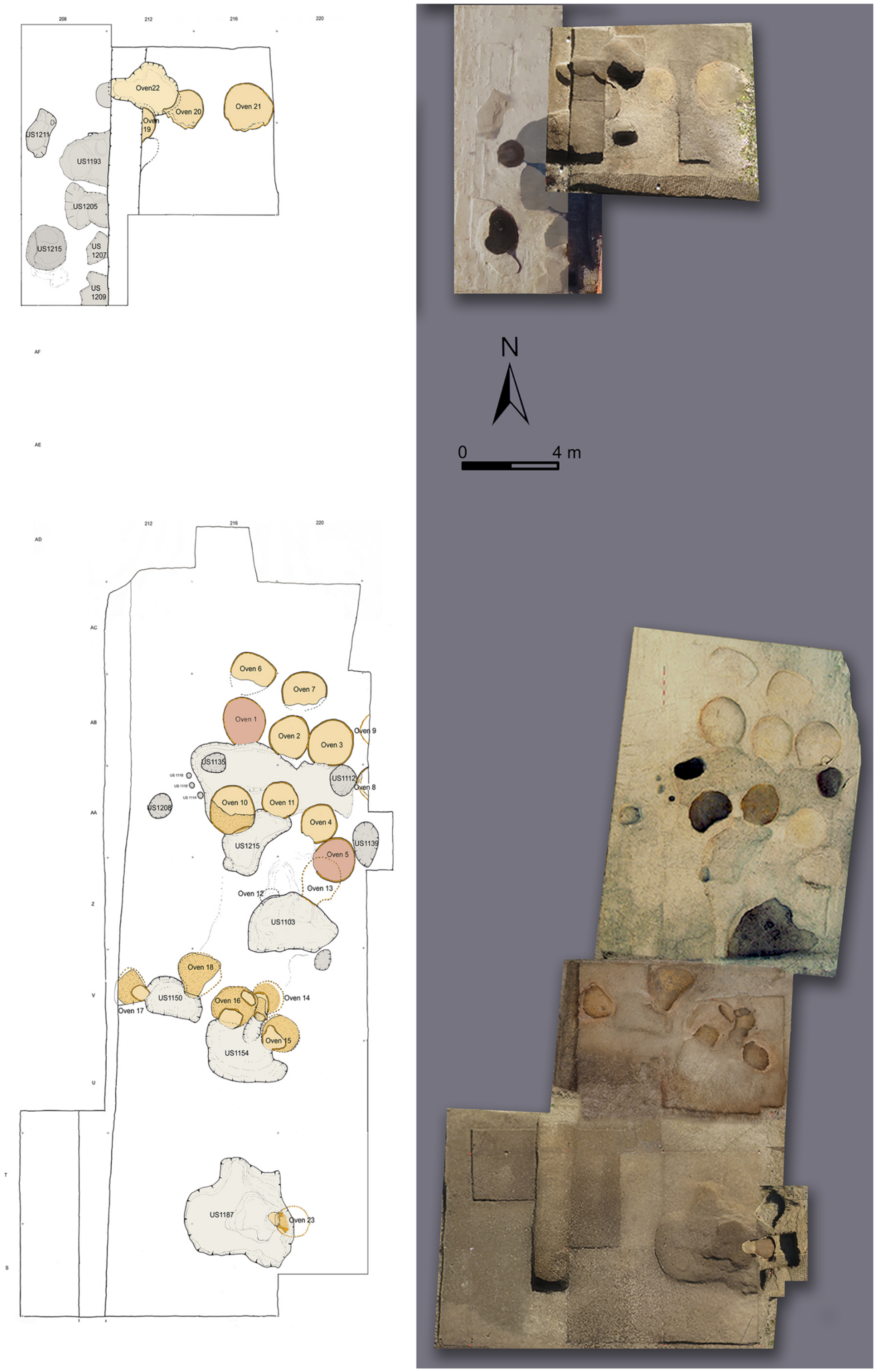

Figure 2: Portonovo (Marche, Italy). General map and aerial view of the archaeological site. (© Portonovo Project; map and photo have the same scale).

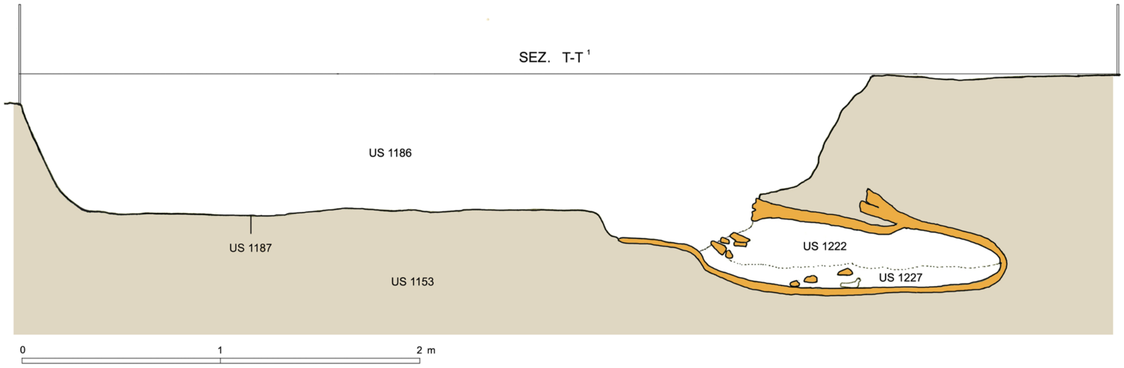

Figure 3: Portonovo (Marche, Italy). Cross section of oven 23 and its access pit US 1186.

3 Investigating the Oven's Function: Archaeological Evidence and Archaeometric Data

According to the archaeological ovens' shape and the first results of the archaeometric analyses, the initial reconstructive hypothesis proposed their use for food processing and consumption. The underground domed shape featured by a single frontal opening immediately suggested a connection with the traditional ovens used for bread baking or toasting cereals. This hypothesis is also based on the consistent presence of charred cereals found in some of these structures (Celant, 2013; Conati Barbaro, 2013, 2019; Conati Barbaro et al., 2019). Moreover, the results of the XRPD (X-ray powder diffraction) analysis of samples of hardened sediment collected along the inner walls of two archaeological ovens showed that the exposure of the structures to the fire did not exceed 500°C (Muntoni & Ruggiero, 2013), a quite low temperature for other Neolithic household activities such as pottery firing. Furthermore, the estimated firing temperatures of the site's coeval ceramic vessels indicate values between 700 and 950°C (La Marca et al., 2017).

Nevertheless, the large size of the archaeological structures and a considerable number (146) of ceramic spalls (La Marca, 2019, p. 107) (Figure 4) suggests a potential role of these pyrotechnological structures for firing or drying vessels. As a matter of fact, clay vessels may be damaged by spalling during drying by heating phase or during the early stages of pottery firing (ca. 100–200°C; Figure 4). This phenomenon consists in the detachment of superficial fragments, of circular, sub-circular, or elongated shape, caused by two not necessarily related conditions such as (1) presence of air bubbles forming during a fast shaping process and (2) the unintentional exposure of a clay vessel to a sudden change of the temperature during firing (e.g. direct contact of the portion of a vessel with the flame) (Gibson & Woods, 1997, pp. 24–26). In both cases, the damage is due to thermal stress. Thus, finding spalls close to a heating area or the negative of spalls on pottery can be considered evidence of damage during the early stages of the firing process, excluding such a damage as a consequence of cooking activities.

The evidence of thermal spalling leads to exploring a range of household activities likely practised at Portonovo (baking, toasting cereals, cooking food, as well as pottery firing) through the lens of experimental archaeology. Moreover, further archaeometric analyses were carried out to test and experience the efficacy of the underground ovens and understand if the Portonovo ovens were multipurpose or specialised structures.

4 Experimental Framework

The experimental process was carried out in two steps. In 2016, the oven's replica was made, and some preliminary cooking and pottery firing (Section 4.6A, prevalent reducing atmosphere) experiments were performed (Conati Barbaro, Forte, & Rossi, 2020). These preliminary experiments allowed us to experience the efficacy of this kind of oven in cooking or firing pottery and to establish a suitable temperature recording system. Indeed, the deepness of the ovens and the only narrow frontal opening make temperature monitoring difficult.

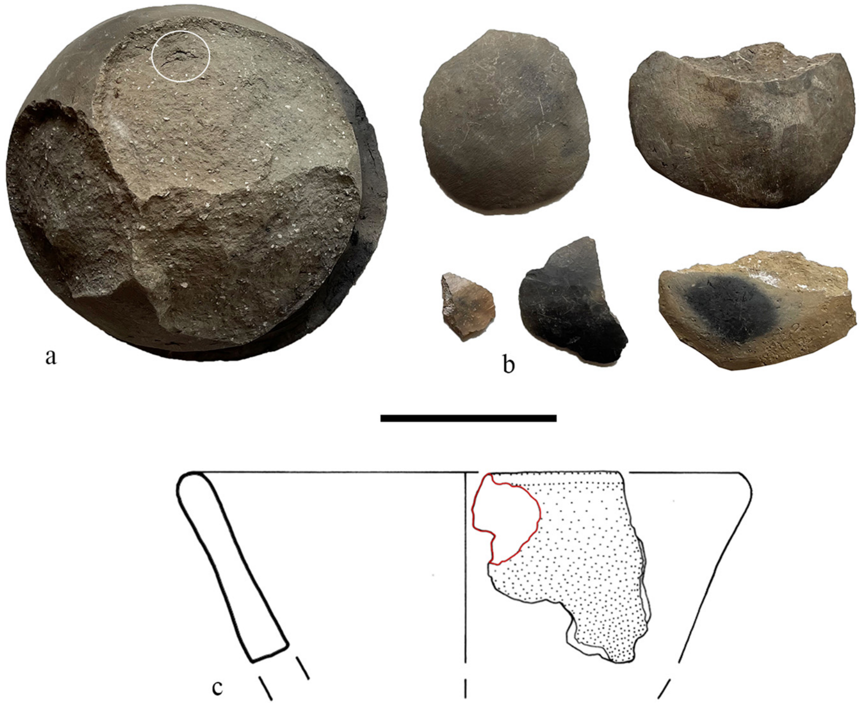

Figure 4: Experimental and archaeological spalls. (a) Negative of multiple spall detachments localised along the bottom and walls of an experimental clay bowl (trace of an air bubble causing the spall highlighted in white); (b) experimental spalls of diverse size and shapes; (c) illustration of an archaeological ceramic fragment from Portonovo with a negative of spall detachment highlighted in red. The experimental examples a and b are part of a reference collection of pottery firing of Vanessa Forte. Black bar is 5 cm.

A second experimental framework of pottery firing (Section 4.6B, prevalent oxidising atmosphere) in 2019 was carefully monitored by placing four thermocouples in specific spots of the structure.

4.1 Oven Preparation

To test the ovens' functionality, we replicated an underground structure of the same geometrical characteristics of the archaeological ones. Moreover, the experimental oven has been dug in the same geological formation as the archaeological specimens. This experiment allowed us to collect necessary information regarding the manufacturing process and the timing needed. We can currently state that the experimental reconstruction of one oven (1.9 m × 1.8 m in diameter at the base, 0.5 m in height; with an opening about 0.5 m large and 0.4 m high) took a total amount of 15 h of work by a single person (Figure 5(a)). Wood and bone tools have been used to excavate the natural sediment. The floor was regularised by spreading some water and smoothing it by hand. The oven's internal walls were consolidated with a heating process during which no use activities (e.g. cooking) were performed. During this step, a fire was lit outside the opening, and it was gradually moved inside the oven to preheat the cavity and avoid cracking. The consolidation process continued gradually moving the fire towards the centre of the oven. A temperature of 230°C was registered on the floor after about 5 h and 590°C in about 7 h. Temperatures were measured with one thermocouple during all the experimental phases (Conati Barbaro, Forte, & Rossi, 2020).

4.2 Fuel

According to the anthracological determination of charcoals from the archaeological ovens (Celant, 2013), only holm oak (*Quercus ilex* cf.) and hornbeam (*Ostrya carpinifolia*) were intentionally selected and used as

Figure 5: Experimental activities: (a) excavating the oven's replica, (b) cooking meat using clay andirons, (c) roasting barley, and (d) unleavened bread baked in the experimental oven (© Portonovo Project).

fuel. Indeed, these *taxa* have a hard, compact wood that burns slowly, producing long-lasting heat. The complete results of the anthropological analysis are not yet published; however, the botanical remains also include other species such as *Cornus* sp., *Buxus sempervirens*, and *Phyllirea/Rhamnus*, and in lower percentages (Celant pers. comm.). Therefore, only oak and hornbeam were used to consolidate the oven's replica and the following cooking and firing experiments. Logs and branches were chosen as the main load, while twigs were employed for starting the fire. The weight of the wood was recorded only during the oxidising firing experiment in 2019. A total of 150.2 kg of wood was needed to complete the experiment.

4.3 Temperature Measurements

Temperatures were registered during all experiments (oven's consolidation, cooking, baking, toasting, and pottery firing) through thermocouples. In 2016, only one thermocouple was used, and the temperature was recorded manually at regular intervals. In 2019, four thermocouples connected to a data logger were employed to measure temperature in different parts of the oven (Figure 8).

4.4 Temperature Estimation

The estimation of the maximum temperatures recorded by the oven's inner surface during both firing experiments in 2016 and 2019 and by the fired pottery was made after the mineralogical data obtained by XRPD (Table 1). The XRPD spectra were acquired using a Panalytical diffractometer Philips X'pert Pro, with Ni-filtered CuKα radiation, and analysed using the software X'Pert High Score 3.0, which includes ICSD

Table 1: Characteristics of the experimental samples and estimated maximum temperature

Sample	Experiment	Type	Position	Minerals*	Max *T* (°C)
PFO50	2016	Oven	Vault, centre-left	Ill/Ms, Chl, Cal, Qtz, Pl, Kfs, Hbl	<550
PFO51	2016	Oven	Vault, centre-right	Ill/Ms, Chl, Cal, Qtz, Pl, Kfs, Hbl	<550
PFO52	2016	Oven	Floor, centre	Ill/Ms, Chl, Cal, Qtz, Pl, Kfs, Hbl	<550
PFO53	2016	Oven	Vault, centre	Ill/Ms, Chl, Cal, Qtz, Pl, Kfs, Hbl	<550
PFO54	2016	Oven	Floor, opening centre	Ill/Ms, Chl, Cal, Qtz, Pl, Kfs, Hbl	<550
PFO100	2016	Oven	Floor, left side	Ill/Ms, Chl, Cal, Qtz, Pl, Kfs, Hbl	<550
PFO101	2016	Oven	Floor, opening left side	Ill/Ms, Chl, Cal, Qtz, Pl, Kfs, Hbl	<550
PFO102	2016	Pottery	Wall	Ill/Ms, Chl$^{\#}$, Cal$^{\#}$, Qtz, Pl, Kfs, Hbl	600–800
PFO103	2016	Pottery	Wall	Ill/Ms, Chl$^{\#}$, Cal$^{\#}$, Qtz, Pl, Kfs, Hbl	600–800
PFO105	2019	Oven	Termocouple 2	Ill/Ms, Chl, Cal, Qtz, Pl, Kfs, Hbl	<550
PFO106	2019	Oven	Termocouple 3	Ill/Ms, Chl, Cal, Qtz, Pl, Kfs, Hbl	<550
PFO107	2019	Oven	Floor	Ill/Ms, Chl, Cal, Qtz, Pl, Kfs, Hbl	<550

*Mineral abbreviations: Ill/Ms = illite/muscovite; Chl = chlorite; Cal = calcite; Qtz = quartz; Pl = plagioclase; Kfs = K-feldspars; Amph = amphibole; # = thermally alterated.

database. Since firing experiments introduce more variables than laboratory conditions, direct temperature measurements in the oven were useful to verify the accuracy of maximum temperature estimation after XRPD.

4.5 Cooking/Baking/Toasting

The experimental oven was used in 2016 to bake unleavened bread, toast barley grains, and cook meat at low temperature by removing the fire and the embers (Figure 5(b–d)). These activities were successfully carried out when the temperature reached 300°C while maintaining a fairly uniform heat throughout the oven.

As regards cereal toasting, the dry and warm environment allowed to succeed in this activity: indeed, the cereals can be toasted directly on the oven surface, once moved the embers laterally to the oven, or placing cereals within ceramic vessels.

4.6 Pottery Firing

After experiments associated with food processing and consumption, the oven was used for two pottery firings (A, "reducing" and B, "oxidising") to test the structure's efficacy and understand its functioning in relation to temperature variations. Both the experiments were carried out during spring to ensure similar weather and environmental conditions.

The experimental vases were made with the same local sediments used by the Neolithic potters (La Marca et al., 2017; La Marca, 2019). Vessel shapes were chosen among the pottery inventory of the archaeological site. Before all experiments, the oven was heated from the inside with fire to remove the ground's residual moisture. The sequence followed for both experiments included a gradual heating, the actual firing, and then the cooling step.

4.6A Reducing Firing

The potter may intentionally obtain a reducing atmosphere during all the pottery firing or the final steps. It consists of overproduction of smoke, low oxygen fugacity, and consequent incomplete fuel combustion.

Figure 6: Reducing pottery firing (A). (a and b) Heating step, (c) firing, (d) reduction step plugging the frontal opening with a mixture of clay and straw, (e) opening of the oven after the cooling phase, and (f) final result.

The abundant smoke absorbed by surfaces of the vessels causes the dark-brown colours typical of some prehistoric productions (Cuomo di Caprio, 2007).

During the reducing firing experiment, 13 pots made with the clay of local sources and previously dried at open-air have been preheated next to the oven's opening as soon as the fire was lit (Figure 6(a)). After preheating, pots were placed on the right side of the oven opposite the burning flame at 400°C. The embers were gradually moved toward the vessels until they were partially covered and adding fuel when necessary (Figure 6(b and c)). After 3 h, the temperature reached 800°C in the middle of the oven. At this point, the oven's opening was plugged with a mixture of clay and straw, leaving embers and pots inside overnight (Figure 6(d)). After opening 15 h later, the inside temperature was 250°C, and the pots were blackish-brown in colour, very hot, and uniformly fired (Figure 6(e and f)). The colour(s) of the ceramic surface records the thermal and redox conditions during the cooling phase of firing, mainly by the $Fe^{(+2/+3)}$ phases (Eramo & Mangone, 2019). Only one vase showed cracking along the bottom.

This first experiment allowed us to observe that these single opening' structures can easily reach temperatures higher enough to transform clay into ceramic.

4.6B Oxidising Firing

Oxidation is a condition of the pottery firing process that corresponds to the burning flame in excess of oxygen and the relative absence of smoke. If free iron phases are available, this produces the usual red-orange colour of the ceramic vessels (Cuomo di Caprio, 2007).

Figure 7: Oxidising pottery firing (B). (a) Preparation of the experiment and setting of the thermocouples, (b and c) heating step, (d and e) firing, (f) state of oven and vessels after the cooling phase, and (g) final result.

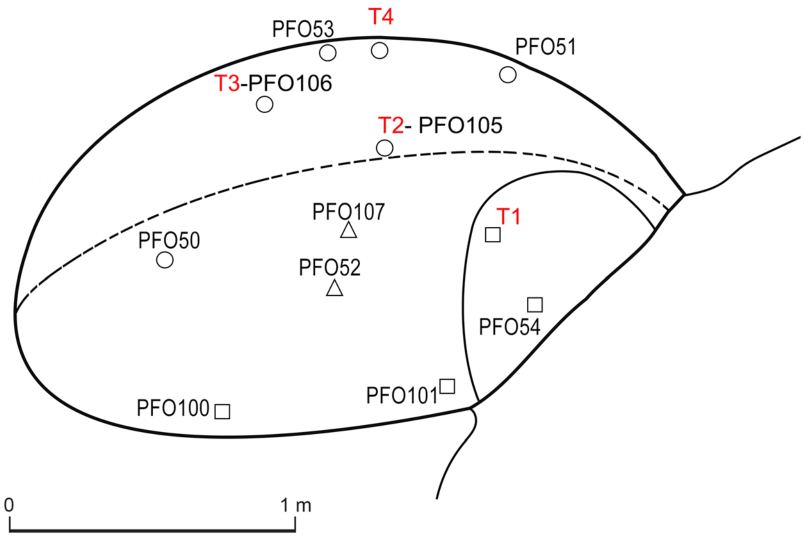

Figure 8: The experimental oven. Position of the analysed samples of hardened sediment (black) and thermocouples (red): circle = vault; square = floor; triangle = floor among vessels.

To understand the functioning of the structures even in relation to temperature dynamics, this second experiment of pottery firing was set with one thermocouple placed in the oven chamber and three thermocouples inserted into the natural soil for recording the temperature reached by the lining of the experimental oven (Figure 7(a)). Therefore, thermocouples allowed to record in detail the temperature evolution of the whole process. One thermocouple (T1) was located within the chamber, precisely in correspondence of the vessels to monitor the temperature in this area and record the approximate maximum temperature of pottery firing (Figure 8). Three thermocouples (2–4) were placed in three diverse spots of the dome to record the temperature reached by the sediment at the intrados. Each thermocouple was inserted deep in the ground until it reached the superficial layer of the dome: two of them (T2–3) were covered with a sediment of the same composition as the natural one and one (T4) was not covered and exposed to the dome environment. T2 was placed at 0.4 m from the opening, which is exactly between the fuel and the opening. T3 was placed at 1.09 m from the opening, corresponding to the fire, and T4 was located laterally along the dome, corresponding to the vessel's location, and precisely at 15 cm from T3 and 0.4 m from T4. The seven vessels were located on the right side of the oven opposite the burning flame, which corresponds to the same position used in the reducing experiment, and the embers were gradually moved until to cover the vessels (Figure 7(b and c)). A total of 150.2 kg of oak wood was burned. Once the thermocouple reached 750°C, a temperature enough to ensure the pottery firing, no more fuel was added to the fire, and the oven frontal opening was not closed (Figure 7(d and e)). The cooling step lasted all night until the following morning, when the uniformly fired vessels were collected (Figure 7(f and g)), all showing a reddish colour. No thermal damage was observed.

4.7 Pottery Firing Temperature Distribution

Thermocouples have allowed to measure the temperatures reached during the experimental pottery firing within the underground oven replica of 2019. The recording has enabled us to observe how temperatures were registered differently by the vessels and by the structure (Figure 9). Measures recorded by thermocouple 1, in correspondence with the vessels in the area closer to the fire, show that the range of temperature reached by the pottery was around 750°C, which is a suitable temperature for transforming clay into ceramic. Thermocouples placed within the dome (T2 and T3) and covered with a light layer of the same

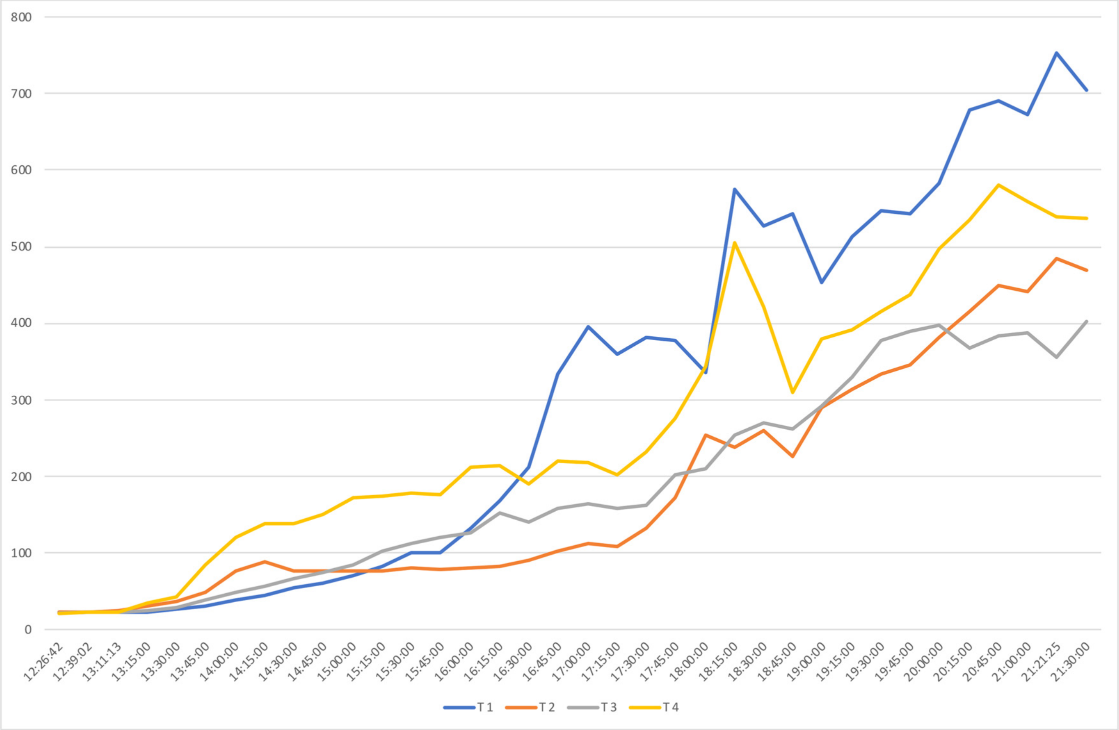

Figure 9: Temperature trend recorded in pottery firing experiment B.

sediment have recorded temperatures lower than 500°C (480 and 400°C, respectively). Such temperature values match with those estimated by the XRPD of lining samples (Figure 8).

Moreover, the samples' mineralogical content features illite/muscovite and chlorite as phyllosilicates, quartz, calcite, plagioclase, K-feldspars, and traces of hornblende (Table 1). The XRPD spectra of all the fragments collected from the oven's inner surface do not show significant differences from the unfired clay spectrum. The mineralogical evolution of marly clays during firing was extensively studied in laboratory conditions by several authors (e.g. Allegretta, Pinto, & Eramo, 2016; Cultrone, Rodriguez-Navarro, Sebastian, Cazalla, & De La Torre, 2001; Letsch & Noll, 1983; Maggetti, 1982; Maritan, Nodari, Mazzoli, Milano, & Russo, 2006; Peters & Iberg, 1978; Riccardi, Messiga, & Duminuco, 1999). It was shown that the temperature and firing atmosphere evolution over time may affect the stability field of the involved minerals. It should not be overlooked that mineralogical association and the microstructure observed in the ceramic body are the resultant of the whole firing process, mainly affected by the highest thermal impact. Since accurate modelling in time and space of outdoor experimental firing is hard to be obtained, the combination of measured (thermocouple) and estimated (XRPD) temperatures here applied was devised to overcome this kind of problem and provide a referenced dataset to interpret archaeological samples. The presence of (001) and (002) peaks of chlorite infers temperatures below 550°C. Conversely, thermocouple 4, placed within the dome but not covered with a clay lining, recorded a temperature of 580°C, higher than other thermocouples. These data suggest that the lining of the ovens and the ceramic vessels reached – and consequently recorded – the different firing temperatures during the firing process. According to the 2019 firing experiment, the pottery fired at least at 750°C, as recorded by the thermocouple placed among the vessels, while the lining reached and recorded temperatures lower than 550°C.

These data are also confirmed by the XRPD spectra of the ceramic vessels and lining samples selected from the firing experiment A of 2016 (reducing firing). In this latter case, the lining reached temperatures lower than 550°C, while the ceramic vessels reached maximum temperatures between 600 and 800°C, estimated after the disappearance of (002) peak of chlorite and the presence of calcite peaks.

5 Discussion

5.1 Temperature Distribution

The temperature distribution inferred by direct measurement and indirect estimation must be interpreted in the combustion framework. In wood firing, the heat transfer is mainly by convection unless the flame temperature is above 1200°C when the radiant heat becomes more and more effective. Moreover, the flame emittance (i.e. thermal energy emitted per unit area per unit time) decays significantly in few centimetres. It should also be considered that the amount of heat transferred by convection in a wood fire is directly related to the draft. In this kind of structure, the air input and the output of the combustion gas occur from the same opening, yielding a flux stratification: air on the bottom and combustion gas on the top. As shown in Figure 8, the vault's central and frontal portions are favoured for heating because of the hot combustion gases oriented outwards. The third way to transfer heat is conduction, and in our case, it involves the vault and bottom of the oven and the vessel bodies. In this way, it is not surprising that only the pots directly in contact with the flame record the highest temperatures since they have the lowest mass and receive more efficiently the heat than the oven's inner surface.

Moreover, an oven dug in the natural sediment has walls of virtually infinite thickness, which affects the system's heat loss (e.g. Eramo, 2005; Eramo & Maggetti, 2013; Hein & Kilikoglou, 2007). This suggests that even if the fire reaches a high temperature, the same temperature is not recorded by the lining of the ovens as suggested by the results of the XRPD of the lining and the temperatures recorded by the thermocouples. According to these data, the lining can reach and record diverse temperatures, which can change in relation to the position and the intensity of the fire within the oven.

5.2 Experiencing Oven's Function: Some Practical Observations

The results of the experiments allowed us to test the functionality of the Portonovo ovens. Independently by the temperature reached, it was possible to prove that these firing structures work even in the absence of a vertical hole for the draft. The frontal opening is the only way for oxygen to come in and feed the flame and at the same time to expel the combustion gases. The main difficulty during the heating of the structure and the firing process was starting the fire. We observed that the more straightforward solution is to light the fire in front of the opening, or in the area immediately around it, where oxygen is enough to feed the flame. Then, it is gradually moved within the oven. If this operation is fast, the risk is that the flame goes out, especially if it is moved along the side of the structure where the lower fugacity of oxygen causes a reducing and smoky atmosphere and makes the operations difficult.

The process of pottery firing requires a specific sequence for accomplishing a gradual and successful process. However, we noticed that the most challenging step in experiencing pottery firing within underground ovens is the starting phase due to the difficulty of managing fire and pottery from the frontal opening. The following steps required a lower effort, especially once the fire reached a higher temperature, and more fuel is necessary (Figure 7(e)). The oven structure proved suitable for firing pottery in both “oxidising” and “reducing” regimes, particularly the reducing one, as the managing of the frontal opening creates an oxygen-poor and smoky environment and vessels with black surfaces easily (Figure 6(f)).

We also experienced that the large pit immediately in front of the oven was necessary to first excavate the cavity itself (Conati, Forte & Rossi 2020) and then for the operations foreseen during the use activities, from fuel management to the loading of food or materials to be cooked.

6 Conclusions

The experimental plan and the mineralogical analyses carried out on seven samples of the oven's inner surface, and two samples of pottery fired in it allowed to verify the hypothesis of multipurpose use of these ovens. Furthermore, it was possible to compare the temperature values estimated on the archaeological ovens and pottery with the temperatures registered on the experimental ones.

One of the main questions is whether these structures could be used for pottery firing in addition to cooking and processing food. Indeed, the presence of thermal spalls in the Portonovo pottery assemblage leads us to assume that ovens were in some way connected to pottery firing. Interestingly, the fragments with spalls were found in a single context, i.e. inside oven 13 and in the related access pit US 1103, chronologically referable to a late phase of the site, when two ovens have been used as tombs after losing their primary function. Therefore, it could be assumed that in the late phase of the site's occupation, the ovens could be adapted to new purposes, including the firing of pottery.

The temperatures here measured and estimated during the diverse experimental activities agree with those of La Marca et al. (2017) as for pottery and with Muntoni and Ruggiero (2013) for the ovens.

A comparison between the temperatures estimated by XRPD and the temperatures measured with thermocouples during the experiments puts in evidence a bias that is the consequence of, at least, the modes of heat transfer and the relative position to the fire.

The experiments suggested that this kind of oven works through a draft system through the frontal opening as observed during activities such as heating the structure or firing with a burning flame.

Once learned the sequence necessary to start and manage the fire within these structures, it is possible to accomplish diverse food processing activities. The structure is suitable not only for toasting cereals but also for processing foods by smoking. The oven's large floor can be easily used to cook meat on embers or a variety of food within ceramic pots placed on top or laterally to the embers or the burning flame.

Nevertheless, the experiments conducted in 2016 and 2019 allowed us to test the pottery firing within the underground structures. The experiments' positive results suggest that these structures are generally suitable also for pottery firing and drying, reaching medium temperatures considered suitable for prehistoric productions. Moreover, the experimental framework results proved that the temperature reached by the lining cannot be considered alone as an indicator of the activities practised within the ovens. Indeed, during firing, the experimental pottery reached higher temperatures than the ones recorded simultaneously by the termocouples localised in diverse spots of the lining and within the dome. These data, along with the identification of the ceramic spalls, suggest that the underground ovens of Portonovo, especially during recent occupation phases, could have been used as multipurpose structures.

Acknowledgments: Our deepest thanks go to Alberto Rossi for his support during the experimental reconstruction of the oven and pottery firing.

Funding information: Funding was provided by Sapienza University of Rome, Istituto Italiano di Preistoria e Protostoria Project 'Science for prehistory', and FFABR Grants – MIUR.

Author contributions: Cecilia Conati Barbaro: project supervision, investigation, funding acquisition; Vanessa Forte: experimental archaeology; Italo M. Muntoni and Giacomo Eramo: archaeometric analyses. Par. 1, 2, 3 were written by C.C.B.; par. 4.1, 4.2, 4.3, 4.5, 4.6, 5.2 were written by V.F.; par. 4.4, 4.7, 5.1 were written by G.E., I.M.M.; par. 6 was jointly written by all authors.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: All data generated or analysed during this study are included in this published article.

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