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Experimental Archaeometallurgy of Early-Middle Bronze Age Cyprus: Pilot Experiments of Copper Smelting at Pyrgos-Mavroraki

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Pyrgos-Mavroraki, an early 2nd millennium BC proto-industrial settlement, is an excellent case-study on which to apply experimental archaeometallurgy because it presents many different elements connected to the *chaine-operatoire* of copper metallurgy, typical of

Early/Middle Bronze Age Cyprus. The site excavated by the Italian Archaeological Mission of the ITABC-CNR of Rome (Institute for Technologies applied to the Cultural Heritage of the Italian National Research Council), revealed different metallurgical areas and a coppersmith workshop equipped with a set of basalt anvils (Belgiorno, 2017). The combination of the metallurgical evidence of the entire copper processing (crucibles, moulds, anvils, stone tools), the huge presence of non-tapping slags all over the site and the identification of several structures interpretable as furnaces, suggested that some sort of smelting process took place at Pyrgos-*Mavroraki*. Some pilot experiments have been preliminarily carried out to test the construction technique, shape and thermal behaviour of the furnaces during a smelting process using different fuels. The simple, but important outcomes of these experiments will be essential to design an accurate protocol for the systematic experimental studies of the archaeometallurgy of this site (objective of a Northern Bridge Training Partnership funded PhD at Newcastle University).

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Experimental Archaeometallurgy and Pilot Experiments

Experimental archaeology applied to archaeo-metallurgical studies (experimental archaeometallurgy) has revealed itself as an essential tool to verify scholars’ hypotheses on the technological processes involved in ancient metallurgy. Experimental archaeometallurgy is a specialist field within experimental archaeology. Examples of this kind of approach can be dated back to the end of the nineteenth century (Cushing, 1894), far earlier than the formal foundation of modern experimental archaeology.[1] This discipline was subject to important developments in the 1970s in terms of contexts and methods (Tylecote and Merkel, 1985), due to the discovery of important ancient metallurgical sites such as Timna in Israel (Tylecote and Boydell, 1978; Merkel, 1977, 1990; Ghaznavi, 1976; Tylecote, Ghaznavi and Boydell, 1977; Bachmann and Rothenburg, 1980). An increasingly large number of archaeometallurgists have decided in the last decades to use experimental archaeology, beside other archaeological sciences, to confirm or refute some of their hypotheses on metallurgical contexts.

Experimental protocols have been designed for every metallurgical field, from ore mining (Timberlake, 2007); ore smelting (Merkel, 1990; Doonan, 1994; Fasnacht, 2009; Bunk *et al.*, 2004; Pryce *et al.*, 2007; Doonan and Dungworth, 2013) and the casting and refining of artefacts (Timberlake, 2013; Barbieri *et al.*, 2015), to even the last use (applying experimental archaeology to the study of use-wear analysis) of the same artefact (Dolfini and Crellin, 2016; Heeb, 2014; O’Flaherty, 2007; Molloy, 2004).

The characteristics of every single experimental research protocol depend on different factors among which is essential to remember: the hypothesis we want to test, the specific questions we want to answer and the archaeological and analytical data we have.

The Archaeological Context

Pyrgos-Mavroraki is an Early/Middle Bronze Age site on the Southern coast of Cyprus, in the territory of Limassol. Pyrgos was excavated by the Italian Archaeological Mission of the ITABC-CNR from 1998 to 2012 under the direction of Dr Maria Rosaria Belgiorno (Belgiorno, 1998; 1999a; 1999b; 1999c; 2000; 2009). The site is located in the Northwest area of the modern village of Pyrgos, at the foothill of *Mavrorachi*. The surveys that lead to its discovery started in 1996, following the hints provided by the already known necropolis of Pyrgos (Belgiorno, 1997; 2002).

The geological map of the area shows clearly the position of Pyrgos on the copper ores deposits (in purple) (See Figure 1). The most important ore formations nearby the site are Pevkos, Mazokambos and, further to the East, Kalavasos (Bear, 1963)

The archaeological site appears as a vast architectural complex, characterised by several structures and rooms whose stone foundations are still visible. The vast complex (2000 m² ca) is probably the industrial area of a bigger settlement, as it appears to be confirmed by the geophysical investigations carried out by ITABC-CNR (Gabrielli *et al.*, 2004).

The site produced a lot of artefacts, such as pottery and stone tools that match quite accurately with the material from the necropolis and can be dated to the Early/Middle Bronze Age of Cyprus (2200/1800 BC). These dates are confirmed by the radiocarbon dates calculated by the laboratory of La Sapienza University in Rome (Calderoni, 2009).

Among the structures excavated, Belgiorno (2009) identified several workshops, including what has been interpreted as an olive press, a textile-making workshop, a jewellery workshop, and a perfume 'factory'. Beyond the food production, olive oil is essential in the textile production for the wool processing; it has also been used in the production of perfumes and cosmetics.

Among all the activities identified within the workshops of Pyrgos, the most evident was metallurgy, for which we have a series of eloquent indicators, including about 1500 fragments of slags that look very rough and different from the Late Bronze Age Cypriot slags obtained by the tapping method. Three main metallurgical areas were identified: the Northern Court (See Figure 2, A), the Southern Court (See Figure 2, C) and what the excavator recognised as a coppersmith workshop (See Figure 2, B).

Mainly two kinds of furnaces, shaft and pit, have been identified. Pit furnaces at Pyrgos are usually simple holes excavated into the earth. Two of these furnaces have been found with a peculiar little jug built in the hearth rim, with the spout facing the internal combustion chamber and the belly, broken toward the surface of the rim. This unusual feature, in addition to the analysis of the burnt soil around the furnaces which confirmed the presence of olive oil, led the excavator to suggest that this device could have worked as a carburettor for the use of olive oil as fuel or, more likely, fuel additive (Belgiorno, 2017, pp.18-24).

Other metallurgical features are the moulds (2 integral), blowpipe-nozzles and a rich repertoire of stone tools and grinders, comparable to the stone tools found at the Cypriot Middle Bronze Age metallurgical site of Ambelikou-*Aletri* (Webb and Frankel, 2013, pp.73-151).

The area identified by the excavator as the blacksmith workshop is characterized by a squared structure defined by big calcarenite plates, possibly used for the annealing Pilot experiments have been carried out on the two different types of furnace: the pit furnaces (mainly found in the Southern Court) and the shaft furnace (from the Northern Court).

Archaeometry

The "Pyrame" (Pyrgos Archaeological and Archaeometallurgical Research) research project carried out on the site (Belgiorno, 2000) with the aim of the identification and preservation of the archaeometallurgical evidence found at Pyrgos involved a preliminary archaeometric study of some slags and artefacts, both from the settlement and from the necropolis. Several analyses were carried out on artefacts (Giardino, Gigante and Ridolfi, 2002), but the large amount of slags found at the site deserves a great amount of attention.

Some preliminary archaeometric analyses (ED-XRF; XRD; OM; SEM-EDX; FTIR) carried out on 5 slags from the Northern Sector (H-I-J/2-3) suggest that the smelting performed at Pyrgos involved mainly copper sulphide ores, within an oxidizing atmosphere, indicated by the presence of magnetite (Giardino, 2000, p.23; Giardino & Rovira, 2007, p.3).

Externally these slags usually appear non-homogeneous, very rich in copper (they are characterized by greenish veins and prills) and with a "chunky" shape that suggests they have been solidified inside the furnace (Giardino, 2000, p.21), very different from the later, more liquidous, types of slags which appear much more liquidous, formed outside the furnace due to a "tapping" technology.

They appear very different from the slags found in the nearby Late Bronze Age metallurgical sites of Kalavassos-*Aghios Demetrios* or Alassa-*Paliotaverna* (Van Brempt and Kassianidou, 2016), obtained with a "tapping" technology inside furnaces that probably could reach higher temperatures and produce more liquid discharge. The fact that these slags are never larger than 10 cm (Belgiorno, 1998, p.296) and usually fragmented, seems to be due to the crushing processing necessary to collect all the copper prills trapped in their glassy matrix (Giardino, 2000, p.23). This hypothesis is supported by the vast amount of stone tools such as grinders, mortars and pestles, recovered all over the site, especially nearby the furnaces.

A more careful, focused and articulated study of slags from all the metallurgical areas of the site is essential to identify their macro and micro characteristics and peculiarities and put them in a wider context.

The First Series of Pilot Experiments

The first experiments were performed by the founder of the Centre for Experimental Archaeology Antiquitates, in Italy (member of EXARC since 2003), Mr Angelo Bartoli, who passed away prematurely on the 25th of February 2014. Mr Bartoli started his experiments on the pit-furnaces in 2006, considering as a model the pit-furnace found in J7 with the carburettor/jug, which shows the clear traces of high temperature exposure. This pilot experiment was carried out at Antiquitates in 2006-2007, unfortunately without the possibility to use Cypriot ores, nor Cypriot building material. Mr Bartoli tested also the structure found in J4, interpreted as a shaft-furnace, reconstructing a similar reactor on-field at the site of Pyrgos, using the autochthonous malachite, (Bartoli and Cappelletti, 2009, pp.142-148).

In J4b a new possible type of furnace was found. It appears as a shaft-shaped furnace, with a stone circle of 50 cm (with an internal room of 25 cm circa) circa height and 35 cm circa diameter. The basis of the circle is made by massive basalt stones, with an upper portion of the wall made in calcarenite stones. The structure has been recovered full of a thick level of ashes and burnt soil (Belgiorno, 2009, p.79).

No airing conduits were found, except a possible opening facing the sea, so the furnace has been built facing the direction of wind. A new pilot-experiment was performed directly on-site at Pyrgos. The autochthonous ore was used for this experiment: malachite formations on green *basaltina* have been crumbled and put in a normal modern pottery vase used as crucible. After starting it with a few small branches, the furnace was run by olive oil, gently added from a small opening on the top of it, using a small bowl. The temperature reached Measured with a thermo-couple chrome-vanadium IEC 584 CR-ALK and a thermometer HANNA HI-93530.
850° without the aid of any air introduced by bellows. The fusion-conglomerate obtained was composed by a black silica matrix, containing copper drops (Bartoli and Cappelletti, 2009, pp.154-156; Bartoli and Romeo Pitone, 2017, pp.171-172). Other pilot experiments have been carried out in 2010 by Belgiorno and her collaborators on the pit-furnaces (Belgiorno, Derro and Loepp, 2012, p.31; Belgiorno, 2017, p.22).

Although, as already pointed out (Bartoli and Romeo Pitone, 2017, p.171), due to a series of inaccurate variables considered at the time (the rough materials, ores and lack of a specific protocol), the above-mentioned experiments should be considered most reliable regarding the behaviour of the furnaces' shapes and fuel, more than for the actual smelting result.

After the premature loss of Mr Bartoli, a new series of experiments was conceived and performed by the author and his team: Cristina Alisi, Eleonora Colasanto, Rina Corzani, Edoardo Gomez, Martina Moneta and Floriana Ortenzi. The author would like to acknowledge the initial precious support provided by Georges Verly to restart the experimental researches at Antiquitates.

In 2014-2015, because of the lack of direct experience, a new series of pilot experiments had to be executed, mainly to test the construction technique, shape and thermal behaviour of the furnace during a smelting process.

The Second Series of Pilot Experiments: Structure and Preliminary Results

The first series of pilot experiments set by Mr Bartoli aimed to test and validate the hypothesis of the use of olive oil to reach temperatures useful for the smelting operations, both with and without the addition of any artificial air.

The information provided both by the pilot-experiments previously performed, and the preliminary archaeometric investigations on the slags from Pyrgos, represented a promising starting point from where new trials and hypotheses could be drawn.

This second series of experiments took place in 2014 at Antiquitates and in 2015 at the Archeosite in Aubechies (Belgium). It comprises one roasting experiment and three roasting/smelting trials using a shaft-furnace, built according to the specifications of the one found in J4.

The experiments assumed the above-mentioned shape of the furnace recovered on the site is the original one (See Figure 3). It is possible that what we see today is just what remains of the furnace's lower section, which could have an upper portion of the walls made simply by mud-bricks, as the coeval general architecture of the settlement suggests (See Figure 4).

In the attempt to remain as faithful as possible to the original structure, big basalt (for the base) and calcarenite (for the upper level) blocks were used to build the furnace, joined by a simple earth-mortar made with clay-less silt (considering the very low presence of clay in Pyrgos's soil). The basalt blocks were gently donated by the quarry "Basalti Orvieto", and the silt was donated by "Calcestruzzi FANANO di Fanano Lorenzo, Franco & C. s.n.c." towards which goes our deepest gratitude. The calcarenite was collected from a natural deposition on the way which take from Terni to Rieti (Italy).

Three fuels have been tested during the experiments: dry pinewood, olive oil (as a starter/additive for the wood) and olive pomace (probably largely available in an olive-oil producing site, and, being a discard product, not precious as the actual oil). Compared to previous pilot experiments, the main novelties of this second series of trials were the use of the sulphidic copper ore as Chalcopyrite (from Congo), which requires a multistep roasting-smelting process, and the record of the thermal data collected during the experiments. A series of videos for each phase of the experiment has been recorded. Despite what is stated by the excavator (Belgiorno, 2017, p.24), the choice to use Chalcopyrite was taken due to the preliminary chemical analyses carried out on the slags from Pyrgos-Mavroraki (Giardino, 2000; Giardino and Rovira, 2007), confirmed by the more recent ones performed by the author, which clearly show that sulphidic ores were used.

A roasting process was performed on 5 kilos of ore. The mineral, once crushed (fragments < 3/4 cm) using two basalt blocks as mortar and pestle, was placed in an open fire set on a rock (pepperino) slab with new pine wood. The process lasted more than 12 hours, trying to maintain an average temperature of between 500° and 900°. The temperature was measured in the central area of the bonfire, where the crushed ore has been positioned. To record the temperature data, a thermos-couple chrome-vanadium IEC 584 CR-ALK and a thermometer HANNA HI-93530 were used during all the experiments. The highest temperature reached was 853°, whereas the lowest one was determined by fuel addition (See Table 1)), with an average disparity between the central and the peripherical areas within the bonfire of circa 100°.

After the roasting experiment and breaking some of the ore fragments, it was possible to observe that they were covered in a thin dusty dark layer, never exceeding 3mm of thickness, while inside they all presented a homogeneous dark-mauve colour. The only exception was a bigger fragment of ore (30x7x6cm), which maintained almost unchanged its internal colour. Another useful observation was that after the complete extinction of the fire, the only material evidence left by the roasting activity was a very thin layer of ashes, which confirmed the difficulty of identifying in the archaeological record a roasting pit, in absence of more complex structures. The validity of olive oil and olive pomace as fuel additives was confirmed by this experiment in a temperature increase at every addition, but pomace, due to its small grains (crushed olive stones) prevent a good oxygenation, so it has been discarded. It should be worth it to test this fuel under another shape, such as keeping the olive stones integral or maybe arranged in pellets.

The following six experiments were then dedicated mainly to smelting trials. The purpose of the first experiment was mainly to test the behaviour/resistance of the furnace. It lasted two hours and a half during which it was possible to observe that the combustion chamber was red in the back, indicating good oxygenation, and white in the hotter frontal area. The limo-lined walls did not undergo a lot of damage due to the heat, except for the upper level of the walls which were slightly cracked. The second experiment lasted two hours and aimed to test the possibility of using the furnace for a two-phase “roasting/smelting” metallurgical process.

The other experiments lasted between 2 and 5 hours, 2 kilos of non-roasted ore were used (adding some silicates in exp. 1 and 2 as flux) for each experiment. The fuel used was dry wood and, in the case of the last three experiments, olive oil as an additive. While the first experiment was carried out without any artificial airing system, all the other ones were performed using two blow-pipes initially, and one or two wood and leather bellows afterwards.

The main preliminary results obtained after these pilot experiments can be summarised as follows:

- The materials used to build the furnace, particularly the limo mortar, showed a great resistance to the heat;
- The blowpipes didn't allow the system to reach the necessary temperature, which was obtained instead using the bellows. This aspect is quite problematic, due to the absence of proper tuyères at Pyrgos (just three nozzles for blowpipe), and, in general, the absence of testified presence of bellows in Cyprus before the Late Bronze Age (Kassianidou 2011;
- The use of silicates as flux didn't work as expected;
- The addition of fuel to the furnace hugely affected the temperature of the combustion chamber (See Table 1), suggesting for the future to pay more attention to the size of the fuel and the modality of addition;
- Overall maintaining the necessary temperature, was made very difficult by the open shape of the furnace.

These simple, but important, outcomes will be essential in the design of an accurate research protocol to carry on experimental studies on the metallurgy of Pyrgos-Mavroraki.

The New Research Protocol

As stated before, the pilot experiments carried out until now were not designed, nor conceived, to keep control of all variables under a strict scientific protocol. It is relevant to stress the importance of taking into account all the variables and data because the experiment could give a possible final result, which still won't necessarily represent the original context (Thomas, 1999, p.181; Forrest, 2008, p.64), but will certainly refute other hypotheses (Shimada, 2005, p.618)

Although, the outcomes presented in this paper lead the author to carry on the investigations within a more academic environment. A brand-new experimental project has been planned within a PhD at Newcastle University, aimed to reconstruct the complex series of actions, gestures, and technological processes that were involved in the ore-processing, smelting and casting at Pyrgos-Mavroraki through a combination of archaeological, analytical and experimental work.

The first stage of the new project will be dedicated to the slag-analysis. A large amount of information can be obtained from the study of this category of archaeological material as every year the analytical methodologies seem to become more accurate (Bachman, 1982; Hauptmann 2007; 2014). A new archaeometric plan has been set up to improve the limited knowledge we have in regards of the nature of Pyrgos's slags. A sample of more than 160 slags will be considered for auto-optical and microscopic analysis. After the accurate auto-optical analysis and the creation of a digital catalogue of the several slags from the major metallurgical contexts of the site, they will be primarily divided considering their external shape and appearance. Their weight and density will be measured in order to distinguish the samples richer in metals (probably result of a first smelting) from the more glassy ones. The most relevant samples, chosen from each one of the categories originating from the preliminary analysis, will be cut and prepared for microscopic analyses. After recording of the standard digital macro images, each sample will be investigated by petrography through OM in order to build a satisfactory selection for the SEM-EDX analyses. OM, SEM-EDX and petrographic analyses of both ores and slags will provide essential information to confirm the kind of copper mineral used in the metallurgical process or if a mixed-charge of different ores was adopted for the smelting. Aside from the slag analysis, all the artefacts involved in the metallurgical process will be studied.

The data collected from the slag-analysis will provide useful information to determine the material conditions and working parameters of prehistoric ore processing, smelting, and copper refining and to formulate hypotheses.

Each hypothesis will then be tested by archaeometallurgical experiments, designed with a strict protocol, and properly described and recorded to make them repeatable, following the latest tendencies in Experimental Archaeology (Shimada, 2005). Different variables will be taken into account and monitored during each experiment, and the data collected will be compared with the archaeological data. The main research questions will cover the following topics: the thermo-physical behaviour of the copper ore, the treatment of it to extract the metallic copper, the shape of furnaces, and the fuel employed.

Conclusions

The pilot experiments performed to preliminarily test the ancient metallurgical technology used at Pyrgos-*Mavroraki* produced a series of interesting information. These results alone cannot provide consistent answers in the archaeological study of this site but can certainly contribute to the general investigation on the archaeometallurgy of Pyrgos. The pilot experiments presented in this paper will facilitate, indeed, the selection of the most relevant variables to be taken in account during the planning of the new research protocol used for the next experiments. Certain choices adopted during the pilot experiments were revealed to be wrong, this will lead to a better design of the experimental structure. In this way, a considerable amount of time will be saved, and our attention will focus on the accurate collection and recording of the experimental data.

1 Usually intended with the publication of John Cole's notorious handbook: Archaeology by Experiment (Coles 1973).

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copper
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Gallery Image

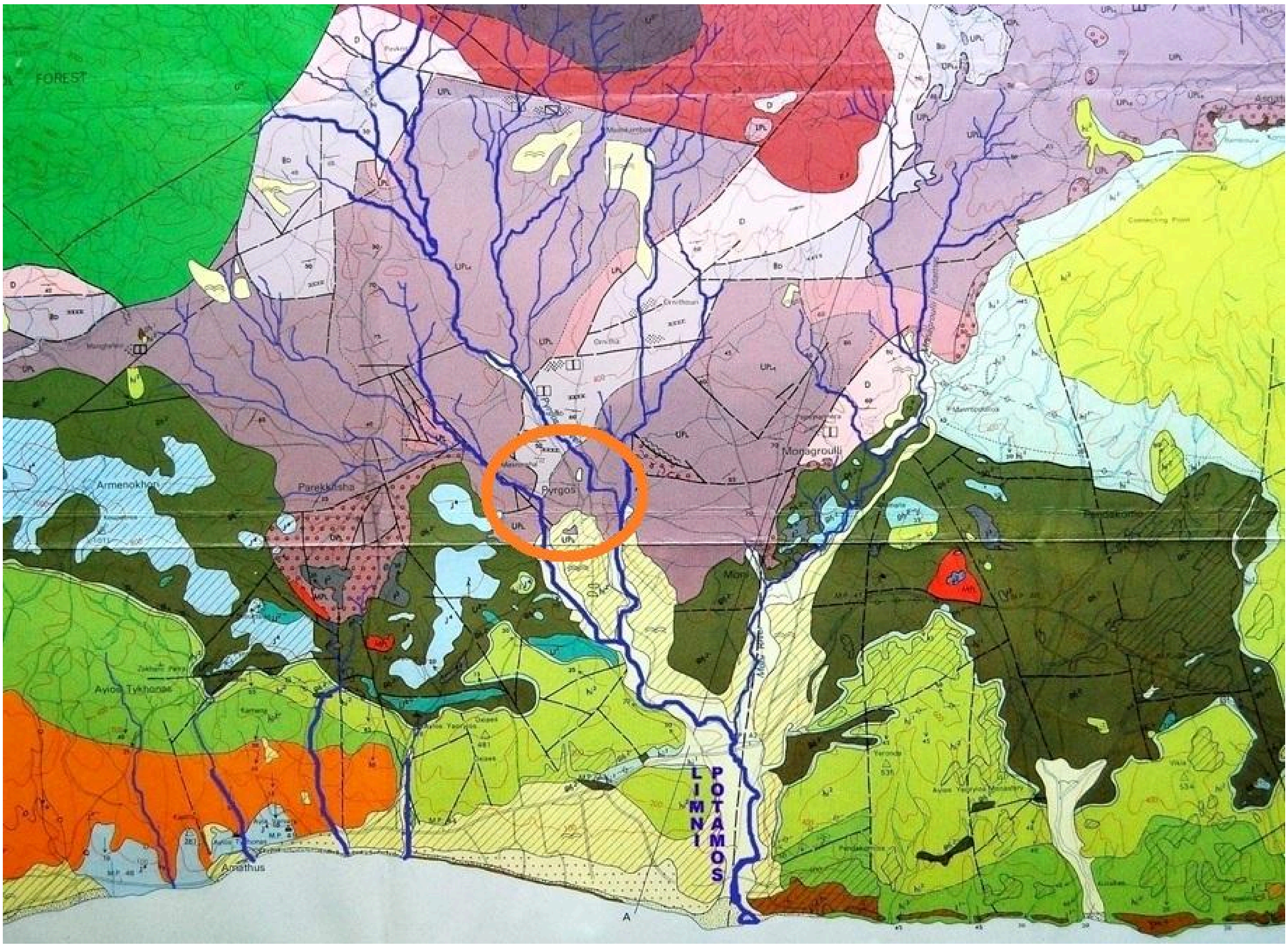

FIG 1. GEOLOGICAL MAP OF PYRGOS AREA. READAPTED FROM THE GEOLOGICAL MAP OF THE PHARMAKAS-KALAVASOS AREA, GEOLOGICAL SURVEY DEPARTMENT OF CYPRUS.

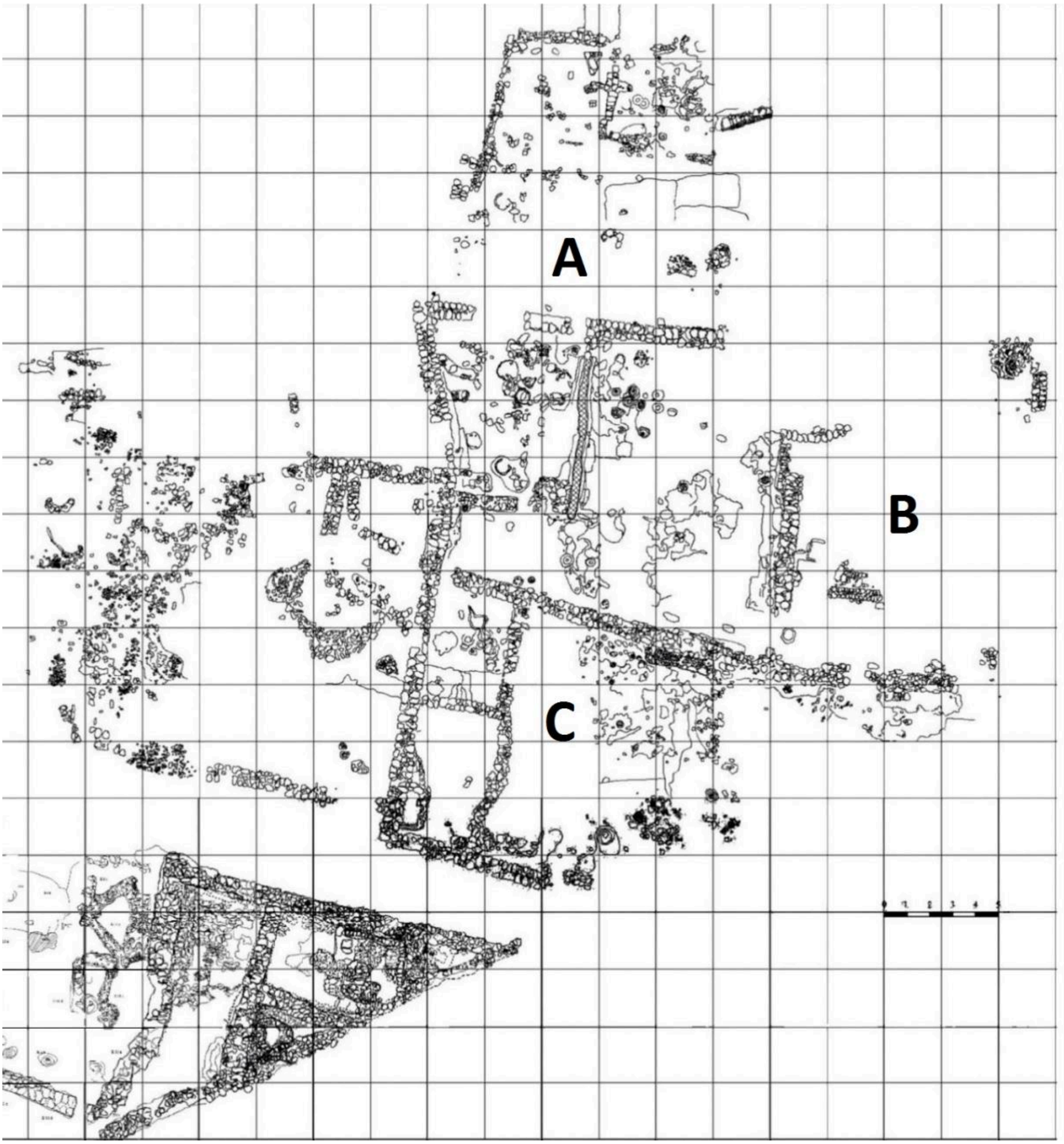

FIG 2. PYRGOS-MAVRORAKI SITE PLAN. READAPTED FROM BELGIORNO 2017, P. 13, FIG. 9.

FIG 3. SHAFT-FURNACE IN J4, PYRGOS-MAVRORAKI. (PICTURE BY THE AUTHOR, SCALE: 25CM).

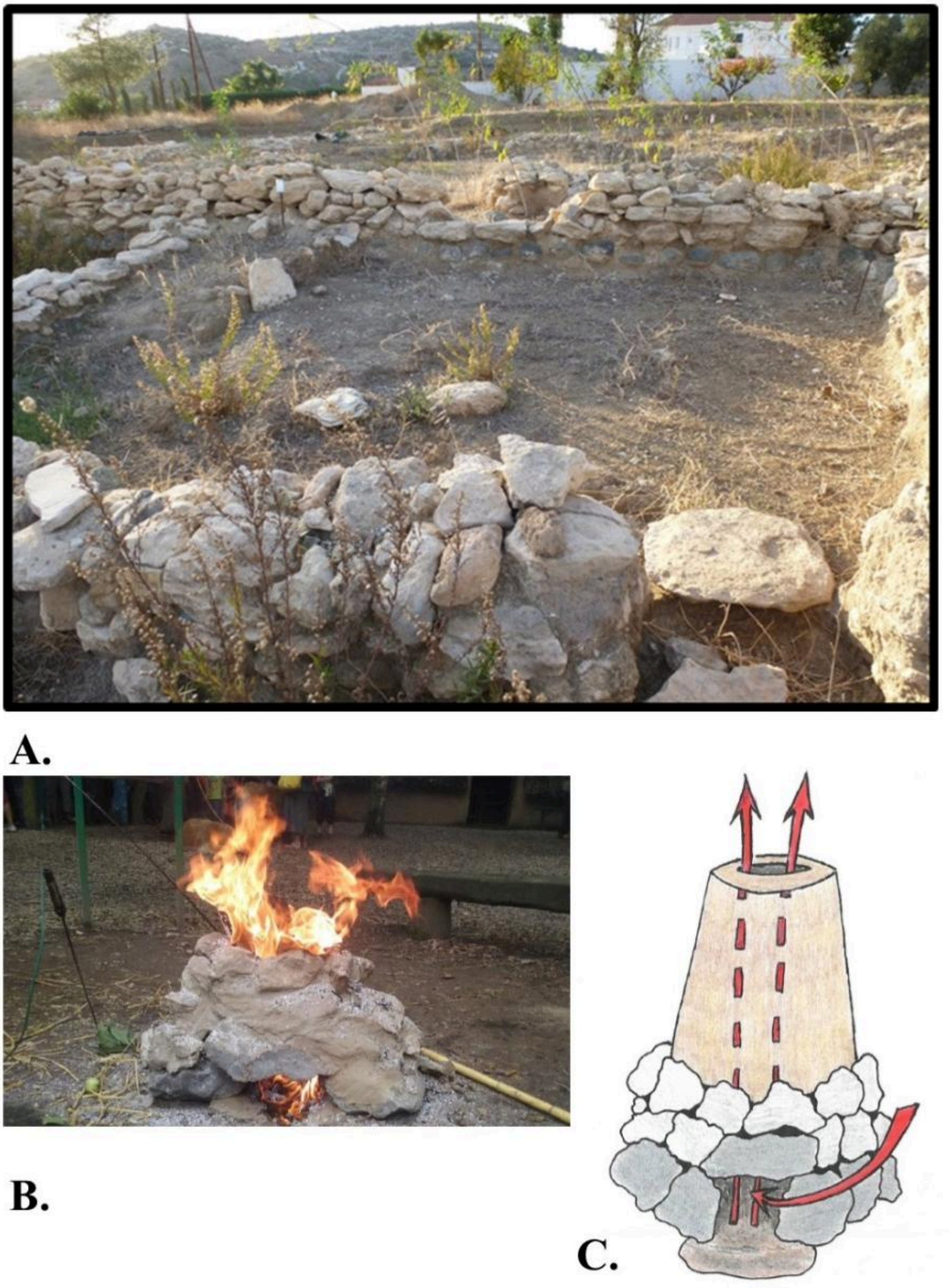

FIG 4. A) PARTICULAR OF A WALL-BASE IN PYRGOS-MAVRORAKI. (PICTURE BY THE AUTHOR); B) EXPERIMENTAL SHAFT-FURNACE RECONSTRUCTED AT THE ARCHEOSITE IN AUBECHIES (BELGIUM). (PICTURE BY THE AUTHOR); C) GRAPHIC RECONSTRUCTION OF AN ALTERNATIVE SHAPE FOR THE SHAFT-FURNACE. (DRAWING BY THE AUTHOR).

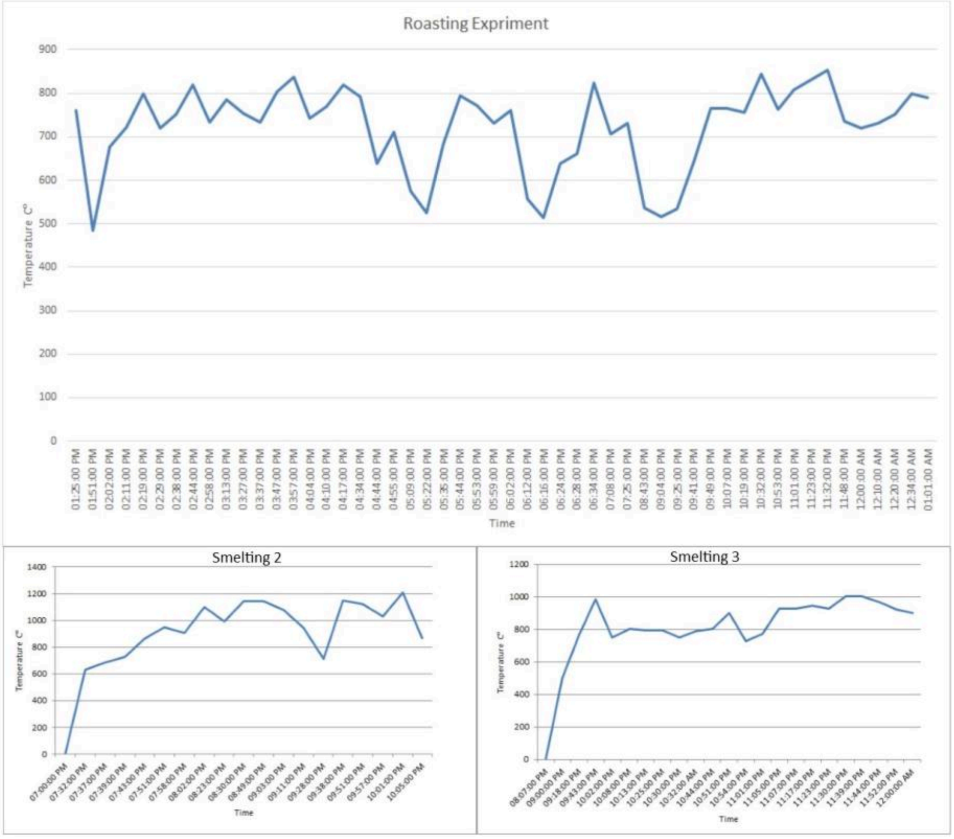

TABLE 1. TEMPERATURES REACHED DURING THE ROASTING EXPERIMENT AND THE 1ST AND 2ND SMELTING, RECORDED IN THE COMBUSTION CHAMBER.