Small-Scale Copper Production in Late Roman Pyrga, Cyprus: Ecclesiastical Influence on Technology

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ABSTRACT: Copper was central to the Late Roman Cypriot economy, represented by large-scale production sites. This study examines often-overlooked small-scale mining by focusing on Pyrga in the Pouzis Valley, Southeast Cyprus. Surveys by the Hala Sultan Tekke Hinterland Survey Project *(2021–ongoing) revealed dispersed slag heaps near potential church remains. Metal slag analysis reveals a consistent manganese-rich composition and low residual copper, suggesting controlled and efficient smelting. Viewed alongside the* Codex Theodosianus *and* Codex Justinianus*, regulating mining, taxation and landownership, and the proximity of churches to production sites, this raises the possibility that Pyrga's production was part of a centrally organised network. This research examines how ecclesiastical institutions may have steered local economy, administration and taxation, and technological practices. This dual exploration of administration and technology deepens our understanding of the relationship between ecclesiastical power and the copper economy of Late Roman Cyprus.*

KEYWORDS: Late Roman, Copper smelting, Cyprus, Slag heaps, Metal slag analysis, Ecclesiastical influence, Hala Sultan Tekke Hinterland Survey Project

Introduction

The Late Roman economy of Cyprus (3rd to 7th century AD) is renowned for its prosperity (Cosentino 2013), with copper production playing a crucial role in this success (Rautman 2000). It was believed copper production had ceased after the 4th century AD (Bruce 1937, 640; Constantinou 1982). However, new evidence, including extensive slag heaps, waste material of smelting, suggests that production continued until at least the 7th century, possibly later (Zwicker 1986; Socratous *et al.* 2015). While Late Roman large-scale copper production sites have been extensively studied (*e.g.* Given and Knapp 2003; Given *et al.* 2013a; 2013b; Kassianidou 2023), these surveys also documented smaller, more dispersed production sites, indicating a more nuanced and complex view of the mining landscape.

During this period, Cyprus was part of the Eastern Roman Empire and under the political control of Constantinople, characterised by imperial authority and ecclesiastical power (Chrysos 1993; Marek 2017). In the 5th century, Cyprus gained more autonomy, allowing bishops to elect their own archbishop (Rapp 2014, 33; Vionis 2018, 52) and under Justinian in the 6th century, Cyprus became part of a broader administrative region, seeing economic reforms and growth (Caraher and Pettegrew 2016, 167). The Church, beyond its religious function, served as a political actor that legitimised power and was a substantial landowner with a role in managing the economy, including the administration and oversight of taxes (Keane 2024, 15-18). However, the exact role of the Church in copper production remains unclear.

In this context, the copper production site of Pyrga, located in the Pouzis Valley, Southeast Cyprus, is characterised by scattered and dispersed slag heaps, rather than massive deposits, suggesting small-scale production. In fact, Southeast Cyprus exhibits only small deposits (Figs. 1, 2). Surveys at Pyrga suggest the presence of a church, near the heaps, raising questions about ecclesiastical involvement. This paper aims to

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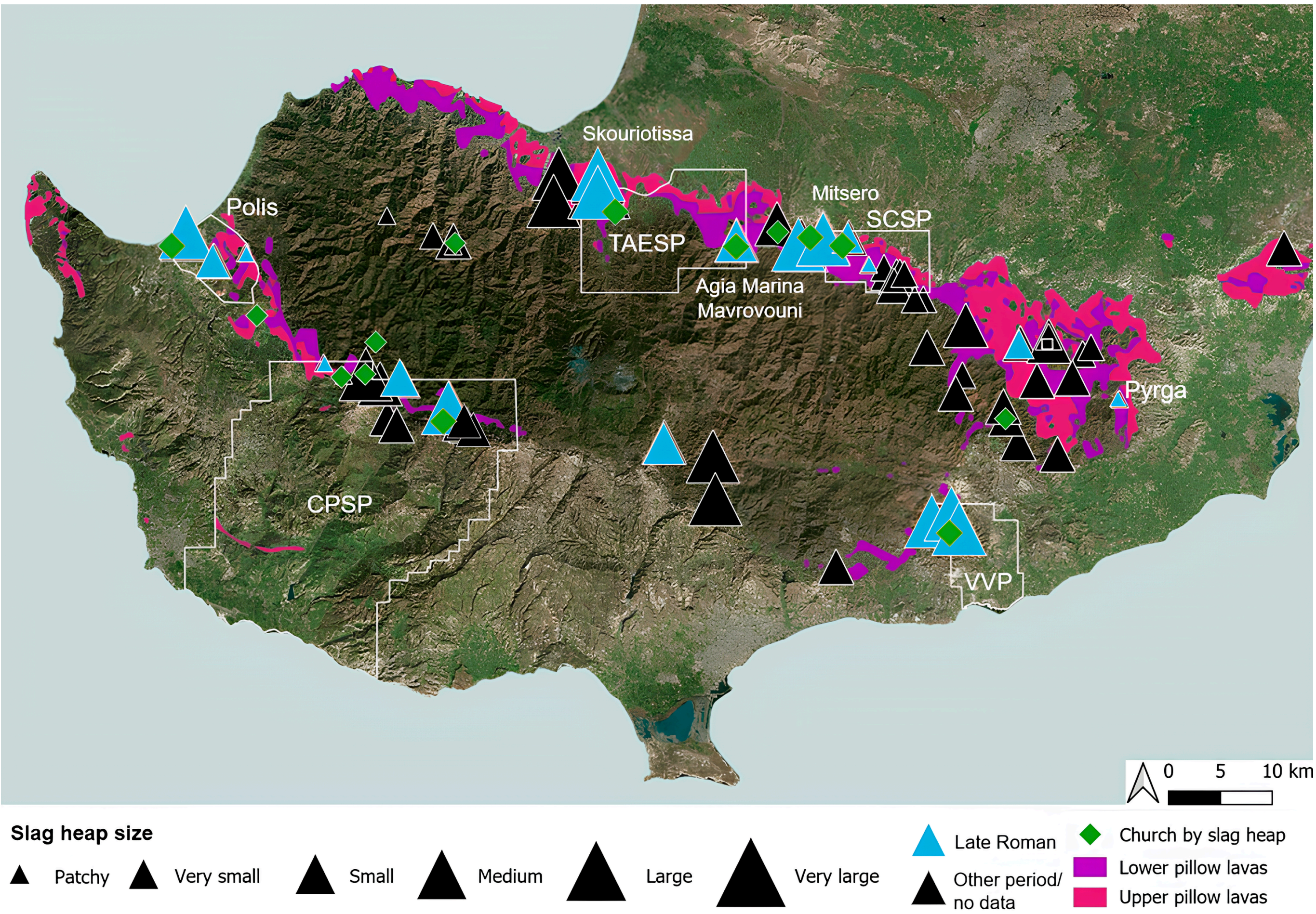

Figure 1: Map of western Cyprus showing copper-rich pillow lava formations, Late Roman slag heaps dating based on the presence of Late Roman ceramics and/or radiocarbon dating (with indicative size from Stos-Gale et al. 1998) and churches associated with slag heaps, with data from Keane (2024) and Given (2018), as well as surveys conducted in previously surveyed regions marked by a white box: Polis region: Raber 1984; 1987; Sydney Cyprus Survey Project (SCSP): Given & Knapp 2003; Vasilikos Valley Project (VVP): Todd 2004; Canadian Palaipaphos Survey Project (CPSP): Fox et al. 1987, Sørensen et al. 1993; Troodos Archaeological and Environmental Survey Project (TAESP): Given et al. 2013a; 2013b; Kassianidou et al. 2021.

contextualise small-scale copper production within the broader economy of Late Roman Cyprus, focusing on the technological aspects of the smelting operation, raw material sources and economic organisation of copper production at Pyrga. It further explores the role of ecclesiastical and imperial authorities in overseeing operations and managing the labour force.

Late Roman Metallurgy

The location of copper slag heaps was first recorded by early miners in the 19th and early 20th century, who documented slag heaps to locate ore bodies (Cullis and Edge 1922; Bruce 1937). Records from the Hellenic Mining Company (Stos-Gale *et al.* 1998) further contributed by indicating the size of the slag heap, ranging from patchy to very large (Fig. 1). Modern reuse of slag as an aggregate in road construction, known as road metal, diminished the original size of the heaps (Bear 1963), complicating the distinction between large and small-scale operations.

A first interest in the archaeology of ancient mining began in the 1920s with engineers recording disrupted ancient adits and the archaeological materials found in them (Bruce 1937). Systematic archaeological and technological research started in the 1970s, with a particular focus on Late Bronze Age urban production centres (*e.g.* Tylecote 1971; Kassianidou and Papasavvas 2012; Charalambous and Kassianidou 2012; Van Brempt and Kassianidou 2016). Steinberg and Koucky (1974) were the first to locate and sample slag heaps in an attempt to create a system to date them, proposing that the presence of manganese in slag was a marker of Roman-era production (Koucky and Steinberg 1982).

While no Roman copper production site has been excavated, regional surveys combined with radiocarbon dating provide chronological context and interpretation. Key projects include the Polis region survey (Raber 1987; Sdralia *et al.* 2023; 2024), the Sydney Cyprus Survey Project (Given and Knapp 2003), the Vasilikos Valley

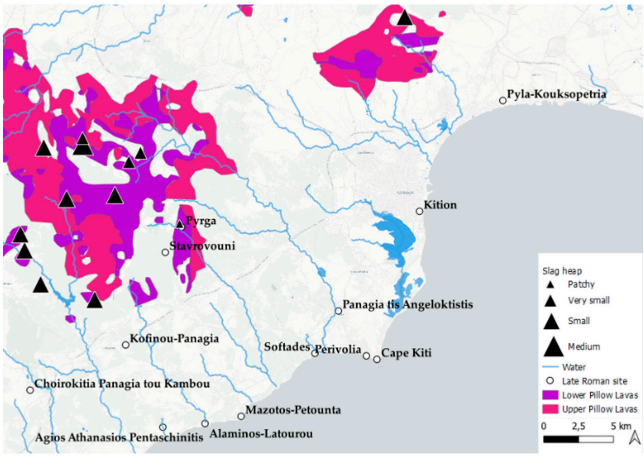

Figure 2: Map of southeast Cyprus showing identified and published Late Roman sites (Georgiou 2013; Papakosta 2020; Vionis 2018), the urban centre of Kition and copper slag heaps (triangles) (Stos-Gale et al. 1998).

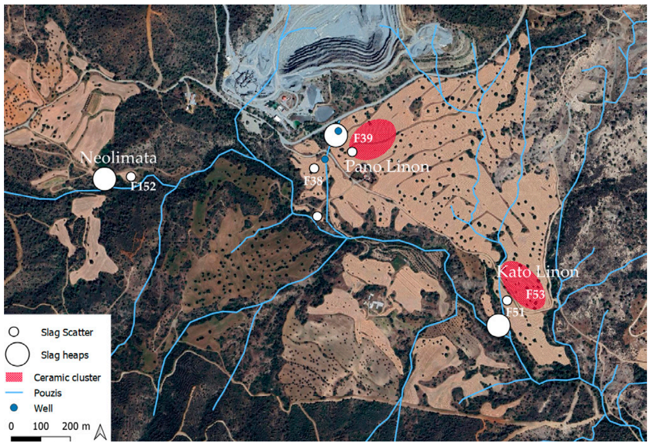

Figure 3: Map of Pyrga showing identified slag heap remains and evidence of a cluster of tiles and pottery, surveyed by the Hala Sultan Tekke Hinterland Survey Project (Vandam et al. 2021).

Project (Todd 2004), the Canadian Palaipaphos Survey Project (Sørensen *et al.* 1993; Fox *et al.* 1987) and the Troodos Archaeological and Environmental Survey Project (Given *et al.* 2013a; 2013b) (Fig. 1). Ongoing debate revolves around landownership, miner identities, and the authority overseeing the industry. However, the presence of churches near slag heaps (Given 2018; Keane 2024) suggests a possible connection between mining and ecclesiastical institutions (Fig. 1). The Church's non-ecclesiastical and participating role in the Late Roman period received only recently attention (*e.g.* Vionis and Papantoniou 2019; Keane 2024). These studies reveal a highly organised settlement structure, where churches functioned as nodal centres within broader territorial and economic networks. The importance of these nodal centres or basilicas is particularly evident in their connections to production centres (Vionis 2018; Vionis and Papantoniou 2019). For a comprehensive overview of churches in association with (ceramics, grain and bread, glass and olive oil) production centres see Keane (2024).

This trend is also observed in the context of copper production (Given 2018; Keane 2024). Surveys revealed industrial-scale copper production, such as the 300-meter-long slag heap (originally extending at least 900 m) at Skouriotissa in association with Roman and Late Roman pottery (Kassianidou *et al.* 2021), near the mid-Byzantine basilica Panagia Skouriotissa, meaning 'Our Lady of the Slag'. Architectural fragments suggest the church may date to the Late Roman period, while a detailed radiocarbon and archaeomagnetic study firmly places the accumulation of more than 20 m in height of the slag heap to the 4th and 5th century AD (Shaar *et al.* 2015). The question remains whether the church functioned within the copper organisation or merely served as an oratory for the mining community (Keane 2024, 189-194; Kassianidou 2023, 218). Despite modern mining activities disrupting the archaeological landscape surrounding the slag heaps, the hinterland reveals a dense network of Late Roman farmsteads, which likely supported the mining community of Skouriotissa (Graham *et al.* 2006, 358). The large production output required a high level of coordination, suggesting external management was essential, with the Late Roman church possibly playing a role in this organisation. Similarly, near the Late Roman medium-sized slag heaps of Agia Marina-Mavrovouni measuring 90 m and 34.5 m in length, respectively (Given *et al.* 2013b, 178), painted plaster fragments and tiles suggest the presence of a church, Agios Kyriakos (Graham *et al.* 2006). Though later in date, its strategic location and the presence of Late Roman ceramics hint at an earlier origin (Keane 2024, 185). Two settlements likely permanently housed the mining community, as indicated by transport vessels and cooking ware (Given et al. 2013a, 329-330). Low quality ceramics suggest external control over profits, rather than profit returning to the community (Keane 2024, 186), while the absence of imported fine ware implies a lack of participation in the economic network of Soli (Given *et al.* 2013a, 330; Given *et al.* 2013b, 198). At Mitsero, the church of Panagia Lambadiotissa, a mid-Byzantine structure that may date to an earlier period (Keane 2024, 197-200), is strategically positioned to overlook the Late Roman mine and large slag heaps (Given and Knapp 2003, 187-190). In the Polis region, northwest Cyprus, there are a large coastal slag heap at Limni (Argaka), the second largest on Cyprus, smaller ones at Kinousa, and the disrupted heap at Pelathousa, both from the Late Roman period (Sdralia *et al.* 2023; 2024). The large slag heap at Limni is situated near the urban center of Arsinou, which contains three basilicas, potentially facilitating trade within the Mediterranean network.

Overall, the strategic positioning of church buildings, overlooking the mining landscape, suggests a deeper involvement than merely serving as oratories for the workforce. This involvement may have extended beyond their religious role, although their exact function remains unclear.

Copper Production at Pyrga: Historical and Material Background

In this wider context, the site of Pyrga provides a good case to study small-scale copper production and its potential link to ecclesiastical power. Located in the foothills of Stavrovouni, Pyrga lies within the Pouzis Valley, well-connected to the south coast and near the urban centre of Kition (modern-day Larnaca). While archaeological evidence for a Late Roman settlement at Kition is scarce (Fourrier 2024; Dept Antiquities 2020), a synodic letter of Theophilus naming major bishoprics indicates that Kition was one of the major administrative centres (Nicolaou 1976, 340). Paleoenvironmental research shows that the Cypro-Archaic to Cypro-Classical harbour at Bamboula, in use from the Late Bronze Age, had silted up by the fourth century AD (Morhange *et al.* 2000, 221; Leonard 2005, 432-438). The disuse of the harbour might have benefited smaller regional ports and anchorages (Caraher *et al.* 2014, 292), leading to the development of a dense coastal network close to the mouth of the rivers Tremithos and Pouzis, south of Kition. Six Late Roman sites, including three anchorages, have been recorded (Fig. 2). These smaller hubs may have been important for local trade, particularly copper, which was transported by using the river bedding as a road system before being transferred to larger coastal urban centres (Papakosta 2020). In this network, churches served as strategic landmarks, helping incoming ships navigate (Georgiou 2013) and simultaneously acted as nodal points or central places in the region (Vionis 2018).

The hinterland of the south coast is marked by the mountain of Stavrovouni, home to the Monastery of the Holy Cross. According to oral tradition, the monastery is believed to be founded by Saint Helena in the 4th century AD but was likely built on the foundations of an earlier pagan temple dedicated to Zeus Olympos, suggested by the find of two limestone statues (Prodromou and Assiotis 1998, 13-19). It was a common practice to build an early Christian church on the foundation of a former sanctuary (Given 2018). In addition, a 6th to 7th century AD

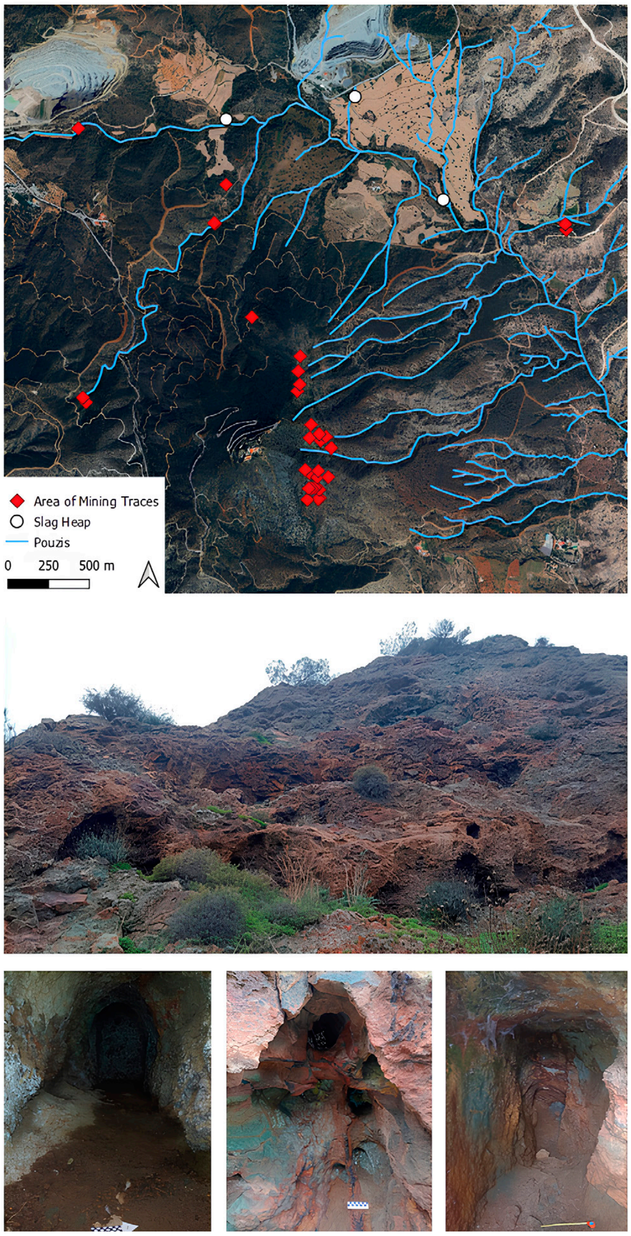

Figure 4: Map showing traces of mining in the area of Pyrga, with pictures of surface traces of mining (top), including evidence of shallow adits (middle) and deeper adits (left and right) at Stavrovouni Pano Teratosotos (top, middle and left) and Stavrovouni Eleti (right). Pictures taken by Yasmine Cornelissen.

lead seal bearing the name Olympos is possibly linked to Stavrovouni. According to Metcalf, this is evidence that the site of Stavrovouni received imperial attention (Metcalf 2004, 199-202; Keane 2024, 243), possibly extending to its surrounding area, including the production site of Pyrga.

Evidence of metal production at Pyrga consists of three slag heaps and scattered slag fragments across the fields (Fig. 3). These slag deposits, indicative of smelting activities, are located in a geological area between the lower pillow lava and the basal group, with andesitic and diabasic dykes and minor pillowed screens (Bagnall

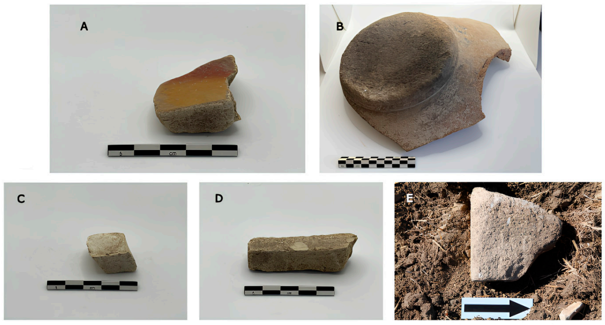

Figure 5: Pictures of A) Painted stone, B) Late Antique dolium disc base, C) Tessera, D) Stone block potentially to make tesserae, E) One of the many carved stone blocks - architectural fragments; Pictures taken by the Hala Sultan Tekke Hinterland survey team.

1960; Gass 1960). Approximately 2 km southwest of the slag heaps, at the east facade of Stavrovouni, at Pano Teratsotos, several shallow and deeper adits suggest surface mining near the summit of Stavrovouni (Fig. 4). Since no timber for supports or pottery were found, the precise dating of these adits remains uncertain. However, an artificial embankment near the mine facilitated extraction at this elevation, confirming that these adits were not merely explorative. In the early 20th century, several prospecting permits were issued to investigate the north side of Stavrovouni, where early modern miners assessed an ore body but deemed it unsuitable for extraction (Cullis and Edge 1922, 43-44; Cullis 1924, 637; Bear 1963, 90). This suggests that the mining activity at Pyrga is likely of an older date, possibly even Late Roman (Cornelissen 2024). The mineralisation of the ore body of Pyrga has been described as scattered and localised, which, together with the small size of the slag heaps, distinguishes itself from other copper deposits with a much richer ore body such as those found in the northern Troodos zone (Bear 1963, 88-90).

The slag heaps of Pyrga, recorded by the Hellenic Mining Company as 'patchy', measure 12, 14, and approximately 3 m in length, respectively (Stos-Gale *et al.* 1998). However, such measurements must be interpreted with caution, as modern reuse of slag and post-depositional processes may have significantly reduced their original size. Compared to major copper production centres, such as the 300-meter-long slag heap at Skouriotissa, the second largest heap at Limni (Argaka), or the medium-sized heaps (90 m and 34.5 m long, respectively) at Agia Marina-Mavrovouni, the Pyrga slag heaps are typically considered small-scale. To our knowledge, no medium to large slag heaps of the scale mentioned above were ever recorded in the vicinity of Pyrga (Fig. 2). This distinction could even mean different organisational structures at play.

The Pyrga heaps were archaeologically investigated only a decade ago by Frixos Markou (Markou 2013). Building on this, the Hala Sultan Tekke Hinterland Survey Project (since 2021) has systematically documented the spatial extent of the site surrounding these slag heaps, aiming to record the human long-term environmental interactions in the broader region (De Weirdt *et al.* 2024). During the 2021 campaign, two concentrations of ceramic tiles were uncovered near the slag heaps, associated with Late Roman pottery. One cluster included pieces of *tesserae*, painted stone fragments, and carved blocks of local field stone, probably construction debris, indicates the presence of a larger estate, potentially even a church (Vandam *et al.* 2021) (Figs. 3, 5).

Materials and methods

Materials

The Pyrga slag heaps are located in the southeast of the Troodos region, approximately 2.5 km south of the centre of Pyrga and 2 km northeast of Stavrovouni, near the Pouzis river and its tributaries, a common pattern at metallurgic sites in Cyprus (Kassianidou *et al.* 2003, 303). Samples were taken from three distinct locations (Fig. 3). Agricultural plowing has partially disturbed, levelled and dispersed the slag heaps, leaving slag scattered in the field. Therefore, their current size is not indicative of their original extent.

1. Three slag samples were collected 70 m east of a small, overgrown slag heap, approximately 3 m long in Pyrga Neolimata at 251 m elevation.
2. A second sampling location is in a different valley, about 500 m to the east of the Neolimata heap. Three slag samples and one potential ore sample were sampled 40 m east of a 14.5 m slag heap in Pyrga Kato Linon, at 220 m elevation, in a narrow strip of land enclosed by the river Pouzis.
3. Seven slag, one potential ore and four furnace wall samples were sampled from a 12 m long slag heap in Pyrga Pano Linon (Fig. 6), at 254 m elevation. One additional sample was taken 140 m southwest of this slag heap.

Methodology

To give an insight in the technology of smelting, metal slag analysis was conducted. The slag microstructure and phase identification offer insights into smelting and cooling conditions. This method is well established in archaeometallurgy (*e.g.* Tylecote 1979, Bachmann 1982; Craddock and Hughes 1985; Craddock 1995; Hauptmann 2007; 2014; 2020). To investigate techno-logical practices at Pyrga, fourteen slag samples, four

Figure 6: Picture of the slag heap, measuring 12 meters long and 5 meters in height, adjacent to field 39, Pyrga; Picture taken by Yasmine Cornelissen.

furnace wall fragments and one potential ore sample were cut to fit a 30 mm mould, embedded in resin and prepared using standard microscopy sample preparation with polishing up to 1 µm. Prospective ore/ore mineral samples were analysed using a Hitachi XMET 8000 hh-XRF in 'Mining' mode to guide sample selection. All prepared samples were studied by reflected light microscopy using a Zeiss Axio Imager with an Axiocam 305 colour camera, and the image was acquired and subsequently processed using the Zeiss Zen 2 core software. Following the optical microscopy, the samples were carbon coated for scanning electron microscopy and compositional analysis using a Zeiss EVO 15 Scanning Electron Microscope (SEM) equipped with an Oxford Instruments AZtec Energy Dispersive Spectrometer (EDS). The system's energy channel alignment was calibrated using copper tape. SEM imaging was conducted using the backscatter electron (BSE) detector at magnifications ranging from 25x to 500x, depending on the features of interest. Lower magnifications (25x–50x) were used for bulk imaging and area acquisition, while higher magnifications were applied to examine individual phases and inclusions.

For quantitative analysis, at least five bulk areas from different regions of each sample were measured to obtain averaged compositional data. The bulk data as well as phases and inclusion compositions are reported in weight percent oxides (wt% oxide), normalised to 100 wt% to remove the effects of beam intensity variation and porosity in the analysed area. Imaging and data acquisition were performed at a working distance (WD) of 8.50 mm, with an accelerating voltage of 20 kV and a probe current of 2.5 nA. Data from the analysis is included in Cornelissen (2024).

Maps were created using QGIS (version 3.28.3-Firenze), projected in Cyprus Local Transverse Mercator, with a geodetic CRS CGRS93 (EPSG 6312).

Results

Slag samples

All slag samples look similar macroscopically, with a black-bluish colour and flow structure typical of tap slags, formed when it was tapped out of the furnace. The average bulk slag composition consists of silica (SiO_2) ranging from 26.6 wt% to 36.0 wt%, manganese oxide (MnO) from 26.8 wt% to 36.3 wt%, iron oxide (FeO) from 9.2 wt% to 19.1 wt% and aluminium oxide (Al_2O_3) from 6.7 wt% to 12.1 wt%, reflecting overall a high level of homogeneity in the slag assemblage (Table 1). These oxides dominate the bulk of the slag composition followed by minor oxides such as lime (CaO, 2–5 wt%). Copper is consistently present at levels of 0.4 to 0.9 wt% expressed as CuO, recognising that the majority of it is present as copper sulfide inclusions. The overall sulfur content of around 3 to 4 wt% expressed as SO_3, equivalent to 1.2 to 1.6 wt% as elemental sulfur, is present as mixed and complex iron, manganese and copper sulfide inclusions.

The slag microstructures of all samples is consistent, showing growth of olivine crystals in a glassy matrix. These olivine crystals, belonging to the knebelite ($(Fe,Mn)_2SiO_4$) group with manganese substituting for iron, are predominantly skeletal. Their elongated lath structure is indicative of a rapid cooling outside the furnace. Tap lines, formed by overlapping slag flows, are marked by a thin line of free iron oxides. The deposition of new slag flows on top of hot, still cooling flows of earlier trapped slag led to slower cooling and the crystallisation of blockier olivine crystals in the new flows. Rapid cooling of the new layer, in contact with relatively cool surfaces of the underlying layer, forms a glassy matrix and a spinifex structure of olivine crystals, a term introduced by Nesbitt (1971) derived from spiky

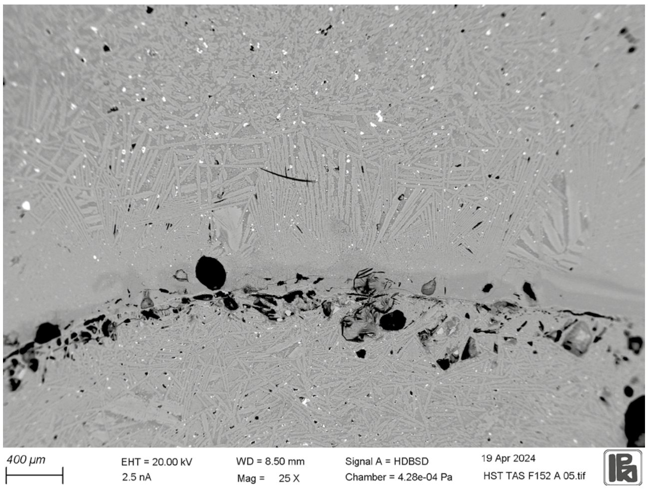

Figure 7: SEM image of sample HST-TAS F152A showing a tapping layer with spinifex texture, a result of the tap flow.

grass, only forming in rapid cooling conditions. The remaining olivine crystals, more central within each flow, form a more blocky structure due to their slower cooling (Fig. 7).

Copper matte or copper sulfide phases are present in all samples, ranging from iron-rich to copper-rich sulfides, including chalcopyrite ($CuFeS_2$), bornite (Cu_4FeS_5), covellite (CuS) and chalcocite (Cu_2S). Copper sulfides occur in the same melt together with manganese iron sulfides and pure metallic copper (Fig. 8). The grid-shape exsolution texture of both the copper-iron and manganese-iron sulfides, formed during the cooling of a high temperature solid solution of copper-iron sulfides (HSS; see Hauptmann 2020, 274-277), are typical of these matte phases (Fig. 8). The copper content is minimal, between 0.4% and 0.9 wt% CuO, indicating highly efficient smelting. For comparison, the broadly contemporary copper slags from Skouriotissa have

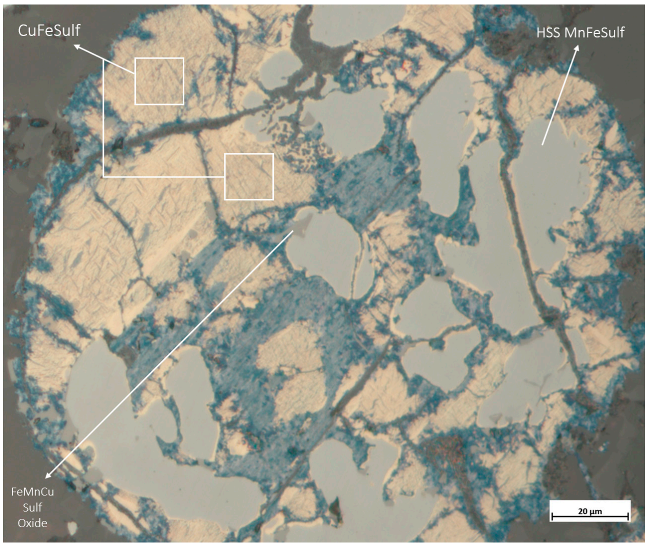

Figure 8: OM image of sample HST-TAS F51 D reflected light, magnified at 50x. The image shows different phases of sulfides: chalcopyrite (yellow), chalcocite (light blue), covellite (dark blue) and manganese iron sulfide (grey).

reported copper contents of around 0.5 to 3 wt% Cu (Georgakopoulou and Kassianidou 2013, tables 3.40, 3.41 and 3.42), pointing to a less efficient process.

Furnace Wall

The furnace wall samples analysed show vitrified, semi-vitrified and unvitrified regions within the same offcuts, reflecting the good insulating properties of the ceramic. The furnace remains indicate the use of ferruginous coarse clay with a composition around 2–5 wt% soda, due to the high albite content (sodium feldspar) in the clay, around 2–5 wt% magnesia, 15–17 wt% alumina, 51–61 wt% silica, less than 1 wt% potash, 2–3 wt% lime, 0.3–3.0 wt% manganese oxide and around 9–11 wt% iron oxide (Table 2). The fabric is rich in quartz and feldspar, and the vitrified parts of the samples

Table 1: Average composition of slag samples analysed by SEM-EDS; oxygen by stoichiometry in wt% oxide, normalised to 100 wt%.

ID	Location	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO	CuO	BaO
F39A	Pyrga Pano Linon	1.1	4.0	8.4	27.1	0.2	4.1	0.7	3.4	0.3	36.0	12.9	0.5	1.2
F39B	Pyrga Pano Linon	0.8	3.2	9.2	29.0	0.1	3.6	0.7	3.2	0.3	35.9	12.5	0.5	0.9
F39E	Pyrga Pano Linon	1.3	3.6	10.4	27.8	0.1	3.8	0.8	3.1	0.4	30.5	16.6	0.5	1.1
F39F	Pyrga Pano Linon	1.1	3.4	8.5	27.0	0.1	4.3	0.7	3.1	0.3	34.4	15.1	0.9	1.0
F39G	Pyrga Pano Linon	1.0	2.9	7.4	29.4	0.2	4.1	0.7	2.2	0.2	30.3	19.1	0.9	1.5
F39N	Pyrga Pano Linon	1.0	3.7	9.2	30.0	0.2	3.3	0.9	5.0	0.3	35.2	9.9	0.4	1.0
F39O	Pyrga Pano Linon	0.5	4.0	10.1	30.4	0.1	3.2	0.5	2.3	0.4	30.4	16.8	0.4	0.7
F39P	Pyrga Pano Linon	1.1	4.4	12.1	32.1	0.2	2.9	0.7	2.8	0.4	26.8	15.1	0.5	0.8
F152A	Pyrga Neolimata	1.1	3.0	9.4	30.5	0.1	3.5	0.8	5.2	0.3	31.1	13.7	0.4	0.6
F152B	Pyrga Neolimata	1.3	3.9	8.8	28.3	0.2	4.2	1.0	3.0	0.3	30.2	16.1	0.8	1.8
F152C	Pyrga Neolimata	0.7	4.3	10.7	29.0	0.1	3.5	1.0	5.1	0.4	28.5	15.8	0.6	0.3
F51A	Pyrga Kato Linon	0.6	3.0	6.7	36.0	0.1	2.1	1.1	4.2	0.2	34.6	9.2	0.5	1.7
F51B	Pyrga Kato Linon	1.0	2.6	7.1	31.7	0.1	4.2	0.6	2.2	0.2	36.3	12.3	0.7	0.7
F51D	Pyrga Kato Linon	0.7	3.2	7.9	26.6	0.1	4.3	0.7	5.1	0.2	35.4	14.8	0.7	0.2
Average		1.0	3.6	8.8	29.0	0.2	2.8	0.6	3.4	0.3	32.0	14.4	0.6	0.7
Maximum		1.3	4.4	12.1	32.1	0.4	4.3	1.0	5.1	0.4	36.0	19.1	0.9	1.5
Minimum		0.5	2.9	7.4	27.0	0.1	0.7	0.2	2.2	0.2	26.8	9.9	0.3	0.2
Standard deviation		0.2	0.4	1.1	1.4	0.1	1.3	0.2	1.0	0.1	3.0	2.3	0.2	0.4

show a slight elevation in soda (to above 3 wt%), lime (3–4 wt%) and potash (around 1 wt%). The furnace fragments contain ilmenite ($FeTiO_3$) and magnetite (Fe_3O_4) inclusions throughout.

Minute particles rich in manganese oxide, and surprisingly rich in copper (between 1.0 wt% and 6.9 wt% CuO), were found in three samples deeply embedded in the surrounding ceramic matrix (Table 3). They were probably trapped in the clay during furnace construction as contaminants and are not naturally found within the clay (Fig. 9). The porous structure and the surrounding shrinkage ring suggest that the particles might have been copper-rich manganese hydroxide, commonly known as umber. They might represent dust from material stored in the workshop that became embedded in the clay during furnace construction.

Other samples

An unidentified geological sample (F39C, about 2 cm maximum dimension), showed a copper content between 1.4 wt% and 27.3 wt%, in low-magnification area analyses by SEM-EDS, together with a high silica content between 59.0 wt% and 75.1 wt% and a relatively low iron content between 4.4 wt% and 9.4 wt% oxide, depending on the area analysed in the SEM. Notably, it had much higher copper than iron content overall, and no sulfur. Another potential ore sample from the slag heap of Field 51 showed a very high copper content of 58.1 wt%, an iron content of 6.6 wt%, and a manganese content of 7.5 wt%, using handheld X-ray fluorescence (hh-XRF) analysis. Due to the lack of proper sample preparation for this screening analysis, these numerical values can only be taken as indicative. They are reliable enough to show that they do not align with the typical content of pure chalcopyrite with 34.5 wt% Cu, 30.5 wt% Fe, and 35.0 wt% S and no manganese (Haldar 2017), the typically assumed main copper ore for Cyprus. Instead, they indicate the presence of secondary copper mineralisation either rich in silica and/or with mixed copper-iron-manganese oxides typical of gossan or umber deposits. Future research will focus on whether these isolated finds are discarded gangue-rich ore fragments deemed unsuitable to be included in the smelting charge, or whether they are lost during charging the furnace and therefore somewhat more representative of the actual ore charge.

Discussion

Technological practices at Pyrga

Late Roman copper production in Cyprus is generally associated with large-scale smelting operations, yet analyses reveal a highly variable manganese content in slag across sites. At Skouriotissa, slag falls into low (0.14–6 wt% MnO) and high (15–40 wt% MnO) manganese content, even within the same layer (Georgakopoulou and Kassianidou 2013, 244-248). Slag from Agia-Marina-Mavrovouni shows a medium to high manganese content reaching up to nearly 40 wt% MnO (Georgakopoulou and Kassianidou 2013, 249, 252, table 3.43). Similarly, at Polis, slags from Argaka and Pelathousa fall into three categories: low (<7 wt%), intermediate (14–16 wt%) and high (13–43 wt%) manganese content, with only 15% of the Argaka slag heap falling into the high Mn range (Sdralia *et al.* 2023). What

Table 2: Average composition of furnace remains and composition of manganese oxide in furnace wall samples analysed by SEM-EDS; oxygen by stoichiometry in wt% oxide (furnace remains) and wt% (manganese oxide), normalised to 100 wt%.

ID	Location	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	V_2O_5	MnO	FeO
Furnace remains												
F39D	Pyrga Pano Linon	2.2	3.6	15.9	61.7	0.3	0.6	2.2	0.8	0.1	0.3	11.7
F39H	Pyrga Pano Linon	2.4	3.5	16.4	60.2	0.3	0.6	2.1	0.9	0.0	3.0	10.0
F39I	Pyrga Pano Linon	4.0	3.1	16.8	61.5	0.1	0.7	2.8	0.9	0.1	0.4	9.4
F39J	Pyrga Pano Linon	3.0	4.0	17.4	58.3	0.1	0.7	2.3	0.9	0.1	1.7	11.1
Average		2.9	3.6	16.6	60.4	0.2	0.7	2.4	0.9	0.1	1.4	10.6
Maximum		4.0	4.0	17.4	61.7	0.3	0.7	2.8	0.9	0.1	3.0	11.7
Minimum		2.2	3.1	15.9	58.3	0.1	0.6	2.1	0.8	0.0	0.3	9.4
Standard deviation		0.8	0.4	0.6	1.6	0.1	0.1	0.3	0.1	0.1	1.3	1.0

Table 3: Composition of (Cu)MnOxide in furnace wall samples analysed by SEM-EDS; all elements in wt%, normalised to 100 wt%.

ID	Location	O	Mg	Al	Si	S	K	Ca	Ti	Mn	Fe	Cu
(Cu)Mn oxide												
F39J	Pyrga Pano Linon	28.4	0.1	2.5	1.6	0.1	0.7	2.8	0.5	55.0	1.1	6.6
F39H	Pyrga Pano Linon	24.9	0.1	0.3	0.7	0.1	0.7	0.4	0.0	70.4	1.2	1.0
F39D	Pyrga Pano Linon	26.3	0.2	1.0	1.8	0.0	0.0	0.4	0.1	61.0	4.8	4.0
Average		26.5	0.1	1.3	1.4	0.1	0.3	1.3	0.3	62.1	2.4	3.9
Maximum		28.4	0.2	2.5	1.8	0.1	0.7	2.8	0.5	70.4	4.8	6.6
Minimum		24.9	0.1	0.3	0.7	0.0	0.0	0.4	0.1	55.0	1.1	1.0
Standard deviation		1.8	0.1	1.1	0.6	0.1	0.4	1.3	0.2	7.8	2.1	2.8

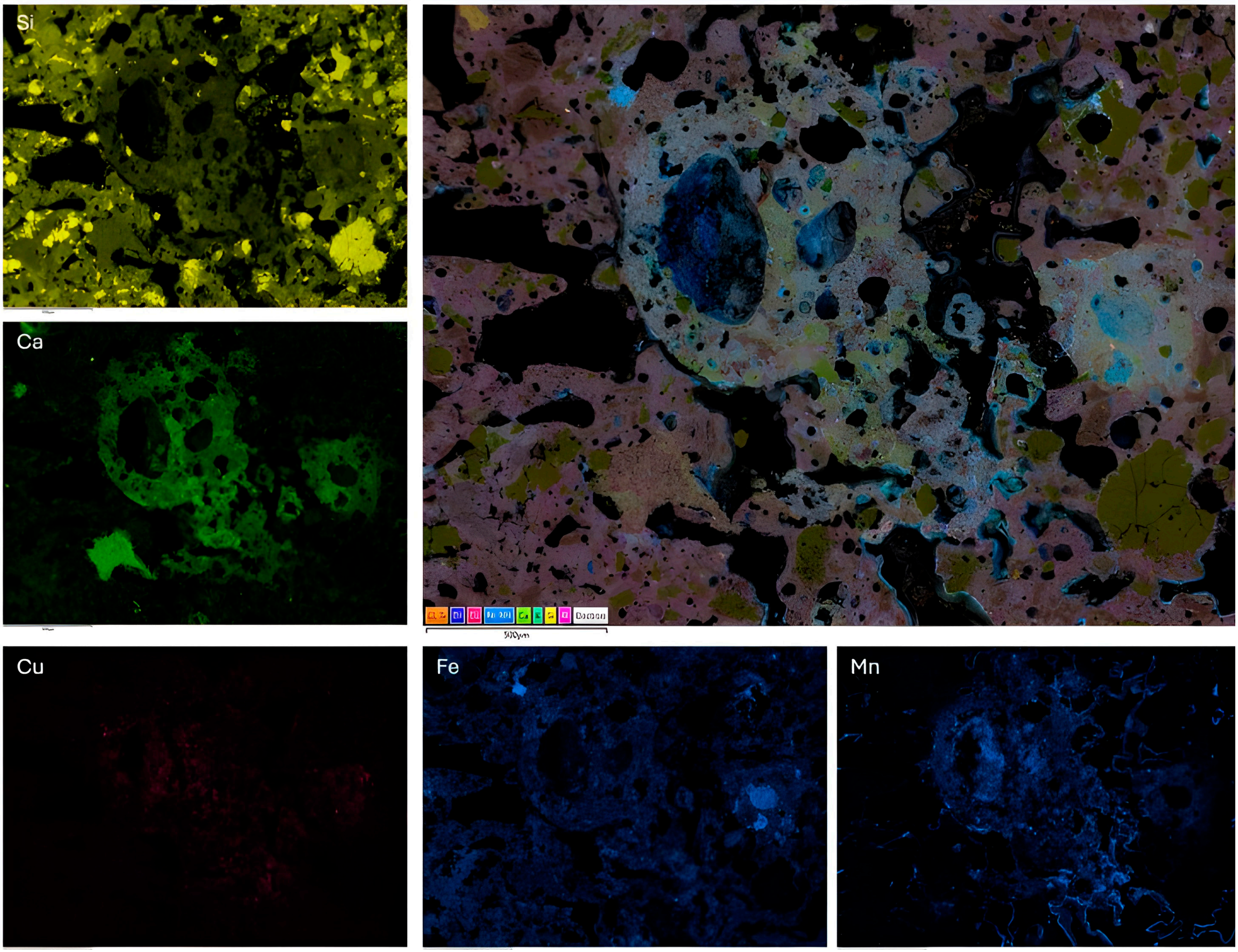

Figure 9: SEM layered image of sample HST-TAS F39H showing a dust particle, potentially a copper-rich manganese hydroxide.

makes Pyrga remarkable is that, despite being a small-scale site, all slags show a high manganese content, a uniformity not seen elsewhere.

This consistent smelting process contrasts with typical small-scale, decentralised smelting operations from earlier periods. At Late Bronze Age Kalavasos-Ayios Dhimitrios, the presence of both tap and furnace slag within the same site suggests multiple households were involved in production. At Maroni-Vournes, smelting itself is thought to have served more of a ceremonial function, with slag containing over 20 wt% copper (Doonan *et al.* 2012, 55).

The relatively uniform composition of the Pyrga slag, particularly the consistently high manganese content, contrasts with the much more variable manganese content of larger-scale production sites such as Skouriotissa and Agia Marina (Georgakopoulou and Kassianidou 2013), suggesting careful preparation of the smelting charge. When plotted on the liquidus surface temperatures of the relevant ternary phase diagram (Fig. 10), the indicative liquidus temperature of most slags is around 1300 °C. The presence of multiple other oxides is known to lower the effective liquidus temperatures compared to pure ternary systems; accordingly, we estimate the actual operating temperature of the furnaces to have been in the range of 1100 °C to 1200 °C. The slags from the Polis region are more heterogeneous in composition and accordingly scatter more widely across the low melting region, with slightly increasing indicative temperatures as they approach the MnO-rich corner (Fig. 10). The low residual copper content and relative compositional uniformity in the whole assemblage points to an efficient and reasonably well-controlled smelting process, characteristic for Late Roman smelting in Cyprus (Georgakopoulou and Kassianidou 2013, 252). While Pyrga appears to be a small-scale site, its practices likely included a relatively consistent furnace charge throughout the period of operation. Remarkably, the efficiency of copper extraction at Pyrga falls at the higher end of what is typical of the larger industrial

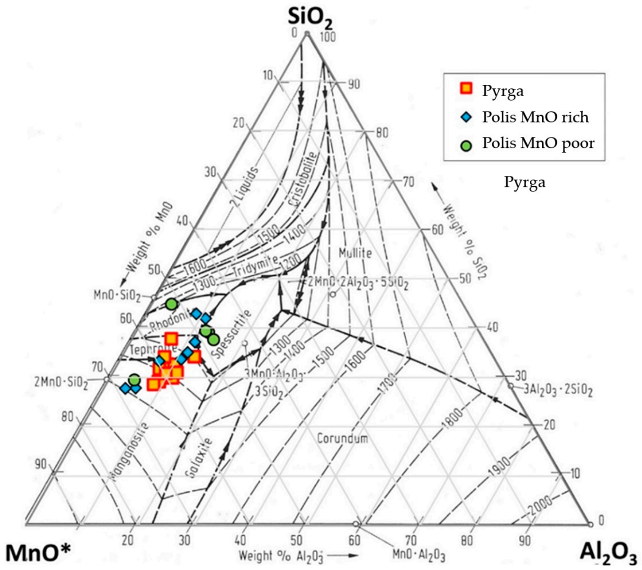

*Figure 10: Plotting slags from Pyrga and from the Polis region (Sdralia et al. 2023) onto the SiO_2-Al_2O_3-MnO ternary phase diagram shows that the HST-TAS slags cluster more tightly than the comparative data from Polis. Their position on the liquidus surface indicates operating temperatures of around 1200 °C to 1350 °C. However, the MnO corner of the ternary diagram is the sum of all 2+ valence oxides in the slags (indicated by the * after MnO), such as lime and iron oxide. The presence of these other oxides reduces the effective liquidus surface of the slag melt system by an estimated 100 °C to 150 °C.*

sites, as indicated by the lower residual copper content in the slags compared to those from Skouriotissa and Agia Marina (Georgakopoulou and Kassianidou 2013).

All slag samples show a high manganese content, consistent with the Late Roman picture of manganese-rich slags (Kassianidou 2003; Georgakopoulou and Kassianidou 2013; Sdralia *et al.* 2023). It is traditionally suggested that manganese-rich materials, such as umber from the Pakhna and Perapedhi formations, were added as flux to counteract the quartz gangue and iron oxide in chalcopyrite during smelting (Bear 1963; Georgakopoulou and Kassianidou 2013, 252; Sdralia *et al.* 2023, 9). However, analysis of potential ore samples and dust particles trapped in the furnace clay, potentially part of the charge, reveals a different picture. Sample F39C shows a high silica and low iron content, while another potential ore sample from near Field 51 contains both manganese and copper. The dust particles contain high manganese and low silica, as well as variable copper contents. This combination of copper and manganese minerals within the same ore-related particles raises the question whether the manganese was indeed added as a separate flux, or whether it might have been part of the copper ore. These compositions do not match that of chalcopyrite ($CuFeS_2$), but as they are found at Pyrga, they seem to be part of the smelting batches, suggesting a manganese-rich flux was not intentionally added. While a comprehensive reconstruction of the ore and smelting process is beyond the scope of this paper and would require further sampling and analysis, our results raise the tantalising possibility that different ore-to-flux dynamics were at play than traditionally assumed for Late Roman copper smelting on Cyprus.

The role of a central authority in production

The standardised production practices and technological uniformity across both large and small-scale sites, along with churches strategically positioned near smelting sites, suggests central oversight. Understanding the degree of control at the small-scale operation of Pyrga may offer additional insight for interpreting the role of the Church within the broader mining and metallurgical practices of the period.

Administration, taxation and landownership

During the early to mid-Roman period, historical records indicate that copper mines were state property, leased to individuals (Kassianidou 2000). For the Late Roman period, specific written records are lacking (Kassianidou 2004; 2011, 539-541), but it is known that Cyprus fell under the administration of Constantinople and followed the same legal framework as other regions in the Eastern empire (Keane 2024, 15-19). Two legal sources, the *Codex Theodosianus* (early 5th century) and the *Codex Justinianus* (6th century), are particularly relevant for understanding the organisation of mining. The laws are significant because, although they do not directly reflect reality, they set guidelines, prescribe behavioural expectations and define the responsibilities of the parties involved in mining.

The codices report a system of both state and private ownership, with the state maintaining oversight of mining activities. This state oversight was sustained through an official known as the *comes metallorum* (Count of the Mines), operating under the *comes sacrarum largitionum* (Count of the Sacred Largess). This *comes metallorum* supervised mining operations and ensured tax collection. By the 6th century, the role expanded to mining engineering as well (Delmaire 1989). Public mines (*metalla publica*, *Codex Justinianus* 11.42.1), benefitted from forced labour, including convicts and other source of labour for the state. Private mining was encouraged, allowing individuals to profit from mineral extraction. However, one law mentioned that state approval was required to mine (*Codex Theodosianus* 10.19.13) and the state retained partial rights over extracted materials, including the right to purchase surplus metals at regulated prices (*Codex Theodosianus* 10.19.3). This model might even align with the observed lack of wealth around production centres (*e.g.* Agia-Marina-Mavrovouni in Graham *et al.* 2006).

According to the codices, the mining sector involved three main parties: the state, the landowner and the miners, with a legal framework ensuring profits were distributed among them (*Codex Theodosianus* 10.19.10, trans. Pharr 1952). The Church was a significant landowner (land at the Pyrga site is still owned by the church) with numerous properties donated to the Church listed in the *Liber Pontificalis*, however, no mines are specifically mentioned. The *Codex Justinianus* reinforced that once land belonged to the Church, it could neither be sold or transferred to an individual (Keane 2024, 15-20). Since the economic organisation of mining highly depended on landownership, the Church's landownership would have given it significant influence over mining activities, in addition to its administrative functions. However, its exact role in the mining process remains unclear.

Workforce organisation

Understanding the identity and organisation of the workforce is key to know how copper production was sustained. The *Codex Justinianus* (11.7.8) explicitly mentions men and women (*metallarii sive metallariae*), indicating a mixed-gender labour force. This workforce was likely composed of non-specialised workers, handling ore mining, fuel acquisition and transport, alongside skilled specialists, responsible for ore selection and furnace operations. Miners and their descendants were legally tied to their occupation, with marriage outside the community discouraged (*Codex Theodosianus* 10.19.15). Those who left the region they originated from (*ea regione deserta, ex qua videntur oriundi*) were legally required to return to their household (*ad propriae originis stirpem laremque*) (*Codex Theodosianus* 10.19.15). By enforcing these legal frameworks, the state prevented labour shortages in mining areas, ensuring transgenerational transmission of skills and leading to a steady and reliable production, thereby forming a socially and geographically distinct mining community, locked into a single economic role centred around mining.

Despite this, signs of mobility complicate the picture. The *Codex Justinianus* (10.7.3) distinguishes between the state, landowners and miners, suggesting miners may have operated with a degree of independence, with landowners not necessarily involved in smelting and distribution of the final product. It is possible this reflects a mobile, semi-autonomous mode of production. This mode would remain largely invisible, as the workforce would likely have been supported by the local community (Raber 1984, 157-185; 1987, 301-302). Workforce mobility would enable the state to prevent labour shortages. As production sites went out of production and new ones arose, the movement of skilled workers ensured an overall steady and consistent supply of copper across the island. As miners were geographically bound to their *regio*, the extent of this mobility depends on the definition of *regio* (*Codex Theodosianus* 10.19.15). While *regio* does not necessarily refer to an administrative unit, movement beyond these borders risked disrupting local tax structures. This would make movement within the hinterland of Kition certainly possible.

The dispersed pattern of slag heaps may reflect different operational strategies or organisational structures. Operationally, the dispersed nature could have been a strategy to optimise and manage space efficiently, balancing industrial and agricultural activities within the same landscape. Waste management could explain why some slag was intentionally broken into smaller pieces during the Late Roman period, as suggested by Kassianidou (2003, 223). Additionally, the placement of smelting sites may have been linked to proximity to mineral occurrences, water, fuel or other local resource availability (e.g., Sdralia *et al.* 2024), requiring further geological and environmental research.

Organisationally, the proximity of churches to smelting sites and the legal framework suggests top-down control by the state and ecclesiastical authorities with the Church playing a more active role in directing production. At the same time, the archaeological evidence may point towards a decentralised approach. The presence of smaller, temporary sites operating across different periods in time, gradually expanding in response to production needs suggests a flexible, potentially seasonal mode of production rather than a full-time specialist operation. A mobile workforce could have moved between the sites, possibly forming a self-organised community, however, one that still depended on support structures. It is also possible that different operations were managed by different landowners, potentially even under imperial lease, with different degrees of investment and involvement, with site locations reflecting fragmented, local decision-making. Despite this, the technological consistency between sampled sites implies either coordination or shared knowledge, or both. This uniformity may be the result of shared training networks. In this context, the Church may have played a role as providing training, together with facilitating infrastructure such as access to capital, land, food and housing. In a more centralised view, the Church may have played a role in the production process itself, imposing standardised production. Overall, however, it is important to consider different types of organisational structures that might have been at play, with the Church just being one of several possible key stakeholders in the copper production of Late Roman Cyprus.

Conclusions

The evidence from Pyrga suggests that the organisation of Late Roman copper production in Cyprus was more complex than previously understood, showing that even on a small-scale level smelting practices were sophisticated and efficient in extracting copper. The high level of control over production and dissemination of standardised practices indicates operations under a central authority. The spatial distribution of slag heaps combined with the proximity of ecclesiastical buildings raises important questions about the role of the Church in overseeing and managing operations. The implications of this study extend beyond the case of Pyrga. The Church's economical and administrative influence, reinforced by a legal framework, suggests a close relationship between ecclesiastical institutions and copper production, potentially extending to technological aspects as well.

From a technological viewpoint, the current study raises the possibility that manganese oxide may not have been intentionally added as a flux but may have been part of the furnace charge of mixed copper ores. While further research is needed to clarify the specific dynamics between the Church, landowners, labour organisation, mining traces in the landscape and technology, the case of Pyrga illustrates the complexity of the Late Roman copper production and highlights the need for integrating archaeological, geological and historical data together to develop a more comprehensive understanding of resource exploitation in Late Roman Cyprus.

Data availability

All data is included in the text.

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Declaration of Competing interests

The authors declare that they have no financial or non-financial interest directly related to the paper.

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