A re-assessment of the evidence and context of the creation and development of Aegean Perforated Furnace

By:

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In loving memory of Aunty Ruth (1958-2019), without whom my University journey would not have happened.

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ii. Abstract

Perforated ceramic fragments from a structure named the Aegean Perforated Furnace (APF), believed to have been used in the process of smelting copper ores, are found within the LN/EBA in the Aegean, specifically in southern mainland Greece, the northern Cyclades and Crete. This evidence is different from other contemporary evidence of copper smelting in the Aegean and its neighbouring regions, suggesting an isolated tradition. Over the past 2 decades, more evidence has been found, increasing the number of sites and also including evidence of an earlier date. A model for the reconstruction of the APF and the method for smelting was proposed by Betancourt (2006) based on the excavated remains from Chrysokamino, and has been accepted as representing all APF evidence in the Aegean. This thesis collates all the evidence for the APF from the Aegean for the first time, in order to compare the evidence and assess whether it all fits the model proposed by Betancourt (2006). The wider context of this technology will be assessed, to understand the chaîne opératoire of the smelting process and to re-assess the model proposed by Betancourt (2006). Based on this assessment, a new model for the way in which the APF functioned is proposed. A series of experiments which test this new model are presented and analysis is carried out on the ceramic furnace fragments and metallurgical debris produced by the experiments, to compare the results with those of analysis on excavated remains, as another level of testing the reconstruction. Then, armed with this new model for the process of copper smelting with the Aegean Perforated Furnace, and taking into account the new early dates for its existence, this thesis will assess how the model for the APF fits with existing models for the inception and transmission of metallurgy.

iii. Declaration

I, the author, confirm that the Thesis is my own work. I am aware of the University's Guidance on the Use of Unfair Means (www.sheffield.ac.uk/ssid/unfair-means). This work has not been previously been presented for an award at this, or any other, university.

Publications arising from the thesis:

Doonan, R. C. P., & Marks, Y. A. (2022). Blowin' in the wind: The beginning of primary metallurgy in the Early Bronze Age Aegean. *Archaeometry*, 64(1), 161–176. https://doi.org/10.1111/arcm.12689

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Glossary of acronyms

APF: Aegean Perforated Furnace

FN: Final Neolithic

EBA: Early Bronze Age

MBA: Middle Bronze Age

GIS: Geographical information system

XRF: X-ray Fluorescence

pXRF: portable X-ray Fluorescence

SEM: scanning electron microscope

1. Chapter 1: Introduction

1.1. Rationale for question

Perforated ceramic fragments have been found at several sites in the Aegean. Due to the context in which they were found at Chrysokamino and Kythnos (Betancourt 2006; Bassiakos and Philaniotou 2007), amongst large slag heaps made up of tons of copper slags, they are believed to be furnace fragments which were used for smelting copper ore in. Over the past two decades, more perforated clay fragments have been identified at several other sites, through new surveys and excavations, as well as re-assessment of previously excavated material (Georgakopoulou, 2017; Betanourt, 2006; Bassiakos and Philaniotou, 2007; Gale *et al.*, 1992; Marinos, 1951; Salemink, 1980; Philaniotou *et al.,* 2011; Coleman, 1977; Dimitriou, 2017; Πλασσαρά, 2020; Theocharis, 1951). This new evidence identifies a more extensive spread of this perforated ceramic furnace technology, named by the author as the Aegean Perforated Furnace (APF), than was initially perceived across Attica, the Cyclades and Crete. Chronologically, the new evidence has provided secure evidence of this technology in the Final Neolithic in Attica (Dimitriou, 2017), which appeared at the time of the first evidence for copper smelting in this region. The reconstruction of the technology is very different from other known contemporaneous technologies for copper smelting in this and neighbouring regions. This raises key questions concerning how this specific type of technology developed and why this technology is isolated within this specific region of the Aegean.

None of the material evidence which fits the APF model has ever been collated and compared in one place before. Previous work looking at the function of the APF relied heavily on the evidence from Chrysokamino (Betancourt, 2006), which has a much later date than the other sites which bear evidence of the APF. Collating all the evidence for the APF to date will demonstrate this technology's geographical and chronological range, which has not been recognised previously. Georgakopoulou (2017) first attempted this presented a number of the sites and discussed the location of the smelting activity and the movement of resources. This moved the understanding of this specific smelting tradition forward, although Georgakopoulou does not present the material in detail but instead summarises the evidence. This does not allow for an assessment or comparison of the evidence and process. Furthermore, since Georgakopoulou published her paper in 2017, more sites bearing evidence of APF have been published, some of which are earlier in date, including the site of the Acropolis (Dimitriou, 2017) and Gerakas (Πλασσαρά, 2020).

1.2. Research Question

This thesis seeks to re-assess the material and contextual evidence for the APF, understand how the technology functions, and whether it is a variation of the existing copper smelting technology or its own isolated tradition. This research aims to understand better how craft was taught and adapted due to environmental and existing skills and knowledge. The thesis also seeks to understand better why this technology takes place in these specific locations and why the technology spread yet stayed isolated. Then, armed with this new information, the way the APF fits into the existing models for the inception and transmission of metallurgy will be considered.

To answer these questions, this thesis uses a holistic approach to investigate the invention, transmission and development of Aegean Perforated Furnace copper smelting technology from the Final Neolithic to the Middle Bronze Age. This is approached through a re-assessment of excavated material evidence, considering its distribution, location and context, to propose a new model for the functioning of the smelting apparatus and a rationale for its location and spread. A series of Experimental Campaigns and analyses will test the new model for smelting in this technology and enable a comparison with the excavated material to determine whether this new method is more plausible.

A series of research aims will be addressed across the thesis:

- APF technology and craft: The research aims to understand how the technology of perforated smelting furnaces works and identify the processes carried out within it. It also aims to understand why the location of this craft was so crucial to the method and how the process can be reconstructed and clarified archaeometrically. In tandem, the research explores how such crafts spread and how people responded to new processes.
- Transmission of technology: where and how the technology was invented, developed over time, and why it fell out of use.

- How and why did the technology spread across the region, why was its distribution isolated to a few specific locations, why were they chosen for its use, and whether the APF technology was used the same way at each site?
- The cultural role of the APF and communication of craft: How does this technology fit into the cultural context of the time?

This new assessment of the material evidence, paired with the comparative analysis and synthesis of the evidence across the region and its chronology, can enable us to understand this specialised and different technology and consider how and why it exists. These regional comparisons (Chapter 4 Section 4.3) will help us understand the factors that motivate this technology: location, temporality, method, and purpose. Understanding this specialised technology, which only appears at specific sites within the Aegean, will add to our understanding of the inception and transmission of metallurgy. A summary and discussion of the current models and syntheses are presented in Chapter 2, and the effect this new isolated tradition has on them is discussed in Chapter 7.

Following this reassessment (Chapter 2), a new model for how the APF functions will be proposed (Chapter 5), which sees the furnaces functioning purely by natural wind without adding forced draft by bellows or blowpipes. To test this method, a series of Experimental Campaigns were conducted (presented in Chapter 6), followed by a series of archaeometric analyses (presented in Chapter 6). The results of the Experimental Campaigns and analyses will be discussed in detail in chapters 6 (Results) and 7 (Discussion) in relation to how this confirms the proposed new model fits with the models for the transmission of metallurgy, considering that it represents an isolated tradition.

1.3. Contribution to the field

This work contributes to a growing body of literature assessing the nature, development and chronology of early metallurgical technology in the Aegean. Through an interdisciplinary approach, this work provides new insight into previous reconstructions and develops new methodological approaches to aid the identification of metallurgic practice in post-excavation. This assessment considers how craft is transmitted and how people respond to ideas, environment and practice. The assessment of the archaeological distribution of the APF technology will consider why it spread to the locations it did and what other factors contributed to its movement, such as transport, agriculture and other technological traditions. The reason behind the locations at which these smelting sites are situated has remained unclear over recent decades, and only through a nuanced understanding of how this technology worked and was used within its natural environment can we understand the choices behind its location and spread and how the craft is shaped due to its interaction with and reliance on the natural environment.

This thesis will also demonstrate that an interdisciplinary approach is needed to understand and reconstruct craft and metal production technology. An example would be that early metallurgical processes did not require temperatures as high as later processes, meaning that the ceramics and the ground where they took place were not as highly altered and, therefore, cannot be identified by the same parameters; for example, ceramics may not be vitrified or highly colour altered. Thus, chemical analysis used in conjunction with macroscopic typological identification can help identify the purposes of past use of ceramics and determine whether they have been used for domestic pyrotechnological purposes such as cooking and heating or during a metallurgical process. This thesis also shows the importance of experimental archaeology and campaigns to test reconstructions of archaeological methods and the subsequently produced material; for example, the demonstration that particular materials can be made or can occur in different ways, as is the case with the “run slag” analysed in this thesis.

2. Chapter 2: Background: The process and material evidence for making copper and the models for the transmission of copper metallurgy

2.1. Introduction to chapter

This chapter provides the necessary background information to re-assess the process for copper smelting at specific sites in the Final Neolithic and Early Bronze Age (EBA) Aegean, where the material evidence differs from elsewhere in the region and other regions. Re-assessing this evidence and better understanding the emergence of this isolated tradition will create a need to re-assess the current models for the transmission of practice for copper smelting in the Aegean and its neighbouring regions.

The first part of this chapter will present a brief overview of the different processes for producing copper in the FN and EBA, as well as the various types of archaeological material produced and used during each stage of the process. The evidence selected comes from the Aegean and its neighbouring regions, Anatolia and the Balkans. These areas are covered in the assessed theories but are also the earliest regions showing evidence for metallurgy. This will enable us to see how different material evidence currently identifies practices and enables a re-evaluation of the interpretation of certain types of material evidence and what processes they may represent. It will also allow an evaluation of the current typologies used to identify copper production technology and possible issues with the misidentification of material and their purpose. Also, providing an overview of the material evidence and descriptions of the practice of copper production will give the reader the context to understand the experimental campaigns and analytical results presented later in this thesis.

The second part of the chapter will focus on the existing models for the early transmission of metallurgy. A summary of the models will be presented, and a discussion of how and why they were formed and what instigated new models to be created. These models will be re-assessed in light of the re-evaluation of the material evidence and proposed chaîne opératoire of the Aegean Perforated Furnaces (APF) used at specific sites in the Aegean, and a discussion of whether this practice fits into these existing models will be presented.

2.2. Copper smelting technology and material evidence

This chapter section will present the different processes involved in producing copper artefacts and how copper is transformed from ore into metallic copper. The various types of archaeological evidence will be presented, including features in the ground, ceramic evidence for technological structures and apparatus, and metallurgical debris. It will be explained which types of evidence are considered to represent which part of the process, as well as how there are several different ways in which copper was smelted in the early stages of copper metallurgy as methods were being developed and determined by what ores were being selected, practitioners' knowledge and limitations of technology. This is followed by a discussion on the identification of metallurgical remains and how some types of material may not have been correctly identified in past excavations, will be presented. Detailing how it can be challenging to ascertain what part of the process the object could have been used in. Reconstruction models of the technology and processes will also be discussed. It will then be assessed if the reconstruction models are accurate. This will provide a background to set a discussion relating to the technology and processes being evaluated in this thesis and allow for a comparison to those used in the Aegean Perforated Furnace (APF) model with other examples of copper smelting in the Aegean and in neighbouring regions.

2.2.1. Metallurgy

By understanding the term metallurgy, we can have a clearer understanding of the process being considered in this thesis and the methods of research used to study these processes within the field of archaeology. “Metallurgy is often considered to be, purely technological, being considered as material and/or process, whereas the word metallurgy itself actually highlights the practice-based nature of itself because the words suffix ‘-urgy’relates to the doing of work. Practice—being the human activity of a process, the habitual way of doing something—determined by peoples' knowledge, experience and place” (Doonan and Marks, 2021, p.162). “During the late 19th century metallurgy was extended to the more general scientific study of metals and alloys and their related processes. The roots of the word are borrowed from Ancient Greek: μεταλλουργός, matallourgos, "worker in metal", from μέταλλον, metallon, "metal" + ἔργον, ergon, "work" (website: Wikipedia; accessed on 24th May 2012). The misuse of the term ‘metallurgy’ has within archaeological research led to metallurgical research focusing upon typological work of finished artefacts. Resulting in scholars attempting to answer questions such as the inception, transmission, development and provenance of metallurgy purely with typology” (Marks, 2012, p.39). Metallurgy should focus on the practice of making, the production process, which is split into two stages: firstly, the primary process, which includes smelting the ore and the secondary process, which consists of the casting and working of the metal (Ottaway, 2001, 93-101) rather, than the study of artefact biographies or trying to understand production by comparing styles of finished artefacts. The study of typology has dominated studies of metallurgy previously, and scholars have in the past attempted to answer questions such as the inception, transmission, development and provenance of metallurgy, with a focus concentrating on typology rather than looking at and comparing production methods, resources and other technology. With the evidence of tools, structures and waste products for smelting being found more often and identified and recorded more frequently over the past two decades in excavations (Doonan and Marks, 2022), an increase in the investigation and the chaîne opératoire of copper production is being considered as well as artefact use (Radivojevic *et al*., 2010, p.2775-6; Bassiakos *et al*., 2006, p.329; Georgakopoulou, 2017; Roberts, 2009, p.461-481). Another example of the issues of understanding the production of metallurgy, as Ottaway (2001, p.87) highlights, is work wherein the production of metal and metalworking are often treated as being synonymous, as one technological process. The reality is there are many individual stages within the sequence of production and working of metal, including the primary stage, beneficiation, smelting and roasting of sulphide ores and the secondary stage, refining, alloying and casting (Ottaway, 2001, 93-101). How these stages look and are carried out varies, depending on the practitioners' location, resources and skill. Different parts of the process may be done at various locations, rather than the whole process from ore to artefact being done in one place. Understanding that multiple processes may use different apparatus and be carried out by others in various locations is immensely important to understanding early copper metallurgy. This thesis focuses on a particular type of furnace structure used for copper smelting and the subsequent method used for smelting with this furnace. However, the full chaîne opératoire for copper production in relation to that furnace will be considered, as it is vital to understand all the processes and stages to understand each stage fully and how specific technology is used. Three main activities take place in the copper production process: mining, smelting (primary), casting, and working (secondary) (*Figure* 2.1). Some types of ore require an additional process before being smelted, but this does not happen in every circumstance. There may also be a step in between smelting and the casting of an object, which is called consolidation. It is also important to remember that metals are recycled and can be repurposed by melting and re-casting, as well as metal being cast into ingots for transport and trade and then being later melted and cast into an object for use. Each stage will be presented and discussed in more detail in the following section, but the information will be provided later. has been summarised in *Figure* 2.1.

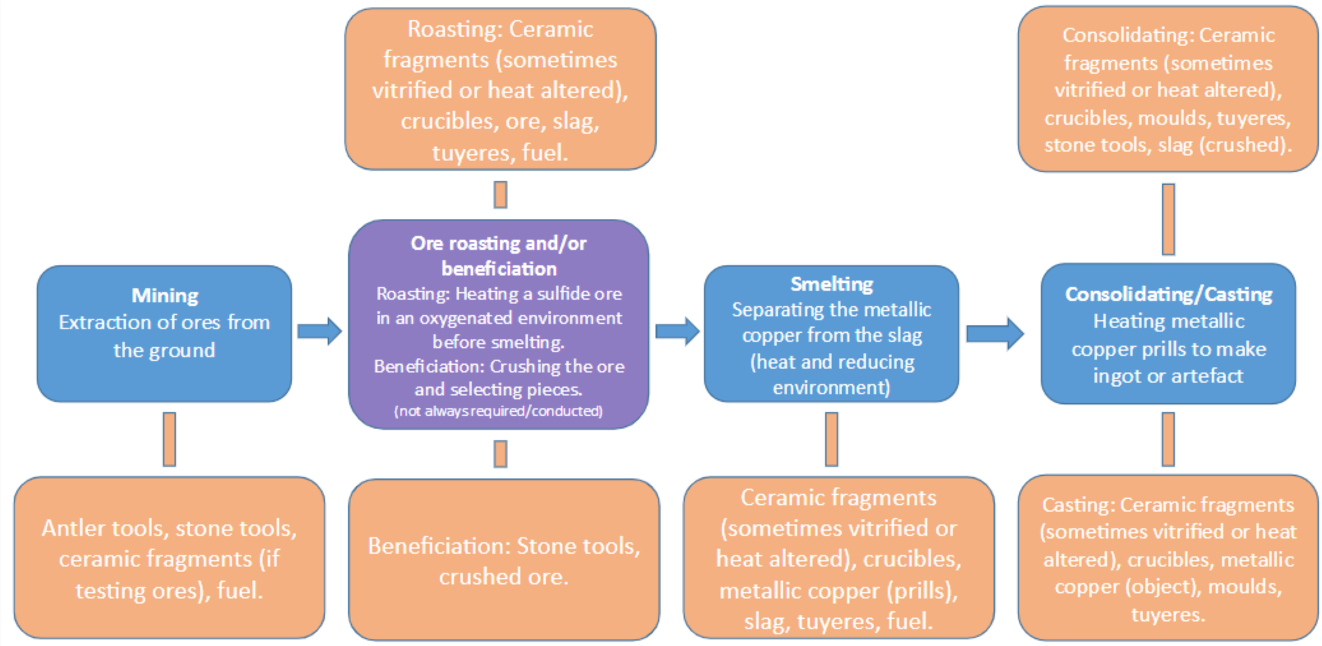

Figure 2.1. The stages of copper production (blue and purple boxes; the purple box is not always carried out) and the material evidence associated with each stage (orange boxes) (Image made by author).

2.2.2. Ore formation, mining and selection

The two main types of copper ores are copper oxides and copper sulphides. Copper oxides were formed within Igneous rocks within "hydrothermal veins born in underground magma chambers far below the deposit. The high temperatures of volcanic magma created hydrothermal veins, allowing some heat to escape near the upper layers of the Earth's crust. This is why copper is often found in the sedimentary layer, where sand and mud are compressed until they form a layer of sedimentary rock on the earth's surface. Copper is also commonly found in the oxidised zones of mineral deposits and basalt cavities in contact with hydrothermal veins. The presence of volcanoes in a region is often a good indicator of the presence of copper because that is where basalt cavities are in abundance near the sedimentary layer of the Earth" (Provident Metals, accessed: April 2021). Copper is formed closest to the earth's surface and includes minerals such as malachite, azurite, cuprite, chrysocolla and chalcocite; between these two is a zone around the level of groundwater where moderately oxidised ores are formed, including covellite, bornite and chalcocite (Sikka *et al.,* 1991; Provident Metals, accessed: April 2021, Killick, 2014, p.16-17). As these oxide ores are present near the surface, they were easier to spot and mine and more straightforward to smelt as they did not need to be roasted beforehand. However, they have a lower copper concentration compared to Sulphide ores. Sulphide ores are less abundant than oxides but are also harder to smelt as the minerals are composed of sulphur and metal, such as pyrite (FeS2) and chalcopyrite (CuFeS2) and need to be pre-roasted to turn them to an oxide before smelting. Sulphide ores are formed when seawater seeps down through the seabed along cracks initiated by the pressure of the underlying magma. The large volumes of water from this are heated then extract metals from the basaltic magma, which are then expelled back through vents known as "black smokers" into the cold ocean, where metal sulphides, including copper, immediately precipitate to form ores (Killick, 2014, p.18).

Successful prospection appears to have been a result of gathering other materials, as mineral resources were used as pigments and for making artefacts such as beads during the Neolithic before ores were smelted (Meures-Balke, 1981, 38; Glumac and Tringham, 1990; Ottaway, 2001, p.90). The mining of copper ores in the Late Neolithic and Early Bronze Age, when the ores were first being exploited, involved either the collection of outcropping pieces of ore or the digging of open pits and trenches to follow a vein of copper-bearing ore, which can be seen from the surface (Ottaway, 2001, p.90). The tools used for ore extraction included stone hammers, antlers, and bone picks. Due to the scarcity of slags in the chalcolithic period, it is believed that the ores being used for smelting were high-grade, and this meant they produced tiny debris due to there not being much material in the ore that was waste material (Bourgarit, 2007, 3). It is also suggested that any slags found were due to low-grade or not well-sorted ores being accidentally smelted or as part of trial and error experiments at the early stages of the development of the technology (Bourgarit, 2007, 3).

Copper-rich minerals were typically beneficiated, which consisted of crushing the minerals and picking out by hand the coloured and heavier minerals from the gangue (the unwanted impurities in the rock besides ore, such as dust, soil, sand, earthy particles, limestone, mica, etc.) (Ottaway, 2001, p.92). The tools used in this process included stone hammers and stone slabs. The stone slabs would get numerous concave depressions on the surface. There may also be heaps of discarded gangue in the area where this process was taking place.

In the first instances of copper being smelted, it appears there are two characteristics which are key to the selection of ores: their proximity to the surface and their quality to be smelt easily. The archaeological evidence from the Balkans indicates that the ores being selected for smelting in the early stages of metallurgical activities were copper-rich ores, selected due to their colour, which craftspeople identified as being the best ores from previous experience with native copper working (Radivojević and Rehren, 2015). Such ores are present at Belovode, Vinca-Belo Brdo sites and Gornja Tuzla (Radivojević and Rehren, 2015). These ores do not require the strict smelting conditions more familiar to us from the Bronze Age (Bachmann, 1982; Maldonado and Rehren, 2009) but instead can be subjected to lower temperatures and a less stable reducing atmosphere. It has been suggested that these copper-rich ores do not leave behind the traces of the archaeological record that we would expect. It can be considered that the smelt of these ores would be more successful, with a clear separation between the metal and slag therefore the slag would not need to be crushed to remove the copper droplets, making it less visible in the archaeological record (Radivojević and Rehren, 2015, p.32). As the smelting process for such ores requires lower temperatures, this will have a lower impact on the ceramics being used in the metallurgical processes, resulting in less or no vitrification. It may also leave less of a mark on the ground, which may not survive thousands of years of deposition (Radivojević and Rehren, 2015).

2.2.3. The process of extracting copper from ore

The process of heating copper ore to extract metallic copper from the oxide or carbonite ore is called smelting. The method of smelting is believed to be a development of the process for firing clay pots and figurines, as this process requires consistently high temperatures and types of firings needing a reducing atmosphere carried out; these conditions are also necessary for copper smelting (Ottaway, 2001, 93). For copper to be transformed from ore to metallic copper, it needs a temperature high enough to melt the gangue in the ore and turn it to slag and an environment that is reduced to enable the copper in the ore to turn to metallic copper. The basic copper smelting reaction for an oxide ore is $2\ Cu_2O + C + Heat = 4\ Cu + CO_2$, which sees copper oxide plus carbon plus heat transformed to metallic copper and carbon dioxide (Fornhammar et al., 2022).

As smelting requires a reducing environment for the copper oxide to reduce to metallic copper, a structure is used to hold fuel - such as charcoal. The ore is placed within a crucible within the charcoal or straight into the charcoal. Evidence for smelting in crucibles exists as early as the 5th millennium B.C. in the Balkans, at the site of Selevac (Tringham and Krstic, 1990; Ottaway, 1998). It is also found in other regions in the 4th millennium B.C., including Austria (Lippert, 1992) and Jordan (Adams 1999, 112; Hauptmann *et al.,* 1996). The material evidence from the excavations at these sites indicates that the smelting processes taking place resulted in the production of a conglomerate where the copper prills are embedded in the solidified slag. This occurs when the temperature is not high enough to produce a fully liquid slag, through which the liquid copper could pass through and collect at the bottom, separating from the slag (Ottaway, 2001, p.93). A structure which holds the fuel is called a furnace and is most commonly made from clay (Tringham and Krstic, 1990; Ottaway, 1998), however sometimes stone is used to support the clay structure (Adams 1999, p.112; Hauptmann *et al.,* 1996; Ottaway, 2001, p.93-4), or they can be made fully from stone (Cradock, 2000, p.159). Examples of furnaces where copper is not placed in a crucible but rather straight into the fuel come from Jordan – 4th millennium B.C. (Adams, 1999, p.112; Hauptmann *et al.,* 1996; Ottaway, 2001, p.93-4; Craddock, 2000, p.159), and the Austrian and Italian Alps – Bronze Age (Cierny *et al*., 1995; Doonan *et al*., 1996; Eibner 1982; Herdits 1993). It is apparent that in the examples of early smelting, the temperatures achieved were not as high as in later periods when the techniques became more developed. As well as these lower temperatures resulting in a conglomerate being produced, there is also evidence of higher percentage copper ores being smelted, which would mean a successful smelt could be achieved with the lower temperatures. The copper minerals found at the Vinca Balkan sites are of two types: oxide and sulphide minerals. The oxide minerals being black/green in colour and the sulphides ores being grey/green in colour. The study by Radivojević and Rehren (2015, p.15) shows a bias in selecting copper-manganese-rich ores, which have a black/green appearance. The analysis conducted by Radivojević and Rehren (2015, p.32) demonstrated that the copper-manganese ores being found across the Balkan sites were being smelted at c.1,083°C where other copper ores would normally need temperatures around 1100-1200ºC (Radivojević and Rehren, 2015, p.32). Bourgarit (2007,7) discusses how petrographic and physio-chemical investigations of slags have demonstrated that chalcolithic smelting was being conducted in the range of 1100-1200ºC. The copper-manganese oxides also do not need as strict a reducing atmosphere either, with successful melts being possible in environments which are not fully reduced (Radivojević and Rehren, 2015). The ability to melt copper-manganese oxides in a less stable environment would have allowed early metal practitioners to successfully melt such ores during experimentation. However, it results in different material remains, which would be less permanent in the archaeological record and different to the expected evidence resulting from smelting other ores. The lower temperatures may also mean that the materials from the smelting activity were less altered and may not survive in the ground for over 6,000 years (Radivojević and Rehren, 2015). If the ceramic evidence from lower temperature smelting does survive, the colour may not be what is expected, as it has been exposed to less intense heat. Therefore, it may not be dark red and black but rather pale orange or light beige. The ceramics may also not be vitrified. Vitrification of ceramics means the silica content in the clay is turned to glass due to high temperatures and rapid cooling. Studies have shown that if there is a low level of silica in the clay (whether this is due to it being at a low level in the natural clay or that it was not added to the clay mix during preparation), then the ceramics may not vitrify, even if exposed to high temperatures (Cropper, 2015). Therefore, it cannot be an indicator on its own of the use of a ceramic for metallurgical activies.

This evidence shows that there are a number of different ways that copper was smelted in the early stages of the technology being developed, determined by the ores being selected and the limitations of the technology. This highlights that the archaeological evidence will be varied and has to be carefully interrogated to understand what processes were taking place and how. This also means that there is not one simple model which represents copper smelting. Therefore, all evidence from the excavations should be carefully assessed and considered within their wider context in order to understand the processes taking place. This discussion also identifies that the material evidence from these early stages of copper smelting may be hard to identify, as they may not be as affected (vitrification, colour alteration from heat, less metallurgical debris such as slag), due to the process taking place at lower temperatures to later smelting activities, were evidence is more commonly documented. These factors are important and should be considered when looking at evidence for metallurgy in the Late Neolithic and Early Bronze Age.

Sulphide ores need to undergo an additional step before they can be smelted (Figure 2.2) Sulphide ores are often mixes of copper, iron and copper-iron sulphides as well as gange materials. The gange can be reduced by washing away the lighter fraction, but the iron sulphides cannot be separated by washing, as the specific gravities are too similar; therefore, they have to be heated. This can be done it two ways. The first method is called matte smelting and involves heating the ore in a reduced environment at 900oC; this is because all the major sulphides melt at 900^{o}C and form matte. This matte then needs to be roasted in air to remove the sulphur as gaseous sulphur dioxide, which leaves behind a mass of mixed copper and iron oxides. The copper is then separated from the iron by smelting this mixture with added quartz. The second method is called dead-roasting and is where the sulphides are completely oxidized by being roasted in the air at c.527oC, which turns the sulphides into oxides. After this, the ore can be smelted (Killick, 2014, p.37; Finnegan, 1948, p.16).

2.2.4. Forced Air

Air needs to be added into the furnaces in order to increase the temperature so it is high enough to make copper liquid (1083°C - 1200^{o}C depending on the type of ore being smelted); this can be done by forcing air into the furnace using blow pipes or bellows, which are connected to the furnace using a tuyère (a clay nozzle). Bellows can have a ceramic base with a material top (Betancourt and Muhly, 2006, 128 – 132; Betancourt, 2006) or be made fully from organic materials such as animal skin. Blowpipes would presumably be made from organic materials such as reeds or wood, and tuyères were small clay pipes or nozzles. Bellows are commonly assumed to be the method of forcing air into furnaces, despite there being a lack of evidence for them, tuyeres, and blowpipe connectors in the archaeological record (Bourgarit, 2007, 7. It can be assumed that there is little evidence for blowpipes because they are made from organic materials. This may also be true for bellows, although there is some discussion about them being made from clay, such as the bellows identified at Chrysokamino, Crete (Figure 2.2 and 2.3) (Betancourt and Muhly, 2006, Fig. 8.3)

(image redacted for copyright purposes)

Figure 2.2 (left) Ceramic Bellows Fragment 189 (Betancourt and Muhly, 2006, Figure 8.3.) and Figure 2.3. (Right) Fragments of Pot Bellows (Betancourt and Muhly, 2006, p.131).

There is only evidence for pot bellows in the LN or BA Aegean from one site currently: Chrysokamino (Betancourt and Muhly, 2006). However, the date for the metallurgical evidence at Chrysokamino is considered to represent the EBA/MBA rather than purely the EBA (Day, 2024; Haggis and Mook, 1993), meaning it may not represent the earliest phase of copper metallurgy in the Aegean. Therefore, this evidence may represent a later version of the technology and process that has developed over time and may not accurately represent this type of technology in its early stages. The evidence from Chrysokamino comes in the form of ceramic fragments found within the context of the metallurgical workshop area. There are 15 catalogued items, numbers 189-203, all recorded as pot bellows fragments (Betancourt and Muhly, 2006, p.128 – 132). The fragments are of a similar thickness, suggesting they are similar. The shape is a cylindrical vessel with straight sides. The ceramic fabric is coloured red to black, with the interior darkened due to a reduced atmosphere; this shows these ceramics have been fired in a kiln before use, as pots for domestic use would have also been. As all the fragments are so similar in form, it is hard to decipher how many pot bellows are represented by them; the excavation report suggests that a minimum of nine pot bellows are represented (Betancourt and Muhly, 2006, p.125). The reconstruction of their use is drawn from representations from iconography, such as the image on the Tomb of Rekh-mi-re, Egypt (Betancourt and Muhly, 2006, Figure 8.1.), which shows bellows being used with a hearth or furnace. The type of metallurgy being conducted would have been similar in technological development and is the closest comparison in terms of technology, which can be drawn from the evidence available. This suggests that the clay pot would form the base of the bellow, with the top part being made with organic material, such as animal hide. Then, the air would be pushed from the bellows by forcing the hide into the pot and the air out through the tuyère. Often, in the absence of evidence for the bellows themselves, they are often deduced by the existence of tuyères at a site.

(image redacted for copyright purposes)

Figure 2.4. Drawing of Workmen using Bellows, from the Tomb of Rekh-mi-re, Egypt. (Betancourt and Muhly, 2006, Figure 8.1. After Davies 1943, pl. 23.)

Betancourt and Muhly describe the bellows as being different in design to those from other sites, such as those from Cyprus (see Table 2.1).

Site	**Date**	**References**
Enkomi	Late Cypriot IIIA, ca.1600-1200B.C	(Dikaios 1971, 500, 516; Hauptmann, A., 2011; Hauptmann, 2011; Kassianidou, 2013; Dikaios, 1971; Davey, C.J., 1979)
Maa-Palaiokastro	LBA Cyprus, c. 13th/12th century	(Zwicker 1988, 430; Karageorghis and Demas, 1988; Kassianidou, 2011)
Alassa-Pano Mandilaris	Late Cypriot IIC-i.e., the 13th century B.C.	(Kassianidou, 2013, 42; Hadjisavvass., 1986; Karageorghis, 1985; Muller Karpe, 2000; Evely, 2000; Blitzer, H., 1995; Dimopoulou, 1997; Betancourt and Muhly, 2006)
Politiko-Phorades	ca. 1650-1500B.C	(Kassiandidou 1999; Knapp, Kassiandou, and Donnelly 2001; Knapp 2003; Knapp and Kassianidou 2008,

Table 2.1. Table showing evidence of sites with bellows.

The pot bellows listed from Cyprus are much later in date than the material from Chrysokamino is believed to be. This suggests that the pot bellows from Chrysokamino may also be later in date or at least do not represent the earliest phase in smelting from the Aegean. Betancourt and Muhly argued that the pot bellows from Chrysokamino were earlier in date than the ones from Cyprus but were early experimental examples of the device (Betancourt and Muhly, 2006, p.125), which we then developed versions of later at other sites and this is why they were present at Chrysokamino earlier than Cyprus.

Air can also be forced into the furnace by the natural wind; examples of this include Wadi Faynan, Jordan, dating to the mid-5th millennium B.C. (Rothenberg & Shaw, 1990; Craddock, 2000; Henderson, 2000); Wadis Um Balad and Dara, Egypt, dating to the mid-5th millennium B.C. (Cradock, 2000, p.159); La Capitelle du Broum, France, dating to the 3rd millennium BC (Bourgarit, 2007, 7); and Samanalawewa, Sri Lanka, dating to the 7th and early 11th centuries A.D. (Juleff, 2009, 558; Juleff, 1998, p.4-5). These are discussed in more detail in Chapter 5. These examples show furnaces which have been built in locations which are subject to strong winds but do not have evidence of bellows and/or tuyères, suggesting that they are located in these places to take advantage of wind, which will force air into the furnaces and increase temperatures, meaning air is not required to be forced manually.

2.2.5. Metallurgical debris from smelting

The other material evidence found alongside the furnace structure and the apparatus used in the smelting process is metallurgical debris. This includes slag, which, if the temperatures were hot enough, would become liquid and separate from the metallic copper and is sometimes tapped from the furnace, or if temperatures are not hot enough, creates a conglomerate, which contains copper prills within it. This conglomerate must be crushed using stone tools, and the copper prills must be picked out by hand. This sometimes results in piles of crushed material deposited near the smelting installations (Ottaway, 2001, p.93-5). Some examples of these piles of crushed slag include: Chrysokamino (Betancourt, 2006, p.187; Bassiakos and Catapotis, 2006, p.330), Kythnos (Bassiakos and Philaniotou., 2007, p.30), Skali (Papadopoulou, 2011, p.153). These slag piles are large concentrations of slag in one area of the site and different from how it is found at other smelting sites, suggesting it occurs from the specific process of crushing conglomerates.

Slag can be identified as having different forms; these forms are considered to be representative of the type of process from which they were made and are often used to determine what technology was used for the metallurgical process in which the slag was produced. There are considered to be three different types (Betancourt, 2006, p.137):

A: Furnace slag – which is formed within the furnace.

B: Tap slag/run slag is formed when a furnace is tapped to remove molten metal. As the slag runs from the furnace, it cools rapidly in the air and solidifies with a fluid appearance.

C: Crucible slag – formed within a crucible when the ore is smelted within a crucible in a hearth.

Some ores, such as sulphide ores, require being put through a roasting process before they can be smelted. Experiments have shown that smelting a mix of oxide and sulphide ores can eliminate the need for this step (Ottaway, 2001, p.96). The roasting process was carried out in shallow pits, which could be lined with clay or stone and could use wood as a fuel rather than charcoal. The evidence this process leaves in the archaeological record is reddened scorched earth (Doonan, 1996, p.106; Eibner, 1982; Herdits, 1993). This roasting process would be very difficult to identify in the archaeological record, or if it were found, it would be hard to identify that the evidence represents roasting and not another part of the process.

2.2.6. Consolidating and casting

Refining or consolidating the copper prills, released from the conglomerate, can be required if the smelting process produces a conglomerate rather than separated copper and slag. This process includes heating the copper prills (which would have been released from the conglomerate by crushing and then hand-picked out) in a crucible until liquid, then left to cool as one piece or poured into a mould. Sometimes, copper could be contaminated with iron or matte from the smelting process, and this would be refined by heating the copper in a crucible in the same manner. The crucible would be made from clay tempered with various additives (including sand and dried organic materials). It would need to be covered in charcoal to produce a reducing atmosphere in order for the chemical process to turn the copper from the ore metallic. Therefore, the charcoal would be held in a structure such as a bowl hearth or lined pit (Ottaway, 2001, p.97).

Casting is a process that allows copper to be shaped into a desired form. This is done by heating the copper in a crucible and then pouring it into a mould. Moulds can be made from sand, stone, clay, and other metals (Ottaway, 1994, p.111). The crucible would be placed in a bowl hearth or lined pit with fuel to enable the temperature to be brought up high enough to make the copper liquid (1084°C).

Copper artefacts can also be shaped by hammering. This can consist of cold hammering or annealing, which is a cycle of heating and hammering the metal. Depending on how successful the smelting and consolidating process was, some artefacts could be shaped by hammering without casting. The only way to identify how a prehistoric metal artefact was formed is to do a metallographic analysis, which involves looking at the structures of the metal and slag via microscopy (Ottaway, 2001, p.99-100). Very few moulds survive in the archaeological record for the early periods of copper metallurgy. The number of moulds found is much lower than the number of artefacts which have been cast, suggesting that sand moulds may have been used, as these do not leave a trace in the archaeological record (Ottaway, 2001, p.100). After being shaped, some objects would be polished and ground (to sharpen the edge). This process is done throughout the object's life as the object dulls and blunts from use.

2.2.7. Fuel

As highlighted by the explanation of the production process, fuel is a vital component that is used in several steps of the process, including roasting, smelting, refining, consolidating, casting, and annealing. The fuel is especially important for the smelting process, as high sustained temperatures are necessary, along with a reducing environment (Ottaway, 2001, p.101). Some natural fuels, such as wood, are not processed and are not sufficient to achieve this atmosphere and temperature, which is why charcoal is used. Tylecote (1986, p.223) distinguished between the two types of fuels used in the metal production process: long-flame fuels (oxidising atmosphere), including wood, and short-flame fuels (reducing atmosphere), such as charcoal. Evidence for non-wood fuels is present in specific locations, such as peat, bone, dung and other organic materials (e.g. olive pressings and date kernels); however, in Europe, it is assumed that charcoal was the most common fuel used (Ottaway, 2001, p.101; Catapotis *et al*., 2008, p.115-7). The fuel for chalcolithic copper smelting is not discussed; however, it is assumed to be charcoal (Bourgarit, 2007, 7).

Charcoal can be produced using two methods. The first uses an underground pit, pit kiln, or pitstead, while the second uses an above-ground stack, known as the 'heap burning process' (Horne, 1982; Kelley, 1086, 9; Schubery, 1957, 222; Oaks, 2020). Both methods consist of setting the wood alight and then leaving it to carbonise through the control or exclusion of air. The process can take 1 to 15 days, depending on how much wood is being carbonised (Ottaway, 2001; Oaks, 2020). The evidence for charcoaling can be hard to identify, with the process not surviving well in the archaeological record and can often be overlooked (Hillebrecht, 1989). However, understanding the process and how it would look is essential to correctly identify all pyrotechnical processes associated with smelting at a site and differentiate between them. When metal production becomes large-scale, charcoal production will require woodland management. Even though the amount of wood used in the copper production process is considered to be considerable, the evidence for it can be hard to see, even with the number of trees cut down to be used. Environmental studies on the impact of mining and metal production in Austria during the Roman period do not show a noticeable effect on the pollen record, except for a decrease in beech (Marshall 1992; Marshall *et al*. 1999). Therefore, when smelting activity became more considerable in the LBA, it would need a more controlled process with an administrative head overseeing all aspects of the production process, including gathering the fuel and managing the trees that grow it.

2.2.8. Concluding comments on the evidence for copper production

This section of chapter (2.2) summarises the processes involved in producing copper and details the material evidence found in the archaeological record for each process.

This presentation of the operational sequence for producing copper will enable a better understanding of how the Aegean Perforated Furnace was used and how it fits into the broader context of the copper production process. It will also allow for comparing the process to other contemporary examples and to inform the understanding of the motives behind the design of this particular furnace and process. This chapter has also demonstrated that there was not just one way to smelt copper within this early phase of metallurgy; in fact, there were several different methods, depending on the type of ore being used and the metalworkers' decisions and preferences. This discussion has also highlighted that the material evidence from these processes during this phase could be limited or less substantial and permanent in the record than that of later metallurgical or pyrotechnical processes. Different temperatures are needed for various stages (*Table 2.2.*) within the process, and these different temperatures leave a distinct signature in the archaeological record. Lower temperature processes may not leave substantial effects on the ground or on the structures being used (ceramic or stone), meaning they may not be vitrified or even altered in their colour, as you would expect with higher temperature metallurgical processes, where the ground and structures will become dark orange, red and even black, from their contact with high temperatures. With high percentage copper ores, there may not be any waste material such as slag produced, let alone be found in the archaeological record. There may be less evidence deposited at the time; these may not survive as well, especially ceramic material, as they might not have been as highly fired. Also, as they are less altered, they may be misidentified. Indeed, they could be identified as ceramics used with lower temperature pyrotechnical activities such as cooking wares. This is vitally important when excavating new sites from this period and interpreting the archaeological evidence. Still, it also should be considered that some evidence in previous excavations may have been missed or misidentified.

Process	**Temperature needed**
Ore roasting	c.527ºC
Matte smelting pre-melt	900ºC
Smelting manganese copper ores	c.1,083°C
Smelting non-manganese copper ores	1100-1200ºC
Melting and Casting coper	1084°C

Table 2.2. Table showing different temperatures required for different processes.

2.3. The early transmission of metallurgy

The second half of this chapter will now turn to look at the previous and current models for the inception and transmission of metallurgy across Eurasia. A synopsis of the models will be presented, with a discussion of why they were formed and how new models arise. These models will then be re-evaluated later in this thesis in light of the new model of practice proposed for the APF.

2.3.1. The importance of understanding the spread of copper metallurgy

Metallurgy has long been an indicator of social complexity within archaeological studies (Childe, 1930). Childe argued that its reliance on the careful control of fire, coupled with the insight needed to undertake operations akin to a kind of proto-chemistry, set it apart from other technological operations. It has then been held as an incredibly sophisticated form of technology and considered indicative of societies that had mastered agricultural production and complex social organisation (Childe, 1930), as only then would the society have the time, resources, organisational skills and ability to be able to learn and carry out metallurgical processes. Childe saw metallurgy as a highly skilled practice requiring substantial resources and time management, something a society would only be able to achieve if it had a well-organised social structure and an efficient agricultural programme. Since Childe’s paper, there has been a renewed interest in the desire to explain the inception of metallurgy in early societies and how it spread worldwide. In Childe and Renfrew’s models, the focus is more on the locations for the inception of metallurgy rather than the adoption of practice and its evolution over time and space. Models such as Amzallag (2009) and Thornton and Roberts (2009) look in more detail at the transmission of craft and how it develops in regions once it reaches them; this is due to more evidence being excavated and the realisation that techniques develop over time.

This section of the chapter presents a detailed critical review of the development of these models for the inception and transmission of metallurgy in order to assess how the understanding of the Aegean Perforated Furnace technology can add to these models and our understanding of transmission in this region. This assessment also explores the way in which an understanding of how communities came to be metallurgical can be formulated and to what extent these practices were shared within the region. The desire to reassess the evidence for early metallurgical processes and the models for transmission comes from recent work by the author (Marks 2013), which has indicated that there are materials and processes in the Aegean that have been misidentified. Evidence from Chrysokamino and Kythnos, which represent the earliest phase of metallurgical processes at each site, is different from other sites in the region during this time period, suggesting there is another practice taking place.

2.3.2. The development of explanatory models

A number of competing models have been used to explain the transformation of Neolithic communities to those which used metals in the Bronze Age (Montelius, 1912; Childe, 1930; Gabriel de Mortillet, 1882; Renfrew, 1973). The diffusionist (Montelius, 1912) and evolutionary models (de Mortillet, 1882; Renfrew, 1973) dominated most discussions for much of the late 19^{th} and early 20^{th} centuries. The diffusionist model was characterised by the premise that ideas and innovations can be transmitted from man to man and group to group. In contrast, the evolutionary model, in the form endorsed by de Mortillet (1882), held that similar developments in different places were due to ‘the like working of minds under like conditions’ (Renfrew, 1973).

As the diffusionist model continued to be accepted by archaeological scholars, it became the central idea of cultural history and started to be used to explain social change. Childe’s (1930) model did not see metallurgical development as an impetus for social development, but rather, it was a symbol/outcome that the society had progressed in terms of agricultural developments or an increased social structure. Therefore, the central principles of the diffusionist model held that change could be explained by acknowledging the role of dominant cultures, who replaced ‘lesser’ communities through either spatial organisation, warfare, invasion, or agricultural success (Renfrew, 1973). However, as more metal artefacts were found throughout the 20^{th} century, archaeologists started to consider how the production of metal fits into the framework of evolving societies in terms of wealth, trade, social organisation, and craft practice. This led to the creation and acceptance of subsequent models such as the Localisation theory and Synthetic theory (Renfrew, 1994; Amzallag, 2009), which will be detailed later in this chapter. Since Childe, scholarship on the transmission of metallurgy has become more focused on mapping the spread of metallurgy geographically, using well-dated sites. However, in the efforts to map where and when metallurgy takes place, the understanding of how it takes place has been overlooked.

One of the problems with these theories is that they are defined by typology. Typology has been used to define cultural groups and identify time periods based on variations of form and design. However, it is not that simple; it has become clearer with more analytical work, such as petrography and isotope analysis, that materials and finished artefacts move and also that some societies imitate the artefacts of others. Therefore, we cannot look at the locations where metallurgy was made purely by looking at the style of the finished artefact; rather, we need to look at the production methods and materials as well.

2.3.3. Development of research after Childe and Renfrew

After Renfrew, studies about metallurgical technology became prominent within research of prehistory, understanding the evidence for production, how metal was made, and how these crafts developed came to be viewed as more important. Craddock (1995) and Sherratt (1998) each developed a synthesis detailing the existing theories of the transmission of metallurgy. These syntheses highlight that although the theories by Childe and Renfrew have different explanations for the instigation of ore smelting, they both identify a need for research beyond typological studies and express the utility of drawing comparisons of the technological processes carried out. Craddock and Sherratt both highlight that to understand how the practice of metallurgy spread, one needs to understand how it was conducted by different civilisations.

A new focus on the transmission of metallurgy came about from a session focused on the emergence of metallurgy in the Old and New Worlds which was held at the Society of American Archaeology (SAA) conference in 2008 (Thornton and Roberts, 2014). This session was aimed at redefining a model for the transmission of metallurgy, following on from Renfrew’s work in 1973. The publication which arose from this conference celebrated the session as a long overdue revival of the focus on the transition of metallurgy in prehistory (Thornton and Roberts, 2014). The main outcome of this session was the agreed call to action that in order to push the studies of ancient metallurgy forward, a more holistic research approach needed to be adopted (Roberts, 2009; Thornton *et al.,* 2010; Roberts and Frieman, 2012). A more “holistic approach” was defined in terms of combining theory of the movement of resources, development of technology and trade, combined with experimental archaeology and material analysis, to understand the full “chaine operatoire” of the production and use of the objects.

I will now present a concise description of the models, in order to be able to critique them. The models will be presented under the title of the author who as the main contributor to the creation and spread of these models within the scholarship of metallurgy.

2.3.4. The Models

The models presented here are considered to be the most important models produced to describe and understand the process of the transmission of metallurgy. These models will be summarised and critiqued, in order to fully assess the characteristics of each model and the motives which influenced their creation, such as the emergence of new evidence or dates. This is necessary in order to be able to demonstrate when models were no longer suitable, and how new data and evidence have grown beyond the parameters of previous models. It will also enable a critique of current models and to discuss how the new evidence for copper production in the Aegean FN and EBA fits with them. The models pre-dating Childe and which influenced his model will not be discussed in detail on their own, as this has been done by Childe (1929) and Renfrew (1973, p.18-19) (*Figure* 2.5), but rather how the new models proposed by Childe and Renfrew outdated and surpassed the ones before them.

2.3.4.1. Childe: the transmission model and diffusionism

2.3.4.1.1. <u>The instigation of Childe’s transmission model</u>

In the early 20th century, the transmission model was first presented by Childe, it was in ‘The Danube in Prehistory’ (1929), which became a focal point of his subsequent works. This model explains the “transmission” of knowledge and skills in architecture, agriculture, and metallurgy. Childe combined two sets of ideas to create this model, those of Worsaae and Montelius, who believed that most of the important discoveries and advances of human culture could have only occurred once and then were transmitted by contact with other areas (Renfrew, 1973, p.18) with that of the ideas of Gabriel de Mortillet, who believed that when similar developments took place in different locations, that it was due to ‘the like working of minds under like conditions’ (Renfrew, 1973, p.18). Childe’s localisation theory followed the existing diffusionist idea set but directed it more towards the development of technology. From 1925 until Renfrew’s work in 1973, diffusionists prevailed, and the majority of prehistory has been understood and explained in the terms set down by Oscar Montelius’s diffusionist terms (Renfrew, 1973, p.18).

Childe’s work was the first critical look at the development of metallurgy as a practice. Childe made a very important observation in his assessment, that understanding that the adoption and development of metallurgy was not an isolated event, separate from other aspects of life or situation. Although Childe has conflicting ideas of itinerancy, as he stated that a society had to be creating a surplus before they had the time and resource to become metallurgical, yet he also stated that metallurgists were itinerant, moving from place to place. His identification of adoption of craft being intertwined with other aspects of socio-political life is vital. Childe’s subsequent works on the early development of technology (1930 and 1944) highlighted the ongoing importance to him of the ‘beginnings of metallurgy’.

2.3.4.1.2. Evolution of diffusionism

As more archaeological evidence for metallurgical production in the Bronze Age was discovered over the 20th century, the map of sites which had evidence for metallurgical processes during the Bronze Age became more populated. As this evidence grew, an understanding of where the different processes took place meant that researchers started to question whether the diffusionist model still fit the evidence. In Childe’s last published volume even he predicted that his model would be superseded as more evidence became available.

As mentioned previously, the models which were formed after the transmission model by Childe (1930) have become more focused on mapping the spread of metallurgy geographically, by using well dated sites and the presence of certain material culture. However, in the efforts to map where and when metallurgy takes place, the understanding of how it takes place has been overlooked. As certain items of material culture or excavated features are used to identify that metallurgy has taken place, there has not been a proper assessment of what processes this material represents and the method of practice used, in light of the now clearer variation in practice and methods for producing copper. For example, within recent works, such as Roberts (Ottaway and Roberts, 2003), they look for any material relating to copper, such as malachite beads, in an attempt to link the process of bead production to what they describe as an inevitable development into copper smelting. However, bead production may not be connected with copper extraction from ore and the processes that follow. Therefore, this should not be considered a signifier of copper smelting taking place or evolving from that process.

The model of the transmission of metallurgy from the Near East to the rest of Eurasia, defined by Childe as being peddled by itinerant smiths, has a pace determined by which communities could establish bonds of relation with smiths through their access to their own surplus. Childe's ideas were supported and promulgated by a number of other scholars looking to explain the dispersal of metallurgical knowledge (Chernykh, 1992; Muhly, 1988; Smith, 1977 and Wertime, 1964, 1973a, 1973b). Thus, diffusionism probably endured for such an extended time because of the common belief that the technological knowledge necessary to transform ores into metal was too complex to have been discovered multiple times, hence transmission needed to be understood from a point of origin.

The first substantial criticism of the diffusionist model for metallurgy came from Renfrew in 1969, with subsequent additions in 1973 and 1986. This criticism was largely inspired by data from recent carbon dating methods applied to archaeological material, and Renfrew's commitment to establishing a systems theory (anti-diffusionist) perspective. Renfrew saw the presence of very early dates for metallurgy in SE Europe as indicative of independent invention, while the relative geographical isolation of the Iberian Peninsula along with similar quite early dates suggested the possibility of an independent tradition emerging in this region. Renfrew therefore contemplates multiple centres of metallurgical development, although his final model endorses a pattern of *regional* diffusionism. This new outlook on the development of metallurgy is supported by an understanding of the role of the economic subsystem (the movement of resources and artefacts through trading between neighbouring regions) and the importance of the production of primary materials (Goodway, 1991).

2.3.4.2. Renfrew: localisation theory

2.3.4.2.1. Renfrew's response to Childe

The next major model for the inception and transmission of metallurgy, which was widely accepted after that of Childe (1930), came from Renfrew in 1973. This was due to the identification of new sites with evidence of copper smelting and new analytical methods (particularly isotope analysis, which tells us where raw materials originate). This theory was named the localisation theory, and it seems there is not one homeland for metallurgy; instead, there are two locations where metallurgical activity was discovered and then spread from there. The two central regions with early metallurgical activity are Anatolia and the Balkans, which both have evidence of copper smelting activities at a comparable date.

Renfrew's revised model for the early development of metallurgy built upon new data relating to the material evidence for the smelting of copper metal from ore of similar date, which was recovered in multiple locations (Renfrew, 1973). This material evidence appears in different regions, which are not near each other geographically, but which are of comparable dates within the Late Neolithic. This therefore suggests that there could not be one homeland for metallurgy and it could not have spread between these two locations so quickly, which is supported by the fact that there is no evidence of a similar date, in the area geographically between these regions.

Renfrew sees the development of copper smelting to be a development of the working of native copper, as did Wertime (Wertime, 1974). Wertime sees an 8 stage progression, starting with the simple use of native copper (stage 1), developing to cold hammering (stage 2) and then hot hammering (stage 3) of native copper. This is followed by the smelting of copper from its ores (stage 4), then the casting of copper in an open mould (stage 5) and then casting in two-piece moulds (stage 6). The final two stages being alloying with arsenic (stage 7) and lost wax casting (stage 8). Renfrew discusses how each stage of development builds on from the previous one (Renfrew, 1973, p.188-9). Renfrew highlights how stages 1 and 2 are present with the evidence of native coper artefacts in Anatolia, before 6000 B.C., and that the Balkans can map a similar sequence of development, with the presence of native copper beads at the cemetery of Cernica in Romania dating to 5000 B.C. (Renfrew, 1973, p.190). Renfrew discussed that the earliest evidence of hot working in the Balkans at the time he was writing, came from a site in the western U.S.S.R and dated to before 4000 B.C. and was a fish hook which had been heated to 300ºC to be worked. He also states that tools created from smelted copper occurred at the same time and can be identified due to their greater content of minor impurities (Renfrew, 1973, p.190). Hot working, stages 3 and 4 appeared in Anatolia around 6000 B.C. and are documented in the remains at Çatal Höyük (Renfrew, 1973, p.190).

2.3.4.2.2. Beyond Diffusion

Renfrew's observations acknowledge that not all areas which develop metallurgical skills during the late Neolithic and Bronze Age are of the same economic and social development (Renfrew, 1973). He suggests that the ability to develop the technical know-how to produce copper is dependent on craft knowledge and skills, rather than the economic or social situation of the settlement. He notes that the most difficult skills required for smelting copper are the pyrotechnological aspects, such as working clay into vessels able to contain hot substances, controlling fire and air flow, and the control of heat. Renfrew highlights how pottery production allied to pyrotechnical skills in the Balkans and Germany, which existed before those of metallurgy, demonstrate how easy it would be for these craftspeople to adapt these skills to metallurgy (Renfrew, 1973). However, he does note that this does not prove independent creation.

2.3.4.2.3. Civilisation and creativity

Renfrew considers that although prehistoric Europe (periods preceding and including the Iron Age) was not as 'civilised' as the Near East with their cities and elaborately written records, the European "barbarians" of prehistoric Europe have been underestimated in creative terms. The development of radiocarbon dating using the C14 method provided a clearer understanding of the dates of evidence in the Balkans and western Eurasia. Previous to this method, dating was done by typology of artefacts which had spread from Egypt and which did not reach further west than the Mediterranean, making it hard to have comparable dates with the Balkans and Anatolia (Renfrew, 1973, p.34-69). The new dates for evidence showed Renfrew, that at the same time as the societies of Near Eastern were being formed, the peoples of prehistoric Europe were erecting large monuments in stone, smelting copper, setting up solar observatories and doing other ingenious things independently, without having to be taught to do so by travelling practitioners (Renfrew, 1973).

2.3.4.2.4. The Collapse of the Traditional Framework

Renfrew called for a re-assessment of prehistory, due to advancements in radiocarbon techniques in the early 1970s (Renfrew, 1973). Renfrew uses the example of Dr Beatrice Blance's thesis (Blance, 1969), whose theories fit within the diffusionsit model. She argues that a number of sites in Iberia were established by Early Bronze Age colonists who came directly from the Aegean. One of the sites in question is Los Millares. Blance believes that this site was actually established by a colony directly from the Aegean (Blance, 1969). The reasoning for this belief was that there were similarities in aspects of the site, such as the fortification walls being similar in design to those from sites in the Aegean. She saw this as being evidence of colonists travelling from the Aegean to Iberia, as the similarity in style was due to them being built by the same people. Renfrew sees a problem with the theory for two reasons, as there is no evidence for imported objects in Iberia dating to this period (the Chalcolithic), and due to the architectural style of the fortification walls (Renfrew, 1973, p.121). He considers there to be an absence of any good evidence for colonisation at this time, apart from the style in architecture of the walls, and therefore he suggests that local innovation and development are a suitable consideration for reasoning behind the similarity in the walls' design.

One of the most important points that Renfrew gets across, which is often overlooked, is how although radiocarbon dating broke the diffusionist model it does not in turn prove the independent discovery model (Renfrew, 1973, p.121-124, p.279).

“Radiocarbon has helped to show the inadequacy of the conventional diffusionist picture, built up by Worsaae, Montelius and Childe. The task now is to build up something demonstrably better to replace it” (Renfrew, 1973, p.279). Rather, a new consideration of the evidence needs to be achieved, re-assessing the relationships of culture and exchange. For example, understanding how cultures adapt to new ideas and develop skills, and as well as understanding what level of exchange was happening at this time period; was it just objects and materials, or ideas and knowledge?

Renfrew discusses and takes inspiration from A. L. Kroeber’s theory of ‘stimulus diffusion’, which is discussed by Joseph Needham in the first volume of *Science and Civilisation in China* (1961). Krober’s theory proposes that the transmission of ideas from one culture into another happened without the associated transfer of objects. Needham uses it to discuss the extent of the transmission of ideas between the East and West. He stresses the importance the theory, explaining it is not the “details of the full complexity and elaboration of a new product or process which is transmitted, but rather the idea, the realisation that such a process is possible, and some understanding of how to bring it about” (Needham, 1962; Renfrew, 1973, p.122).

Renfrew’s localisation theory, which proposes that there are multiple homelands of metallurgy, became widely accepted by archaeologists considering the transmission of metallurgy, and came to replace Childe’s diffusionist theory over time. Renfrew proposes two homelands for the discovery of metallurgy, Anatolia had already been accepted, but also a European region which discovered it independently spreading across the Balkans (Renfrew, 1973, p.183-7). Further work has revealed additional possible homelands: South America and Thailand (Amzallag, 2009, p.497-8; Roberts *et al.*, 2009, p.1012-1020). As discussed above, Renfrew sees the emergence of metallurgy as a continuation of the working of native copper (Amzallag, 2010, p.318), a theory which is later a pivotal point to Roberts’ work.

Figure 2.5. Map showing the different homelands for metallurgy and the direction of the spread as set out by Childe's transmission model (Orange), Renfrew's Localisation theory (green) and the region where the APF evidence is present (blue) (Image made by author).

2.3.4.3. Amzallag

Amzallag's model, known as the Synthetic theory, was "created with the desire to cause discussion and debate within the scope of the inception and development of metallurgy. The main purpose of the synthetic theory is that it differentiates between two modes of copper production; crucible metallurgy and furnace smelting, then comparing for the first time. Amzallag the creator of the synthetic theory discusses that furnace smelting emerged in a context devoid of native copper and therefore the production of copper in a furnace is not directly connected and cannot be seen as an improvement or acceleration of working native copper. But rather copper production was an evolution from a different unknown technique" (Amzallag, 2010, p.317; Marks, 2012, p.39).

2.3.4.3.1. Native copper and smelting

Amzallag's proposal arose within the start of the resurgence of studies on the early development of metallurgy in 2009, and was the perfect time to discuss the two most significant models together. Amzallag's discussion does that, but also presents a new theory; that copper smelting in furnaces was developed in an environment separate to the use of native copper, where in fact there was no evidence of native copper. Therefore, the process of smelting copper in a furnace is not linked to working native copper. Instead, the first instance of smelting copper in a furnace was probably a process of creation of matter previously unknown (Amzallag, 2009, p.512). Amzallag's concept was quickly criticised by Thornton *et al*. (2009) who said that his paper was "rife with misunderstandings of both an archaeological and a technical nature, leading to a skewed vision of early metallurgical development" (Thornton *et al*., 2009, p.305). This has unfortunately led to a lack of further discussion and consideration of points raised by Amzallag, such as the critique of the transmission and localisation theories. Amzallag discussed the flaws he saw in Renfrew's theory in relation to the emergence of metallurgy being a development of the process of working native copper (Amzallag, 2010, p.318). He goes on to critique the localisation theory too, explaining how it can be seen to be related to nothing, and therefore can be challenged. If the desire is to propose a new theory for the creation and inception of metallurgy, then the discussion and critique of previous models is valid, in order to assess how new evidence can question them. This is something which Amzallag does, but which is lost due to the dismissal and criticism of the model he proposes.

2.3.4.4. Roberts

2.3.4.4.1. Roberts and Migration

Roberts' (2008) re-assessment of the role of migration within the earliest transmission of copper objects and metal production practices in Western Europe was encouraged by the prominence of new analytical techniques being used to understand migration patterns, such as the analysis of strontium and oxygen isotopes on teeth. Roberts suggests this research is necessary to address the current increase in focus on metal production and to properly approach the subject (Roberts, 2008, p.28).

Roberts uses radiocarbon dates to show that the transmission of metallurgy from the Balkans to Ireland took 2750 years. This demonstrates how analysis can contribute to these discussions although it does not replace the need for regional approaches. However, understanding the transfer of metallurgical knowledge between these regions would ideally include an assessment and identification of the origins and associated processes of the earliest copper metallurgy in regions between the Balkans and Ireland; a large feat which is not easily done. A criticism of only assessing migration is that it ignores the broader context underlying the adoption of a new material and technology within each region. Roberts' (2008) paper not only discusses the problems with a migration approach to the investigation of the early transmission of metallurgy, but also highlights how difficult the study of the early transmission of metallurgy is.

<u>A holistic approach</u>

A session hosted at the SAA in 2008 was a watershed in the discussion of the early development of metallurgy from across the globe and the implementation of a holistic approach (Thornton and Roberts, 2009, p.182). One of the main contributors to this conference was Roberts, who had a number of subsequent publications which focused on the development of Copper metallurgy in Europe.

In his 2008 paper Roberts identifies that some of the issues with the previous approaches and models of the transmission of metallurgy are due to different political and cultural backgrounds of the scholars involved, and more importantly how they are often limited by regional and local perspectives, which results in researchers ignoring potential migration-related issues. This is in addition to a lack of discussion regarding results, their implications and of new analysis and research techniques applied over the recent years (Roberts, 2008, p.28).

Roberts highlights some interesting restrictions with previous approaches and models; he discusses how their regional approach restricts them. He also discusses how new implications and results from scientific analysis are not appropriately discussed, how migration in prehistory is also not appropriately considered, and how research is often too focused on one aspect of archaeological study, rather than considering all areas of research. These issues highlight the need for a more combined approach, and how analysis can add more to our understanding. It is the hope of this thesis to consider archaeological evidence, analysis and experimental archaeology, in order to assess and reconstruct process and technology. This thesis will also compare the evidence from the focal region, the Aegean, with that of the neighbouring regions, the Balkans and Anatolia, to follow this model of best practice proposed at the session in 2008 (Thornton and Roberts, 2009).

2.3.4.5. The Rise of Metallurgy in Eurasia

The Rise of Metallurgy in Eurasia project (Radivojevic, *et. al.*, 2021) enabled a move forward from the limited understanding of early metal production in the Balkans, based on evidence mainly limited to mining sites, to having a better understanding of copper smelting due to new analysis and excavations, including analysis of slags from the National Museum of Belgrade as well as excavations in Belovode, Pločnik and Jarmovac and subsequent analysis of material from the excavations (Radivojevic, *et. al.*, 2021; Cvetkovic, 2021, 5-6). The work presented in the Radivojevic, *et. al.* (2021) volume, demonstrates a new movement in scholarship around the invention of metallurgy, which uses analysis to consider the when, where and why (Radivojevic and Roberts, 2021, pp.601). The project aims to answer 6 main questions;

1. "How did the mineralogical and technological basis for early metal production in the Balkans emerge and evolve during the 6th–5th millennia BC?
2. To what extent was metallurgy related to pottery technology and production, and how did pre-existing technological knowledge influence the emergence of metallurgy?
3. How were ore sources, smelting, and casting connected and organised?
4. Where did the smelted metals circulate?
5. What metal types were being made and how did these evolve?
6. Was there a close relationship between ore sources, metallurgical technology, and artefact types?" (Radivojevic and Roberts, 2021, pp.601).

Radivojevic and Roberts (2021, pp.602) conclude three inter-related models define the mineralogical and technological emergence of metallurgy in the Balkans, within the 6^{th}-5^{th} millennia BC and these are all focused around copper minerals and their relationship we ceramic pyrotechnology.

They detail the three models as follows:

- "The migration of individuals and groups from the east with the necessary knowledge relating to selecting copper minerals/ ores and expertise in pyrotechnology.

- The transmission, via existing socio-economic networks, of knowledge and expertise relating to copper ores, copper minerals and pyrotechnology from the east into communities in the Balkans.
- The independent invention of metallurgy by communities in the Balkans who exploited the rich abundance of copper minerals and their knowledge of them and, through time, adapted their pyrotechnological expertise to smelt metal" (Radivojevic and Roberts, 2021, pp.602).

The culmination of the research conducted in the project concludes that although the practice of sourcing copper minerals and native copper originated outside of the Balkans and was brought into the region with other materials such as obsidian, the development of copper metallurgy took on its own distinctive and independent route in the Balkans as early as 6200 BC ((Radivojevic and Roberts, 2021, pp.601; (Radivojevic, 2015).

2.3.5. Synthesises

This section will now present the syntheses of the evidence of early metallurgy by Craddock and Sherratt, as these present a valuable discussion and critique necessary for the re-consideration of this material.

2.3.5.1. Craddock

Craddock provides a synthesis of early metal mining and production, in which he calls for new literature on the subject of metallurgy to be carefully targeted due to the existing abundance of comprehensive and accomplished literature on the history of mining and metallurgy (Craddock, 1995). He highlights, in particular, the extensive literature on metallurgical processes, especially that of later periods, as well as many general significant advances published in surveys on the subject, such as that of Tylecote (1976). Rather than repeating literature on the history of mining and metallurgy, research should be carried out with a focus on gaining a broader understanding of technology. Craddock's synthesis focuses on significant advances which had been recently published, and how documentary or ethnographic evidence is used in an attempt to better understand technology. However, at this point in time (when Craddock was writing the synthesis), the understanding of metal technologies still had not been integrated into the discussions of overall socioeconomic life of the communities that use them. Meaning, that the work Craddock was doing, was to some extent, still looking at metallurgy as a separate activity and did not put it back into the context of society and other technological processes and other aspects of life such as farming or economy.

Another consideration that Craddock raises is that he believes the theory that the smelting of metals almost certainly followed from the heat treatment of native copper. However, this has been deliberated by many other scholars (Charles,1985; Tylecote, 1976; Rapp, 1988; Wertime, 1964, 1973; Craddock, 1995, p.122). Despite Craddock holding this opinion, he does state that there is little direct tangible evidence for the transition of the heat treatment of native copper to the smelting of metals and that “we must be content with conjecture” (Craddock, 1995, p.122). Therefore, the idea is based on his assumption of the development of copper metallurgy rather than evidence of the development of processes. He states that native copper is frequently found in the upper oxidised part of the ore bodies, alongside copper minerals such as malachite and azurite, which were selected first. These were used as pigments and for cold working artefacts such as beads and pendants at sites such as Cayonu Tepesi (Muhly, 1988; Maddin *et al.,*1991) and Feinan (Hauptmann, 1990) during the Neolithic. At this point, the association between metal and minerals must have become increasingly apparent (Craddock, 1995, p.112). The consideration of whether smelting copper ore is a development of a pre-existing skill, such as working native copper or a new one, does affect the understanding of the progression of technology and practice or the inception of a new technology. It also does not consider the process of making metal appropriately and the difference in practice and process between working native copper and smelting metal ores. This will be discussed further in Chapter 4 when discussing the evidence from the Balkans.

2.3.5.2. <u>Sherratt</u>

That metallurgical technology is a focal part of all archaeological studies, along with all technology, is highlighted by Sherratt (2000). The re-consideration of metallurgical technology in light of new data with the advances in carbon dating methods during the early 1990’s is addressed. However, it is pointed out that the discussion of invention and diffusion is not a new topic. Sherratt's synthesis of 'A History of Technology' (1954-58) highlights this (Raper 1954). One of the points praised about this collection of journals is its discussion of how technology can be adopted and developed in relation to contributing factors such as environmental conditions, the availability of materials, economic surplus supporting craft workshops and trade relations (Raper 1954), such considerations have been lost in some more recent discussions.

In France during the 1980s and 1990s, technology was being considered and written about in a new style, coined as 'the social construction of technology' (Bijker *et al*., 1987; Pfaffenberg 1988). Since ethnographers such as André Haudricourt (1988), François Sigaut (1975), Bruno Latour and Pierre Lemonnier (1994) see technology as an integral component of social change and use it to discuss how technology is a choice, with the people who adopt and practise such skills having a conscious choice in how they do so. Sherratt builds on this by discussing how, if technology is a choice, each example reflects local traditions and that we should not expect uniformitarian sequences (Sherratt 2000, p.17).

2.3.6. Discussion of theories for the early transmission of metallurgy

This section (2.3) of the chapter has presented a summary of the previous models and approaches for understanding metallurgy's early inception and transmission. By providing an explanation and summary of the modes and a brief description of how they came into being, it hopes to give a better understanding of them and whether they are still applicable. It is evident from this discussion that as new evidence and analysis are realised, these models do need to be re-assessed, although much can be learnt from their creation. This discussion has also demonstrated that any modern approach to understanding the transmission of metallurgy must be holistic and assess material outside of one region alone. How or if the APF model fits into these existing models for the transmission of metallurgy will be discussed in Chapter 11, as well as whether understanding these models can help illuminate how and why the APF technology is so isolated yet lasts for such a long time.

3. Chapter 3: Methodology

3.1. Chapter introduction

Chapter 2 explained the process of copper smelting, the terminology and the types of archaeological evidence found from each process, and detailed the current models for the emergence and transmission of copper smelting technology across Eurasia. This thesis will assess the evidence (Chapter 4) for the Aegean Perforated Furnace (APF), which is present within the southern Aegean, and it will then propose a new model for its use. This chapter will present the methodology this thesis uses to re-assess the evidence for the APF (Chapter 4) and to test the new proposed model for how the furnace functioned (Chapters 5 and 6). The thesis will then detail (Chapter 7) how and why this new assessment will affect the existing models for the emergence and transmission of copper smelting technology across Eurasia.

This thesis used an interdisciplinary approach to re-assess the evidence and context for the APF and test the new model for how the technology functions. The methods used are summarised below in Table 3.1 and will be explained in more detail in this chapter:

Analysis	**Contribution/Aims**
Desk based assessment	Collation of all the evidence for copper smelting in the LN/EBA Aegean, Balkans, and Anatolia. Reassessment of archaeological evidence detailed in publications and archives for LN/EBA copper smelting to identify if any perforated ceramic fragments have been overlooked. A re-assessment of the evidence from the sites bearing perforated ceramic fragments is needed to understand the context and practice of the APF.
Experimental campaigns	To test the method of function proposed for the APF furnaces (wind-powered) and see if this mode of functioning can smelt copper.

Macroscopic analysis	To identify what types of metallurgical material were produced during the experimental smelts (slag, copper, conglomerate). To assess the alteration of the ceramic material (furnace fragments) and its appearance after the smelt. To then compare the material produced during the experimental smelts with the excavated material to see if the colour alteration and material adhering to the ceramics are comparable, as another way to test the plausibility of this method.
GIS	To map the sites chronologically and consider variation in material evidence at each location, to understand the choice of location for the smelting sites and the movement of activity. Finally, to understand the importance of the wind and the site locations.
Microscopy	To assess the metallurgical material (slag, conglomerate, and copper prills) to identify structures that tell us about internal temperatures and conditions (reducing, cooling). To assess how the slag formed and compare it to the archaeological material analysed from excavations to see if the conditions achieved are comparable. To therefore test the plausibility of this natural draft method, and whether it is more accurate than the method tested in previous experimental campaigns (Pryce *et al*., 2007; Catapotis *et al.,* 2008).
SEM	To achieve a higher magnification assessment and images of structures identified in the microscopy and to perform chemical analysis of the metallurgical material to understand how successful the smelt was by looking at the amount of copper in the slag (representing copper loss). To assess the plausibility of this method and

	understand how efficient this type of furnace and method would have been in prehistory.
pXRF	To analyse the ceramic furnace fragments to see the levels of copper on them. To compare them to analyses of other experimental furnaces and to see if copper residues can be found on ceramics that do not look like they were part of the metallurgical process in different ways (e.g., colour alteration, vitrification).

Table 3.1 Synthesis of the different types of analysis used in this thesis and their aims.

3.2. Re-assessment of material evidence

The material evidence associated with the APF will be re-assessed. In order to do this, a database was created collating all the evidence for copper smelting in the FN and EBA Aegean, Balkans and Anatolia (Appendix 1), as the evidence had not been collated in one place previously and had not been re-assessed with the new understanding of perforated furnace technology. The collation of this information allowed an assessment of the different methods and technologies used for copper smelting at this time in these regions to assess precisely where the APF was present. Georgakopoulou (2017, p.57, p.61) carried out a physical re-assessment of the evidence at Kephala on Keos as the excavation archive was available to her, and she did identify perforated furnace fragments, which had not been detailed as such previously. This demonstrated the importance of re-assessing old excavation archives when new information and analyses advance our understanding. As there are now multiple sites with evidence of perforated ceramic furnaces, it is clear this is a ceramic tradition for a smelting technology different in style and possibly function from other contemporary ceramic furnaces in the region. However, when some of these sites were excavated, the archaeologists only looked for evidence of copper smelting and did not differentiate between different types of technology/furnaces. Therefore, we can now see two distinct structures for smelting copper: bowl hearths and perforated shaft furnaces. A re-assessment was needed to understand which material is present at which site and to realise the extent of the APF technology. Also, we now know from chemical analysis that early copper smelting furnaces may not be highly colour-altered or vitrified, and therefore, some ceramic fragments may not have been identified as being used for smelting but rather as having domestic uses; this will, thus, be assessed as well.

This thesis assesses the excavation publications and records, where possible, to look for evidence of perforated furnaces that may have been missed. Furthermore, it looks at the other evidence in context to see if wind-powered smelting took place; for example, looking at the site's location and other associated evidence, such as tuyères, bellows, and stone tools. The summary of the findings of the collation and re-assessment of evidence is presented in Chapter 4, and the databases are included in Appendix 1.

Previous work looking at the function of the APF relied heavily on the evidence from Chrysokamino (Betancourt, 2006), which is the latest in date of all the sites dating to the EBA/MBA and less contemporary with the majority of evidence which fits the APF model (FN-EBA). Collating all the evidence for the distribution of APF demonstrates this technology's geographical and chronological range, which has not been recognised previously. Georgakopoulou (2017) presented a number of the sites, more than had been discussed together previously, and discussed the location of the smelting activity and the movement of resources, which progressed the understanding of this tradition of smelting (see Chapter 4 for further discussion of her work). However, Georgakoupoulou did not present the evidence from the sites in detail, which does not allow for comparing the evidence and process. Since 2017, more sites have been published, some of which are earlier in date, including the site of the Acropolis (Dimitriou, 2017) and Gerakas (Πλασσαρά, 2020). Once the evidence was collated, it was assessed to see whether it was considered to be used in the process of smelting or whether, alternatively, it could have been used in a different stage of the copper production process, such as beneficiation, consolidation or casting, using the guidelines set out in Chapter 2. The evidence was then assessed under the following categories:

- What stages of the copper production process are present?
- Is the evidence definitely the result of copper smelting?
- Why is the smelting process carried out in that location?
- Is there evidence of forced draft?

These re-assessments enabled a critique of the existing models for the APF and enabled a new model to be proposed (Chapter 5).

3.2.1. The Aegean Perforated Furnace's Experimental Campaigns: methodology

(image redacted for copyright purposes)

Figure 3.1 reconstruction of the perforated furnace (Betancourt, 2006, Figure 7.3).

The method used for both experimental campaigns was the same. The second campaign built on the first one and was undertaken to gain more data and to conduct more tests with experience of the method and technology. In the second campaign, I was able to use copper ore rather than copper pipe and slag, which had been the only possibility when conducting the first series of experiments. The shape and dimensions of the model reconstruction of the ceramic furnace were the same as those presented by Betancourt (2006), which had been based on the furnace fragments from Chrysokamino (*Figure* 3.1). This model was also used in the experiments by Pryce (*et al.* 2007) and Catapotis (*et al.* 2008), making the results comparable to their experiments. As the thickness of the walls at Chrysokamino is comparable to the majority of the material from other sites, with the exception of those from Kythnos, it is a suitable model to use to test this furnace design. A third experimental campaign, directed by myself, was conducted by students as part of a module at the Department of Archaeology at the University of Sheffield. This reconstruction was also based on the model of the experimental campaign developed for Campaigns One and Two, which used the same mould built for those experiments to ensure that a comparable furnace was built. The third campaign mimicked the experiment carried out in Campaigns One and Two but used a ceramic furnace with thicker walls and slanted perforations to match the measurements of fragments found on Kythnos (Bassiakos and Philaniotou*,* 2007). The methodology used to build the furnaces and conduct the experiments in all three experimental campaigns will be presented below.

3.2.1.1. Building the furnaces

(image redacted for copyright purposes)

Figure 3 Reconstruction drawing of the perforated shaft furnace (Bassiakos et al., 2007, Figure 2.8.).

The dimensions (*Figure* 3.2) for the ceramic furnace were based on the reconstructed model by Betancourt (2006), who based this on the ceramic fragments excavated at Chrysokamino. This was due to the large number of fragments, including rim pieces, base pieces, and fragments with multiple perforations, which were present at the site. This enabled Betancourt to estimate the height and diameter of this type of furnace. The same model and measurements were used by Pryce (*et al.* 2007) and Catapotis (*et al.* 2008). The furnaces for my experimental campaigns were built using a mould to enable the furnaces to be slab-built and to ensure the correct dimensions were achieved. The mould enabled the ceramic cylinder to be built to the correct dimensions without shrinkage or failure. This was especially important given the high level of skill which would have been required to free-form a clay cylinder of this size.

Figure 3.2 Mould in production (left) and Figure 3.3 Finished mould (right) (photo by author).

The clay used to build the furnaces was a natural coal measure clay excavated from Sheffield (Glennie 2000). The clay was tempered with sand and chaff to replicate the recipe of the clay used in the Aegean Perforated Furnaces (Myer & Betancourt 2006, p.291; Bassiakos and Philaniotou, 2007, p.28-9; Coleman, 1977, p.4, p.66; Dimitriou, 2017, p.28-29; Πλασσαρά, 2020, p.331). The clay was left to dry until it was damp but not leather-hard, and the furnaces were removed from the moulds. This meant that the clay was dry enough to keep its form and shape but wet enough that the perforations could be made. The lip found around the perforations on the interior side of the ceramic fragments suggests that the perforations were made whilst the clay was still wet (Dimitriou, 2017, p.29). The diameter of the perforations ranges between 1.5-2.0cm at all sites except Kythnos, where the external diameter of the perforations is 3cm, and the internal diameter is 2cm, which is considered to be due to the thickness of the wall. Betancourt (2006, p.110) suggested that the perforations were made by pushing a finger through the wet clay. This would account for the variation in the size of the perforations across a site and would also explain why the external diameter of the perforation in the thicker walled fragments from Kythnos is wider than the diameter on the interior; as fingers taper and get thicker closer to the hand, a slanted perforation would have been created in a thicker wall. Therefore, it can be accepted that the perforations were made by pushing a finger through the clay.

 

Figure 3.4 Built furnace in the lab (left) and Figure 3.5 Built furnace at the start of the experiment (right) (photos by author).

3.2.1.2. Firing the furnaces and smelting

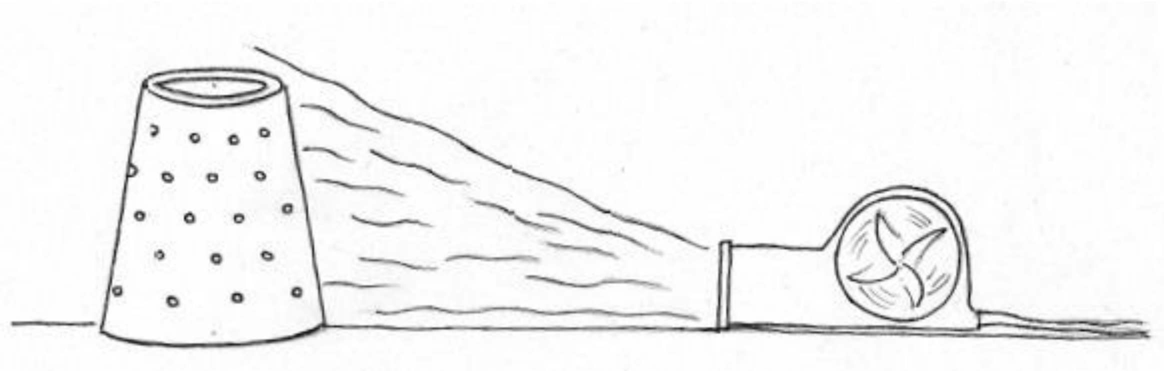

Figure 3.6 Image showing how the experimental campaign was set up with a furnace and simulated air. (Drawn by author).

Once the furnaces were built, with the perforations created, they were left to dry until leather-hard. They were then transported to the field, where the experiments would be conducted. The experiments were conducted in a fenced-off area so that the wind speed could be controlled. Both the wind direction and the wind speed were controlled by using an electric fan. This was done to mimic the natural environments of the smelting sites, where intense wind speeds would come from a specific direction. Wind speeds which were recorded by myself at Chrysokamino (Table 3.1) during the windy season were replicated using an electric fan and an anemometer to ensure the correct wind speeds were replicated (*Figure* 3.7). The modern wind speeds can be considered comparable to those in the FN and EBA, as the environmental conditions in the eastern Mediterranean based on observations made by Aristotle and Theophrastos are very similar, meaning the conditions such as pressure regions which cause differences in wind patterns and speeds as similar enough to assume they are comparable (Murray, 2008, p.139-167).

Latitude	**Longitude**	**Wind speed m/sec**
25.835969	35.136917	19.4
25.835971	35.136803	17.6
25.835951	35.136699	18.1
25.835926	35.136594	12.2
25.835919	35.136488	8.5
25.835893	35.136378	5.7
25.835851	35.136262	6.1
25.835870	35.137036	21.1
25.835812	35.136936	20.7
25.835756	35.136829	18.3
25.835707	35.13672	16.2
25.835629	35.136625	14.1
25.835567	35.136513	9.1
25.836261	35.136989	14.8
25.836244	35.136775	11.6
25.836162	35.136752	12.1
25.836145	35.136464	6.4
25.836082	35.136329	8.2

Table 3.2 Wind speeds recorded at Chrysokamino in autumn 2016 by the author.

At the start of each experiment, a wood fire would be lit to heat the furnace up slowly and gradually bake the clay in order to prevent cracking from the extreme temperatures that would be experienced during the smelt. Once the clay had hardened and the wood fire burned well, a small amount of charcoal was added. Once this charcoal was ignited, the furnace was filled to the top with more charcoal. Thermocouples were added to record temperatures throughout the furnace during the smelts (*Figure* 3.8). The placement of the thermocouples was configured to gain an understanding of temperatures at different areas of the furnace.

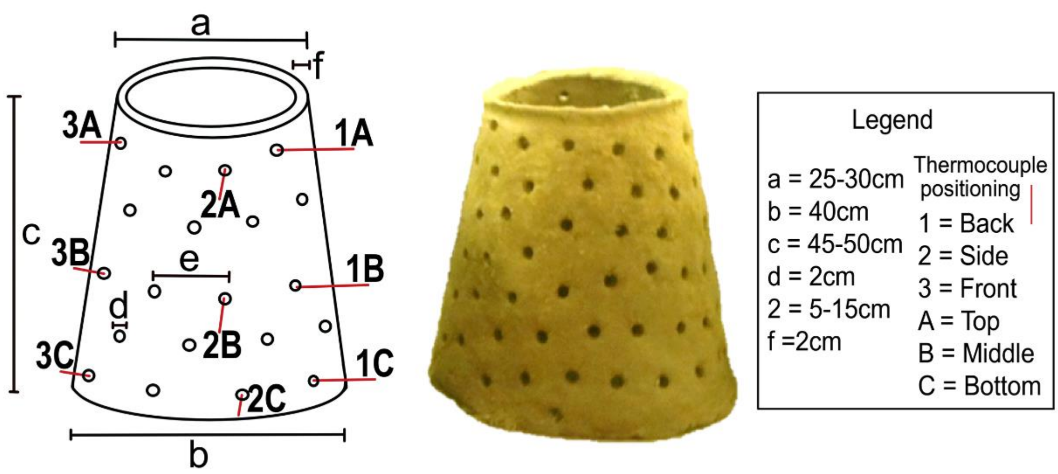

Figure 3.7 Photograph of reconstructed furnace, and drawing showing dimensions of the reconstruction and position of thermocouples (Doonan and Marks, 2021, Figure 2).

Once the fuel was lit and burning, more fuel was added. The timing of a new charge of fuel was determined by the furnace rather than being done at a set interval. Fuel was added when the fuel had dropped 5cm from the top of the furnace, topping the charcoal back up to the level of the rim. Using this method of refilling the fuel allowed us to see how quickly the furnace is burning and compare the fuel consumption between smelts. If fuel had been added at set times, this would not have allowed recording the rate at which the fuel was burnt during the smelt and across smelts. Once the smelts were complete, the furnaces were dismantled, and the ceramic and metallurgical materials were photographed and brought back to the lab for further inspection (photography, identification of metallurgical material adhering to surfaces, and pXRF analysis - Chapter 6) to allow for comparison to other experiments and excavated material. The macroscopic evidence of the remains of the furnace and the temperatures recorded via thermocouples during the smelt are presented in Chapter 6.

3.3. GIS analysis

Spatial analysis of the distribution and location of sites with APF technology was undertaken using a Geographical Information System (GIS). It was hoped that this mapping of the distribution of the sites would enable site-by-site analysis and the identification of trends in the locations of sites to identify possible motivations for the choice of that location to conduct the smelting activity. Furthermore, it would assess patterns of specific material evidence at sites (type of furnace, evidence for forced draft) to look for patterns, as well as the date of each site and its location in relation to the wind speed and direction. Together this information would help assess the progression and movement of the technology and the rationale for locations.

The aims of the GIS were:

I. Map all of the sites in the Aegean which have evidence of copper smelting in the FN-EBA.
II. Identify which sites have evidence of perforated smelting furnaces (APF), and which do not have perforated technology.
III. Identify which sites have different smelting processes taking place, by identifying different aspects of ceramic smelting technology; bellows, tuyères, crucibles, and moulds.
IV. Identify the date of sites and determine whether there is a pattern in the spread of the technology across the region.
V. Map the sites with evidence of smelting alongside regional/local wind speed and directional data, to assess whether all the APF sites would experience strong winds.

The method used for the GIS analysis was as follows:

I. An Excel spreadsheet was created using the data compiled in the region databases, which listed the sites, their coordinates, and the different attributes I wanted to plot. This included the date of site, bellows, tuyères, and whether the furnace walls were perforated or non-perforated.
II. The sites were plotted on a base map using the WGS84 CRS (Coordinate Reference System). QGIS version 3.12 'București' was used for data processing and map creation. The database was imported as comma-separated value (CSV) files; these delimited text files were easily created from previously established Excel spreadsheets showing site names, locations, and other relevant data.
III. Within QGIS, site data were divided by regions (Aegean, Balkan, and Anatolian sites) and represented as vector data, with individual points representing each site within a given region.
IV. Data from the Aegean were further divided into sub-layers representing sites by date, by evidence of perforated furnaces (i.e. APF), and by evidence of forced air (i.e. tuyères). Subsequent maps were created to show these sub-layers; the map, which shows sites by date, employs the abbreviations FN, EBA, and MBA for the Final Neolithic, Early Bronze Age, and Middle Bronze Age, respectively.
V. Windspeed data were added to the map. Wind data were downloaded from Global Wind Atlas (current version GWA 3.3), which exists as a partnership between The Technical University of Denmark's Department of Wind Energy and the World Bank Group. The data available through GWA results from local wind data being calculated at 250 metres at 10, 50, 100, 150, and 200 metre heights. On a 250m grid, every node has a local wind climate estimate. Datasets and tools for analysing statistics based on the 250m grid values are available on the GWA website. This allows the data to account for varying levels of topography within a given locality. Data from GWA were used in maps *APF_Date_Wind, APF_Thickness_Wind* and *APF_Tuyères_Wind* to visualise wind speeds around relevant sites in the Aegean data set.

3.4. Proposal of the new model for the method of smelting in the APF

The reassessment of the APF evidence (Chapter 4) paired with the GIS analysis (Chapter 6), demonstrated that the APF is always situated on windy promontories. This factor, combined with a lack of evidence for forced draft (bellows/tuyères) at the sites, led to the proposal of a new smelting method in the APF (Chapter 5). A study of other wind-powered technologies was undertaken to understand how the furnaces function using natural draft (Chapter 5), and also a study of the fluid dynamics of the APF using only natural wind (Chapter 5). This new model was tested by a series of experimental campaigns (Chapter 6), followed by the analysis of the material from the smelts, which was compared to the archaeological records to assess the accuracy of this model (chapter 6).

3.5. Analysis performed on the material from the Experimental Campaigns

3.5.1. Macroscopic analysis

The macroscopic assessment of the material produced from the Experimental Campaigns (ceramic furnace fragments, conglomerate, copper prills, and slag) determined how successful the smelt was and what metallurgical materials had been produced (conglomerate, copper prills, slag). Furthermore, it allowed for a comparison of the experimental material with the evidence from the archaeological record to assess whether the method of function created the same effects on the ceramic material of the furnace and produced the same metallurgical material. The material evidence which was assessed macroscopically included:

- Ceramic furnace fragments
- Copper prills
- Slag
- Conglomerates

This material and the macroscopic assessments are presented in Chapter 6. This assessment helped assess whether this method of smelting in the APF is accurate based on the physical material produced and affected by it. If the same conditions were achieved in the experiments as in the excavated furnaces, the ceramic material from the furnace should be altered in the same way from the heat, flames and reducing environment, and therefore, the same metallurgical materials would be produced and would have comparable shapes to those discovered on archaeological sites.

3.5.2. Scientific Analysis

Three types of scientific analyses have been employed to assess the material produced from the experimental campaigns and compare it with the material excavated from the sites that bear evidence of the APF. These analytical methods were microscopic metallography, chemical analysis by pXRF, and SEM analysis (microscopic imaging and chemical analysis). The analysis of the slags and copper products was intended to enable us to assess how comparable this smelting method is to that from the archaeological record by determining whether the same conditions were experienced within the reconstructed furnaces and the excavated furnaces. In addition, I assessed whether the ceramic furnace material was affected by the process in the same way (heat alteration, change of colour, vitrification). This provides an understanding of whether the environment was reducing or oxidising, the temperatures achieved, how the ceramic furnaces were altered by these, and how these environments affect the production of metallurgical material. The results of these methods of analysis are presented in Chapter 6.

3.5.2.1. Microscopy

The slag and conglomerate samples were taken from the material produced in Campaigns One and Two. The micrographs for Campaign One were taken as part of my MSc and have been referenced appropriately. However, a new assessment of the structures was undertaken and is presented in Chapter 6. This has enabled further discussion and comparison. Samples were taken from different types of furnace products (slag and conglomerate), ensuring each different type of slag was tested from a morphological point of view. Samples were taken from different areas across the conglomerates. The samples from Campaign One were mounted in Bakelite, using a Buehler Metaserv mounting press in order to keep the structure of the material intact and to enable analysis under the microscope. The samples from Campaign Two were mounted in Buehler epoxy cure resin and mixed according to the instructions, as this varies from batch to batch. The difference in the resin used to mount the samples between Campaign One and Two is the result of a change in the practice of the laboratory in the Department and because epoxy resin became a more suitable resin for mounting metal samples.

Both sets of samples were then prepared for microscopy by grinding and polishing in the same way to remove scratches from the surface and enable the structures to be observed. The samples were ground on a Buehler grinding machine with grit papers ranging from P220 to P2500. The samples were then polished on a Buehler polishing machine, using Buehler MetaDi II Diamond Polishing Compound, ranging from 6 microns to 1 micron in size. Between each stage of grinding and polishing, the samples were cleaned in an ultrasound bath using deionised water to remove all grit or paste from the previous stage and prevent cross-contamination.

The samples were then assessed using a Leica DM 2700P polarisation microscope using reflective light, and the micrographs were created using a Leica MC10 HD camera and the LAS V4.12 imaging software.

Evidence of copper and different structures within the slag and conglomerate material enabled the determination of how hot and/or reducing the internal conditions were. This allowed for the reconstruction of how the furnace worked, and allowed for a comparison with the material evidence from excavations across the Aegean. The main structures identified were iron oxides, magnetite, wüstite, and delafossite. Comparison to other analyses (Bassiakos *et al.*, 2007; Georgakopoulou, 2007) was carried out to support the identification of these structures, as was the use of guides such as Scott (1991) and training notes from a module in metallographic analysis conducted as part of an MSc.

When the PhD was started, it had been planned that the author would get access to archaeological material from some of the excavated sites to conduct microscopy on to have more excavated material to compare to than just that from Chrysokamino. However, this was no longer possible due to the COVID-19 pandemic and changes in the supervisory team. However, it was essential to analyse material from more than one experiment to show that these conditions were consistent and the norm for these furnaces.

3.5.2.2. Chemical Analysis via pXRF

Chemical analysis was conducted using a portable X-ray fluorescence (pXRF) instrument. The Niton XL3T model was used in handheld mode to conduct this non-destructive analysis (Price and Burton, 2011, p.86). XRF was chosen for this analysis because it was affordable, non-destructive, and more readily available than SEM. It is hoped that by using a more available and non-destructive method, more work can be done to compare this data in the future. The method was previously conducted on other furnace fragments used for copper smelting experiments (MacKinnon, 2013; Mlyniec, 2016; Bruyere, 2018), and to analyse archaeological material believed to be from copper smelting activities (Bassiakos *et al., forthcoming*). This technique thereby enabled comparison with the current data. Portable XRF machines are often used on metallurgical material, as they are portable and can be used without destructive sampling for some analysis.

To conduct the analysis, the analyser window was placed in contact with the point of analysis. Readings were taken across the interior and exterior of ceramic samples from experimental Campaigns One and Two. This method of analysis was chosen as it has been used on ceramic fragments from excavation (Bassiakos *et al., in prep*). The method was also preferred as it is non-destructive and analyses the first few millimetres of surface (Dussubieux and Walder 2015, p.170), which was desired in this instance, to enable the detection of elements deposited on the exterior and interior of the ceramic fragments during the smelting process, rather than assessing the composition of the ceramic material itself. The same method has also been used to analyse ceramic fragments associated with copper production for Experimental Campaigns reconstructing Balkan material, as discussed in Chapter 5 (MacKinnon, 2013; Mlyniec, 2016; Bruyere, 2018), providing comparable data.

The setting used to conduct the analysis was mining mode, detecting Cu/Zn, with the main range scanning for 30 seconds and the light range selected for 15 seconds. This is the mode recommended by Niton for scanning ceramic material when looking for traces of metals. The main element being assessed was Cu (copper), which was detected in the main range setting. The units recorded were ppm (parts per million) as the amount of copper in each reading was being assessed to compare it across the samples being scanned. This was done to enable detection of the amount of copper left on the ceramic fragments from these processes, and to compare it across the samples from these smelts and other experiments and archaeological material. As the copper is left as a residue, we did not want to see what percentage it comprised of the material being scanned. This is more important when identifying copper as part of an alloy, in which case the unit used would be %. Readings were taken at multiple points across the ceramic fragments, and at each point a reading was taken three times and averaged. This was done to achieve a reasonable degree of accuracy, as metals can be affected by corrosion and can give a false impression of the chemical composition (Pollard, *et al.,* 2007, p.310; Thompson, 2019, p.180). This was not as much of a concern for this analysis, as we were looking at the comparable amounts of copper present across samples, rather than its percentage in an alloy. Macroscopic images were also taken of the samples which were analysed, and the points which were analysed were identified, in order to help identify areas affected by corrosion.

It was determined that, for the purpose of this analysis, the data did not need to be normalised, as is sometimes done with data when looking at only some elements from the spectrum. As the standard deviation for the reading of copper on the analysis of the standards did not vary beyond 1, it was deemed the data were within a limit of accuracy. Also, the data from these analyses look at the relative variance across the samples being analysed, to identify areas of increased readings and patterns, rather than the specific composition of certain elements from a spectrum (as would be the case when looking at the recipe of a metal alloy), and therefore it was not deemed necessary to assess the data in that way. Normalisation of data is only important and necessary if the standard deviation varies across the standards and data, and if specific amounts of an element are needed, such as when identifying the amount of copper in an alloy, which was not the purpose of this analysis.

3.5.2.3. Scanning Electron Microscopy (SEM)

SEM analysis is used in archaeology for two main purposes: the use of the secondary electron image (SEI) to observe the surface topography of a sample and the determination of the composition through energy-dispersive X-ray analysis (EDAX) (Hawkes, 1988, p.357). Both methods are used in this thesis. The structures of the slag and copper conglomerate were assessed via SEI, and the chemical composition of the metal products (slag and conglomerate) were assessed through EDX. The samples were either pre-prepared mounted-polished samples, prepared by the method detailed in section 3.5.2.1, or placed in the chamber whole.

An SEM is a powerful microscope which uses electrons instead if light energy to create images. It creates a grey-scale image with a good depth of field at high magnification. The image is created by a narrow beam of electrons being produced by an 'electron gun', and the beam creates its focus by electromagnetic coils, called lenses. This is then scanned very quickly back and forth across the sample being analysed. The sample is scanned within a vacuum, so that the beam and the electrons within it do not interact with air molecules. As the electron beam hits the sample, there are three main types of interaction, which respectively produce backscattered electrons, secondary electrons, and X-rays. Both types of electrons provide imaging information, and most SEMs allow switching between secondary electron images (SEI) and backscattered electron images (BSE). SEI is the most common mode used for archaeological investigation, particularly metallography, as it is good for the study of microstructures and textures (Frahm, 2014, p.6847; Ponting, 2004, p.166-7).

SEM analysis was conducted on a selection of mounted samples from Campaign Two which were prepared for microscopy. New samples also were taken from the metallurgical remains from Campaign One, as the mounted samples used for my MSc were no longer usable. Samples were taken across the same range of metallurgical materials: slag, conglomerate, and copper prills, ensuring all different types of slag were tested from a morphological point of view, and samples were taken from different areas across the conglomerates. In addition, new samples from both campaigns were taken, and included furnace wall and vitrification, to precisely identify the material adhering to the furnace wall. The new samples were mounted in Buehler Epoxy Cure 2 resin, and were ground and polished by the same method detailed for the microscopy (section 3.5.2.1).

The samples were carbon coated with a layer of 5 microns, using a Q150R ES machine, before being placed in the SEM. The SEM used was a JEOL IT300 with Bruker EDX and Quantax 2.5 version software. The machine was used in BED-C mode, Back Scatter Electron mode, which looks at the composition and elemental differences. The machine was checked and calibrated using pure silver standards.

The machine was then calibrated and the settings were selected, using the following standards: Orthoclase $KAlSi_30_8$ and Wallastanite $CaSi_3$.

For the majority of the samples, initial assessment was carried out at 100x and 250x, and elemental analysis was carried out at 500x. Two types of elemental analysis were conducted: firstly - object analysis, where three areas of the same size were selected and an average was made (Pearce *et al.,* 2022; Hauptman, 2000; Bachmann 1982) Secondly - elemental mapping, where the elements of the whole area were identified. The chemical analysis will be compared to that conducted on the Chrysokamino slags (Pearce, *et al*., 2022, p.6; Bassiakos *et al*., 2006, p.331) Also, images of structures were taken for more in depth analysis of structures.

The aims of the SEM analysis were:

Material	**Aim**	**Comparative reference**
Slag	Assess redox conditions by identifying elements which demonstrate different reducing conditions (e.g. moderately reducing conditions - cuprite and delafossite, more reducing conditions - and from the % of copper content in the matte (above 75%), and iron content in copper prills).	(Bassiakos *et al*., 2006, p.331)
Slag	Assess the structure of the slag to compare with Chrysokamino slags (where the current interpretation believes tapping took place) - looking for evidence of rapid cooling - e.g. banding, fine dendritic texture.	(Bassiakos *et al*., 2006, p.331)
Slag	Look at copper content in slag to see how successful the slag-metal separation was; what were the copper losses in the slag were (what percentage of the slag is copper;	(Bassiakos *et al*., 2006, p.331)

	Chrysokamino is 1% which is very efficient smelting with low copper losses).	
Slag	Amount and size of copper prills in slag.	
Conglomerate	To identify the chemical composition of the smelting process (chemical composition of the smelted copper)	
Furnace fragments	Look at metallurgical ceramics to assess the level of vitrification, and see the amounts of copper or other elements from the copper ore left on the surfaces (vitrified and none vitrified areas).	(Hein *et al*., 2007)
Fragments of ceramic wall with vitrification	Compare slag on ceramics with slag collected from the bottom of the furnace.	

Table 3.3 aims of SEM analysis.

The compositional analysis was carried out via energy-dispersive X-ray analysis (EDX). EDX is a fully automated process, in which the X-rays are emitted and collected simultaneously as a series of pulses (Ponting, 2004, p.169). The pulses are amplified and sent to a multichannel analyser (MCA), which creates a histogram of all the different energies detected. The analyst then decides which peak of the series will be measured to quantify the amount of that element present (Ponting, 2004, p.169).

3.6. Conclusion

This chapter has presented the different interdisciplinary methods employed by this thesis to re-asses the material evidence for the APF using desk-based assessment (Chapter 4) and GIS analysis (Chapter 6, section 6.3), Experimental Campaigns (Chapter 6, section 6.2), macroscopic analysis (Chapter 6, section 6.2), microscopic analysis (Chapter 6, sections 6.4 and 6.6), and chemical analysis (Chapter 6, sections

6.6 and 6.6). This enabled the thesis to propose (Chapter 5, section 5.2.3) and test a new method for how the smelting process took place within the APF. The next chapter (Chapter 4) will present the findings and summary of the desk-based assessment.

4. Chapter 4: Evidence for Aegean Perforated Furnace and contemporary evidence for copper smelting in the Aegean, Balkans and Anatolia

4.1. Chapter Introduction

This chapter is split into two sections. The first section will present the archaeological evidence and material for the Aegean Perforated Furnace (APF). The second section will detail contemporary evidence for copper smelting in the Aegean, which does not fit the model of the APF and evidence for copper smelting in the neighbouring regions of Anatolia and the Balkans to enable a comparison of the material evidence and to assess if the APF is an isolated tradition or if it is an adaption of a tradition which had spread to the Aegean. A desk-based assessment looking at published work, including excavation reports, papers and chapters, as well as archival records (British School at Athens) of excavation notes and diaries from academics when visiting the sites to do observational surveys, were assessed. This assessment collated details of the archaeological evidence from sites that bear evidence for copper production in the FN and EBA in the Aegean, Balkans and Anatolia. The evidence was compiled into three region databases, which are included in the appendix (Aegean Region database Ap1.1.1., Balkan Region database Ap1.1.2. and Anatolian Region database Ap1.1.3.). The types of evidence that could represent copper smelting, as discussed in Chapter 2 (section 2.2.), were listed. I reassessed which sites have evidence for copper smelting based on this material rather than accepting the interpretations published. This collation and assessment also enabled me to identify the differences in the style of smelting apparatus and look for additional sites with evidence of the APF and similar types of technology. This chapter presents a discussion of the evidence found in each region, focusing on the sites which bear evidence of the APF in the first part of the chapter (section 4.2.). This assessment will enable an understanding of the location of the APF and how it fits with other contemporary copper smelting technology and methods (section 4.3.) and allow an assessment of whether it is an isolated tradition or an adaption of another method.

4.2. Evidence for the Aegean Perforated Furnace

Figure 4.1. Map of sites with perforated furnace fragments. A - Athenian Acropolis; B - Gerakis, Attica; C - Raphina, Attica; D - Kephala, Keos; E - Sideri, Kythnos; F - Paliopyrgos-Aspra Spitia; G - Avessalos; H - Kephala, Seriphos; I - Akrotiriaki/Skali; Siphnos; J - Chrysokamino, Crete (Image drawn by author).

The first part of this chapter details the sites where evidence for perforated furnaces in the Aegean is currently known to be present. The definition of a perforated furnace used in this thesis is a clay conical structure used in conjunction with a metallurgical pyrotechnical process, which bears perforations within its ceramic wall. The furnace has an open top and bottom based on the ceramic material which has been found. The walls vary in thickness, ranging from 1-6cm. Currently, there are ten known sites (Figure 4.1) that have evidence of ceramic furnace fragments that bear perforations and can be considered to represent the perforate furnace. These all appear to have been and are used for copper smelting. These furnace fragments are reconstructed to represent a truncated furnace that is used to smelt copper ore. This chapter will list the sites where this evidence is present and detail the context of the site location and the date of the material, as well as provide a detailed description of the material evidence, including the clay furnace fragments, slag, copper prills, clay nozzles, stone tools and ore. Details of analysis carried out on the metallurgical material will be detailed also. The evidence from these sites will be critiqued to assess if the material evidence represents smelting activity, or another part of the copper production process. The motives for the location will be discussed also.

4.2.1. Sites with evidence of perforated furnace fragments

4.2.1.1. Chrysokamino, Crete

Chrysokamino is the latest dated material of the perforated furnace style, of that currently known. However, it was one of the earliest identified sites with substantial evidence for perforated furnaces and has had the most research carried out on its reconstruction. Due to the substantial number of ceramic fragments found, especially rim and base fragments, a reconstruction of the full furnace was possible, including height and diameter measurements (Betancourt, 2006, p.109-11). This reconstruction has become the most prominently referred to when reconstructing other perforated ceramic fragments. A number of experimental reconstructions were carried out based on this reconstruction (Bassiakos and Catapotis, 2006; Pryce, *et al*., 2007) due to the detail provided. Therefore, this site will be described first, to enable comparison throughout the chapter.

4.2.1.1.1. <u>Location</u>

The Chrysokamino smelting site is located on a headland overlooking the Mirabello bay on the north-eastern coast of Crete (Fig.1.2.) (Betancourt et al., 1999). The metallurgical site is notable in that it is not directly associated with any settlement, as it is located several hundred metres away from the domestic area of the site. This promontory is known for being subject to extremely strong winds" (Marks, 2012, p.22). As well as being exposed to the wind, "the site's position on the promontory, puts it on an exposed terrace which is secluded, yet visible from afar. The Gulf of Mirabello, is a large bay including several harbours, meaning this sight would be observed by many passing sea farers. Chrysokamino is visible from Pacheia Ammos, however would not have been easy to travel to" (Betancourt, 2006, p.3-7; Marks, 2012, p.22).

4.2.1.1.2. Date

The smelting site and material at Chrysokamino were dated by Betancourt, *et al*. (1999, p.352) and material ranges in date from the Final Neolithic (FN) to Early Minoan III (EMIII), based on the ceramic evidence. However, Haggis and Mook see the ceramic fabric of the pot bellows, associated with the smelting activities, as being the Mirabello Red Fabric (Day, 2024) which dates between EMII and MMIA (1900-1700BC) based on their Bronze Age ceramic chronology (Haggis and Mook, 1993), making it slightly later than the initial date given by Betancourt and putting it into the EBA/MBA transition period.

4.2.1.1.3. Material evidence

4.2.1.1.3.1. Furnaces

"The archaeological evidence from Chrysokamino comes in two forms; ceramic evidence (related to the furnaces and their design) and metallurgical (in the form of slags and prills)" (Marks, 2012, p.24). The ceramic evidence is made up of thousands of furnace fragments (*Figure* 4.2. and *Figure* 4.3), which are heavily tempered ceramic body sherds which measure between 10mm and 20mm thick and bear perforations measuring 20mm in diameter, spaced 5-15cm apart. "The fragments' curvature indicates that the cylinders had a diameter c.16-44cm. Rim sherds indicate that both ends of the cylinder were open" (Marks, 2012, p.24). "The majority of bases have diameters that are substantially larger than that of the rims, indicating the cylinders were tapered. The rim diameters measure c.20-30cm and base diameters c.40cm! (Betancourt, 2006, 109-11; Marks, 2012, p.24). Reconstructions of these furnaces by Betancourt show a truncated conical structure.

The Aegean furnace can therefore be reconstructed to comprise of a tapered, truncated cone with perforations which seemingly acts as a brassier (Betancourt, 2006, p.109-110; Bassiakos and Catapotis, 2006, p.330).

The ceramic furnace fragments have all been fired and are red on the exterior and dark grey to black on the interior (the glassy exterior is not present on rim sherds). Small lenses of copper alteration products (under 0.5cm) occur within this glassy coating. The interior also has a dark glassy deposit adhering to it. The clay material is coarse and has many voids within it, created by organic material burning out. Petrographic analysis revealed this organic material was chaff and moulds from types of chaff can be identified including: barley grains, one olive leaf (as well as other marks which cannot be identified) (Betancourt, 2006, p.110). Inclusions of carbonite, crystalline and cryptocrystalline quartz and phyllite are present within the clay fabric and are not comparable with the igneous rocks found in the Mirabello Fabric which was used for the majority of pottery at the site (Betancourt, 2006, p.110).

(image redacted for copyright purposes)

Figure 4.2. Ceramic fragment of perforated furnace. Left side exterior, right side interior, a glassy deposit can be seen on the interior (Betancourt, 1999, Figure 7.1).

(image redacted for copyright purposes)

Figure 4.3. Reconstruction of the perforated furnace (Betancourt, 2006, Figure 7.3).

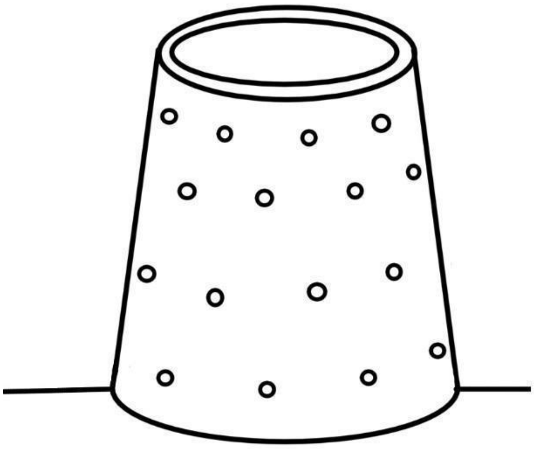

Figure 4.4. Image of reconstruction of furnace from Chrysokamino (Image drawn by author).

4.2.1.1.3.2. Other clay evidence

Other notable ceramic evidence includes fragments of at least ten pot bellows (Betancourt, 2006, p.112). The evidence for pot bellows has been used by some scholars to propose a model of smelting which seemingly relies on both bellows and wind to raise the temperature, to temperatures that are suitable for the smelting of oxide ores (Betancourt 2006 and Pryce, *et al*., 2007).

4.2.1.1.3.3. Metallurgical evidence

The ceramic evidence is accompanied by a range of archaeometallurgical evidence including slag, copper prills and artefacts such as stone crushing tools and crushing platforms. The metallurgical evidence from the site, such as slags and copper prills, is very informative and allows a better understanding of the technological process. “Evidence such as slags and prills, especially the ‘glassy’ state of the slag, indicate that high temperatures were achieved during smelting” (Betancourt, 2006; Marks, 2012, p.25). “Many tons of dark-coloured slags were found during excavation of the site, predominantly small pieces c.2cm in size, or completely pulverized. The slags from Chrysokamino fall into two groups, some which have reached 100^{o}C higher than others (Betancourt, 2006, 187; Bassiakos *et al.*, 2006, 330; Marks, 2012, p.24), Reinforcing the inconsistency of temperatures reached during firings with the perforated furnaces. “The slags also indicate that different amounts of reduction took place during the smelts, this is indicated by the relative amounts of fayalite, which suggests varied temperature conditions and an inability to maintain constant conditions within the furnace between different firings” (Betancourt, 2006, p.188; Marks, 2012, p.24).

4.2.1.1.3.4. Ores

The analysis showed that the ores smelted at Chrysokamino were not local, or from Crete, but were brought from the western Cyclades, this theory is due to results from lead isotope analysis which indicates the ores are not Cretan (Georgakopoulou, 2017, p.55; Stos-Gale and Gale, 2006). Despite extensive survey in the area of Chrysokamino, no evidence of copper mineralisation has been noted (Catapotis and Bassiakos, 2007) and geologically, it appears unlikely that copper mineralisation was ever in evidence. With isotope analysis suggesting that Cycladic and mainland (Lavrion) malachite (Stos and Gale, 2007) was smelted at Chrysokamino it suggests that mineral proximity was not an important consideration when choosing smelting location. It seems certain that ores were transported to the site by sea and it is relevant that within 200m of the promontory existed a good landing spot for small vessels. Broodbank (2000) has argued that transport in the EBA relied on paddled canoes and the beaching point to the south of the sites seems a likely location where travellers could land consignments of ore. Quite why Chrysokamino was chosen is difficult to understand. There is unlikely to be copious fuel deposits in the vicinity and clay deposits have not been noted. Smelting was undoubtedly practised here and it seems that the secluded nature of the site was a key consideration. It is a prominent location that is visible from afar, yet it is isolated and difficult to reach and offers both privacy and a degree of advertisement from afar (Broodbank, 2000; Day and Doonan, 2007).

4.2.1.1.4. Discussion

The smelting site is located on an exposed promontory, which is exposed to strong winds. There is plenty of available space around the promontory, which was situated far enough away from the settlement, yet what not used. The smelting site could have been extended or situated in a more sheltered area, however only the promontory has been used for smelting activity. The ceramic fragments are coarse in nature and have had temper added to them purposely, such as chaff (Betancourt, 2006, p.110), which makes them better suited to being used with high temperatures (Betancourt, 2006, p.109-11). The ceramic fragments have different stylistic features, which enables identification of rims and bases, as well as diameter, allowing for a detailed reconstruction, which demonstrates the furnace is open bottomed and tapers, making it comparable to a brazier, which may be placed on a fire to help increase temperatures before cooking. However, it can be recognised that these ceramic fragments were not used domestically, but rather as part of a metallurgical process, as the fragments are altered in colour from exposure to extreme heat, much higher than they would be if used during cooking. The fragments have colour alteration including black (inside) and red (outside) as well as having glassy material, which comes from the clay being exposed to intense heat and the silica in the clay vitrifying. The metallurgical material that accompanies the ceramic fragments tells us the activity taking place was copper smelting, due to the presence of copper prills and slag. The slag was the most frequently found material, with many tons being present at the site. The slag came in two different forms, showing that the smelting conditions were not stable, probably due to an unstable method of air input. The slags had also been pulverised into small pieces around 2cm in size (Betancourt, 2006, p.187; Bassiakos and Catapotis, 2006, p.330). The presence of stone crushing tools, paired with the fact the slag had been pulverized into small pieces and copper prills being present at the site, as well as the slags showing evidence of different smelting conditions, suggests that the smelting process may have not been fully successful, and rather than the slag becoming fully separated from the copper, it produced a conglomerate instead, which would require the slag to be crushed and prills to be released. Due to the smelting site being located on the windy promontory and as the slags indicate changeable conditions within the furnace, it can be considered that the smelting furnaces were being powered by the natural wind, the ceramic evidence for clay nozzles (tuyères) and bellows, would represent part of the consolidation and casting process (Doonan and Marks, 2021).

4.2.1.2. Paliopyrgos-Aspra Spitia and Sideri, Kythnos

Kythnos is another of the more well reported and known sites featuring perforated fragments. There have been a number of different excavations and surveys conducted at Kythnos over a number of decades and which revealed a number of ceramic fragments which has enabled a reconstruction of the furnace (*Figure* 4.3) (Bassiakos and Philaniotou, 2007, Figure 2.8).

4.2.1.2.1. Location

(image redacted for copyright purposes)

Figure 4.5. Map of Kythnos with sites of archaeological and metallurgical interest indicated (Bassiakos and Philaniotou, 2007, 23, Figure 2.1.).

Kythnos is an island situated in the western boundary of the Cycladic islands, between Kea and Serifos. “Kythnos has a mountain spine and several coastal plains, with steep coastlines” (Bassiakos and Philaniotou, 2007, p.23-4; Marks, 2012, p.29). The island’s geological construction is made up mainly of metamorphic rocks (Bassiakos and Philaniotou, 2007, p.20). Paliopyrgos-Aspra Spitia (known as Paliopyrgos or Aspra Spitia) is located c.250m above sea level on the southern slopes of Kakovolo. The concentrations of broken copper slag and clay furnace fragments lie on the sloping ground to the south and west of the tower on top of Kakovolo (Bassiakos and

Philaniotou., 2007, p.30). "Sideri is located about 100m northeast of Pounta (450m away from Paliopyrgos-Aspra Spitia), on the saddle of the promontory, upon a small rocky eminence at 174m above sea level" (Bassiakos and Philaniotou., 2007, p.20-8; Marks, 2012, p.29).

4.2.1.2.2. Date

The excavation and survey at the sites found evidence of ceramic fragments for copper smelting, which dated the activity to ECII (3000-2000BC). "The dating using the ceramic evidence was supported by AMS ^{14}C of charcoal in the slag used for copper smelting" (Bassiakos and Philaniotou, 2007, p.25; Marks, 2012, p.29). An earlier survey conducted by Gale *et al.*, (1992, p.85) also revealed obsidian blades and copper prills c.1cm in size, which suggested Bronze Age exploitation at the mines.

Paliopyrgos-Aspra-Spitia: Among the metallurgical material were fragments of pottery dating to MC as well as a scatter of obsidian (Bassiakos and Philaniotou, 2007, p.30). Georgakopoulou (2017, p.62) lists the site as EBA.

Sideri: thermoluminescence dating of vitrified furnace walls from Sideri present a date within the EBA (Zacharias *et al.,* 2006, p.28; Bassiakos and Philaniotou, 2007, p.29; Georgakopoulou, 2017, p.62). There are no diagnostic pottery sherds from this site (Bassiakos and Philaniotou, 2007, p.29).

4.2.1.2.3. Material Evidence

4.2.1.2.3.1. Furnaces

4.2.1.2.3.1.1. *General Kythnos survey*

(image redacted for copyright purposes)

Figure 4.6. Photograph showing a piece of intact furnace fragment (above the camera lens cap) (Gale et al., 1992, 85, Plate 8).

A furnace fragment found by Gale *et al.*, (1992, p.85, p.100) is one of the larger intact pieces from the earlier survey and reconstructs to a furnace with a diameter of c.50cm. The average thickness of the fragments discovered by Gale *et al.* (1992, p.85) was 3cm thick. Previous surveys reported these fragments as furnace lining, however Gale *et al.*, (1992, p.85) suggest that they are in fact fragments of furnace walls instead. Gale *et al.* (1992, p.85) consider that the reason more furnace fragments are not found on Seriphos and Kythnos, is that the furnaces were deliberately destroyed. The reasoning for the destruction considered by Gale *et al.* was ritual. However, the destruction could be due to practical reasons; such as to remove the conglomerate formed by smelting which may have stuck to the furnace wall, or due to the furnaces breaking during use.

Further exploration was carried out with surface surveys by Philaniotou-Hadjianastasiou (2000, p.201-18) followed by a metallurgical programme by the Ephorate of Prehistoric and Classical Antiquities of the Cyclades and the Demokritos Research Centre, which began in 1995 (Bassiakos and Philaniotou, 2007), this survey revealed more evidence for copper smelting than there had been previously and bore evidence for perforated furnaces from the sites of Sideri and Paliopyrgos-Aspra Spitia on Kythnos. “Over 700 clay furnace fragments were recovered from Sideri and

Paliopyrgos-Aspra Spitia, with almost all fragments showing at least one downward slanting perforation. Many fragments were vitrified and slagged with some perforations being blocked (Bassiakos & Philaniotou 2007, 44–45). The furnace fragments were much thicker (25–60 mm) than those encountered at Chrysokamino. Again, the evidence points towards furnaces being conical frustums. No evidence of any ceramic sherds that resemble pot bellows was found. Clay nozzles interpreted as blowpipe are found, but they are believed to be used in association with blowpipes, rather than bellows due to their size" (Doonan and Marks, 2021, p.164).

4.2.1.2.3.1.2. *Sideri*

On top of the hill (174m above sea level) lies the site of Sideri, which is a small collapsed construction, whose use and date is unknown. Around this construction is concentrations are of furnace fragments, angular copper slag, as well as a few fragments of copper ore (malachite and/or haematite embedded in quartz) (Bassiakos and Philaniotou, 2007, p.28). The furnace fragments measure c.1.5-6cm thick and are made of a very coarse clay which, from the impressions in it, appears to have been tempered with straw and other organic materials and large grits, as can be seen in *Figure* 4.7 (Bassiakos and Philaniotou, 2007, p.28-9). The inner surface of the furnace fragments is heavily vitrified, with some fragments having copper slag adhering to them (*Figure* 4.7). A number of fragments bear perforations (*Figure* 4.7) which measure c.2cm in diameter. Bassiakos and Philaniotou (2007, p. 28-9) consider the furnace fragments to represent two different structures, a bowl hearth and a perforated shaft furnace (Bassiakos and Philaniotou, 2007, p.28).

2007, Figure 2.3).

(image redacted for copyright purposes)

Figure 4.7. Image showing four photographs of metallurgical ceramics and slag from Sideri (a-c) and a clay nozzle from Paliopyrgos-Aspra Spitia (d), Kythnos: a, Copper slag. b, Fragment of metallurgical furnace wall consisting of clay, tempered with coarse quartz girtsm bearing a thermally collapsed hole. c, Fragments of furnace wall bearing 2 holes and with straw imprints. d, a broken conical clay nozzle (inside). (Bassiakos and Philaniotou, 2007, 29, Figure 2.4a-d).

(image redacted for copyright purposes)

Figure 4.8. Image of reconstruction of furnace from Kythnos (Bassiakos and Philaniotou,

2007, Figure 2.8.).

4.2.1.2.3.1.3. Paliopyrgos-Aspra Spitia

Clay furnace fragments with perforations (similar to those found at Sideri) were found amongst the concentrations of broken copper slag on the slopes (Bassiakos and Philaniotou*,* 2007, p.30). No photographs, measures or more description is given, just a note of their presence. There was also a broken clay nozzle which is shown in *Figure* 4.7d, the photograph is of the inside of the clay nozzle. This is considered by Bassiakos and Philaniotou (2007, p.30) to be part of a blowpipe tip.

4.2.1.2.3.2. Metallurgical remains

The slag heap on Kythnos is located c.150 meters above sea level, situated at the cliff top about 2km to the north of Cape Ioannis. Part of the slag heap covers a steep plunge of the cliff down to the sea (*Figure* 4.9). The remainder of the heap forms a medium/thin scatter situated on top of the cliff. The majority of the slag is copper stained and is mixed with a high number of clay furnace fragments (previously considered as furnace lining) (Gale *et al.*, 1992, p.85). The typical slag contained copper prills or c.1-7cm in diameter (Gale *et al.*, 1992, p.86). Amongst the slag is also many pieces of oxidised copper ore (malachite and iron ore) and many fragments of quartz (could have been an ideal flux) (Gale *et al.*, 1992, p.85). The slag pile consists of both large broken slabs of tap slag and small fragments of crushed copper, considered to be to retrieve copper prills, spherical hammers (*Figure* 4.10) of imported granite were found and believed to be used for this purpose (Gale *et al.*, 1992, p.85).

(image redacted for copyright purposes)

Figure 4.9. Photograph showing a general view of part of the Kythnos copper slag heap which lies on a steep plunge of the cliff down to the sea (Gale et al., *1992, Plate 6).*

The site of Skouries had a large slag heap which contains remains from copper smelting including fragments of clay furnace lining and pieces of oxidised copper ore, as well as spherical hammers (Bassiakos, 2007, p.25; Gale *et al.,* 1992, p.81). The survey and excavation of the site revealed evidence of ceramic fragments used for copper smelting (Bassiakos, 2007, p.25). These ceramic fragments were described by Bassiakos as bowl hearth, however he also notes that the clay fragments had vitrified copper slag adhering to them and says the ceramic fragments are peculiar and noteworthy, due to the numerous fragments featuring perforations. Although not identified by Bassiakos, these ceramic fragments are probably pieces of truncated braziers typical of the Aegean furnace.

The “analyses of copper prills by Stos and Stos-Gale (mentioned above) showed that arsenical copper was produced at the site. Secondary copper mineralization was found, thin veins of malachite (2cm to 4cm thick). Laboratory analyses have shown a strong geochemical relationship between ores from this area as metallurgical residues such as slag, matte and copper prills from Skouries” (Bassiakos et al., 2007, 25-7; Marks, 2012, p.30).

Bulk analysis of the slags from Kythnos showed that copper fluctuates between 0.5 – 12%, with an average of 3.7%. Lime is also present at a higher mean than usual at 8%, fluctuating up to 17%. This level is too high to be from the charcoal, but may come from the ore, rather than being added as a flux (Gale *et al.*, 1992, p.86). Sulphur is low at an average of 0.2%, which is consistent with the oxidised ores found in the slag heap. Microscopy was undertaken by Gale *et al.* (1992, p.86, Plate 9) and this showed that the copper prills were often surrounded by a copper sulphide. It was concluded by Gale *et al.*, that this presence of sulphur was not from the smelting of sulphide ores, but was an amount consistent with oxides ores (Gale *et al.* 1992, p.86).

Analysis of the slags has been carried out, including bulk chemical analysis and lead isotope analysis. Additionally, microprobe analysis was carried out on some of the copper prills within the slag (Gale *et al.* 1992, p.81). The dominant phases identified within the slags were fayalite and iron oxide (consistent with their classification into Bachmann’s System 2). Microprobe analysis of the copper prills identified nickel contents up to 1% and arsenic contents up to 4.5%, which probably resulted accidently from the smelting of oxidised copper ores with no deliberate addition of arsenic (Gale *et al.* 1992, p.81).

4.2.1.2.3.2.1. <u>Sideri</u>

On the top of the hilltop concentrations of angular copper slag were found, as well as a few pieces of copper ore. Slag was also found adhering to a number of perforated clay furnace fragments. A test pit located between rocky outcrops on the hill revealed slag, amongst fragments of furnace lining and stones, some of which were burnt. Below the layer which contained the burnt material, in a layer of soil above bedrock, two fragments of slag were found containing copper prills (Bassiakos and Philaniotou, 2007, p.28-9). “Lab analysis of the slag found adhered to the furnace fragments from Sideri shows that there was not a complete control of the temperature within the furnaces, as well as the inability to retrieve all of the copper” (Marks, 2012, p.32).

4.2.1.2.3.2.2. Paliopyrgos-Aspra Spitia

Copper slag is reported at Paliopyrgos-Aspra Spitia in concentrations on the slopes of the hill (Bassiakos and Philaniotou, 2007, p.30), but no further detail is given.

4.2.1.2.3.2.3. Other Materials at Paliopyrgos-Aspra

Pottery and obsidian artefacts were found within the slag heap (Gale *et al.*, 1992, p.81). Spherical hammers used for crushing, possible of slag to relieve copper prills were found amongst the slag heap (*Figure* 4.10). These are made of imported granite (Gale *et al.*, 1992, p.85). The example in *Figure* 4.10 shows the two diametrically opposed hollows to aid in holding the hammer in the hand whilst using it to crush slag (Gale *et al.*, 1992, p.100).

(image redacted for copyright purposes)

Figure 4.10. photograph snowing a typical granite hammer found in situ within the Kythnos copper slag heap (Gale et al., 1992, Plate 7).

4.2.1.2.3.3. Discussion

The smelting sites located on Kythnos are also on exposed promontories which experience strong winds. The locations of the smelting sites are situated on the side of the island which was in the path of the winds, with no smelting sites on the coasts which do not experience the winds as strong. The sites feature large slag piles, which again suggests a large amount of smelting took place and the slag had to be processed and then disposed of, such as crushing the slag to retrieve copper prills as at Chrysokamino. The slag pile did have some large slabs, but there was also crushed slag and copper and hammer stones (Gale *et al.*, 1992, p.85), indicating the slag was being processed. The clay fragments are coarse, with organic temper and grit added (Bassiakos and Philaniotou, 2007, p.28-9), to make them resilient to high temperatures. The ceramic fragments can be confidently interpreted as being used within the copper smelting process, as the insides are heavily vitrified and some bear copper prills. The island has a number of smelting locations, which are all on the coastal promontories, subject to high winds, rather than one large site, or using sheltered locations. The hammer stones are made of imported granite, indicating the importance of this tool, as it was brought there specially for its purpose. The only evidence of forced draft from the sites on Kythnos is a fragment of a clay nozzle (tuyère) from Paliopyrgos-Aspra Spitia (*Figure* 4.7) (Bassiakos and Philaniotou, 2007, p.29, Figure 2.4a-d). One would expect to see more fragments of clay nozzles amongst the clay furnace fragments, if they were part of the process for the functioning of the furnaces, such as forcing air through bellows or blow pipes. Perhaps this represents a later stage of the process such as consolidating or casting, and this was taking place at a small scale at the smelting site for testing purposes.

4.2.1.3. Avessalos and Kephala, Seriphos

4.2.1.3.1. Location

Seriphos is an island in the Greek Cyclades, situated in the western islands, between Kythnos and Siphnos. An EBA habitation site was revealed during a project including survey and excavation in 2000 (Philaniotou, *et al.,* 2011, p.157-8). The habitation site is situated on the southern western coast of the island, separate from the three smelting sites located further north on the western coast of the island. Three ore deposits are identified on the island: magnetite, hematite and limonite (Marinos, 1951; Philaniotou, *et al.,* 2011, p.158). There is also a rich sulphidic deposit in the north-eastern part of the island, in the Moutoula area, containing: pyrite, galena, sphalerite, and a small amount of chalcopyrite (Marinos, 1951; Salemink, 1980; Philaniotou, *et al.,* 2011, p.158).

(image redacted for copyright purposes)

Figure 4.11. Map of Seriphos showing location of settlement site and metallurgical sites, as well as simple geology (Philaniotou, et al., 2011, 158, Figure 16.1).

4.2.1.3.2. Avessalos, Seriphos

4.2.1.3.2.1. Date

Some of the material evidence dates to the EBA (3000-2000 BC), however a large amount of the evidence is later in date. There is an estimated total of 100,000 tons of slag at the site, but it is not possible to gauge how much of this is from the EBA activity (Georgakopoulou, 2017, p.51; Gale *et al*. 1985; Philaniotou *et al*. 2011). Dating Avessalos to a particular phase is difficult as it was not excavated stratigraphically (Georgakopoulou, 2017, p.58).

EBA sherds were found at Avessalos (Philaniotou, *et al.,* 2011, p.161-2, Figure 16.8.). The Avessalos slag heap is often believed to be of a post-Bronze Age date, due to its large size, especially in comparison to other known EBA smelting sites (Philaniotou, *et al.,* 2011, p.161; Gale *et al.* 1985). This belief is also supported by finds of coins dating to the 4th century A.D. (Philaniotou, *et al.,* 2011, p.161; Davies, 1935, p.260). However, Philaniotou, *et al.,* (2011, p.161) argue that the identification of several EBA sherds during their field study in 2000 confirms the dating of the slag heap to the EBA. This further supported by the prehistoric pottery on the site by Weisgerber (1985, p.112 n.28). Philaniotou, *et al.* (2011, p.161) also argue that the contextual evidence comparable with other EBA copper smelting sites in the Cyclades supports the dating of the slag heap to the EBA, including the setting of the site on the slope of a windy promontory and the presence of perforated furnaces. It is therefore likely that, due to its size, that part of the heap dates to the EBA and some of the heap is from later periods, representing a continuous use of this location for smelting over many periods.

4.2.1.3.2.2. Material Evidence

(image redacted for copyright purposes)

Figure 4.12. The slag heap of Avessalos (Philaniotou, et al., 2011, 160, Figure 16.5).

4.2.1.3.2.2.1. Slag

Avesallos hosts the largest known slag heap on Seriphos (*Figure* 4.12), as well as within the Cyclades as a whole. The slag heap is situated on the north facing slope of a hill on the south facing side of the Avessalos bay, starting as the crest and extending down the hill. Smaller quantities of material were also located on the south facing side, which was separated from the main deposit by a flat schist bedrock (Philaniotou, *et al.,* 2011, p.160). The slag heap has been disrupted by modern road works, with the creation of a modern dirt track and road cutting sections through the layer. The overall depth of the slag layer is variable, it appears to exceed 2m in depth in areas and is estimated at being at least 100,000 tons (Philaniotou, *et al.,* 2011, p.160). The section created by the road construction allowed for assessment of the heap vertically. In some thicker parts, two to three superimposed layers can be distinguished, each bearing different sizes of slag: small slag (1-3cm), medium slag (6-10cm) and larger slag (which usually sits on the top). The reason for the division of the layers is not clear and the archaeologists studying the material gauge it impossible at this stage of the investigation to say whether the different layers correspond to distinct operation carried out in different chronological periods or not. The division of the slags could be due to a natural distribution as the material eroded from the hilltop (Philaniotou, *et al.,* 2011, p.160-1).

(image redacted for copyright purposes)

Figure 4.13. Photograph of a partial view of the Avessalos copper slag heap above Avessalos Bay (Gale et al., *1992, Plate 1).*

The Avessalos slag heap is full of broken slabs of tap slag and broken fragments of clay furnace walls or lining (Gale *et al.,* 1992, p.83). In areas the depth of the slag heap measures up to four meters thick, which is a substantial amount of slag pieces piled together (*Figure* 4.13). Also amongst the slag heap were pieces of oxidised copper ore (Gale *et al.,* 1992, p.83).

(image redacted for copyright purposes)

Figure 4.14. Photograph showing section of the Avessalos copper clag heap where the heap is c.2m thick at this point (Gale et al., *1992, Plate 2).*

Eight slag samples from Avessalos (and 4 from Kephala) were analysed by Gale *et al.,* (1992, p.83-4). The chemical analysis revealed that the copper content ranges from 1 to 19% and the sulphur content is low, consistent with slags from the smelting of oxidised copper ores (Gale *et al.,* 1992, p.83-4).

(image redacted for copyright purposes)

Figure 4.15. Rock carved pits situated at the top of the Avessalos slag heap (Philaniotou, et al., 2011, 161, Figure 16.6.).

(image redacted for copyright purposes)

Figure 4.16. Photograph showing cluster of small rock carved pits and grooves on a schist outcrop at the top of the Avessalos slag heap (Philaniotou, et al., 2011, 161, Figure 16.7.).

4.2.1.3.2.2.2. Features

Small rounded shallow pits measuring c.10cm in diameter and up to 8cm in depth, were carved into the schist bedrock on the plateau at the top of the hill, situated just above the north-facing slope and slag deposit. These were situated in small clusters where the bedrock was exposed (Philaniotou, *et al.* 2011, p.161). There were also larger pits present, with a diameter of 40cm, with a number of smaller pits at the perimeter. One of the larger pits was situated alone in a different part of the bedrock (*Figure* 4.15), however in a different area there were three large pits situated close to each other (Philaniotou, *et al.* 2011, p.161). These were interpreted by Philaniotou *et al.* (2011, p.161) as being installations to facilitate ore or slag crashing. This interpretation is supported by the identification of numerous lithic tools (intact and fragmented) at this area of the site. There were also peculiar grooves carved in this area on to a steeply sloping schist outcrop, located close to a cluster of small pits (*Figure* 4.16) (Philaniotou, *et al.* 2011, p.161).

4.2.1.3.2.2.3. Furnace fragments

Ten fragments of furnaces bearing perforations have been recovered, 10 fragments have been recorded so far (Philaniotou *et al.* 2011, p.161). Only one of these fragments bears two perforations. Philaniotou *et al.* (2011, p.161) state that the number of fragments bearing perforations is a minority of the furnace fragments, suggesting that a large number of furnace fragments do not bear perforations, however these are not discussed further and there is no drawings or photographs presented.

4.2.1.3.2.2.4. Stone tools

There is a large number of stone tools found at Avessalos, especially in comparison with the other smelting sites on Seriphos and the sites on the neighbouring island of Kythnos (Philaniotou *et al.* 2011, p.161; Bassiakos and Philaniotou, 2007). There are seven almost-intact stone tools recovered and ten fragments. All these stone tools were located at the top of the slag heap on the schist bedrock, close to the rock carved pits. Alongside these tools, there was also a schist slab found, roughly orthogonal in shape, with six shallow holes carved in two parallel lines. This slab measures c. 25 x 35cm, with the holes' measuring c. 4cm in diameter and c.1cm in depth. This bears similarity to one found at the site of Potna on Kythnos (Philaniotou, *et al.,* 2011, p.161; Bassiakos and Philaniotou, 2007, p.28).

4.2.1.3.3. Kephala, Seriphos

4.2.1.3.3.1. Date

In contrast to Phournoi and Avessalos, there were no diagnostic pottery fragments found at Kephala, EBA (3000-2000C). A programme of thermoluminescence dating of furnace fragments was undertaken for Kephala (Georgakopoulou, 2017, p.57), due to the lack of diagnostic sherds (Philaniotou, *et al.,* 2011, p.162). Radiocarbon dating could not be carried out, due to the lack of charcoal remains in the slags; this is a common occurrence across Cycladic smelting sites (Bassiakos and Philanioutou, 2007; Philaniotou, *et al.,* 2011, p.162). Four samples were submitted for thermoluminescence dating from Kephala (two from Kephala 1 and two from Kephala 2). Numerous samples were required for Kephala due to the large and disbursed nature of the slag heap, as well as the variation in type of furnace fragments (perforated and non-perforated) to investigate possible chronology. One of the samples submitted was a perforated ceramic furnace fragment (KEF2B) (Philaniotou, *et al.,* 2011, p.162). The results presented a mean value of 4640+-240 years B.P. (Zacharias, *et al.,* 2006a, 2006b; Philaniotou, *et al.,* 2011, p.162). This dates the metallurgical activity at Kephala to the first half of the third millennium B.C., which falls within the Aegean EBA (Philaniotou *et al.* 2011, p.162). The two analyses of Kephala 2 gave an earlier date to that of the two samples from Kephala 1, however Philaniotou, *et al.,* (2011, p.162) state that with such a small sample number it is hard to make secure observations about this. The perforated fragment did not present a significant difference in date to the non-perforated samples (Philaniotou, *et al.,* 2011, p.162).

4.2.1.3.3.2. Material Evidence

(image redacted for copyright purposes)

Figure 4.17. Photograph showing the general view of the Kephala copper slag heap (Gale et al., *1992, Plate 3).*

4.2.1.3.3.2.1. Slag

The slag heap at Kephala (*Figure* 4.17) had first been reported in the 1980's (Barber, 1987; Gale *et al.,* 1985), however only limited investigations had been carried out. A re-examination was carried out in 2000 as part of a project reassessing archaeometallurgical remains on Seriphos (Philaniotou *et al.* 2011, p.159). The slag heap was reassessed to be significantly larger than originally estimated.

The report from Gale et al*.* (1985' reprinted in 1992) states that the slag heap was estimated to have been 3000 tonnes and consists of many pieces of clay lining mixed in with the slag. The slag has numerous large broken slabs of tap slap, but there are also abundant areas where the slag had been broken into centimetre-sized fragments (*Figure* 4.18), possibly to remove copper prills (Gale *et al.,* 1992, p.83)

The largest concentration of the material making up the heap was situated on the north-facing slope of the promontory. The material was divided into two deposits situated c.100m apart: Kephala 1 (eastern concentration) which measured c.2,500m^2

and Kephala 2 (western concentration) which measured c.4,5000 m^2. Both deposits have a maximum depth of 50cm (Philaniotou, *et al.,* 2011, p.158). There is also evidence of metallurgical material on the south facing slope, in substantial quantities, however it is much more dispersed than deposits 1 and 2. Within this material on the southern slope, there was concentrations of slag in smaller pieces, around one centimetre in size, this was interpreted to represent areas where slag was deliberately crushed, to extract copper prills (Philaniotou, *et al.,* 2011, p.159).

(image redacted for copyright purposes)

Figure 4.18. Photograph showing a region of the Kephala slag heap where slag has been broken into centimetre-sized fragments (Gale et al., 1992, Plate 4).

Analysis carried out by Gale *et al.* (1992, p.83-4) on the slags from Avessalos and Kephala identifies that the copper content ranges from 1 to 19% and the sulphur content is low. These results suggest that the ores being smelted were oxidised copper ores (Gale *et al.,* 1992, p.83-4). The chlorine content of the slags from Kephala is considered to be due to weathering from the exposure to salt-laden spray from the winds coming off the sea.

4.2.1.3.3.2.2. Furnaces

Two in situ furnaces were discovered in the south of Kephala 1, just below the ridge of the promontory. The furnaces were carved into the bedrock (schist), as can be seen in *Figure* 4.20. Their base diameter is c.30cm. Metallurgical debris is present on the furnace walls; one furnace bears a layer of slag on one side of the wall. There were also smaller droplets of slag adhering to other parts of the furnace wall, as well as green stains. There was no evidence of metallurgical material within the furnaces, except what was adhering to the walls (Philaniotou, *et al.,* 2011, p.159). There was dispersed scattered metallurgical material in the surrounding area.

Ten clay furnace fragments were found which bear evidence of perforations (*Figure* 4.19), these fragments were all found in one confined area of the Kephala 2 deposit only (Philaniotou *et al.* 2011, p.159). The majority of these fragments bear only one perforation, however one fragment bears two perforations. Only one fragment bears an intact perforation in the centre of the fragment, all the others bear part of a perforation on their fractured edge (Philaniotou *et al.* 2011, p.159-60; Georgakopoulou, 2017, p.61). The diameter of the intact perforation is 3cm on the external side of the fragment and 2.5cm on the internal side. The positioning of the perforation is not straight and is described by Philaniotou *et al.* (2011, p.159) as being inclined inward and slightly downward, as if formed by pushing wet clay from the outside toward the inside. Unlike other sites that bear furnace fragments with perforations in the southern Aegean (such as Kythnos and Chrysokamino) not all furnace fragments have evidence of perforations, actually the fragments with perforations make up a small percentage of the total furnace fragments (Philaniotou *et al.* 2011, p.159-60; Georgakopoulou, 2017, p.61), is this due to the way they broke, or as two types of furnace were present.

(image redacted for copyright purposes)

Figure 4.19. Ceramic furnace fragments bearing perforations from Kephala. Arrows indicating edges of perforations. (Philaniotou, et al., 2011, 160, Figure 16.4).

4.2.1.3.3.2.3. Stone tools

Only a single hammer stone has been found so far (made from igneous rock), however there are two round slag fragments which have been interpreted as being used as crushing tools (Philaniotou, *et al.,* 2011, p.160).

4.2.1.3.3.2.4. Ore

The ore source for Kephala is believed to have not been local, being brought from a source elsewhere on Seriphos or even further afield. Although there is a slight opper ore source located near the slag heap at Kephala, there is no evidence that it was a substantial deposit and there are no indications of ore exploration (Georgakopoulou, 2017, p.54).

(image redacted for copyright purposes)

Figure 4.20. Furnaces carved into the bedrock at Kephala (Philaniotou, et al., 2011, 160, Figure 16.3).

4.2.1.3.4. Discussion

The settlement is situated on the western side of the island, with the smelting sites to the north (Philaniotou, *et al.,* 2011, p.157-8). The strong winds come from the north and the smelting sites would be subjected to them, while the settlement would be more sheltered. The sites on Seriphos both feature substantial slag piles, which again consisted of slag which had been processed – by being smashed and pulverised into smaller pieces, even as small as centimetre sized fragments (Gale *et al.,* 1992, p.83; Gale *et al.,* 1992, Plate 4). As the slag has been left as large heaps in the landscape, it suggests that there was a purpose being the pulverisation of the slag. At Kephala, there are broken ceramic fragments amongst the slag, suggesting the slag had adhered to the clay structure. However, as a large amount of the slag was processed to centimetre size pieces, it seems likely it was crushed to retrieve copper prills. Stone tools were found in association to the slag heaps, and not only crushing stones, but a stone slab too (Philaniotou, *et al.,* 2011, p.161; Bassiakos and Philaniotou, 2007).

4.2.1.4. Kephala, Keos

4.2.1.4.1. Date

Georgakopoulou lists Kephala on Keos (Kea) as being dated to the FN (4500-3200BC), stating metallurgical ceramics dating to the Final Neolithic bear perforations (Georgakopoulou, 2017, p.57, p.61; Coleman, 1977, p.4). There are two other Late Neolithic sites roughly contemporary with Kephala within the region (Thorikos and Kistos cave – both in Attica) and it is therefore argued that the main cultural affinities of the site are with Attica, Euboea and the Saronic Gulf, rather than with the other Cycladic islands (Coleman, 1977, p.1).

4.2.1.4.2. Location

Keos is an island in the Cyclades, the island is called Kea in the modern day. The site of Kephala is situated on the north-western coast of the island. The promontory is exposed to the prevailing northerly and north-westerly winds. The site is situated close to a bay that could be used as a harbour, but not at the bay (20 min walk away) (Coleman, 1977, p.1). The site of Kephala is a significant size and includes habitation (houses), craft (obsidian, pottery, metallurgy) and a cemetery (Coleman, 1977, p.2).

(image redacted for copyright purposes)

Figure 4.21. Map of Keos showing location of Kephala (Coleman, 1977, Plate 1).

4.2.1.4.3. Material Evidence

The promontory has been heavily weathered and eroded (Coleman, 1977, p.1).

(image redacted for copyright purposes)

Figure 4.22. Map showing general plan of the site of Kephala, settlement: areas D, E, G, H, J, K and L, Cemetery Areas A, B, C, F (Coleman, 1977, Plate 3).

4.2.1.4.3.1. Artefacts

All of the copper artefacts from the site were found on the surface. Four items are identified, three of them being tools: a pin (**28***), two fragments of sharp edged tools (**82*, 147***) and a fragment of a narrow but blunt end (**83***) (Coleman, 1977, p.3). One of the fragments of a sharp edged tool (**147***) was analysed and was found to be made of almost pure copper (Coleman, 1977, p.3). All of these items were found on or near the surface and must be regarded as un-stratified (Coleman, 1977, p.33). Coleman (1977, p.4) states that there is no doubt of the date of the copper objects, despite their lack of secure stratigraphic context, as they resemble early copper tools from other sites of this date, but also as he believes them to have been made at this site (Coleman, 1977, p.4).

4.2.1.4.3.2. Furnaces

(image redacted for copyright purposes)

Figure 4.23. Drawings of seven of the furnace fragments from Kephala, Keos, scale: c.3:5 (Coleman, 1977, Plate 22).

Fragments of burnt clay are found within the settlement area and also the cemetery. The fragments are all small in size and are made of a coarse fabric. A number of the fragments bear perforations, measuring c.2cm in diameter. The fragments are red on the exterior and grey or grey-black on their interior. The exterior surfaces are rough and the interior surface on some fragments is pitted (from material burning out) and fused, from being subjected to high temperatures (Coleman, 1977, p.4, p.66). Three of the fragments have slag adhering to them: 174, 76* and 175 Figure 4.24). The other fragments do not have slag adhering to them and are not colour altered in the same way from heat, however they have the same ceramic material and have perforations which appear to have been formed in the same way (Coleman, 1977, p.4).

The fragments measure between c.1-2cm, the slag layer adhering to some samples measures c.2-5mm. Sample **148*** measures thicker than the other samples at 3cm in thickness. Fragment **175** has small beads of oxidize copper embedded in the slag adhering to its surface.

There are nine fragments in total which appear to be areas connected with copper working (**15**, **76*, 107 108, 148*, 174, 175, 203, 204**). Two of these fragments were found within the settlement: **15** was found in Area G and **76*** was found in Area L (see *Figure* 4.22 for Area locations within the site) (Coleman, 1977, p.4). Although some of the fragments were found in the cemetery (Area F), they were not funerary in nature, but rather were found within the soil used to fill in the graves during burial (Coleman, 1977, p.4, p.53).

(image redacted for copyright purposes)

Figure 4.24. Photograph of eight of the furnace fragments from Kephala, Keos (Coleman, 1977, Plate 66).

These fragments are described by Coleman (1977, p.4) as burnt clay from furnace linings which were used to reduce ore, or from crucibles. However, he acknowledged that, as the fragments are very small, their exact purpose cannot be determined. None of the fragments are strongly curved, suggesting that the original objects may have had a fairly large diameter (Coleman, 1977, p.4). One of the fragments (**148**) has part of a rim preserved on its edge, which suggests a broad flat top to the object. There is a hole positioned just below the rim (*Figure* 4.24). Coleman (1977, p.4) suggests that the holes may have been present to allow the use of a tuyère, for it to be inserted into the hole in conjunction with a bellow, to increase the temperature to that needed to reduce the ore (Coleman, 1977, p.4).

4.2.1.4.3.3. Slag

Analysis was carried out on four pieces of slag (1. sample no. 80 from Area D unstratified, 2. Slag from surface of Area E, 3. Slag from surface near Area D, 4. Slag from surface 25m north of Area D), fragments of two crucibles (5. **175** and 6. **76***) and one fragment of a copper tool (7. **147*)**, by qualitative XRF analysis (Coleman, 1977, p.113). Analysis of the slag identifies that the slag in samples 1-6 was not produced by a simple melting of copper in crucibles, but rather represents the reduction of copper ore. This conclusion is due to the slag being ferruginous (Coleman, 1977, 4, p.113). In addition to the XRF analysis, to verify the interpretation of the ferruginous nature of the slag, chemical analysis was also carried out, which revealed the copper was in the form of oxide, which supported the conclusion of the reduction of high percentage copper ores (Coleman, 1977, p.113-4).

4.2.1.4.4. Discussion

The smelting site is situated on the north-western coast of the island, on a promontory which is exposed to the prevailing northerly and north-westerly winds (Coleman, 1977, p.1). The clay fragments are described as being coarse in nature, and on the interior surface of some fragments, there is pitting indicating where material has burnt out. The clay fragments are heat altered, with the outside of the fragments being described as red and the interior as grey/black (Coleman, 1977, 4, p.66). There is also a number of fragments with slag adhering to the inside of the fragment. There are some fragments which are not heat altered, but they are made from the same clay material as those which are. The analysis of the slag indicates that it was copper which was being smelted at this site, it also shows that it was high percentage copper ores which were being used (Coleman, 1977, p.113), which would require a less stable firing environment than other ores. Although the ceramic fragments are small, the perforations are clear, as can be seen in *Figure* 4.24.

4.2.1.5. Athenian Acropolis, Attica

4.2.1.5.1. Location

Southern slope of the Acropolis in Athens, Attica. Excavated in association with a “Neolithic hut” (Dimitriou, 2017, p.25). The excavation was investigating “the remains of the hut were identified on the SW of the south slope of the Acropolis area” (Dimitriou, 2017, p.26). The remains of the hut were identified “by a narrow trench of 0.65m wide running in an E-W direction” (Dimitriou, 2017, p.26). Dimitriou interprets the remains of the “hut” to be that of a fenced off area cut into the natural rock and earth, rather than a covered structure (Dimitriou, 2017, p.26).

4.2.1.5.2. Date

Final Neolithic (4500-3200 BC), dated by pottery present within the excavations on the south slope (Dimitriou, 2017, p.25). Pottery was also found in 1922 by Levi’s excavations dating to the Middle and Late Neolithic within a hut with a hearth. “All six fragments derive from contexts in which FN pottery was found” (Dimitriou, 2017, p.26). Four of the fragment “were found in the upper part of the lower layer which corresponds to the pavement of the “hut”, one in the lower part of the upper layer (in contact with the pavement of the “hut”) and one without specification” (Dimitriou, 2017, p.26).

4.2.1.5.3. Material evidence

4.2.1.5.3.1. Ceramic Fragments

Six perforated fragments, made of course ceramic were found within a “hut” structure with evidence of other craft technologies such as obsidian knapping and stone grinding tools. Possible associated evidence includes a hearth, reddened clay floor surface, charcoal and carbonaceous veins.

The perforated fragments from this location were excavated in 1922/3 by Levi and the Italian Archaeological School in Athens (Dimitriou, 2016, p.15-33). In the original study they were interpreted as being grills or strainers, due to the large perforations the ceramics bore (Levi, 1930/1, 432-434; Dimitriou, 2017, p.26). Due to evidence from other sites of perforated fragments being representative of furnace structures used for the smelting of copper or lead-silver ores, these ceramic fragments were reinvestigated (Dimitriou, 2017, p.26). A macroscopic investigation was carried out on the six perforated ceramic fragments by Dimitriou (2017).

(image redacted for copyright purposes)

Figure 4.25. Table indicating the location and context each fragment was found in. (Dimitriou, 2017, 31, Table 2).

(image redacted for copyright purposes)

Figure 4.26. Table showing details of the perforated clay fragments from the Southern slope of the Acropolis. (Dimitriou, 2017, 28, Table 1).

Dimitriou (2017, p.29) interprets from the macroscopic observations that the perforations were made while the clay was wet. The perforations are not angled. The thickness of the ceramic fragments ranges between 1.0 and 1.5cm with the diameter of the perforations ranging between 1.5-2.0cm. Three of the fragments are slightly curved in shape. All of the fragments are made of a coarse clay fabric, which has visible traces of organic remains and are highly tempered and appear to have been naturally dried rather than fired before use with smelting. The fragment bears a red orange and slightly pink colour (*Figure* 4.27 fragments 2-6), due to contact with fire during their use, which is suggested to be smelting activity (Dimitriou, 2017, p.29). Fragment 4 also bears traces of more intense burning on the inner surface, in the form of a black patina covering the inner surface and possible traces of slag (*Figure* 4.27, fragment 4). Although the fragments are similar, it is not possible to tell if they are from the same objects or from multiple. It is considered they may be from multiple objects as the temper and consistency of the clay appears different in some fragments (Dimitriou, 2017, p.29).

(image redacted for copyright purposes)

Figure 4.27. Furnace Fragments from the Southern Slope of the Athenian Acropolis (Dimitriou, 2017, 30-31, 1 = Figure 4., 2 = Figure 5., 3 = Figure 6., 4 = Figure 7. 5 = Figure 8a, 6 = Figure 9a).

Alongside the ceramic evidence was evidence of obsidian working, including flakes, cores, blades and arrow heads, as well as stone tools, such as grinders and millstones (Dimitriou, 2017, p.29). There were also possible remnants of a meal (*Cardium Edule* shells and animal bones).

4.2.1.5.4. Discussion

Although this site is not on an island, it is still situated on a windy location; instead of a coastal promontory, it is located on a hillside, which would still experience high winds, which would come from the Aegean Sea.

These ceramic fragments are not as heat altered as those from other sites, with the colouring been orange and pink rather than black, suggesting a lower temperature process. They are also not pre-fired before use.

4.2.1.6. Gerakas, Attica

4.2.1.6.1. Location

The site of Gerakas is situated in Athens, within East Attica, set in the junction of the Ymittos and Penteli foothills. The finds being discussed here came from an excavation held in 2013 on a low hill in the area of Gerakas. “The context of the finds was architectural remains, including a stone pavement, part of a wall of a deposit pit and destruction layers” (Πλασσαρά, 2020, p.331). Excavations held in 1996-8 on land nearby, revealed evidence of EH settlement in this area (Πλασσαρά, 2020).

4.2.1.6.2. Date

Pottery from this context is mainly dated to the Early Helladic I period (2700-2200BC) (Πλασσαρά, 2020, p.331). The main pottery being found is the hemispherical bowl, aiding this dating. Evidence for settlement in the area also dates to EH. Pottery found in the lowest investigated layer dates to the Neolithic, showing a continuous occupancy at this site throughout these periods (Πλασσαρά, 2020, p.331).

4.2.1.6.3. Material evidence

4.2.1.6.3.1. Ceramic Fragments

Twenty-nine clay fragments bearing perforations come from the excavation in 2013 from the context on the lower hill within the architectural structure (Πλασσαρά, 2020, p.331). The clay fragments are made of a reddish clay with coarse inclusions. The outside of the fragments bears a bright red colour, whereas the internal surface is light grey, this indicates it has been used for pyrotechnical purposes with temperatures high enough to smelt copper. Fifteen of the fragments bear parts of perforations, the perforations have a diameter of 2cm (*Figure* 4.28). The fragments are comparable to that of other perforated fragments which are believed to be part of a conical furnace used for smelting copper (Μπασιάκος, 2005; Παπαδοπούλου Γ. 2013; Πλασσαρά, 2020, p.335). Analysis is being conducted by the excavators on four of the fragments, which will be published in the future. A fragment of ceramic material with slag adhering to it was found at Point 18, which strengthens the interpretation for them being part of a smelting apparatus. Chemical analysis of this artefact has been conducted by pXRF and detected the presence of copper and traces of lead (Πλασσαρά, 2020, p.335).

Alongside the ceramic furnace fragments was other evidence for craft technology, including spindle whorls and obsidian stone tools, blades and core and several unpainted shells which have embossed rope decoration on them (Πλασσαρά, 2020, p.331-5).

(image redacted for copyright purposes)

Figure 4.28. Ceramic fragments with perforations from Gerakas (Πλασσαρά, 2020, 335, Figure 6. BE7968).

4.2.1.6.4. Discussion

The material from this site shows that the settlement has a continuous occupation from the Neolithic through to the EH, therefore although the ceramic evidence representing smelting dates to the EH, it could be a technology that started in the Neolithic and continued. These furnace fragments are similar to those from the Athenian Acropolis site, in that they are very thin and not very altered in terms of colour, suggesting a lower temperature process, but also why this material may not have been identified as metallurgical previously.

4.2.1.7. Raphina, Attica

4.2.1.7.1. Date

The date for metallurgical workshop at Raphina comes from recovered pottery which dates to the EBII period (3000-2000BC) (Gerogakopouklou, 2017, p.56; Theocharis, 1951, 1952).

4.2.1.7.2. Location

Raphina is located on the east coast of Attica (*Figure* 4.29), close to copper mineral sources at Kallianou in Euboea and Kamareza and Sounion in the Lavrion region. The site lies very close to the seashore and is exposed to the sea (*Figure* 4.30). There is also a fortified acropolis 2km south of Raphina, which was excavated at the same time.

(image redacted for copyright purposes)

Figure 4.29. Map of the Lavrion region, Attica, showing the location of Raphina and the copper deposits of Kamareza and Sounion regions of Lavrion (Gale, et al., 2008, Figure 2).

(image redacted for copyright purposes)

Figure 4.30. Image showing the site of Raphina, image belonging to The Archaeological Society of Athena, accessed at http://webapps.servers.archetai.gr/scarabaeus/viewer/archetai/viewer.html?t=a08e78b2-ff04-11e4-aa77-00155d10e309&id=3c174981-364c-4176-a4f7-2e5be301b3da accessed on 15th January 2021.

4.2.1.7.3. Material Evidence

4.2.1.7.3.1. Features

(image redacted for copyright purposes)

Figure 4.31. plan of workshop and pit A (Theochares, 1952, Figure 2.).

Theochares (1951, 1952) interpreted an area which comprised of a small rectangular building and a pit (pit A), which hosted a large amount of EH pottery (such as spoons, ladles, sauceboats, pans and four legged pots), to be a metallurgical workshop (*Figure* 4.31 and *Figure* 4.32) (Gale *et al.,* 2008, p.91). The pit measures 4.40m long, c.1m-3.40m wide and had a flat bottom (Gale *et al.,* 2008, p.91). A large number of round slag pieces with copper staining were found inside and around pit A. Stones had been placed at the north side of pit A (*Figure* 4.33), which Theochares (1952, p.133) describes as a foundation, and could be considered to be a step (Gale *et al.,* 2008, p.91), this is the area which Theochares believed a furnace to stand.

In addition to the metallurgical production material detailed, Theochares (1952, p.132) also reports that there were some objects made from copper excavated from pit A. Theochares also details a second pit (pit B) located 15m south of pit A, where more evidence for copper metallurgy was revealed, in the form of copper slags. Only EH pottery was found among the copper slags at the bottom of the pit, however the higher levels of the pit had been disturbed by later activity (MH and LH pottery was recovered) (Theochares, 1952; Gale *et al.,* 2008, p.92).

(image redacted for copyright purposes)

Figure 4.32. Photograph of pit A (Theochares, 1952, Figure 3.).

(image redacted for copyright purposes)

Figure 4.33. Photograph of stone area in pit A (Theochares, 1952, Figure 4.).

4.2.1.7.3.2. <u>Furnaces</u>

At the bottom of this pit A in the 'metallurgical workshop' Theochares found many fragments of ceramic "disk-shaped bottoms of metallurgical furnaces" (Theochares, 1952; Gale *et al.,* 2008, p.91). There are unfortunately no photographs or illustrations (Gerogakopouklou, 2017, p.61). Theochares does note that some of these furnace fragments bear perforations and have evidence of molten metal adhering to them (Theochares, 1952, p.131; Gale *et al.,* 2008, p.91).

4.2.1.7.3.3. <u>Other metallurgical ceramics</u>

Five tuyères were found in total at Raphina: four from metallurgical pit A and one from an unspecified room of the prehistoric settlement (Theochares, 1951, 1952). The tuyères were originally identified by Theochares as pouring cones, but Muhly re-identified them as tuyères (Theochares, 1951, 1952; Gale *et al*., 2008, 90-2; Muhly, 1977). The tuyères have also been compared by Zachos (Papathanassopoulos, 1996, Pl. 187) to be like those found at the EHII strata of the site of Ayios Dimitrios (SW Peloponnese), however no perforated furnace fragments are known from Ayios Dimitrios.

4.2.1.7.3.4. Metallurgical remains

The metallurgical material from Raphina includes: a large number of round slags (*Figure* 4.34) (metallurgical pit A), other remains from smelting and casting – no further detail given (metallurgical pit A), traces for the working of lead (no excavation context given), pieces of slag (Trench III, Pit B and the upper level of the house deposits), and copper slags (trial trench close to metallurgical pit A) (Theochares, 1951, 1952, 1953, 1955; Gale *et al.,* 2008, p.90).

(image redacted for copyright purposes)

Figure 4.34. Photograph of a lump of copper slag excavated by Theochares from pit A (Gale et al., 2008, 92, Figure 3).

4.2.1.7.3.5. Metal artefacts

Metal artefacts were found within House A including: two lead clamps attached to a large pithos, a lead clamp and several lead pieces of unknown use, two copper fish hooks (and fragments of a third one), and two copper nails (Gale *et al.,* 2008, p.93). There were also some metal artefacts found within the settlement (Theochares, 1953) including: a few copper nails and a lead weight. Within the settlement was some material from metal production including a few pieces of copper slag found in the upper levels of the house deposits (Gale *et al.,* 2008, p.93).

4.2.1.7.3.6. Other material

Other items related with metallurgical activity include: pieces of a stone mould (trial trench close to metallurgical pit A) and a schist mould for making arrow-heads (Askitario) (Theochares,1955; PAE, 1954; Gale *et al.,* 2008, p.90; Papathanassopoulos, 1996, Pl. 187).

4.2.1.7.4. Analysis

The bulk chemical analysis (*Figure* 4.35) of the copper slags (*Figure* 4.34) conducted by Gale *et al.,* (2008, p.93) gave results typical of iron silicate smelting slags. The copper concentrations in the slags were 4-7% and confirm these are copper slags. The low concentrations of lead present (20ppm) are consistent with the smelting of an oxidized copper ore such as malachite or azurite. The copper slags were also represented in a ternary system, as discussed by Bachmann (1980). This allowed for comparison with slags from other copper smelting sites and to infer furnace temperatures in which the slags were formed (Gale *et al.,* 2008, p.94-5). Gale *et al.* (2008, p.94-8) created a number of systems with evaluated these phase diagrams and concluded that the slags from Raphina are classifies within Bachmann's System 2, fayalite slags, which suggests a liquidus temperature of the order of 1100^{o}C.

(image redacted for copyright purposes)

Figure 4.35. Image of table showing data from Chemical analyses from the Raphina furnace (Gale et al., 2008, Table 3).

Lead Isotope analyses of the copper slags and lead artefacts revealed that the lead artefacts at Raphina were not smelted from lead or copper ores on Euboea, but were smelted from the ores in the Lavrion region in Attica (Gale *et al.,* 2008, p.101).

4.2.1.7.5. Discussion

There is limited evidence available as not all the material is described and there are no photographs available. However, as the limited description does detail perforations, it does confirm this as another site which had the APF type furnaces. There are tuyères at this site, but there is also significant evidence of moulds, which could mean that the tuyères were associated with secondary process of melting and casting in the moulds, rather than being used with the smelting in the APF.

4.2.1.8. Akrotiriaki/Skali, Siphnos

4.2.1.8.1. Date

Akrotiriaki is dated from the FN but also has activity dating between EC I - ECIII, with the majority of the evidence coming from ECII (3000-2000BC) (Wagner *et al.,* 1980; Georgakopulou, 2017). Skali is dated to the EBA (Papadopoulou, 2011, p.152-3).

4.2.1.8.2. Location

(image redacted for copyright purposes)

Figure 4.36. Map of Siphnos showing location of Akrotiraki and Skali (Papadopoulou, 2011, Figure 15.1).

Siphnos is located in the southern Cyclades, south of Kythnos and Seriphos and west of Naxos and Keros. Akrotiriaki and Skali are located on the southeast coast of the island. Akrotiriaki is located on a low hill promontory c.20m above sea level, which separates the bay of Platy Gialos (north) from the small cove of Lazarou (south) (Papadopoulou, 2011, 1p.50). Skali is located on a ridge between Platy Gialos and Chlakopo (*Figure* 4.36 and *Figure* 4.37). The site is located c.130m above sea level and looks over Akrotiraki (Papadopoulou, 2011, p.153).

Two mineralisation belts, one containing silver and lead and one gold, were recorded on the island as part of a programme run by the Max Planck Institute in Heidelberg, Germany in the 1970's (Papadopoulou, 2011, p.149).

(image redacted for copyright purposes)

Figure 4.37. Photograph of a view of Platy Gialos bay and Siphos, showing the location of Akrotiriaki (A), Skali (B) and Kasela (C) (Georgakopoulou, 2017, 56, Figure 4.4.).

4.2.1.8.3. Material Evidence

4.2.1.8.3.1. Furnaces

4.2.1.8.3.1.1. Skali

The site of Skali bears evidence of a EBA copper smelting site. Two trenches were placed in the spread of slag at this site where a large number of furnace wall fragments were situated alongside scattered slags (Papadopoulou, 2011, p.153). Trench I revealed the remains of two smelting furnaces. One was made up of a thin layer of vitrified earth on the bedrock and wall fragments found in situ. The second furnace had only a piece of wall in situ, placed almost upon the bedrock. The bedrock appeared to be carved to create a supporting structure for the furnace (Papadopoulou, 2011, p.153). In the northeast of the trench stones has been formed to make a shelter structure, probably against the north wind. More furnace fragments were found in a layer, amongst small stones. This layer was limited by a semi-circular construction, which had been formed by carving rock (on the west) by a series of stones (*Figure* 4.38) (Papadopoulou, 2011, p.153). A thick layer of furnace wall fragments was discovered during the excavation of the semi-circular construction. A number of these fragments have traces of fire.

(image redacted for copyright purposes)

Figure 4.38. Photograph showing the north-eastern side of Trench I at Skali and the two in situ furnaces (Papadoppilou, 2011, Figure 15.6).

The evidence from Skali suggests that the smelting operations made use of the wind, with the presence of the semi-circular construction in Trench II, aimed at controlling the strong wind coming from the north. No evidence of perforated furnace fragments was found (Papadopoulou, 2011, p.153-4).

4.2.1.8.3.1.2. Akrotiraki

Rescue excavations at Akrotiraki revealed important evidence for EBA lead/silver production, which had not been seen by previous surveys (Papadopoulou, 2011, p.150). The EC levels revealed an abundance of pottery and lithic including: saddle querns, grinders, pounders, obsidian tools and fragments of stone vases. There was evidence of few structural remains, however there were various metallurgical materials found including: litharge, hearth bases and lead objects (Papadopoulou, 2011, p.150-2). At least 46 fragments of litharge were found, some of these join to reconstruct the shape of a shallow bowl (*Figure* 4.39). The largest fragment measures 18cm in diameter and weighs 2,700g. The total weight of the fragments of litharge is 18.5 kilos (Papadopoulou, 2011, p.150-1).

A semi-circular hearth (*Figure* 4.39) is present in trench (I 4), which is considered to be related to the smelting activity (Papadopoulou, 2011, p.150-1). Around 130 ceramic sherds were found which have been connected with metallurgical activity. These sherds bear lead oxide on either their inner or both inner and outer surfaces. A large quantity of these sherds (88) came from trench (I 4) alone (Papadopoulou, 2011, p.152).

(image redacted for copyright purposes)

Figure 4.39. Photograph of litharge from Akrotiraki (Papadopoulou, 2011, Figure 15.3).

(image redacted for copyright purposes)

Figure 4.40. Photograph of a semi-circular hearth from Akrotiraki (Papadoploulou, 2011, Figure 15.4).

Perforated furnace fragments have been identified at Kasela, which is close to Akrotiraki on Siphnos (Georgakopoulou, 2017, p.10; Papadopoulou, 2013, p.44). The evidence from Kasela is interesting as they are the only example associated with lead smelting. The evidence from Kasela suggests that only lead smelting was taking place (Georgakopoulou, 2017, p.10; Papadopoulou, 2013). There is a copper smelting site nearby (Skali), which does not bear any evidence of perforated furnace fragments. Both the metallurgical sites of Kasela and Skali appear to be linked with the local settlement site (Akrotiraki), as both copper and lead slags have been found within the settlement itself (Georgakopoulou, 2017, p.10).

Blowpipe tips have been found at Akrotiraki near Kasela, which fit in the perforated fragments found from Kasela exactly (Georgakopoulou, 2017, p.10; Papadopoulou, 2013, p. 44)

4.2.1.8.3.2. Metallurgical material

4.2.1.8.3.2.1. Skali

The surface of the site of Skali is covered in a large quantity of slag, which is highly ferrous and contains small copper prills (Papadopoulou, 2011, p.153). Amongst the slags are furnace fragments and coarse ware ceramics. Iron ore is still seen on the surface, which is considered a remnant of open-pit mining, as copper minerals are often associated with iron ores (Papadopoulou, 2011, p.153).

In Trenches I and II a very large number of slags were found amongst the fragments of furnace wall. The size of the pieces of slags decreased as the excavators went lower into the layers. A tool consisting of slag was found in Trench II (*Figure* 4.41) (Papadopoulou, 2011, p.154). The volume of furnace wall lining and slag was significant from Trench II with the total slag weighing c.150 kilos (Papadopoulou, 2011, p.154).

(image redacted for copyright purposes)

Figure 4.41. Photograph showing copper slags, furnace fragments and stone tools from Skali (Papadopoulou, 2011, Figure 15.7).

4.2.1.8.3.2.2. <u>Akrotiraki</u>

Several lead slags come from the Pittis plot at Akrotiraki, as well as a few copper slags. One of the copper clags has been modulated as a tool (Papadopoulou, 2011, p.152). Lead artefacts were found, including: a small handle, part of a rim of a vessel and a triangular object with decoration on one side (two diagonal incisions) (Papadopoulou, 2011, p.152).

4.2.1.8.3.3. <u>Other material</u>

4.2.1.8.3.3.1. <u>Skali</u>

Obsidian objects were found amongst the slags and furnace fragments covering the surface at Skali (Papadopoulou, 2011, p.153).

4.2.1.8.3.3.2. <u>Akrotiraki</u>

There were several stone tools found in the Pittis plot at Akrotiraki, which have been associated with metallurgical activities (Papadopoulou, 2011, p.152).

4.2.1.8.4. <u>Discussion</u>

The locations of the smelting furnaces in all areas of Siphnos were to take advantage of the strong winds from the sea. Large slag piles are found, with evidence of crushing tools, indicating that slag was crushed, probably to release copper prills.

4.2.2. Conclusion to evidence of the APF

Site Name	Date	Located on a windy promontory	Fragment thickness	Evidence of forced air
Chrysokamino, Crete	MBA	Y	thin	Y
Paliopyrgos-Aspra Spitia, Kythnos	EBA	Y	thick	N
Sideri, Kythnos	EBA	Y	thick	Y
Avessalos, Seriphos	EBA	Y	not detailed	N
Kephala, Seriphos	EBA	Y	not detailed	N
Kephala, Keos	FN	Y	thin	N
Athenian Acropolis, Attica	FN	Y	thin	N
Gerakas, Attica	EBA	Y	not detailed	N
Raphina, Attica	EBA	Y	not detailed	Y
Akrotiriaki/Skali, Siphnos	EBA	Y	not detailed	N

Table 4.1. Summary of evidence of APF material.

This first part of the chapter has presented the material evidence and context for ten copper smelting sites in the Aegean which bear evidence of the APF technology, the summary of which is presented in Table 4.1. This detailed description and comparison of the material evidence at each site has enabled a better understanding for the motives behind the locations chosen to conduct this activity, with their positions being in locations where strong wind is present. It has also enabled a new model to be proposed by the author for the function of the APF to be realised, which sees these furnaces as being powered solely by wind and not forced air such as bellows or blow pipes. The presentation of this information also enables comparisons with evidence and practice of copper smelting elsewhere in the Aegean and in its neighbouring regions, which can help identity if the APF is an isolated tradition, or an adaption of a traditions which has spread from the Balkans or Anatolia. Providing details of the material evidence and the context of its location, allows for an assessment of the practice and consideration of the new model of use for the APF.

4.3. Comparative copper production in the Late Neolithic and Early Bronze Age, in the Aegean, Balkans and Anatolia

This part of the chapter will present a summary of the material evidence and the chaîne opératoire for copper smelting activities which are contemporary to that of the Aegean Perforated Furnace (APF), from elsewhere in the Aegean and in the neighbouring regions of Anatolia and the Balkans. This is to enable a comparison between the material and sequence of practice proposed to be conducted in the reconstructed models based on the archaeological material. The purpose of the following section is to assess if the APF is an isolated tradition of practice, where copper smelting is conducted using a different method, or if it is a stylistic variation of the existing traditions of copper smelting. Understanding if the APF technology and its chaîne opératoire are different, to other equipment and process, is important, as the existing models for the emergence and transmission of metallurgy see either the homeland, or homelands of metallurgy being located outside of the Aegean and the technology spreading into the Aegean (Chapter 2). However, if there is a practice of copper smelting in the Late Neolithic and Early Bronze Age Aegean which is different, this questions these current models, as it may represent a new example of inception, or independent reinvention (to be discussed further in Chapter 7).

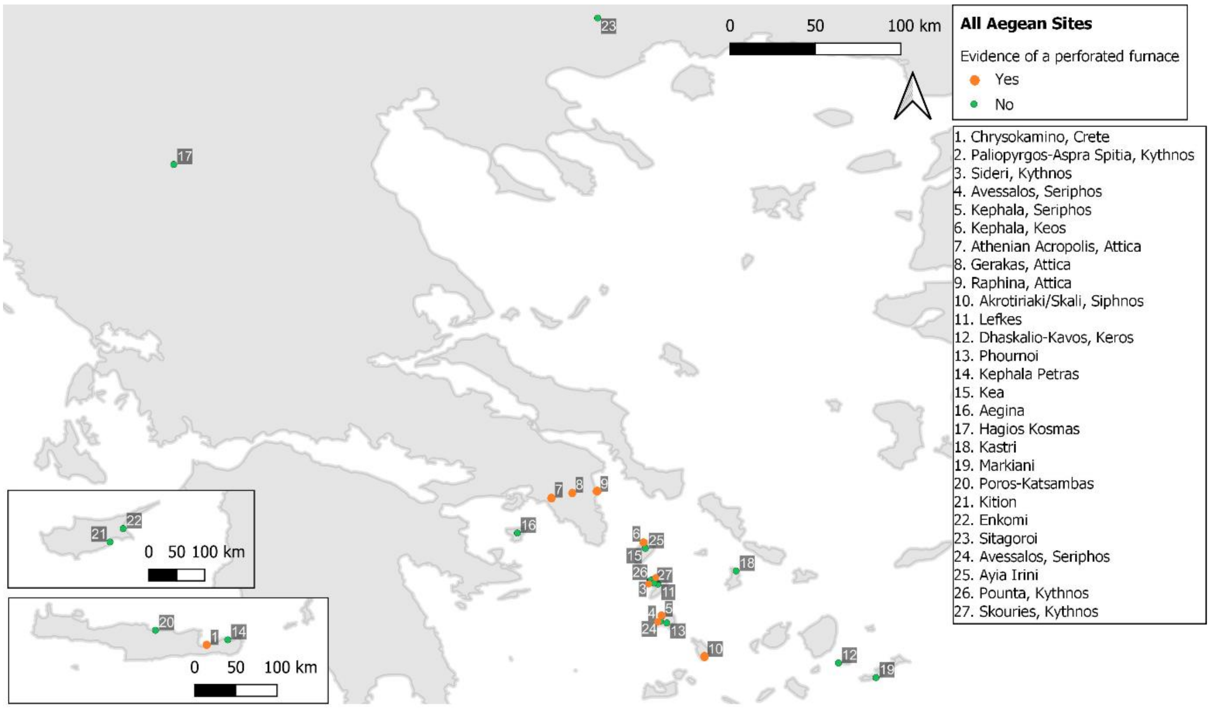

Figure 4.42. Map showing all copper smelting sites in the Aegean (Made by author).

4.3.1. Copper smelting evidence in the Aegean

4.3.1.1. Method for identifying copper production in the Aegean

When assessing the available evidence for copper production in the Aegean, it is important to understand how metal has been studied in the region over the past decades and how this affects what information has been shared and published, but can also show how new evidence and understanding has been revealed in recent decades. One of the most dominating methods for studying metal in the EBA Aegean has been typology studies, this method was predominant in the first half of the 20th Century (Childe, 1942), but has now been joined by studies of the technological production of metal (Branigan, 1967, 1974, 1991; Muhly, 1973; Betancourt, 1970). Typological studies look at the intended deposition of metal as being a signifier of a community being metal using, as well as using the presence of metal artefacts in the archaeological record as signifying the location of metal production and use (Doonan and Day, 2007, p.1). In contrast studies of the technological process can identify the different locations different processes took place, as well as considering cultural affinities with neighbouring regions, in order to discuss the appearance of practice or artefact (Doonan and Day, 2007, p.1-2). The reasoning behind the lack of intentionally deposited artefacts (in burial and ritual deposits), may be due to the items being made are being used practically, with items considered to be part of the “toolbox” such as awls, flat axes, chisels and spatulas (Sherratt, 2007, p.247). As the metal items being made are being used practically, it can be considered that when they broke, the metal would be recycled. It therefore appears that during this period, a surplus of metal was not available, resulting in other materials (representing wealth or importance) being deposited as methods of ritual (such as the marble at Daskaleio-Kavos; Broodbank, 2000, p.225-36; Renfrew, 1984). What therefore should be reconsidered, is that the presence of metal in the archaeological record is not the only signifier of a community being metal using or to identify the spread of sites making and/or using metal (Catapotis, 2007, p.218-9). Studies by Broodbank (1993) and Nakou (1995) used spatial distribution of the various stages of metal production in the EBA to identify, understand and demonstrate the mechanisms by which different stages of metal production could take place and be controlled by communities (or elites). These studies identified the difference in location of ore sources (mining sites) and smelting sites (Catapotis, p.2007, 219). The separation of these activities can be seen to reflect a number of different things: to allow for a separation between producers and traders (Broodbank, 1993, 2000, p.294-6), as a strategy to keep secret and control the technical knowledge (Nakou, 1995) or to represent a lack of a one method of control of its production (Catapotis, 2007, p.219).

In the Late and Final Neolithic there is an increase in metal finds and an increase in the range of types of artefacts too. The artefacts being found are functional tools, such as awls, flat axes, chisels and spatulas (Sherratt, 2007, p.247). This increase in number is too small to demonstrate regional distribution patterns, but can show that by the FN metal production and use was well established in both cultural and practical ways of life (Sherratt, 2007, p.247). Sherratt (2007, p.248) discusses the possibility of the relationship between copper artefacts and their stone counter parts in the transitionary period (FN-EBA). In this period artefacts such as copper flat axes can be seen as a substitute for their stone counterparts, in practical as well as cultural aspects (Phelps, *et al.,* 1979; Nakou, 1995, p.6; Zachos, 2007). Sherratt (2007, p.248) raises the important point that, despite more evidence for metal being discovered from the FN, it is also a period when there may have been a lot more metal in use than we can actually (or will ever) see in the archaeological record. This is due to the patterns of deposition (whether deliberate or accidental) and the evidence for re-melting and recycling of metal. Sherratt (2007, p.251) also points out the importance of the increasing evidence for copper production in the FN which has increased even further since 2007, including the remains of furnaces, bellows, blowpipes, slags, crucibles, prills, moulds and stone tools. The amount of evidence from the FN is becoming equal to that of the Aegean Bronze Age. This increasing body of evidence is demonstrating the varied nature of the technology, from different abilities and efficiency with ore exploitation, to the difference in organisation, even to the different locations that each stage takes place (Sherratt, 2007, p.251).

When a site is excavated now, careful attention is paid to record all material evidence and to not interpret at the stage of excavation and recording, but to create a complete record that can be interpreted later and even reinterpreted as new analysis is completed and new comparative evidence and data are found. However, in older excavations in the first half of 20th century, often limited records of excavated material is presented and interpretations have been made by looking at evidence in a generic sense. Certain material evidence has been seen as a signifier for copper production, and was stated as such, and without awareness of the method and chaîne opératoire of the technology and practice. Evidence such as crucibles, bellows or vitrified ceramics can be seen as a signifier for copper production, but investigations into what the processes were and how they were carried out, have not always been carried out. This is where a programme of research combining experimental archaeology and analysis can help with understanding and reconstructions of practice.

The presently known evidence for copper smelting in the Aegean will now be presented, concisely, to enable comparison. This thesis will not re-assess this evidence, but present it as a means for comparison.

4.3.1.2. Sites with no evidence of smelting furnaces

4.3.1.2.1. Final Neolithic (FN)

Evidence for copper smelting technology which does not fit into the category of the APF and which dates to the FN is currently found at six sites in the Aegean: Paoura and Ag. Eirini on Kea, Giali on Nisiros (Dodecanse), Kephala Petras on Crete, Sitagroi in Macedonia and Promachon in northern Greece (Papadatos, 2007, p.115; Papadatos, 2008, p.269; Muhly, 2002, p.77-82; Dimitriou, 2017, p.26, Bassiakos and Filippaki, 2021). None of these sites bear evidence of perforated furnaces, but all have evidence of copper production. No furnace fragments at all are found at Kephala-Petras on Crete, Giali on Nisyros (Dodecanese) or Sitagroi in Macedonia (in the FN levels), with the evidence which is recorded being described as representing crucible smelting, and with evidence of slag being present (Dimitriou, 2017, p.30-1). Promachon (early 5th millennium B.C.) in northern Greece bears evidence of pits used in association with smelting. These types of pits are associated with crucible smelting (process explained in Chapter 2). The pits at Promachon total 15 crucible sized pits (c.12-15cm diameter), which are dug into the local clay bedrock (*Figure* 4.43). Ash and charcoal were found in the pits and SEM analyses of samples taken from the baked clay bottoms of these pits show varying concentrations of copper (0.2-2.5%), alongside iron oxides (5-10%) and alumina-silicate constitutes (Bassiakos and Filippaki, 2021). This evidence is representative of crucible smelting in small bowl heaths/pits, rather than furnace smelting.

(image redacted for copyright purposes)

Figure 4.43. Image showing the pits dug into the clay bedrock at Promachon (Bassiakos and Filippaki, 2021).

4.3.1.2.2. Early Bronze Age (EBA)

There are currently thirteen known and presented sites from the EBA period which have evidence for copper smelting (*Figure 4.44*) (Georgakopoulou, 2017; Πλασσαρά, 2020; Bassiakos and Philaniotou, 2007; Philaniotou, *et al.,* 2011; Coleman, 1977;

Dimitriou, 2017; Theocharis, 1951; Papadopoulou, 2011). Six of these sites do not bear evidence of perforated ceramics (Table.4.2). The majority of these sites are situated in the western Cyclades. The amount of evidence and detail at each site varies, due to level of investigation at the sites. Some of the sites have been excavated and reports published (Hadjianastasiou and MacGillivray, 1988; Betancourt, 2006; Papadatos, 2007; Papadopoulou, 2011), whereas others have only had surface surveys carried out and have been dated using surface pottery, thermoluminescence dating of furnace fragments (Zacharias *et al*. 2006a; 2006b) and on the rare occasion by radiocarbon dating (Stos-Gale, 1989). There are 12 additional sites identified by the author during the collation of this evidence, as having possible evidence for smelting, but these are not listed by other authors, they are detailed in the below table (Table.4.1).

Name of site	**Date**	**Furnace fragments Y/N**	**slag Y/N**	**Copper prills Y/N**
Akrotiraki	FN - EBA	Y	Y	N
Kea	FN	N	Y	N
Aegina	EBA	Y	N	N
Hagios Kosmas	EBA	Y	N	N
Kastri	EBA	Y	N	N
Markiani	EBA	Y	N	N
Poros-Katsambas	EBA	N	Y	N
Kition	EBA	N	Y	N
Enkomi	EBA	N	Y	N
Sitagoroi	LN	N	Y	N
Avessalos	EBA	N	Y	N
Ayia Irini	FN-EBA	N	Y	N

Table 4.2 Table showing 12 additional sites which have evidence for copper smelting in the Aegean and whether there is evidence of furnace fragments, slags and/or copper prills at them.

Broodbank (2000, p.293-7) presents a model for the Early Bronze Age Cyclades, in which he proposes that there was a spatial separation between the local metallurgical process of primary production (smelting) which was carried out in the western islands of the Cyclades and the secondary production stage (melting and casting) which took place in settlements across the Cyclades and the product of the smelt was distributed for this purpose. However, evidence for metallurgical activities within settlement sites is scarcer than at the production sites (Georgakopoulou, 2007, p.123-4). Small amounts of evidence from settlements come from Ayia Irini on Kea (Gale *et al.,* 1984; Stos-Gale 1989, Wilson 1999), Kastri on Syros (Busser 1967; Tsountas, 1899) and in association with the cemetery of Avyssos on Paros (Tsountas, 1898), however evidence is so limited, it is hard to ascertain what processes the evidence represents.

Site Name	**Date**
Skouries, Kythnos	EBII
Pounta, Kythnos	EBA
Lefkes, Kythnos	EBA
Phournoi, Seriphos	EBA
Dhaskalio-Kavos, Keros	EBA
Kephala-Petras, Crete	FN-EMI

Table 4.3. Table showing the six copper smelting sites dating to the EBA and their date, which have evidence of copper smelting, but no evidence of perforated furnaces.

The evidence Skouries on Kythnos is problematic in terms of dating, as it was not stratigraphically excavated, and the large size of the slag heap indicates it had likely been used over a long period, possibly throughout a number of generations (Georgakopoulou, 2017, p.58). Skouries has numerous large furnace fragments visible on its surface. However, they are not perforated fragments (Georgakopoulou, 2017, p.61). As well as large ceramic furnace fragments and structures which were lined with stones which were over 4m in width are present near the slag heap is tioewards the top of the slope. A smaller furnace base was found within one of the structures, suggesting that smaller furnaces were placed inside, and the stones marked out a particular working station (Hadjianastasiou and MacGillivray, 1988). There are also large ceramic fragments present at Phournoi on Seriphos, visible on the site's surface, but none bear perforations (Georgakopoulou, 2017, p.61). The slag heap at Phournoi is remarkably large compared to other sites, suggesting sustained use over multiple generations (Meltzer, 2003, p.237). The evidence from Lefkes and Pounta on Kythnos is very limited, with only a few fragments of slag being present (Bassiakos and Philaniotou, 2007). The same applies to Kephala Petras on Crete, with only a few fragments of slag being present (Papadatos, 2007; Catapotis *et al.,* 2011). There are very few ceramic fragments from Lefkes and Pounta on Kythnos and Kephala Petras on Crete, with the few fragments that are present being very fragmented. The evidence that is present from Kephala-Petras, the few slag and ore fragments, are some of the earliest in date in the southern Aegean, dating between the FN-EMI periods (Papadatos, 2007, p.161-2). The evidence from Dhaskalio-Kavos consists of slag resulting from copper smelting found on the Kavos promontory of Keros; however, no ceramic evidence of furnace or crucibles was found. There is, however, evidence of secondary production activities on Dhaskalio dating between the EBII-III periods.

The sites discussed in this section are those confidently dated to the EBA (with the exception of Kephala-Petras on Crete which spans from the FN into EMI). Georgakopoulou, (2016, p.4) details how there are a number of sites listed by Catapotis (2007) which do not have concrete evidence for dating to the EBA or enough published evidence to understand the technology present and whether it represents copper smelting. These sites include the copper slag scatter at A. Symeon on Kea, which currently cannot be dated (Caskey, *et al.*, 1988), Petalloura and Aerata with their locations uncertain (Bassiakos and Philaniotou, 2007, p.36), Kolonna on Aegina, where the purpose of the furnace structure is unclear and no smelting slags have been found so far (Gauss, 2010, p.741; Walter and Felten, 1981, p.23-8) and Konakia on Keros where there has been a small number of undated slags found, but analysis did not reveal if they were related to copper or iron metallurgy (Bassiakos and Doumas, 1998).

4.3.1.3. Crucible smelting

The evidence for copper smelting in the LN and EBA Aegean currently fits two models:

1. smelting within perforated furnaces, where the ore charge is placed within the charcoal within the ceramic perforated furnace (Georgakopoulou, 2017; Πλασσαρά, 2020; Bassiakos and Philaniotou, 2007; Philaniotou, *et al.,* 2011; Coleman, 1977; Dimitriou, 2017; Theocharis, 1951; Papadopoulou, 2011).

2. Smelting in crucibles, where the ore charge is placed in a crucible, then the crucible is placed in a small pit or bowl hearth, either dug into the bedrock or lined with clay (Dimitriou, 2017, 30-1; Bassiakos and Filippaki, 2021). Examples of smelting copper in crucibles exists in other regions as well as the Aegean, such as the Balkans (5th millennium B.C.), Austria and Jordan (4th millennium B.C.) (Tringham and Krstic, 1990; Ottaway, 1998; Lippert, 1992; Adams 1999, p.112; Hauptmann *et al.,* 1996).

There is also evidence for 'baking pans' (*Figure* 4.44) which are shallow clay vessels with a wide diameter (Georgakopoulou, 2021). These have been considered to have been used as hearth and are often referred to as hearths. These fragments of baking pans have signs of intense burning and have visible remains of copper upon them (*Figure* 4.44). Their method of use it not yet understood, it is clear from the remnants of copper on their fabric and signs of intense heat they were use in some part of the copper production process, however it is currently unclear which stage this was. As the copper is on the ceramic fragments, it seems unlikely these were a hearth which held a crucible inside of them, rather they would have had copper or copper ore within in them amongst fuel. As the pans are so shallow and wide, it would be hard to maintain a reducing environment, even with charcoal piled up. Therefore, if used for smelting, the ores would need to be high percentage ores. The other possibility is that they were used in a roasting process, with sulphide ores, to prepare them for smelting (Ottaway, 2001, p.96).

(image redacted for copyright purposes)

Figure 4.45. Photographs of fragments of baking pans from Dhaskalio (Georgakopoulou, 2021).

4.3.1.4. Smelting evidence without ceramic fragments

4.3.1.4.1. Keros:

The promontory known as Kavos North on the Island of Keros bears evidence of copper smelting; however, what is interesting is that no substantial and clear ceramic evidence for furnace structures survives. Excavations have not taken place on the promontory. However, a surface survey was undertaken (Georgakopoulou, 2007), and a soil chemistry survey was carried out during the field season of 2016 (Lester, forthcoming). These surveys confirm that copper smelting took place on this promontory. However, the method and technology used for smelting remains elusive.

There were a few metallurgical ceramic fragments found on the promontory during the field survey. However, they are small and shapeless, allowing no inferences to be made about their original shape or size (Georgakopoulou, 2007, p.127-8). A thin slag layer was attached to the inner surface of most of these samples and analysis suggested that these slags came from smelting due to the compositional variance (Georgakopoulou, 2007, p.127-8).

The surface survey also retrieved 14 slag specimens, of which a sample of each was taken for analysis (Georgakopoulou, 2004, p.6). Macroscopic analysis divided the slags into two groups, due to their macroscopic characteristics. Group one consisted of nine sherds. “They are all grey-black in colour with little or no external green staining. A ropey-flow texture is visible on the upper surface of some of the specimens. With the exception of a couple of samples that showed a little magnetism, the majority did not respond to a handheld magnet” (Georgakopoulou, 2004, p.5). The microscopic analysis of these samples suggested that they were a result of a smelting process rather than a melting process. “The slags are virtually free of any unreacted or partially reacted primary materials, as are typically observed in early (usually pre-EBA) copper production slags (see for example Hauptmann 1989, 2003). The predominance of fayalite indicates reducing conditions, with oxygen pressures below 10-8 atm (Moesta and Schlick 1989), while the overall microstructure of these specimens suggests that the primary materials fully reacted to form a relatively homogeneous melt. Low copper losses are attested from the bulk composition measurements” (Georgakopoulou, 2004, p.6). Entrapped prills in the Group 1 slags are mostly mixed copper and iron sulphides (matte). In the larger ones, different phases of the Cu-Fe-S system can be discerned within individual prills” (Geogakopoulou, 2004, p.6). Different methodologies have concluded that sulphidic copper ores did not need particularly strong reducing conditions to be able to be smelted successfully (Georgakopoulou, 2007, 127-8; Hauptmann *et al* 2003; Moesta and Schlick, 1989; Rostoker *et al*. 1989; Zwicker *et al*. 1985).

Group two consists of four slags, three of which show very similar external characteristics. “They are greyblack in colour, with iron oxide and green copper oxide staining on their outer surface, the latter being particularly intense in and around the pores observed upon sectioning” (Geogakopoulou, 2004, p.6). “A very characteristic feature of these samples is the appearance of several tiny (c. 0.1 cm) green prills, which protrude on the outer surface” (Geogakopoulou, 2004, p.6). Bulk analysis revealed that these samples have higher iron oxide contents, compared to the group one samples, as well as the copper content being much higher. The microstructure of the slags is generally very heterogeneous. It appears that the slags in group two were by-products of arsenical copper production, due to their chemical composition” (Georgakopoulou, 2007, p.127-8). The “production of arsenical copper alloys can be achieved via several pathways depending on the nature of the starting materials (see for example Budd et al. 1992; Lechtman 1991, 1996; Lechtman and Klein 1999; Pollard et al. 1991; Rostoker and Dvorak 1991)” (Geogakopoulou, 2004, p.8). “The identification of quartz crystals with traces of copper found within the slags suggests that copper most likely entered the charge as a mineral rather than in its metallic form. The presence of other base metals in the slag in addition to arsenic such as lead, antimony, and nickel suggest the use of polymetallic ores, but whether these elements co-existed in the ore or whether different minerals were deliberately mixed in the furnace charge remains at present uncertain” (Georgakopoulou, 2004, p.9).

“Evidence for processing of at least two different types of copper was brought forward, while a single litharge specimen identified, raises the possibility that lead-silver metallurgy was also practised on the site” (Georgakopoulou, 2004, p.130). In the absence of stratigraphic evidence from Daskaleio-Kavos, due to excavations not yet taking place here, it is not possible to produce a timeline for when these different production processes were taking place (Georgakopoulou, 2007, p.130).

4.3.1.5. Aegean metallurgy – local process?

Renfrew (1976) and Branigan (1974) theorised that sources for ores for Aegean metallurgical activity were local, with small deposits of copper and lead/silver being exploited. This led to the belief by a number of scholars, not just Renfrew and Branigan, that metallurgical activity in this period was mostly a local process, even though the specific techniques being used had been gained from overseas (Renfrew, 1972, p.338; Branigan 1977, p.121; Barber, 1987, p.112; Stos-Gale and Gale, 1990, p.74; Bassiakos and Philanioyou, 2007, p.19). Bassiakos and Philaniotou (2007, p.19) point out how these theories come from the study of the finished artefact and movement of them, rather than the evidence from the production process. At the time these studies were undertaken, there was little evidence for smelting structures and associated material. There was also a lack of material evidence for mines as many have been destroyed by modern mining activities. Also when ancient mines do survive, they are very difficult to date, due to the lack of datable evidence such as pottery (Bassiakos and Philanioyou, 2007, p.20; Barber, 1987, p.106-10).

4.3.2. Evidence for copper smelting in the Late Neolithic and Early Bronze Age Balkans

4.3.2.1. Summary of the research on metallurgy in the Late Neolithic and Early Bronze Age Balkans

The Balkan region, for the purposes of this thesis, is the area known as the Balkan Peninsula, the countries included within this region are Albania, Bosnia and Herzegovina, Bulgaria, Hungary, Croatia, Kosovo, Montenegro, Romania, Serbia, Slovakia and Slovenia. The Balkan region has been of particular interest to scholars, due to the finds of metal artefacts, which are of a very early date. There are over 4000 objects from the Balkan Region, which date to the 5th century B.C. (Chernykh, 1978; Pernicka *et al* 1997; Radivojevic, 2013), as well as the additional evidence for metal production from Belovode, in the form of metal slags dating to c.5000 B.C. (Radivojevic *et. al.* 2021; Radivojevic, 2010, 2013). The Balkans became one of the main foci of metallurgical studies, for research into the emergence and transmission of metallurgy, after Renfrew (1969) proposed the Balkans as a centre of independent metallurgical invention. Renfrew's attention was drawn to the Balkans by the early fluorescence of metal goods and limited reports of crucibles (Tringham 1990; Jovanovič, 1982, 2009) and mining evidence. Critically, at the time there was no compelling evidence for primary metallurgical production. Since then evidence for Vinča period mining (Jovanovič, 1982, 2009; Jovanovič and Ottaway, 1976) has been better dated and documented, especially around early sites like Rudna Glava; debate has continued as to whether these were mines for metal or mineral to be used in jewellery (Pernicka, *et al*., 1997). More recently The Rise of Metallurgy in Eurasia project (Radivojevic *et. al.,* 2021) enabled analysis of slags held at the National Museum of Belgrade as well as excavations in Belovode, Pločnik and Jarmovac in 2012 and 2013, with subsequent analysis. The project also facilitated an experiment in ore smelting, reconstructing the evidence from these sites (Kuzmanović-Cvetkovic, 2021, p.5-6).

The Balkan region currently holds the earliest date for copper production, in the form of smelting slag from the Vinča site of Belovode in Serbia. "The earliest smelting event at Belovode is now dated to c.5000.B.C., which is the earliest securely dated record of extractive metallurgy anywhere" (Radiojevic *et al.*, 2010, 2276). This paired with the evidence for copper mineral deposits at mines such as: Rudna Glava, Zdrelo, Majdanpek and Ai Bunar, make this region an appealing case study for the early inception of metallurgy. The metal production debris studied by The Rise of Metallurgy in Eurasia project has enabled a better understanding of metal-making recipes, the transmission of metallurgical knowledge and ore province, which was not achievable from the previous studies of final products (Radivojević *et al*., 2021, 8).

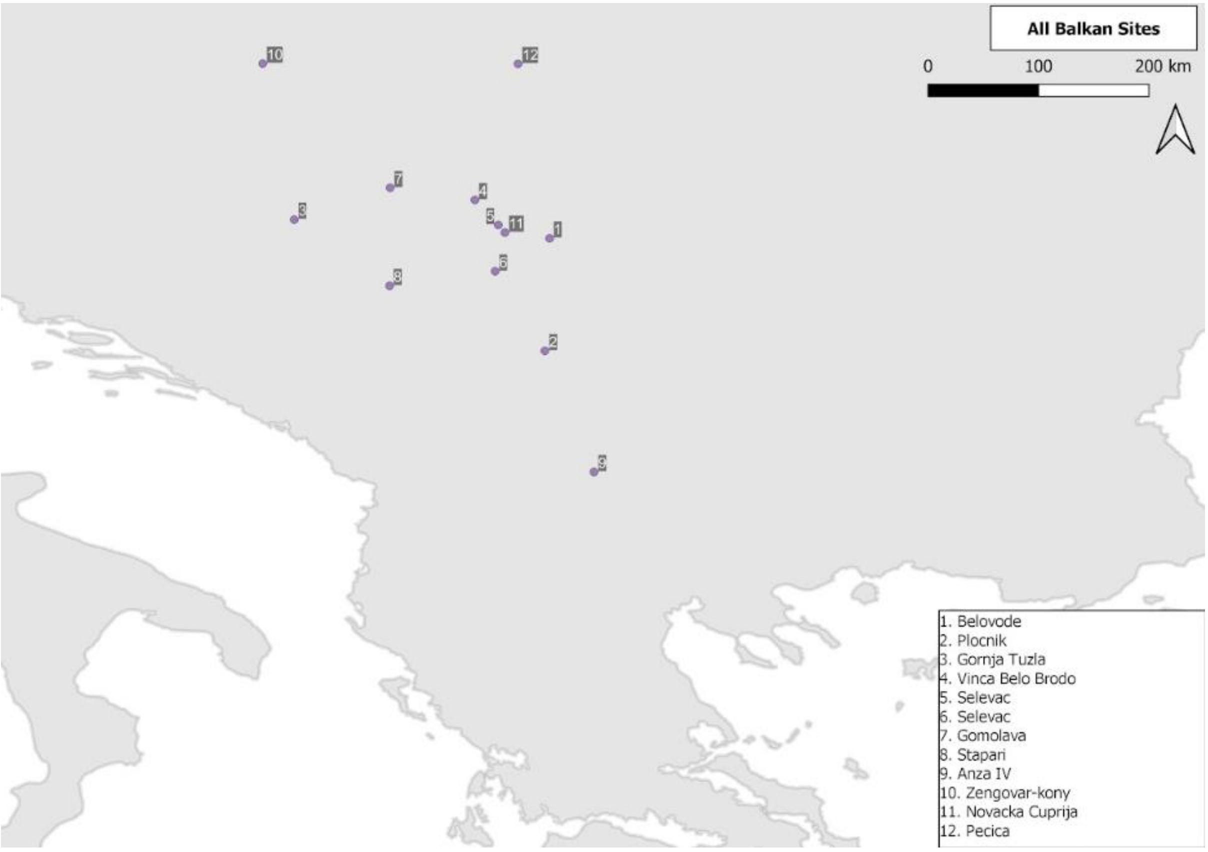

Figure 4.46. Map showing all sites in the Balkan Region (Made by author).

4.3.2.2. The Vinča Culture

The estimated duration of the Vinča culture is between c.5400-4600 B.C., with the start of the metallurgical activities dating to around c.5000 B.C. (Radivojević *et al* 2021. 201010; Radivojević, 2013). The different phases this period is split into are detailed in Table 4.3.

Phase	**Date**
Vinča A	c.5400/5300 B.C. - 5200 B.C.
Vinča B	5200 B.C. - c.5000/4950 B.C.
Gradac Phase	c.5000/4950 B.C. - c.4900 B.C.
Vinča C	c.4900 B.C. – c.4850/4800 BC
Vinča D	c.4850/4800 BC – c. 4650/4600 B.C.

Table 4.4. phases of the Vinča period (Borić 2009, 234; Radivojević, 2013).

There is evidence in the Balkan region that demonstrates knowledge of pigments and their properties, before evidence of smelting. This provides a context for the inception of this practice, as they appear to have selected ores in accordance with certain properties, indicating an understanding of the differences. There is also evidence of the working of native copper, as well as high percentage copper ores, which would need less skill and precision to smelt. This information will be presented in more detail later in this section, and can provide an understanding of how the copper smelting technology developed in this region. The evidence for early copper smelting in the Balkans primarily comes from household contexts. This is different to the Aegean, although we also need to keep in mind the organisation of the Vinča culture and its settlements is different to that of the Aegean. There is also evidence of reduction firing of pottery, which predates the evidence for copper smelting. This demonstrates the knowledge and skill to control a pyrotechnical environment, which could be adapted to the copper smelting process.

4.3.2.3. Copper smelting in settlement sites

Vinča settlements are highly organised sites, which follow a close settlement patterning. The sites range in size from 6 hectares to 100 hectares (Crnobrnja, 2012, 158; Bailey, 2000, p.163). The most well-known type of settlement is the tell sites, due to their long occupation, such as Vinča-Belo Brdo, Gomolava and Belovode. The tell sites are slightly more disorganised than the other sites, due to the nature of their development (Chapman 1981, p.60), however they have designated specialised craft areas. For example, the workshop for producing malachite beads at Divostin (Glumac, 1988). Pottery is the most evidenced type of craft activity, but there is also evidence of the production of lithic, loom weights, and grinding stones, indicating that craft activities were taking place within the domestic context (Chapman, 1981, p.63).

The evidence of metallurgical activity, which takes place within the house environment, is the ceramic chimneys, which are believed to have been used to smelt copper ores (Šljivar, 2006, p.97-98; Borić, 2009, p.208; Mlyneic, 2016, p.36, Kuzmanović-Cvetkovic, 2021, p.3-5; Radivojević *et al* 2021, 50). Pyrotechnological production processes, such as ceramic production and metallurgical production, were taking place in the domestic setting and shed light on the scale of production during this phase as well as the organisation of craft technologies. The fact that such activities were taking place within the house suggests that they are small scale production processes, which are not centrally organised across the settlement.

4.3.2.4. Evidence for reduction pyrotechnology

The Vinča pottery demonstrates a wide array of specialised skill, especially knowledge and skill of reduction pyrotechnology. The Vinča pottery is distinct, and different from earlier wares, due to its dark grey/black colour, which is gained through reduction firing (Kaiser, 1989). The use of inclusions in certain wares shows the potters' understanding of different materials and the different properties they have and how they react to being fired within clay (Tringham 1988, p.258). Firing is believed to have been carried out between 950ºC and 1050ºC (Tringham, 1988, p.256). The evidence for pyrotechnical skill and knowledge demonstrated by the ceramic assemblages from Vinča sites can provide an insight into the capabilities for metal production technology for metal production. Firing temperatures above 1200◦C could also be achieved, as evidenced by the ceramics produced (Stevanović, 1997, p.336), which shows that the pyrotechnical skill to achieve the temperatures needed to smelt copper was present and was developed in this period. The black burnish wares are a particular demonstrator of the high skill practised by potters, due to the technical skill needed to achieve this finish. Burnishing causes a reaction with the silica within the clay make-up, to create a matt/polished affect (Kaiser, 1989). Temperatures must remain above 1100◦C, with reducing conditions being maintained, for this technique to work (Renfrew 1969, p.41). Reducing conditions and the maintenance of high temperatures are necessary for the transformation of copper ore into metal (Kaiser, 1989; Chapman 1981; Šljivar 2015; Tringham, 1988, 256; Renfrew 1969, p.41).

Understanding the technological processes of the Vinča period is difficult, as there have been no pottery kilns discovered so far at any Vinča sites (Kaiser, 1989). This makes it not only difficult to piece back together the pottery production technology and practices, but also hinders our understanding of pyrotechnological processes and therefore metallurgical technology too. The only comparison we can draw, is the up-draft bread ovens within the dwellings (Kaiser, 1989). Glumac and Tringham (1990) have claimed that the link between ceramic kiln technology and metallurgical furnace technology is overemphasized, due to the lack of kiln evidence. At Selevac, there are pits which are situated next to dwellings, which contain layers of ash and wasters, these have been interpreted as firing pits for pots (Kaiser, 1989). If this interpretation is accepted, then this shows a small scale domestic based technology for producing pots. This supports the theory that there is no centralization or organisation of the craft practices at Selevac, but rather it is being carried out independently by families within their domestic settlements.

4.3.2.5. Copper Production in the Vinča Period

While Belovode holds the earliest date for metallurgical activity, there are a number of sites that are also dated to the early phase of metallurgy, such as Selevac, Plocnik and Vinča Belo-Brodo. Evidence for copper metallurgy can also be seen at mining sites. However, there is significantly more evidence in the Balkans during this period for copper mining, than there is for copper smelting (Radivojević *et al.* 2021; Rehren and Radivoyevik, 2015); this may be due to the method of smelting taking place and how well the evidence from its practice survives in the archaeological record. But it is also in part, to the amount of excavation and analysis which has taken place. The Rise of Metallurgy in Eurasia project (Radivojević *et al*. 2021) enabled new analysis and excavations to be undertaken, including analysis of slags held at the National Museum of Belgrade as well as excavations in Belovode, Pločnik and Jarmovac for two years starting in 2012 and then three years of subsequent analysis (Kuzmanović-Cvetkovic, 2021, 5-6). The limited evidence means it is vitally important to pull all the evidence together from across the region for this phase, to be able to better understand what processes were taking place.

4.3.2.5.1. <u>Copper ore</u>

The evidence of copper ore is often discussed as a signifier of copper metallurgy, however on its own it cannot signify smelting. Copper ore can be used for many other purposes within craft activities: from the cold working of ore into ornaments and jewellery, to the creation of pigment for decorating objects and the human body. The presence of native copper artefacts and evidence for ore processing for pigment identifies how copper ore was used throughout the Balkans before it was smelted to make copper objects. There appears to have been a preference for using black copper ores within the Vinča culture. It is argued by Radivojević and Rehren (2015) that ores of black and green were initially selected for smelting, due to their colour and the preference for these colours within craft activities. Copper-manganese oxides which are black in colour, which are found at Belovode, do not need the same smelting conditions as other more commonly used ores during the late Neolithic and Bronze Age. Copper-manganese oxides can facilitate the formation of a melt under lower operating temperatures (c.1,083°C) than that of other more commonly used ores such as iron rich oxides. Copper-manganese oxides also do not need as strict reducing atmosphere either, with successful melts being possible in environments which are not fully reduced (Radivojević and Rehren, 2015). The ability to melt copper-manganese oxides in a less stable environment would have allowed early metal practitioners to successfully melt such ores, during experimentation, resulting in different material remains, which would be less permanent in the archaeological record and different to the expected evidence resulting from smelting other ores. It can be considered that the smelt of these ores would be more successful, with a clear separation between the metal and slag; therefore, the slag would not need to be crushed to remove the copper droplets, making it less visible in the archaeological record (Radivojević and Rehren, 2015, p.32). The lower temperatures may also mean that the materials from the smelting activity were less altered and may not therefore survive in the ground for over 6,000 years (Radivojević and Rehren, 2015). These copper-rich ores which were being selected for smelting in the early stages of metallurgical activity in the Balkans, are believed to have been selected due to their colour (Radivojević and Rehren, 2015). Such ores are present at the sites of Belovode, Vinča-Belo Brdo and Gornja Tuzla (Radivojević et*. al.,* 2021, 50; Radivojević and Rehren, 2015).

As time progressed, ores of a lower percentage of copper were utilised, and the technological process would have started to resemble the more familiar process of smelting that archaeometallurgists are used to observing. However, in this transitional period the technology may not be as easily recognisable. The ‘furnaces’ being used may not be as robust, as coarse or as vitrified in the archaeological record, therefore they may not leave much of a mark, perhaps something as subtle as a burnt mark in the ground (Craddock 1995; Rehder, 2000, p.180). We may need to look to other pre-existing crafts to be able to understand and recognise the technology which would have been used. Another important point to consider is the diversity that may have existed in this early phase, as craftspeople adapt pre-existing knowledge and skills to this new idea and technical process (Roberts, 2008).

4.3.2.5.2. Evidence for Copper Smelting Technology

4.3.2.5.2.1. Pits for smelting

There is unfortunately a lack of evidence for copper production in the Vinča period. There is significantly more evidence for copper mineral processing (Radivojević *et. al.*, 2021; Rehren and Radivoyevik, 2016) and this had led to discussions around the inception of metallurgy in the Balkans being interwoven with the process of mineral processing. The earliest evidence for smelting comes in the form of shallow pits lined with pre-fired ceramic fragments found at Belovode and Gornja dating to c.5350-4650BC (Radivojević *et. al.*, 2021; Rehren and Radivojević, 2016; Craddock and Hughes, 1995). Rehren and Radivojević (2016) have reconstructed the evidence of slagged sherds and slag coming from the same context at Belovode and Gornja Tuzla, to create a proposed method of smelting at these sites. They reconstruct the material to represent a shallow pit, rimmed with broken sherds, in which the copper ore could be placed amongst charcoal, and air would be forced into the pit to increase the temperature using blowpipes (Rehren and Radivojević, 2016; Radivojević *et. al.*, 2021). Rehren and Radivojević (2016) argue that the structure for their proposed shallow pit would not have survive in situe, due to the subsequent re-use of the area afterwards. It is also argued that the simplicity of this design would fit into this early stage of the evolutionary process of metallurgy (Craddock 1995).

Glumac and Tringham (1990) propose a similar method for Vinča smelting, they propose a crucible being used to hold the copper ore, which would be placed in a hearth, filled with charcoal. They also believe sand would be included in the crucible, mixed with the ore, to act as a flux. There is also evidence which suggests ceramic chimneys used for copper smelting, which can indicate a progression in the technology.

4.3.2.5.2.2. Ceramic chimneys

Ceramic chimneys found at a number of Vinča sites have been proposed as a possible furnace structure, which was used for smelting copper ore (Šljivar, 2006, p.97-98). "The chimneys have traditionally been referred to as double rimmed vessels with no known function" (Mlyneic, 2016, p.36), however in 2006 Sljivar (2006, p.97-8) stated that these chimneys could have been used for metallurgical practice. To date, evidence of these Vinča chimneys has only been reported at three sites: Belovode, Divostin, and Pločnik (Borić, 2009, p.208). They vary in form, with some chimneys having solid walls (Belevode, Divostin) and others bearing perforations (Plocnik). Understanding the metallurgical processes at Belovode and Plocnik would be hugely important, as some of the most important data in relation to metallurgy comes from these sites. Belovode currently appears to represent the earliest date for metallurgy in the Balkans (and possibly the world), at the beginning of the Gradac phase (c.5000/4950 B.C. - c.4900 B.C.). Whereas Pločnik hosts the largest collection of metal artefacts found for this region, during this period, with some examples being very advanced (Mlyneic, 2016, p.36).

The chimneys measure between 50cm and 80cm in height, with tapered walls (Šljivar 2006, p.97, Radivojević *et al*. 2010, p.2779). There is debate regarding which way up these chimneys were used, whether the narrow end is the top or the bottom (Mlyneic, 2016). However, if you consider the fluid dynamics of truncated cones, it would be logical to have the narrower end at the top, as this would help pull air up through the chimney. Some examples have handles attached, these alternate between which ends they are attached to. The thickness of the walls varies too, with the ceramic being thicker at the wider end. The perforations on the Plocnik chimneys are c.2cm in diameter, spaced between 8cm and 10cm apart. The perforations are placed in uniform straight columns, rather than sporadically across the body (Mlyneic, 2016, p.37).

The clay fabric of the Belevode chimneys has inclusions of coarse sand, organics, and small gravels. The Pločnik chimneys fabric contained very fine sand and possibly mica.

Macroscopic analysis of the chimneys showed that the break patterns are consistent with slab forming, indicating that these chimneys were built by forming slabs of clay into a cone shape, either by forming around a ‘mould’ (possible sand, or sticks to support the shape), or using the coil method. There is evidence of burnishing on the outside of the chimney, this is likely to have been a finishing method to prevent cracking (this technique is seen within ceramic production of the period also). The chimneys were fired at high temperatures before use, as the clay is fired evenly which comes from pre-firing rather than being fired during use (Mlyneic, 2016, p.37).

4.3.2.5.2.2.1. <u>Plocnik</u>

The site of Pločnik is situated 19km west from Prokuplje, south Serbia, and covers around c.100 ha (Radivojević *et. al.*, 2021, 60; Radivojević and Rehren, 2015; Šljivar *et al*. 2006). Recent geophysical analysis has established the site is c40 ha (Radivojević *et. al.*, 2021, 60). There are 34 large copper metal implements found at this site. Pločnik’s occupation is estimated to c.5200 B.C. – 4650 B.C. “The Gradac date for the site is uncertain the upper levels have not been properly tested yet” (Borić, 2009; Bruyere, 2018). The use of copper minerals is evident at this site, as pieces of copper minerals are scattered across the settlement, often found outside potential domestic structures and in workshop areas, similar to Belovode (Radivojević and Rehren, 2015; Rehren and Radivojević, 2016). Excavations have revealed three building horizons which correspond to Vinca A, B1 and B2 (Radivojević *et. al.*, 2021, 61; Sljivar, 1996). Horizons I and II contain large remains of dwelling structures which contain pits filled with ash, charcoal and bone. The metallurgical debris analysed includes copper minerals, malachite beads, copper artefacts and a single copper droplet - sample Plocnik 52 (Radivojević *et. al.*, 2021, p.60-61).

Copper objects have been found at this site, including: “4 bracelets, 4 hammer-axes and 25 chisels of the Pločnik-type” (Šljivar, 2006, p.101). The majority of these artefacts were found on the western part of the site, which led to it being described as a workshop or ‘artisan area’ (Trench 20) (Šljivar, 2006, p.102; Šljivar and Kumzmanovic-Cvetcovic, 2009, p.58). In Trench 20 two perforated chimneys (*Figure* 4.47), alongside structures for smelting malachite and copper were identified, as well as smithies for the production of artefacts (Šljivar, 2006, p.102; Šljivar and

Kumzmanovic-Cvetcovic, 2009, p.58). There was also a copper chisel found in situ within Trench 20 (Radivojević *et. al.*, 2021, p.60; Šljivar, 2006, p.102; Šljivar and Kumzmanovic-Cvetcovic, 2009, p.58).

(image redacted for copyright purposes)

Figure 4.47. A: Trench 20, "Plocnik, 8x8m kiln (right) and nearby chimneys (top left). (Sljivar and Kumzmanovic-Cvetcovic, 2009, p.58). B: Perforated chimneys in Trench 20, Plocnik" (from Mlyneic, 2016 courtesy of Dusko Sljivar).

4.3.2.5.2.2.2. Belovode

Belovode is situated in eastern Serbia, and dates to c.5350-4650BC. AMS radiocarbon dating was carried out on animal bones from Belovode confirmed the date as Vinča culture (Late Neolithic/Early Chacolithic) (Borić 2009; Radivojević, 2013). The site lies near a spring near the village of Veliko Laole which is c.140km southeast of Belgrade. It is located on a large ellipsoidal plateau at an altitude of *c*200m, surrounded by pastoral land (Šljivar *et al* 2006, p.251-2; Radivojević, 2013, p.14-5).

The site was excavated in 1993 by the National Museum of Belgrade and the Museum in Požarevac (Šljivar and Jacanović 1997; 1996a; 1996b; Jacanović and Šljivar 2003; Šljivar *et al* 2006). Belovode has revealed the best quality of material for the study of the beginning of metallurgy in the Balkans to date. The material evidence comes in the form of nineteen samples, including: copper minerals, ores, slags, slagged sherds and a metal droplet, indicating copper mineral use and metallurgical activities (Radivojević, 2013).

There is 5g of slag dating to c. 5000 B.C. (Gradač I) which was found at Belovode and analysis has shown that it was produced by smelting, due to its "high levels of Mno, FeO, ZnO and CoO using black and green Mn-rich ore" (Radivojević *et al* 2010, p.2781). It was concluded, that the "smelting atmosphere must have been partially oxidizing and the minimum temperature c.1084°C, due to analysis showing due to the presence of delafossite, spinels, and previously molten copper" (Radivojević *et al.,* 2010, p.2781). Copper mineral is found within all layers at the site (Rehren and Radivojević, 2016). Metallurgical material including slag, slagged ceramic sherds, a copper metal droplet and a casting vessel, is present at the site and comes from within a domestic context (Radivojević *et al* 2010, p.2781; Sljivar, 2006). The exact location where the ceramic chimneys (*Figure* 4.48) were found is not detailed, however they are described as being for metallurgical purposes (Sljivar, 2006, p.97). Sljivar (2006) draws comparisons with a kiln from Durankulak in Bulgaria, "which had evidence of malachite and bellows" (Sljivar, 2006; Radivojević and Kuzmanović-Cvetcović, 2014, p.12).

(image redacted for copyright purposes)

Figure 4.48. Reconstructed Belevode chimneys (left and centre) and proposed smelting apparatus (right). (Sljivar, 2006).

The smelting activities were determined by slag sampled and ceramics sherds with slag adhering to them which were found in Trench 3. The slag pieces do not appear to have been crushed, but this may be due to their already small size of around 10mm. The slagged sherds were stained green, due to their contact with the metallurgical slag, which has returned to its green (malachite) colour, due to corrosion during deposition, they were also described as highly viscious and rich in copper metal (Radivojević, 2007, 2013, p.16). The ceramic fragments are heavily vitrified, as well as bearing slag adhering to the sherds.

Ceramic fragments with charred surfaces and malachite adhering to their surfaces, are a common find within household contexts in Belevode. There are also conical pottery vessels, made of a coarse material, with copper ore adhering to the outside (Trenches 7 and 8); technological analysis has revealed that these are not crucibles (Radivojević, 2007, 2013, p.16). There are also structures which are identified as smelting furnaces, made from pits lined with ceramic sherds (Trenches 10 and 13);

(Šljivar *et al* 2006, p.253, p.260, plate II/4; Dimitrov, 2002). Stone tools associated with processes such as beneficiation were also found (Šljivar *et al* 2012, p.259, plate I/4). Similar tools have been found at Rudna Glava (Jovanović 1982; Radivojević, 2013, p.16).

4.3.2.5.2.2.3. <u>Divostin</u>

Ceramic vessel fragments which have identified as domestic cooking wares from Divostin have a very similar shape to the 'ceramic metallurgical chimneys' identified at Belovde and Plocnik. There are two possible hypotheses proposed by the author, the first is that they are domestic cooking ware vessels and this shows a similarity between domestic cooking vessels and early ceramic vessels used of metallurgy in the Vinča period. Or that they are in fact misidentified chimneys, which have been classed as domestic cooking ware due to lack of evidence for use in metallurgical practices. It is discussed elsewhere in this chapter that the metallurgical activities taking place in this period are of a lower temperature to other Bronze Age copper smelting activities and therefore do not always alter the ceramic in such a drastic way as we would usually expect metallurgical ceramics to be altered and also, they may not be vitrified. Not all metallurgical ceramics bear vitirification after use, this may be due to the temperatures experienced or the lack of silica in the material (Cropper, 2015). It can therefore be hard to distinguish whether ceramics have been used for cooking or metallurgical practices when there is no evidence of copper present. It could also be considered that the ceramic vessels had been made for metallurgical use, but not smelted in yet. It has been discussed that chimneys have been identified at Divostin, however this has been poorly documented (Borić 2009; Mlyniec 2016, p.37; Bruyere, 2018, p.74), perhaps these vessels are the ones which the excavators had in mind.

(image redacted for copyright purposes)

Figure 4.49. Reconstructed ceramic vessel from floor of House 16 (left) and house 14 (middle and right). (Madas, 1988, Figure 6.13:12, Figure 6.8.:1 & 2).

Two copper beads were identified at Divostin, as well as a copper bracelet (McPherron 1988, p.457 Tringham 1990, p.555). “It was never determined if this bracelet was cast or annealed native copper, but it bears a resemblance to a later cast copper bracelet found with one of the skeletons at Gomolava” (Chapman 1981, p.128 Tringham 1990, p.559, Mylniec, 2016, p.26).

4.3.2.6. Reconstruction of the Balkan smelting chimneys

The chaîne opératoire for copper smelting in these furnaces sees the ceramic chimney being placed over a clay lined pit in the ground (Sljivar, 2006). The chimney would then be filled with charcoal, and then copper ore would be added in layers within charcoal, as the charcoal burns down. The chimneys are believed to have functioned using natural draft, meaning no additional air is forced into them using bellows or blow pipes (Sljivar, 2006; MacKinnon, 2013; Mlyniec, 2016; Bruyere, 2018). A series of Experimental Campaigns have been carried out between 2013 and 2018 (MacKinnon, 2013; Mlyniec, 2016; Bruyere, 2018) with the aim of testing this reconstructing and suggested chaîne opératoire.

Three Experimental Campaigns were conducted at Sheffield University by MacKinnon’s (2013), Mlyniec (2016) and Bruyere (2018), these were aimed at seeing what temperatures could be achieved in these ceramic chimneys and if it was possible to successfully smelt copper ore within them. The results of these campaigns will be summarised here.

4.3.2.6.1. MacKinnon

MacKinnon's (2013) experiments were aimed at testing if these chimneys could facilitate the internal environment needed to smelt copper ore. The ceramic furnaces were constructed to match the dimensions outlined by Šljivar (2006, p.97): diameter – 15cm, base – 15cm, rim – 10cm, height – 60cm. The furnace was built using the coil method, based on the archaeological material. The furnaces were built by hand and the diameter ended up being was wider than the original furnaces. As well as testing the working parameters of the furnaces', such as temperature and burn rates, copper ore was added to see if the ore could be smelted and prills produced, as well as to observe the affects that smelting has upon the ceramic material. Both furnaces which were tested reached above 1200^{o}C which are the temperatures needed to smelt copper ore, as well as achieving a reducing atmosphere. Both smelts achieved the production of some metallic copper. The first experiment achieved 94 copper prills (4g), alongside slag and roasted ore (40g), from the 128g of malachite added (MacKinon, 2013, p.38). The second experiment produced 16g of copper prills, and 172g of slag and roasted ore from 292g of copper (II) oxide ore added (MacKinnon, 2013, p.41). However, as the furnaces were wider than the archaeological material, this could have affected the fluid dynamics and air draught within the furnace and therefore the results may not be an accurate representation of the conditions achieved by the archaeological examples.

Chemical analysis was carried out on the interior of the chimneys after the experiments had taken place, by using a pXRF analyser. The results consisted of eight readings between 44ppm and 582ppm of copper, with six of the readings ranging between 44ppm and 138ppm, demonstrating the range of copper levels left on the ceramic material when being used for smelting (MacKinnon, 2013, p.42). These readings are similar to those taken by Doonan (Mlyneic, 2016) on the ceramic fragments of the excavated chimneys from Belevode.

4.3.2.6.2. Mlyniec

The Experimental Campaign conducted by Mlyniec (2016) was instigated to test whether the wider diameter of MacKinon's (2013) furnaces affected the temperatures achieved and to try and achieve a more comparable reconstruction to that of the archaeological material. The furnaces produced for these experiments were coil built around a mould, to ensure the correct measurements were achieved. The furnaces were kiln fired before the experiment, as the evidence from excavation suggests the chimneys were fired before use. The furnaces were constructed using the methods which would have been used by potters at the time (coil method), and the inclusions observed in the archaeological material were added to the clay mix. The clay chimneys were left to air dry before being kiln fired at 950°C.

The results of the Experimental Campaign demonstrated that temperatures of over 1000°C are achieved easily, when the chimney is filled to the top with charcoal. The internal environment showed the bottom half of the chimney's charcoal to be ignited, with coals glowing white and orange, and flames coming out of the top of the chimney. Flames were a blue and purple colour, showing a reducing environment. The furnaces cracked quickly during the smelting procedure, but as long as the chimney was filled to the top with charcoal, they kept their form and did not collapse. When the furnaces were run for longer periods, temperatures over 1100°C were achieved (Mlyneic, 2016, p.53-67). Two of the four experiments attempted to smelt copper ore, however metallic copper was not produced, but rather the ore was only roasted. Mlyneic (2016) also recreated perforated chimneys, reconstructing the evidence from Pločnik. These chimneys were reconstructed by the same method. These chimneys showed a larger combustion region within the bottom half of the furnace, and temperatures at the top of the furnace reached above 600°C (Mlyneic, 2016, p.75-77). These experiments suggest that the perforated style of Vinča chimney produces a more even burn profile inside, with a larger region reaching temperatures over 1000°C.

Chemical Analysis, using a pXRF analyser, was also conducted on these chimneys after the experiments. No traceable readings were achieved on the external surface of the chimneys. Readings were achieved on the internal surface of the Pločnik style chimney. Of the eight readings taken, seven of these read between 89ppm and 366ppm (Mylneic, 2016, p.81-2). The readings from the Belevode style chimney resulted in 21 readings, with levels between 53.46ppm and 291.02ppm (Mylneic, 2016, p.84-5).

4.3.2.6.3. Bruyere

The conditions recorded by the Experimental Campaign by MacKinnon (2013) and Mlyneic (2016) had demonstrated that the Vinča chimneys could achieve the temperatures needed to smelt copper ores, as well as creating a reducing atmosphere. However, the experiments carried out by Mlyneic (2016) did not manage to produce metallic copper, only roasting of the ore was achieved. The furnaces which Mlyneic produced cracked heavily during firing. It was considered that the cracking may be a factor in why the copper ore did not smelt during Mlyneic's campaigns (2016). It was also decided that experimentation with the loading technique of the charcoal, and method for bringing the furnaces up to temperature would be beneficial. Therefore, Bruyere (2018) carried out another Experimental Campaign, consisting of five experiments in total to test if changing the loading method could result in a successful smelt.

The furnaces constructed by Bruyere (2018) also experienced substantial cracking, resulting in structural failure and resulting in the experiments having to be stopped (Bruyere, 2018). The cracking and subsequent structural failure appears to be due to two main factors. Experiments 1-4 trailed different loading techniques for the charcoal, to determine whether allowing the charcoal to slowly ignite would result in a higher overall temperature within the furnace. This meant when the chimneys began to crack, they were not held in place by the charcoal inside (as the chimney was not full of charcoal), as in experiments conducted by Marks (2012), MacKinnon (2013) and Mlyneic (2016). Instead, in Experiment 5, calcareous sand was added to the clay, which resulted in some of the clay wall exploding during the pre-heat, which resulted in areas of the chimney wall being heavily damaged before the smelt began.

Experiment 5 reverted back to the method of filling the chimney up to the rim, as undertaken in the MacKinnon (2013) and Mlyneic (2016) experiments. During experiment 5, temperatures at the bottom of the chimney reached over 1000°C, with the centre of the chimney ranging between 600°C and 800°C (Bruyere, 2018). Unfortunately, this furnace failed again, due to the ceramic chimney cracking during the pre-heat, due to calcareous sand having been added, as the chalk inclusions within it explode in high temperatures, causing cracks in the clay, which left the chimney weak. This resulted in failure during the smelt as the cracked expanded and the furnace walls collapsed. Therefore, copper ore was not added.

Although Bruyere's (2018) experiments did not go to plan, due to cracking and structural failure, they did provide us with a lot of information regarding the working parameters of the Vinča chimneys. We know that these chimneys would have most likely being filled to the brim with charcoal from the start of the smelting procedure, with the bottom third of the chimney achieving the temperatures needed to smelt the copper, and the charcoal in the upper two thirds creating the reducing atmosphere needed for the reaction to take place.

The ceramic material produced by Bruyere's (2018) experiments allowed for further comparison to that from excavation. Bruyere noted that the chimneys' ceramic fired differently according to the temperatures achieved, along with the oxygen levels within each region of the furnace. The ceramic material from the Pločnik chimneys (perforated) was a bright brownish/red colour, all the way up the shaft. This did not differ under different loading techniques and levels of charcoal within the chimney (Bruyere, 2018, p.56). Whereas the Belevode chimneys (non-perforated) varied in colour, with the base fragments being a bright brownish/red and the top fragments being brown. The colourings of the ceramic material from these Experimental Campaigns match that of the ceramic evidence from excavation (Bruyere, 2018, p.56).

4.3.2.7. Understanding the model for the Balkan chimneys

The three Experimental Campaigns presented have confirmed the hypothesis that these Vinča ceramic chimneys were used in association with copper minerals. The burn profiles on the ceramics from the Experimental Campaigns match those of the ceramic fragments found in excavation, including details such as the colour change in the clay, scorch marks and placement of vitrification (Mlyneic, 2016, p.67-84; Bruyere, 2018, p.54-59). Chemical analysis carried out by pXRF of the chimneys after the experiments in 2016 (Mlyneic, 2016, p.80-6) and 2018 (Bruyere, 2018, p.60-3) also matched those of the results from the pXRF analysis of the fragments from Belevode

(Mlyneic, 2016, p.38-44). These results confirm that the chimneys have been used at high temperatures with copper ore. The temperature profiles from the Mlyneic (2016) experiments ranged between 800°C and 1000°C (Mlyneic, 2016, p.71-80) and the temperature profile for the Bruyere (2018, p.40-53) experiments were between 750°C and 1100°C. These temperatures are high enough to smelt high percentage copper ores or copper-manganese oxides, which are believed to have been selected for smelting during this phase (Late Neolithic and Early Bronze Age) in the Balkans, due to the analysis of copper artefacts from that period, as discussed earlier in this chapter (Radivojević and Rehren, 2015). The early smelting stage has been described as a two-step process: Step 1: the reduction of copper ore to copper metal which requires temperatures of 700°C upwards and reducing conditions. Step 2 the melting of copper metal, which requires temperatures above 1090°C (but has fewer constraints over the firing redox conditions) (Budd, 1991, Radivojevic *et al.*, 2010, p.2777).

As high percentage ores and copper-manganese oxides can facilitate the formation of a melt under lower operating temperatures than that of other more commonly used ores such as iron rich oxides: neither does it require a strict reducing atmosphere (Radivojević and Rehren, 2015), the working parameters and internal environments of these ceramic chimneys have been demonstrated as suitable for the smelting of these types of ores. However, if higher percentage copper ores were used, then it seems unlikely from the results of these experiments that these furnaces were used for smelting. It can be considered that these chimneys could have been used for the pre roasting process instead. Although these furnaces are natural draft, the context they are found within, within domestic/household areas, means they were not wind powered like the APF. Rather they would draw on stable air in the vicinity, this results in lower temperatures being achieved. It also demonstrates a different chaîne opératoire, as the organisation of the copper smelting activity for the APF revolves around the activity taking place in a windy location, moving other resources to that location and being present at specific times of the year. In contrast these Balkan chimneys are used in the household context, alongside other activities all year round.

4.3.2.8. Balkan material summary

The evidence for Balkan metallurgical production during the Vinča period presented in this chapter has demonstrated that there were two processes of copper smelting taking place: small scale crucible smelting in pit hearths (e.g. Selevac) and possibly smelting activity or ore roasting in ceramic chimneys (e.g. Belevode and Plocnik). Both of these practices appear to have been taking place at lower temperatures than other copper smelting activities and therefore high percentage copper ores and copper-manganese oxides are being smelted. This therefore means that the smelting activities are taking place within domestic settings, in small scale processes, which are not centrally controlled by the settlement.

4.3.3. Evidence for Copper Metallurgy in the Late Neolithic and Early Bronze Age Anatolia

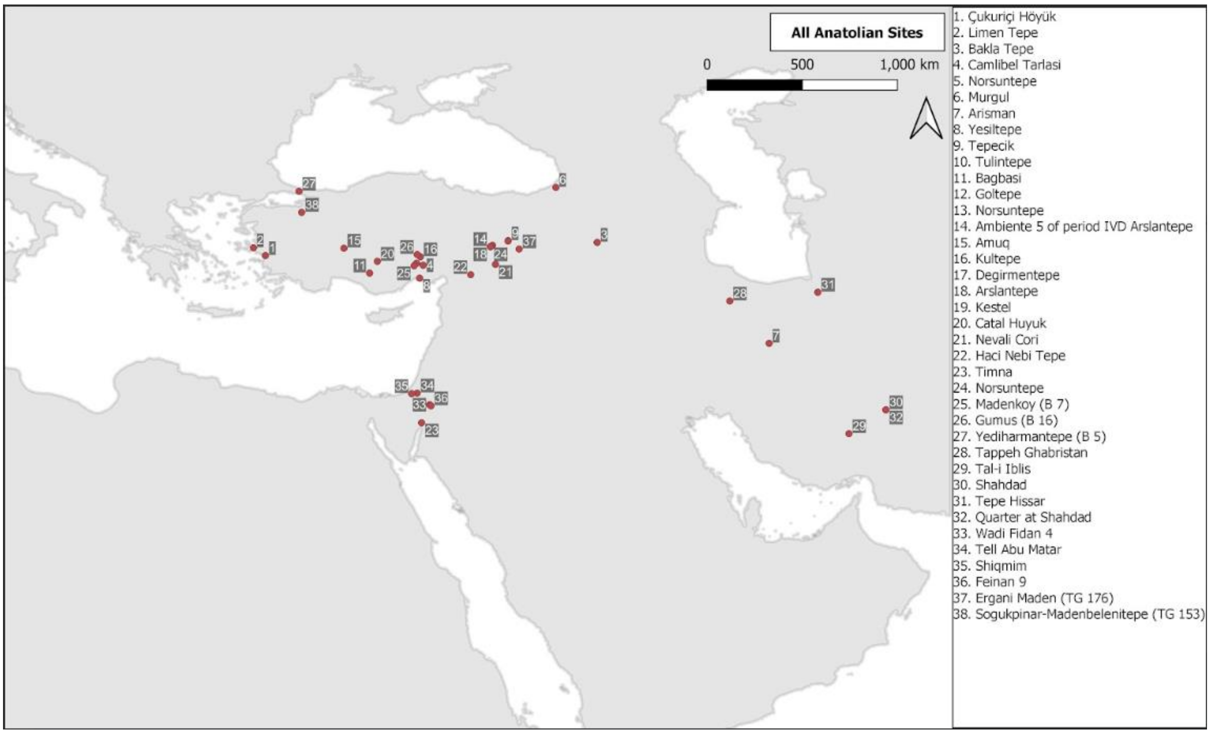

Figure 4.50. Map showing all sites in the Anatolian Region (made by author).

4.3.3.1. Summary of the research on metallurgy in the Late Neolithic and Early Bronze Age Anatolia

The focus of archaeological studies in Anatolia in relation to metal in the Late Neolithic and Early Bronze Age has been primarily concerned with locating the ore procurement sites. There has also been a predominance on the study of finished metal artefacts, with analysis being carried out to mainly identify the ores being used and to provenance them. With a lack of evidence for smelting technology, understanding technological processes and materials used has been gained by analysis of finished artefacts (Caneva 2000; Esin 1969; Yalcin 2000b; Lehner & Yener, 2014, p.539).

The main corpus of fieldwork for the Anatolian region was carried out during the 1980's and 1990's. These projects aimed to map all sites across the region associated with metal and included sites that contained evidence of production, not just ore procurement (Hauptmann *et al*., 1989; Pigott, 1999). The existence of copper artefacts and ore sources has been enough for scholars to present Anatolia as one of the earliest homelands for metallurgy. Lehner and Yener (2014, p.530) highlight that "research in this region has the potential to evaluate the origins of metallurgy and the relationships between social complexity, technology, and long-distance trade" (Lehner & Yener, 2014, p.539). For example, looking at the types of axes found has been used to demonstrate possible casting technologies (Caneva 2000; Esin 1969; Yalcin 2000b; Lehner & Yener, 2014, p.539). Also, analysis of metal artefacts can reveal not only the composition of the metal but also the process which may have been used for its production (Yalcin 2000b, p.114).

4.3.3.2. Copper Production

4.3.3.2.1. <u>Evidence for ore types used.</u>

Oxidic copper ores were used in the Chalcolithic period (Thornton, 2009, p.302-3). Oxide ore deposits start to be depleted during the Bronze Age and copper sulphide ores had to become the main source of copper. Copper sulphide ores must first be roasted in an oxidising atmosphere, before being smelted to produce a copper oxide (De Ryck, *et al.*, 2005, p.261). Chemical analysis from metal objects at Mersin identified that polymetallic ores were used (Yalcin 2000b, p.114; Yener, *et al.,* 1991; Lehner & Yener, 2014, p.539).

4.3.3.2.2. Evidence for organised or local/household production

There is evidence of large-scale organised metallurgy in Anatolia during the late fifth and early fourth millennium B.C., with evidence of administrative activities. There is also evidence of smaller scale metallurgy taking place on a household, independent level. Understanding the technological tradition in Anatolia during this early phase of metallurgy is very complex, as there is evidence for a range of different traditions across this vast region. For example, in Anatolia the presence of arsenical copper alloys being present at sites such as Ilipinar in north-western Anatolia (Begemann, *et al*, 1994) and Ikiztepe which is near the Black Sea (Bilgi 1984, 1990; Ozbal *et al*., 2002a, b), shows “that while divergent patterns of production which were localized, some metallurgical techniques, perhaps utilizing spies, were shared across very long distances” (Lehner and Yener, 2014, p.544).

The site of Degirmentepe is an example of a large-scale site with administrative organisation, with “evidence from the late fifth and early fourth millennium B.C. (Lehner and Yener, 2014, p.544), which demonstrates that copper smelting was conducted in a domestic setting and had a significant reliance on local ore sources (Esin and Harmankaya 1988; Yener, 2000, p.33-44; Lehner & Yener, 2014, p.540). Several houses were excavated, hosting evidence of “metallurgical activities from ore processing to smelting and possibly melting and casting” (Lehner & Yener, 2014, p.540, *Figure* 20.5) showing that households were doing a range of different processes. Not only does Degirmentepe show such evidence of multiple metal production methods, but it also reveals evidence within the households of “administrative activities, including seals, sealing’s, tokens, and bullae of local and foreign styles” (Lehner and Yesin, 2014, p.540) and their production (Esin, 1990; Arsebuk, 1986; Lehner & Yener, 2014, p.540).

The metallurgical debris indicates that nearby ore sources were heavily relied on. The proximity of the ore may explain how this major production site was able to develop and suggests that location and transportation were significant factors in the development of a large-scale metallurgical production and administrative organisation. It appears primary production was taking place as there was ore and several furnaces.

Parallels for these activities are seen at Norsuntepe, which is close by (Hauptmann, 1982) and Tepecik (Esin,1982; Lehner & Yener, 2014, p.540-1).

The site of Arselntepe, which dates to the late Chalcolithic (Early 4th millennium B.C.), displays evidence of varied technological processes of extractive metallurgy. The metal processes here demonstrate a degree of interaction with Uruk Mesopotamia but with a local elite presence independent of Uruk control (Lehner & Yener, 2014, p.542). In addition to the evidence of large-scale smelting with administrative and/or elite control, there is also evidence of small-scale independent production within households. Evidence from sites such as Yarikkaya in north-central Anatolia (See Schoop 2005, Plate 30.1; Lehner & Yener, 2014, p.542-3).

The site of Tepe Ghabristan in north-central Iran has a controversial date, either to the early fifth millennium BCE or the early fourth millennium BCE. Regardless of this, it is still one of the earliest copper smelting sites in southwest Asia (Majidzadeh. 1979, 1989; Pigott 1999b, 111-112; Matthews and Fazeli 2004, p.64). This site is located only 20 km from the nearest copper ore source, again showing that in Anatolia, the proximity to copper ore seems vital to the instigation of copper smelting sites.

4.3.3.2.3. Evidence for smelting technology

The earliest evidence for copper smelting is using crucibles in fire pits, hearths and portable brazier such as at the sites of Yesiltpe, Tepecik, Goltepe, Tappeh Ghabristan, Tal-i Iblis and Tell Abu Matar during the 5th-3rd millennium B.C. (Mehofer, 2014; Yener, 1993, 2000, p.33-44; Stollner, 2005; Pigott, 1999; Hauptmann, 1989). The hearths or pits dug in to the ground are used as a means to hold fuel to create the temperatures and reducing environment needed to smelt copper. The material used to create or line the walls of these structures differs between pre-used ceramic fragments and clay line pits across different sites and regions. This can be due to available materials and existing knowledge and skills. The technology developed in the late fifth and early fourth millennium B.C. when furnace structures started to be used. At sites such as Degirmentepe (Esin, 1990; Arsebuk, 1986; Esin and Harmankaya, 1988; Lehner & Yener, 2014, p.540), Norsuntepe (Hauptmann 1982) and Tepecik (Esin 1982; Lehner & Yener, 2014, p.540-1).

4.3.3.2.4. Location of smelting technology

Sites with evidence of smelting are located relatively close to copper sources; for example, Tepe Ghabristan is located 20km from the nearest ore source (Majidzadeh. 1979, 1989; Pigott 1999b, p.111-112; Matthews and Fazeli 2004, p.64). Examples of large-scale copper smelting sites with administrative organisation and elite control, as well as smaller-scale smelting by individuals within domestic settings (Schoop 2005, Plate 30.1; Lehner & Yener, 2014, p.542-3). The site of Degirmentepe demonstrates how copper smelting was organised within domestic contexts from as early as the late fifth and early fourth millennium BC (Esin and Harmankaya 1988; Yener 2000, p.33-44; Lehner & Yener, 2014, p.540). Smelting also takes place within mining sites, as discussed previously.

4.3.3.3. Traditions comparable with other regions

There is evidence of wind-powered furnace technology from Anatolia at the following sites: Tepe Hissar (Pigott, 1999), Yediharmantepe (Yener, 2000) and Fenan (Yener, 2000). This is comparable with the wind-powered furnaces from the Aegean in the sense that it harnesses the natural wind rather than using tools (bellows or blowpipes) that force draft into the furnace. Although this technology utilises natural wind, the furnace structures are not perforated furnaces, which identifies a different method of using a similar technique and the same resource. The use of the natural wind shows a similar understanding of the natural environment and of pyrotechnical technology. It could be considered that the use of natural wind was developed separately or that this understanding was passed on and then realised in a different way using different technology and techniques.

4.3.3.4. Summary of Anatolian evidence

This section of the chapter has detailed the evidence for copper smelting in the Late Neolithic and Early Bronze Age Anatolia. The earliest evidence for copper smelting shows that it was carried out in clay crucibles in fire pits, hearths and portable braziers, as seen in Yesiltpe, Tepecik, Goltepe, Tappeh Ghabristan, Tal-i Iblis and Tell Abu

Matar during the 5th-3rd millennium B.C. (Mehofer, 2014; Yener, 1993, 2000, p.33-44; Stollner, 2005; Pigott, 1999; Hauptmann, 1989). This early smelting utilised oxide ores (Thornton, 2009, p.302-3), which had been depleted in the Early Bronze Age, and sulphide ores began to be used (De Ryck *et al.*, 2005, p.261). This is also when the evidence suggests that furnace structures start to be used in place of crucibles for smelting at sites including Degirmentepe (Esin, 1990; Arsebuk, 1986; Harmankaya, 1988; Lehner & Yener, 2014, p.540), Norsuntepe (Hauptmann 1982) and Tepecik (Esin 1982; Lehner & Yener, 2014, p.540-1). This discussion has also highlighted that smelting took place local to ore sources and was conducted in or in association with settlements.

4.3.4. Summary of evidence for copper smelting contemporary to the APF

This section of the chapter (4.3) has presented a concise summary of the types of evidence for copper smelting elsewhere in the Aegean and in its neighbouring regions of the Balkans and Anatolia, which do not fit the model of the APF. A discussion of the context in which the smelting activity took place was included. These summaries will enable a comparison with this evidence and that of the APF to assess if the APF is a new independent tradition of practice or a development of an existing practice.

The dates of each site is summarised here (Figure 2.51) with details of absolute dates as well as the Aegean periodization to help with comparison of the dates at each site.

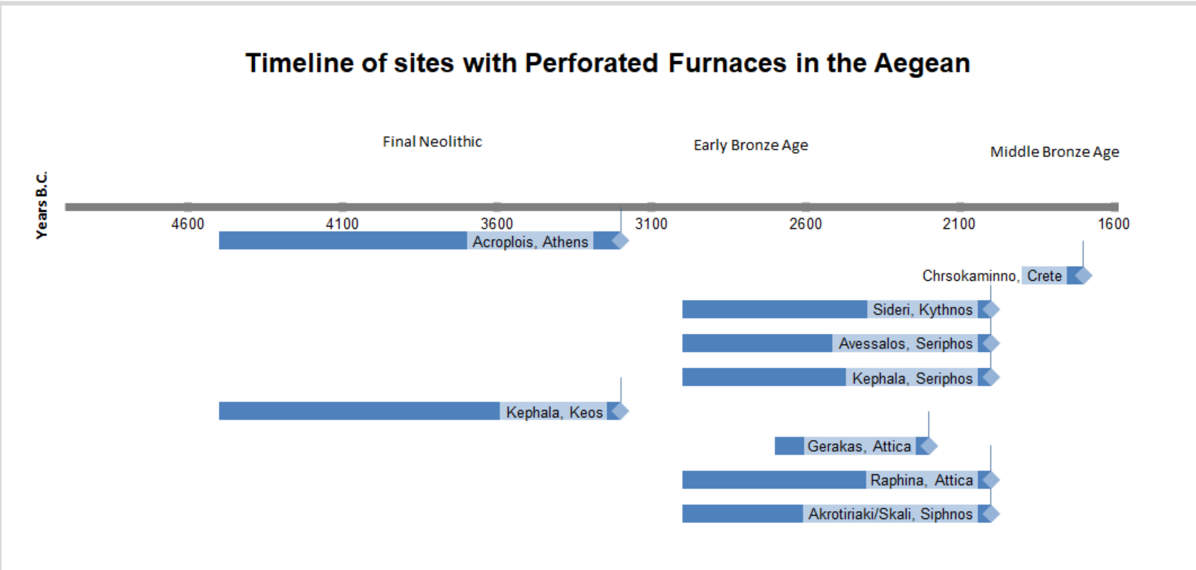

Figure 4.51. Timeline of sites with evidence of perforated furnaces in the Aegean (Made by author).

4.4. Chapter Conclusion

The evidence presented in this chapter of the archaeological material representing the APF as well as the evidence for other structures and methods for smelting copper in the Aegean, Balkans and Anatolia has identified that the APF is an independent tradition. There is no other technology or copper smelting process that features perforations and is located on windy promontory and uses only natural wind as the air flow for the furnace.

5. Chapter 5: Experimental Reconstruction of the APF

5.1. Introduction to Chapter

This chapter will present the existing models for the reconstruction and use of the APF and other examples of wind-powered furnace technology. The existing models will be critiqued in light of new understanding gained from the study of wind-powered furnace technology. A new model for the reconstruction and chaîne opératoire for the Aegean Perforated Furnace material will be presented. Details of which material evidence from the excavations is classed as part of the smelting process will be presented, and I will discuss how this technology was used. The rationale and thinking behind this new proposal will be explained. This will provide the background and context for the development of this model of reconstruction and chaîne opératoire for the APF and provide a basis for an Experimental Campaign and analysis to be conducted.

5.2. Existing model for the APF

5.2.1. Previous Experimental Campaigns

Who conducted the experiment	**What was its purpose**	**Reference**
Pryce	To compare the operation of a perforated and a non-perforated furnace, with an aim to understand the effect that the perforations had on the smelt and to therefore understand their function	(Pryce *et al.,* 2007)
Catapotis	To explore the use of fuel, specifically olive pits. It also used more appropriate reconstructions of pot bellows, rather than using simulated air through a blower as Pryce did in his.	(Catapotis *et al.,* 2008)

Table 5.1. Table showing details of previous experiments done before author conducted theirs.

To date, there have been two previous campaigns of experimentation carried out by other scholars except myself (*Table. 5.1.*), who were trying to understand the working parameters of the reconstructed furnaces of the perforated ceramic fragments from the southern Aegean. These were done by Pyrce in 2007 and Catapotis in 2008 (Pryce *et al.,* 2007; Catapotis *et al.,* 2008). Both campaigns used the reconstruction model for the shaft furnace (*Figure* 5.1) designed by Betancourt (2006), which was based on the evidence from Chrysokamino, to recreate their ceramic furnace. The evidence from Chrysokamino is later in date than any of the other evidence for the APF. However, its reconstruction was the easiest to achieve, as the ceramic fragments were most intact and survived the best. The assemblage included rim and base pieces, meaning a height could be estimated, as well as larger fragments with multiple perforations and some curvature, meaning a diameter could be estimated and the distribution of the perforations across the furnace wall. This reconstructed model has been used repeatedly, as it has an estimation of height and diameter, which would be impossible to achieve from the ceramic evidence from other sites as it is more limited. Experimental Campaigns use this model and adjust the wall thickness to match the material from the site being considered. Also, once a model is used for an experiment, using this model for subsequent experiments enables comparison. However, it should be regarded as if this model is accurate to the earlier examples of the APF, as they are much earlier in date, and the walls are much thinner. Also, if the model can be deemed an accurate representation of the material across all the sites and chronology, if this is the case, then this demonstrates a continuous use of a technology and tradition across multiple periods without alteration, something which is unique.

The model reconstructs the APF ceramic evidence as a conical clay furnace placed on top of a clay-lined bowl, with tuyères placed between the bottom of the furnace cylinder and the top of the bowl. These tuyères were to facilitate pot bellows, which would force air into the furnace. The furnace would be filled with fuel (this is different in different experiments, depending on the evidence from the site being reconstructed), and then copper ore is placed into the furnace, amongst the fuel (not in a crucible). The furnace is fired for several hours; then the material is removed. The models by Betancourt (2006), Pryce *et al.* (2007), and Catapotis et al*.* (2008) do not specify if a conglomerate is made or if the materials are separated completely. However, they suggest the furnaces may have been tapped (a hole pushed into the side of the furnace to remove slag during the smelt). However, the archaeology at the sites of the APF reveals evidence of the crushing of slag (crushed slag fragments and stone tools), which would suggest a conglomerate was produced and crushed to expose the copper prills.

(image redacted for copyright purposes)

Figure 5.1. reconstruction of the perforated furnace (Betancourt, 2006, Figure 7.3).

"The campaign reported by Pryce et al. (2007) compares the operation of a perforated and a non-perforated furnace to understand the effect of the perforations, while the later campaign (Catapotis et al. 2008) sought to explore the use of fuel, specifically olive pits, and appraise the function of more appropriate pot bellows" (Doonan and Marks, 2021, p.164-5). But neither of these considered the utilisation of natural wind without bellows. "Both these campaigns, however, tested the operation of bellows and made use of similar reconstructions where the frustum sat over a prepared bowl hearth with tuyères, guiding forced air from the bellows in tandem with any draught facilitated by the perforations" (Doonan and Marks, 2021, p.165). The set up of the experiment can be seen in *Figure* 5.2, showing the tuyères attached to bellows, which provided forced air.

(image redacted for copyright purposes)

Figure 5.2. Reconstruction of the APF in Catapotis et al.'s *Experimental Campaign (Catapotis, 2008).*

The method for the use of these perforated furnaces, used within these Experimental Campaigns, and which has been accepted and used in subsequent discussions about the perforated furnaces (Georgakopoulou 2004, 2007, 2013, 2017; Bassiakos and Philaniotou 2007; Day and Doonan 2007; Papadatos 2008; Catapotis *et al.,* 2011) sees forced draft being used to power the furnaces, used in association with clay nozzles/tuyères, as is seen in the experimental campaigns also. This is based on evidence of pot bellows, which comes from Chrysokamino (Betancourt and Muhly, 2006, p131), which influenced the inclusion of them in the reconstruction by Betancourt (2006), which has been accepted in scholarship on copper production in the region since. The evidence for the pot bellows at Chrysokamino is limited, with only a few fragments representing part of one bellow (Betancourt and Muhly, 2006, p.131), and the interpretation as bellows is also questionable, as they could be domestic ware based on their fabric type (Peter Day, *pers comms.* 2021). There is no evidence at any of the other sites where the APF evidence comes from for pot bellows, and again, it is essential to remember that Chrysokamino is later in date than the rest of the sites that bear evidence for the APF. There are some sites that bear evidence for clay nozzles/tuyères, including Paliopyrgos-Aspra Spitia on Kythnos (Bassiakos and Philaniotou, 2007, p.29, Figure 2.4a-d) and Raphina (Theochares, 1951, 1952). Still, these tuyères could have been used in conjunction with consolidating or casting processes rather than smelting. The pot bellows at Chrysokamino have been discussed in Chapter 2 (section 2.2.4.). As perforated furnace fragments are only present at locations with strong seasonal winds, and the other sites with examples of contemporary copper smelting do not see perforated furnace fragments, this leads to the logical conclusion that the furnaces are wind-powered. Therefore, any apparatus for forced draft, such as bellows and tuyères, would be associated with a secondary stage of consolidating or casting rather than as part of the smelting process.

The two smelts conducted by Pryce *et al.* (2007) and Catapotis *et al.* (2008) reached the temperatures needed to smelt the copper ore into a conglomerate. Pryce et al.'s (2007) experiment demonstrated that the perforated furnace functioned better than the non-perforated furnace, demonstrating how the perforations add to the functioning of the furnace and the flow of air. However, what is particularly interesting in their experiment is how the bellows affected the temperatures of the furnace. When they set the furnaces going and allowed them to burn on their own accord, just with the simulated wind, the temperatures rose, with the perforated furnace reaching higher temperatures than the non-perforated. After a certain amount of time (reason for time not given), the forced air (which was simulated bellows created by tuyères attached to an electric fan) was instigated. When the forced air was started, the temperatures stopped rising and plateaued. The temperature of the non-perforated furnace remained lower than that of the perforated furnace. This suggests that the forced air is, in fact, counterproductive, and the furnaces function better solely with wind. And when they function efficiently without forced ait, why would the resource and people power and time, be put into something that was not necessary?

Another benefit of these Experimental Campaigns is the material assemblage they create. The ceramic furnaces used in the Catapotis et al. *(*2008) shown in *Figures* 5.2-5.3 show how the smelting process alters the ceramic fabric. The lower part of the ceramic furnace is heavily heat-altered, appearing black in colour, with the top half of the furnace being less black with orange and pink hues. The bottom section of the furnace wall also has slag material adhering to it. The top section of this ceramic furnace is barely altered; it has been baked, as a pit would be during a firing in a kiln, but does not have the intense heat alteration or alteration in its physical shape, nor does it have any metallurgical debris adhering to it. Therefore, if the fragments from the top half of the furnace were found in excavation, in isolation from the bottom pieces, it could be hard to identify them as metallurgical.

(image redacted for copyright purposes)

Figure 5.3 Fragments of the clay furnace (interior) from the experiments carried out by Catapotis et al., *2008 (Dimitriou, Figure 16).*

5.2.2. Critique of the existing model of the APF

As discussed, the existing model for the reconstruction of the use and method of smelting in the APF sees forced air being driven from pot bellows into the furnaces via tuyères. The inclusion of pot bellows in this model, I feel, is two-fold. Firstly, there have been accepted methods for metal production at all sites across the globe at specific points of the process's development, and these methods are applied to the evidence rather than the evidence being scrutinised and reconstructed. These methods are discussed in Chapter 2 (section 2.2). There are two set methods for smelting copper: a) crucible smelting and b) adding the charge to charcoal in a bowl or shaft furnace. All these methods see forced air being added via tuyères. However, as we find more material evidence, we start to see more variation in the styles of ceramics being used, other materials being used for furnace structures, such as stones as well as clay, and different ways of conducting these practices. We see similar differences in the production of pottery, too (Urem-Kotsou, 2017, p.34). Secondly, the ceramic evidence from Chrysokamino, which was interpreted as bellows (Betancourt and Muhly, 2006, p.131), has since been linked to its use. This is the only APF site that bears evidence of the bellows; it is also the site with the most recent date, as all the sites which bear evidence for the APF are in windy locations (coastal promontories and hillsides). This seems too much of a coincidence, but rather, the wind is an integral factor in how the furnaces function—paired with the evidence that resources were being shipped from far away to be used at these specific locations (Georgakopoulou, 2017). The evidence points to the idea that these sites were chosen for a particular reason and for a resource that was more valuable than ore and clay – wind.

The second piece of evidence that questions the model of smelting in the APF with bellows is the slag. The archaeological slag shows banding within its structure, with mixed iron oxide dendrites (magnetite and wüstite) co-existing. This indicates that the different layers of slag were formed under different conditions within the furnace (oxidising and reducing), with a layer forming under a reducing environment. The next layer forming an oxidising one and repeating. The changes in the environment from oxidising to reducing, seen in some of the slags which would be formed at the furnace's exterior could be caused by air being drawn into the furnace through the perforations, creating an unstable environment just inside the walls of the furnace. The very centre of the furnace must be reducing as copper is successfully formed. Betancourt (2006), Pryce *et al.* (2007) and Catapotis et al. (2008) believe that the furnaces were tapped, and the slag solidified as it hit the air when it came outside the furnace. They explain the banding of different structures in the slag to be from this activity. However, I believe if the banding of various types of structures in the slag did occur from the slag hitting the air when tapped, it would result in one layer within the slag, not multiple. Instead multiple layers were formed over time, as the slag was formed within the furnace near the wall, where conditions would change as air is brought into the furnace through the perforations.

5.2.3. New model for the APF

The new model proposed in this thesis for the method by which the Aegean Perforated Furnace (APF) was used comes from the assessment of the material evidence for the APF, the perforated ceramic fragments and associated material, within its physical and geographical context. The assessment of the sites that bear evidence for the APF (Chapter 4, section 4.2.) demonstrated that every smelting site that uses the APF is located on a windy promontory. This is different to examples of copper smelting from Northern Greece (Bassiakos, 2021) (Chapter 4, section 4.3.1.), which use crucibles in a bowl hearth and are not situated on windy promontories, but rather within settlements. There is also currently no parallel to this technology in the neighbouring regions (Chapter 4, sections 4.3.2 and 4.3.3.). As there is a strong correlation between the furnace fragments with perforations and their location on windy promontories, this suggests that the wind is a vital component in their function. There also does not appear to be any other motivational reason for the activity to take place in these specific locations, such as being located near domestic settlements or close to a source of a resource (ore or fuel) rather the only consistent factor is the presence of the wind. Therefore, this new model sees the wind as an integral part of the furnace's functioning. Also, as the perforations only appear on the furnaces located on the windy promontory, it suggests that the perforations are linked to how these furnaces work. In order to understand how these perforations and this technology work in relation to the wind, other examples of wind-powered furnaces will be assessed.

5.1.4. The new model

A new model will now be proposed, which is based on the assessment of the archaeological material from the sites where the APF is present and the consideration of the location and context it is set within, combined with the understanding of wind-powered furnaces and the fluid dynamics of how they function and a critique of previous Experimental Campaigns. This new model sees wind power at the centre of its design and function, with the perforations being present on the ceramic walls of the furnace to increase the performance of the furnace and by facilitating and improving air flow within the furnace as it is dragged into the furnace through the perforations, due to the different regions of air pressure within the furnace. It is only through this process that perforated furnaces can reach the temperature needed to smelt copper ore, using only the natural wind present at the smelting locations. This technology is created and carried out alongside an in-depth knowledge of the natural environment, with knowledge of areas which experience strong and constant winds at certain times of the year. These areas are selected to host smelting sites. The wind is not present throughout the year. Therefore, the craft is organised so that all the materials and resources would have been ready when the windy season arrives, and smelting could commence. These locations were chosen purposefully, and materials and equipment were transported to them for the smelting activity. This shows the level of organisation underway and how important it was to smelt at these sites, using the wind, rather than at another location using forced draft. This method of smelting using the APF, solely with natural wind, will be tested in several Experimental Campaigns (Chapter 6, section 6.2.) and subsequent analysis of the material produced (Chapter 6, sections 6.3. – 6.6.) to compare with the material and analysis conducted from the excavations and previous experiments. This method of testing will enable an assessment of the model to see if the results match those from the excavated sites and, therefore, deem it a plausible reconstruction of the chaîne opératoire for the practice of smelting in the APF.

5.1.5. Other examples of wind-powered furnace technology

Evidence for other wind-powered furnaces is essential, providing insight into how such technology works. The following archaeological and ethnographic examples demonstrate how furnace designs can enable furnaces to function purely with the natural wind which is present in the location, creating a system where the wind will increase the temperatures inside the furnace, without additional forced draft. Examples such as the *Huayrachina* (Van Buren and Mills, 2005), which have recorded observational information of them being used traditionally, allow us a more in-depth look at how such technology functions, which otherwise would have been hard to understand if we were trying to understand how this technology functioned just from the material evidence. As we have accepted models of how smelting furnaces work, which usually see air being forced into the furnace from bellows or blow pipes, it would be difficult to imagine that these tall shaft furnaces could function and reach temperatures high enough. The fluid dynamics of smelting furnaces are complex, and it is, therefore, easy to stick to known models for function. However, the observations of the *Huaurachina* widened our understanding of natural draft furnaces and their capabilities and opened up possibilities for how other smelting technology functioned.

Name of furnace/site	**Location**	**Type of furnace**	**Date**
The Huayrachina (Van Buren and Mills, 2005)	Porco Bolivia	Clay-built shaft furnaces with holes in the walls, placed on tops of ridges or hills.	Modern, ethnographic studies - 16th-20th century AD
Wadi Feinan (Rothenberg & Shaw, 1990; Craddock, 2000, p.130; Henderson, 2000, p.247)	Southern Jordan	Open front, built into hillside, stacked stones	Early Chalcolithic, mid-5th millennium B.C.
Wadis Um Balad and Dara (Cradock, 2000, p.159)	Egypt	Stone built into the hillside, open front.	Early Chalcolithic, mid-5th millennium B.C.
Samanalawewa (Juleff, 1998, p.5).	Sri Lanka	Clay trough-shaped furnaces, with re-used tapering tuyères placed in the front wall, were built on the slope of the hillside.	7th and early 11th centuries A.D.

Table 5.2. Information on other wind-powered furnaces.

5.1.5.1. The Huayrachina

(image redacted for copyright purposes)

Figure 5.4. Photograph of an individual with two huayrachina furnaces near Porco, Bolivia ([Peele 1893:9] in Van Buren and Mills, 2005, 5).

The Huayrachina (*Figure* 5.4), which are located in Orco Bolivia, are modern, ethnographic example from the 16th-20th century AD. They are a “natural draft, single chambered furnace, which has a roughly cylindrical shape, used for smelting of lead, silver and copper. The chamber wall features a series of holes. The *huayrachinas* were erected particularly in windy places situated on the tops of ridges or hills” (Marks, 2012, p.42). Not only is their location and design to other wind powered furnaces, ethnographic obeservations provide information about their use. The “ethnographic observation of two smelts were carried out in 2001 and provided information about furnace operation. Furnaces were fired in the evening, taking advantage of strong consistent winds (Van Buren and Mills, 2005, 12). Such observations provide insight into not just furnace operation but also suggests that temporality of practice is an important aspect of wind-blown furnaces” (Marks, 2012, p.42). This demonstrates that the wind is needed to increase the temperatures and allow the furnaces to function solely on wind power without forced draft. It also shows that smelters are aware of what conditions are required for the furnaces to function. The study does not provide an explanation for the perforations, but as these furnaces are created and used with the wind, it suggests that they are beneficial to the smelting process when using wind. There is evidence suggesting furnaces of this style were used from the 16th century AD through to the 20th century (Rehren, 2011, p.76).

5.1.5.2. Wadi Feinan

(image redacted for copyright purposes)

Figure 5.5. Copper smelting furnaces at Wadi Feinan (Craddock, 2000).

At Wadi Feinan, the copper smelting furnaces (Figure 5.5) are located in Southern Jordan and are dated to the early chalcolithic (mid-5th millennium B.C.). They are built into the side of a hill, which experiences prevailing wind. The furnaces are 40cm tall and have a diameter of 60cm. It was noted that the afternoon winds were strong, sustained and dependable in this location by the excavators (Doonan and Marks, 2021; Rothenberg & Shaw, 1990; Craddock, 2000, p.130; Henderson, 2000, p.247). "The furnaces are laid out in lines, which follow the contours of the hill very carefully. The furnaces were made of loosely stacked stone slates or clay. Fragments of clay bars were found, which are only fired on one side, it has therefore been hypothesised that these bars formed a grill on the opening of the furnace at the front, to hold the contents of the furnace in, but allow the wind to be blown in (Rothenberg & Shaw, 1990) (Craddock, 2000, 130) (Henderson, 2000, 247)" (Marks, 2012, p.44). These furnaces demonstrate that hillsides are ideal locations to take advantage of or experience fast and strong winds. They also show how positioning and designing a furnace to receive winds can create temperatures high enough to smelt, yet the atmosphere can be reducing enough to smelt copper successfully. The open-front design of these furnaces could raise concerns about the reducing environment of the furnace, yet material evidence shows they were successful in smelting.

5.1.5.3. Wadis Um Balad and Dara, Egypt

(image redacted for copyright purposes)

Figure 5.6. A furnace from Wadi Dara, Egypt. Left – view from the front, right – view from above (Photo courtesy of G. Castel in Craddock, 2000, Figure5a,b).

The furnaces at Wadis Um Balad and Dara (Figure 5.6), Egypt, date to the early chalcolithic (mid-5th millennium B.C.) “The furnaces’ were positioned just below the crest of steep ridges, facing into the prevailing wind. The furnaces were made of stone slabs c.40cm apart, to form a rectangle” (Marks, 2012, p.45) (Figure 5.6). The inside of the stone structure was lined with clay to create an internal smelting space c.30cm in diameter. There is no evidence for the front of the furnaces; perhaps they had a grill like the furnaces at Wadi Feinan to utilise the wind but to keep the fuel and charge inside. “It is believed that these furnaces would have produced a conglomerate with no free copper” (Marks, 2012, p.45). “No tuyeres or blow pipe tips were found, however the melting furnaces were found with benches surrounding them, which blowers were believed to have sat on (Cradock, 2000, 159)” (Marks, 2012, p.45). These furnaces again see the utilisation of hilltops to make use of strong winds. They also show that c.30cm is an internal size that can achieve temperatures hot enough via wind but remain reducing enough. It is believed these furnaces would produce a conglomerate, which would then need to be crushed to remove the prills and consolidate them. This seems to be a typical result of smelting, which means it was either the only way to smelt for these crafters or deemed efficient.

5.1.5.4. Samanalawewa, Sri Lanka

(image redacted for copyright purposes)

Figure 5.7. Reconstructed plan drawing of the furnace from Samanalawewa from excavation (Juleff, 2009, Figure 2).

The Samanalawewa furnaces (*Figure* 5.7), located in Sri Lanka, date to the 7th and early 11th centuries A.D. They are situated on west-facing hill slopes, which receive high-velocity winds during the monsoon season between June and August. The sites date between the 7th and early 11th centuries AD (Juleff, 2009, p.558; Juleff, 1998, p.4-5). The furnaces are made of clay and are very large, measuring between 1.2m to 2.0m wide, c.0.35m deep and 0.5m high (Juleff, 1998, p.5). The front wall of the furnace features a foundation of re-used tapering tuyères, which are positioned in a line horizontally, with an additional row of tuyères situated higher in the wall. This is believed to allow the air to flow into the furnace (Juleff, 1998, p.5). Juleff carried out a series of experimental smelts which were successful in smelting metal (*Figure* 5.8). These experiments also demonstrated how these furnaces function by utilising natural wind. Air is drawn into the furnace due to wind blowing over the top, creating a strong venturi effect as the pressure lowers within the furnace, which then drags air in through the tuyères. This means that wind is not being blown into the tuyères but sucked in due to the venturi effect. Therefore, the furnaces can be considered wind-powered rather than wind-blown. This method sees a continuous blast being dragged into the furnace. The experimental trials also proved that the furnaces could achieve a reducing atmosphere even though it is quite an ‘open’ structure powered by wind (Juleff, 1998, p.4-8; Juleff, 2009, p.561).

These Samanalawewa furnaces again see the planned location of furnaces on a hilltop so they can take advantage of strong winds. It also shows an understanding of the wind and seasons to place the furnaces in the right direction to receive the strongest winds and when to carry out the activity. This demonstrates that crafters were in tune with their environment and nature and adapted their craft to exploit it. Juleff's (1988, 2009) experiments are vital, as they demonstrate and explain that wind-powered furnaces with perforations are not powered by air being pushed into the furnace through perforations. Still, the perforations and wind flow create a venturi effect, which affects the pressure regions in and around the furnace and results in air being drawn into the furnace through the perforations (Juleff, 1988, 2009). This explains how the furnaces can remain reducing, as the air is drawn through the fuel.

(image redacted for copyright purposes)

Figure 5.8. Experimental smelting of a reconstructed furnace from Samanalawewa (Juleff, 2009, plate 2).

5.1.5.5. Discussion of wind-powered furnaces

These examples of furnaces which utilise the natural wind, rather than using the forced draft, to increase internal temperatures high enough for smelting demonstrate that not only is this type of furnace technology possible, but also that the manufacture of the furnace and the location is well thought out and understood. The furnaces have to be built in a way that air can be dragged into the furnace due to the venturi effect, where the wind creates different pressure zones in and around the furnace, meaning air is drawn into the furnace, whether this be through perforations/holes in a furnace wall or an open-sided furnace with a grill. The furnaces also need to be situated on a hilltop that experiences high winds and be placed in the right direction to receive them. These examples also indicate how the temporal considerations are critical, as the strong winds are seasonal. This evidence demonstrates that different furnace technologies rely on other technical skill bases and understandings, which can be considered in relation to the Aegean furnace. It also demonstrated that the craftspeople using this technology were in tune with their environment and understood geography, seasons, and weather. The furnaces at Samanalawewa and the experimental reconstructions indicate a critical point: the wind is not blown into the furnaces. Still, due to different pressure regions caused by the high-speed winds blowing past the furnace and the still air inside, the air is drawn into the furnace. This is important as it allows us to understand better how natural draft furnaces function and can remain reducing. The knowledge of these different pressure regions can allow us to understand better how these furnaces function and understand the material produced by them.

5.1.6. Fluid Dynamics of Wind-Powered Furnaces

As revealed by the Experimental Campaign and studies of Juleff (1998, 2009), the furnaces which are not powered by forced draft, such as bellows or blow pipes, but rather are situated in windy locations, have a design which creates spaces within the furnace wall for air to go in and out. These can be considered to be wind-powered rather than windblown, as the air is not forced into the furnaces through the perforations or gaps but is instead drawn into the furnace through them due to different pressure regions. The wind blowing around the furnace, creates a high pressure region and as the slow moving air inside the furnace is a low pressure region, the low pressure wants to be high, and drags the air from the outside in. To understand this effect and method better, the study of fluid dynamics can be applied (Marks, 2012). The Bernoulli equation allows us to quantify how flow velocity impacts the pressure of the fluid, “A fluid’s (e.g. air or water) pressure is linked to how fast it is going, and the Bernoulli equation allows us to quantify how flow velocity impacts the pressure of the fluid. The Bernoulli equation is written as:

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2 = p_o = \text{constant}$$

The total pressure p_o is the sum of static pressure P and dynamic pressure $\frac{1}{2}\ pV^2$ and the static pressure is represented by the actual thermodynamic pressure of the fluid (Cimbala *et al*., 2008, p.133-135; White, 2011, p.172; Massey, 2012, p.92-95)" (Marks, 2012, p49). "The Bernoulli equation states, "the total pressure along a streamline is constant" (Cimbala *et al*., 2008, p.135). This means that if the dynamic pressure is increased (fluid speeds up), then the static pressure must reduce by the appropriate amount, so that the sum of the two can remain constant" (Marks, 2012, p.49). This means that the fast wind blowing across and around the furnace creates different pressure regions inside the furnace compared to outside the furnace. The perforations, holes or spaces within a furnace wall enable air to be drawn from one region to another, creating a circulation of air and enabling the furnaces to function on this air flow alone, meaning additional forced air is not required.

The assessment of other windblown furnace technology has elucidated how wind-powered furnaces work. It highlights their placement on a windy promontory, in a position that experiences the strong winds as they blow in that direction. This demonstrates that the craftspeople who built the furnaces placed them in these locations to utilise the wind, and they understood the natural environment well. The study of the fluid dynamics of the wind blowing past a furnace demonstrates that the perforations enable a better working furnace when powered by wind, as they enable more air to be drawn into the furnace than if it had solid walls. Therefore, this strengthens the theory that the perforations on the APF's the locations of the furnaces were placed in specific locations intentionally, so they experience strong winds. These furnaces were designed and positioned to harness that natural wind. Before this theory is tested by the method of an Experimental Campaign, the previous Experimental Campaigns concerning the APF will be assessed.

5.1.7. Wind power and stability

The material evidence from the excavated material indicates that the internal environments of these furnaces were unstable. The microscopic analysis of the slags found at Chrysokamino revealed that the internal environment was changeable between mildly oxidising and mildly reducing phases (Betancourt, 2006). This can be considered to be due to air being drawn in through the perforations. The metallurgical material also suggests an unstable environment, or one not as hot or reducing as other smelts, as Experimental Campaigns produce conglomerates, where copper prills are located amongst masses of slag. The slag would need to be crushed to release the prills. This could explain the large heaps of crushed slag at the sites where the APF is present and stone tools used for crushing (detailed in Chapter 4, section 4.2.). What other need would there be to pulverise slag if not to release something from it? If the APF produced a conglomerate, then it requires processing to release copper prills. Then, the copper prills would need to be heated and consolidated. This process would consist of melting the prills in a crucible within a hearth, then pouring the liquid copper into a mould. This would be the same process for casting objects from ingots or recycling metal objects. The apparatus for this would look different to that of the smelting process. Also, as melting does not require as high temperatures as smelting, the ceramic apparatus, such as the crucible and hearth, will not be as heavily altered. This means that it may not survive as well in the archaeological record and may not be as easily identified as being metallurgical. Some of the equipment used may be lost due to the material it is made from. It has been considered that, due to the lack of moulds in the archaeological record from the early periods of metallurgy, that they may have been made from sand (Ottaway, 2001, p.100).

5.1.8. Testing the new model - Experimental reconstructions

In order to test this new theory, a series of Experimental Campaigns were carried out. The methodology for the campaigns is presented in Chapter 3, and the results are presented in Chapter 6. The campaigns will test if this new model is suitable for smelting copper. I will then compare the material evidence produced by macroscopic analysis, microscopic analysis and chemical analysis to that of the archaeological evidence and the previous experiments to assess if this model is a better match for the reconstruction of the method of use of these furnaces. Finally, the implications of this new model in the wider context of craft and transmission will be assessed (Chapter 7).

6. Chapter 6: Results of Experimental Campaigns and analysis of the material produced during the Experimental Campaigns

6.1. Introduction

This chapter will present and discuss the results of the Experimental Campaigns which reconstruct the Aegean Perforated Furnace (APF) and test the new model of function proposed in this thesis, which sees the provision of air to be from natural wind rather than forced draft via bellows or blowpipes. The macroscopic analysis of the material produced from the experiments, furnace fragments and metallurgical materials (copper, conglomerate, and slag) will be discussed. Then, a range of analyses will be presented, which were conducted to understand better the evidence for the Aegean Perforated Furnace (APF) and to test the reconstruction proposed by the author in this thesis for its function. After the Experimental Campaigns and macroscopic analysis, GIS analysis will be presented, which was conducted to understand the distribution of sites and evidence, as well as the sites' association with the wind. Subsequently, three types of analysis performed on the material produced by the Experimental Campaigns (slag, copper conglomerate, and ceramic furnace fragments) will be presented: microscopy, SEM/EDX and pXRF. The Experimental Campaigns were carried out to test the new reconstruction of the APF, which sees a new method for the process of smelting conducted in the (APF) proposed in this thesis. This new model came about after a reassessment of the archaeological evidence and spatial distribution of the sites (Chapter 4). The analysis of the metallurgical material (slag and copper conglomerate) and metallurgical ceramics (furnace fragments) which were produced in the experiments will enable comparison with the excavated archaeological material to see if the identical residues are left upon the metallurgical ceramics and if the slag and conglomerate were formed in the same way and experienced the same conditions (reducing/oxidising/temperatures). If the internal conditions of the furnace, as seen by this analysis, are the same as that of the archaeological material, this will strengthen this theory for its function.

Analysis	Contribution/Aims
Experimental Campaigns	To test the method of function proposed for the APF furnaces (wind-powered) and see if they can smelt copper.
Macroscopic analysis	To identify what types of metallurgical material were produced during the experimental smelts (slag, copper, and conglomerate). To assess the alteration of the ceramic materials (furnace fragments) and their appearance after the smelt. Then, the material produced during the experimental smelts will be compared to the excavated material to see if the colour alteration and material adhering to the ceramics are comparable, as another way to test this method.
GIS	To map the sites location in relation to their chronologically to see where they moved to over time. This will enable a consideration of the variation in material evidence at each location to assess the understanding behind the choice of location for the smelting sites and the movement of activity. Also to understand the importance of the wind and the site locations.
Microscopy	To assess the metallurgical material (slag, conglomerate and copper prills) to identify structures that tell us about internal temperatures and conditions (reducing, cooling), how the slag formed, and to compare it to the material analysed from excavations, this allows us to see if the conditions achieved are comparable, to test the plausibility of this method, and to determine if it is more accurate than the method tested in previous Experimental Campaigns (Pryce *et al*., 2007; Catapotis *et al.,* 2008).

SEM	To achieve a higher magnification assessment and images of structures identified in the microscopy and to perform chemical analysis of the metallurgical material, to understand how successful the smelt was by looking at the amount of copper in the slag (representing copper loss). To assess the plausibility of this method and understand how efficient this type of furnace and method would be.
pXRF	Analyse the furnace fragments to see levels of copper on them, compare with analysis of other experimental furnaces, and see if copper residues can be found on ceramics that do not look metallurgical in different ways (colour alteration, vitrification).

Table 6.1. Synthesis of the different types of analysis used in this thesis and their aims.

6.2. Results of the Aegean Perforated Furnace's Experimental Campaigns

Three Experimental Campaigns will be presented in this chapter. Campaign One was conducted as part of my MSc thesis (Marks, 2012), and the material produced (furnace fragments, metallurgical materials) is analysed in this thesis using the analytical methods which were conducted in Campaign Two. Campaign Two was conducted as part of this thesis and used copper ore for the smelt, to compare with Campaign One, which used copper pipe and crushed copper slag, as ore was unavailable at the time. Campaign Three was designed by myself to replicate the thicker walled APFs, replicating the experiments presented in Campaigns One and Two. While these campaigns were conducted with students as part of a module under my supervision (Giannakopoulou *et al.*, 2022), the results will be presented here to compare them to Campaigns One and Two and enable me to critique and discuss the results.

Campaign number	Material being reconstructed	Purpose of experiment	Who conducted experiment
Campaign One	APF thin walls (1.5-2.0cm)	To test if the conditions needed for smelting copper ore could be achieved, with the only source of air being natural draft mimicking wind speeds found at the sites of the APF.	Yvette Marks
Campaign Two	APF thin walls (1.5-2.0cm)	Repeat the successful experiment conducted in Campaign One, this time using more accurate copper ore to ensure the results' replicability.	Yvette Marks
Campaign Three	APF thick walls (4.5cm)	Conduct the experiment by reconstructing the thicker walled furnace variant of the APF.	Experiment conducted by Magda Giannakopoulou and Tom Olliffe. Experiment designed by Yvette Marks

Table 6.2. Aims of the three Experimental Campaigns.

6.2.1. Results of Campaign One

Figure 6.1. Photo showing action shot from Campaign One (photo taken by author).

6.2.1.1. Temperatures

The first campaign (*Figure* 6.1) tested (a) the effect that different wind speeds had on the smelting conditions in these furnaces and (b) whether wind alone could provide enough air input for these furnaces to function sufficiently. The initial tests measured temperatures achieved within the furnace, with lit charcoal, at different wind speeds without adding copper ore. The wind speeds tested were 3.2 metres per second (m/s), 4.0 m/s, 4.9 m/s, and 6.5 m/s. This was repeated twice, using two different furnaces, one which measured 35cm in height and one which measured 45cm, to test the difference between the two extremes of the proposed measurements of the model. Both firings were successful and comparable, with the height of the furnace shown to be an unimportant variable. The temperatures within the furnace were high across all four wind speeds, reaching above 900^{o}C minimum, with temperatures at the bottom of the furnace reaching above 1200^{o}C, providing an environment suitable for smelting copper. However, the most efficient speed was 4.9 m/s, as this enabled the furnace to burn at the most optimum temperatures, which would be used for subsequent experiments. As the necessary temperatures needed to smelt copper ore were being achieved with just wind, it was decided to add a charge of simulated copper ore (as real ore was not available) and attempt to smelt the copper and see if it affected the temperatures achieved. At the time, it was impossible to acquire any copper ore, so as a substitute, copper pipe and crushed copper slag were added to simulate copper ore. This was done to mimic a charge of ore and to test if the conditions were suitable for smelting copper ore. The slag could also be analysed to see the conditions within the furnace, as it would melt and the structures would reform, allowing us to see whether the environment was reducing or not. A charge was added nine times, using the layered method, during which a charge of ore was added first, followed by charcoal and repeated a number of times rather than being added as one amount (Tylecote, 1986). A total of 1350g copper slag and 135g metallic copper was added. After the last charge of copper was added, the furnace continued to be charged with charcoal (the same amount originally required to fill the furnace) to enable the charge to reach the bottom of the furnace. Once the furnace had burnt down, it was left to cool before emptying and dismantling.

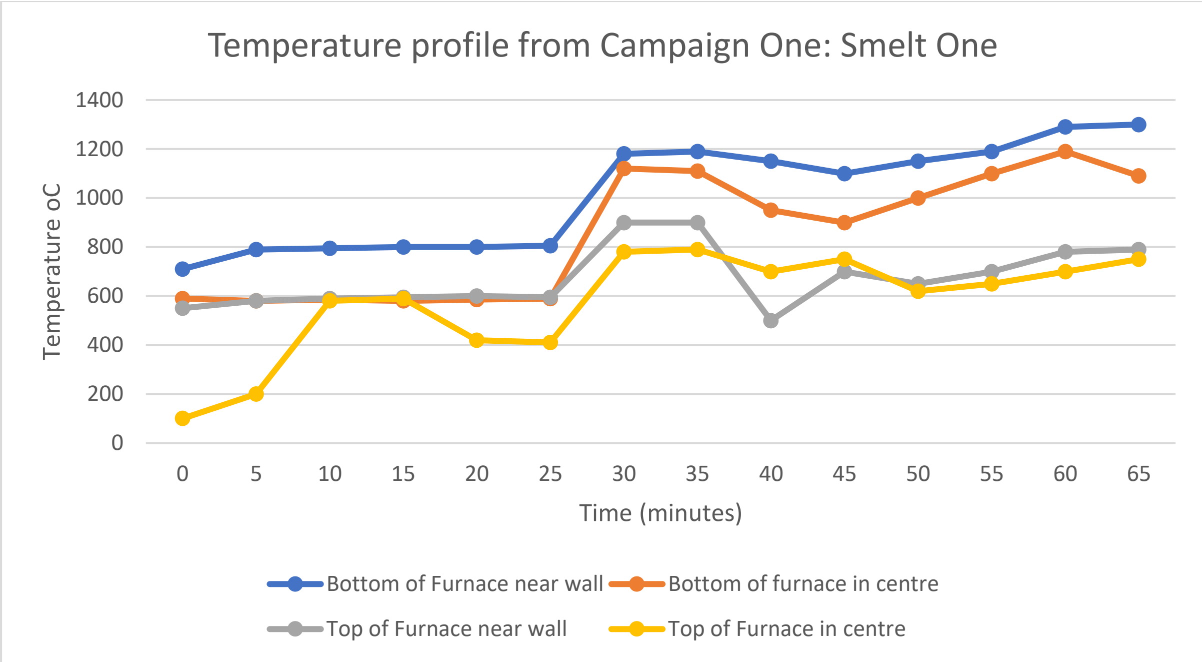

Figure 6.2. Graph of Thermocouple temperature readings for Campaign One: Smelt One (Marks, 2012).

6.2.1.2. Ceramic material – macroscopic analysis

Figure 6.3. Interior of two furnace fragments from the top of the furnace (rim pieces). From Campaign One (photo taken by author).

Figure 6.5. Interior of furnace fragment from the middle of the furnace with vitirification. From Campaign One (photo taken by author).

Figure 6.4. Interior of 2 furnace fragment from the bottom of the furnace with vitirification and slag. From Campaign One (photo taken by author).

A new macroscopic assessment of the ceramic furnace fragments (Figures. 6.3 - 6.5) was conducted, now that more varied fragments had been assessed (Chapter 4). This analysis showed that they had altered during the smelt; the colour of the fragments was altered due to the temperatures they had experienced. The clay on the exterior of the furnace altered from a pale yellowish brown when leather hard, to a pinkish orange when fired. The internal fragments were more heavily altered, especially towards the bottom of the furnace. There was a stark difference between the clay fragments from the top of the furnace and the bottom on the interior. The fragments from the top (*Figure* 6.3) were lighter in colour and less altered, and had little, if any, material adhering to the interior furnace. The interior of the fragments from the middle of the furnace wall (*Figure* 6.4) started to become darker in colour, turning more reddish brown, and black in places. The fragments at the bottom of the furnace (*Figures* 6.5) were the most heavily altered, with blackening on the exterior of some of the fragments around the perforations and the interior being heavily vitrified. There were also some fragments with a white ash on the interior surface. The metallurgical conglomerate that was produced was fused to part of the interior wall at the bottom (*Figures* 6.8 and 6.9). The interior of the fragments showed pitting as well, where organic material (straw) had burned out. The physical alteration of the ceramic material, including the pitting and vitrification, matches that of the ceramic fragments found in the archaeological record (Chapter 4). The colour of the fragments also matches, although there are more examples in the archaeological record of fragments which are less altered and lighter in colour, such as the fragments which came from the top half of the furnace. This is assumed to be because the conglomerate would fuse to the wall, and these fragments would need to be broken to remove it. This would result in pieces from the top of the furnace being larger and more intact, as they did not have conglomerate attached to them. It can also be considered that the white ash and black colouring on the interior of the fragments from the bottom could disappear over time, due to weathering and deposition. Chemical analysis (which had not been carried out as previously) was conducted on the ceramic fragments, and will be presented and discussed later in this chapter.

Figure 6.6. Exterior of furnace fragments from bottom of furnace. From Campaign One (photo taken by author).

Figure 6.7. Exterior of furnace fragments from middle of furnace. From Campaign One (photo taken by author).

5.6.2.1.3. Metallurgical material – macroscopic analysis

Figure 6.8. Conglomerate fused to interior of furnace, view from exterior. From Campaign One (photo taken by author).

Figure 6.9. Conglomerate fused to interior of furnace, view from interior. From Campaign One (photo taken by author).

The macroscopic analysis of the metallurgical material produced during the smelt divided the material into two categories: conglomerate and slag. The conglomerate (Figures 6.8 and 6.9) consists of copper prills within a mass of slag. The prills range in size from 1-2cm. They are clear to see within the conglomerate and could be extracted by crushing and hand picking. There is also slag, which can be divided into two types: fluid and spiky. The fluid slag (*Figure* 6.10) is very light and does not contain any copper prills. It is comparable to tap slag (Betancourt, 2006, p.137; Bassiakos and Catapotis, 2006, p.340) where the slag is frozen in fluid movement as it is hit by the air being dragged in through the perforations as the furnace is running through the field just inside of the furnace wall. The furnace was not tapped and no slag escaped, all slag was formed in the interior of the furnace. This fluid shape must have been created by air cooling the slag as it ran through the internal environment; the air would have been dragged in through the perforations. The second type of slag, described as ‘spiky’ here (*Figure* 6.11), is also light in weight, but occasionally contains a very small copper prill. The material may be part of the conglomerate which has fallen off, or part of ore which has not fully undergone the separation of silicates and metallic copper. It is very different in texture to the fluid slag. The conglomerate and slag were taken back to be sectioned and analysed under the microscope; this will be presented and discussed later in this chapter.

Figure 6.10. (left) Slag from Campaign One with fluid shape (photo taken by author).

Figure 6.11. Slag from Campaign One with ‘spiky’ texture (photo taken by author).

6.2.2. Results of Campaign Two

Figure 6.12. Photo of Campaign Two experiment in action (photo taken by author).

The purpose of Campaign Two (*Figure* 6.12) was to conduct a smelt using a more authentic charge than that used in Campaign One, and to test the replicability of the results of the method of the furnaces being powered solely by the wind. The method of simulating the wind that was used in Campaign One was replicated in Campaign Two. The archaeometallurgical investigations at Chrysokamino suggested that the primary mineral being smelted was malachite (Bassiakos and Catapotis, 2006) fluxed by locally available iron oxides. The previous Experimental Campaigns by Pryce *et al.* (2007) and Catapotis *et al.* (2008) used a simulated charge. This campaign used a synthetic copper carbonate cemented with iron oxide and sand, like that used by Pryce *et al.* (2007) and Catapotis *et al.* (2008). This charge would be more comparable to the copper ore used in antiquity. The charge was crushed to c.5mm and was administered using the same layered technique as in Campaign One.

6.2.2.1. Temperatures

The temperatures achieved in this smelt were comparable, with temperatures at the top of the furnace reaching c.900^{o}C, and the bottom of the furnace reaching above

1200ºC (*Figure* 6.13). The thermocouple readings were started after the furnace reached a temperature suitable for smelting (1200ºC) and were taken every 5 minutes for 145 minutes. The maximum temperature the thermocouples used could read were 1200ºC. This smelt also produced a conglomerate, which was taken back to the lab for assessment. The ceramic material matched that of Campaign One, in terms of colour alteration and material adhering to the internal surface.

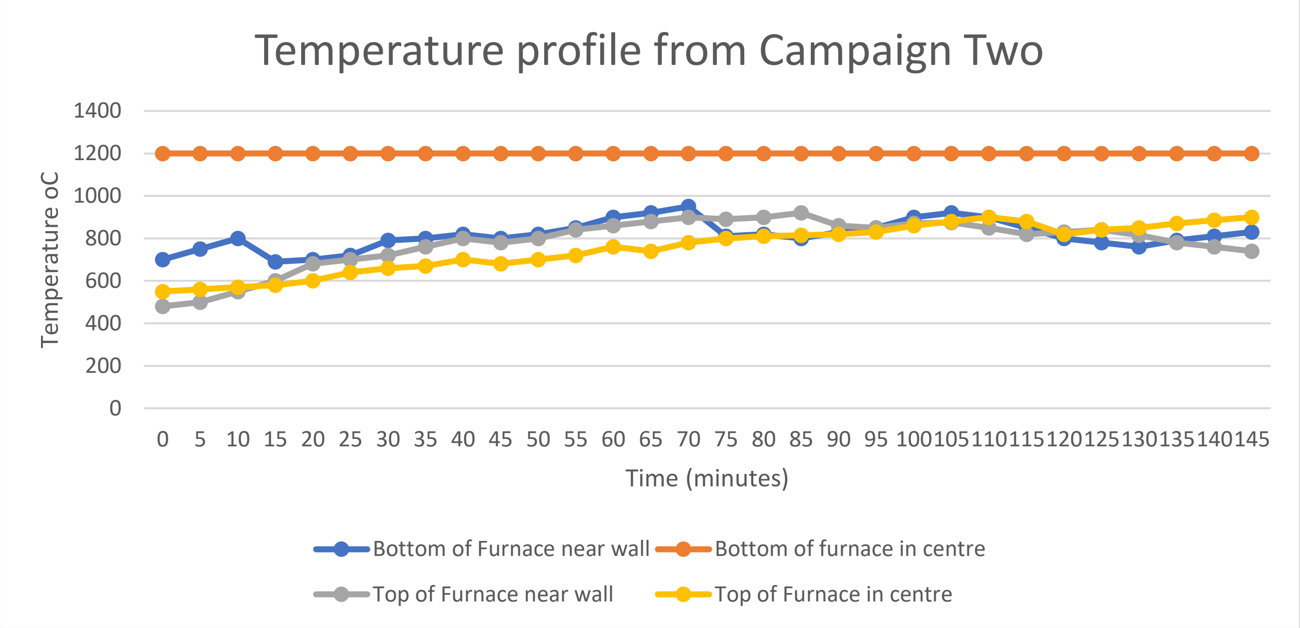

Figure 6.13. Graph showing the thermocouple data from Campaign Two.

<u>6.2.2.2. Ceramic Material – macroscopic analysis</u>

The macroscopic analysis of the ceramic material shows that it is comparable to the material from Campaign One. The colour alteration pattern matches, with the exterior of the furnace turning from a yellowish brown to a pinkish orange after firing (*Figure* 6.14). The colour on the exterior is a deeper reddish orange towards the bottom of the furnace, with some blackening around the perforations. Observations during the experiment, suggested that this was produced by flames protruding through the perforations. The ceramic structure of this furnace held together better than the furnace from Campaign One. Cracking did not occur until later in the smelt. When taking the furnace off the hearth to retrieve the metallurgical material, it came apart in larger pieces. When the cracking did occur, this happened along the area where clay slabs were joined (*Figure* 6.14). The fragments had pitting from organic material burning out, comparable to those from both Campaign One and the archaeological record. Vitrification was also present on fragments from the bottom of the furnace, and the conglomerate was fused to the wall again (*Figures* 6.16 and 6.17). The ceramic fragments were not taken straight back to the lab after this campaign, but were left in the field to see how they weathered over time. When the fragments were retrieved, the ceramic fragments had broken up into pieces which were smaller than when they had been left. Some of the black and white dust had washed off in the rain. Although few large pieces of the ceramic furnace had remained intact, these were the pieces which had been positioned underneath others, leaving them less exposed to the weather. The ceramic material was taken back to the lab after being left in the field for two months. Chemical analysis by XRF was conducted and will be presented and discussed later in this chapter.

Figure 6.14. Ceramic furnace fragments (left) from the top of the furnace including rim pieces and (right) from the middle of the furnace (crack formed along the line of slab from formation). From Campaign Two (photos taken by author).

Figure 6.15. A range of ceramic furnace fragments from the furnace, base pieces at the top, in small fragments showing how the material breaks up over time. These fragments were left outside and photographed a month after the firing took place. From Campaign Two (photo taken by author).

Figure 6.16. (left) Ceramic furnace fragment from the bottom of the furnace with conglomerate attached view from outside (photo taken by author).

Figure 6.17 (right) Ceramic furnace fragment from the bottom of the furnace with conglomerate attached view from inside. From Campaign Two (photos taken by author).

Figure 6.18. Exterior (left) and interior (right) of broken ceramic furnace fragment from the bottom of the furnace. The interior has vitrification and copper prills. From Campaign Two (photos taken by author).

Figure 6.19. Exterior (left) and interior (right) of broken ceramic furnace fragment from the lower middle of the furnace. The interior has vitrification and traces of copper. From Campaign Two (photos taken by author).

6.2.2.2. Metallurgical material – macroscopic analysis

Figure 6.20. Copper prills which were found in the furnace but not contained within slag or conglomerate. From Campaign Two (photo taken by author).

The macroscopic analysis of the metallurgical material from Campaign Two shows that the smelt produced a conglomerate and slag. The conglomerate had fused to the furnace wall. Both types of slag identified previously (fluid and ‘spiky’) were seen here too. There were more pieces of ‘spiky’ slag from this campaign, and within it more evidence of copper prills, although the conglomerate was smaller in size. There were also a number of copper prills free from the slag and conglomerate material (*Figure* 6.20) in addition to those entrapped in the slag and conglomerate (*Figure* 6.23). Again, fluid slag was present, but the furnace had not been tapped and all slag was formed within the furnace. The metallurgical material was sampled and analysed under the microscope; this will be presented and discussed later in this chapter.

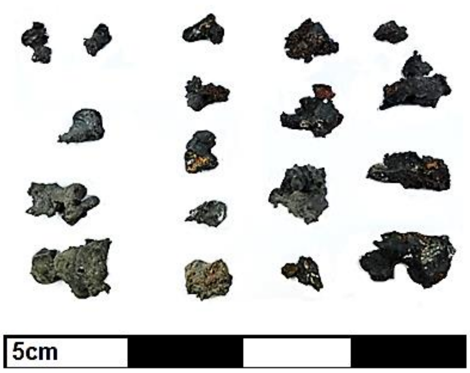

Figure 6.21 Slag material: left row, fluid in style, other rows, ‘spiky’ in style, with copper prills inside. From Campaign Two (photo taken by author).

Figure 6.22. Slag material and fragments of conglomerate: orange box = fluid slag, the rest consists of fragments of conglomerate. From Campaign Two (photo taken by author).

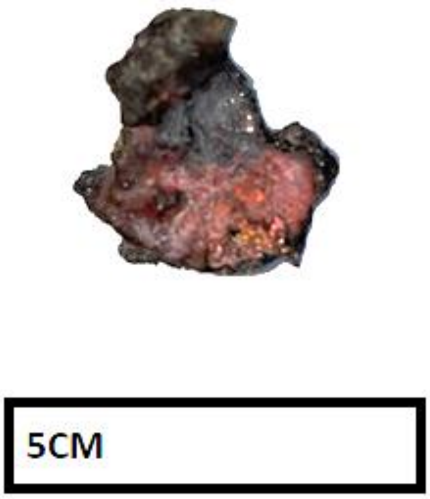

Figure 6.23. Copper prill within slag. From Campaign Two (photo taken by author).

6.2.3. Results of Campaign Three

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Figure 6.24. Photograph of experiment in process – Campaign Three (Giannakopoulou, 2018, Figure 5).

The purpose of Campaign Three (*Figure* 6.24) was to replicate the method used in Campaigns One and Two, but with a thicker walled furnace, more comparable to that represented by APF ceramic fragments found at the two sites on Kythnos (Chapter 4) (Bassiakos and Philaniotou*,* 2007). The furnace was built around the same mould, but the walls were made to a thickness of c.4-6cm, rather than c.2cm. One noticeable difference between this furnace and the thinner walled furnace from the first two campaigns is the difference in weight. The furnace required double the amount of clay (60kg) to create the thicker walls, which are double the thickness (Giannakopoulou, 2018). The increased weight made it heavier to lift and therefore more than one person was needed to move it, whereas the thinner furnaces could be lifted comfortably by one person. The perforations were added at a 50^{o} incline, to match those present in the ceramic fragments from Kythnos (Bassiakos and Philaniotou*,* 2007; Giannakopoulou, 2018).

The firing method was replicated from Campaign One and Two, with the electric fan simulating the wind at the speed of 4.6 m/s. Temperature readings were also taken, at the same points within the furnace, using thermocouples. Charcoal was added to the furnace, in addition to a malachite ore (36.5% copper). The same layered method was used for loading the charge and fuel into the furnace.

6.2.3.1. Temperatures

The temperatures measured within the furnace were similar to those of smelts from Campaigns One and Two. They were characterised by temperatures rising as the furnace heated up, then plateauing and being sustained during the smelt, and gradually dropping as the furnace burns down. However, the temperatures in this campaign were higher in the middle region, rather than in the lower region as was seen in Campaign One and Two. The highest temperature in the furnace was in the middle, and plateaued around 1200ºC, dropping slightly below at certain points to c. 1200ºC, whereas the thinner walled model in Campaigns One and Two had reached above 1200ºC. As can be seen in *Figure* 6.25, the temperature drops over a couple of readings, then increases again over two readings. It is assumed that his correlates with the fuel burning down from the rim of the furnace, then being topped up again. The overall temperature profile has a pattern which is comparable to Campaigns One and Two, with a gradual rise as the furnace heats up, then plateauing whilst fuel is added, then, once the furnace is left to burn down, the temperature gradually drops again. Forty minutes after the start of firing, the temperatures reached above 800ºC at the top, and 1200ºC in the middle. In the lower half of the furnace, it took 1 hour 40 minutes for the temperature to rise to 1100ºC, at which it then plateaued for an hour, then slowly dropped to 800ºC as the fuel was burned down over the remaining hour (Giannakopoulou, 2018). The temperatures at the top and middle are consistent once they reach their peak after 40 minutes, despite the temperatures being slightly lower in this campaign than in Campaigns One and Two. Fluctuating around 1200ºC, a conglomerate and a number of ‘spiky’ pieces of slag with copper prills in, similar to those from Campaigns One and Two, were produced. My assessment of the temperature data concludes that the reason the top temperature may be slightly lower, and that the temperature profile is slightly different to the thin walled APFs (Campaigns One and Two), with the hotter zone in the middle of the furnace, rather than the bottom, could be due to the thicker wall, making the perforations longer tubes rather than holes. This could result in less air being dragged in during the smelt.

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Figure 6.25. Graph showing the temperature readings from the furnace during Campaign Three (Giannakopoulou, 2018, Graph 1).

6.2.3.2. Ceramic material – macroscopic analysis

During the smelt the furnace cracked after 20 minutes of being fired, but the furnace held together for the smelt (Giannakopoulou, 2018; Giannakopoulou, *et al.,* 2022). The thinner furnaces also cracked during the smelts, but this was much later in the process. My macroscopic analysis of the ceramic fragments from Campaign Three identifies that the colour pattern of the furnace fragments matched that of Campaigns One and Two. In each instance the fragments on the exterior were a pinkish orange at the top (*Figure* 6.27) while the bottom half was reddish orange, with black on the interior (*Figures* 6.26 and 6.27). The fragments from the very bottom were heavily vitrified on the interior. The fragments had pitting from organic material burning out. The fragments broke through the perforation, and when the furnace was dismantled, it broke into many small pieces. New chemical analysis by pXRF was conducted on the interior of the ceramic fragments, and will be presented later in this chapter.

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Figure 6.26. Interior of furnace after smelt completed (Giannakopoulou, 2018, Figure 13).

(image redacted for copyright purposes)

Figure 6.27. Interior of furnace fragments after smelt completed (Giannakopoulou, 2018, Figure 14).

6.2.3.3. Metallurgical material – macroscopic analysis

Macroscopic analysis of the metallurgical material identified that the smelt produced a slag conglomerate which contained copper prills, as well as separate slag. Macroscopically, this material is comparable to that produced in Campaigns One and Two, as can be seen from the photographs (*Figures* 6.28-6.30). The slag is mostly of the spiky style, although there are a few pieces which look fluid in texture (*Figures* 6.28). Unfortunately, microscopic analysis was not conducted and the material is not available for analysis.

(image redacted for copyright purposes)

Figure 6.28. Slag pieces retrieved from smelt (Giannakopoulou, 2018, Figure 18).

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Figure 6.29. Conglomerate attached to interior of furnace wall from the base (Giannakopoulou, 2018, Figure 23).

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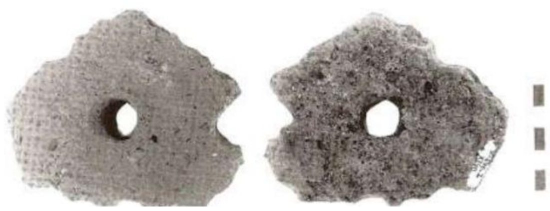
Figure 6.30. Copper prills separated from the slag (Giannakopoulou, 2018, Figure 24).

6.2.4. Discussion of the results of the Experimental Campaigns

The three campaigns produced comparable results, especially in terms of the success of firing the furnaces solely with the natural wind (wind speeds experienced in the Aegean), without the addition of forced draft from bellows or blowpipes. The campaigns proved that the temperatures needed can be achieved with the model of natural wind. The experiments and macroscopic analysis of the metallurgical material produced did show that the copper is not fully separated from the slag material but rather that a conglomerate is produced, with copper prills inside. Indeed, this is comparable with the material evidence from the archaeological record, as there are slag pieces from Chrysokamino with copper prills inside (Betancourt, 2006, p.138), as well as the evidence from multiple sites of pulverised slag, alongside evidence of stone crushing tools. The crushed slag at Chrysokamino is considered to have been crushed by human activity rather than weathering, as the pieces were the same throughout the pile, not just on the surface (Betancourt, 2006, p.138). The products of these experimental smelts suggest that the reason we find such large quantities of crushed slag at the sites of the APF is that the smelting process does not manage to fully separate the copper from the silicates in the ore. Instead, it is present as prills within conglomerates and slag pieces, which then had to be crushed to retrieve the copper prills.

The macroscopic analysis of the ceramic material from all three smelts showed that the material was altered in similar ways and was visually comparable to each other in colour and physical state, after the smelts. The ceramic material from the experimental campaigns is also comparable to the ceramic evidence from the archaeological record (Table.6.3.). The change in colour of the clay due to the smelting process, is similar, with areas higher up on the furnace walls, being turned a light orange, with not much blackening and not much slag or vitrification adhering to the interior surface. The areas that have been altered, are more of a grey colour than an intense black. The interior of the ceramic has a different texture due to the direct contact with the fuel and high temperatures, and the organic material has burnt out to leave impressions of where it was. Also, the cracking of the furnace wall occurs through the perforations, as this would be a weak point. The similarity in the ceramics from the experiment to the excavated materials suggests the temperatures and atmosphere experienced were the same. The observations made during the smelts and of the dismantling of the furnace, along with the weathering of the ceramic material afterwards together provide a better understanding of why the furnace fragments are found as small broken fragments.

	
Figure 6.31. Interior of 2 furnace fragment from the top of the furnace from authors experimental reconstruction - Campaign One (photo taken by author).	*Figure 6.32. Ceramic fragment of perforated furnace from excavation at Chrysokamino. Left side exterior, right side interior, a glassy deposit can be seen on the interior (Betancourt, 1999, Figure 7.1).*

	(image redacted for copyright purposes)
Figure 6.33. Ceramic furnace fragments from the top of the furnace authors experimental reconstruction - Campaign Two (photos taken by author).	*Figure 6.34. Image showing photographs of metallurgical ceramics and slag excavated from Sideri (a-c) and a clay nozzle from Paliopyrgos-Aspra Spitia (d), (Bassiakos and Philaniotou, 2007, 29, Figure 2.4a-d).*
(image redacted for copyright purposes)	(image redacted for copyright purposes)
Figure 6.35. Ceramic furnace fragments bearing perforations excavated from Kephala. Arrows indicating edges of perforations. (Philaniotou, et al., 2011, 160, Figure 16.4).	*Figure 6.36. Photograph of 8 of the furnace fragments excavated from Kephala, Keos (Coleman, 1977, Plate 66).*
(image redacted for copyright purposes)	(image redacted for copyright purposes)
Figure 6.37. Furnace Fragments excavated from the Southern Slope of the Athenian Acropolis (Dimitriou, 2017, 30-31, 1 = Figure 4., 2 = Figure 5., 3 = Figure 6., 4 = Figure 7. 5 = Figure 8a, 6 = Figure 9a).	*Figure 6.38. Ceramic fragments with perforations excavated from Gerakas (Πλασσαρά, 2020, 335, Figure 6. BE7968).*

Table 6.3. Table showing ceramic furnace fragments from excavation and the experimental campaigns for comparison.

	
Figure 6.39. Slag material and fragments of conglomerate from experimental campaign by author - Campaign Two (photo taken by author).	Figure 6.40 Slag material with copper prills inside from experimental campaign by author - Campaign Two (photo taken by author).
	
Figure 6.41. Slag from experimental campaign by author - Campaign One, with 'spikey' texture (photo taken by author).	Figure 6.42. Slag from experimental campaign by author - Campaign One, with fluid shape (photo taken by author).
(image redacted for copyright purposes)	(image redacted for copyright purposes)
Figure 6.43. Photograph showing a region of the Kephala slag heap from excavation, where slag has been broken into centimetre-sized fragments (Gale et al*.,* 1992, Plate 4).	Figure 6.44. Photograph showing copper slags, furnace fragments and stone tools excavated from Skali (Papadopoulou, 2011, Figure 15.7).

Table 6.4. Table showing slags from the experimental campaigns and the excavated material, for comparison.

The comparison of the excavated slags and the slags from the experimental campaigns (Table.6.4.) shows there are two main slag types: spiky slag, which forms loosely or as a conglomerate with copper prills within, which would need to be crushed to relieve the copper, and fluid slags (often referred to as tap slags). The majority of the copper prills formed within the experimental campaigns were formed within slag, and the slag had to be crushed to retrieve the copper. This results in centimetre-sized slag pieces, which are comparable with the excavated material. This is due to the size and the frequency of prills within the slag.

One of the most interesting observations of the macroscopic analysis of the metallurgical material is the presence of fluid slag, which was formed within the furnace. The formation of fluid slag is attributed to the slag being tapped from the furnace (Betancourt, 2006, p.137-8). A hole is created in the furnace wall to allow the slag to run out, to prevent it from building up and filling the bottom of the furnace. As the slag pours out from the furnace and hits the air, it is rapidly cooled and hardened, trapping it in its fluid state. This resulted in the two Experimental Campaigns conducted prior to this thesis by Pryce *et al.* (2007) and Catapotis *et al.* (2008), both of which attempted to tap the furnace. Tapping was unsuccessful during the Catapotis *et al.* (2008) smelt, due to the high viscosity of the slag. As the slag could not be tapped, it built up and eventually blocked the tuyère holes where the bellows were attached, and consequently it was not possible to put any air into the furnace, resulting in the experiment coming to a halt. Fluid slag was formed in all three Experimental Campaigns, which would fit the description of tap slag. However, as already discussed in this chapter, none of the furnaces from any of the three campaigns were tapped, and this slag was formed within the furnace. This demonstrates that there is not just one way in which material can be formed, and that we must be careful when creating reconstructed models of practice based on typology. This also shows the importance of studying and assessing archaeological material within its context. However, it also supports the theory that these furnaces were wind-powered, as the slag known from the archaeological record can form within the furnace and the build-up of slag within the furnace, without having been tapped, does not prevent the furnace from functioning from wind power alone.

6.3. GIS analysis

GIS analysis was conducted to visualise the spread of a range of types of material representing different processes of copper smelting during the LN and EBA Aegean, to understand the locations in which this activity was taking place. This enabled an assessment of the processed which took place, their motivation for movement, and the reasons for the choice of location.

6.3.1. Distribution analysis

All of the sites in the Aegean which have evidence for smelting copper in the FN and EBA were plotted, including an indication of whether they have evidence for the APF technology or a different method of smelting copper (*Figures* 6.45). This type of mapping enabled analysis of the distribution of those with APF in relation to the other sites. This assessment of the location of these sites showed that sites with the APF are limited to a specific region in the Aegean, suggesting that it is an isolated tradition (*Figures* 6.45). This type of analysis also enabled investigation into whether there are any key patterns in their physical location which might allow us to draw conclusions as to their function.

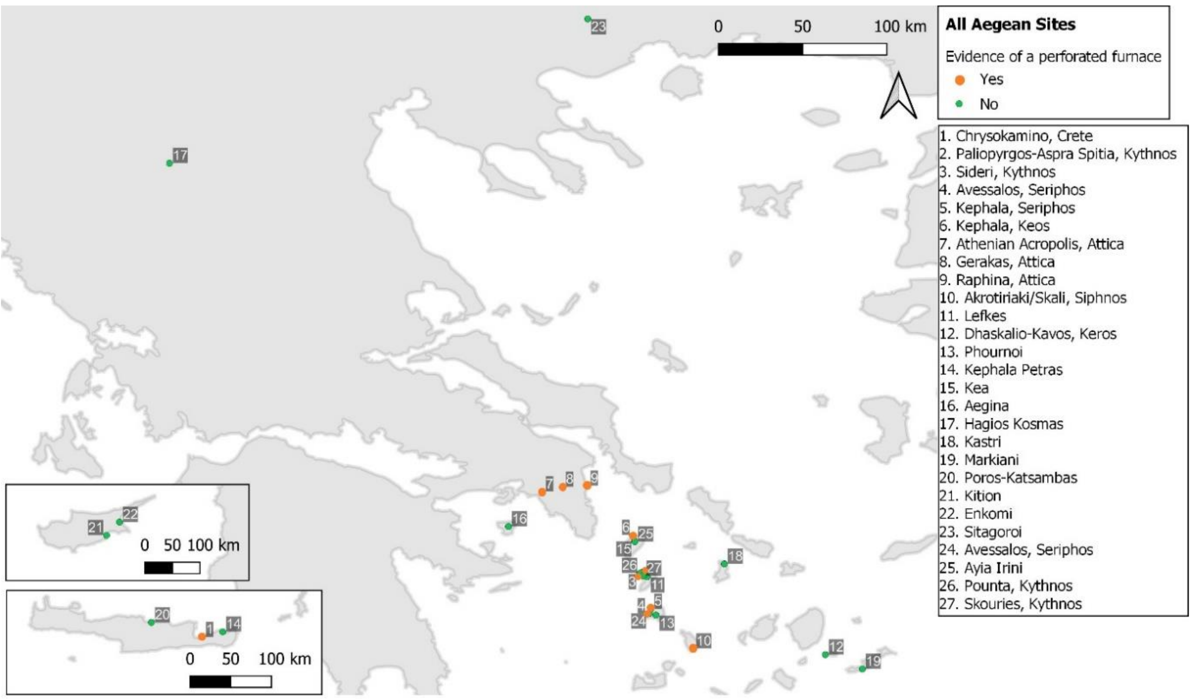


Figure 6.45. Map of all Aegean sites, indicating which sites have evidence of the APF and which do not (made by author).

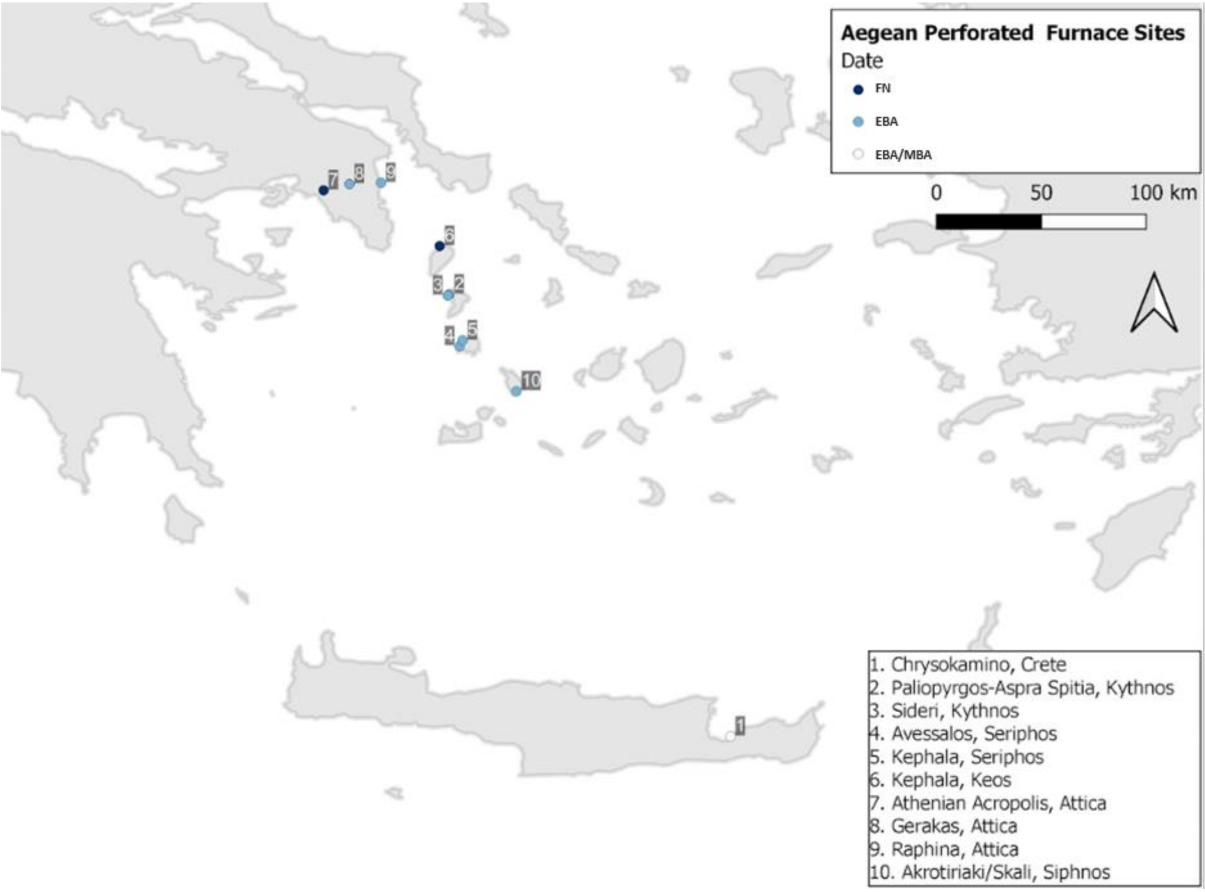


Figure 6.46. Map of sites with evidence for the APF, showing the period to which material can be dated (made by author).

Previous studies examining some of the known locations where the APF was used for smelting copper have demonstrated that the motive for their locations is not related to the proximity of the domestic site or to a natural ore source, as they are not located close to either of these (Georgakopoulou, 2017). Georgakopoulou (2017) was able to demonstrate that these sites are not located in accordance with their proximity to ore sources by mapping the locations of the ore sources and illustrating that in some instances, ores were being transported to these smelting sites from distant locations. The location and movement of ores is discussed further in Chapter 7, section 3. Another assumption is that the choice of a smelting location is determined by its proximity to a domestic site; however, at the majority of the sites which have the APF, there is no contemporary domestic settlement nearby (Chapter 7, section 7.4.2. and Table 7.1).

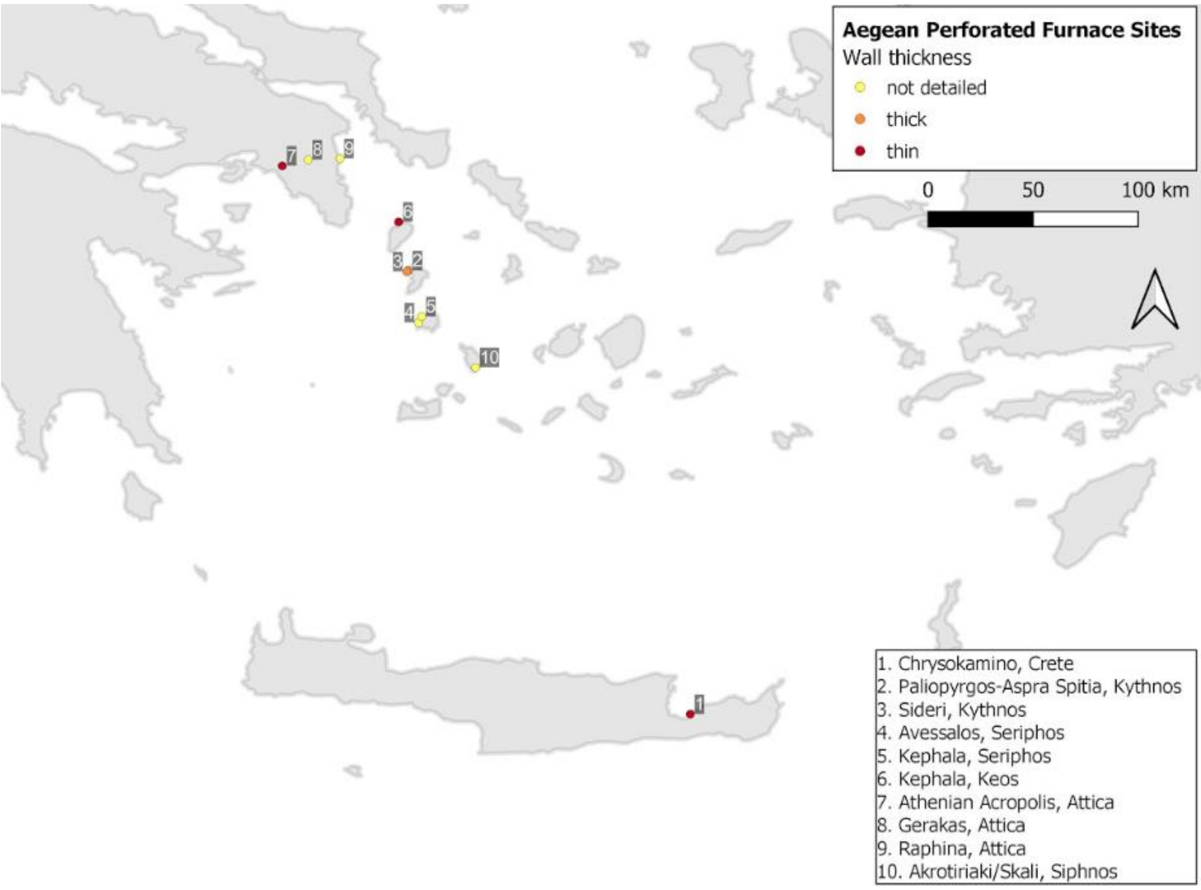


Figure 6.47. Map of all APF sites, indicating which sites have the thin-walled variation, which have the thick-walled variation, and the sites where publications did not detail this information (made by author).

All the sites which have evidence of the APF technology were plotted indicating the chronology of the sites (*Figure* 6.46). The map shows that the two earliest sites which bear evidence for the APF are on the Acropolis in Athens, and in Kephala on Keos in the FN. There is then a burst of sites appearing in the EBA further afield in the Cycladic islands, with later sites appearing elsewhere in Attica and then finally, much later, on Crete (EBA/MBA). As Keos is the closest main Cycladic island to the mainland and the earliest island on which the APF appears, this indicates that there was a later decision to move the smelting activity into the Cycladic islands from the mainland, as the locations were windier. This suggests that as these communities became more familiar with the wind and began to travel further afield, they started to utilise the wind on the islands further away. In view of this chronological spread and the choice of location, moving into the Cycladic islands, I would like to suggest that throughout prehistory, the increased knowledge of APF technology led to an increase of sites located on naturally windy locations in order to make best use of the wind.

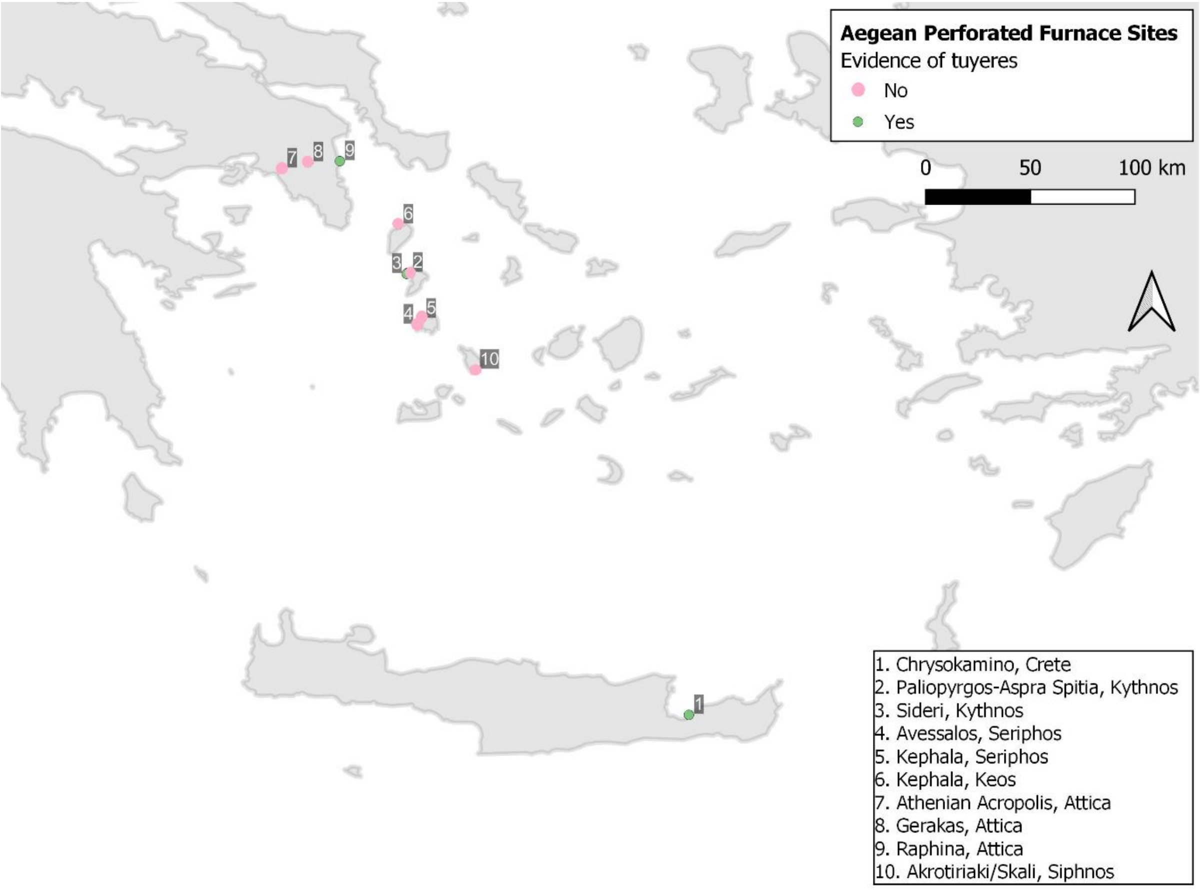


Figure 6.48. Map of APF sites, showing which sites have tuyeres, which do not, and which sites do not detail this in their report (not known) (made by author).

Another pattern, recognised by plotting the sites and different attributes of the evidence for the APF, is that only one location provides evidence for thicker furnace walls, whereas the other locations either have the thin variation of the furnace walls, or the thickness is not stated in the archaeological report. The Acropolis in Athens (A), Kephala on Keos (D) and Chrysokamino on Crete (J) (*Figure* 6.47) all have thin-walled furnaces (Chapter 4). Two of these are the earliest locations where this technology is found, and one is the latest. The only known thick walled fragments come from both sites on Kythnos: Sideri (E) and Paliopyrgos-Aspra Spitia (F) (Chapter 4). This suggests that the thick walls are a local variation created by craftspeople on Kythnos due to their ceramic skills and experience. Another interesting factor, also realised by plotting the differences in archaeological evidence at each site on a map, is the location of the sites where tuyères are present. Only three sites have evidence for ceramic tuyères, which would suggest the use of forced air by blow pipe or bellows (see Chapter 2 for more information). These are Raphina in Attica (C), Sideri on Kythnos (E), and Chrysokamino on Crete (J) (*Figure* 6.48). Chrysokamino is much later in date (EBA/MBA) than the other sites (Betancourt, 2006) and it is claimed that there is also evidence for bellows at this site (Betancourt, 2006, p.112). It is possible that the bellows and tuyères were associated with melting and casting, due to other evidence found at the site for these stages. Raphina is later in date as well, being in the 3rd phase of sites with this evidence and dating to the EBII. Then the other site to have evidence for tuyères is Sideri on Kythnos, and Kythnos is the only known location of the thicker-walled furnace fragments. It can therefore be suggested that the function of the tuyère was related to the thickness of the walls. A theory discussed by the author and the late Myrto Georgakopoulou (*pers. comms.,* 2018) is that internal environment required for the thicker walled furnaces may not have been as easily achieved as the thinner furnaces, as the perforation in a thicker wall become more restrictive for air to pass and could cause areas in the interior to drop in temperature. The tuyères in this case could have been used in conjunction with blow pipes, to blow air into certain perforations to raise internal temperatures. This would explain the isolation of this aspect of the material across the sites which bear evidence for the APF. The two other sites which have evidence for tuyères are later and they can be seen to represent use of equipment used for melting and casting.

The GIS mapping has highlighted that the most common factor for the location of these sites is that they are all situated on coastal promontories or on the side of hilltops. Also, there is a shift in the locations from the FN in to the EBA, from sites on the mainland, to sites within the Cycladic islands, which shows at the presence of the wind was an important resource. The previously proposed method for the use of the APF (Pryce *et al.*, 2007; Catapotis *et al., 2*008) saw the furnaces being powered by forced draft, via tuyères which would have been attached to bellows or blow pipes. However, the theory being proposed in this thesis sees the APF functioning purely with natural draft. To test this correlation between the movement of the technology and the use of natural draft (as the movement of this technology sees the sites move into the Cycladic islands), it was decided to plot the sites against the path of the Meltemi winds, and to visualise the difference in wind speeds across these areas. The image in *Figure* 6.35 shows the path of the Meltemi, it comes from over the mainland of Greece and Turkey, then funnels through the Aegean Sea between the two land masses and over the Cycladic islands ending up hitting Crete. The map in *Figure* 6.49 shows the wind speeds in Greece within the late Meltemi season (September) and the location of the

APF sites. This image shows the areas of strong wind (deep red) and how this comes across the island hitting the northern promontories.

(image redacted for copyright purposes)

Figure 6.49. Image showing the location and direction of the Meltemi winds in the Aegean (Kavas Yachting, 2021).

The Meltemi winds are strong winds which come from the north (*Figure* 6.49) and are usually present for a number of weeks during the months of June to September (Bassiakos and Filippaki, 2021). The winds register an average of 4 to 5 on the Beaufort Scale, but can reach as high as 8 (Kavas Yachting, 2021). The Meltemi is only present in the Aegean Sea, not in the Ionian Sea, and the two seas experience very different weather. These areas do experience wind in other months, but it is not as strong or as consistent. The Meltemi winds would also make it difficult to conduct other activities, such as farming, whilst they are present. Our understanding of the Meltmi winds comes from monitoring modern winds, it is accepted that the wind pattern and speeds are the same in this region to the FN/EBA Aegean, as the environmental conditions described by Aristotle and Theophrastos are very similar to that of today, suggesting that winds experienced would be comparable (Murray, 2008, p.139-167). Until more detailed palaeo-data becomes available, for the Late Neolithic and the Bronze Age, present weather conditions can be used (McGrail, 2001, 89; Bar-Yosef, 2015, 419)

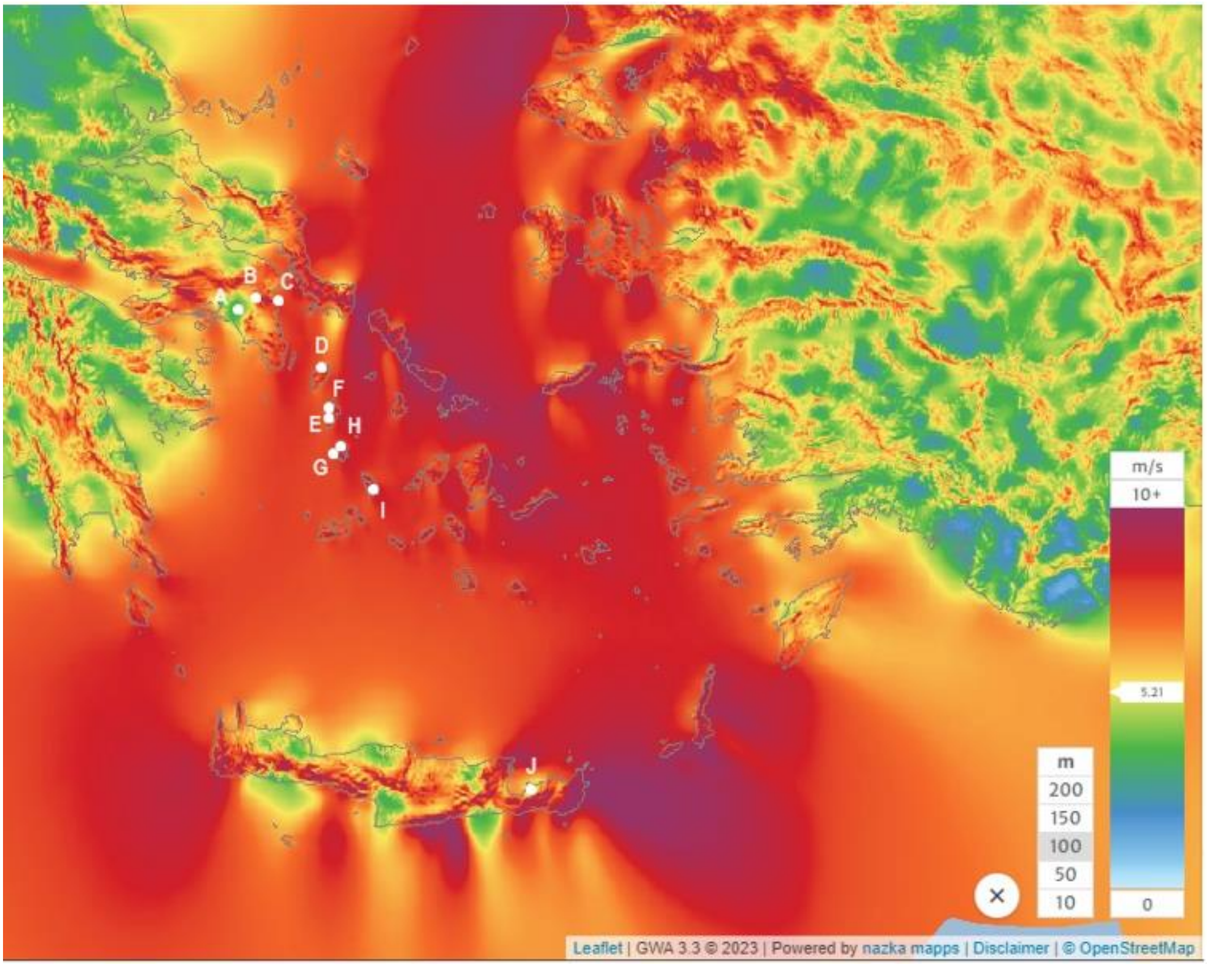


Figure 6.50. Map showing wind speeds in the Aegean with APF sites located. Base map from https://globalwindatlas.info/en/ edit by author (Dec 2023). A - Athenian Acropolis; B - Gerakis, Attica; C - Raphina, Attica; D - Kephala, Keos; E - Sideri, Kythnos; F - Paliopyrgos-Aspra Spitia, Kythnos; G - Avessalos; H - Kephala, Seriphos; I - Akrotiriaki/Skali; Siphnos; J - Chrysokamino, Crete. Wind speed gradient in m/s = meter per second.

Site	**Location of smelting site**	**Relation to Meltemi**
A - Athenian Acropolis	Southern slope of hill	The Meltemi circles across mainland, will be experienced on higher ground.
B - Gerakis, Attica	On slope of hill (direction not detailed)	The Meltemi circles across mainland, will be experienced on higher ground.
C - Raphina, Attica	East coast, exposed promontory	The Meltemi comes from the north, to the south between Greece and Turkey in the Aegean sea and will hit the east coast of mainland Greece.

D - Kephala, Keos	North facing promontory	The Meltemi blows from north to south across the Aegean sea and the Cycladic islands
E - Sideri, Kythnos	North-east facing coast	The Meltemi blows from north to south across the Aegean sea and the Cycladic islands
F - Paliopyrgos-Aspra Spitia, Kythnos	c.250m above sea level on the southern slopes of hill	The Meltemi is coming from the north, but at this point starts to split and move south-west moving between the coast of mainland Greece and the west of Crete and south-east between the west coast of Turkey and the east of Crete.
G – Avessalos, Seriphos	North facing promontory	The Meltemi is coming from the north, but at this point starts to split and move south-west moving between the coast of mainland Greece and the west of Crete and south-east between the west coast of Turkey and the east of Crete.
H - Kephala, Seriphos	North facing promontory	The Meltemi is coming from the north, but at this point starts to split and move south-west moving between the coast of mainland Greece and the west of Crete and south-east between the west coast of Turkey and the east of Crete.

Table 6.5. Table showing the locations of the smelting sites in relation to the Meltemi winds, the letters used to annotate the sites on the maps has been included also.

Table 6.5. shows the location of the smelting sites in relation to the Meltemi winds. Understanding the location of these sites in relation to the Meltemi winds can help us look beyond nature and distribution of material remains but enable us to see how the site, its location, structure, layout and material actually connect to human behaviour or actions and allows us to consider factors such as human relationships, social landscapes, and cognitive decision-making (Whitley, 2017, 103), putting people and decision making back into the material culture. Locating smelting sites on Cycadic islands would not be sufficient on its own to experience the high speed winds, the smelting apparatus would also need to be located on an exposed promontory facing

into the wind. The Meltemi winds circle across mainland Greece and Turkey, then come down the Aegean seas between mainland Greece and Turkey, then towards the southern Cycladic islands it starts to split and goes south-west moving between the coast of mainland Greece and the west of Crete and south-east between the west coast of Turkey and the east of Crete. The location of each smelting site, demonstrates that each one has been placed within that area in a location which would experience the strongest gusts of winds. With the sites in main land Greece being on the sides of hills, then the northern Cycladic islands having their sited location on north facing promontories, the more southern Cycladic islands have their sites on promontories which are more south-west facing to experience the Meltemi as it splits off to go between Crete and the mainland and then finally the site on Crete as it is on the north facing edge, is on a north-facing promontory. This demonstrates that the smelters were aware of the wind, its direction and speed and wanted to take advantage of it. This is also supported, by the fact that there are not often domestic sites associated with these smelting sites, but when there are, they are located away from the promontory edge, which would be more sheltered from the wind (Table 7.1.).

6.3.2. Discussion of GIS analysis

The GIS analysis of the copper smelting sites in the Aegean and the variation in evidence of the APF, mapped against the wind speeds in this region, has enabled the following conclusions:

A: The distribution of the copper smelting sites in the Aegean has demonstrated that the APF technology is an isolated tradition, within this region. This has not been discussed previously.

B: The plotting of sites in relation to their chronology has suggested that the practice moved from the mainland to windier locations; another new realisation.

C: The plotting of the differences in material evidence, such as thickness of the ceramic furnace walls, and the types of evidence present such as tuyères, has helped reveal that there was one island, Kythnos, where the thickness of the APF walls is different to elsewhere. A related finding is that the presence of tuyères is associated to the thicker-walled furnaces, or is a later adaption to the technology (such as at Chrysokamino). The tuyères found at sites with thicker-walled furnaces could represent the need to add forced air into these furnaces through the perforations, or increase areas that are not as hot, as the efficiency of the air being dragged into the thicker-walled furnaces is not as good as that of the thinner-walled furnaces, which was demonstrated in Campaign Three of the experimental reconstructions, presented earlier in this chapter. This can provide an explanation for the tuyères, and shows that they are not part of the main functioning of the APF as was thought in previous reconstructions and experiments (Pryce *et al*., 2007; Catapotis *et al.,* 2008). Or the tuyères were used at the stages of the process for melting and casting.

D: Mapping the location of the APF paired with wind speed data also strengthened the theory that the motivation for the locations of these sites was the presence of strong winds, which were the main resource needed for this process. This supports the theory that these furnaces were wind powered, rather than bellow driven as previously thought (Pryce *et al*., 2007; Catapotis *et al.,* 2008).

6.4. Microscopy

Samples were taken from the metallurgical material from Campaigns One and Two, to be analysed under the microscope to identify structures and understand the internal firing conditions within the furnace. Samples were taken from the different types of metallurgical material identified during the macroscopic investigation, presented earlier in this chapter (6.1), namely slag, conglomerate, and copper prills. Three samples from each type of material were cut, mounted, ground, and polished, as per the method detailed in the methodology chapter (3.5.2.1.). Samples were taken from a variety of pieces, ensuring each different type of slag was tested from a morphological point of view, and samples were taken from different areas across the conglomerates, to gain a full representation of all the material. Structures were identified to assess the following:

A: Whether the internal environment was oxidizing, reducing or changeable.

B: If slag was cooled quickly or slowly; this can give an idea of the internal environment, as slag was not tapped.

C: How much of the conglomerate was partially reacted and what stages in the production of copper it was at.

D: Structures were compared to microscopy conducted on material from previous experiments (Pryce *et al*., 2007; Catapotis *et al.,* 2008) and from archaeological material (Bassiakos and Catapotis, 2006, p.340).

Identification of structures was based on training gained during my MSc studies, developed through consultancy work and teaching, with reference to publications of metallurgical micrographs (Scott, 1991) and analysis conducted on previous experiments (Pryce *et al*., 2007; Catapotis *et al.,* 2008) and from archaeological material (Bassiakos and Catapotis, 2006, p.340).

6.4.1. Campaign One

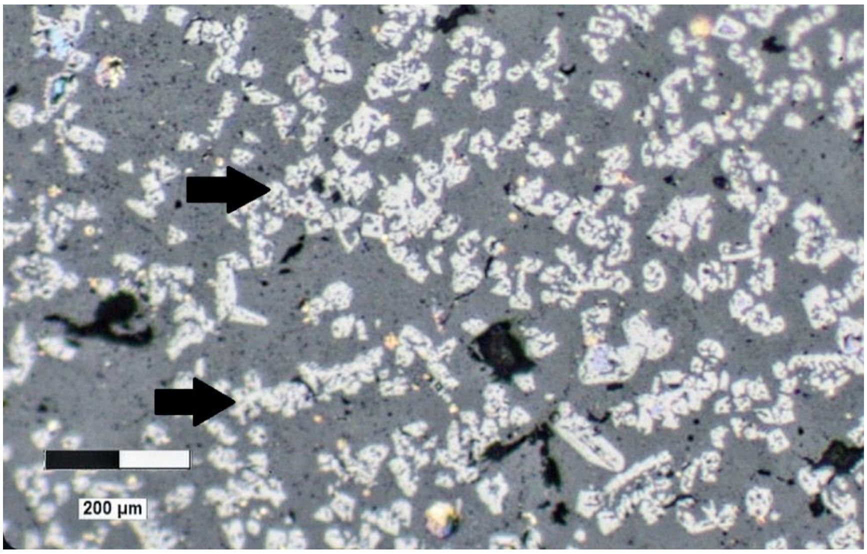


Figure 6.51. Micrograph of slag from Campaign One, showing slag matrix with frequent magnetite (examples of magnetite indicated with black arrow) 100x. (Marks, 2012, Figure 5.29).

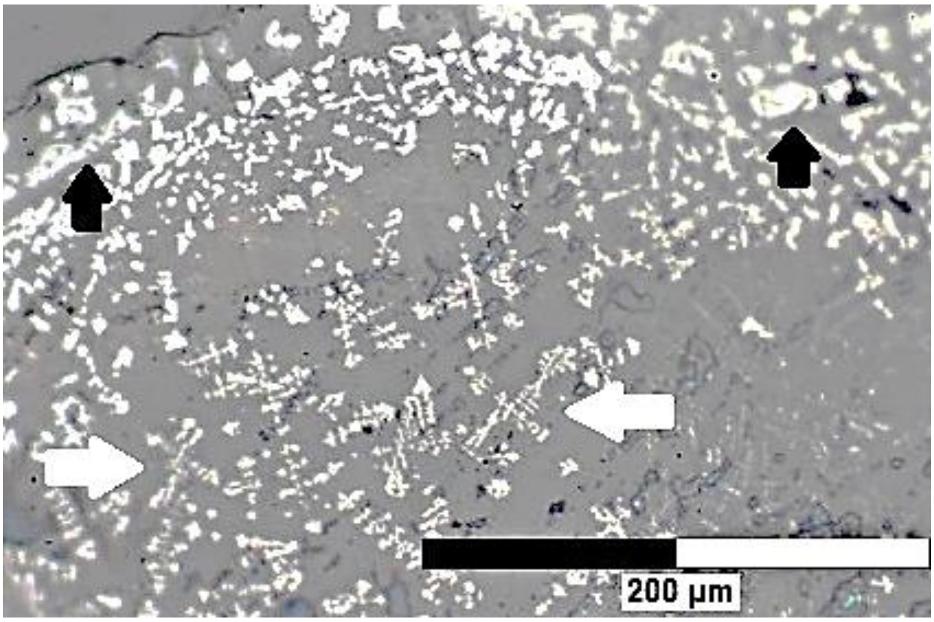


Figure 6.52. Micrograph of a slag part of the conglomerate from Campaign One showing mixed iron oxide dendrites with examples of magnetite (white arrows) and Wüstite (black arrows) co-existing which demonstrates that the furnace environment was mildly oxidising to mildly reducing. 200x. (Marks, 2012, Figure 5.30).

Microscopy of the slag part of the conglomerate and the slag pieces indicates that the atmosphere inside the furnaces during the smelt within campaign one was variable, changing from mildly reducing to mildly oxidising. This is demonstrated by the indeterminately structured iron oxides, such as mixed iron oxide dendrites (see *Figures* 6.51 and *Figure* 6.53). Delaffosite is also present, which indicates the atmosphere was mildly reducing (*Figure* 6.53). Delafossite and cuprite are copper phases which are associated with moderately reducing conditions. These two phases are present in the archaeological slags from Chrysokamino as can be seen in Table 6.6. However, Bassiakos and Catapotis (2006, p.348) detail them as being a rare occurrence in the slags and suggest that the conditions within the furnaces at Chrysokamino were more reducing. The occurrence of these structures in the slags from the experimental campaigns, where copper was formed and trapped within other slags, demonstrates that slags with such structures in, were probably formed close to a perforation, in an instance when air was being dragged in creating the mildly reducing atmosphere. Where the centre of the furnace remained reducing.

In addition to the variable environment, with changes between reducing and oxidizing states, there is also evidence of rapid cooling, which can be seen by sulphide prills exhibiting Widmanstätten structures, as well as the difference in structure of the dendrites. The cooling rate of a slag will alter the dendritic structure of Wüstite; the more rapid the cooling is, the longer and finer the arms of the dendrites will be (Bassiakos and Catapotis, 2006, p.338). Long fine dendrites are present within the slags of Campaign One (*Figure* 6.53), but there are also smaller dendritic structures and clear areas of banding, showing that different cooling rates took place.

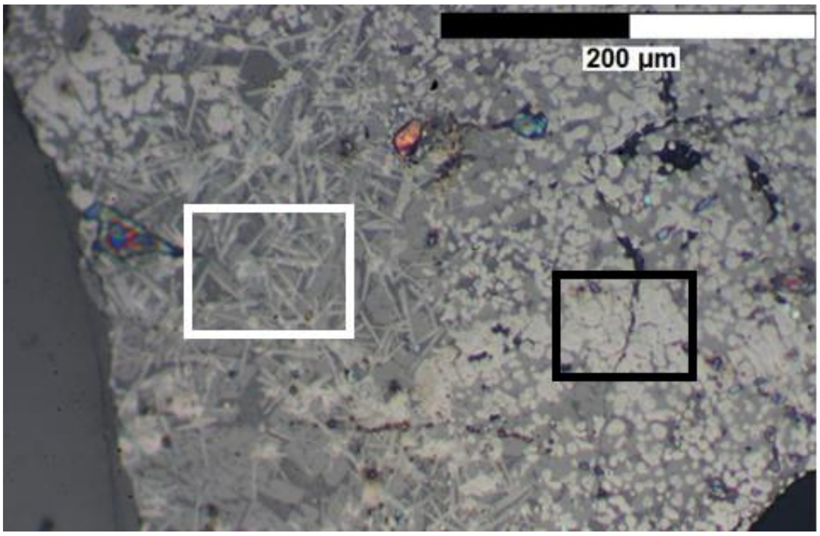


Figure 6.53. Micrograph of slag part of the conglomerate from Campaign One showing Wüstite (black outlined box) coinciding with Delaffosite (white outlined box) structures. 200x (Marks, 2012, Figure 5.32.).

The changing environment is most clearly evidenced by areas of banding, which can be seen within the slag parts of the conglomerate and the slags (*Figure* 6.54).

This is "where mixing of iron oxide dendrites occur, including co-existing examples of magnetite and wüstite. This demonstrates the product has gone through different cooling rates during its formation" (Marks, 2012, p.87), with each 'band' being created whilst experiencing different atmospheric conditions, such as oxidizing and reducing. This change in environment could be due to air being dragged into the furnace, increasing the oxygen levels. The main difference between each band is the length of the arms of the dendritic structures, identifying that they were formed during different cooling rates, as a consequence of the effects of different amounts of air being brought into the furnace through the perforations. As the slag and conglomerate moves within the furnace, from the top to the bottom, as the charcoal burns down (see description of smelting process in Chapter 2, section 2.2.3.), there may be times when the conglomerate and slag is blocked from this air by charcoal. I feel the banding is a result of the changeable environment within the furnace, due to it being wind powered. A bellow powered furnace would have a more consistent environment in which the air flow is constant, due to multiple bellows being pumped intermittingly, meaning there is always air coming into the furnace. In contrast the wind gusts ebb and flow, making the pressure change as a result of more and less air being dragged into the furnace at different times. Banding of this nature is also present within the slags of the archaeological material from Chryoskamino, although Bassiakos and Catapotis (2006, p.340) interpret the bands as being formed by the “folding” of a relatively viscous slag, while it was being tapped out of the furnace. Magnetite bands indicate solidification by contact with the air, and these authors believe that this contact occurred as slag was tapped and released from the furnace (Bassiakos and Catapotis, 2006, p.340). The furnaces in Campaign One were not tapped and this banding was still present.

Copper prills are present macroscopically within the sample. There are also copper prills in associations with sulphides within the conglomerate (*Figure* 6.55), indicating that more copper was being formed and perhaps more copper prills would be present, if the conditions had been more stable or the material had been left in the furnace to smelt for longer.

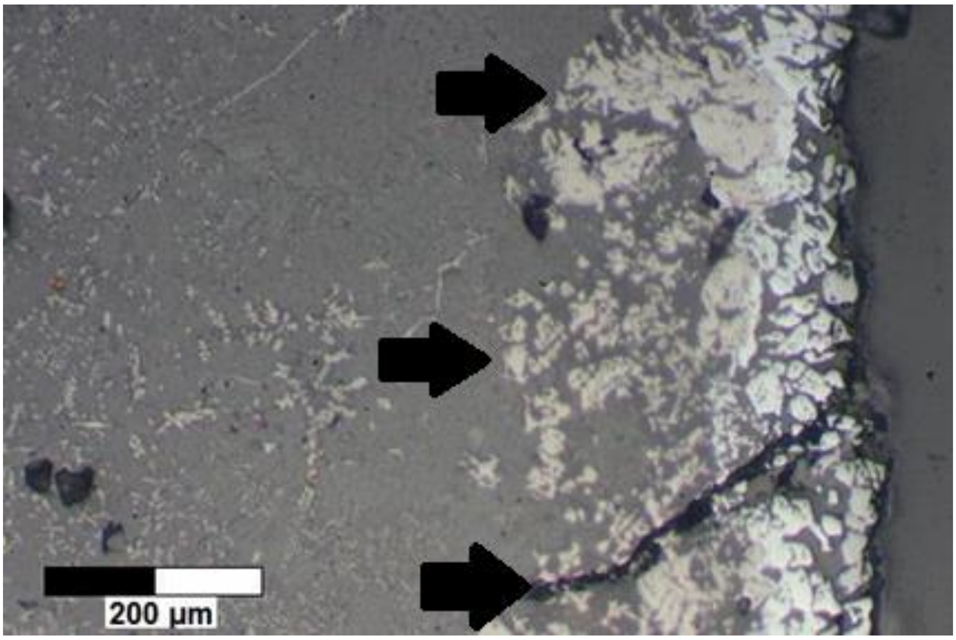


Figure 6.54. Banding of iron oxide structures. Arrows pointing to edge of one band. 100x (Marks, 2012, Figure 5.33).

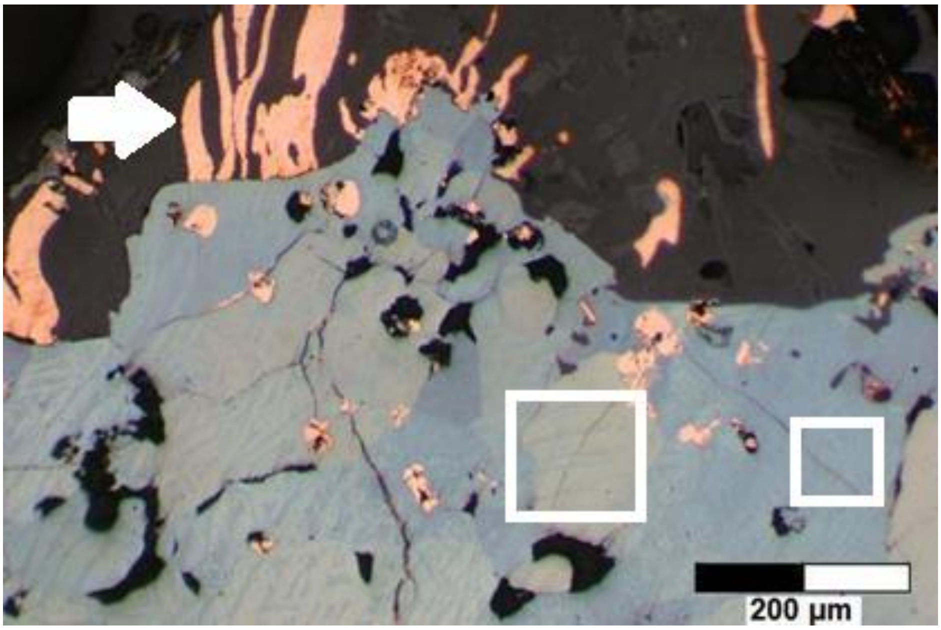


Figure 6.55. Metallic copper (indicated by white arrow) in association with sulphides (indicated by white outline box) 100x. (Marks, 2012, Figure 5.28.).

6.4.2. Campaign Two

As copper ore could not be used in Campaign One, a second campaign was conducted to enable an assessment of the slags smelted from a copper ore, and also to test the repeatability of the results (see Chapter 3 section 3.2.1 for more detailed explanation). The assessment of the slags from this campaign will enable another level of confirmation of the environmental conditions experienced within the APF when being powered solely by wind power, without the use of bellows. This confirms that the same structures and materials are produced when using copper ore as when using the substitute materials used in Campaign One, to add a more accurate test of this method. The method of microscopic analysis was the same as that used in Campaign One.

The analysis of the slag and conglomerate material from Campaign Two shows that the structures present in the slags are comparable to those from Campaign One, with banding being present again throughout the samples. This can be seen by the mixing of magnetite and Wüstite (*Figures* 6.56 and 6.57) alongside iron oxide dendrites. This mixing indicates again that the environment was variable where the slag was formed, changing between mildly reducing to mildly oxidizing at different points in the formation of the material. Some of the slag would have been formed near the inside of the wall of the furnace, solidified by the blast of air being dragged into the furnace. The interior of the furnace must have been reducing enough for metallic copper to form. Iron oxides and magnetite can be seen to be forming on the exterior parts of the conglomerate (*Figures* 6.57 and 6.58) showing that the conditions were at times sufficiently reducing for the formation of copper. We also see a band of copper prills forming along the outside part of the conglomerate (*Figure* 6.59), in addition to the larger copper prills identified macroscopically. The different sizes and shapes of iron silicate laths (*Figures* 6.56 and 6.57) and magnetite structures indicate that different cooling rates occurred during the formation of different parts of the conglomerate. As discussed in relation to Campaign One, this could have occurred as a result of the amount of air being pulled into the furnace through the perforations, due to the fluid dynamics creating pressure areas in and outside of the furnace (Chapter 4, section 5.4). The are some copper prills present, which are large enough to be handpicked from the crushed conglomerate. These could be handpicked and then consolidated by melting together in a crucible. However, if the conglomerate was to be crushed and re-smelted, more copper could be formed, from material such as that shown in *Figure* 6.59.

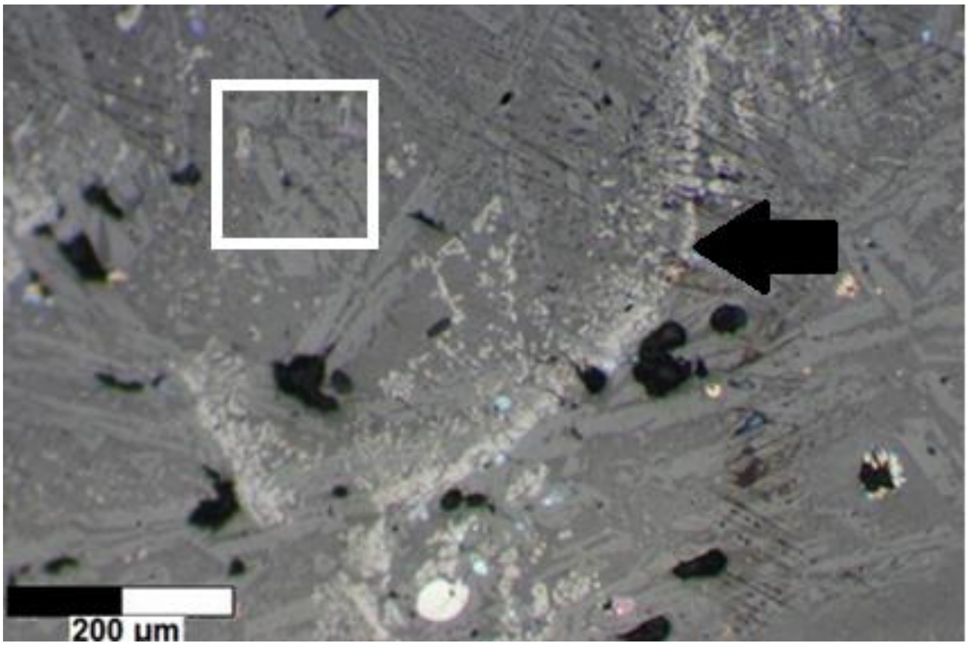


Figure 6.56. Micrograph of slag part of conglomerate from Campaign Two, showing banding of structures. High copper content silicates (white outline box), with a band of iron oxide dendrites in the centre (indicated by black arrow), demonstrating examples of magnetite and Wüstite co-existing

(demonstrates that furnace environment was mildly oxidising to mildly reducing). 100x (Micrograph taken by author).

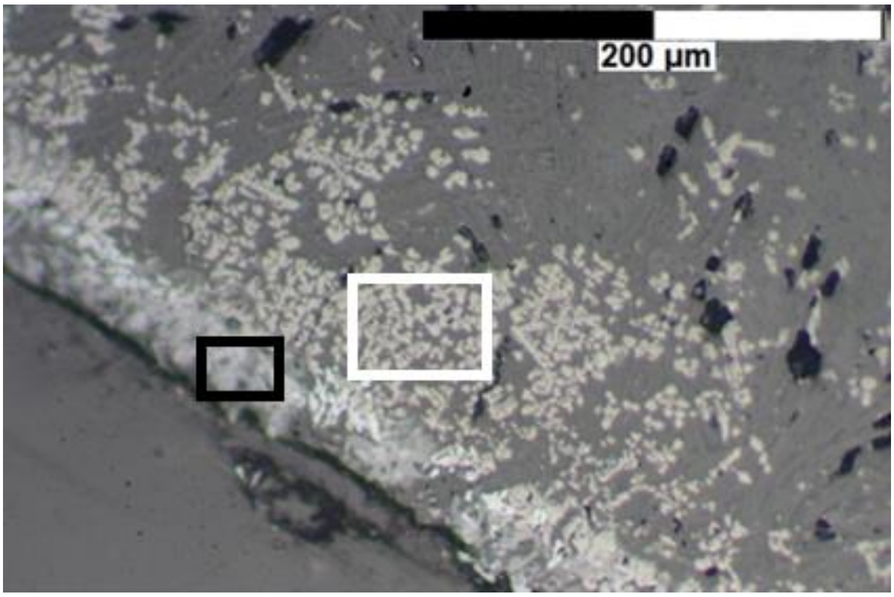


Figure 6.57. Micrograph of slag part of conglomerate from Campaign Two, showing a band of iron oxides (white outline box) towards the outside of the conglomerate (bottom left), next to a band of Wüstite structures (black outline box) on the very edge. 200x (Micrograph taken by author).

The microscopic analysis identified that the slag material from the conglomerate contains a mixture of Wüstite and magnetite, albeit with more magnetite present. The Wüstite is present in the dendritic form, and the magnetite structures are generally present as skeletal structures in the middle of the samples. The difference in these structures is due to the different cooling rate experienced during the formation of these areas. When the cooling is faster, this results in rapid crystal growth.

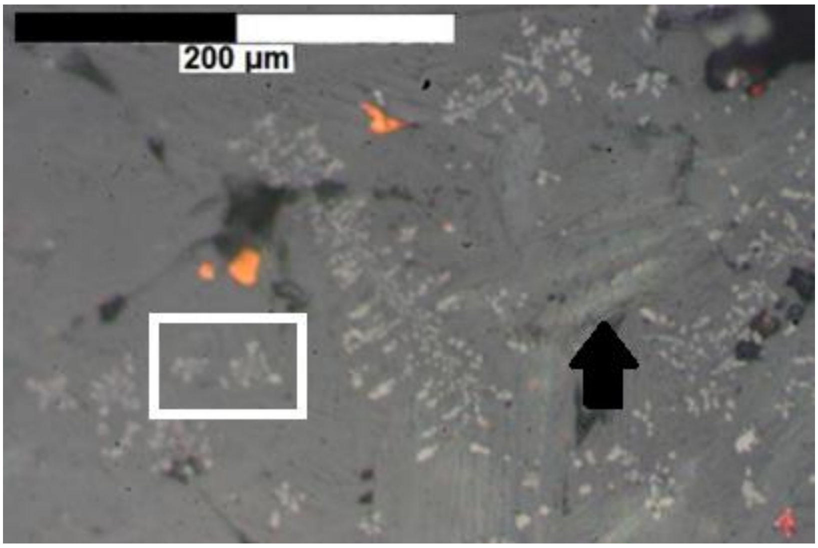


Figure 6.58. Micrograph of slag part of conglomerate from campaign two, showing iron silicate laths (indicated by black arrow), with magnetite structures forming (indicated by white outlined box), 200x (Micrograph taken by author).

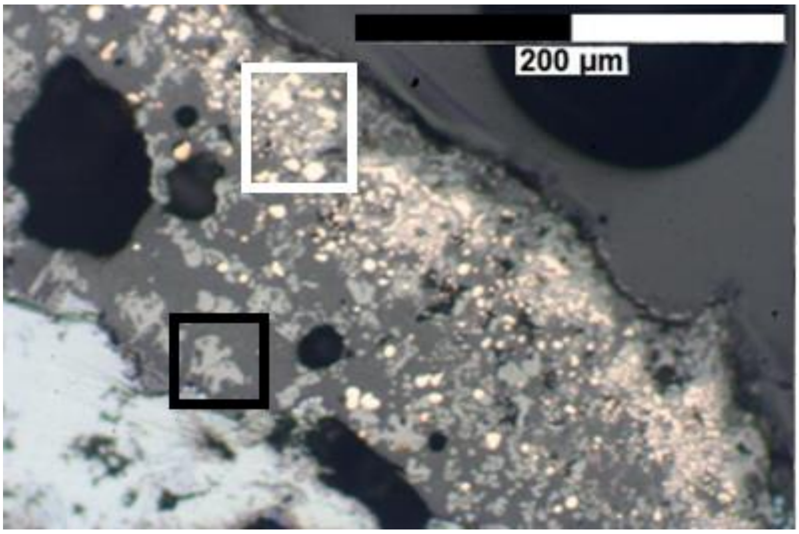
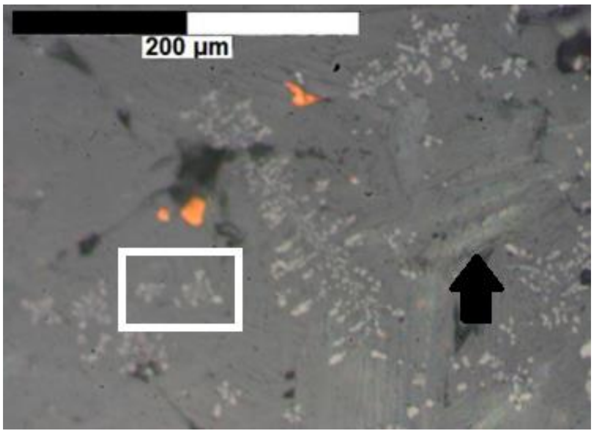


Figure 6.59. Micrograph of slag part of conglomerate from campaign two, showing copper sulphides (black outline box) with copper prills (white outlined box) at the edge of the conglomerate. Magnetite spinels in association with sulphide in the centre. 200x (Micrograph taken by author).

6.4.3. Discussion of microscopy

(image redacted for copyright purposes) Micrograph showing typical micro-structures in slags from Chrysokamino (Bassiakos et al., 2006, Figure F.8).	 Figure 6.60. Micrograph of slag part of conglomerate from campaign two, showing iron magnetite structures forming (indicated by white outlined box), 200x (Micrograph taken by author).

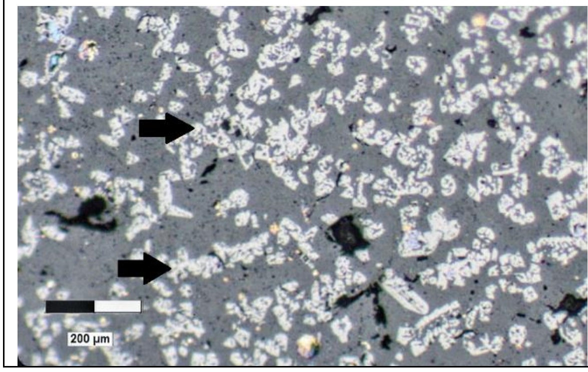


Figure 6.61. Micrograph of slag from campaign one, showing slag matrix with frequent magnetite (examples of magnetite indicated with black arrow) 100x. (Marks, 2012, Figure 5.29).

Table 6.6 Table comparing slags from Campaign One and Two with those from excavation.

The presence of mixed iron oxides, associated with mixed structures of magnetite and Wüstite, as well as bands of different structures within the slag material, is a characteristic of the metallurgical material from Campaigns One and Two as well as from the excavated material at Chrysokamino (Table. 6.6). The presence of both these types of iron oxide structures, particularly the dendritic structure of Wüstite (Table. 6.7.), is caused by the material (slag and conglomerate) becoming solid under different cooling rates. The analysis of the slag from Campaigns One and Two demonstrates that the environments within the furnace from the experimental campaigns using wind power are comparable to those which existed within the furnaces at Chrysokamino (Bassiakos and Catapotis, 2006, p.348), as discussed above. In addition to the mixed variations of iron oxides, magnetite and Wüstite, there are also different stages and shapes of crystal growth, which are determined by the cooling rate. This is present within the samples from Chyrsokamino and the material analysis from the experimental smelts.

(image redacted for copyright purposes)

Micrograph showing typical micro-structures in slags from Chrysokamino (Bassiakos et al., 2006, Figure F.8).

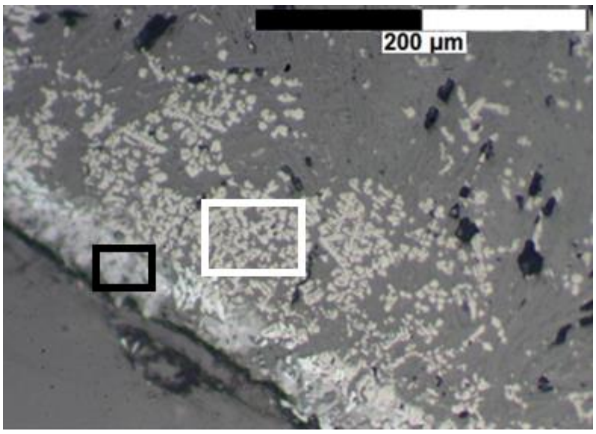


Figure 6.62. Micrograph of slag part of conglomerate from campaign two, showing a band of iron oxides (white outline box) towards the outside of the conglomerate (bottom left), next to a band of Wüstite structures (black outline box) on the very edge. 200x (Micrograph taken by author).

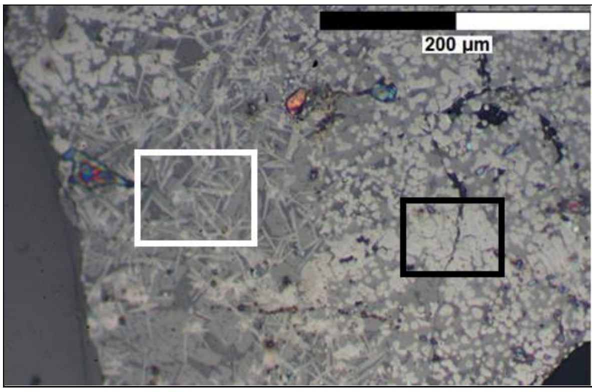
	Figure 6.63. Micrograph of slag part of the conglomerate from campaign one showing Wüstite (black outlined box) coinciding with Delaffosite (white outlined box) structures. 200x (Marks, 2012, Figure 5.32.).

Table 6.7. Table comparing micrographs of slags from the experimental campaigns with slags from the excavation showing comparable structures of mixed iron oxides, associated with mixed structures of magnetite and Wüstite.

Banding is also visible within the micrographs of the analysis from the slag samples excavated at Chrysokamino (Bassiakos *et al*., 2007, Figure F.6, p.338). If a furnace was being powered by bellows, it is assumed that the internal environment will be more consistent since the bellows are pumped in tandem, so there is always air being pumped in, maintaining consistency of the internal environment. As the model presented by Bassiakos and Catapotis (2006, p.340) considers the furnaces as being bellow driven, this may have led them to the interpretation that the banding in the slags from Chrysokamino was formed by the slags being tapped, as this would put them into a different environment, with the air outside the furnace being different to inside. However, the slags from Chrysokamino show multiple layers of banding, which would be difficult to create through tapping a slag, even if folds are created, as these authors suggest. This is because the slag coming out of the furnace and solidifying due to lower temperatures is a single event, not multiple events. The smelts which took place in Campaigns One and Two did not include tapping of the furnace, and this banding is seen within slags from both campaigns (Table. 6.7.). Therefore, I propose that the banding is not formed during the tapping process, but rather is formed whilst the slag material is within the furnace, and at points at which the material is in a position closer to the wall of the furnace, and so is cooled due to air being dragged into the furnace through a perforation. The multiple layers of the slag, which reflect different cooling rates, are created as the conglomerate builds over time during the smelt, and by the changeable environment within the furnace, as it is not experiencing the constant airflow of bellows, but rather a more changeable environment due to being wind powered.

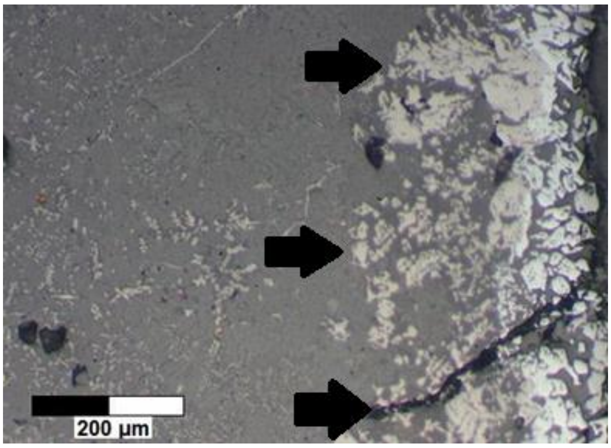
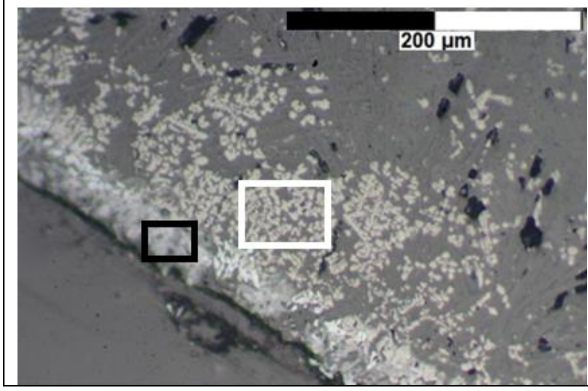
(image redacted for copyright purposes) Micrograph of slag showing magnetite “bands” forming three slag “layers” (Sample A04) (Author, Aug 2012). (Bassiakos et al., 2006, Figure F.5).	 Figure 6.64. Banding of iron oxide structures. Arrows pointing to edge of one band. 100x (Marks, 2012, Figure 5.33).
 	Figure 6.65. Micrograph of slag part of conglomerate from campaign two, showing a band of iron oxides (white outline box) towards the outside of the conglomerate (bottom left), next to a band of Wüstite structures (black outline box) on the very edge. 200x (Micrograph taken by author).

Table 6.8. Table showing comparison of samples from excavation and the experiments which both have bands of different structures.

The experimental smelts carried out in Campaigns One and Two produced copper prills which demonstrate that although the internal atmosphere of the recreated APF is not completely reducing all of the time, it does not need to be, in order for the smelting process to be successful. The archaeological material from the sites where the APF is present (Chapter 4) demonstrates a process of smelting and consolidating. This would indicate that the smelting process represented at these archaeological sites likely produced a conglomerate which contained copper prills and had to be crushed and consolidated to create copper objects.

6.5. pXRF analysis results

Chemical analysis by pXRF was conducted as part of this thesis on the ceramic furnace fragments from Campaigns One and Two, in order to assess the levels of copper left on the interior and exterior of the furnaces after smelting. This analysis can be compared to analysis of ceramic fragments from archaeological contexts, and also with fragments from other experimental campaigns. A portable XRF was used as that is what was available within the budget of the thesis project, but also as the author hoped to show how it could be a useful tool and be used in future as non-destructive analysis on archaeological material. The fragments from Campaigns One and Two were analysed by the author, using pXRF, a number of years after the smelting activity was conducted (Campaign One – 9 years after, Campaign Two – 6 years after). When the experiments were conducted, pXRF analysis had not been conducted in this way on ceramics, and therefore, there were no data with which to compare it. Now, however, this analysis has been conducted on a number of experimental campaigns associated with copper production (Mylneic, 2016; Bruyere, 2018 – reconstruction of Balkan ceramic structures associated with copper production) and on excavated material from the site on the Athenian Acropolis in Attica (Dimitriou, 2017, p.25). Six of the ceramic sherds of perforated furnaces from the Neolithic 'hut' site on the Athenian Acropolis in Attica have had XRF analysis carried out on them, and copper residues are present (Dimitriou, *pers comms.;* Bassiakos *et al.,* in prep). These ceramic fragments (discussed in Chapter 4, section 4.2.1.5.3.1) do not look metallurgical from macroscopic analysis, as they are not heavy altered in colour, being a pale pinkish orange rather than a dark red or black, and have no vitrification or metallurgical debris adhering to them. This recent presence of comparable data, made pXRF analysis on these furnace fragments worthwhile, to enable comparison.

The aims of the pXRF analysis are:

A: To assess whether the copper imprint left on a ceramic structure varies when different processes take place inside the furnace. For example, whether it would it be possible to tell the difference between the chemical imprint left by smelting copper ore compared to that produced by ore roasting or casting copper, and whether this can help us understand the function of ceramics used for metallurgical processes from excavation.

B: To compare the pXRF data from the ceramic fragments of Campaigns One and Two with the ceramic fragments from Campaign Three.

C: To compare the pXRF data from the APF reconstruction experiments (Campaigns One, Two, and Three) with pXRF analysis from ceramic fragments from experimental reconstructions of ceramic chimneys from the Vinca period Balkans (Mlyniec, 2016; Bruyere, 2018), which were assessed by the author (Chapter 4, section 4.3.2.6), who concluded that they were used for roasting copper not smelting copper.

D: To test a theory about the possible application of pXRF to identify the function of metallurgical ceramics, by comparing analyses of experimental reconstructions. The theory tests whether the levels of copper identified on different parts of the ceramic material used for smelting copper can identify patterns and reveal what function was served by metallurgical ceramics, to differentiate between structures from smelting, casting, and ore roasting.

The fragments from Campaign One were brought back to the lab after the furnace was dismantled, and were photographed and then stored in a sealed plastic storage box. The fragments from Campaign Two were left in the field for 1 month after the smelt, before being brought back to the lab. This was done to determine what the effects of weathering would be, as they were left out in the natural environment. Once brought back to the lab, they were also stored in a sealed plastic storage box. The storage of these fragments meant there could be no contamination.

The pXRF results from Campaign Three (Giannakopoulou, 2018; Giannakopoulou, *et al.,* 2022), which reconstructed the thicker walled variation of the APF from the sites on Kythnos, are presented in this Chapter to enable comparison and discussion, as they are not published elsewhere. This experimental campaign was designed by the author, to follow the methods used in Campaign One and Two, but the experiment and analysis was carried out by PGT students as part of their module assignment. The experiments and results of the pXRF analysis conducted on the Balkan furnaces was presented in Chapter 4 (section 4.3.2.6.), but a comparison and discussion of the data will be included in this section. The experiments on the Balkan furnaces were also designed and supervised by the author, but were carried out as part of other PhD student project work. The fragments from Campaign Three and from the two Balkan furnace experiments were brought back to the lab straight after the smelt was completed, and were analysed immediately (Giannakopoulou, 2018; Giannakopoulou, *et al.,* 2022; Mlyniec, 2016; Bruyere, 2018).

6.5.1. pXRF analysis of ceramic furnace fragments from Campaign One

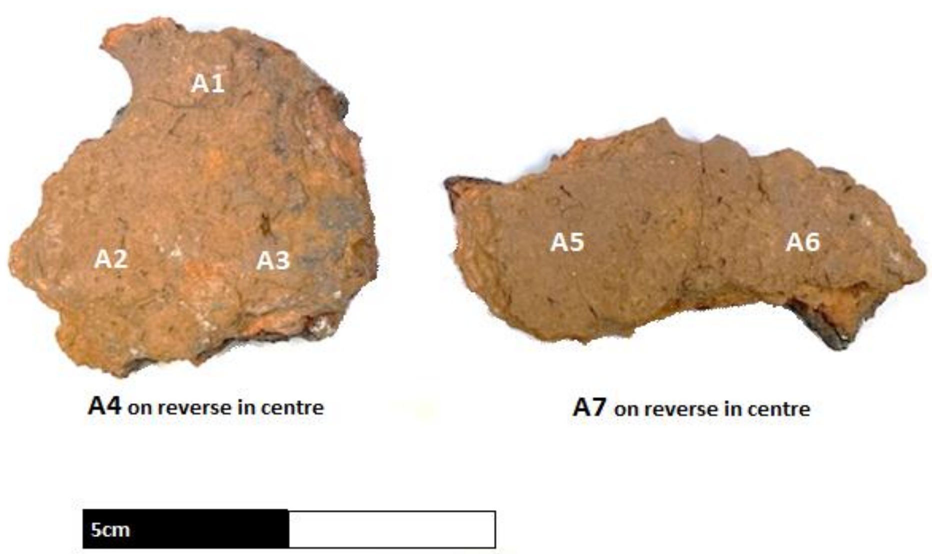


Figure 6.66. Image of furnace fragments, exterior surface (orange/red) up, from Campaign One showing locations of XRF readings (A1-A7). Photo taken and edited by author.

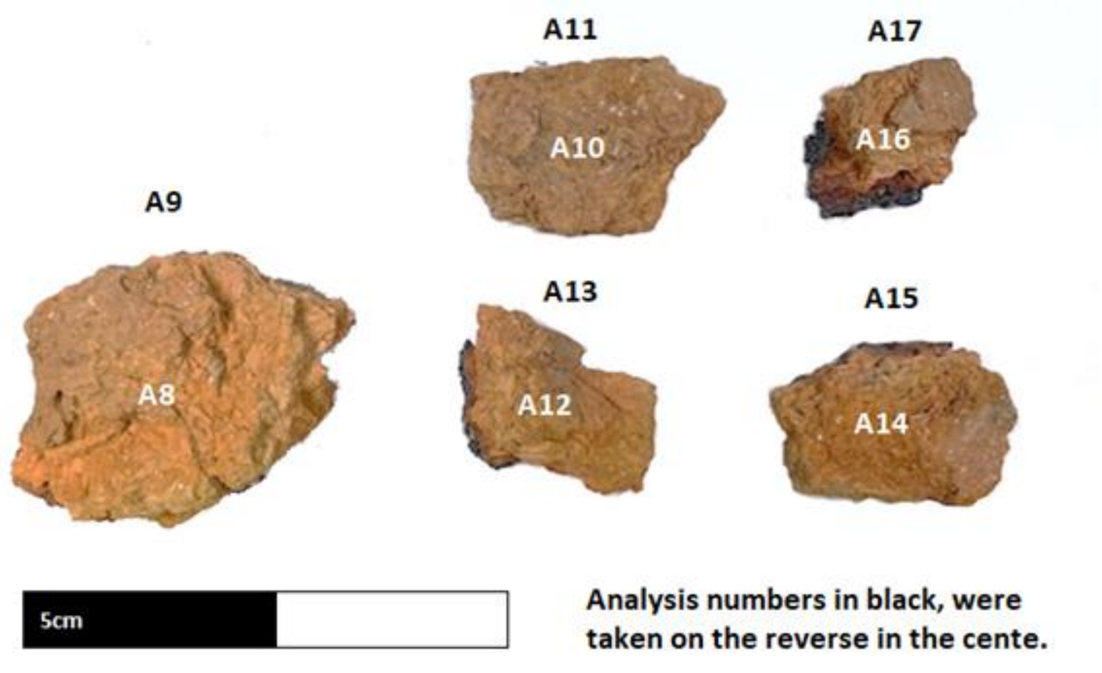


Figure 6.67. Image of furnace fragments from Campaign One, exterior surface (orange/red) up, showing locations of XRF readings (A8-A17). Photo taken and edited by author.

SAMPLE	Cu/ppm
APF exp1 A17	4598
APF exp1 A16	0
APF exp1 A15	3355
APF exp1 A14	0
APF exp1 A13	2358
APF exp1 A12	114
APF exp1 A11	407
APF exp1 A10	0
APF exp1 A9	27076
APF exp1 A8	0
APF exp1 A7	3407
APF exp1 A6	81
APF exp1 A5	0
APF exp1 A4	2745
APF exp1 A3	288
APF exp1 A2	38
APF exp1 A1	613

Table 6.9. pXRF readings of copper on the ceramic furnace fragments of Campaign One, readings taken in ppm by the author.

The method for taking the readings and the settings used is detailed in Chapter 3 (Section 3.5.2.2.) Readings were taken across the interior and exterior of ceramic samples from Experimental Campaigns One and Two. Multiple readings were taken on each side of each fragment, and each reading was taken three times and an average was calculated. The only element being assessed is copper, as this analysis is being used to see if copper residues are being left on the ceramic furnaces due to pyrotechnical processes using copper taking place. This is comparable with the analysis carried out on experimental fragments (Giannakopoulou, 2018;

Giannakopoulou *et al.,* 2022; Mlyniec, 2016; Bruyere, 2018) and archaeological fragments (Bassiakos, *et al.*, *in prep*). The pXRF analysis from the ceramic fragments of Campaign One shows that the levels of copper on the exterior side of the furnace fragments are below the level of detection or very low (under 613ppm). The readings on the interior of the furnace fragments are much higher (in their thousands and tens of thousands; between 2358-27076ppm), and this indicates that copper is present on the ceramic fragments, but predominantly on the interior of the fragments. This can be considered as being due to the smelting process taking place within the furnace and the copper being transferred onto the interior of the ceramic furnace structure, as a result of the direct contact of the copper mineral and/or the copper product being produced. The lower amounts detected on the exterior of the ceramic furnace structure could come from small amounts of copper ore (crushed) falling on the exterior when being added into the furnace, or from copper particles being present in the flames and gas being emitted through the perforations and being deposited; they come into contact with the ceramic on the exterior. The amount of copper present will be lower, as this will occur less frequently than the contact within the furnace.

6.5.2. pXRF analysis of ceramic furnace fragments from Campaign Two

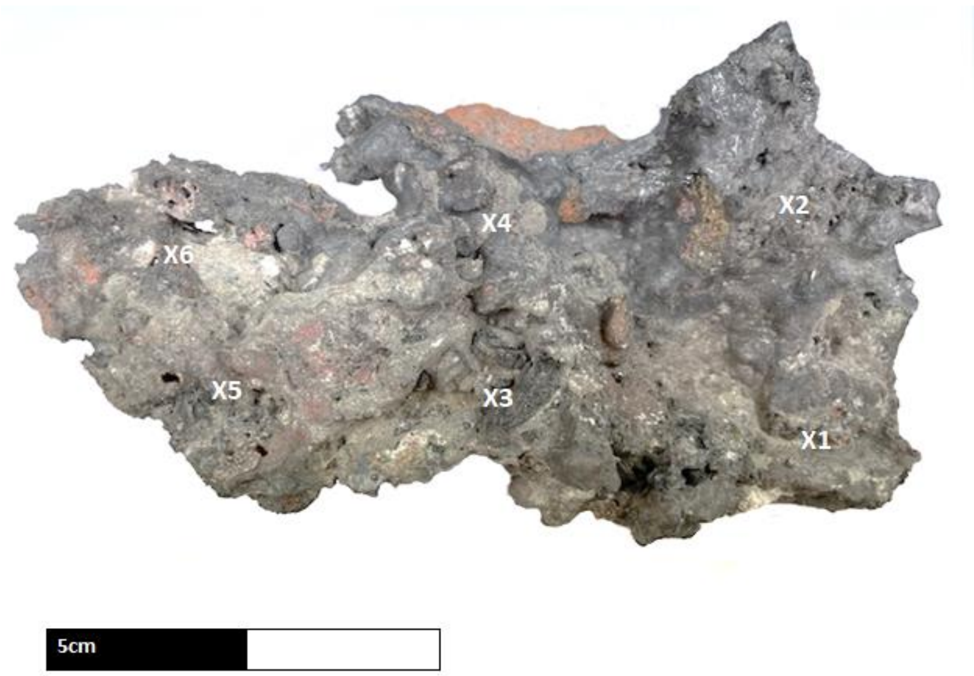


Figure 6.68. Image of furnace fragment from Campaign Two showing locations of XRF readings (X1-X6), interior of fragment with slag adhering to surface. Photo taken and edited by author.

Figure 6.69. Image of furnace fragment from Campaign Two showing locations of XRF readings (X7-X11). Exterior of furnace fragment (orange/red ceramic), interior has conglomerate attached. Photo taken and edited by author.

Figure 6.70. Images of furnace fragments from Campaign Two showing locations of XRF readings (X12-X15). Left: exterior of the fragment (orange/red ceramic), right: interior of the same fragment with vitrification adhering to interior surface. Photo taken and edited by author.

Figure 6.71. Image of furnace fragments from Campaign Two showing locations of XRF readings (X16-X25). Left: exterior of the fragment (orange/red ceramic), right: interior of the same fragment. Photo taken and edited by author.

SAMPLE	Cu/ppm	SAMPLE	Cu/ppm
APF exp2 x25	112372	APF exp2 x12	1865
APF exp2 x24	134591	APF exp2 x11	177
APF exp2 x23	163342	APF exp2 x10	958
APF exp2 x22	123766	APF exp2 x9	383
APF exp2 x21	328	APF exp2 x8	776
APF exp2 x20	281	APF exp2 x7	671
APF exp2 x19	424	APF exp2 x6	143725
APF exp2 x18	226	APF exp2 x5	113912
APF exp2 x17	508	APF exp2 x4	135925
APF exp2 x16	117	APF exp2 x3	89790
APF exp2 x15	113556	APF exp2 x2	77635
APF exp2 x14	174438	APF exp2 x1	133148
APF exp2 x13	549		

Table 6.10. pXRF readings of copper on the ceramic furnace fragments from Campaign Two, readings taken in ppm, by the author.

The pXRF analysis data from Campaign Two is comparable to that of Campaign One, with the detection of copper on the outside of the fragments being much lower, with the readings (ppm) being in the hundreds (c.100-900ppm) in comparison to the readings on the interior of the furnace, which were in the tens and hundreds of thousands (c.70,000-140,000ppm). The one exception to this is reading X12, which is 1865ppm. This is still much lower (as it is only in the thousands, not tens of thousands) than the readings on the interior, but it is higher than the other readings on the external surface. This reading was taken near a perforation where the colour of the clay had been altered to black. Perhaps this colour alteration was created by flames touching the clay, as we see from the experiments that flames were coming out of the perforations, and it could be considered that there were copper particles in the fumes which have been deposited onto the clay. These clay furnace fragments were left outside, exposed to the weather for a month (this included rain), but the levels of copper, especially in the interior, still remain very high, which indicates that archaeological material which has experienced weathering and deposition is likely to still bear copper on its surfaces, and that it will be possible to detect it using pXRF analysis. The clay fragments from Campaigns One and Two were both analysed years after the smelting took place, which shows that the copper adhered to the clay and will remain afterwards. We can therefore also expect to still see chemical data like this from archaeological fragments, depending on their deposition conditions.

6.5.3. pXRF analysis of ceramic furnace fragments from Campaign Three

Point of Analysis	**Reading: Cu/ppm**	**Point of Analysis**	**Reading: Cu/ppm**
1	0	6	15000
2	0	7	18000
3	0	8	0
4	48000	9	0
5	4000	10	0

Table 6.11. pXRF readings of copper on the ceramic furnace fragments of Campaign Three, readings taken in ppm (Giannakopoulou, 2018; Giannakopoulou et al., 2022).

The pXRF data from Campaign Three are limited, and readings were only taken in the interior of the ceramic furnace structure. The highest readings of copper are found to have been from the area which was close to the conglomerate or to where the conglomerate was formed (Giannakopoulou, 2018; Giannakopoulou *et al.,* 2022). Giannakopoulou (2018) suggested that the high readings were due to material which consisted of partial remains of the conglomerate remaining on the wall in this area (Giannakopoulou, 2018, p.4). This would mean that the high copper readings (see Table 6.11, readings 4-7) are actually analysing conglomerate adhering to the furnace, rather than ceramic material which has residues on it. The other areas analysed on the furnace wall did not reveal any traces of copper on them, which is considered by Giannakopoulou (2018) to demonstrate that the ore passing through the furnace did not leave a chemical imprint.

6.5.4. Discussion of pXRF analysis

The chemical analysis conducted by pXRF on the ceramic furnace fragments from Experimental Campaigns One, Two, and Three have demonstrated that copper remains can be detected on ceramic fragments, especially if copper was successfully smelted within the structure, and the metallurgical material (conglomerate and slag) adheres to the inner surface. The results from Campaign Three alone would suggest that copper readings can only be detected from areas where metallurgical material remains in contact with the ceramic. However, the analysis from Campaigns One and Two show that this is not the case. There are some low readings of copper on the exterior of the surface, but there were also areas of the internal ceramics which did not have metallurgical material such as slag or conglomerate adhering to them, and they still showed very high levels of copper. For example, from Campaign One, the readings A9, A11, A13, A15, and A17 (Table 6.9) were taken on the interior of the furnace, but these fragments did not have any metallurgical material adhering to them, nor were they discoloured black or vitrified, and they had readings between 407-4595ppm, except for A9 which was even higher at 27,076ppm. Readings A4 and A7 were taken on the interior of fragments which were vitrified, and read 2745ppm and 3407ppm. These readings show that the interior areas of the furnace, where there is no metallurgical material adhering to the ceramic, irrespective of whether the ceramic fragments are vitrified, have levels of copper high enough to be detected, and significantly higher than in the exterior of the furnace. From Campaign Two, readings X1-X6 (Table 6.9.) were taken from conglomerate material adhering to the interior of the ceramic fragments and read between 77635ppm and 143725ppm. These levels are extremely high, and are comparable with the readings of the conglomerate present on the ceramic fragments from Campaign Three, as they are at least in the tens of thousands (ppm). This indicates that metallurgical materials adhering to ceramic fragments will have a much higher reading of copper than the ceramic fragments which have copper present in other forms. For further comparison, readings X14 and X15 were taken from an area on the internal side of the ceramic fragments where they were vitrified; these areas had copper levels of 13556ppm and 174438ppm. Readings X22-X25 however were taken on non-vitrified areas of the ceramic fragments, which were also only slightly heat altered, being grey in colour, and had copper levels of 2035ppm and 4127ppm. This indicates that areas which do not have metallurgical material adhering to them, or are not vitrified, will have lower readings of copper, but they will still have identifiable readings, showing that copper smelting has taken place within them. This shows that furnace fragments which may not look metallurgical will still have levels of copper on them, as a successful smelt took place. However, ceramic structures which have used copper for other purposes, such as roasting, will not have levels of copper on them (Mylneic, 2016; Bruyere, 2018). This is because the chemical process to transform ore in to metallic copper has not happened and there has not been gasses containing metallic copper in them, reaching the ceramic material. This suggests that ceramic fragments which are not found alongside slag, or which do not have metallurgical material on them, can still be identified as having been used in copper smelting. It is not clear why the other readings from Campaigns Three did not provide readings of copper; perhaps the furnace was not kept full to the rim with charcoal, meaning that the smelting process only took place in the bottom half of the furnace, where the readings did contain copper.

6.5.5. Comparison of pXRF data with Balkan experiments

In order to assess how chemical analysis of ceramic furnace fragments can help us understand and identify the practice conducted within the furnace, comparison of pXRF analysis with other ceramic structures from experimental campaigns was undertaken.

Chemical analysis by pXRF was conducted on reconstructed conical ceramic structures which were used for experimental smelts. The structures reconstructed are based on archaeological examples believed to have had a metallurgical function in the Balkans. These experiments were carried out as part of two MSc dissertations (Mylneic, 2016; Bruyere, 2018). Two furnace types were tested: the Pločnik style, which is a tapered conical ceramic structure and has perforations (Radivojević and Rehren, 2015; Šljivar *et al.,* 2006), and the Belovode style (Sljivar, 2006; Radivojević, 2007; 2013, p.16), which is similar in shape, but the walls did not have perforations. These conical structures have been discussed in Chapter 4. Experimental campaigns (Mylneic, 2016; Bruyere, 2018) were carried out to try and smelt copper in these furnaces, to assess whether they were used for smelting. However, as discussed in Chapter 4, the smelts were not successful, as they did not produce any metallic copper. Analysis using pXRF was conducted after both attempts. The results from both sets of the pXRF analysis (Mylneic, 2016; Bruyere, 2018) showed that the amounts of copper (Cu) remaining on the furnace walls after the smelt was low. From the analysis of the campaign carried out by Mylneic (2016), no traceable readings were achieved on the external surface of the furnace structures. Copper was identified from readings taken on the internal surface of the Pločnik style chimney; of the eight readings taken, seven of these read between 89ppm and 366ppm (Mylneic, 2016, p.81-2). The readings from the Belovode style chimney resulted in 21 readings, with levels between 53.46ppm and 291.02ppm (Mylneic, 2016, p.84-5). The results from the campaign carried out by Bruyere (2018) was comparable to that by Mylneic (2016), with one of the furnaces from her experiments (B1 = Belovode style experimental furnace 1) not presenting any readings showing copper was present, with 4 out of 7 of the pXRF readings not being able to detect copper at all. The readings from the other furnaces in her experimental campaigns had an average of 50 ppm of copper (Bruyere, 2018, p.60). Although the copper ore had partially reacted in Bruyere’s (2018) experiments, the smelt was not successful as there was no metallic copper, even within a conglomerate. Therefore, as the copper did not go through the smelting process, it could be considered that the copper did not diffuse into the ceramic in the way it does when it is smelted. This then leads to the conclusion that for copper to be present on the furnace walls, it must come from the formation of copper when smelted from ore, rather than simply being from copper ore being present within the furnace. This indicates that the levels of copper on ceramic structures used for metallurgical purposes could help identify what process was taking place, for example whether it was ore roasting (low or no copper present) or smelting (high levels of copper).

6.6. SEM analysis

A selection of mounted samples, taken from the metallurgical materials produced during the experimental smelts in Campaigns One and Two, were chosen to undergo SEM analysis. Samples which had been used for the metallographic microscopic analysis from Campaigns One and Two were selected. Samples were taken from the different types of metallurgical material identified during the macroscopic evidence, presented earlier in this chapter (6.1): slag, conglomerate, and copper prills. Three samples from each type of material were cut, mounted, ground and polished, as per the method detailed in the methodology chapter (3.5.2.1.) Samples were taken from a variety of pieces, ensuring each different type of slag was tested from a morphological point of view, and samples were taken from different areas across the conglomerates to gain a full representation of all the material. SEM analysis conducted on these samples had the following aims:

A: Assess what temperatures the slag experienced, or if cooling rates can be identified,

B: Compare the material and the conditions experienced with those from the excavations (Pearce, *et al*., 2022, p.6).

C: Asses structure of the slag to compare to Chrysokamino slags (they believe they were tapped) - looking for evidence of rapid cooling - e.g. banding, fine dendritic texture (Bassiakos *et al*., 2006, p.331).

D: To assess how successful the slag-metal separation was (Bassiakos *et al*., 2006, p.331) by looking at copper content in slag.

E: Assess the extent of the copper losses in the slag (what percentage of the slag is copper). The percentage of copper in slag is 1% at Chrysokamino, which Bassiakos *et al*. (2006, p.331) say is very efficient smelting with low copper losses).

6.6.1. SEM analysis of metallographic samples from Campaign One

Analysis of the conglomerate from Campaign One (*Figure* 6.52) showed that the conglomerate is made up of slag, copper prills, and inclusions which are high in copper but which did not completely transform into metallic copper. Chemical analysis was taken from three areas on the sample (areas indicated by squares in *Figure* 6.52). A conglomerate is formed when metallic copper gets trapped within slag and/or partially reacted copper ore. The silica component (green outlined box in *Figure* 6.52) of the slag part of this conglomerate is very low in copper (less than 9%). This indicates that the conditions were present for the separation of copper from the ore, but that the material did not stay within these conditions long enough for all of the material to turn into metallic copper. The copper prill (black outlined box, *Figure* 6.52) is 95% copper, while the area near it, section 2 (white outlined box, *Figure* 6.52) is 65% copper, showing that it was transforming into metallic copper. The limited space within the furnace can cause the copper prills to remain amongst the slag material, and the changeable conditions within the furnace cause slag to solidify when it has only travelled half way down the furnace, rather than running and pooling at the bottom. Analysis of a sample material which is purely slag, and would be described typologically as run slag, but was formed in the furnace, has less than 1% copper (table 6.11). This shows that some material was separated very efficiently, with little copper loss.

Element	At. No.	Net	Mass [%]	Mass Norm. [%]	Atom [%]	abs. error [mass%] (1 σ)	rel. error [%] (1 σ)
Oxygen	8	11806	---	32.43	48.43	1.67	5.15
Aluminium	13	25917	---	10.84	9.60	0.38	3.48
Silicon	14	92389	---	38.35	32.63	1.28	3.33
Sulfur	16	282	---	0.15	0.11	0.03	19.42
Potassium	19	2282	---	1.12	0.69	0.06	4.99
Calcium	20	14863	---	7.25	4.32	0.21	2.84
Iron	26	8779	---	9.86	4.22	0.28	2.82
Copper	29	0	---	0.00	0.00	0.00	100.03
			Sum	**100.00**	**100.00**		

Table 6.12. Chemical composition of a run slag sample from Campaign One.

The slags from Chrysokamino had 1% copper, which as Basiakos *et al*. (2006, p.331) state, is very efficient smelting with low copper losses. This demonstrates that the slag from the experimental campaigns, which was fully smelted and separated from the conglomerate, had a very efficient separation and was comparable to the run slag analysed from Chrysokamino. The slag which makes up the conglomerate demonstrates that the conditions were variable and not all the material was fully smelted. The crushed slag part of the conglomerate could be put back into the furnace and smelted again to get more copper from it. It would also act as a flux, encouraging new ore which is added to smelt.

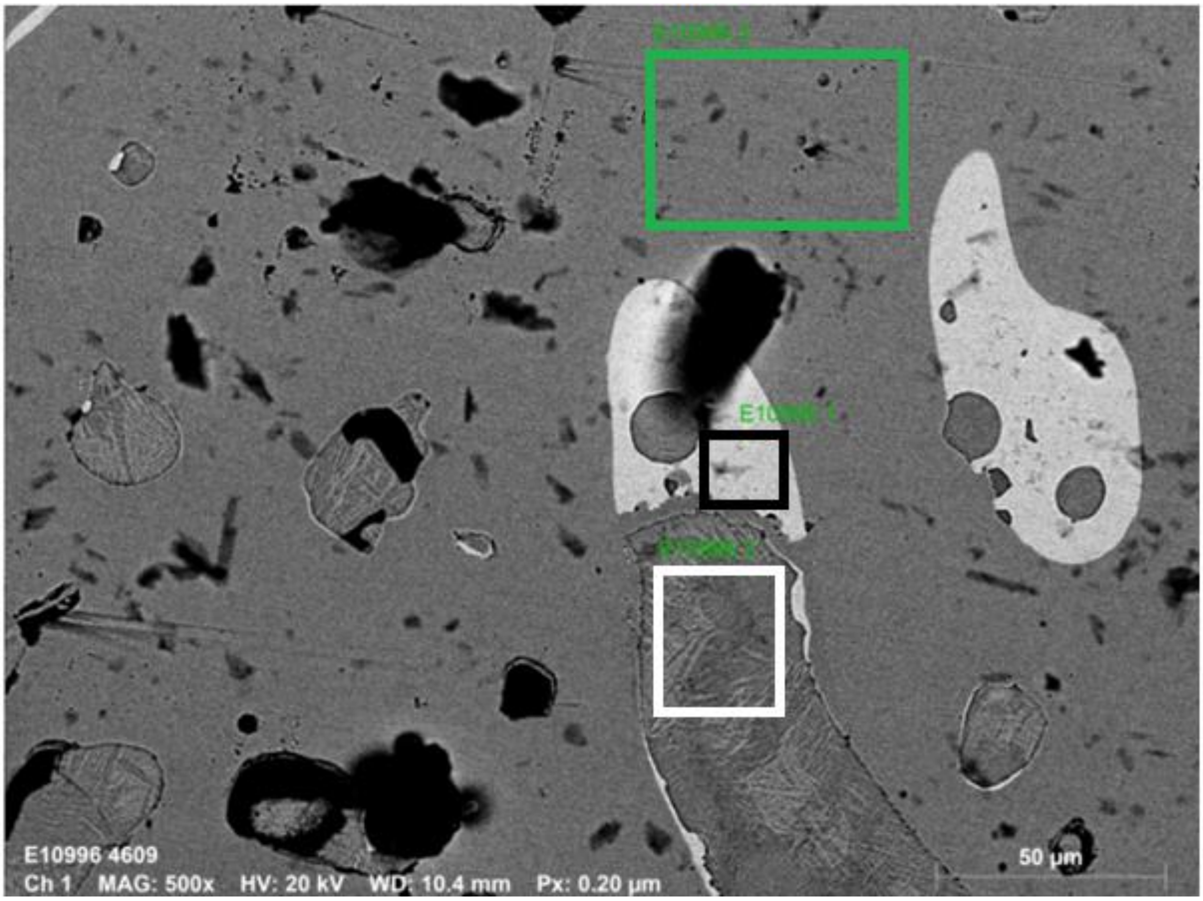


Figure 6.72. SEM micrograph, showing areas which were selected for chemical analysis; copper prill, (black outlined box), partially formed copper (white outlined box), and silica (green outlined box (Image taken and edited by author).

Another area of the conglomerate (*Figure* 6.53) shows an area where copper was forming but the process was stopped due to the material solidifying. This can be seen by metallic copper (indicated by black arrows, *Figure* 6.53) forming on the edge of iron oxides (white outlined box, *Figure* 6.53). This shows that the conditions were suitable for a period, but the material did not stay in these conditions long enough. The image in *Figure* 6.54 highlights the chemical composition of this material, showing the crescent of copper, along areas of iron within the slag. If this material had stayed within the correct environment long enough (above 1250^{o}C and reducing), the iron areas would also have converted to metallic copper.

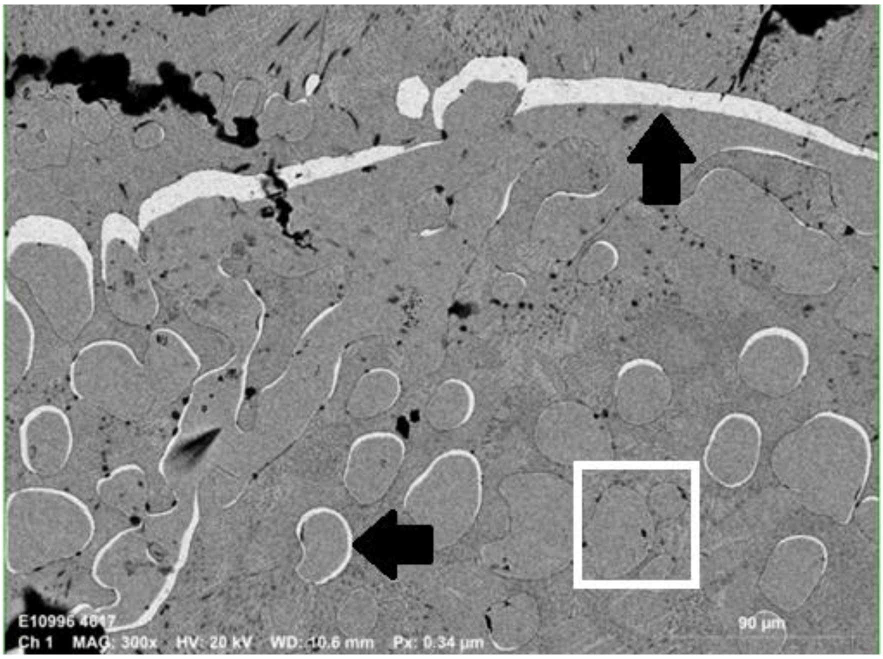


Figure 6.73. SEM Micrograph of part of conglomerate from Campaign One, showing areas of copper forming (indicated by black arrows) on the edge of iron oxides (white outlined box) (Image taken and edited by author).

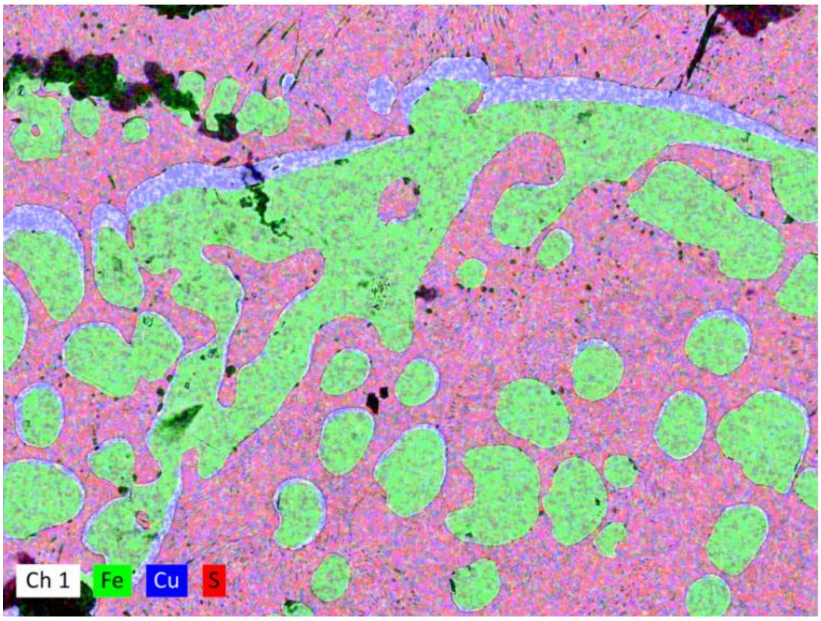


Figure 6.74. Chemical map showing which parts of the material are made up of which element, created during SEM analysis (Image taken and edited by author).

A sample of slag from Campaign One (*Figure* 6.55) shows areas of rapid cooling demonstrated by long skeletal magnetite (indicated by black arrows, *Figure* 6.55). This strengthens the conclusions drawn from microscopy, that areas of the slag are cooled, within the furnace and rapidly, instead of forming outside the furnace and folding (*Basiakos et al*., 2006, p.331) as none of the slags were tapped. This is a characteristic created due to air being brought into the furnace through the perforations present in the APF structures, and as the air hits the slag, it rapidly cools and solidifies it.

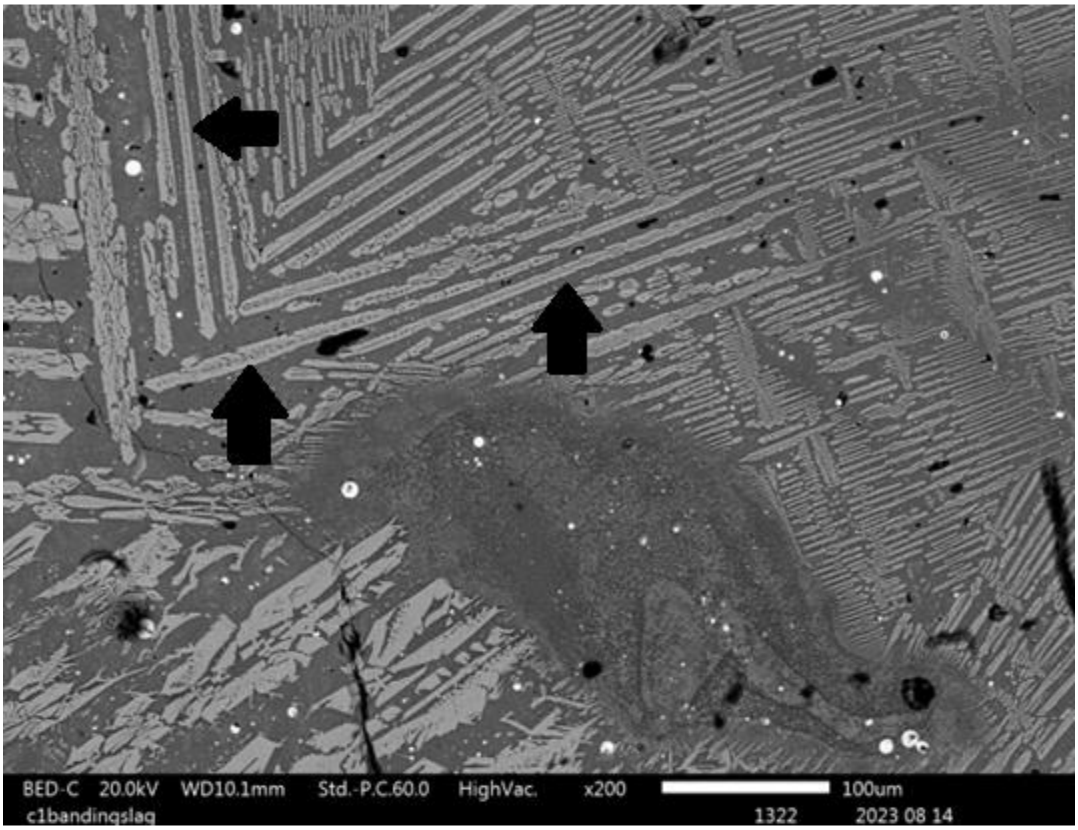


Figure 6.75. SEM micrograph of a piece of slag from Campaign One, showing long skeletal magnetite (indicated by black arrows) (Image taken and edited by author).

Areas within the slag samples from Campaign One show areas of banding, which is when areas of different types of oxides are situated next to each other. In this instance, it is a layer of iron oxide dendrites, next to a layer of magnetite and Wüstite (*Figures* 6.56 and 6.57). The existence of these different types of structures, in 'layers' next to each other, shows that the material was under different conditions (reducing or oxidising) when the structures were formed, indicating variation inside the furnace. As a result of these varying conditions, the slag is being cooled at different speeds and also at varying levels of oxygenation, in addition to instances of rapid cooling (which creates long skeletal magnetite laths – *Figure* 6.56 indicated by black arrows).

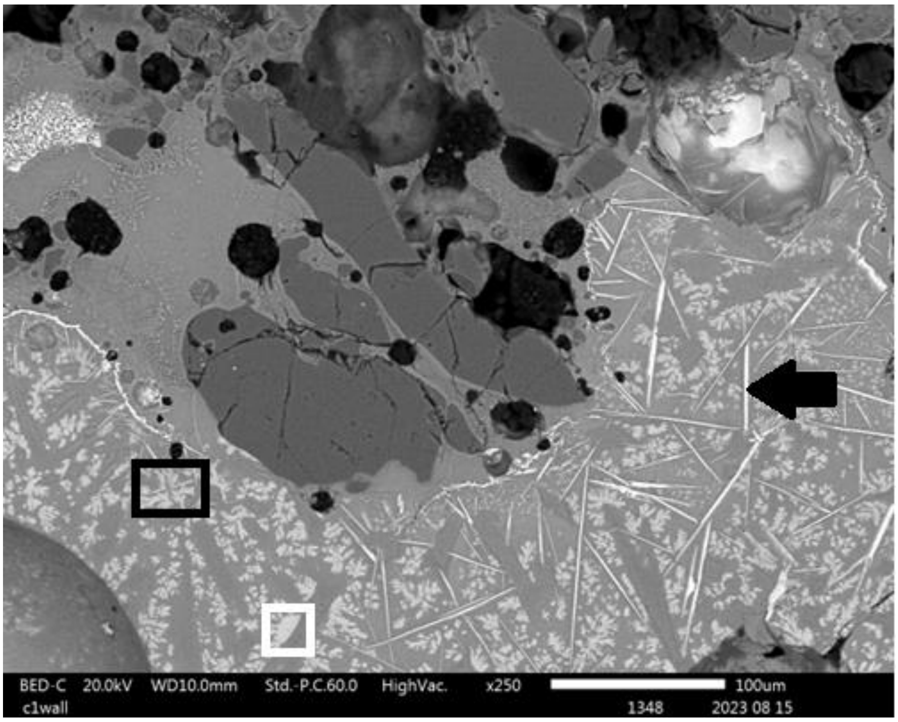


Figure 6.76. SEM micrograph of a piece of slag from Campaign One, showing mixing of iron oxide dendrites (black arrow), including co-existing examples of magnetite (black outlined box) and Wüstite (white outlined box) (Image taken and edited by author).

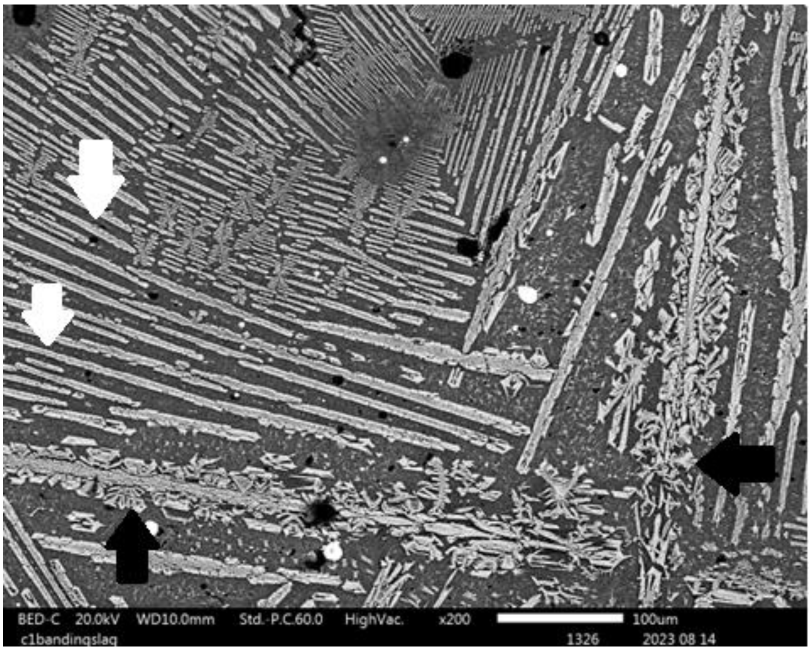


Figure 6.77. SEM micrograph of a piece of slag from Campaign One, showing long skeletal magnetite (white arrows), with a band of small branching iron oxides (Wüstite: black arrows) at the bottom and right hand side of the image, with long skeletal magnetite recurring either side of the band (Image taken and edited by author).

The microscopy and SEM analyses of the slags produced during the experimental campaigns shows that they are not homogenous, but are varied. This is comparable to the slags analysed from the excavated material at Chrysokamino (Basiakos *et al*., 2006, p.331), although these authors explained the variation to be due to slags being tapped and hitting the environment outside of the furnace. The slags from the experimental campaigns were not tapped, and were all formed within the furnace. This then presents a different explanation of how this formed, and provides a different understanding of the environment inside the APF. As the material is so variable, it is not easy to make an assessment of temperatures reached, or cooling rates, from metallographic analysis of the slags in the way it has been with slags from other types of furnaces (Pearce *et al.,* 2022, p.6-7).

6.6.2. SEM analysis of metallographic samples from Campaign Two

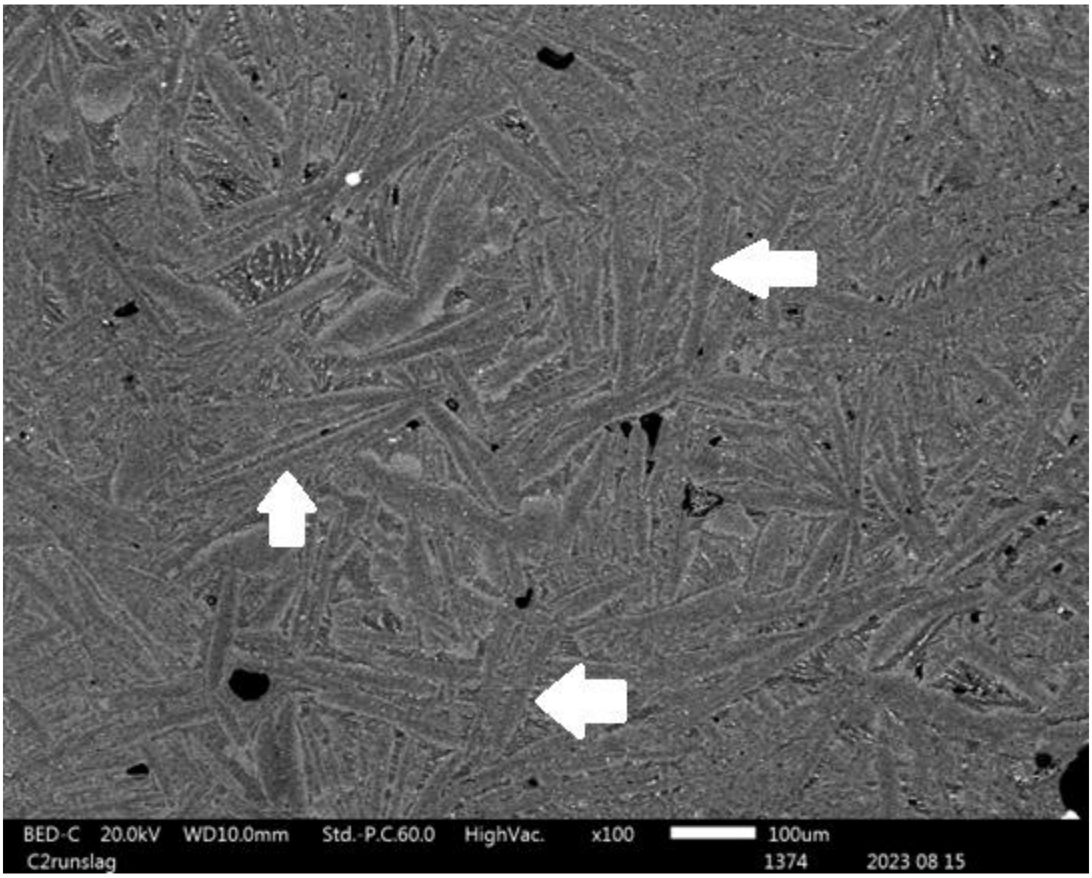


Figure 6.78. SEM micrograph of a piece of slag from Campaign Two, showing long skeletal magnetite (Image taken and edited by author).

The slag from Campaign Two also demonstrates areas of rapid cooling (*Figure* 6.58), by the presence of long skeletal magnetite. This again suggests that areas of the slag are cooled rapidly within the furnace. This is often a feature of slag which is tapped from a furnace (Chapter 2, section 2.2.5), as when it pours out from the hot furnace environment and enters the cold air, the contrast creates rapid cooling. However, these slags were formed within the furnace, and we know from thermocouple data (Graph. 6.2.) and the formation of copper that areas of the furnace were above 1200ºC. Therefore, it is assumed that air being drawn into the furnace hit these pieces of slag and rapidly cooled and solidified them. The perforations in the furnace walls, allowing air to be pulled into the furnace, not only caused rapid cooling of slags, but also conglomerates to form layers at different temperatures and under different reducing conditions, as can be seen in *Figure* 6.59 and *Figure* 6.60.

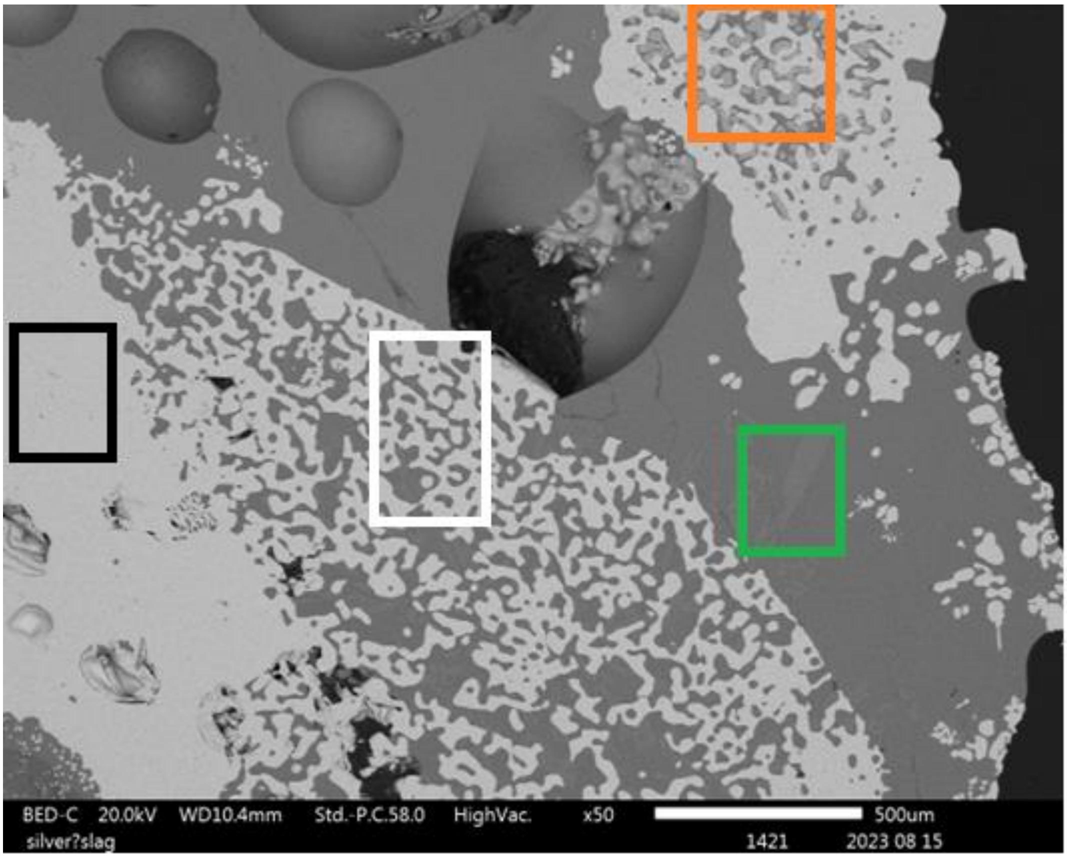


Figure 6.79. SEM micrograph of a piece of conglomerate from Campaign Two, showing banding; the far left sees a band of copper (black outlined box), with a band of iron oxides - Wüstite (white outlined box) adjoining it to the right, next to it a band of silica (green outlined box), and then on the far right another band of iron oxides (orange outlined box) (Image taken and edited by author).

Banding is also present within the slags and conglomerates from Campaign Two, indicating that the environment was changing, rapidly and repeatedly, from oxidising to reducing and with instances of rapid cooling. This is demonstrated by banding of different types of iron oxides in *Figures* 6.59 and 6.60 alongside formed copper. The presence of long skeletal magnetite and Wüstite iron oxides, containing copper prills, is also evidence of rapid cooling. These areas show that different materials are formed in quick succession and as part of the same piece of slag or conglomerate due to the changeable environment. This is comparable to the slags from Chrysokamino (Bassiakos *et al*., 2007, Figure F.6, p.338). As discussed earlier in this chapter, banding is evidence of an unstable environment which is more likely to have come from a wind powered furnace, as bellows create a more consistent environment. This, paired with evidence of rapid cooling when the slags remained inside of the furnace, strengthens the conclusion that the material from Chrysokamino was also from within the furnace, and represents a changeable environment due to it being wind powered, rather than it being tapped slag.

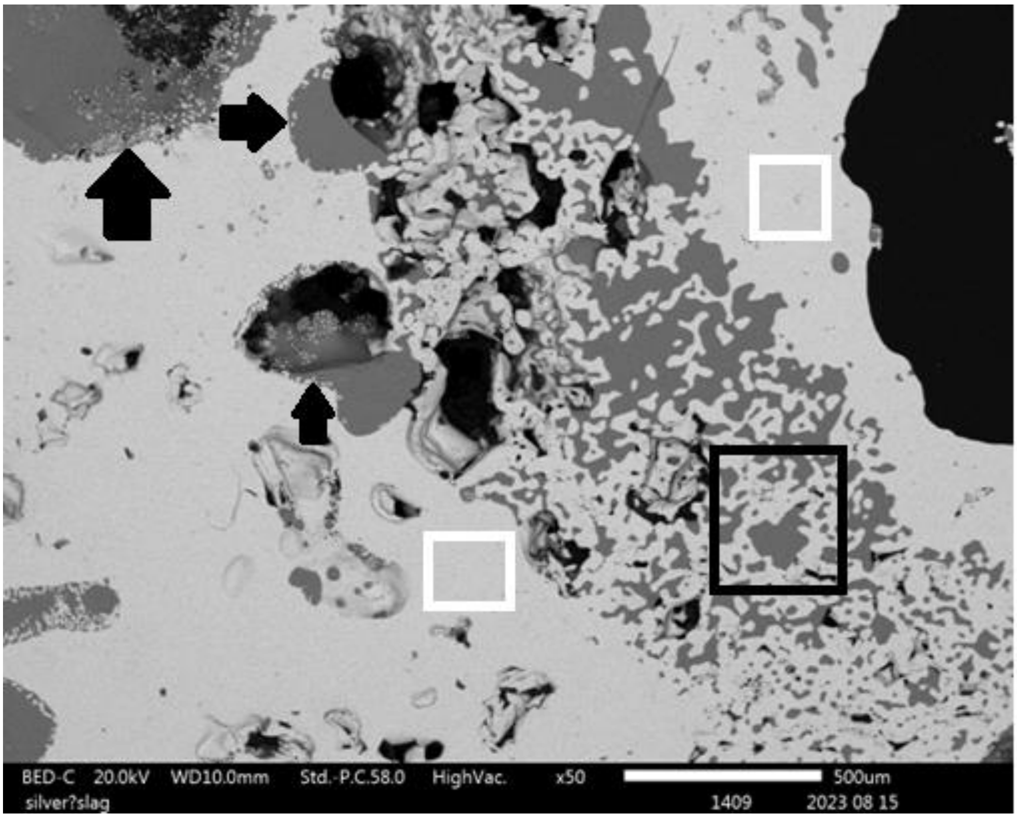


Figure 6.80. SEM micrograph of a piece of conglomerate from Campaign Two, showing banding, with a band of iron oxides – Wüstite (black outlined box) in the middle of copper (white outlined boxes), with pockets of slag with small iron oxides forming on the exterior of the pockets (indicated by black arrows) (Image taken and edited by author).

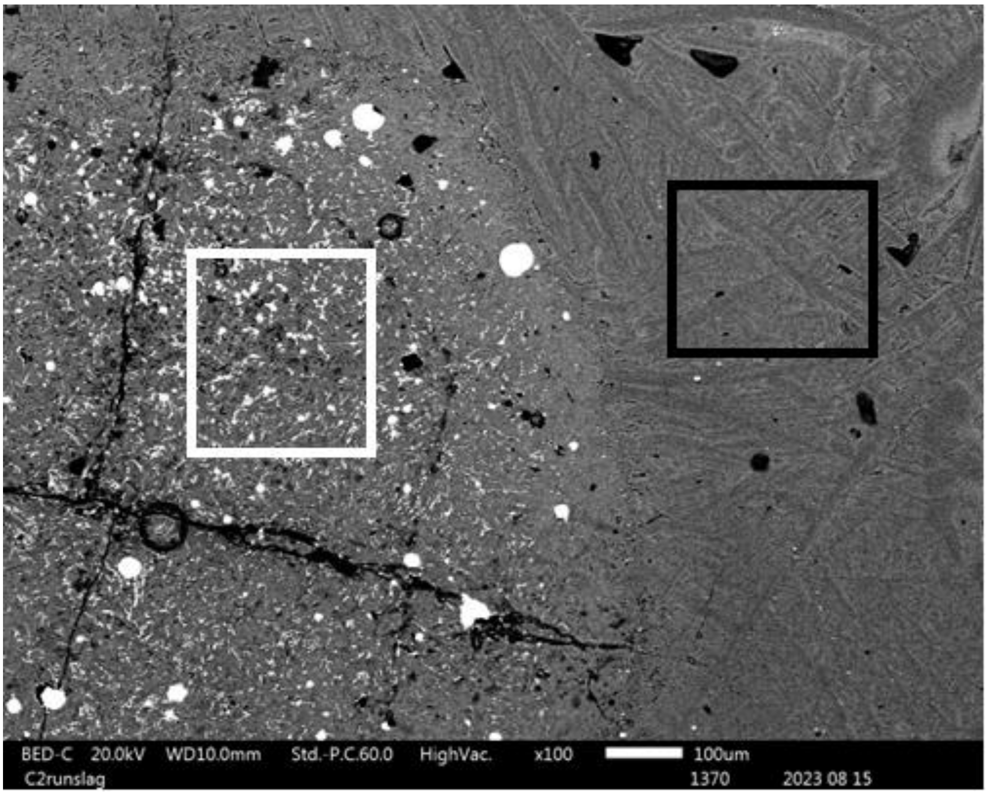


Figure 6.81. SEM micrograph of a piece of conglomerate from Campaign Two, showing banding, with a band of iron oxides on the bottom left (white outlined box), adjacent to a band of long skeletal magnetite on the top right (black outlined box) (Image taken and edited by author).

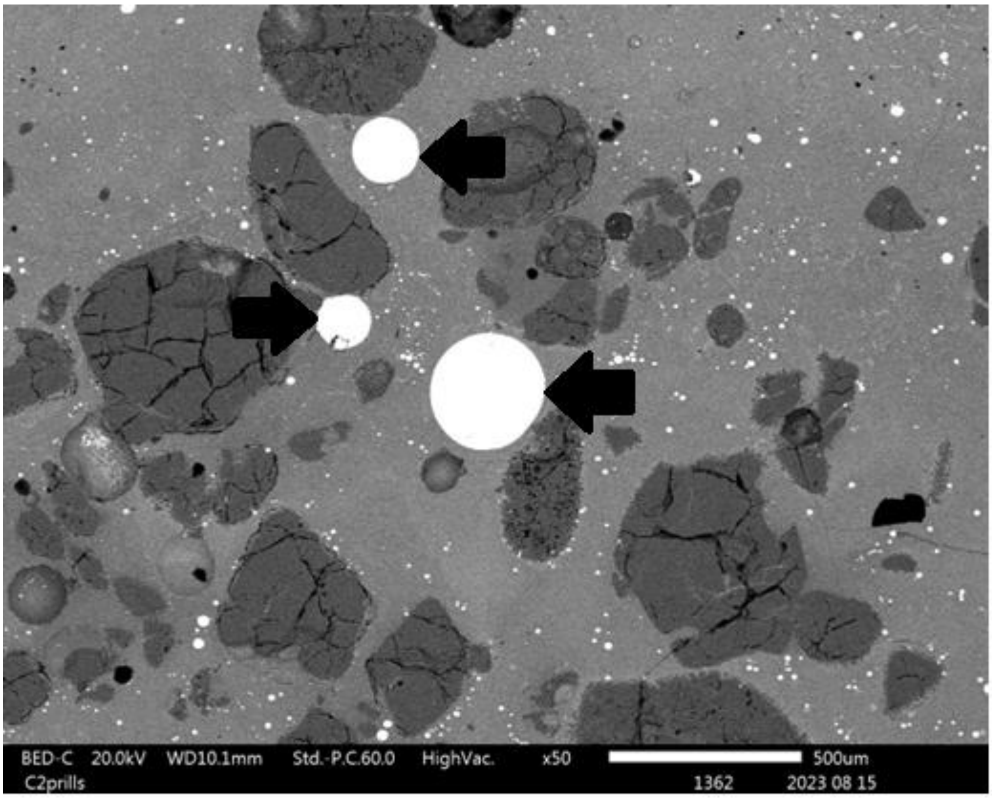


Figure 6.82. SEM micrograph of a piece of conglomerate from Campaign Two, showing varying-sized copper prills (indicated by black arrows) (Image taken and edited by author).

The macroscopic analysis (this chapter, sections 6.2.1.2 and 6.2.2.2) of the conglomerates from both campaigns showed that copper prills were produced. Some were completely separate from the slag (*Figure* 6.21), and some were formed in a conglomerate but were large enough to be picked out by hand after the conglomerate had been crushed (*Figure* 6.19 and *Figure* 6.24). SEM analysis is seen in *Figure* 6.53. demonstrates that smaller copper prills were also formed, which cannot be seen macroscopically. These would have become larger if left in the right conditions longer. The sample in *Figure* 6.54 also has copper prills of varying size, with a band of smaller copper prills amongst long skeletal magnetite, indicating that this area cooled rapidly, pausing the formation of copper.

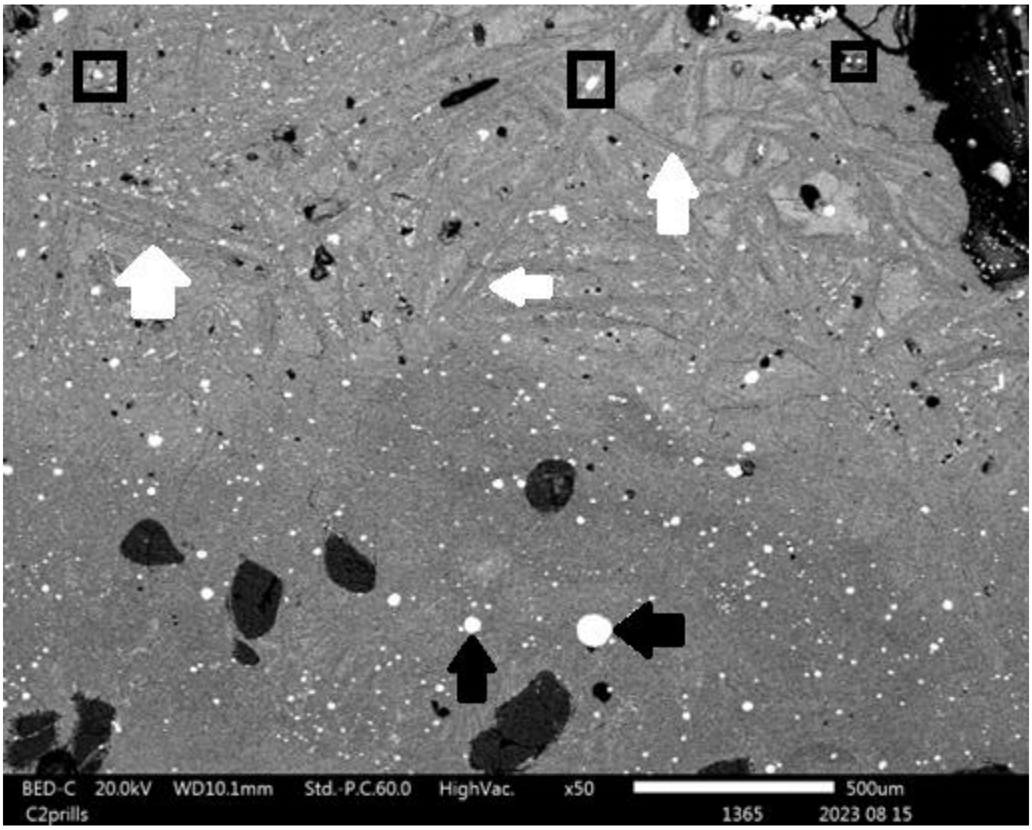


Figure 6.83. SEM micrograph of a piece of conglomerate from Campaign Two, showing copper prills (some indicated by black arrows) of varying size, with a band of small prills (some indicated by black outlined boxes - top of image) amongst long skeletal magnetite (white arrows) (Image taken and edited by author).

6.6.3. Discussion of SEM analysis

The SEM analysis confirmed identifications made during microscopy and provided more detail, such as the presence of banding with a variation of iron oxide dendrites occurring. This shows that the slag was formed under different conditions, with the slag being cooled during alternate oxidising and reducing conditions, as well as instances of rapid cooling. It also showed evidence of the process of copper forming being paused due to cooling, causing the solidification of the material. The SEM analysis added new information on the composition of the copper, conglomerate and slag. The chemical analysis showed how successful the smelting within this furnace was and enabled a comparison with the analysis conducted on material from the Chrysokamino excavation (Bassiakos *et al.,* 2007). The percentages of copper within the slag demonstrated that the slag was fully smelted and separated from the conglomerate, which is comparable to the run slag analysed from Chrysokamino (Bassiakos *et al*., 2007). The SEM analysis confirms that the method of reconstruction of the APF presented in this thesis is a more accurate reconstruction than that presented previously (Pryce *et al.,* 2007; Catapotis *et al.,* 2008). This is because the material analysed is more comparable to the material from excavation (Bassiakos *et al*., 2007), showing that the internal environment was changeable. This is in contrast to the previous experiments, which used forced air (Pryce et al., 2007 and Catapotis et al., 2008) and therefore had a more consistent environment. The presence of copper prills within the conglomerate, paired with evidence of crushing slag (stone tools, piles of crushed slag) present at multiple APF sites (Chapter 2), suggests that this wind-powered technology produced conglomerates with copper prills and that these conglomerates were crushed to retrieve the copper prills, which were then melted to consolidate them. The process of copper smelting resulting in copper prills which are not entirely separated from the slag material is not limited to the APF; it is also common in other early copper smelting processes (Pearce *et al.*, 2022, p.6; Hauptman, 2000, p.102). As more investigation and analysis is done on earlier copper smelting using very rich copper ores, we will be able to understand the process better. It is essential we understand and view this earlier stage of copper smelting as a process in its own right and does not view it as a ‘failure’ as the copper prills have to be picked out of crushed slag and re-melted, but an earlier method which therefore might not be as straight forward, as a later process where the copper may form separate to the slag. It is essential to try not to view it through the lens of copper smelting in the later Bronze Age, when roasting and fluxes are part of the process and a complete separation is seen. From a modern viewpoint, having a conglomerate with copper prills not fully separated might seem unsuccessful (Pearce *et al.*, 2022, p.6), but producing copper at all is an achievement at this early stage. The process would need manual beneficiation to separate the copper prills from the slag (Pearce *et al.,* 2022, p.6; Hauptmann, 2000, p.101–116; Hauptmann *et al.,* 2003; Bourgarit, 2007), which can be seen as additional work, but would have been worth it to be able to produce copper at this point in time. Therefore, although the APF had unstable environments because they were wind-powered, they were not less successful but were comparable to other early copper smelting furnaces (Pearce *et al.*, 2022, p.6; Hauptman, 2000, p.102).

6.7. Conclusions

This chapter has presented the analyses undertaken on the material produced during experimental smelts in Campaigns One, Two and Three. Specifically, results of the experimental campaigns (temperatures and observations), macroscopic analysis of material produced in the smelts, GIS analysis, SEM and microscopic analysis conducted on the metallurgical material produced during the smelts of Campaign One and Two, and the chemical analysis conducted by pXRF on the ceramic materials of the furnaces used to conduct the smelts for campaigns One, Two and Three. The results have been presented, and initial interpretations on the internal conditions resulting within the furnaces with APF during smelting have been put forward. Further, these results have been compared with the analysis conducted on sherds of APF furnaces from an excavated site (Bassiakos and Catapotis, 2006, p.340), which has shown that the wind-powered method produces conditions and material which match the archaeological material, making this wind-powered method of use plausible. The pXRF analysis across the three campaigns has demonstrated its ability to detect copper on metallurgical ceramics and hopefully to help interpret ceramics that are not vitrified or do not have metallurgical debris adhering to them but have been used for metallurgical purposes. The pXRF analyses across these three campaigns, together with a comparison with other experimental campaigns (Mylneic, 2016; Bruyere, 2018), suggest that the levels of copper left on ceramic material may be able to signify what processes were undertaken in the structures and apparatus and enhance our understanding of the processes that took place.

7. Chapter 7: Discussion

7.1. Introduction to Chapter

This chapter will discuss how my results (presented in Chapter 6) support the new model (Chapter 5) for the function of the Aegean Perforated Furnace (APF) and offer a more accurate reconstruction of this technology. The chapter will then reflect on the motivating factors for the location and spread of APF technology through prehistory. This is followed by a discussion of where this new model fits into the larger context of existing models for the early transmission of metallurgy (summarised and discussed in Chapter 2).

7.2. Discussion of Results

The results of the experimental campaigns presented in Chapter 6 demonstrated that the APF furnace design could function solely by utilising natural wind and did not require the addition of forced draft through bellows or blowpipes. This was shown by the temperatures achieved within the furnaces and the production of copper prills, either alongside slag or within conglomerates of partially reacted ore and slag. This metallurgical material evidence matches that found in the archaeological record at the sites where the APF is found (Chapter 4). The evidence at the archaeological sites which bear the APF technology, of stone tools which are typologically used for crushing, as well as piles of crushed slag, also strengthens the interpretation of the evidence as being a smelting product which is made up of copper prills entrapped within slag and conglomerate, which is then crushed to be released. Further analysis was carried out to strengthen this theory of reconstruction by comparing the material produced during the smelts in the experimental campaigns to that from excavation. The metallographic analysis using microscopy and SEM (Chapter 6) identified that the internal firing environment was unstable but that copper prills were still able to be formed. My interpretation of that unstable environment, which sees instances of rapid cooling within the furnace and a change in levels of oxidisation, is that it is caused by air being dragged into the furnace through the perforations. This would increase and decrease with the change in speeds of the wind. Whereas if instead forced air was being used to power the furnaces via bellows or blow pipes, this would provide a constant supply of wind, which would make the internal environment more stable. Therefore, as the material from the experiments matches that from the excavations microscopically, in terms of the conditions inside the furnace and metallic material produced (copper prills), this strengthens this model of function (solely natural draft). Previous models for the reconstruction of the APF (Betancourt, 2006; Pryce *et al*., 2007; Catapotis *et al.,* 2008) interpret the furnaces as being powered by bellows. However, the temperatures from the experimental campaigns presented in this thesis (Chapter 6) are higher, with just the natural wind, than those achieved by the previous experiments using bellows (Pryce *et al*., 2007; Catapotis *et al.,* 2008). The experiments with bellows saw the temperatures drop and plateau at a lower temperature to that experienced in my experiments, which used solely wind power. As the material from my campaigns match that from the excavations, macroscopically and microscopically, this strengthens this theory of reconstruction (Betancourt, 2006; Pryce *et al*., 2007; Catapotis *et al.,* 2008).

The chemical analysis of the slags from the experimental campaigns presented in this thesis (Chapter 6) also shows similarities with the archaeological record, with the same amount of copper losses in the slag being present. This indicates that some materials can be fully smelted and that other material forms a conglomerate within these furnaces. The presence of 'run slag' forming within the furnace during the experiments, rather than from tapping (when slag is released through a hole and runs and sets outside the furnace), also shows that material can be formed in different ways. As all of these lines of evidence from the experimental reconstruction match the excavated material, when combined, they strengthen this new model for the method of the functioning of the APF technology, which views the furnace as being powered solely by natural draft, with no addition of bellows or blowpipes. The comparison of the microscopic and chemical analysis of the material produced in the experiments with that from the excavations not only strengthens the new model but also shows the importance of testing models through a holistic approach, combining experimental reconstructions and analysis. This is because there can be many ways to conduct an act or make a thing. Still, it is only when the material is analysed in more detail by microscopy or chemical analysis that the production and process details can be seen.

The chemical analysis by pXRF also helped confirm that ceramics that do not look metallurgical in nature, as they were from higher parts of the furnace or experienced lower temperatures, can be identified as metallurgical by finding traces of copper upon them. This analysis is significant, especially when dealing with ceramics from early versions of technology or low-temperature metallurgical processes. Many technological ceramics will share shapes and styles with those from other processes; for example, cooking pots may look similar to metallurgical apparatuses, especially in the early stages of development. It can be difficult to identify whether ceramics were used for a particular process, especially when contextual information is lost due to bad depositional preservation or because details were not recorded during excavation and the material is now being stored out of context in a museum or store. As we learn more about the early stages of copper production and the technology variation, many previously excavated artefacts must be reassessed. Chemical analysis may be the only way to identify whether a ceramic was used in a metallurgical process or not. This study has shown the danger of identifying ceramics purely on typological form or assuming a method of use as a result of assigning other known methods to similar technology. The excavated material of the APF has shown that not all metallurgical ceramics will be heavily heat altered, vitrified, or even have slag or copper adhering to them (Chapter 4) and that their forms are similar to other types of ceramic vessels and equipment (*Figures* 7.1 and 7.2). Therefore, chemical analysis can be a powerful tool to help with identification going forward. These results have already had an impact and have led to chemical analysis on Neolithic ceramics from a site in the North East of England, which were believed to have been used for salt production, to help with the identification of the use of the ceramics and to test theories based on typological identifications (Marks, 2021; Sherlock, 2021). The use of chemical analysis in this instance was again a valuable tool to help support interpretation. It was used on the basis of the results of the pXRF analysis in this thesis.

The experiments and analyses in this thesis show that the wind was the key factor and resource for these furnaces. This was also demonstrated by the GIS distribution analysis (Chapter 6), which highlighted that the choice of location for these furnaces is connected to the presence of prevailing winds (hilltop or coastal promontory) and also showed the movement of the activity from the mainland into the Cycladic islands, which provided more consistent exposure to strong winds. The importance of the wind in the broader context of this region and period will now be assessed better to understand its contribution to the development of this technology.

7.3. The importance of the wind

(Image redacted for copyright purposes)

Figure 7.1. Beaufort scale, image from https://www.radar-live.com/2023/11/wind-force-beaufort-scale.html.

As discussed briefly in Chapter 6 (section 6.3.1), in the Aegean, the Meltemi, which are strong winds from the north (*Figure* 6.35), are usually present from June to September (Bassiakos and Filippaki, 2021). The wind speeds were mapped using GIS in relation to the sites (*Figure* 6.36) to assess whether the location of the sites was related to the presence of strong winds. This analysis showed a pattern, with the APF sites being present in locations that would experience strong gusts from the Meltemi. Therefore, the Meltemi winds and their importance throughout prehistory will be assessed here. The winds during the Meltemi register an average of 4 to 5 on the Beaufort Scale but can reach as high as 8 (Kavas Yachting, 2021). The Meltemi is unique to the Aegean Sea and is not experienced in the Ionian Sea; the two seas experience very different weather and are very different to sail on. All of the sites where evidence of the Aegean Perforated Furnace technology is present are exposed to these strong winds (*Figure* 6.36), as they are either situated on the sides of hills or are on coastal promontories. The position and location of these smelting (Table 6.5) sites highlight the importance of the wind in this specific technological process of smelting copper ores. The winds from the Aegean Sea would be felt on the highlands of Attica (not as intensely but still powerful), where one of the earliest sites bearing this technology is found (the Acropolis) and also where two more locations are present, dating to the EBA (Raphina and Gerakas).

In the EBA, when the APF technology moves into the Cycladic Islands from mainland Greece, we also start to see an increase in the movement of people, objects, and technologies due to the innovation of transport technologies (canoes) for land and sea travel (Kristiansen, 2017, p.154). In the EBA Aegean, there is evidence of objects and technologies travelling vast distances, in addition to the APF technology. A variety of motivations for travel in the EBA Aegean have been considered, including trade, political alliances, warfare, and the search for natural resources (Kristiansen, 2017, p.154). The mapping of the evidence for the Aegean Perforated Furnace (*Figure* 6.32) shows a movement from the mainland into the Cycladic islands around the FN/EBA period. We now know that people had travelled to and inhabited the islands before the Neolithic, with evidence now dating to the Mesolithic and Palaeolithic periods (Berg, 2019). However, in this period, people started moving through the islands more as trade increased, as well as an increase in the movement of objects and materials for craft over much farther distances (Berg, 2020).

The choice of location for the APF sites is considered to be due to the wind as there is evidence of other methods of smelting copper which do not use the perforated design at Skouries, Pounta and Lefkes on Kythnos, Phournoi on Seriphos, Skali on Siphnos, Dhaskalio-Kavos on Keros, Kephala-Petras on Crete, Paoura and Ag. Eirini at Kea, Giali in Nisiros and Sitagroi in Macedonia (Georgakopoulou, 2016, Table 1; Papadatos, 2007, p.115; Papadatos, 2008, p.269; Muhly, 2002, p.77-82; Dimitriou, 2017, p.26), it can be considered that the design of the Aegean Perforated Furnace is related to its function, and therefore the choice of location was pivotal to its successful use. The results of the experimental campaigns and the microscopy and SEM analysis (discussed earlier in this chapter) demonstrate that the technology depends on wind. Therefore, the location where this technology is carried out is critical to its use. It can also be considered a motivation for selecting a new location and, therefore, for the migration of this technology.

The evidence provided in this study of (a) the dependency of the APF on the natural wind as opposed to bellows and (b) the location of the archaeological sites associated with evidence of APF use on isolated windy islands makes it less likely that the location of these sites reflects any reason for the movement of a group of people who use APF other than the most efficient function of the technology. This, combined with the fact that the majority of the sites, especially those in the Cycladic islands, have no domestic sites associated with these smelting sites (Table 7.1), shows the location is purely for smelting copper in the APF.

Site	**Location of Settlement**
Kephala, Keos	Not detailed
Raphina, Attica	Has a homonymous settlement <500m (Theocharis, 1952).
Gerakas, Attica	Settlement in the area.
Athens Acropolis, Attica	There is evidence of habitation but no known settlement currently. Caves on the south slopes, pottery in wells on the north slope.
Paliopyrgos, Kythnos	No contemporary settlement (Georgakopoulou, 2016, p.5-6).
Sideri, Kythnos	No contemporary settlement (Georgakopoulou, 2016, p.5-6).

Kephala, Seriphos	No contemporary settlement (Georgakopoulou, 2016, p.5-6).
Avessalos, Seriphos	No contemporary settlement (Georgakopoulou, 2016, p.5-6).
Chrysokamino, Crete	Not connected with one large settlement, a series of farmhouse clusters developing in EMIII (Betancourt, 2006b; 2006c; Haggis 2006).
Akrotiriaki, Siphnos	Has a homonymous settlement <500m (Papadopoulou 2011; 2013).

Table 7.1. Table showing details of settlements contemporaneous with APF smelting sites.

It has been suggested that one of the motivations for travel across land and sea in the EBA Aegean was to locate and source copper ore (Kristiansen, 2017, p.157). It has also been suggested that the motivation for setting up a smelting site was the proximity of the ore (Bassiakos and Philaniotou, 2007). The copper ores being exploited and smelted in the FN and EBA (oxide ores) are formed close to the earth's surface, meaning they are often quickly depleted, and so new sources have to be found (Sikka *et al.,* 1991; 2021; Ottaway, 2001; Bassiakos and Philaniotou, 2007; Bassiakos and Filippaki, 2021). Analysis (Gale and Stos-Gale, 2002; Georgakopoulou, 2017, p.3) has indicated that the ore sources located in the south-east of Attica and the Western Cyclades have been the most prominently used during the EBA, despite there being several sources of copper (and lead-silver) in the south-central Aegean. The sources from the south-central Aegean do not appear to have been used substantially in this period (Gale and Stos-Gale, 2002; Georgakopoulou, 2017, p.3). This picture was obtained through a combination of lead isotope analysis and direct evidence of mining provided by several local mining and smelting sites (Gale and Stos-Gale, 2002; Stos-Gale and Gale, 2003; Georgakopoulou, 2016, p.3). Lavrion, situated in the south-east of Attica, is known as a sizeable multi-metallic ore deposit. Lead isotope analysis has shown it was a lead, silver and copper source in the EBA (Georgakopoulou, 2016, p.3). However, there is a lack of direct evidence for prehistoric exploitation in this area as a result of classical and modern large-scale exploitation (Conophagos, 1980; Kakavogiannis, 2005; Spitaels, 1984; Mountjoy, 1995).

The Cycladic islands have an abundance of small-scale mineralisation's which are widely dispersed and too small to be of modern economic significance (Gale and Stos-Gale, 2008; Bassiakos and Tselios, 2012; Georgakopoulou, 2016, p.3). However, there is evidence for historic exploitation of silver deposits, such as those at Ayios

Sostis on Siphnos (Wagner and Weisgeber, 1985), but there is no clear evidence for copper exploitation in the EBA at the mining sites, this is considered to be due to modern large-scale mining of iron ore has probably destroyed evidence of prehistoric copper ores and mining (Bassiakos and Philaniotou, 2007; Gale *et al*., 1985; Hadjianastasiou, 1998; Hadjianastasiou and MacGillivray, 1988; Georgakopoulou, 2016, p.3-4). “Broodbank, acknowledged that there is no evidence for direct control of ore sources in the EBA Aegean, but suggested that control of metal production would have been indirect, based on resources (human and material) for maritime travel (as far as access to the western Cyclades is concerned) and metallurgical knowledge” (Georgakopoulou, 2016, p.8).

The understanding that not all stages of the copper production process took place in one location has already been confirmed (Doumas, 2011; Betancourt, 2006, 2007; Bassiakos and Philaniotou, 2007; Catapotos, 2007; Catapotis and Bassiakos, 2007 and Tsipopoulou, 2007). It was previously believed that the smelting of ores would have taken place in close proximity to where they were mined (Doumas, 2011). However, as more evidence for copper smelting in the BA Aegean is excavated and published, it is evident that this is not the case (Day and Doonan, 2007; Berg, 2020). The study carried out by Georgakopoulou (2017), identifying the location of ore sources in relation to smelting sites in the EBA Aegean, demonstrated that many of the copper ores being used at the APF smelting sites had been transported from other locations, some of which were very far away (discussed further in Chapter 4).

Smelting site	**Location of Ore**
Kephala, Keos (Kea)	Not known
Raphina, Attica	Site is located within a broadly metal-rich zone, but no know source at location of site.
Gerakas, Attica	Site is located within a broadly metal-rich zone, but no know source at location of site.
Athens Acropolis, Attica	Site is located within a broadly metal-rich zone, but no know source at location of site.
Paliopyrgos, Kythnos	Source near site <1km
Sideri, Kythnos	Source near site <1km

Kephala, Seriphos	Small-scale mineralisation near the site initially, then elsewhere on the island.
Avessalos, Seriphos	Small-scale mineralisation near the site initially, then elsewhere on the island.
Chrysokamino, Crete	Source not from Crete.
Akrotiriaki, Siphnos	Source near site c. 2km

Table 7.2. Table showing locations of ore sources associated with the APF copper smelting sites in the FN and EBA Aegean.

The location of the ore sources in association with the smelting sites presented in the table above (Table 7.2.) demonstrates that there is no evidence of smelting sites being located close to ore sources (Georgakopoulou, 2017; Betancourt, 2006; Bassiakos and Philaniotou, 2007; Gale *et al.*, 1992; Marinos, 1951; Salemink, 1980; Philaniotou *et al.,* 2011; Coleman, 1977; Dimitriou, 2017; Πλασσαρά, 2020; Theocharis, 1951). Therefore, the location of the ore cannot be the primary and/or only motive for the location of these smelting sites. Or at least it is not the motive for the location of all these sites. This then supports the theory that the main factor for the choice of location was the presence of strong wind. Why the wind was so important is interesting. The craftspeople would have been aware of the Meltemi winds, as they would have affected their farming and travel. We know the ores were transported from mines to islands, and the crafters would have to navigate the sea, and the wind would have affected that; winds that blew too strong or from the wrong directions would delay seafarers as they waited for calmer conditions (Berg, 2020, p.292). With perforations, it also functions better when used in windy locations, showing an understanding of the seasonal wind patterns and how they function with the technology. Transporting the ores across these vast distances shows a significant amount of resources and time dedicated to the copper production process and adds value to the metal (Berg, 2020, p.287). As Berg (2020, p.287) discusses, “the transformation of copper from unprepossessing rock into a hard, usable object, and its symbolic value, are deeply affected by the elemental, spatial, and temporal properties of its journey across the Mediterranean Sea, and it is these elements that assign meaning and social value to copper objects in the eyes of their users”. As well as the transformation of the rock and the journey of the ore to the smelting locations, the wind can also be seen as a vital component, as the elemental aspect, as the functioning of the APF smelting apparatus works better (higher temperatures) when used in a windy location. It could also be considered that the reason behind creating a technology that utilises the wind is also due to the cultural importance of the wind, and it could add cultural and ritual value to the metal being produced by it being part of the process.

The use of natural wind to power these furnaces could also reduce the number of people needed to smelt copper, but it also eliminates the need for equipment such as bellows and/or blowpipes. The utilisation of wind means more copper ore can be smelted at once by fewer people. Using the wind makes the smelting activity less physically demanding than implementing multiple craftspeople to manually work bellows or blow into blowpipes. The wind was something people needed to be aware of, as it dictated the calendar of agricultural activity, especially the harvest; it can be considered that they had a deep understanding of its patterns, enabling them to utilise it for their smelting activity. We see evidence from Homer's *Iliad* and *Odyssey*, which are considered to have reflected upon life in the Bronze Age, the appreciation and respect for the wind, and descriptions of its strength at different times of the year. Cerveny (1993) assessed how accurate the winds described in Homer's *Odyssey* are in relation to meteorological records. Their assessment showed that the winds described in the Odyssey are accurate and fall within the time of the Meltemi. For example, "the tragedies experienced by the Achaeans in the Odyssey may have been caused by a cyclonic storm crossing the area in the early summer" (Cerveny, 1993, p.1025), this matches the time of the Meltemi. The *Odyssey* describes activities such as travellers making offerings and praying to Poseidon, the god of the sea, to provide strong wind to power their sails or protect them from dangerous winds that would sink their ships. The *Odyssey* also includes the character Aeolus, who was the keeper of the winds, and it describes prayers and offerings made to the gods of the wind (one for each season) to provide strong winds for the cremation of bodies during funeral rituals:

> *"Howbeit the pyre of dead Patroclus kindled not. Then again did swift-footed goodly Achilles take other counsel; he took his stand apart from the pyre, and made prayer to the two winds, [195] to the North Wind and the West Wind, and promised fair offerings, and full earnestly, as he poured libations from a cup of gold, he besought them to come, to the end that the corpses might speedily*

> *blaze with fire, and the wood make haste to be kindled. Then forthwith Iris heard his prayer and hied her with the message to the winds. [200] They in the house of the fierce-blowing West Wind were feasting all together at the banquet and Iris halted from her running on the threshold of stone."* (Homer, *Iliad:* 23.192 - Translation by Murray, 1924).

Purves (2010) discussed how the wind plays a subtle but fundamental role in shaping the narrative of both the *Iliad* and *Odyssey* since it causes many events that occur in the stories or are invoked to support an activity, such as sea travel or cremation. The wind is also featured in many of the similes in the Iliad and Odyssey, showing the importance and prevalence of the wind in everyday life and highlighting that everyone understood the workings of the wind.

The strong winds of this region are also discussed in the Argonautica (2,498 - 527), where Apollonius of Rhodes recounts how, at the end of their visit to the blind seer Phineus, the Argonauts were delayed for forty days by the Etesian winds (Jackson, 2003, p.101). The Etesian winds are another name for the Meltemi winds. This description of the winds in the *Argonautica*, delaying them for forty days, shows the intensity and duration of the winds. Murray (1987) also assessed how accurate the description and seasonality of the winds were in the fourth century BCE compared to the modern day. He states that because Aristotle and Theophrastos presented a single set of observations which attempted to explain a balanced system of winds, we cannot hope for sensational results. However, the degree of agreement (in the area of the eastern Mediterranean) between conditions of the fourth century BCE and the present day is striking (Murray, 1987, p.159). This strengthens the ability to project and understand the winds in the FN and EBA by studying the Meltemi today.

The design of the APF itself can be seen to facilitate the use of the natural wind in the most efficient way. The APF furnace is a clay truncated brazier with perforations. As discussed in Chapter 5, the perforations allow air to be drawn into the furnace due to different pressure regions created inside and outside of the furnace due to high-speed wind moving around the furnace. The knowledge of how perforations can enhance the function of ceramics used in association with pyrotechnology already existed in the LN Aegean, as evidenced by ceramic vessels used in association with fire for non-metallurgical purposes, which also bear perforations. Such vessels are present in the Late Neolithic and Early Bronze Age. The examples include Zakros: bee smoker, firestands, and incense burners (Figures 7.1 and 7.2) (Museum of Sitia, Crete), Knossos: sprinklers (Gimbutas, 2007, 75), and Dhaskalio: brazier-'mask' (Sotirakopoulou, 2016).

Figure 7.2. (left) The incense burner is from Zakros (photo taken by author). Figure 7.3. (right) First and from Zakros (photo taken by author).

The presence of perforations on braziers used within the copper smelting technology demonstrates a continuation of this use of perforations in pyrotechnical ceramics. It suggests that this feature was understood to have a positive function. The perforations for ceramics used with flames allow air to be drawn inside due to different pressure regions, as discussed in Chapter 5. Therefore, I believe that the design of the furnace is intentional to optimise the functioning of the furnace by utilising natural wind flow to stoke the flame and increase the temperature. The use of perforations suggests that the APF technology was a regional response to the development of copper smelting technology, where local crafters adapted their existing skills and knowledge to utilise local resources and enable them to smelt copper most efficiently. The creation of force draft technology, especially bellows would have been complex, and could have taken longer to develop. However, it is clear there was an existing knowledge about pyro-technological ceramics, which was then adapted to conduct this technology in a way familiar to the craftspeople, in tandem with the development of understanding of the wind and the ability to harness it. As seen by the experiments and the modelling of the fluid dynamics, the strong winds moving across these ceramic furnace structures increase the temperatures inside, demonstrating that the wind makes them work better. However, this does not take away from the symbolic power and cultural meaning the use of the wind added to the process. The utilisation of the wind and its making the process work better would only heighten beliefs around the symbolic power of the wind and the added potency or power of the metal due to the fusion of elements in its creation (Berg, 2020, p.291-2).

7.4. Transmission of metallurgy and the APF

7.4.1. The context of APF technology in the Aegean

The APF technology appears in the Aegean in the LN and does not have any parallels in the neighbouring regions of the Balkans or Anatolia (Chapter 4). The evidence for copper smelting technology in the Balkans and Anatolia relies on forced draft technology and utilised ores related to other activities, such as metal used for pigments (Chapter 4). The early smelting technology in these regions also reflects the technology and practice carried out in their pottery production, repurposing the ability to create controlled pyrotechnological environments which can be reducing. There is no evidence to date of any other technology from the LN or EBA that utilised wind power to smelt. There are examples of perforated ceramics used in conjunction with copper ore from the Balkans, which were discussed in Chapter 4 (section 4.3.2.5.2.2) however, experimental campaigns (Chapter 4 section 4.3.2.6) have revealed they cannot be used successfully for smelting copper ores, instead they could have been used in conjunction with a pit, to help stoke the fire, as a brazier would. Perhaps this would have been for a pre-smelt preparation process such as ore roasting, which has resulted in copper ore residue being located on the internal surface of the brazier (Chapter 4, section 4.3.2.7). The archaeological evidence demonstrates that the braziers were used in non-windy locations, probably within walled domestic structures. Therefore, this technology is not comparable with the APF in terms of context or function of use (Chapter 4, section 4.3.2.7). The Balkan perforated chimneys are more similar to a brazier placed over a domestic hearth to help increase the fire within the hearth before cooking, rather than a furnace used for smelting.

There is evidence in the Aegean of copper smelting taking place using methods and technological apparatus other than the APF, such as crucibles placed within hearths, as detailed in Chapter 4 (section 4.3.1). For this technology, copper was smelted in a crucible and placed amongst fuel within a bowl hearth, with a forced draft used to raise temperatures. This technology is contemporary with the APF and continues when the APF technology goes out of use at the start of the MBA (Bassiakos and Filippaki, 2021). This crucible technology is more comparable with the technology and processes taking place within the neighbouring regions of the Balkans and Anatolia (Chapter 4). There is evidence for copper smelting in crucibles from northern mainland Greece, such as Sitagroi in Macedonia and Promachon in northern Greece, detailed in Chapter 4 (Papadatos, 2007, p.115; Papadatos, 2008, p.269; Muhly, 2002, p.77-82; Dimitriou, 2017, p.26; Bassiakos and Filippaki, 2021), which could suggest that this technology spread to these sites from the Balkans across the land into mainland Greece. However, despite this crucible technology appearing in Greece in the FN, this is not the only technology we see appear, as the APF technology appears in the FN in Attica and Keos. Therefore, it can be considered that the APF developed in isolation but contemporary with the crucible smelting that was taking place in northern Greece. This leads to the theory that the APF is an independent tradition, realised and developed in isolation from other copper smelting technology, developing existing knowledge and skills in an effort to smelt copper using the understanding of other fire-using activities. It was developed in response to specific circumstances, such as the ability to use ceramic vessels to hold fuel and gain high temperatures and the use of perforated ceramics to increase the firing temperature through the utilisation of the natural wind. The APF fits within a specific geographic and temporal context, being carried out alongside the seasonal schedule of the planting and harvesting crops, at the peak of the Meltemi winds. This technology makes use of existing knowledge of the landscape and climate, as well as the technology for pyrotechnological crafts.

The APF smelting technology was successful only with primary oxidised ores. Once primary oxidised ores had been depleted, the secondary sulphidic ores began to be used (MBA). This technology was no longer suitable, as the conditions were not reducing enough. This marked a shift to the exclusive use of crucibles for smelting, allowing for a more controlled environment that would enable these ores to be smelted.

By the MBA, the switch to crucible smelting and forced draft technology had been completed.

The evidence for copper smelting in the Aegean, with the presence of crucible smelting in certain areas (northern Greece), which is separate to the isolated tradition of the APF (Chapter 4, section 4.3.1.3), suggests that the knowledge of how to smelt copper ores was introduced to the Aegean from the neighbouring regions, specifically from the Balkans into northern Greece. Then, craftspeople adapted this technology, making use of skills, knowledge and ceramic technology they already had to control fire. By using ceramic technology in association with fire (as with incense burners and braziers for ovens), they developed a new technology (the APF) which could harness the natural resource available to them: the Meltemi winds, which they were able to harness successfully to smelt copper effortlessly. The use of the wind could also be related to rituals important to the culture, as the wind would have played an important part in scheduling their farming and travel around the Meltemi. The APF technological tradition stayed isolated to specific areas in the Aegean, as it required strong winds to function. This means that at other locations in the Aegean crucible smelting continued to be carried out. We see the APF disappear in the MBA, when the ores being mined and smelted required a different method of smelting. The movement from the mainland of Greece into the Cycladic islands is mirrored by the movements relating to trade across the Aegean in the FN/EBA and can be considered that the different crafts are connected, therefore as crafts, people are moving to collect resources or trade items across the Aegean, as they pause on the islands in the Cyclades, they take advantage of the Meltemi winds, which are stronger in these locations and smelt their copper.

As the evidence for the wind-powered perforated furnace technology is limited to several sites within a small area of the Aegean and does not prevail for long at any site, it suggests it was not part of a controlled process of copper production run by an authority-stretching across the whole of the Aegean. Instead, the limited nature of the technological process, when there are other sites across the Aegean using different methods which are comparable with other regions, suggests it was an isolated community carrying out a practice using their own methods based on their own experience and circumstances. Also, as the windblown technology dies out around the time that the palaces start to take control of technology and trade, this demonstrates how this method is more suited to small communities producing metal for their own purposes, rather than a unified controlled process across the Aegean. Parallels can be seen with the prehistoric obsidian quarrying sites in the Aegean (Torrence, 1984, 220), as the APF sites appear to be controlled by craftspeople who have enough knowledge to conduct the process, but the evidence does not appear to suggest they were full-time employees of an organised industry. The temporal aspect of the technology, being conducted in the windy season, also suggests this was smaller scale smelting conducted around the agricultural season, rather than large scale all-year round smelting, again supporting the theory this was not controlled by a central overseer but was isolated communities making metal for themselves. The choice of smelting locations, especially when the technology moves from mainland Greece onto the Cycladic islands, suggests that the technology is more entwined with cultural significance and ritual than it is for economic means. The combination of the movement of the ore across vast distances, navigating the sea and planning around the wind, in relation to avoiding the windy season for sea travel, but then utilising it for the smelting, shows a process that is in tune with the elements and can even be considered that the incorporation of these elements added ritual and cultural meaning and power into the metal (Berg, 2020, p.287-296). The movement from the mainland onto the Cycladic islands itself can be seen to have a powerful cultural significance, especially with the sea's association with death and ritual beliefs (Berg, 2020, p.295-6).

It can be considered, however, that the communities conducting this type of smelting were connected or originated from one place, being one culture. As Renfrew discusses, for a new innovation to be adopted, it must have managed to overcome the scepticism and hurdles when it was first introduced, and the community must also be functioning well in other aspects of society, such as agriculture and other crafts to be able to adopt an innovation. He also states how different crafts can be linked and how societies were travelling within the Aegean through the Cyclades to source materials for these craft activities (Renfrew, 1972,197-202), this can therefore explain the move of this technology from the mainland of Attica into the Cycladic islands. Were the craftspeople seeking other materials on the islands, such as marble, obsidian, and ceramics (Marthari et al., 2019), and carried out copper smelting while there, taking advantage of the strong Meltemi winds? The wind-blown smelting technology is an efficient means of producing copper by travelling craftspeople to the Cycladic islands in the windy season when farming could not be done. Being able to utilise the wind and not have to make or transport bellows would be very efficient and convenient. The fact that this technology stayed isolated within the region of the south of mainland Greece, the Cyclades and Crete, can be considered to be part of Renfrew's international spirit phenomenon, which sees the Aegean at this time having a period of increased trade but also isolated within its own subsystem (Renfrew, 1972). Travel from mainland Greece across the Cyclades was spurred by trade and crafts such as marble, obsidian, and pottery production, and the APF method of copper smelting suited these locations and the temporal pattern of craft activity around farming. Another factor that strengthens the theory of this being an isolated tradition, but part of the international spirit of the Aegean is the isotope analysis demonstrating that the ores do not come from the same location where the smelting takes place but elsewhere in the Aegean (Georgakopoulou, 2017, p.55; Stos-Gale and Gale, 2006), highlighting that the craft and trade activity within the Aegean is linked and travel within the islands is a key part of the activity of the culture. The sanctuary at Keros demonstrates that people were travelling to this remote island with the main purpose of leaving a ritual deposit to their gods (Renfrew, 2015). It is unknown whether this island was a stopping point when travelling through the Cyclades, to leave the offering to ensure safe sea travel, or is the only example surviving when many islands would have had them. It demonstrates the importance of ritual and the types of items travelling through the Cyclades for production and trade.

In the LBA, metal is an essential factor in the economy of the palaces, being used for elite items, burials, and everyday items, which kept the trade world lucrative (Hakulin, 2016). In the FN and EBA, when we saw the APF technology develop, metal was not a necessity at first but was a desirable item due to its appearance and rarity. It would have soon become a valuable trade commodity. Metal artefacts would have come into the Cycladic islands from Anatolia via trade (Branigan, 1968, 8). The people from the islands and mainland Attica would have come into contact with it and adapted their existing pyrotechnical skills, utilising perforated ceramic structures and wind to smelt copper themselves. This technology works for them, and they can utilise the strong winds of the Meltemi whilst travelling across the Cyclades due to other craft and trade activities. However, in the LBA, when the Aegean became controlled by the palaces and organised authority and the demand for metal increased, this technology was no longer suitable. As the palaces started to control the production and trade of metals, we saw a significant increase in the types of items being produced, developing from tools and jewellery to a vast range of items, including toilet articles and weapons (Branigan, 1968, 56). In the Minoan period, the majority of metal appears to have been used for utilitarian artefacts, not just by the elite but also by everyone (Hakulin, 2016). Haukulin states that "The Minoans seem to have considered metal mainly from an economic point of view" (Hakulin, 2016), which indicates a change in the culture and trade of metal and its production. Not only were the types of objects being made increasing, but access to metal and skilled metal smelters were key to the development of the palatial civilisation (Hakulin, 2016).

7.4.1.1. How does the APF fit within the models for the transmission of metallurgy?

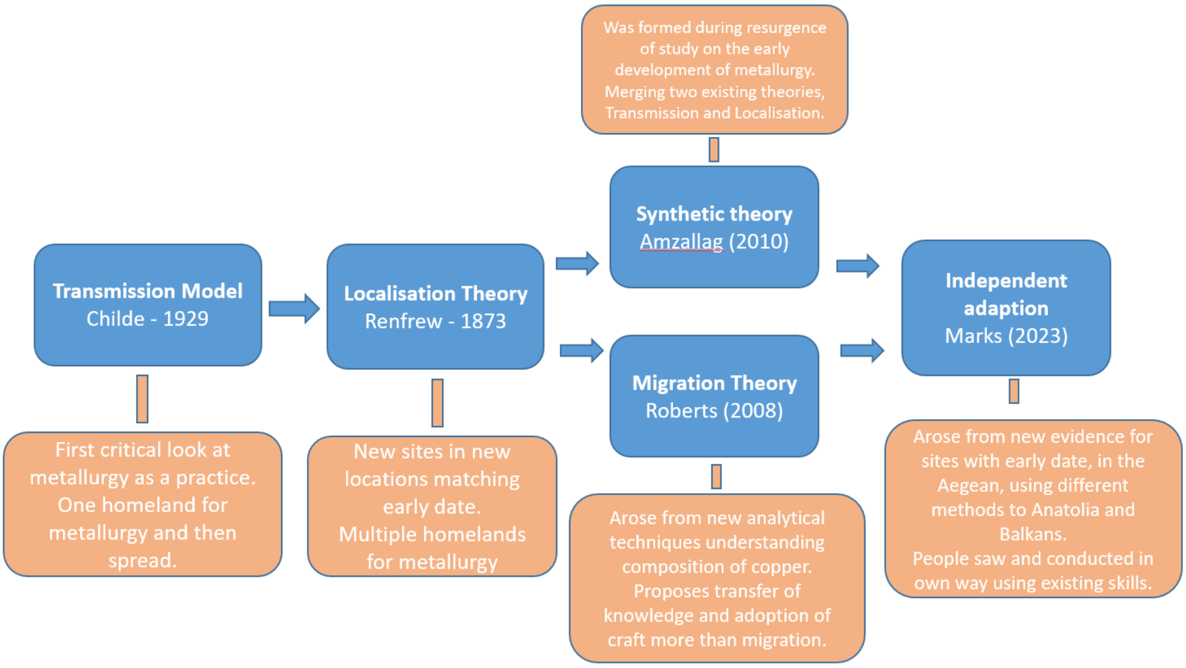


Figure 7.4. Summary of the models for the transmission of metallurgy (Image made by author).

The model for the development and use of the APF proposed in this thesis does not fit exactly into the existing models for the transmission of metallurgy (*Figure* 7.3), which were discussed in Chapter 2. The models presented and discussed in Chapter 2 propose two possibilities for this transmission; one suggestion is that Anatolia was the homeland for metallurgy, with a westward spread across Eurasia as people (metal smelting craftspeople) migrated from East to West. The knowledge and skills were passed to new communities by 'travelling smiths' who taught as they travelled. An alternative proposal is that there were multiple homelands of metallurgy at locations where the ability to smelt copper was discovered independently in isolation. Then this technology dispersed, again being peddled by travelling smelters, teaching a specific method at each new location. This thesis has demonstrated that the APF technology represents the development of a particular process. It has taken the knowledge of existing non-metallurgical pyrotechnological activity and developed a method to achieve copper smelting by evolving these existing technologies and skills and adapting them to a new purpose. The APF does not mimic a pre-existing metallurgical technological smelting process using different apparatus. Instead, it develops the idea that the copper ore, once placed into an environment that is hot and reduced enough, can transform and produce another material, copper, which can then be used to craft objects. The craftspeople who developed the APF and its purpose as a smelting furnace took this idea that copper ore could be smelted and created a new method to do the process based on existing skills and knowledge of non-metallurgical pyrotechnological equipment and processes. It can, therefore, be argued that this was a case of independent adaption. They did not invent it from scratch or mimic the technology; instead, they took the idea and created a new method, adapting it to their work with their existing skills. Therefore, it can be considered that the knowledge of how to smelt copper ores was transmitted into the Aegean through connectivity with northern Greece and the Balkans, either by trade or travelling craftspeople. There is evidence of sites in northern Greece and the Balkans (Chapter 4) (Bassiakos and Filippaki, 2021) that carried out copper smelting in crucibles within pits. This shows how the idea spread into Greece, but the APF represents a different process and a different method of creating that process.

7.5. Conclusion to chapter

This thesis proposes that the APF technology represents a local response to technological processes and resulted in an isolated local tradition, which was not only shaped by the natural resource of the wind but was dependent on it. Its dependence on the wind led to the locations of the smelting sites. Its reliance on the wind is also a contributing factor in its decline, as when technology became centralised by the palaces and more copper was needed, this wind-powered technology was no longer suitable. The experimental and analytical campaigns have tested and proved the model's plausibility.

8. Conclusion Chapter

This thesis sets out to re-assess the material and contextual evidence for the APF, understand how the technology functions (Chapter 4), and determine whether it is a variation of the existing copper smelting technology or its own isolated tradition (Chapter 7). The research aimed to understand better how the craft was taught and adapted due to environmental and existing skills and knowledge (Chapter 7). The project also sought to understand better why this technology took place in the specific locations it did and why the technology spread yet stayed isolated (Chapter 6). This new information was intended to provide insights into how the APF relates to existing models of the inception and transmission of metallurgy (Chapter 7).

To answer the above research question, this thesis has re-assessed the evidence for copper smelting in the LN and EBA Aegean to understand how many sites have ceramic furnace fragments with perforations (Chapter 4, sections 4.2 and 4.3.1). These perforated furnace fragments represent a different style of furnace than the typical copper smelting furnace used elsewhere in these periods (Chapter 4, sections 4.3.2-3). The evidence for copper smelting in the Aegean and the neighbouring regions of Anatolia and the Balkans was collated (Appendix 1, sections 1.1.1 – 1.1.3) to identify whether this technology appears elsewhere and understand its spread. The collation of the evidence for FN and EBA copper smelting sites demonstrated that the APF is an isolated tradition. To build on this assessment, the thesis used GIS analysis to understand further why the APF technology took place in the locations it did and why it spread into the Cycladic islands yet remained isolated to this part of the Aegean (Chapter 6, section 6.3). The GIS analysis demonstrated that wind was the main resource being sought and was the factor that determined its location and spread. To test this theory, a series of experimental campaigns (Chapter 6, section 6.2) and different forms of chemical and metallographic analysis (Chapter 6, sections 6.4 – 6.6) were conducted. The results of these campaigns supported the hypothesis and have been discussed in detail in Chapters 6 (Results) and 7 (Discussion). The conclusions of these results are summarised below.

The main conclusions which have been derived from the reassessment of the excavated evidence for the APF technology are:

- The previous reconstruction and proposed functional model of APF technology as being powered by bellows or forced air is not supported by the majority of the archaeological evidence. Therefore, a new functional model was presented, utilising natural draft (strong winds).
- The collated evidence for the APF technology shows that it started earlier than previously believed and stayed isolated within a particular area in the Aegean.
- The experimental campaigns tested natural wind as the source of air, demonstrating that this method is possible. The material produced from the experiments using wind (copper prills, slag, and conglomerate) and material which is altered by the process (ceramic furnace fragments) is more comparable in terms of structure, chemical composition and colour, to the excavated material of the APF, that the material from other experimental campaigns using bellows.
- The contextual information for the distribution and the choice of locations for sites with material evidence of APF technology supports the theory that strong natural winds were the most important resource and reason for travelling to these locations to undertake this activity. This can also explain the limited area for the use of this technology.
- This evidence shows a different practice to contemporary copper smelting in the region and neighbouring regions, suggesting that the transmission of metallurgy is not as simple and linear as some models suggest. Instead, it demonstrates that there could be imitation and adaption, even at the early stages of metallurgical practice, as craftspeople adapted existing skills from other crafts and skills which harness the wind, such as sailing, cooking with braziers, smoking bee hives, and using incense burners. Examples of some of these comparable ceramics which utilised air flow in association with pyro-technology were presented and discussed in Chapter 7 (section 7.3).

- Lower temperature pyro-technological processes, do not alter the ceramics in which they take place, or the associated, which means it is harder to identify the practice in the archaeological record. Therefore, chemical analysis combined with macroscopic typological analysis can help identify early metallurgical technology in ceramics and sediments.
- Experimental campaigns are necessary to test theories of practice and technology, as there can be multiple ways in which a material is made.

An important finding of this thesis is that there may be more sites which have evidence for perforated furnaces that we do not know about yet, either because they have not been excavated, or because during the recording process, no differentiation was made between perforated and non-perforated ceramics. This furnace design has only been widely recognised and understood during the past 20 years. As many of the excavations of the sites with copper smelting evidence were conducted before the APF technology was recognised, excavators did not take note of the differences in the ceramic furnace technology (bowl hearth or shaft furnace, perforated or non-perforated), but only that their existed ceramics in association with smelting. For example, Georgakopoulou (2017) re-assessed material from previous excavations and identified perforated ceramic furnace fragments which had not been identified initially. In the desk-based assessment for this thesis, I was able to identify some material which was presented in drawings and photographs as perforated furnace shaft fragments, which previously had not been identified since they had just been listed as ceramics associated with smelting because different variations of the technology were not being identified then. Unfortunately, not all of the previously excavated sites are well documented, and many have inaccessible material evidence, making this type of re-assessment limited. There are also smelting sites, such as Keros, where only field surveys, rather than excavations, have been carried out in areas where smelting is believed to have occurred. A field survey which finds slag can identify that smelting took place, but without excavation and ceramic evidence, it may not be able to determine which type of process (bowl or perforated shaft furnace) took place. We now have more information about the smelting process from the slag analysis, but to fully recreate the process, ceramic fragments are key. Therefore, we need not only the knowledge that smelting activity took place but also an understanding of which type of process took place. This means that excavations are needed where surveys would previously have been enough. Another problematic factor is that excavators may not be familiar with early ceramic metallurgical remains, specifically those of the Aegean Perforated Furnace, because these can look non-metallurgical due to the lack of heat alteration and slag adhering to them, and can look a lot like domestic cooking wear. This could result in them not being identified correctly during the excavation process. This is an important factor, which this thesis and subsequent publications hopes to illuminate; by sharing an awareness of what this technology may look like, and of the methods which can be used to detect whether it is domestic cooking wear or metallurgical (pXRF), the identification of the material will be facilitated in the future. Another factor is that post excavation study is often done by find type (pottery, metallurgical, lithic, etc.), frequently by different archaeologists and specialists, who were not present on site during the excavations. Sometimes the specialists are unable to work in the trenches during the excavation, and will only see the material months later in the lab. This means important contextual information from the find spot may not be recorded or passed on to the specialists, as the excavator may not be experienced in metallurgical archaeology (or another specialism, depending on what is being excavated). Ceramic fragments are often washed by teams of students during the field school. Therefore, if metallurgical ceramics are not identified as such and are placed into the pottery bags, they will be washed and could result in important material, such as vitrification, slag, and metal prills being washed off and lost. It is only after they are washed that the pottery experts will look and them and identify them. By this time, if material is lost, they could be misidentified as non-metallurgical pyrotechnical ceramics, such as incense burners or braziers for hearths for cooking. The detailed description of the material evidence for smelting using the Aegean Perforated Furnace in this thesis will hopefully work as a guide for future excavators, enabling an easier and more successful identification of metallurgical ceramics and associated tools (stone crushing tools, tuyères, and moulds etc. – discussed in Chapter 2 section 2.2) during excavation.

Excavation methods which facilitate the identification of metallurgical activity are developing in the Aegean. Projects such as the Dhaskalio Keros Project (Cambridge University), which I was able to experience first-hand, are leading the way in combining a range of analytical techniques, some in the field (pXRF geochemical surveys), with detailed recording methods, combining GPS, photogrammetry and laser scanning, to create the best possible record of the excavations and contexts of excavated artefacts, in order to help understand past metal production (Georgakopoulou, 2021). For example, in the field seasons of 2016-18 a geochemical survey was carried out in the trenches during excavation, providing additional information on metallurgical activities, and this will help support interpretation of ceramics involved in the process (Lester, *forthcoming*). This type of analytical approach in the field will significantly help with the identification of early copper smelting ceramics and processes.

This thesis has shown the importance of understanding different processes for metallurgical activities, and recognising the various types of material evidence for different processes, within the archaeological record. My methodology, pairing desk based assessment of excavated material (Chapter 4), GIS analysis (Chapter 6, section 6.3) with experimental campaigns testing the theory of the reconstruction and method for copper smelting within this furnace (Chapter 6, section 6.2), along with analyses on the material produced from the experimental campaigns to compare with that done on the excavated material; macroscopic (Chapter 6, section 6.2), microscopic (Chapter 6, section 6.4), pXRF (Chapter 6, section 6.5) and SEM (Chapter 6, section 6.6), has achieved an in-depth re-assessment of the method for copper smelting with this material evidence. This re-assessment, proposal, and testing of a new model has not only identified a new practice within the LN/EBA for copper smelting, but has also shed light and new understanding on the way the process of copper smelting developed and spread in the Aegean (Chapter 7).

Another important finding for this thesis was understanding how there can be variation of craft activates within a region, even at such an early phase in the development of an activity (in this case copper smelting). This thesis has also shown how craft activities relate to one another and share methods and learning. This isolated tradition of copper smelting, within such an early phase in the transmission of metallurgy, has shown how the transmission of metallurgy was not a simple process, as there was one way to smelt copper, and people had to be taught in-person how to do it. In reality, craftspeople could see a practice and use existing skills to undertake it themselves, which created variation.

This thesis has gathered significant information about the identification of material associated with early copper smelting, as well as developing a methodology to test new theories of practice (craft and technology). It is essential that this work is shared through publication to help future studies of this nature. One planned aspect of the research, which it was not possible to conduct due to COVID and other circumstances, was an experiment to test whether using blowpipes in conjunction with wind for the APF with thicker walls (Kythnos), would help keep the internal environment more even, to see if the tuyères at those sites were used for that reason, or if they were only used for consolidating and casting purposes. I would like to do this at some point in the future.

In conclusion, this thesis has combined a number of different methods, to not only reassess the archaeological evidence the APF, but also to conduct a series of experimental campaigns to test a newly proposed method for their function. This was followed by a range of analyses to further test these propositions. This then allowed for a consideration of how this isolated tradition, fitted into the model for the early transmission of metallurgy. This thesis demonstrates how a holistic approach can enable a detailed reassessment of materiel evidence, and also assess its place in the wider archaeological and theoretical context.

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Appendix 1 – additional data

1.1. Ap1.1. Region databases and excel sheets for GIS

1.1.1. Ap1.1.1.

Aegean region database: this database was compiled as part of the desk-based assessment which gathered all the currently published sites that date to the FN and EBA in the Aegean with evidence for copper smelting. Information was gathered including what type of evidence representing copper smelting was present. This data base was then used to form Chapter 4. The database is too large to insert into the appendix, but has been uploaded to ORDA and can be viewed here: https://figshare.com/s/a8e6639e6c76234870be

1.1.2. Ap1.1.2.

Balkan region database: this database was compiled as part of the desk based assessment which gathered all the currently published sites which date to the FN and EBA in the Balkans which have evidence for copper smelting. Information was gathered including what type of evidence representing copper smelting was present. This data base was then used to form Chapter 4. The database is too large to insert into the appendix, but has been uploaded to ORDA and can be viewed here: https://figshare.com/s/a8e6639e6c76234870be

1.1.3. AP.1.1.3.

Anatolian region database: this database was compiled as part of the desk based assessment which gathered all the currently published sites which date to the FN and EBA in Anatolia which have evidence for copper smelting. Information was gathered including what type of evidence representing copper smelting was present. This data base was then used to form Chapter 4. The database is too large to insert into the appendix, but has been uploaded to ORDA and can be viewed here: https://figshare.com/s/a8e6639e6c76234870be

The excel sheets were condensed with data to represent different aspects of material present, location and date, to enable GIS analysis. The method for the creation of the GIS maps is in Chapter 3 (section 3.3).

1.1.4. Ap1.1.4. Table with data in for Aegean GIS maps

Latitude	Longitude	Site Name	Date	Fragment thickness	Bellows	Tuyères
35.136861	25.835389	Chrysokamino, Crete	EMII	thin	Y	Y
37.429936	24.376594	Paliopyrgos-Aspra Spitia, Kythnos	EBA	thick	N	N
37.424342	24.369826	Sideri, Kythnos	EBA	thick	N	Y
37.16108	24.430276	Avessalos, Seriphos	EBA	not detailed	N	N
37.192169	24.446287	Kephala, Seriphos	EBA	not detailed	N	N
37.681461	24.327512	Kephala, Keos	FN	thin	N	N
37.970685	23.725718	Athenian Acropolis, Attica	FN	thin	N	N
38.002762	23.859912	Gerakas, Attica	EHI	not detailed	N	N
38.00923	24.023767	Raphina, Attica	EBII	not detailed	N	Y
36.927793	24.725249	Akrotiriaki/Skali, Siphnos	EBA	not detailed	N	N

1.1.5. Ap1.1.5. Table with data in used for Anatolian GIS maps.

Coordinates	Date of material	Furnace fragments Y/N	Slag Y/N	Copper prills Y/N	Site Name
37.948861, 27.346389	4th millennium B.C.	Y	Y	Y	Çukuriçi Höyük
38.324389, 26.761833		Y	Y		Limen Tepe
38.590361, 43.583611	4th millennium B.C.	Y	Y		Bakla Tepe
37.474611, 35.067611	4th millennium B.C.		Y		Camlibel Tarlasi
38.656750, 39.219806	Chalolithic period	Y	Y		Norsuntepe

41.274611, 41.560333	4th millennium B.C		Y		Murgul
33.662667, 51.995861			Y	Y	Arisman
36.846278, 34.895361	date or provenance unsecure	Y	Y		Yesiltepe
	c. 5000 BC		Y		Tepecik
	c. 5000 BC		Y		Tulintepe
37.091667, 32.445778	second half of 4th millennium BC	Y	Y		Bagbasi
	third millennium BC, EBA		Y		Goltepe
38.656750, 39.219806	Chalcolithic period, 5th and 4th millennium B.C. - Early Bronze I	Y			Norsuntepe
38.380917, 38.361306	EBIII	Y			ambiente 5 of period IVD Arslantepe
	3400-2900 BC	Y			Amuq
39.271583, 45.454677	2nd millenium B.C.	Y			Kultepe
	Ubaid related Chalcolithic period (4500-3900 B.C.)	Y	Y	Y	Degirmentepe
38.381622, 38.359090	c.3800-2900B.C. (Uruk-related Chalcolithic periods VII, VIA amd VIB).		Y	Y	Arslantepe
	EBA (3000-2000 B.C.)	Y			Kestel
37.666436, 32.825660	7th-6th millennium B.C. (6250-5400 B.C.)		Y		Catal Huyuk
	Chalcolithic period, 5th and 4th millennium B.C. (5400-5200 B.C.)		Y		Tulintepe
	Chalcolithic period, 5th and 4th millennium B.C.	Y			Tepecik
37.518325, 38.605556	EBI (c.3000 B.C.).		Y		Nevali Cori
	pre-Uruk	Y	Y		Haci Nebi Tepe
	Chalcolithic	Y			Timna
38.380917, 38.361306	Early Bronze Age	Y	Y		Norsuntepe
37.449260, 34.624449	Early Bronze Age		Y		Madenkoy (B 7)
	Early Bronze Age		Y		Gumus (B 16)

	Early Bronze Age	Y			Yediharmantepe (B 5)
	5th - 4th millennium BC		Y		Tappeh Ghabristan
	4th millennium BC (ca.5500-3500 B.C.)		Y		Tal-i Iblis
30.416403, 57.709507	Bronze Age	Y			Shahdad
36.155644, 54.379621	Bronze Age	Y	Y		Tepe Hissar
30.416995, 57.710022	Bronze Age - second half of the third millennium B.C.	Y			Quarter at Shahdad
	Early Chalcolithic		Y	Y	Wadi Fidan 4
31.234758, 34.77526	Mid 4th millennium BC	Y	Y		Tell Abu Matar
	Chalcolithic		Y		Shiqmim
30.611137, 35.447067	EBA II/III	Y	Y	Y	Feinan 9
38°16'00.9"N 39°45'41.4"E	EBA		Y		Ergani Maden (TG 176)
40.055668, 29.121920	EBA?		Y		Sogukpinar-Madenbelenitepe (TG 153)

1.1.6. Ap1.1.6. Table with data in used for Anatolian GIS maps.

Furnace fragments Y/N	**Copper prills Y/N**	**Slag Y/N**	**Site Name**	**Coordinates**	**Date of material**
Y		Y	Belovode	44.365139, 21.394056	Vinca
Y		Y	Plocnik	43°12'02.9"N 21°20'45.3"E	Vinca, 3200BC.
		Y	Gornja Tuzla	44°33'30.2"N 18°45'24.6"E	Vinca-Plocnik phase, 3760-3200BC.
		Y	Vinca Belo Brodo	44°45'43.2"N 20°37'23.7"E	Vinca-Plocnik phase, 3800BC
		Y	Selevac	44°30'10.5"N 20°51'52.8"E	Vinca, 4170-3800BC, Middle and late neolithic
Y			Divostin	44°01'28.4"N 20°49'55.7"E	Vinca culture, 3300BC (Divostin II)
		Y	Gomolava	44°53'18.3"N 19°44'53.5"E	Vinca culture, 3500-3200BC
		Y	Stapari	43°52'23.1"N 19°44'30.7"E	Vinca culture, 3300BC

		Y	Anza IV		Early Vinca, 3400 BC
		Y	Zengovar-kony	46°10'26.8"N 18°25'54.4"E	Lengyel culture, middle and late Neolithic, 4500-3200
		Y	Novacka Cuprija	44°25'29.0"N 20°55'56.7"E	Baden culture, Early Bronze Age, 2600-2200BC.
		Y	Pecica	46°10'16.2"N 21°04'04.4"E	Early/Middle Bronze Age

1.2. Ap1.2. Temperature data from experimental campaigns.

1.2.1. Ap1.2.1. Table with data from temperature readings taken using thermocouples, for smelt in campaign one.

Time (Minutes)	Bottom of Furnace near wall (temp in ºC)	Bottom of furnace in centre (temp in ºC)	Top of Furnace near wall (temp in ºC)	Top of Furnace in centre (temp in ºC)
0	710	590	550	100
5	790	580	580	200
10	795	585	590	580
15	800	580	595	590
20	800	585	600	420
25	805	590	595	410
30	1180	1120	900	780
35	1190	1110	900	790
40	1150	950	500	700
45	1100	900	700	750
50	1150	1000	650	620
55	1190	1100	700	650
60	1290	1190	780	700
65	1300	1090	790	750

1.2.2. Ap1.2.2. Table with data from temperature readings taken using thermocouples, for smelt in campaign two.

Time (Minutes)	Bottom of Furnace near wall (temp in ºC)	Bottom of furnace in centre (temp in ºC)	Top of Furnace near wall (temp in ºC)	Top of Furnace in centre (temp in ºC)
0	700	1200	480	550
5	750	1200	500	560
10	800	1200	550	570
15	690	1200	600	580
20	700	1200	680	600
25	720	1200	700	640
30	790	1200	720	660
35	800	1200	760	670
40	820	1200	800	700
45	800	1200	780	680
50	820	1200	800	700
55	850	1200	840	720
60	900	1200	860	760
65	920	1200	880	740
70	950	1200	900	780
75	810	1200	890	800
80	820	1200	900	810
85	800	1200	920	815
90	830	1200	860	820
95	850	1200	850	830
100	900	1200	870	860
105	920	1200	875	880
100	900	1200	850	900
115	850	1200	820	880
120	800	1200	830	820
125	780	1200	840	840
130	760	1200	815	850
135	790	1200	780	870
140	810	1200	760	885
145	830	1200	740	900

1.3. Ap1.3. pXRF raw data

1.3.1. Ap1.3.1. pXRF data, analysis of ceramic furnace fragments from Experimental Campaign 1 and 2.

Type	Units	SAMPLE	Bal	Nb	Zr	Sr	Rb	Bi	As	Pb	W	Zn	Cu	Ni	Co	Fe	Mn	Ti	Al	P	Si	Cl	S	Mg
Mining	ppm	APF exp1 A17	479310.81	12.32	207.56	757.7	92.85	<LOD	<LOD	<LOD	<LOD	24.44	5799.88	<LOD	<LOD	36083.93	620.4	2501.6	66292.14	2616.36	360452.56	294.08	981.79	43933.89
Mining	ppm	APF exp1 A17	558050.69	12.22	198.69	1027.42	84.75	<LOD	<LOD	<LOD	<LOD	26.52	4041.03	<LOD	<LOD	33474.64	722.79	2747.3	48348.5	3005.04	345692.97	303.09	2249.63	<LOD
Mining	ppm	APF exp1 A17	580463	12.06	199.33	1000.91	82.31	<LOD	<LOD	<LOD	<LOD	29.7	3953.37	<LOD	<LOD	32557.96	653.63	1896.08	48592.34	3690.48	324453.44	332.92	2063.22	<LOD
Mining	ppm	APF exp1 A16	539046.19	13.67	211.34	99.58	84.32	8.05	23.11	10.58	<LOD	66.1	<LOD	<LOD	<LOD	45376.23	304.67	4666.58	100923.66	<LOD	308719.19	<LOD	445.14	<LOD
Mining	ppm	APF exp1 A16	569713.5	14.48	224.52	107.24	89.33	8.44	20.14	12.57	<LOD	71.2	<LOD	<LOD	<LOD	47681.46	494.08	5184.39	89466.55	<LOD	269370.38	<LOD	335.35	17206.28
Mining	ppm	APF exp1 A16	585272	15.17	218.95	99.77	88.09	<LOD	19.01	11.89	<LOD	69.95	<LOD	<LOD	<LOD	44484.15	357.47	5061.65	84463.88	<LOD	279141.53	<LOD	310.26	<LOD
Mining	ppm	APF exp1 A15	689346.19	10.36	176.71	397.66	96.62	<LOD	<LOD	<LOD	<LOD	19.87	2761.86	<LOD	<LOD	32391.85	264.41	1703.34	24480.2	1219.37	244809.59	<LOD	2316.5	<LOD
Mining	ppm	APF exp1 A15	705606.63	12.91	176.31	378.66	103.06	<LOD	<LOD	<LOD	<LOD	17.9	3047.65	<LOD	<LOD	30723.15	220.96	2244.42	23173.7	1314.59	230598.13	<LOD	2376.47	<LOD
Mining	ppm	APF exp1 A15	732196.19	14.3	179.17	282.77	111.21	<LOD	<LOD	<LOD	<LOD	<LOD	4255.91	<LOD	<LOD	24747.6	118.71	2392.31	19784.53	1229.44	211462.69	145.85	3053.27	<LOD
Mining	ppm	APF exp1 A14	639033.94	12.41	201.95	80.08	80.97	<LOD	22.14	9.06	<LOD	63.73	<LOD	<LOD	<LOD	44081.98	165.17	4594.73	61855.35	<LOD	233510.72	<LOD	1406.69	<LOD
Mining	ppm	APF exp1 A14	678131.81	13.17	196.68	82.31	83.77	<LOD	18.85	8.9	<LOD	66.32	<LOD	<LOD	<LOD	44364.71	176.9	4677.71	54823.24	<LOD	215952.02	<LOD	1397.4	<LOD
Mining	ppm	APF exp1 A14	539563.5	14.15	186.27	85.48	80.55	<LOD	21.03	9.14	<LOD	57.9	<LOD	<LOD	<LOD	42024.43	177.96	4882.86	97594.23	<LOD	299625.41	<LOD	885.66	<LOD
Mining	ppm	APF exp1 A13	595354.44	7.4	127.57	224.25	58.62	<LOD	15.81	25.62	<LOD	52.95	1839.24	<LOD	<LOD	41792.1	590.08	2370.87	45696.66	<LOD	287768.81	2916.1	236.48	<LOD
Mining	ppm	APF exp1 A13	474565.25	10.72	140.41	311.02	62.1	<LOD	15.74	<LOD	<LOD	50.4	1186.29	108.39	<LOD	41861.81	459.01	5581.59	73998.36	<LOD	400672.59	<LOD	<LOD	<LOD
Mining	ppm	APF exp1 A13	666875.25	10.95	124.26	1828.98	57.31	<LOD	<LOD	<LOD	<LOD	20.1	4049.13	53.33	<LOD	58453.16	519.91	3020.08	35481.02	1870.7	209183.38	353.69	1687.19	<LOD
Mining	ppm	APF exp1 A12	530587.94	14.37	233.34	111.02	89.2	<LOD	18.44	16.31	<LOD	64.65	282.12	<LOD	<LOD	47136.51	514.43	5050.62	101541.8	<LOD	312529.19	67.87	1295.3	<LOD
Mining	ppm	APF exp1 A12	515475.5	13.61	208.16	91.79	77.31	7.32	22.58	11.18	<LOD	60.77	32.95	<LOD	<LOD	40881.15	237.25	5047.28	108005.2	956.01	309968.84	<LOD	942.32	17959.15
Mining	ppm	APF exp1 A12	554325.19	11.97	210.4	89.12	79.34	<LOD	22.42	11.43	<LOD	75.54	28.61	<LOD	<LOD	40824.91	239.65	5081.57	96174.55	989.38	300984.5	<LOD	849.49	<LOD
Mining	ppm	APF exp1 A11	612779.88	14.85	212.45	140.13	89.84	<LOD	9.88	<LOD	<LOD	144.7	356.9	<LOD	<LOD	33067.63	476.57	3203.93	60860.86	1522.32	242865.8	<LOD	20493.88	23758.1
Mining	ppm	APF exp1 A11	654759.06	12.4	207.48	122.65	82.55	7.51	7.74	6.54	<LOD	99.18	199.69	<LOD	<LOD	30753.61	350.93	3589.11	61203.4	1262.98	230804.59	<LOD	16530.56	<LOD
Mining	ppm	APF exp1 A11	651985.88	14.3	220.07	155.79	92.69	<LOD	7.49	8.75	<LOD	150.33	664.74	<LOD	<LOD	31692.86	322.58	2756.51	43055.47	1959.4	241242.97	<LOD	4405.57	20978.01
Mining	ppm	APF exp1 A10	503838.19	17.38	278.46	113.74	92	<LOD	14.16	8.55	<LOD	68.79	<LOD	<LOD	<LOD	45449.14	451.91	6368.46	114367.73	<LOD	310310.56	<LOD	511.42	18097.71
Mining	ppm	APF exp1 A10	544028.81	15.79	269.74	111.4	93.41	<LOD	10.27	11.33	<LOD	70.01	<LOD	<LOD	<LOD	45081.09	394.44	5446.78	101997.71	<LOD	301550	<LOD	552.54	<LOD
Mining	ppm	APF exp1 A10	531224.31	15.48	253.65	107.76	90.67	<LOD	13.84	9.12	<LOD	73.34	<LOD	<LOD	<LOD	44765.67	426.47	5600.83	104439.93	<LOD	312455.47	<LOD	523.4	<LOD
Mining	ppm	APF exp1 A9	788483.25	<LOD	99.35	1220.13	37.84	<LOD	16.69	<LOD	<LOD	<LOD	14571.02	<LOD	<LOD	114401.02	1360.9	1944.03	<LOD	1197.94	68101.48	<LOD	3060.53	<LOD
Mining	ppm	APF exp1 A9	768737.44	<LOD	91.27	1276.69	32.31	<LOD	28.64	<LOD	<LOD	<LOD	34289.48	<LOD	<LOD	127543.98	1379.66	1451.8	5075.4	625.42	56378.36	<LOD	2834.49	<LOD
Mining	ppm	APF exp1 A9	778007.19	7.48	92.27	1261.3	35.51	<LOD	21.32	<LOD	<LOD	<LOD	32366.02	<LOD	<LOD	125252.88	1421.33	1467.49	<LOD	1115.58	56400.83	<LOD	2280.21	<LOD
Mining	ppm	APF exp1 A8	708065.25	14.2	226.86	91.89	74.89	<LOD	9.49	10.3	<LOD	51.08	<LOD	<LOD	<LOD	38650.02	976.35	4090.56	43341.55	<LOD	203456.28	<LOD	645.34	<LOD
Mining	ppm	APF exp1 A8	709531.56	16.04	228.45	98.07	75.56	<LOD	10.46	10.33	<LOD	52.67	<LOD	<LOD	<LOD	38818.43	1003.43	4540.22	41221.11	<LOD	191447.13	<LOD	614.97	<LOD
Mining	ppm	APF exp1 A8	581591.38	14.08	209.63	97.93	84.56	<LOD	7.93	14.02	<LOD	59.12	<LOD	<LOD	<LOD	40323.15	351.29	4416.96	80532.45	<LOD	270169.16	<LOD	919.49	20839.02
Mining	ppm	APF exp1 A7	728144.06	11.13	200.2	593.2	85.12	<LOD	<LOD	<LOD	<LOD	<LOD	3646.97	<LOD	<LOD	23687.35	311.76	2886.7	21019.95	1317.68	217220.84	<LOD	874.99	<LOD
Mining	ppm	APF exp1 A7	696596.81	8.37	196.12	584.86	83.32	<LOD	<LOD	<LOD	<LOD	<LOD	3710.82	<LOD	<LOD	23687.83	312.54	2394.69	24712.86	1363.94	245191.48	<LOD	1141.29	<LOD
Mining	ppm	APF exp1 A7	717600.13	7.55	188.39	718.88	76.96	<LOD	<LOD	<LOD	<LOD	<LOD	2861.86	<LOD	<LOD	22001.09	289.42	1841.8	21688.71	1383.66	230375.88	<LOD	965.62	<LOD
Mining	ppm	APF exp1 A6	571123.75	14.43	185.55	117.41	81.77	<LOD	18.17	<LOD	<LOD	68.13	54.8	<LOD	<LOD	37895.14	288.77	4207.93	82085.74	592.38	271592.44	<LOD	20578.3	<LOD
Mining	ppm	APF exp1 A6	553568.44	14.21	186.66	121.02	84.69	<LOD	13.95	8.32	<LOD	70.94	90.9	<LOD	<LOD	40074.93	354.74	4612.62	90310.14	855.74	286328.16	<LOD	23299.49	<LOD
Mining	ppm	APF exp1 A6	551805.06	14.45	183.16	113.65	82.93	<LOD	16.53	8.87	<LOD	63.88	97.63	<LOD	<LOD	40129.07	364.22	4431.39	90548.73	689.6	286751.69	<LOD	24696.3	<LOD
Mining	ppm	APF exp1 A5	546968.81	15.69	243.32	103.2	86.01	<LOD	13.61	10.9	<LOD	70.33	<LOD	<LOD	<LOD	42004.8	383.1	5908.73	87208.3	591.24	314226.56	<LOD	2103.79	<LOD
Mining	ppm	APF exp1 A5	489183.34	15.56	241.53	101.47	87.64	<LOD	14.37	10.41	<LOD	67	<LOD	<LOD	<LOD	41435.8	395.39	6221.18	103455.86	477.08	334319.53	109.79	1694.66	22161.63
Mining	ppm	APF exp1 A5	593050	17.92	244.46	102.45	86.66	7.35	11.59	12.22	<LOD	69.98	<LOD	<LOD	<LOD	41952.93	364.15	5987.14	71575.59	768.58	265017.63	80.35	1551.61	19099.44
Mining	ppm	APF exp1 A4	641903.38	14.13	197.91	707	110.08	<LOD	<LOD	<LOD	<LOD	17.17	2911.65	<LOD	<LOD	34376.93	386.92	2528.79	37204.55	3292.52	273770.81	<LOD	2563.64	<LOD
Mining	ppm	APF exp1 A4	640308.81	13.49	203.17	705.83	107.88	<LOD	<LOD	<LOD	<LOD	27.26	2829.3	<LOD	<LOD	33728.3	397.42	2066.13	38402.63	3183.62	275328.63	<LOD	2680.85	<LOD
Mining	ppm	APF exp1 A4	637743.31	12.69	198.82	714.26	103.64	<LOD	<LOD	<LOD	<LOD	16.31	2495.02	<LOD	<LOD	32673.82	440.36	2211.26	38434.41	2522.59	279241.44	<LOD	3177.55	<LOD
Mining	ppm	APF exp1 A3	600630.75	14.39	188.38	129.36	84.4	<LOD	15.27	16.81	<LOD	72.2	292.19	<LOD	<LOD	39361.97	290.91	4448.63	80243.78	611.77	265171.66	114.91	8310.9	<LOD
Mining	ppm	APF exp1 A3	561356.88	14.31	193.59	133.79	85.18	<LOD	14.14	13.15	<LOD	70.23	305.9	<LOD	<LOD	39637.66	262.98	4700.2	89264.47	499.85	274005.84	151.34	9914.51	19368.21
Mining	ppm	APF exp1 A3	595329.13	14.22	197.09	133.76	86.98	<LOD	18.3	14.73	<LOD	77.54	266.22	<LOD	<LOD	40563.39	281.81	4448.7	81656.26	<LOD	265798.03	184.16	10463.75	<LOD
Mining	ppm	APF exp1 A2	488074.41	17.72	247.27	113.33	92.9	7.2	16.22	10.68	<LOD	68.36	31.59	<LOD	<LOD	44783.75	340.14	4964.28	113963.59	616.94	319574.19	135.6	4754.04	22187.83
Mining	ppm	APF exp1 A2	467347.16	17.48	234.93	115.41	91.4	<LOD	13.9	14.16	<LOD	66.64	36.89	<LOD	<LOD	43421.37	415.65	5445.86	120263.73	<LOD	329932.56	208.53	4906.97	27092.06
Mining	ppm	APF exp1 A2	510771.25	15.19	236.71	106.71	87.22	<LOD	13.9	15.3	<LOD	59.8	44.2	<LOD	<LOD	47199.29	610	5366.5	106693.7	<LOD	325744.31	90.46	2942.41	<LOD
Mining	ppm	APF exp1 A1	956546.19	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	43118.07	<LOD	<LOD						
Mining	ppm	APF exp1 A1	529312.13	13.22	212.74	112.94	77.22	<LOD	14.51	10.89	<LOD	65.85	585.76	<LOD	<LOD	39582.44	283.48	4228.7	93517.7	693.16	280642.69	167.51	25222.97	25247.55
Mining	ppm	APF exp1 A1	576387.5	14.91	209.77	110.8	76.62	<LOD	13.7	12.51	<LOD	60.16	566.96	<LOD	<LOD	39406.43	263.39	4440.44	81812.52	1097.63	270151.69	152.51	25222.4	<LOD
Mining	ppm	APF exp1 A1	584350.69	13.13	201.55	120.35	78.95	<LOD	16.73	11.94	<LOD	51.88	685.7	<LOD	<LOD	38804.7	229.05	3756.92	81516.44	597.2	265503.97	156.73	23903.94	<LOD
Mining	ppm	APF exp2 x21	521092.13	16.08	193.44	103.99	81.74	<LOD	15.36	8.84	<LOD	61.48	165.23	<LOD	<LOD	51756.7	486.02	5953.31	93621.32	1448.86	322426.88	308.8	1971.55	<LOD
Mining	ppm	APF exp2 x21	520952.16	14.69	198.34	103.96	79.05	<LOD	11.04	12.18	<LOD	67.78	209.33	<LOD	<LOD	53425.94	515.3	5611.34	95222.62	1316.82	319976.97	375.56	1899.28	<LOD
Mining	ppm	APF exp2 x21	500342.25	14.75	192.54	106.49	79.86	<LOD	11.7	13.25	<LOD	62.85	170.57	<LOD	<LOD	54768.11	519.05	5432.06	99557.13	1267.93	320034.16	381.15	1617.28	<LOD
Mining	ppm	APF exp2 x20	556955.31	12.95	214.91	100.62	71.8	<LOD	10.39	7.56	<LOD	55.74	280.39	<LOD	<LOD	54836.97	474.81	4645.19	81864.28	881.47	276703.34	287.69	22596.49	<LOD
Mining	ppm	APF exp2 x20	534384.5	13.21	212.59	99.33	74.48	<LOD	8.09	6.96	<LOD	57.73	277.06	<LOD	<LOD	55215.74	539.34	4901.64	87942	963.64	278657	297.8	23062.32	<LOD
Mining	ppm	APF exp2 x20	554081.31	13.71	212.27	96.17	73.98	<LOD	14.05	<LOD	<LOD	62.32	285.39	<LOD	<LOD	55192.42	442.8	4695.67	82255.47	995.05	278455.16	286.87	22837.29	<LOD
Mining	ppm	APF exp2 x19	599998.38	15.82	212.82	99.08	82.8	<LOD	8.18	16.14	<LOD	76.35	406.12	<LOD	<LOD	52045.58	590.06	4999.05	73980.29	854.11	265419.72	479.75	715.69	<LOD
Mining	ppm	APF exp2 x19	555834.19	16.31	217.61	99.09	82.42	<LOD	10.07	13.68	<LOD	73.96	394.39	<LOD	<LOD	52156.08	723.29	5715.69	84794.31	790.96	277442.88	362.19	660.82	20612.02
Mining	ppm	APF exp2 x18	562902.44	15.92	227.22	110	84.31	<LOD	14.54	22.92	<LOD	71.06	470.94	<LOD	<LOD	51497.77	1009.36	4752.25	86408.8	698.41	290378.31	585.54	750.24	<LOD
Mining	ppm	APF exp2 x18	503270.75	15.74	223.84	97.85	78.59	<LOD	13.34	<LOD	<LOD	57.76	252.71	<LOD	<LOD	51081.97	602.5	5168.64	101498.56	588.96	316684.31	367.65	3883.42	<LOD
Mining	ppm	APF exp2 x18	528352.38	14.72	221.24	101.7	80.88	<LOD	7.84	10.06	<LOD	56.52	209.01	<LOD	<LOD	55537.28	560.24	4904.52	95659.23	<LOD	298166.31	294.04	3706.67	<LOD
Mining	ppm	APF exp2 x18	485348.78	16.39	209.61	106.35	78.12	7.87	9.63	9.36	<LOD	63.29	214.89	<LOD	<LOD	50416.79	440.41	4291.5	108206.42	620.53	318578.81	324.27	3692.43	27362.85
Mining	ppm	APF exp2 x17	507147.78	14.38	220.84	117.01	82.03	<LOD	11.86	8.25	<LOD	63.17	441.46	<LOD	<LOD	51707.13	474.05	5488.39	106855.85	<LOD	293183.13	413.8	2317.76	31118.98
Mining	ppm	APF exp2 x17	548840.44	14.77	217.66	123.99	80.45	<LOD	7.79	10.84	<LOD	59.7	533.65	<LOD	<LOD	51143.93	530.62	5358.68	96262.86	<LOD	293719.25	391.76	2277.75	<LOD
Mining	ppm	APF exp2 x17	942599.5	13.7	218.47	124.27	84.75	<LOD	<LOD	<LOD	<LOD	66.49	549.59	<LOD	<LOD	50722.54	505.27	5088.91						
Mining	ppm	APF exp2 x17	551825.44	12.93	224.45	95.95	79.15	<LOD	9.1	9.13	<LOD	60.41	416.55	<LOD	<LOD	45283.74	501.14	5047.88	91443.14	704.21	302173.19	470.31	1643.29	<LOD
Mining	ppm	APF exp2 x17	577409.38	13.17	213.2	118.54	78.02	<LOD	10.3	7.08	<LOD	55.15	779.41	<LOD	<LOD	45361.61	541.66	4926.35	83641.46	842.65	280867	676.71	4415.26	<LOD
Mining	ppm	APF exp2 x16	594744.31	12.23	197.25	89.8	78.74	<LOD	9.92	9.95	<LOD	63	96.87	<LOD	<LOD	48486.6	392.68	5141.93	70958.43	542.39	277395.91	236.59	1543.35	<LOD
Mining	ppm	APF exp2 x16	531838.56	12.37	196.45	94.22	76.21	<LOD	8.66	12.1	<LOD	62.63	87.66	<LOD	<LOD	48310.12	425.63	4927.01	86031.37	678.13	311765.72	290.07	1419.38	<LOD
Mining	ppm	APF exp2 x16	651019.56	17.09	236.01	97.44	79.5	<LOD	8.13	14.24	<LOD	59.86	124.73	<LOD	<LOD	43385.64	469.13	5030.94	57087.66	451.66	239830.25	171.04	1917.11	<LOD
Mining	ppm	APF exp2 x16	601386.31	14.95	254.32	94.13	81.71	<LOD	9.91	10.45	<LOD	57.24	130.77	<LOD	<LOD	43871.38	540.02	4886.94	72923.65	<LOD	271854.44	230.84	3652.95	<LOD
Mining	ppm	APF exp2 x15	695995.19	<LOD	61.69	1783.03	63.41	<LOD	<LOD	<LOD	<LOD	<LOD	118974.19	<LOD	<LOD	33250.53	692.51	<LOD	13329.97	3821.59	129459.35	896.96	548.67	<LOD
Mining	ppm	APF exp2 x15	696331.38	<LOD	62.1	1740.87	64.87	<LOD	<LOD	<LOD	93.91	<LOD	120676.56	<LOD	<LOD	32849.93	634.55	984.1	17273.11	3350.92	124023.34	870.99	797.45	<LOD
Mining	ppm	APF exp2 x15	733736.88	<LOD	83.63	679.73	54.81	<LOD	13.16	<LOD	<LOD	<LOD	101048.24	<LOD	<LOD	31442.77	429.4	<LOD	6166.06	3124.06	120063.91	527.34	1794.16	<LOD
Mining	ppm	APF exp2 x14	693750.25	<LOD	68.72	2195.65	34.81	<LOD	<LOD	<LOD	<LOD	<LOD	183144.67	<LOD	<LOD	19051.73	295.44	1449.05	12016.35	3909.19	81517.24	1015	1015.13	<LOD
Mining	ppm	APF exp2 x14	720626.94	<LOD	61.62	2213.66	38.44	<LOD	<LOD	<LOD	<LOD	<LOD	176948.31	<LOD	<LOD	20298.54	327.52	1873.59	6740.08	2574.11	66535.13	746.22	600.55	<LOD
Mining	ppm	APF exp2 x14	686875.06	<LOD	77.58	2076.86	40.25	<LOD	<LOD	<LOD	<LOD	<LOD	163221.56	<LOD	<LOD	21570.62	322.76	1093.05	<LOD	3594.04	74117.92	854.03	720.98	<LOD
Mining	ppm	APF exp2 x13	522705.41	15.44	250.52	100.27	90.83	<LOD	11.21	8.98	<LOD	72.8	498.27	<LOD	<LOD	61764.45	468.33	5647.63	101584.9	683.89	303277.06	310.55	2509.36	<LOD
Mining	ppm	APF exp2 x13	508522.47	15.03	252.49	101.61	88.05	<LOD	9.97	11.56	<LOD	69.89	473.59	<LOD	<LOD	61027.25	506.78	4974.74	101736.45	810.57	302574.38	312.85	2548.29	<LOD
Mining	ppm	APF exp2 x13	516856	16.4	239.67	95.87	88.48	<LOD	21.6	17.37	<LOD	104.89	675.35	<LOD	<LOD	53077.48	426.44	5502.83	101679.57	750.66	301688.03	199.68	3787.91	<LOD
Mining	ppm	APF exp2 x12	590341.94	15.1	226.29	100.69	87.43	<LOD	13.53	11.79	<LOD	71.41	1904.59	<LOD	<LOD	52833.03	523.56	5121.73	76693.27	1037.66	269729.53	502.86	785.62	<LOD
Mining	ppm	APF exp2 x12	589854.31	16.24	227.02	103.01	86.72	<LOD	14.11	13.58	<LOD	74.59	1831.77	<LOD	<LOD	54001.34	625.8	5454.97	78543.72	1148.5	266662.81	445.8	887.47	<LOD
Mining	ppm	APF exp2 x12	581164.5	17.23	231.46	101.31	87.98	<LOD	12.56	20.77	<LOD	82.7	1859.91	<LOD	<LOD	51994.96	477.17	4645.17	76671.26	1370.74	259662.2	610.23	1211.12	19777.06
Mining	ppm	APF exp2 x11	482427.13	15.09	249.5	96.08	82.4	<LOD	8.91	12.74	<LOD	66.98	172.87	<LOD	<LOD	50814.92	456.6	5731.51	113622.7	579.3	329085.59	220.26	839	<LOD
Mining	ppm	APF exp2 x11	472474.81	14.47	248.11	95.3	82.53	<LOD	10.64	9.17	<LOD	62.74	175.25	<LOD	<LOD	51879.21	506.73	5293.22	116837.66	676.04	336039	206.38	934.07	<LOD
Mining	ppm	APF exp2 x11	544884.88	16.39	250.13	95.23	79.25	7.83	11.01	11.54	<LOD	63.78	182.43	<LOD	<LOD	49060.08	402.49	4471.56	94551.52	673.25	304148.63	193.79	896.26	<LOD
Mining	ppm	APF exp1 x10	689751.31	10.78	188.8	97.76	70.08	<LOD	9.45	<LOD	<LOD	51.46	697.78	<LOD	<LOD	61842.4	309.34	4788.62	47614.94	766.54	192619.14	159.09	1016.79	<LOD
Mining	ppm	APF exp1 x10	648928.94	13.33	195.88	96.06	70.4	<LOD	9.63	<LOD	<LOD	48.57	1298.05	<LOD	<LOD	63792.04	413.46	3877.19	61292.38	860.76	218044.22	259.2	800	<LOD

Mining	ppm	APF exp1 x10	605518.56	12.42	190.68	91.52	70.61	<LOD	7.07	<LOD	<LOD	53.85	876.98	<LOD	<LOD	65984.52	445.12	4456.47	72250.32	517.01	229678.84	249.81	612.56	18983.67
Mining	ppm	APF exp1 x9	493149.53	14.68	232.18	103.34	84.84	9.06	13.46	9.09	<LOD	54.08	426.4	<LOD	<LOD	57104.87	411.03	4957.85	107831.16	650.85	323344.16	338.36	980.32	<LOD
Mining	ppm	APF exp1 x9	501702.44	15.82	245.77	99.82	84.84	<LOD	7.23	11.22	<LOD	64.12	220.69	<LOD	<LOD	52861.44	325.71	4994.04	105827.18	1117.63	325703.66	287.31	6431.17	<LOD
Mining	ppm	APF exp1 x9	485168	12.77	222.41	92.24	85.11	<LOD	6.05	12.74	<LOD	62.24	500.61	<LOD	<LOD	52607.92	392.36	4624.1	111404.13	832.87	325282.19	352.59	1768.82	<LOD
Mining	ppm	APF exp1 x8	529257.25	15.36	233.19	95.86	81.89	<LOD	9.98	12.34	<LOD	50.32	726.44	<LOD	<LOD	53278.15	376.94	4569.9	94179.77	878.43	293799.56	242.98	2479.45	19712.22
Mining	ppm	APF exp1 x8	583029.63	13.22	213.42	97.01	80.68	<LOD	12.75	8.14	<LOD	62.21	939.84	<LOD	<LOD	72870.13	499.02	5134.35	85472.13	734.15	249962.91	215.55	654.84	<LOD
Mining	ppm	APF exp1 x8	557990.19	14.51	207.86	95.57	80.99	<LOD	14.55	11.95	<LOD	53.97	662.72	<LOD	<LOD	50978.05	389.71	4768.83	83567.88	692.52	281061.22	166.92	2955.45	16287.11
Mining	ppm	APF exp1 x7	577258.13	14.54	244.81	98.3	80.69	<LOD	8.78	10.45	<LOD	58.02	912.96	<LOD	<LOD	40010.33	278.75	4865.63	85043.6	828.76	289303.25	178.74	797.39	<LOD
Mining	ppm	APF exp1 x7	568039.13	15.82	223.81	98.73	80.48	7.75	10.68	11.69	<LOD	53.9	565.8	<LOD	<LOD	38490.29	310.68	5031.81	89885.88	759.23	283892.31	101.4	630.72	<LOD
Mining	ppm	APF exp1 x7	548077.81	16.46	217.97	97.31	84.29	<LOD	12.44	12.69	<LOD	59.92	534.9	<LOD	<LOD	40577.29	291.48	5644.54	92880.27	811.63	287132.91	121.83	720.56	22705.71
Mining	ppm	APF exp1 x6	660249.81	<LOD	42.93	1487.14	23.14	<LOD	18.46	<LOD	<LOD	<LOD	143637.5	<LOD	<LOD	136630.38	977.7	<LOD	5898.97	843.35	45898.74	747.29	3071.09	<LOD
Mining	ppm	APF exp1 x6	719092.63	<LOD	46.53	1428.03	19.62	<LOD	<LOD	<LOD	<LOD	<LOD	142437.84	<LOD	<LOD	134477.52	983.76	<LOD						
Mining	ppm	APF exp1 x6	723436.38	<LOD	42.42	1438.69	24.36	<LOD	<LOD	<LOD	<LOD	<LOD	136495.88	<LOD	<LOD	135821.11	830.07	1567.46						
Mining	ppm	APF exp1 x6	647806.88	<LOD	39.73	1446.33	24.91	<LOD	19.23	<LOD	<LOD	<LOD	143376.3	<LOD	<LOD	132067.3	1014.89	974.4	<LOD	1306.28	63601.81	1003.36	3631.95	<LOD
Mining	ppm	APF exp1 x6	651615.13	<LOD	47.53	1447.75	21.92	<LOD	<LOD	<LOD	<LOD	<LOD	144159.67	<LOD	<LOD	136889.63	994.87	<LOD	<LOD	798.86	55473.2	994.64	3540.96	<LOD
Mining	ppm	APF exp1 x5	465208.28	<LOD	65.16	763.47	72.43	<LOD	12.46	<LOD	<LOD	<LOD	143790.91	<LOD	<LOD	44877.56	613.44	<LOD	26552.06	3194.37	289370.06	751.24	24619.53	<LOD
Mining	ppm	APF exp1 x5	634939.63	<LOD	67.9	927.19	64.95	<LOD	13.86	<LOD	<LOD	<LOD	92433.37	<LOD	<LOD	51343.96	675.6	<LOD	13913.05	2038.3	185702.23	342.83	17398.1	<LOD
Mining	ppm	APF exp1 x5	631193.38	<LOD	66.98	771.33	74.07	<LOD	<LOD	<LOD	<LOD	<LOD	105512.27	<LOD	<LOD	48247.13	679.91	<LOD	15724.64	1623.28	177748.11	344.19	17890.62	<LOD
Mining	ppm	APF exp1 x4	671274.94	10.01	89.58	1232.72	43.82	<LOD	<LOD	<LOD	<LOD	<LOD	140603.52	<LOD	<LOD	35481.94	569.57	1591.28	10703.76	1038.39	134744.53	1257.78	1001.16	<LOD
Mining	ppm	APF exp1 x4	633228.25	6.44	113.93	1295.78	47.19	<LOD	<LOD	<LOD	<LOD	<LOD	137772.41	<LOD	<LOD	38040.6	599.11	<LOD	13243.84	657.04	126948.09	1128.01	1001.55	44762.63
Mining	ppm	APF exp1 x4	683592.75	6.99	132.48	1207.05	53.87	<LOD	<LOD	<LOD	<LOD	<LOD	129398.9	<LOD	<LOD	39377.05	596.88	1354.37	7979.85	1209.81	132981.02	1103.29	771.17	<LOD
Mining	ppm	APF exp1 x3	596915.88	5.92	70.66	2531.21	57.51	<LOD	42.98	<LOD	<LOD	<LOD	106328.89	<LOD	157.51	53138.05	662.93	<LOD	15348.16	4959.33	146635.02	595.93	34166.38	<LOD
Mining	ppm	APF exp1 x3	540806.88	<LOD	60.28	1181.84	48.52	<LOD	13.88	<LOD	<LOD	<LOD	86657.48	<LOD	<LOD	49921.37	605.79	<LOD	14500.32	1944.13	277976.06	<LOD	538.92	<LOD
Mining	ppm	APF exp1 x3	641233.13	6.03	55.34	1414.56	42.5	<LOD	20.36	<LOD	<LOD	86.46	76384.38	<LOD	<LOD	63440.7	761.74	<LOD	10666.96	1846.13	202030.2	<LOD	<LOD	<LOD
Mining	ppm	APF exp1 x2	735511.25	<LOD	78.03	1410.1	38.28	<LOD	<LOD	<LOD	<LOD	70.74	103121.43	<LOD	<LOD	26957.96	446.34	<LOD	6358.92	1396.64	122040.19	265.09	1043.13	<LOD
Mining	ppm	APF exp1 x2	760982.56	6.77	84.16	1909.6	35.82	<LOD	<LOD	<LOD	<LOD	95.49	68588.95	<LOD	<LOD	47423.19	719.43	1364.12	8068.49	2731.86	105746.02	<LOD	1821.39	<LOD
Mining	ppm	APF exp1 x2	770831.94	8.28	128.61	1437.91	56.05	<LOD	<LOD	<LOD	<LOD	64.08	61194.21	<LOD	<LOD	47195.8	713.31	2054.34	9894.23	1838.5	104067.11	<LOD	389.91	<LOD
Mining	ppm	APF exp1 x1	840765.31	<LOD	<LOD	2204.85	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	120749.12	<LOD	<LOD	36280.75	<LOD	<LOD						
Mining	ppm	APF exp1 x1	750594.69	<LOD	64.58	1183.36	58.94	<LOD	<LOD	<LOD	<LOD	112.74	121664.92	<LOD	<LOD	13518.83	199.79	<LOD	5468.11	2093.73	102964.25	715.11	1240.2	<LOD
Mining	ppm	APF exp1 x1	673366.94	<LOD	69.33	1611.98	49.8	<LOD	<LOD	<LOD	<LOD	<LOD	136860.16	<LOD	<LOD	19130.96	351.13	<LOD	7724.01	2062.81	94437.38	561.71	1054.71	61748.09
Mining	ppm	APF exp1 x1	733737.56	<LOD	68.6	1746.95	42.24	<LOD	<LOD	<LOD	<LOD	<LOD	140917.59	<LOD	<LOD	19613.76	446.67	<LOD	6050.39	2120.61	92855.63	517.88	880.43	<LOD
Mining	ppm	stnd 180-706	497195.06	28.74	264.98	154.78	134.71	11.18	50.95	916.38	<LOD	795.36	227.92	<LOD	<LOD	17770.25	895.44	1238.44	71079.52	<LOD	393539.09	305.01	1309.45	<LOD
Mining	ppm	stnd 180-649	583415.13	10.38	124.08	235.85	79.96	7.01	9.97	12.14	<LOD	83.57	<LOD	35.14	<LOD	34065	399.28	2621.16	71090.65	726.65	306100.47	233.88	732.41	<LOD
Mining	ppm	stnd 180-661	567568.88	14.79	301.86	81.79	54.85	<LOD	552.92	534.23	<LOD	30.67	<LOD	<LOD	<LOD	18287.65	<LOD	2402.67	55391.25	484.14	342558.22	255.45	319.74	<LOD
Mining	ppm	stnd 180-647	565195.94	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	73.85	<LOD	<LOD	<LOD	<LOD	434664.81	65.38	<LOD	<LOD