Laurion

Interdisciplinary Approaches to an Ancient Greek Mining Landscape

Including Selected Papers Presented at the International Conference »Ari and the Laurion from Prehistoric to Modern Times«, Bochum, November 1st–3rd 2019

edited by

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Cover Image
Ari (Attika), landscape with ancient and modern mining remains at Charvalo hill seen from West
(Photo: H. Lohmann, No. N13_2754).

Frontispiece
The speakers at the international conference »Ari and the Laurion from Prehistoric to Modern Times
« in the entrance hall of the Institute for Archaeological Studies, Bochum (Photo C. Haubenthal, No. DM19_05386).

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Cuiusvis hominis est errare, nullius
nisi insipientis in errore perseverare

Cic. Phil. 12.2.5.

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Preface of the editors

Laurion – the term has fascinated scientists of all kinds as well as interested laypeople for generations. Countless publications in the humanities and natural sciences have repeatedly invoked the cultural and historical significance of the Laurion as well as its exceptional position as one of the major resources of silver, lead and copper in the eastern Mediterranean since the Early Bronze Age.

With his seminal paper "a Dissertation on the Silver-Mines of Laurion" August Boeckh founded economic history as an independent branch of the historical sciences in 1815. In 1840 Karl Gustav Fiedler laid the foundations for the geological and mineralogical exploration of the Laurion. Today, 200 years after Boeckh, the flood of publications on the Laurion is hardly manageable. And while not all of the old questions have been resolved, new ones arise constantly and will keep the scientific disciplines busy for decades.

Despite numerous modern interventions and destructions of this largest and most important industrial area of ancient Greece, the Laurion forms a unique, world-class cultural and industrial-historical ensemble. At this point, we would like to congratulate the responsible authorities and all inhabitants of the Municipality of Lavreotiki on the great success that in May 2023 the Laurion was included in the list of UNESCO Global Geoparks.

Since scientific progress can only be achieved through transdisciplinary cooperation, the Laurion is also a field par excellence for the often difficult dialogue between the humanities and the natural sciences. At the same time, the disciplines involved have to do their homework. The editors can only speak here about the field of ancient studies, which has fallen behind in terms of documenting the material legacies of the Laurion as well as creating a considerable publication backlog. Although numerous sites have been excavated over the past sixty years (see: site catalogue in Nomicos, 2021) and made known in preliminary reports, final publications are in many cases still pending.

Experience has shown that scientific progress usually takes place in small steps – especially in the humanities and cultural sciences.

In this sense, Ari one of the smallest Attic mining districts was explored in an archaeological project funded by the Deutsche Forschungsgemeinschaft (DFG, PI Hans Lohmann) from 2014–2016 in a synergasia between the Ephorate of East Attica (ΕΦΑΑΝΑΤ), the Ruhr University Bochum, and the German Archaeological Institute at Athens. The editors would like to take the opportunity to warmly thank Andreas Kapetanios, field director of the Ari-Project, for what has been a most fruitful collaboration not only in the field, but also along all steps of the process.

Ari is located in the north of the littoral embayment of Anavyssos. In the Classical Period it belonged partly to the ancient deme of Anaphlystos, partly to the deme of Phrearrhioi, from which its name apparently derived. The project focused on further clarifying the workflow of processing the silver-containing lead ores in transdisciplinary cooperation with natural scientists and processing specialists. Associated with the Ari-Project and pursuing similar goals is the evaluation of the excavations by Evangelos and Olga Kakavogiannis in the area of the Thorikos power station by Frank Hulek, who is most gratefully supported by Olga Kakavogianni. This project is ongoing and the results will be published as a monograph.

The research at Ari, which will be presented in full detail in a further supplement of "Der Anschnitt", prompted the urgent desire to bring together natural scientists and humanities scholars interested in the Laurion at an international and interdisciplinary conference for an exchange of ideas in order to integrate the knowledge gained at Ari into a wider scientific framework. Thanks to the funding of travel and subsistence expenses by the German Research Foundation (DFG), an international conference on the subject of "Ari and the Laurion from Prehistoric to Modern Times" was realised in Bochum from November 1st to 3rd, 2019. Speakers from five European countries – Belgium, England, France, Germany and Greece – as well as one speaker from Australia presented new scientific findings on Laurion in 21 lectures. Eleven out of these papers are published here, while other papers are especially written for this volume, i.e. the contributions of Roald F. Docter, Sophie Duchène, Andreas Hauptmann, Andreas Kapetanios, Hans Lohmann and Sophia Nomicos. A third group will be published within the second volume devoted to the project at Ari. Numerous other scholars from home and abroad enriched the conference with lively discussions. The editors would like to express their deepest gratitude to all of them for their commitment. They would consider themselves lucky if the conference, in addition to an interim assessment, had provided a new and strong impetus for further research in the Laurion.

The conference started on October 31, 2019 with a tour through the newly re-opened mining archaeological collection of the German Mining Museum (Deutsches Bergbau-Museum Bochum, DBM), which met with great interest from the participants. On November 1st the director of the Museum, Stefan Brüggerhoff, opened the conference with greetings, emphasising not only the close cooperation between the Ruhr University Bochum and the German Mining Museum (Leibniz-Research Museum for Georessources). He also stressed the successful interdisciplinarity of research between the Institute of Archaeological Sciences (RUB) and the research fields of Montan-Archaeology and Archaeometallurgy (DBM).

The conference was organised in English language. Abstracts of all lectures were distributed to the participants and offered the possibility to download the institute's homepages. Topics adressed at the conference covered the entire range of research activities at Laurion, beginning from geoscience and materials science to history, archaeology and archaeometallurgy. It covered the long history of exploitation and dressing from prehistoric to modern times. The research in the mining area of Ari was thus only one focus of the conference among others.

The volume editors would like to thank all participants of the conference for their contributions and the timely submission of their papers. The board of directors of the Institute for Archaeological Studies at the Ruhr University Bochum kindly provided the institute's premises and the students thankfully supported the conference behind the scenes and during coffee breaks. It is particularly important to the editors to thank our research partner, the Ephorate of East-Attika (ΕΦΑΑΝΑΤ) under the directorship of Eleni Andrikou for their support of the research at Ari and their participation in the Bochum conference. For the careful editing of the contributions presented here, we would like to thank Petra Eisenach and Bernd F. Lehnhoff. Sherrie and Theresa Stewart and Miriam Skowronek kindly proofread and corrected the texts. Georg-D. Schaaf was entrusted with the typesetting of this volume – a task which he patiently undertook. Last but not least, the editors would like to express their appreciation to Thomas Stöllner, colleague at the RUB and vice director of the DBM, and the Deutsches Bergbau-Museum Bochum, for generously enabling the publication of the conference papers in the series "Der Anschnitt, Beiheft".

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The volume editors Frank Hulek – Hans Lohmann – Sophia Nomicos – Andreas Hauptmann

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Alexandre Tarantola, Christophe Scheffer, Olivier Vanderhaeghe, Panagiotis Voudouris, Adonis Photiades, Denis Morin

Geologic and metallogenic overview of the Lavrion mining district: A guide for archaeological exploration

ABSTRACT: *The Lavrion mining district (SE Attica, Greece) comprises ore deposits of (1) low-grade Mo-Cu porphyry style, (2) Cu-Fe skarn, (3) high-temperature carbonate replacement Pb-Zn-Ag-(Au), and (4) vein and breccia Pb-Zn-Ag mineralizations. These are the result of the transport and deposition of economic elements from fluids that circulated from the construction to the gravitational collapse of the Hellenides-Aegean Domain along the Africa-Eurasia convergent plate boundary active for the last 80 Ma. Oceanic and continental rocks of the African plate were buried to high pressure conditions in the subduction zone. Progressive southward slab retreat was accompanied by magmatism and exhumation of metamorphic rocks along high- and low-angle detachment systems, with associated mineralized systems. The porphyry and skarn deposits are spatially and genetically related to the Plaka magmatic intrusion dated 12 – 8 Ma. Carbonate replacement is associated with decarbonation and the liberation of* CO_2 *during exhumation at the ductile to brittle transition. Fluorite and calcite gangue minerals enclosing the vein and breccia Pb-Zn-Ag mineralization were precipitated during brittle deformation from a fluid resulting from mixing of meteoric water with evaporated seawater closer to the surface. Base and precious metals were exploited since the Bronze Age to the late 20*th *century. As such, the Lavrion area represents an exceptional site to study the evolution of mining technologies through history.*

KEYWORDS: LAVRION, DETACHMENT, GEOLOGICAL FLUIDS, ORE DEPOSITS, MINING ARCHAEOLOGY

Introduction

The Lavrion mining district (SE Attica, Greece) is known at least since 3000 BC for its Pb-Zn-Ag deposits, among others. It was intensively mined during the 5th – 4th centuries BC, corresponding to the so-called Classical Hellenic period, where it was an essential piece for the development of Athens. It continued to be exploited over historical times until the late 20th century by the Compagnie Française des Mines du Laurion (CFML) (Conophagos, 1980). To understand how the metals were deposited at this specific place is of key importance to better apprehend how they were mined during history. Why are these deposits here and not somewhere else? When and how did they form? These are questions of major importance to understanding the Aegean world during the past centuries and also to bring keys for the discovery of other such deposits. The purpose of this paper is to situate the deposits of the Lavrion mining district in their geological dynamic framework with a particular interest in geological fluids based on the latest published papers. Moreover, this contribution aims to be understandable by a large audience of readers who are not familiar with the geological jargon.

During geodynamic evolution, rocks are modified (formation of metamorphic rocks through recrystallization processes, which include deformation and apparition of new minerals) due to changes of tectonic stress and of pressure (*P*) and temperature (*T*) conditions. In active tectonic settings rocks experience burial and exhumation. During this cycle, temperature and pressure vary within the Earth's crust. The rocks are then deformed and their minerals thus recrystallize through metamorphic transformations. During exhumation, metamorphic rocks evolve from elevated *PT* conditions with a ductile rheologic behaviour (plastical deformation with no rupture in the structure, the result is stretched deformed rocks showing intense dynamic recristallisation named mylonites) to more superficial low-temperature (L*T*) and low-pressure (L*P*) conditions where deformation is brittle and localized along fractures or faults. The resulting cohesive brittle fractured rocks are named cataclasite, the fragments of which are cemented thanks to interactions with fluids (hydrothermal breccia). The ductile to brittle transition was thus demonstrated to be a structural, rheological, and thermal boundary separating an upper crust dominated by the percolation of meteoric, marine, and basinal fluids and a lower crust marked by the circulation of magmatic and metamorphic fluids (e.g. Ingebritsen and Manning, 1999; Siebenaller, et al., 2013). Therefore, many case studies reported that the mylonitic-cataclastic transition is pivotal for ore deposition, as it corresponds to preferential zones of fluid circulation and possible mixing of reservoirs associated with fluctuations in the pressure regime (e.g. Lindsay, et al., 1995; Baker and Laing, 1998; Boiron, et al., 2003; Moritz, et al., 2006). This transition occurs during exhumation along low-angle detachments that correspond to regional scale normal faults formed in extensional tectonic regime (Jolivet, et al., 1998; Jolivet and Faccenna, 2000; Scheffer, et al., 2016).

Fluids carry heat and matter under the form of dissolved elements within the Earth's crust (Fyfe, et al., 1978; Etheridge and Wall, 1983; Thompson and Connolly, 1992). Geological fluids of various nature have been demonstrated to flow within the Earth's crust, including magmatic (metal- and salt-rich aqueous solutions, and vapour exsolved from magma), metamorphic (issued from dehydration [water] or decarbonation [carbon dioxide] reactions), connate (water-dominated aqueous solutions contained in pores of sedimentary rocks), marine (aqueous solutions containing salts; the concentration of standard seawater is of around 3.5 wt.% $NaCl_{eq}$, this value increases with evaporation), or meteoric (water derived from the atmosphere by precipitation or condensation, i.e. rain water) origin (Taylor, 1974, 1997; Arndt and Ganino, 2012). The geochemistry of geological fluids is dominated by water and salts (with NaCl, $CaCl_2$ and KCl as the predominant species), but they may also contain gases, where CO_2, N_2 and CH_4 are the most commonly found. Their characterization is a central part of the study of mineralized systems as hydrothermal fluid circulation permits leaching, mobilization, transport, and deposition of elements of economic interest at the crustal scale. It is thus of major interest to constrain the source of ore-forming fluids and associated fluid-fluid and fluid-rock interactions to characterize the mode and conditions of formation of metal deposits. Indirect evidence of hydrothermal fluid circulation within the Earth's crust are mineralized veins and alteration minerals. Geological fluids may also be trapped in micrometric tiny pockets within minerals called fluid inclusions. Fluid inclusions (FIs) trapped a fluid (water, dissolved salts, gases) circulating during rock history. The physical and geochemical properties of FIs thus directly witness the conditions of paleofluid circulation. Inclusions may be found as isolated FIs or aligned underlining crystal growth zones thus suggesting entrapment during mineral growth (primary FIs). Inclusions may also have trapped a fluid present in a fracture formed during (pseudo-secondary FIs) or after (secondary FIs) crystal growth (Roedder, 1984). The analysis of fluid inclusions in the laboratory by specific techniques like microthermometry, Raman spectrometry and Laser Ablation ICP-MS permit the composition (*X*) and density or molar volume (*V*) of individual FIs to be quantified. These information are key constraints to the discussion of element transport and *PT* conditions of formation of a hydrothermal deposit. Stable isotope signatures ($\delta^{13}C$, δD, $\delta^{18}O$, $\delta^{34}S$) of host-minerals and FIs complement *VX* data and provide information regarding the temperature and the source of the fluid and possible fluid-rock interactions. The integration of fluid inclusion petrography and their *VX* properties in their tectonic and petrographic context provides a dynamic view of mineralization evolution through time.

The Lavrion Pb-Zn-Ag mining district (Greece), located along the western boundary of the Attico-Cycladic Metamorphic Complex in the internal zone of the Hellenic-Aegean orogenic belt, is an illustrative and emblematic example of the involvement of multiple ore fluid systems in the formation of various ore type deposits. We will show in this paper the particular geological context of the Lavrion area and its location in the Attico-Cycladic system, the main lithologies and tectonic units, the types of ore deposits and their link with the circulation of geological fluids. The Lavrion mining district is the result of favourable geological conditions that permitted deposition of exceptional base metal content over a small area. Consequently, metal exploration lasted over centuries, making this place a reference case study for mining archaeology and the evolution of mining technologies over History.

The Lavrion area in the Attico-Cycladic system

Attica is part of the Alpine belt, which extends from Morocco to extreme SE Asia and which results from the closure of the Tethys Ocean since Mesozoic times (Fig. 1a). During Jurassic (Lias and Dogger), the region was situated at tropical latitudes and was subjected to alternating sedimentation of limestones and marls. Since 80 Ma, due to Atlantic opening, Africa slowly rotated anticlockwise towards the north and Eurasian continent. The result is the Hellenides domain formed during subduction at this convergent plate boundary, with a slab (portion of the African tectonic plate that is being subducted) oriented to the North, including several oceanic and continental fragments (Aubouin, 1973; 1976; Dewey and Sengör, 1979). During the subduction stage, oceanic rocks (ophiolitic rocks made of gabbros and basalts often altered to serpentinites, also referred to as green rocks) and rocks deposited on the continental shelf (limestones and marls) were submitted to elevated *P* conditions. Rocks were deformed and new minerals witnessing these *PT* conditions appeared through recrystallization and metamorphic reactions. Limestones and marls became marbles and schists, respectively. The subduction zone with the Aegean slab progressively retreated from Rhodopes massif (since around 30 Ma) to the currently active Santorini Island as indicated by the migration of calc-alkaline arc magmatism (Fytikas, et al., 1984). The metamorphic rocks formed in this subduction zone were then exhumed due to the southward retreat of the slab beneath the Aegean domain and the associated Metamorphic Core Complex (MCC) (Dürr, et al., 1978; Jacobshagen, et al., 1978; Jacobshagen, 1986). The present situation of the Aegean slab and the lithospheric structure was shown by

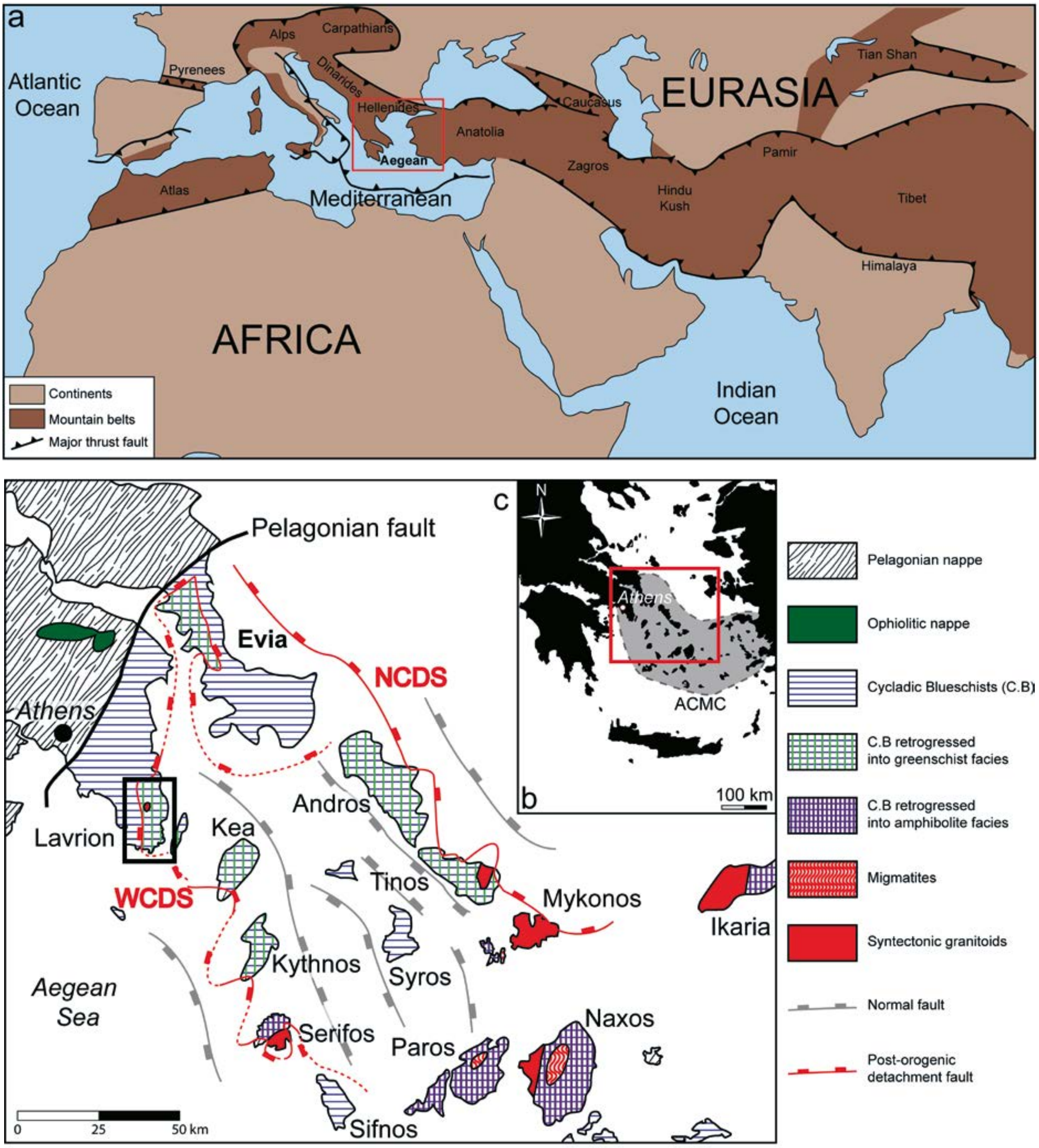

Fig. 1: a. Location of the Hellenic domain within the Alpine orogenic system (modified after Vanderhaeghe, et al., 2007). – b. Attico-Cycladic Metamorphic Complex (ACMC) and location of map c in red. – c. Tectono-metamorphic map of the ACMC with syntectonic magmatic rocks and position of the Western and Northern Cycladic Detachment Systems (WCDS and NCDS, respectively) low-angle faults accommodating post-orogenic exhumation. The black rectangle area corresponds to the location of the Lavrion map of Fig. 2.

seismic tomography with the subduction trench that now lies beneath south of Creta Island (Spakman, et al., 1988; Bijwaard et al., 1998).

The Attico-Cycladic MCC (Fig. 1b,c) is composed mainly of the Cycladic Blueschists. These H*P* rocks were partially or totally retromorphosed by retrograde greenschist to amphibolite H*T* metamorphism during their exhumation along the low-angle North and West Cycladic detachment systems. The extensional phase of the Aegean domain occurred during Oligocene-Miocene (Lister, et al., 1984; Gautier and Brun, 1994a, b; Jolivet, et al., 2010; Grasemann, et al., 2012). Naxos, Paros, Mykonos and Ikaria islands exposed the core of the Attico-Cycladic MCC where high-temperature rocks showing

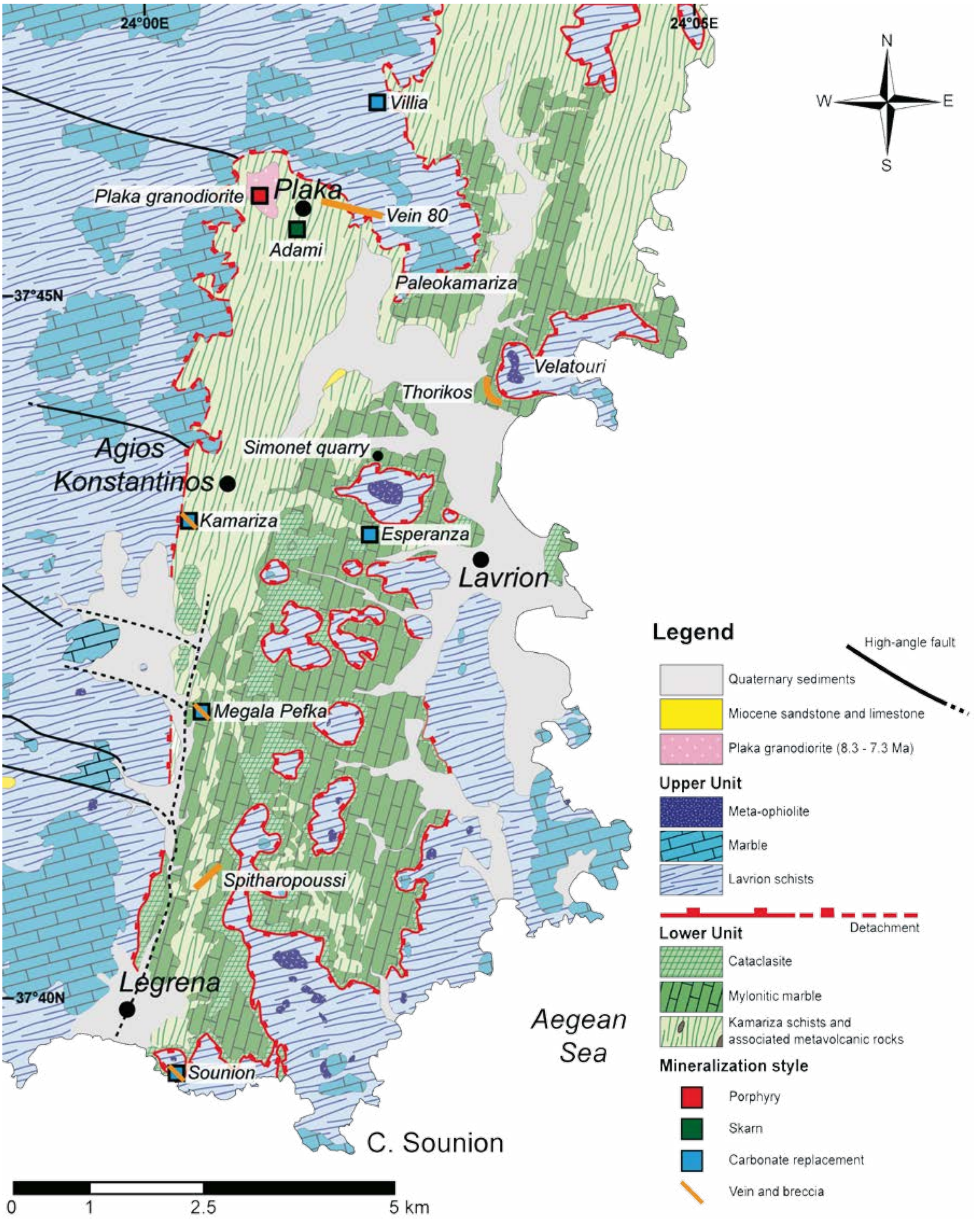

Fig. 2: Geological map of the Lavrion Peninsula and SE Attica with main types of ore deposits (modified after Scheffer, et al., 2016).

partial melting (migmatites) are observed (Fig. 1c; Keay, et al., 2001; Vanderhaeghe, 2004; Martin, et al., 2006; Ring, 2007; Kruckenberg, et al., 2011).

The Lavrion Peninsula, located some 40 km SE of Athens, represents the southern part of Attica and marks the western boundary of the Attico-Cycladic MCC. As such, the Lavrion area represents a highly strategic place from a geological point of view, where intensely deformed and metamorphosed oceanic (green metabasalts and serpentinites) and sedimentary (schists

Fig. 3: Typical landscape of the Lavrion Peninsula (Legrena Valley) showing the superposition of the Lower marble, Kamariza schists and Upper marble of the Lower unit (photo: A. Tarantola).

and marbles) are exposed (Fig. 2). The area is marked by the West Cycladic detachment, which localizes deformation and fluid circulation during exhumation of the rocks. Moreover, the extension phase is associated with magmatic intrusions.

Lithologies and tectonic units of the Lavrion area

The geology of the Lavrion area is marked by the low-angle post-orogenic West Cycladic detachment fault system that separates the Lower and Upper units in the extension regime during exhumation (Grasemann, et al., 2012; Scheffer, et al., 2016). The area is dominated by the Lower unit (also referred to as the Kamariza unit) composed of alternating folded marbles (Lower and Upper marbles) and the Kamariza schists (Fig. 3), which host boudins of metavolcanic basic rocks. The Lower and Upper marbles are generally white or blue as a function of the amount of detrital materials in them (Fig. 4a,b). These rocks are strongly deformed with intense mylonitization (ductile deformation). Towards the top of the Upper marble, the metamorphic marbles show cataclastic texture resulting from brittle deformation (Fig. 4c). The last meters of the Lower unit is composed of an orange dolomitic hydrothermal breccia suggesting intense fluid circulation (Scheffer, et al., 2017b; Fig. 4d). This shallow dipping mylonitic to cataclastic transitional shear zone marks the location of the detachment fault over the Lavrion area (Scheffer, et al., 2016; 2017b). This low-angle detachment, which was active during the Miocene, lies within the metamorphic nappe stack and localizes the deformation during orogenic gravitational collapse with a transition from ductile to brittle conditions (Scheffer, et al., 2016).

The Upper unit (also named the Lavrion unit), above the detachment fault, (also referred to in the literature as the phyllite nappe or the Lavrion Blueschists tectonic unit), exposes alternating marbles and schists (Lavrion schists; Fig. 4e) with small lenses of metabasic rocks. The whole area is marked with magmatic activity as evidenced by the Plaka granodiorite, which represents the exposed part of a larger batholith at depth (Marinos and Makris, 1975; Tsokas; et al., 1998) dated 12-8 Ma by U-Pb on zircon (Liati; et al., 2009) and several felsic and mafic dykes (Fig. 4f) that intruded the metamorphic nappe stack (Skarpelis, et al., 2008; Voudouris, et al., 2008a,b; Liati, et al., 2009; Bonsall, et al., 2011; Coleman, et al., 2019). The structural distribution of the dykes witnesses their continuous emplacement at the ductile to brittle transition. Some of the dykes are boudinaged and partially transposed within the mylonitic structures of the lower unit and some of the dykes are purely brittle and crosscut the rock units and the detachment shear zone (Liati, et al., 2009). The upper part of the Upper unit shows green meta-ophiolitic rocks (metamorphosed basalts and serpentinites of the oceanic domain) (Fig. 4g,h).

Tectonic phases and deformation of metamorphic rocks

Two main successive stages of metamorphism were noticed at the scale of the Cycladic system. The Cycladic blueschists underwent a first event to the blueschist (H*P*) facies (up to 1.2–2.2 GPa and 450 to 550 °C) during Eocene subduction phase (50–40 Ma; e.g. Altherr, et al., 1982; Buick and Holland, 1989; Bröcker, et al., 1993; Avigad, 1998; Groppo, et al., 2009). The second event was recorded during exhumation of the Cycladic Blueschist unit and is characterized by medium-pressure and temperature conditions between 25 and 15 Ma at ~0.9 GPa and 550 to 570 °C (Andriessen, et al., 1979; Altherr, et al., 1982; Ring, et al., 2001; Parra, et al., 2002; Bröcker, et al., 2004; Duchêne, et al., 2006; Seward, et al., 2009).

Three successive stages of deformation (D) and metamorphism (M) were identified within the rock units

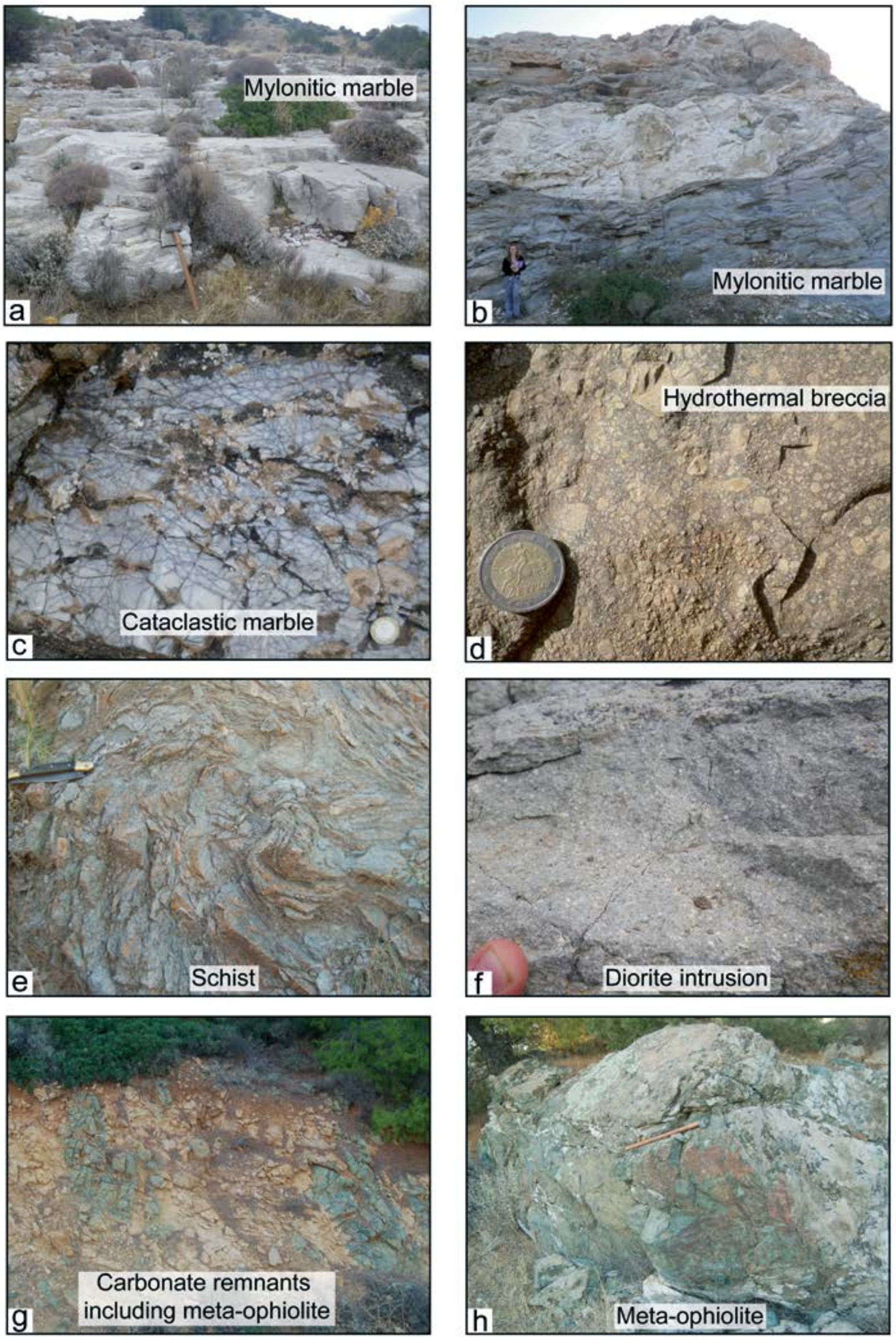

Fig. 4: Field photographs showing main lithologies at the scale of the Lavrion Peninsula. – a. Upper mylonitic white marble transposed into S_3 shallow-dipping schistosity (Velatouri hill). – b. General view of the Simonet quarry showing boudins of white pure marble wrapped within foliated impure blue marble. – c. Brittle fractures within marble superimposing over the mylonitic fabric. – d. Hydrothermal cataclastic dolomitic level marking the detachment. – e. Deformed and folded blue schist of the Upper unit. – f. Dyke of dioritic/andesitic composition intruding marbles of the Lower Unit and blue schists of the Upper Unit (W Velatouri hill). White minerals are plagioclase; black minerals are amphibole. – g. Carbonate and green serpentinite within the upper part of the Upper unit. – h. Green metabasalts of the upper part of the Upper unit (photos a, b, c, d: Scheffer, et al., 2017b; photos e, f, g, h: C. Scheffer).

of the Lavrion area with (i) burial of the rocks during subduction (D_1M_1), (ii) syn-orogenic exhumation (D_2M_2) during collision stage and (iii) post-orogenic exhumation along the low-angle detachment fault system (D_3M_3) accommodating orogenic collapse. The rocks of the Lavrion nappe stack reached D_1M_1 pressure and temperature conditions of 0.9–1.3 GPa and 315 ±30 °C during the subduction stage (Scheffer, et al., 2016). The D_2M_2 syn-orogenic exhumation stage recorded *PT*-conditions of 0.6–0.9 GPa and 300 ±30 °C (Scheffer, et al., 2016) between 32 and 23 Ma, based on $^{40}Ar/^{39}Ar$ ages of white mica (Coleman, et al., 2019). The D_3M_3 post-orogenic exhumation phase is associated with the formation of the Western Cycladic and Northern Cycladic detachment systems, in relation to orogenic gravitational collapse induced by slab retreat during the Miocene (Gautier, et al., 1999; Vanderhaeghe and Teyssier, 2001; Vanderhaeghe, et al., 2007; Jolivet, et al., 2010; Grasemann, et al., 2012; Scheffer, et al., 2016). The D_3M_3 post-orogenic exhumation event was accompanied by isothermal decompression that resulted in H*T* metamorphism, as evidenced by the occurrence of migmatite (rocks showing partial melting) in the Nax-

Fig. 5. Folded schist layer in a mylonitic blue marble of the Upper unit mainly characterized by a shallow-dipping schistosity S_3 (Velatouri hill) (photo: A. Tarantola).

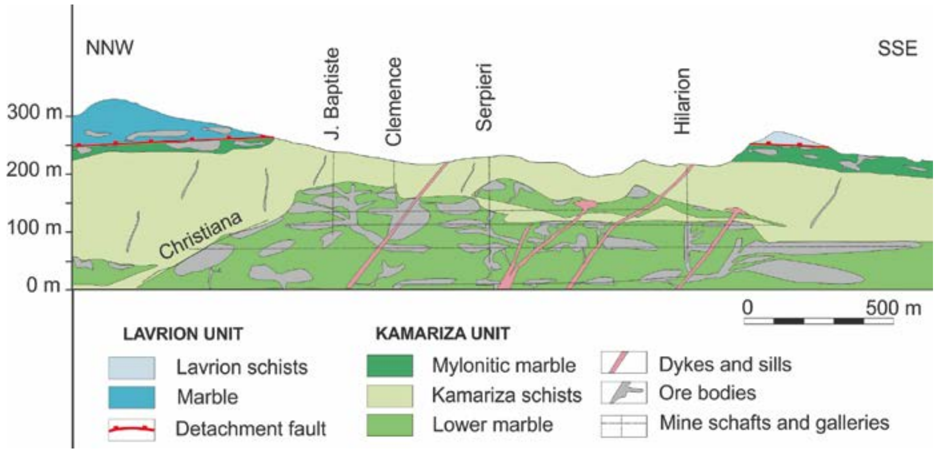

Fig. 6. Geological location of main ore bodies in the area of Kamariza with the mine shafts and galleries. Figure modified after Ottens and Voudouris (2018), and references therein.

os, Paros, Mykonos, and Ikaria islands (Keay, et al., 2001; Vanderhaeghe, 2004; Martin, et al., 2006; Ring, 2007; Kruckenberg, et al., 2011). In the Lavrion area, the D_3M_3 post-orogenic exhumation event was marked by an increase in temperature that reached 350 ±30 °C at a pressure of 0.50 to 0.85 GPa (Scheffer, et al., 2016). The main location of the D_3 deformation is at the contact between the Lower and Upper units, which marks the location of the West Cycladic detachment system with a transition from mylonitic to cataclastic deformation (Lekkas, et al., 2011; Berger, et al., 2013; Scheffer, et al., 2016; 2017b).

Relics of steep-deeping and folded structure related to early D_1 and D_2 deformation stages may be observed in the rocks of the Lavrion Peninsula (Fig. 5). However, the dominant feature is the subhorizontal D_3 feature observed at all scales of observation from the foliation of the rocks of the Lower unit (Fig. 5) to the landscape outcrops (Fig. 3,4a,b).

Main characteristics of metal deposits in the Lavrion mining district

Metal deposition in the Lavrion mining district is subdivided in hypogene and supergene stages (i.e. primary and secondary mineralizations), whether it refers to the Miocene original mineralization associated with the D_3M_3 event or to later remobilization. The hypogene stage itself is divided into four styles of mineralization with their particular structural setting and mineral paragenesis or association: (i) Mo-Cu porphyry, (ii) Cu-Fe skarn, (iii) Pb-Zn-Ag-(Au) carbonate replacement (non-skarn) and (iv) Pb-Zn-Ag epithermal veins and breccias (Leleu, et al., 1973; Skarpelis, 2002; Voudouris, et al., 2008a, b; Tombros, et al., 2010; Bonsall, et al., 2011; Scheffer, et al., 2019). The supergene mineralization consists of

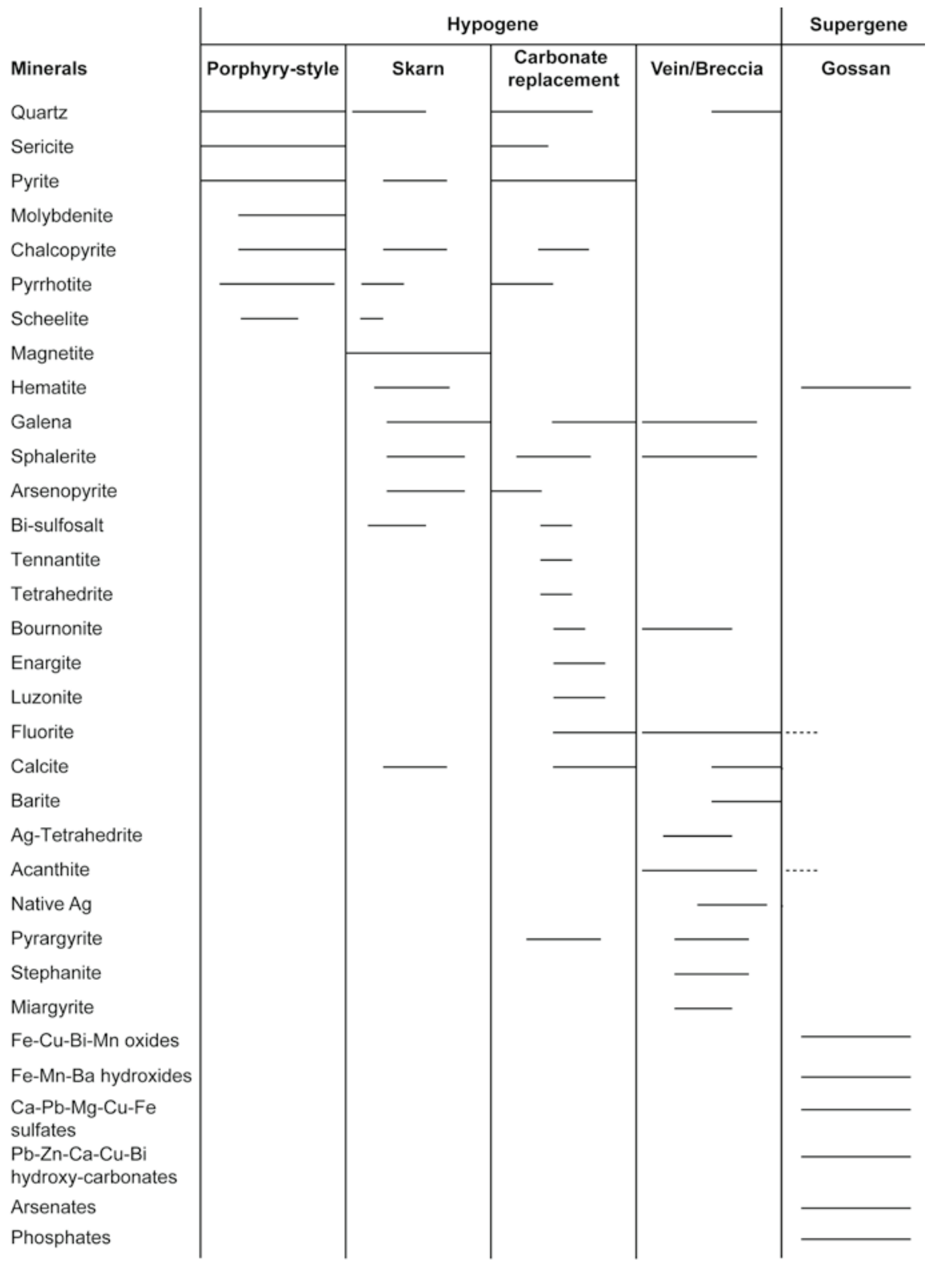

Fig. 7: Paragenetic sequence of the Lavrion district for porphyry-style, skarn, carbonate replacement, vein and breccia, and gossan/supergene ore (modified after Voudouris, et al., 2008a,b; Skarpelis and Argyraki, 2009; Bonsall, et al., 2011; Scheffer, et al., 2019).

late oxidation essentially found under Fe-(hydr-)oxides (gossan) (Skarpelis and Argyraki, 2009). The geological location of main ore bodies, corresponding to carbonate replacement, epithermal veins and breccias and supergene oxidation, is represented in the cross-section of Fig. 6 drawn in the area of Kamariza. In Fig. 7 only the main features of each mineralization style are presented.

Mo-Cu porphyry style of mineralization

This low-grade, sub-economic, porphyry-style mineralization is localized and restricted within the Plaka granodiorite. It occurs predominantly as discrete pyrite (FeS_2)-molybdenite (MoS_2) sheeted decimetric quartz veins trending northwest-southeast (Fig. 8a), with minor pyrrhotite ($Fe_{1-x}S$) and chalcopyrite ($CuFeS_2$) (Voudouris, et al., 2008a). Associated potassic alteration is suggested by the presence of hydrothermal centimetric biotite in subvertical quartz veins within the altered granodiorite (Fig. 8b).

Cu-Fe skarn style of mineralization

A skarn corresponds to the development of a contact metamorphic and metasomatic aureole within calcareous rocks during the intrusion of a magmatic body. In the case of the Lavrion area, skarn developed at the vicinity of the Plaka granodiorite intruding marbles and schists of the

Lower and Upper units. The rocks are green and dominated by minerals of the epidote-, pyroxene-, amphibole- and garnet-groups with additional feldspar, chlorite, calcite, titanite, scapolite, magnetite, pyrrhotite and marcasite. They were estimated to be formed at 440–600 °C and 1.0–1.5 kbars (Leleu, et al., 1973; Baltatzis, 1981). Magnetite and magnetite-hematite are found close to the granodiorite within the Upper Marble, whereas the assemblages composed of pyrite-pyrrhotite and sphalerite-pyrite-galena are present within the Kamariza schists, farther away from the Plaka granodiorite (Leleu, et al., 1973).

Pb-Zn-Ag-(Au) carbonate replacement

These deposits together with epithermal veins and breccias were the most economically significant ore types in the Lavrion district with dominating galena, sphalerite, pyrite and chalcopyrite. They are found along the low-angle detachment fault and at the contact between marbles and schists of the Lower units forming several parallel mineralized levels. Their location is thus both structurally and lithologically controlled and results in sub-horizontal deposits (Fig. 6; Fig. 8d,e). The carbonate-replacement deposits occur as centimeter-scale lenses to bedded replacement and chimneys that are up to tens of meters in length (Fig. 6; Bonsall, et al., 2011). Base metal mineralization along the detachment fault was mentioned by Skarpelis (2007). The sulfides occur as massive pods and veins along shear bands in marble (Fig. 6).

Pb-Zn-Ag epithermal veins and breccias

Pb-Zn-Ag vein and breccia deposits are generally localized below, but also above, the Lavrion detachment (1) within the marbles of the Lavrion unit, (2) within the Upper marble, (3) within the Kamariza schists, and (4) at the interface between the Kamariza schists and the Lower marble (Fig. 6; Scheffer, et al., 2019). The crosscutting relationship between the vein and breccia ore deposits and the S_3 mylonitic deformation suggests deposition in a purely brittle regime. The deposits are mainly characterized by fluorite and carbonate gangue minerals enclosing Pb-Zn-Ag sulfides and/or oxides (Voudouris, et al., 2008a,b; Scheffer, et al., 2019).

Supergene alteration

Subsequent alteration of the primary sulfides resulted in an extensive and deep oxidation zone (up to 270 m thick) from which about 600 mineral species of oxides, hydroxides, carbonates, sulfates, arsenates, native metals, etc, have been described (Skarpelis and Argyraki, 2009; Ottens and Voudouris, 2018). Supergene oxidation resulted among others in replacement of pyrite by goethite and limonite, of sphalerite by smithsonite and of galena by cerussite and anglesite and secondary deposition of the silver-bearing sulfide acanthite. According to Marinos and Petrascheck (1956) and Conophagos (1980), cerussite in addition to galena is a major carrier of silver in Lavrion deposit.

Fluid circulation and ore deposition in a dynamic setting

Earlier published data based on fluid inclusion investigations showed the existence and possible interaction of several fluid reservoirs associated with ore deposition in the Lavrion mining district. Two dominant fluid systems were described with high-temperature magmatic-hydrothermal fluids associated with the Plaka granodiorite intrusion and related magmatism and low-temperature surface derived fluids circulating in the last stages of exhumation in the brittle domain.

Bonsall, et al. (2011) observed the presence at room temperature of salt-poor vapor-rich (VL) and aqueous dominated halite-saturated (LVH) fluid inclusions in quartz veins associated with porphyry style mineralization within the Plaka granodiorite (Fig. 9a,b). Their coexistence within single fluid inclusion assemblages (FIAs) and their similar temperatures of homogenization (T_h), temperature at which one single phase is present during microthermometric experiments, are evidence of fluid boiling. This process is generally observed in magmatic-hydrothermal environments resulting in porphyry-style deposits where high-temperature fluids exsolved at shallow depths, and thus at low pressure conditions. Boiling is an efficient process for phase and metal separation between an aqueous liquid salt-rich phase and a salt-depleted vapor phase (e.g. Roedder, 1984). During boiling, metallic elements also partition into one or the other phase leading to supersaturation and metal precipitation under the form of oxide and/or sulphide. For instance, Bonsall, et al. (2011) suggested the presence of chalcopyrite within LVH inclusions. Another particularity of these systems is that, because VL and LVH FIs are demonstrated to have been trapped contemporaneously, their entrapment *PT* conditions must be similar. This is shown by their behaviour during microthermometric experiments with the similar homogenization temperatures. In such systems, the *PT* conditions at homogenization reflect directly the conditions of entrapment without any pressure correction (e.g. Diamond, 2001). In the Lavrion district, the formation of porphyry-style mineralization was thus estimated to take place at 300–400 °C after FI measurements in quartz veins for a pressure below 300 bars, reflecting the shallow environment during magmatic intrusion (Voudouris, et al., 2008a,b; Bonsall, et al., 2011).

The emplacement of the porphyry system in Plaka is also responsible for decarbonation of carbonate rocks, as demonstrated by the presence of CO_2-rich fluid inclusions (Fig. 9c,d) (i) dismembered and deformed along subgrain boundaries, (ii) within deformation lamellae and (iii) in planes crosscutting subgrains. Microstructural

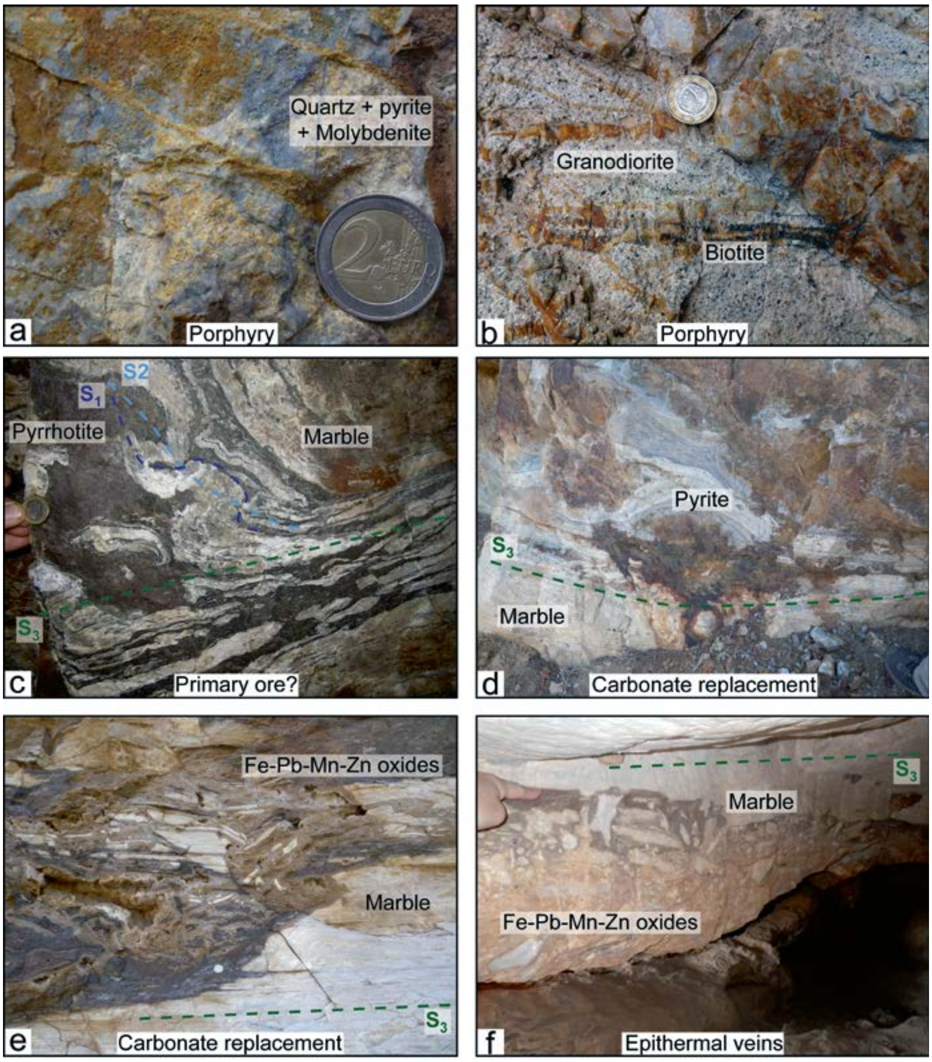

Fig. 8: Photographs illustrating the structural position of the main ore type deposits in the Lavrion mining district. – a. Quartz-pyrite veins with molybdenite coating within Plaka granodiorite. – b. Evidence of potassic alteration by strongly altered granodiorite and crosscutting veins containing centimetric hydrothermal biotite crystals. – c. Interstratified massive pyrrhotite layers folded with marbles suggest primary ore probably related to the sedimentary sequence before subduction (ante-S1). – d. The carbonate replacement deposits associated with the emplacement of the Plaka granodiorite attest to a set-up during ductile deformation of the marble. – e. The carbonate replacement deposits also point to an entrapment at the ductile-brittle transition as evidenced by ore deposits found both concordant and discordant to the S3 mylonitic foliation. Deposits are nowadays strongly altered by supergene alteration. – f. The more surficial Pb-Zn-Ag ore deposits are localised within marble breccia parallel to the low-angle detachment in agreement with a late brittle deformation event (photos a,b: A. Tarantola; photos c,d,e,f: Scheffer, et al, 2017b).

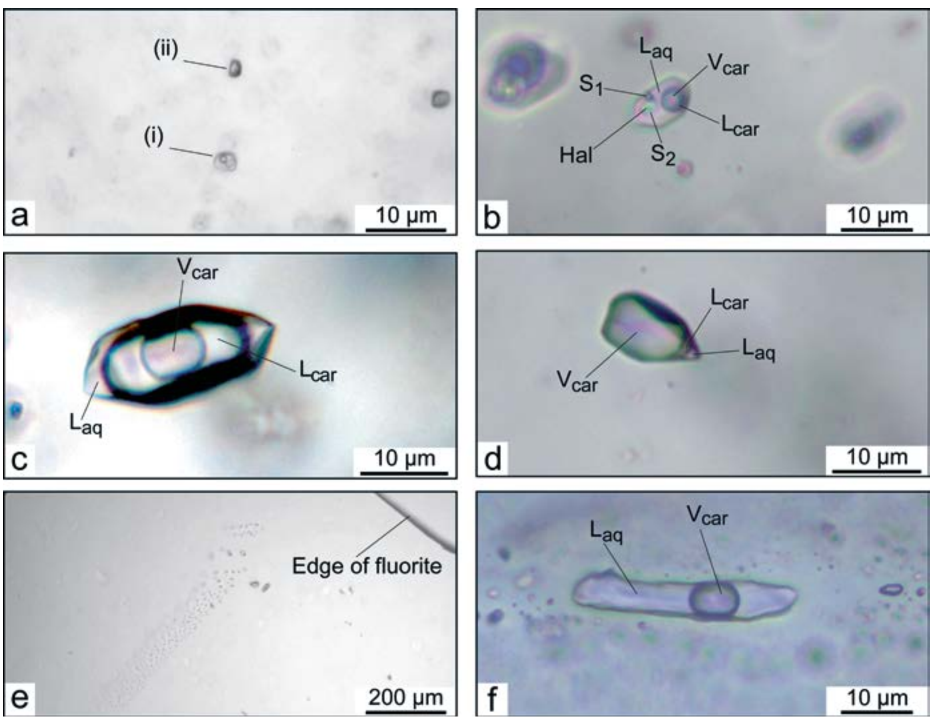

Fig. 9: Microphotographs showing the phase state at room temperature of the main types of fluid inclusions found in the Lavrion mining district. – a. Coexisting halite-saturated liquid-rich (i) and vapor dominated (ii) fluid inclusions. – b. Multiphase halite saturated aqueous-carbonic fluid inclusion. – c. Three-phase CO_2-rich fluid inclusion dominated by carbonic liquid. – d. Three-phase CO_2-rich fluid inclusion dominated by carbonic vapor. – e. Pseudo-secondary plane of two-phase liquid-vapor fluid inclusions within fluorite. – f. Two-phase aqueous fluid inclusion. Hal.: halite, L_{aq}: aqueous liquid, L_{car}: carbonic liquid, V_{car}: carbonic vapor, S_1 and S_2: unidentified solids (photos a, e: A. Tarantola; photos b,c,d,f: Scheffer, et al., 2017a).

analysis, stable isotope equilibrium and *VX* properties showed that CO_2 release took place under a heat flow with a thermal gradient of 70–115 °C·km^{-1} at the ductile to brittle transition, during exhumation accommodated by regional NNE-SSW extension. The $\delta^{18}O$ signatures of the marble enclosing the carbonate replacement deposits (Scheffer, et al., 2017a) indicate that deposits are related to this decarbonation process with implication of magmatic fluids. The contribution of Miocene seawater was also invoked in the deposition of the carbonate replacement mineralization and is supported by $\delta^{34}S$ values of sphalerite and galena (Bonsall, et al., 2011). In the same way, $\delta^{13}C$ pointed to interaction with organic matter during sulfide precipitation of the carbonate replacement deposits (Scheffer, et al., 2017a; 2017b).

The low-angle detachment fault is marked by a transition from mylonitic to cataclastic deformation, demonstrating the evolution from ductile to brittle behaviour of carbonate rocks during exhumation. For example, a cataclastic sub-horizontal zone of some 1–2 meters thick is visible all around the western side of the Velatouri hill (Scheffer, et al., 2017b; 2018). This zone is formed by cataclastic calcitic marble with lower $\delta^{18}O$ values, which is overlain by dolomitic breccia (Fig. 4d), thus suggesting the localisation of fluid circulation at the detachment fault during exhumation (Scheffer, et al., 2017b). It is interesting to note that ore deposition is not strictly located at the detachment fault but a few meters lower as shown in the Velatouri hill and Simonet quarry. This indicates multiple domains of preferential fluid circulation during transition from ductile to brittle deformation, likely due to a strong local lithological control marked by micaceous lenses in the calcitic marble (Scheffer, et al., 2017b).

The analyses of fluid inclusions found in fluorite, sphalerite and calcite from vein and breccia deposits with lower T_h have suggested an ongoing dilution and mixing of magmatic-hydrothermal fluids by surficial fluids in the purely brittle stage (Bonsall, et al., 2011). However, Scheffer, et al. (2019) suggested the existence of two independent fluid systems (magmatic-hydrothermal and surficial) without mixing and interactions in the more superficial mineralizing stages. Primary and pseudo secondary fluid inclusions (Fig. 9e,f) in fluorite and calcite are characterized by a wide range of T_h (92–207 °C) and salinity of up to 17.1 wt.% $NaCl_{eq.}$. The stable isotope signatures ($\delta^{18}O$ and δD) and low Cl/Br ratios of water extracted from fluid inclusions are compatible with a surficial fluid being the result of mixing of meteoric water with evaporated seawater.

Geology and mining archaeology

Mining is essentially a full destructive and irreversible process and the geologist generally can only deal with partial remnants of original rocks to reconstruct the conditions of formation of ore deposition. Mining areas are however key in the technological development of past and present civilization and are thus of particular interest for archaeologists to better understand past history thanks to human and mechanical traces left by mining activities. At Lavrion, the extraction of base metal resources has had a profound impact on the landscapes (Morin-Hamon and Morin, 2006).

The rise of metallurgy in mainland Greece is observed in Early Helladic II, between 2900 and 2400 BC (Cosmopoulos, 1991; Coleman, 1992). At Lavrion, the exploitation of mineral veins probably began in Early Helladic period as evidenced by the presence of ceramic and stone mining tools (hammerstones), which corresponds roughly to the 3rd millennium BC (Bourhis, et al., 1981; Spitaels, 1981; McGeehan Liritzis, 1996, p.176; Kayafa, et al., 2000). At this time, metal exploitation was generally confined to relatively restricted working areas unlike the subsequent extensive surface and underground working at Thorikos and in some areas on the Spitharopoussi plateau. The Classical Hellenic period is shown by pluridecimetric (usually 80 cm) squared galleries and plurimetric (up to 100 m) vertical shafts that allowed ventilation and access to deep levels. The Roman-Byzantine period is evidenced through the discovery of artifacts (lamps, pottery) and charcoal ^{14}C-dating found by firesetting mining. Technological advances that are known to have taken place during the Classical and Late Roman period, provided greater opportunities for mineral exploitation and ore-dressing activities (Morin and Photiades, 2012a; Morin, et al., 2013). It was not until the Industrial Age that the metal mining industry began to have a more profound and visible impact upon the landscape. The increasing demand for raw materials during the 19th century led to rapid expansion of mining activities all over the Lavrion district. Extensive workings were focused on the already known mineralized veins and levels that were exploited during the past centuries. However, with time, new mineralized levels were needed to be found at increasingly deeper locations (Levat, 1885). The result was the three horizontal levels that were exploited at Kamariza and below the Spitharopoussi plateau. Some places like Thorikos were not, or only to small extent, exploited during the Industrial era and are thus unique places to describe mining archaeology in ancient times.

The subsequent decline of mining activities during the 20th century has left a rich legacy of abandoned metal mining landscapes. They represent a dialogue with the landscape and its resources that lasted for almost 5,000 years from the Early Helladic period (Spitaels, 1984; Treuil, et al., 2008; Gale and Stos-Gale, 1982; Stos-Gale and Gale, 1982) to the late 20th century. Archaeological investigations are therefore needed to unravel the meaning of mining landscapes, to understand what is still visible from the past history and from technological developments. In this way, it is necessary to make mental associations between what might appear to be a confusing array of waste tips and bumps, discarded ruins, trackways, washeries, cisterns and buildings that remain scattered widely across the plateau and the mountainside, to provide an interpretation of the technologies involved in the winning and processing of ores, and to assess how these may have changed through time.

Today, archaeology focuses on the physical remains of mining and metallurgical activities and on interpretation of mining landscape evidences that were created by the metallurgical process (Morin-Hamon, 2013a; 2013b). The particular value of a mining landscape is that it can provide a clear illustration of the inter-relationship of the orebody itself, the various structures to be found within an entire mining complex, and of the developments that were made in extraction and processing techniques over the course of time.

Underground mining archaeology, through survey representation of the works, leads to an exhaustive knowledge of the general architecture of the orebody, i.e. remnants of the veins or layers that were exploited, including the gangue and the mineralized part, both in terms of direction and inclination (Ancel, 2001). Thus, the topographical representation of an underground network can reveal the main architecture of the mineralization and its volume. Geology defines history: as a potential natural heritage, geology governs the economic prosperity of a site. As a science, geology enlightens the whole history of a mining district as Lavrion (Morin and Photiades, 2012b). Beyond its architecture and volume, the mineral content of the site is another element in the foreground, including: (i) portions of bedrock like breccias, (ii) gangue made of non-metallic substances such as quartz, calcite and fluorite, (iii) minerals not useful at the time like zinc sulphide rejected on waste tips, and (iv) the ore itself. The morphology of the ore deposit conditions the organization of the mining works. Within the framework of the structurally and lithologically controlled shallowly dipping mineralized clusters of the Lavrion area, exploration will take the form of low-cut mining works according to the main concentrations. Finally, geology conditions mining technologies, i.e. the organisation and technology of driving galleries, shafts, stopping areas, ore dressing workshops and buildings.

Conclusions

The area of Lavrion was the largest mining site of Antiquity that contributed to the economic growth of the City of Athens. This exceptional ore deposit is the result of a long geologic and geodynamic evolution. The most recent interpretations point to metal deposition in a very active dynamic setting during the last stages of exhumation of the Attico-Cycladic Metamorphic Core Complex. The associated tectonic extension led to emplacement of magmatic bodies such as the Plaka granodiorite and numerous felsic/mafic dykes all over the peninsula at the ductile to brittle transition, associated with Mo-Cu porphyry style and Cu-Fe skarn deposits where magmatic-hydrothermal fluids are observed. This change in the deformation dynamics is demonstrated by the sub-horizontal detachment marked by cataclastic rocks at the contact between the Lower and Upper units of the Lavrion area. High-temperature Pb-Zn-Ag carbonate replacements and late veins and breccias were the most economic deposits over time. The different mineralization styles are the results of two hydrothermal systems, magmatic and meteoric water mixed with evaporated seawater where the detachment fault plays as a hydrogeological barrier at the ductile to brittle transition. Although the geodynamic setting of the Lavrion mining district seems to be constrained, some questions remain regarding (i) the absolute age of magmatism and ores at all scales, (ii) the provenance of the metals and (ii) the role of organic compounds, as a reducing agent, during ore deposition.

The geologic and particular metallogenic environment of the Lavrion area resulted in an exceptional district that was mined for their base and precious metals over centuries since the Early Helladic/Early Bronze Age periods.

Although the Industrial era and the extensive mining works of the French Mining Company (Compagnie Française des Mines du Laurion—CFML) destroyed much of the ancient archaeological mining evidence, it also opened access to antic galleries as is the case at Ari or at Spitharopoussi. Overall, the Lavrion district is an exceptional site, where geology and archaeology meet and allow us to understand the evolution of mining and metallurgical technologies over the past 5,000 years.

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What did the ancient Greeks mine at Laurion and when did they mine it?

ABSTRACT: *The Laurion district was one of the most extensive and influential silver mining areas in the ancient world. Evidence from archaeology and lead isotopes indicate that it was exploited for silver from the 4th millennium BC, probably accompanied by production of lead and copper, with exploitation of iron considered very likely in the 1st millennium BC. This paper integrates new and existing information to reassess the character of the mineralization mined by the ancient Greeks. It then applies these results to assess when the differing styles of mineralization may have been mined. The outcomes have significant implications for archaeology at Laurion. Foremost is the contrasting character of mineralization at the first and third contacts. Their significant differences are considered in several contexts: stratigraphy and structure; distribution of the mineralization; what the ancients mined; the impacts of weathering and oxidation; and their differing silver content. As a result, we believe that production from the exposed and shallow first contact mineralization was largely based on widely dispersed, thin, irregular, oxidised and lower grade deposits. These would favour numerous small independent operations with variable production that began in the 4th millennium BC and continued until the 1st millennium BC. In contrast, production from the third contact was based on substantial, thick, continuous and higher grade deposits, focussed around the central area of Kamariza. These deposits would support several larger scale, continuous and systematic mining and processing operations capable of providing a surge in silver output that could be maintained at a much higher level. This contrast in the character and grade of mineralization at the first and third contacts is sufficiently strong to link discovery of third contact mineralization with the windfall surplus received by Athens, according to Herodotus (VII.144), and dated at 483/2 BC by Aristotle (Ath. Pol. 22.7).*

KEYWORDS: SILVER, COPPER, ATHENS, IRON, OXIDATION

Introduction

Mineralization at Laurion occurred over an area of more than 100 km^2 (Fig. 1). It was one of the most extensive and important silver mining districts in the ancient world and appears to have been exploited almost continuously from the 4th millennium BC until the early Christian era. For much of that period it likely to have also been a source of copper and lead, with the probable addition of iron in the 1st millennium BC. Discovery of the concealed, thick, continuous and higher-grade deposits of the deeper third contact, most likely early in the 5th century BC, enabled a substantial and sustained increase in silver production that transformed the Laurion district and underpinned the rising wealth of Athens.

Assessing ancient mining districts is difficult, because subsequent phases of mining usually destroyed most, or all, preceding evidence; Laurion is no exception. Our reassessment leans heavily on extensive observations made by scholars and mining professionals in the 19th century when much of the evidence of ancient mining and processing was still preserved. Their observations are augmented by substantial recent geological and archaeological research at Laurion and adjacent areas.

To answer the question posed by the title we have addressed five key topics: the stratigraphy and structure of the district; the distribution of mineralization and its stratigraphic and structural contexts; insights into what the ancients mined; the differing impacts of weathering and oxidation; and the differing silver content of the first and third contacts, before considering the archaeological implications.

The key outcome of this work is the contrasting character of the mineralization at the first and third contacts. They share essentially the same primary mineralogy, but differ significantly in their distribution, form and silver grade. Within each of these contacts there also appear to be spatial variations in grade, which may be linked to structural factors, and proximity to the Plaka granodiorite. Another notable difference is the impacts of surface and near-surface weathering at the first contact, and sub-surface oxidation of third contact mineralization. The resulting supergene alteration of primary sulfides had economic consequences, which stemmed from the mobility of silver, copper, iron and zinc, and the stability of lead. Not only did this supergene alteration influence mining during the first three thousand years, but it led to revival of the district in the 19th century to mine secondary zinc carbonates.

Laurion stratigraphy and structure

At the district scale the geology of the Laurion mining district is deceptively simple with layer cake stratigraphy characterised by gentle folds and dips and dominated by marbles and schists. Nevertheless, young topography with relief in excess of 300 m, and faulting within the upper units, complicates the geological picture (Fig. 2). Southern Attica lies at the northern extremity of the Western Cycladic detachment (Grasemann, et al., 2012) and this fundamental structure, locally referred to as the South Attic Detachment (SAD), together with its subsidiary structural elements, introduces additional complexity. The presence of the SAD challenged accurate interpretations of the stratigraphy at Laurion until the work of Lekkas, et al. (2011). Importantly, the SAD has also strongly influenced the location and character of a significant proportion of the mineralization at Laurion.

Fig. 3 shows a summary of the conclusions of Lekkas, et al. (2011; 2020) about the stratigraphy, structure and age estimates at Laurion. It also shows where mineralization is located within the stratigraphic column. At the base is the principal host of mineralization, the metamorphosed, 200–230 Ma Kamariza series of three rock units: the Lower Kamariza marble; the Kamariza schist; and the Upper Kamariza marble. This series is capped by the SAD, which is overlain by the Laurion series that includes: a discontinuous basal Pounta marble, the overlying Laurion schists, and the capping Mavrovouni marbles. A second detachment separates the upper, unmetamorphosed Pelagonian unit, with an estimated age of 140–70 Ma (Katsiavrias, Solakius and Salaj, 1991; Photiades and Carras, 2001).

Stratigraphic boundaries within the Kamariza and Laurion series clearly indicate differential movement between units and even within them (Lekkas, et al., 2020). These zones of movement are consistent with the considerable movement of the SAD, interpreted as top to south-southwest and attributed to extension of the Western Cycladic Detachment caused by slab roll-back and trench retreat (Iglseder, et al., 2011; Lekkas, et al., 2011; Grasemann, et al., 2012; Scheffer, et al., 2016; Coleman, et al., 2019). Discontinuity of the Pounta marble is interpreted to result from normal faults rooted within SAD, and probably associated with its movement. Descriptions of all stratigraphic units and their internal structure are published by Lekkas, et al. (2020). These include the SAD, which ranges from a few centimetres to tens of metres of laminated Upper Kamariza marble,

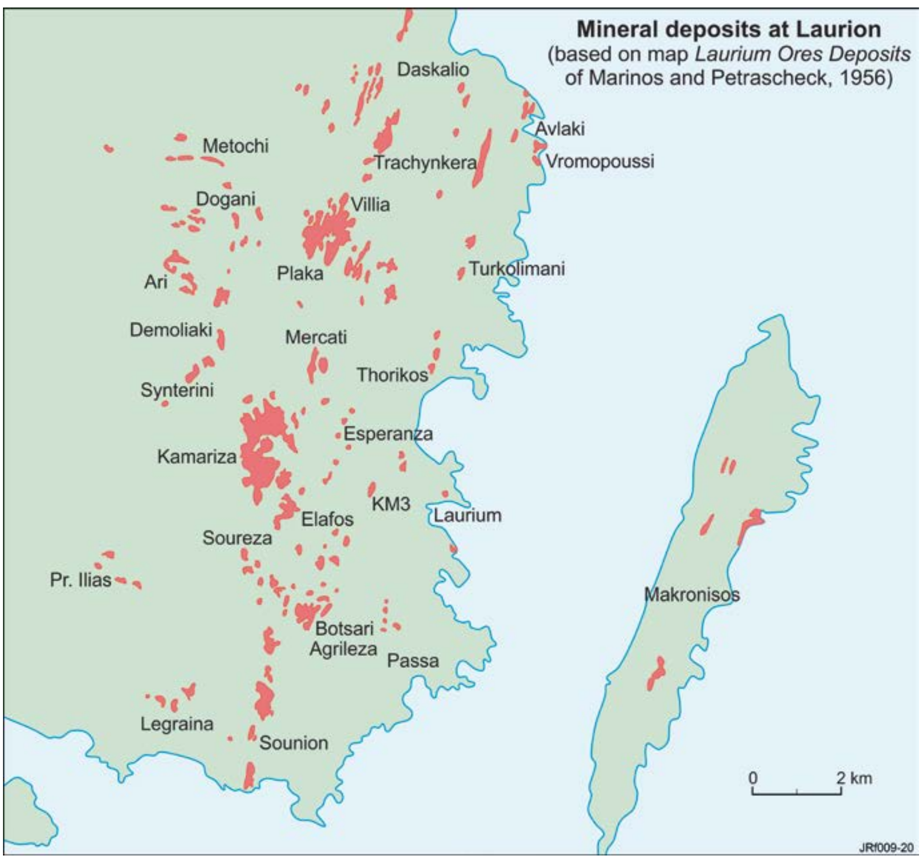
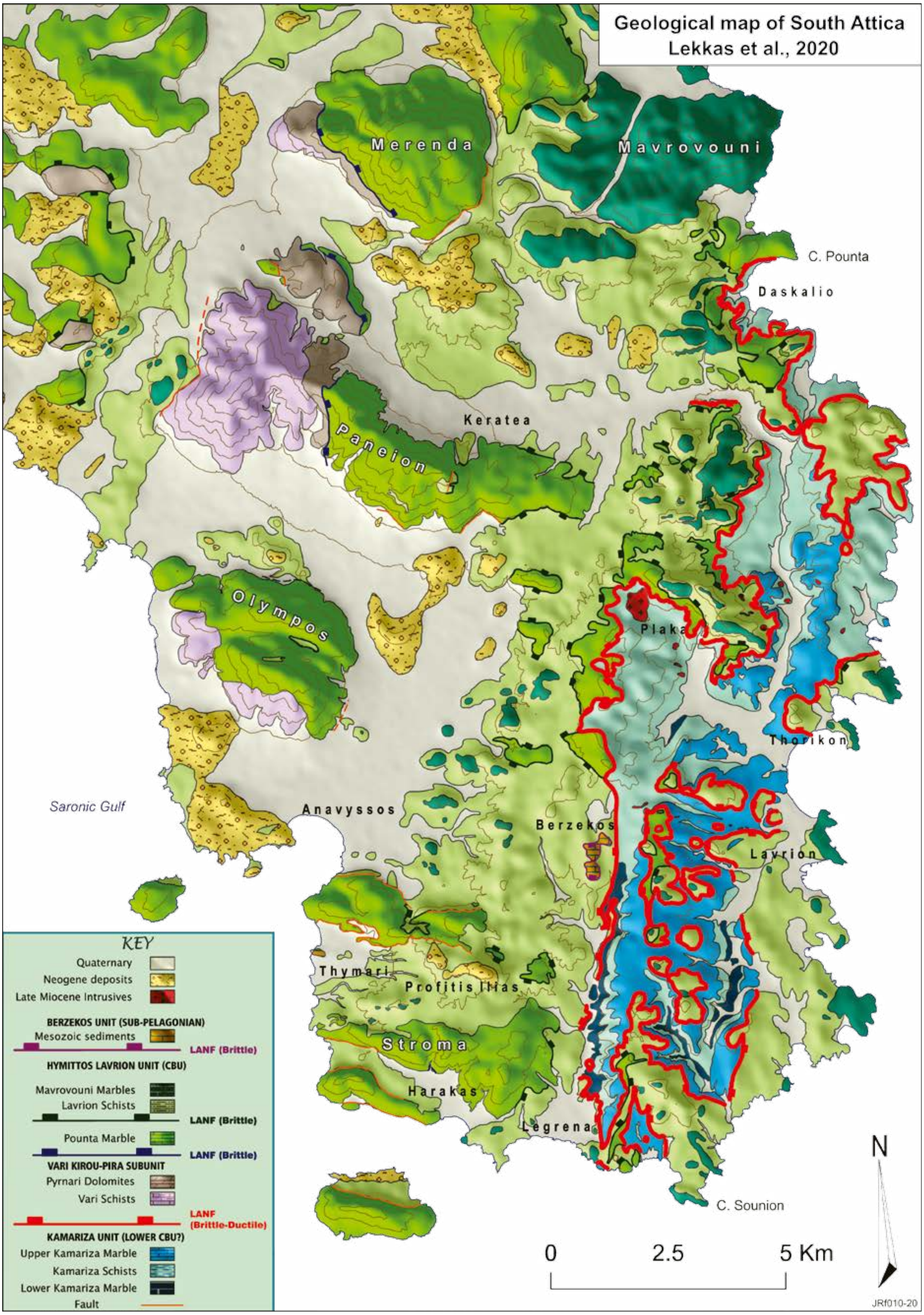


Fig. 1: Location map showing areas of mineralization on first, third and Pounta contacts (undifferentiated) within the Laurion district in plan projection, and deposits referred to in this paper. Based on the map "Laurium Ores Deposits" in Marinos and Petrascheck (1956) (preparation: by J. Ross).



together with overlying cataclastic melange, which can exceed 4 m in thickness, and is composed of angular and

Fig. 2: Geological map of the Laurion district, modified from Lekkas, et al. (2020) (preparation: by J. Ross).

rounded blocks, dominantly from the Laurion series, in a finer grained matrix.

The strongly deformed (ultramylonitic) Upper Kamariza marble represents a ductile component of the crustal scale detachment structure. This ductile deformation was followed by a brittle stage, which included both the marble and Kamariza schists. Deformation above the SAD was limited to the brittle stage with both the Pounta marble and Laurion schist being affected.

Fig. 3 also includes the younger granodiorite and granitoid intrusions, which appear to predate the bulk of the mineralization, with exceptions in the Plaka area (Voudouris, et al., 2008a; Skarpelis, Tsikouras and Pe-Piper, 2008; Liati, Skarpelis and Pe-Piper, 2009; Berger, 2013). These intrusions also appear to postdate most movement on the SAD. The prominent Plaka granodiorite has a surface area of about 0.5 km^2 and an extensive thermal aureole of hornfels within adjacent Kamariza schists. The fission track age of apatite, potassium-argon ages on biotite, feldspar and whole rock, and uranium-lead and uranium-thorium/helium ages on zircon yielded an age of 9.4 to 7.1 Ma for the igneous and hydrothermal activity of the Plaka granodiorite (Marinos, 1971; Altherr, et al., 1982; Skarpelis, Tsikouras and Pe-Piper, 2008). In addition, more than 50 narrow granodiorite and granitoid dykes occur throughout the district (Marinos and Petrascheck, 1956) and usually strike east-west and dip north.

The location of mineralization shown in Fig. 3 varies widely, but the most important concentrations exploited by the ancient miners were at, or close to, the contact between the Lower Kamariza marble and overlying Kamariza schist, commonly known as the “third contact” (Fig. 3). Second in importance, but first to be exploited, was the “first contact” located at or close to the contact between the Upper Kamariza marble and the SAD. In this paper, reference to the first contact has been extended to include mineralization that immediately overlies the SAD, within both Laurion schists and Pounta marble. Mineralization also occurs as lenses within the Lower Kamariza marble (Fig. 3), and within the Kamariza schist in association with thin lenses of marble. Mineralized lenses occasionally occur within the Upper Kamariza marble and at its lower contact with Kamariza schist, where it is known as the “second contact” (Fig. 3). Significant veins of mineralization can occur within Kamariza schist but are rare, with known mining restricted to the Filoni 80 vein at Plaka (Conophagos, 1980; Voudouris, et al., 2008a) and Vromopoussi (Potier, 1880). Substantial mineralization has also been exploited some stratigraphic distance above the SAD, at deposits such as Ari and Demoliaki, which appear to be focussed around the contact between the Pounta marble and overlying Laurion schist (Fig. 3). These occurrences are referred to as “Pounta contact”.

Although primary sulfide mineralization at Laurion occurs in diverse stratigraphic and structural settings, it is clear from numerous detailed studies (e.g. Voudouris and Economou-Eliopoulos, 2003; Voudouris, 2005; Skarpelis, 2007; Voudouris, et al., 2008a; 2008b; Bonsall, et al.,

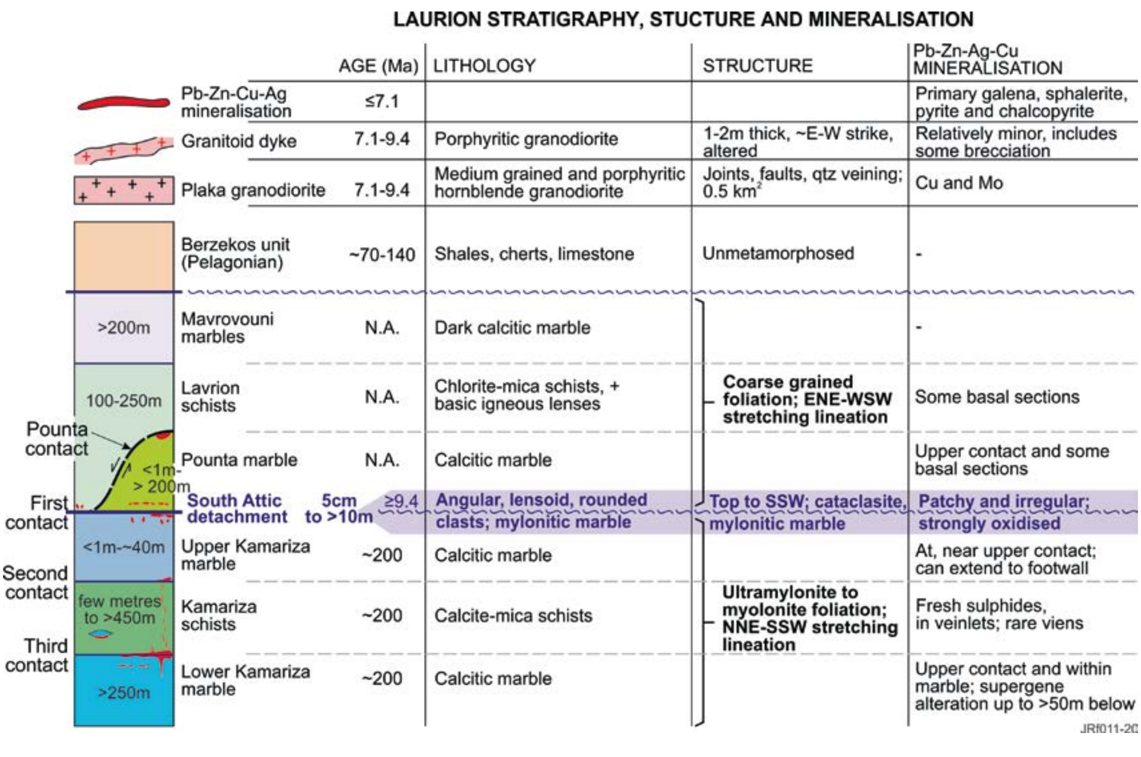


Fig. 3: Summary of Laurion stratigraphy, structure and mineralization based on Lekkas, et al. (2020). Note that the SAD (South Attic Detachment) also includes ultramylonitic Upper Kamariza marble, which represents the ductile component of this ductile/brittle crustal scale structure (preparation: by J. Ross).

2011; Scheffer, et al., 2019) that its primary mineralogy appears to be relatively consistent throughout the stratigraphic column and across the district. Pyrite, galena, sphalerite, chalcopyrite and arsenopyrite are usually the major constituents, with significant pyrrhotite present in the Plaka area (Voudouris, et al., 2008a). Furthermore, almost all Laurion mineralization conforms to one or both of two main criteria. Firstly, most mineralization associated with the first, second, third and Pounta contacts is located at or close to the interface between mechanically stronger marble and weaker schist, a location with rheological contrast. This is a typical location for dilatant openings in dynamic tectonic settings, and a well-recognised locus for hydrothermal mineralization (Ridley, 1993; Chauvet, 2019). Secondly, many of these settings also have less permeable schist overlying marble made selectively permeable by brittle fracturing, thus providing a potential trap seal (Megaw, Ruiz and Tetley, 1988).

The concept of a trap seal for mineralizing fluids at Laurion is strengthened by the exceptional concentration of third contact mineralization in the Kamariza area. This approximately north-south trending zone is the most substantial mineralized area in the district, extending over a length of almost 3 km, and widths from 300 to 900 m. It coincides with the crest of a doubly plunging, north-south trending fold (Marinos and Petrascheck, 1956), forming an elongate domal shape.

There are extensive exposures of the SAD and first contact mineralization along the 20 km from Sounion to Daskalio (Figs. 1 and 2), resulting from interaction of topography and stratigraphy. In contrast, the third contact is rarely visible at the surface and, when exposed, mineralization is absent or just of low grade. Consequently, extensive mining of first contact mineralization is almost certain to have preceded that of the largely concealed third contact. Surface exploitation of the Pounta contact is known (Morin and Delpech, this vol.), but mapping of the main deposits, such as Ari and Demoliaki, indicate that they have been essentially exploited following shaft sinking to access steeply dipping contacts between Pounta marble and overlying Laurion schist, as shown in the map by Ardaillon (1897).

Distribution of mineralization

The book "Laurium", published in 1956 by Marinos and Petrascheck, is an underutilised resource on Laurion. Their surface geological map was a significant advance and identified some of the key structural component we now know as the SAD. They also published other maps, including their 1 : 50,000 Mining Map of the Area of Laurium (Mining Map) which shows structural contours for two stratigraphic markers: the third and first contacts, and their elevation above sea level. The Mining Map identified the domal Kamariza fold closure, described above, but their mistaken inclusion of Pounta marble as part of the upper Kamariza marble detracted from the utility of this map.

Nevertheless, this valuable map does show the location of individual deposits of mineralization on the first and third contacts, and their elevation above sea level. These data indicate that the authors had access to surface and underground maps produced by the French mining companies during the 19th and 20th centuries. Our inspection of some of these French maps revealed that they show both the extent of ancient exploitation, and any extensions of mining areas during the modern phase. Therefore, we assumed that the outlines of the third and first contact mineralization on the Mining Map provide the limits of the deposit, as defined by any exploitation activities, i.e. the development of ancient mining, and the extensions of modern mining. These outlines are shown in plan projection in Fig. 4.

Fig. 4A shows the widespread distribution of first contact mineralization throughout the district, including that associated with the upper contact of the Pounta marble (Pounta contact). Also shown is the surface outcrop of the Plaka granodiorite and its associated hornfels, historically referred to as "Plakite". In addition, the map shows outcrops of thin granitoid and granodiorite dykes, and the limits of a deeper intrusion, some 15 km^2 in area, as interpreted from 20th century aeromagnetic data by Tsokas, et al. (1998).

The spatial distribution of third contact mineralization is shown in Fig. 4B which highlights the dominance of the central Kamariza area. This mineralization is much more focussed than that at the first contact, with all known deposits occurring within a radius of about 5 km from the central Serpieri shaft at Kamariza. The core Kamariza area is located within a north-south trending domal fold closure, but north-northwest and northeast fractures within the lower Kamariza marble may also have influenced the location and trend of the mineralized lenses at the third contact (see below). Nevertheless, we do not have a detailed understanding of the main structural controls on third contact mineralization, or the distribution of the mineralized structures that acted as feeder fractures and pipes for primary mineralization.

The other third contact deposits, away from the central Kamariza area, appear to be thinner and lower grade, but information is very limited. Comparison of Figs. 4A and B suggests limited overlap of mineralized areas at the two contacts, but this difference may simply result from erosion of the SAD and first contact above the Kamariza domal crest.

What did the ancients mine at Laurion?

It appears that interest in the ancient silver mines of Laurion increased in the 19th century, when at least two authors published comprehensive studies (Cordella,1869;

Ardaillon,1897). They were able to enter well-preserved workings, largely untouched by any mining activity for more than a millennium, and their observations ranged from geology and mineralization through to mining methods, mineral processing, water storage and final smelting. Their preliminary observations about the form and character of the mineralization the ancients mined have been complemented by more detailed studies and mapping by French mining engineers and geologists in the 1870's and 1880's. Most of this detailed work is believed to result from due diligence assessments of operations on behalf of French banks.

Examples include Huet (1879; 1887), Potier (1880), and Cambrésy (1889). Their work was in turn complemented by the observations of Marinos and Petrascheck (1956). When combined, these records tell us much about the distribution and thickness of mineralization, and the variable alteration of primary sulfides by surface and sub-surface oxidation. They also provide information about oxidation and the resulting downwards redistribution of zinc, iron and copper, especially within marble beneath the third contact. An important factor was the horizontal development of underground mining levels at the 96, 80, 65 and 50 m RL's. These levels were largely in Lower Kamariza marble, beneath the third contact in the core Kamariza area, and were used to determine the potential of secondary zinc mineralization and explore for deeper primary mineralization. Their locations enabled a three-dimensional view of the distribution of primary and secondary mineralization. They also provided insights into the processes that formed them and that appear to have modified the grade and distribution of silver at the third contact.

Fig. 5 provides several examples of first contact mineralization. A generalised version by the geologist Potier (1880) is shown in Fig. 5A. Unfortunately, it lacks scale, but numerous observations indicate that first contact mineralization is rarely >1 m thick. This version shows

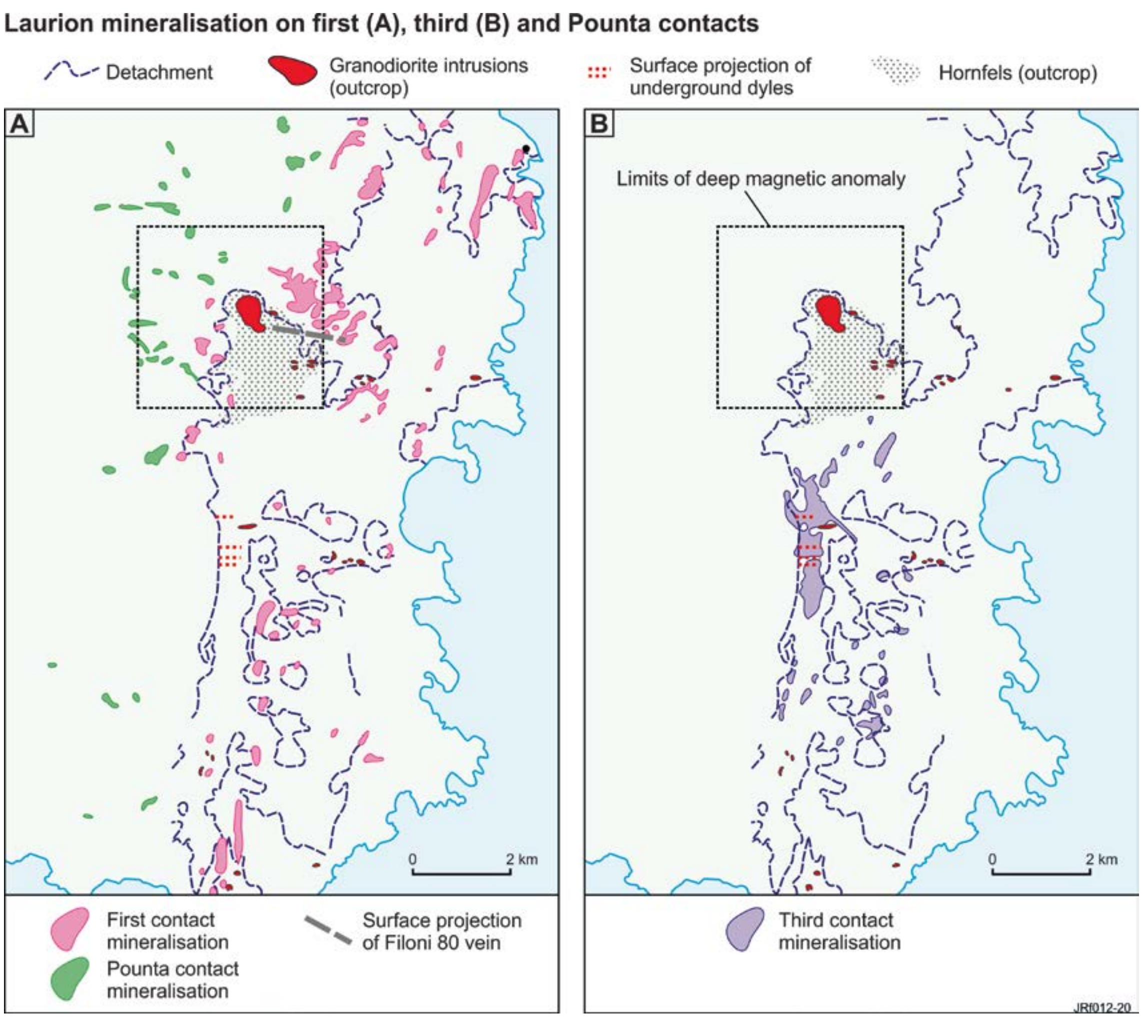


*Fig. 4: Plans of Laurion district showing the surface expression of the SAD and extent of mineralization on the first and Pounta contacts (**A**) and third contact (**B**) in plan projection, derived from the 1 : 50,000 scale Mining Map of the Area of Laurium, published by Marinos and Petrascheck (1956). In addition, these plans include the surface expression of the Plaka granodiorite and narrow granitoid dykes, the hornfelsed Kamariza schist at Plaka, the plan projection of the Filoni 80 vein (Voudouris, et al., 2008a), and the approximate location of the deep magnetic anomaly identified by Tsokas, et al. (1998) (preparation: by J. Ross).*

the common features of strong oxidation of first contact sulfides and downwards redistribution of secondary zinc minerals into fractures within the Upper Kamariza marble. Here it has accumulated as calamine, a mixture of the secondary zinc carbonates, smithsonite and hydrozincite, and zinc silicate, hemimorphite (Katerinopoulos, Solomos and Voudouris, 2005). A representative version of the first contact mineralization entirely within Upper Kamariza marble (Fig. 5B) was provided by Cordella (1869), with iron oxides sandwiched between secondary iron carbonates, and both containing irregular masses of residual galena. Figs. 5C and 5D from Marinos and Petrascheck (1956), provide other typical examples of the patchy and irregular first contact mineralization. Although the scale is absent, the ancient mine opening at Trachynkera in Fig. 5C is unlikely to exceed 0.9 m in height (Ardaillon, 1897). These images confirm that first contact mineralization occurs dominantly within the Upper Kamariza marble, but also within, and immediately above, the SAD. They also show mineralization at the second contact between Upper Kamariza marble and Kamariza schist. Ardaillon (1897), observed that most mineralization outside of Kamariza varied from a few centimetres to 2–3 m in thickness and was highly irregular.

Examples of third contact mineralization from the Kamariza area are shown in Figs. 6 and 7, and come from Huet (1879; 1887), Potier (1880) and Ardaillon (1897). Fig. 6A is a north-south section through the northeast trending Jean Baptiste lens at Kamariza, which shows a 400 m extent of ancient mining with thicknesses of 8–12 m for most of that strike length. The “mine waste” within the void created by ancient mining, indicates substantial underground sorting. The north-south section in Fig. 6B shows where a shorter lens, about 15 m thick, has been mined from the central Kamariza area. This substantial thickness may have been increased by roof collapse. Old mine plans and cross sections indicate that these elongate thick lenses of Kamariza mineralization at the third contract can have widths up to 50 m.

An interesting feature of these sections is the layer of low grade oxidised “ore”, left intact by the ancients, presumably uneconomic at that time. It forms a thin base to the originally thick mineralization and extends north and south beyond the limits of ancient mining. A second feature is the near-vertical, irregular, downward-thinning lenses of calamine, often with abundant iron oxides, that extend up to 40 m below the contact in Lower Kamariza marble and can have a galena-rich core (Huet, 1879). These correspond to the term of griffons of the French miners and their dominant trend is reported as northeast (Huet, 1887), but with some northwest branches.

The formation of griffons through redistribution of zinc and iron from contact mineralization into underlying marble appears strongly influenced by steeply dipping

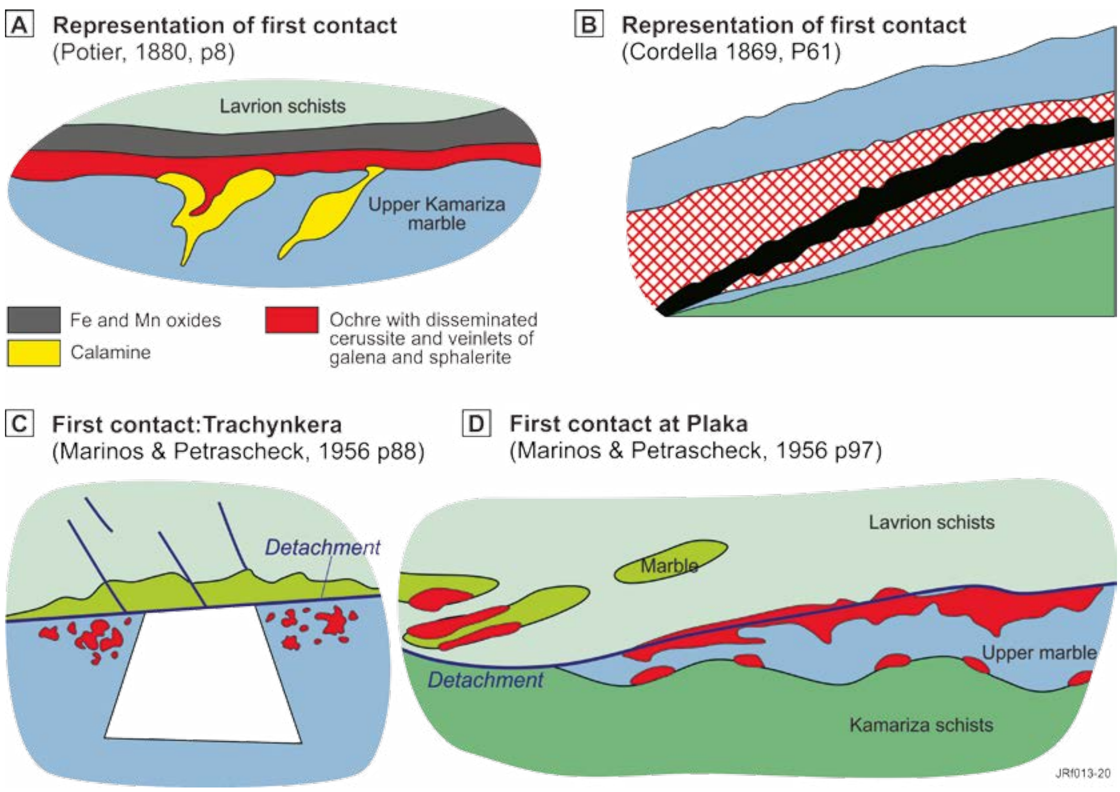


Fig. 5: First contact mineralization at Laurion: – A. Composite representation derived from Potier (1880); – B. composite representation from Cordella (1869); – C. At Trachynkera; – D. At Plaka, both derived from Marinos and Petrascheck (1956). The ancient opening in C is believed to be no more than 0.9 m high (Ardaillon, 1897), and provides scale (preparation: by J. Ross).

pre-existing fractures that mostly trend northeast. However, as shown in Fig. 6C (from Huet, 1887), it shows a horizontal concentration of calamine, about 80 m long and 5 m thick, located about 10 to 15 m below the contact. It contained a 2,000 kg pod of secondary copper minerals with about 10% native copper, indicating that copper could also migrate downwards from the oxidising third contact mineralization. The abundance and vertical length of griffons in Fig. 6A appears to correlate with the proximity to thick contact mineralization. However, extensive griffons at the underside of the thin granodiorite dyke in Fig. 6B also indicates lateral migration of acidic

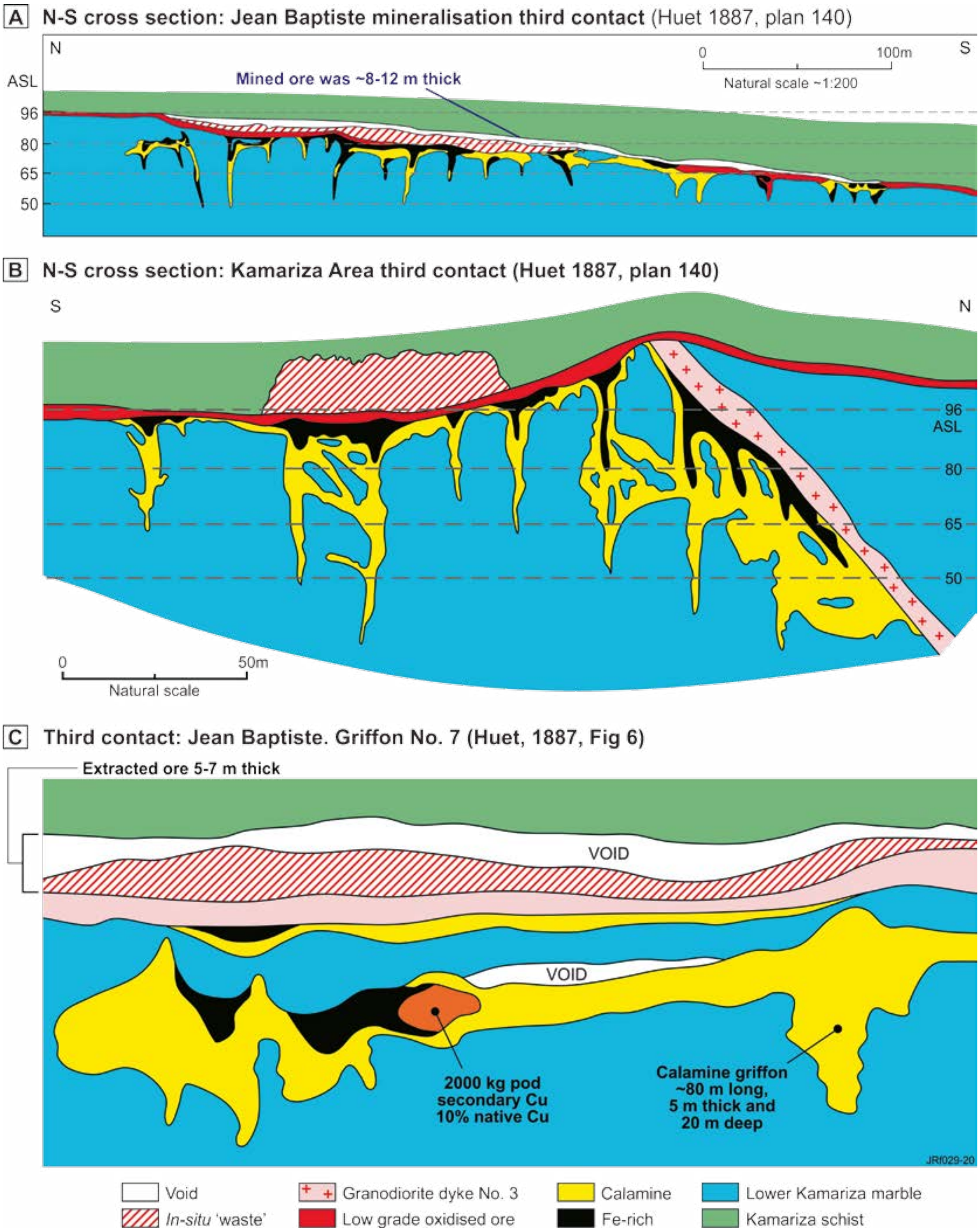


Fig. 6: North-south cross sections at natural scale of third contact mineralization at Kamariza, derived from Huet (1887, plan 140, fig. 6). – A. Section of the Jean Baptiste lens from plan 140. – B. Southerly continuation of the Jean Baptiste section (A) through the central Kamariza area. – C. Partial section through the Jean Baptiste lens showing contact mineralization and griffon no. 7 within the Lower Kamariza marble, derived from Huet (1887, fig. 6) (preparation: by J. Ross).

groundwater carrying zinc and iron. Huet (1887) noted that these griffons associated with undersides of dykes were devoid of lead minerals, but contained variable amounts of copper. These characteristics indicate a secondary origin for their zinc, iron, and copper contents, and that oxidation may not have caused any significant migration of lead away from the third contact.

At the south end of the main section in Fig. 6A there is a single lens of oxidised primary mineralization, which extends about 15 m below the contact. It is an example of the steeply dipping mineralized fractures within the Lower Kamariza marble, which the French termed croiseurs. Marinos and Petrascheck (1956), noted that such wedge-shaped veins usually trended 20–50° west of north, contained primary and oxidised sulfide mineralization, and generally extended no more than 15 m below the third contact. They attain their maximum width, or diameter, at the intersection with the third contact and probably represent channel ways for primary mineralizing fluids. Marinos and Petrascheck (1956), also noted that the northeast trending griffons are dominantly, but not exclusively, zinc-rich and can have some lead minerals in the core, whilst the northwest trending croiseurs consist mainly of primary and oxidised sulfides.

The croiseur trend is a central feature of Fig. 7, with Fig. 7A being a plan representation of the southern half of the Kamariza mineralization by Potier (1880). It shows elongate lenses of mineralization at the third contact up to 600 m long, 30 m wide and 10 m thick, set in a surround of low-grade oxidised mineralization and barren contact. These lenses also appear to be associated with the intersection of the griffon and croiseur trends. This sketch does not extend to the other lenses of mineralization in the northern half of the Kamariza area, north of the Serpieri shaft. Fig. 7B shows an unnamed cross section of a mineralized lens by Ardaillon (1897), with its dimensions scaled to the ancient underground drives, no more than 0.9 m high. The width and thickness are consistent with observations by other authors. There is very limited information about other third contact deposits away from Kamariza, but sections of the Mercati deposits by Huet (1879), show significant oxidation and limited griffon development, a combination consistent with thin mineralization. This observation is supported by the observations of Vaxevanopoulos, et al. (this volume).

So, what did the ancient Greeks mine? Until they reached the concealed, thick lenses of mineralization on the third contact in the Kamariza area, the available records indicate they were essentially mining the relatively thin, discontinuous, irregular, and often strongly oxidised shallow mineralization associated with the first contact. Oxidation equated with lower grades, according to empirical evidence from the French mining engineers and geologists. Furthermore, one published analysis suggests the possibility that primary galena in the first contact may have contained less silver than that in the third contact (see below). An exception is the higher grade, sulfide rich mineralization at Plaka in the first and second contacts,

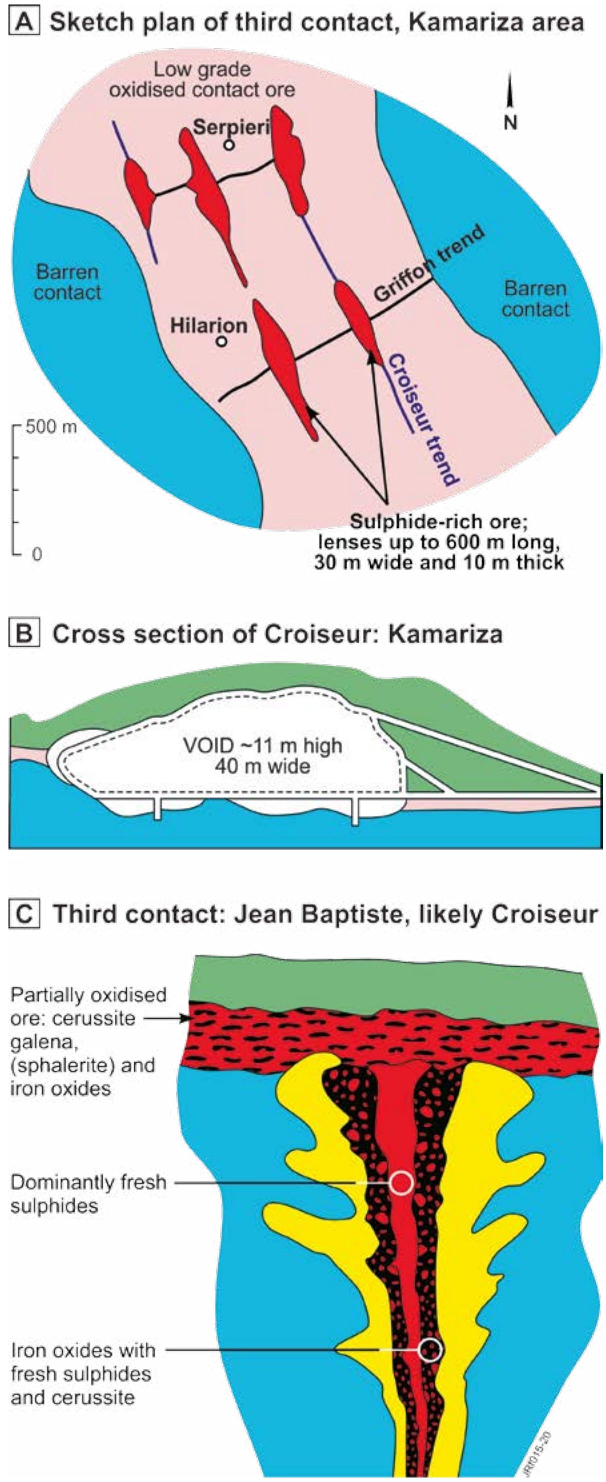


Fig. 7: Croiseurs and third contact mineralization at Kamariza. – A. Sketch plan of lenses of thick contact mineralization south of Serpieri shaft aligned on the croiseur trend and surrounded by thin, unmined, low grade oxidised mineralization; derived from Potier (1880). Note that scale bar only applies to north-south direction. – B. Cross section of a thick lens by Ardaillon (1897), showing interpretation of initial mine development by ancient miners; scale based on ancient workings being no more than 90 cm high. – C. Partially oxidised croiseur with primary mineralization at core and calamine margin, located beneath the third contact at the Jean Baptiste lens. Redrawn from Huet (1879), without scale, however its vertical extent is unlikely to exceed 15 m according to Marinos and Petrascheck (1956) (preparation: by J. Ross).

which was mined by the French at depths of more than 50–100 m below surface. However, there is no evidence that the ancient near surface workings at Plaka extended sufficiently beyond the strongly oxidised, low grade mineralization described below. By comparison, sinking a shaft in Kamariza schist to depths of <30 m at Kamariza would have either intersected a thick lens of mineralization or, more likely, reached low grade oxidised mineralization on the third contact. Once there, lateral development would eventually lead to the bonanza discovery.

Supergene alteration

Surface exposure of Laurion stratigraphy is believed to have occurred about 5 Ma ago, following tectonic uplift (Krohe, et al., 2010), and would be followed by supergene alteration of any near surface mineralization. This alteration would result from the combined influence of oxidation, meteoric water and chemical weathering. Optimum conditions for oxidation of sulfides occur in hot, arid to semi-arid climates, with a preservation of the resulting non-sulfide minerals enhanced by switches of paleoclimate to hyper-arid (Reichert and Borg, 2008; Borg, 2015). These conditions resulted in iron-rich gossans and ochres at surface with varying proportions of secondary oxides, carbonates and sulfates derived from original sulfides. Such assemblages characterise near-surface first contact mineralization at Laurion, which often includes relict primary sulfides. Variations in paleoclimate, which favoured oxidation and preservation, are believed to have occurred several times at Laurion in the last 5 Ma (Biltekin, 2010). Furthermore, during the last million years oxidation processes have been amplified by several fluctuations of up to 120 m in sea level, which lowered the water table and deepened oxidation to far below current levels.

Initial oxidation of pyrite (FeS_2) and accompanying iron-arsenic sulfides can generate acidic, metal-rich solutions which then leach other sulfides and their marble host rocks and promote mobilization of metals into the groundwater (Reichert and Borg, 2008; Skarpelis and Argyraki, 2009). Low *pH*-values (3–6) favour the formation of goethite (FeO(OH), that then dehydrates to hematite (Fe_2O_3) which forms residual gossans, and sometimes siderite ($FeCO_3$), as shown in Figs. 5A and 5B. Galena (PbS) is partially or completely replaced by cerussite ($PbCO_3$) and anglesite ($PbSO_4$), whilst alteration of sphalerite (ZnS) eventually leads to precipitation at secondary sites of smithsonite ($ZnCO_3$), hydrozincite ($Zn_5(CO_3)_2(OH)_6$), and hemimorphite ($Zn_4(Si_2O_7)(OH)_2H_2O$), i.e. calamine (see Fig. 6). Chalcopyrite alters to a range of secondary copper minerals, including malachite ($Cu_2(OH)_2CO_3$), azurite ($Cu_3(OH)_2(CO_3)_2$), cuprite (Cu_2O) and native copper. Pre and post mining oxidation has also generated a remarkable array of other secondary minerals which have been thoroughly documented (Katerinopoulos and Zissimopoulou, 1994; Rieck and Rieck,1999; Baumgartl and Burow, 2002; Ottens and Voudouris, 2018; Voudouris, et al., 2021).

Oxidation of primary sulfides by ingress of meteoric waters along fractures, faults and lithologic boundaries can extend to considerable depths at Laurion (Fig. 8), including below current sea level (Skarpelis and Argyraki, 2009). Initial access and movement of groundwater would have depended on factors such as thickness of mineralization, structural setting, and effective porosity and permeability of host rocks. The strongest oxidation of the third contact mineralization occurs at the base of thick lenses, or when the mineralization is relatively thin (Figs. 6, 7), suggesting influence from lateral groundwater movement along the contact between the Lower Kamariza marble and overlying Kamariza schist. In addition, the distribution of associated griffons highlights the role of vertical and horizontal fractures in the Lower Kamariza marble, and at the margins of granitic dykes, in channelling both downward and lateral movement of acidic groundwaters transporting zinc, iron, copper and silver (Fig. 6).

The impacts of weathering and oxidation on primary mineralization at Laurion is consistent with observations at similar deposits elsewhere in the world (Borg, 2015), and with well-understood chemical processes. They are also consistent with gradual neutralisation of acidic, metal-bearing solutions as they react with, and dissolve, adjacent marble (Sangameshwar and Barnes, 1983). Under such conditions lead is relatively stable, therefore cerussite and anglesite will often be intimately associated with primary galena. Anglesite is favoured at lower *pH*, then cerussite as *pH* increases from reaction with marble. In some samples these secondary minerals appear to armour the remaining galena from complete oxidation (Skarpelis and Argyraki, 2009; Fig. 9). In contrast, zinc, iron and copper are much more mobile and require an increase in *pH* to almost neutral before precipitation of their secondary minerals. Consequently, when primary mineralization is thick and has substantial capacity to generate acid from oxidation, their secondary minerals are likely to be some distance from the source. Comparison of Figs. 5A and 6 demonstrates the link between thickness of primary mineralization, oxidation, and movement of iron and zinc.

Silver is soluble in acid solutions and the apparent loss with oxidation, indicated in Fig. 6, is consistent with solution chemistry. However, it is not obvious where the resulting secondary silver is precipitated, a question first raised by Huet (1887). Secondary silver at Laurion occurs as the low temperature sulfide, acanthite (Ag_2S), the chloride, chlorargyrite (AgCl), and as native silver (Rieck and Rieck,1999; Skarpelis and Argyraki, 2008; Ottens and Voudouris, 2018; Scheffer, et al., 2019), and their stability fields are determined by the oxidation potential and activity of Cl (Keim, et al., 2016). The presence of Cl is consistent with Laurion's proximity to the sea and its relatively dry climate, conditions that favour significant chloride contents in pre-mining groundwaters and precipitation of chlorargyrite.

Primary silver in galena occurs as inclusions of acanthite, and/or sulfosalt (e.g. matildite, $AgBiS_2$; and miargyrite, $AgSbS_2$), and in solid solution (George, et al., 2015). However, with alteration of galena to cerussite and anglesite there is no place for silver in the lattice of these minerals (Keim, et al., 2016). The location of silver, which has been mobilised by oxidation of primary galena and silver-bearing sulfosalts (Voudouris, et al., 2008b), is a vexed question at Laurion, and one with significant archaeological implications.

Chalcopyrite is a significant component of the Laurion sulfide mineralization, and its mobility under oxidising conditions can result in concentrations of secondary copper minerals. Poitier (1880), noted that substantial quantities of copper were found in the form of malachite, azurite and native copper (Fig. 6C). Marinos and Petrascheck (1956), also emphasised the significance of copper at Laurion, as did Broomehead (1948). Unfortunately, analytical results are rare, but Skarpelis and Argyraki (2009) reported averages of 0.4% copper for twelve samples of gossan and 1.0% copper for nine samples of supergene mineralization. Their gossan samples appear to be a mix of first and third contact samples, whilst the supergene samples appear to all come from the third contact in the Kamariza area and indicate some concentration of copper during oxidation.

If these results are representative, then Laurion contained sufficient copper to ensure obvious signs of green and blue secondary oxides in outcrops of oxidised first contact mineralization. Oxidation of the thinner and more irregular first contact mineralization would have also resulted in concentrations of secondary copper close to residual sulfides, which would have caught the attention of ancient miners.

Silver contents of mineralization at the first and third contacts

Assessing the abundance and distribution of silver at Laurion is fundamental to understanding the archaeology of this region, and its consequences for ancient Athens. There is widespread agreement that mineralization at the first contact is lower grade than the third contact, but what does that mean, because there are also evi-

Fig. 8: Five examples of oxidised mineralization from the first and third contacts. workings – A. Exposures of first contact at Kilometre 3 with opening at right hand side about 2 m high; base of vegetation at top right is contact between the top of the detachment zone and the overlying Laurion schist (photo by James Ross). – B. Oxidised, near surface, first contact mineralization at the Elafos ELA-01 mine (photo by M. Vaxevanopoulos). – C. Jean Baptiste mine at the 80 m level in the Kamariza area; thin, oxidised third contact mineralization visible at left hand side in foreground and large void in background (photo by M. Vaxevanopoulos). – D. Thin, oxidised mineralization within Lower Kamariza marble at Mercati, at a depth of 88 m and 6 m below the third contact; camera lens cover central left hand side is 7 cm in diameter (photo by M. Vaxevanopoulos). – E. Steeply dipping oxidised contact between Pounta marble and overlying Laurion schists at Demoliaki; ancient workings clearly visible in central area of image and indicate the irregular nature of mineralization at this location. (photo by M. Vaxevanopoulos).

dence of variations in grade at both contacts? Ardaillon (1897), noted very little silver at Plaka, important levels at Kamariza, and high levels at Soureza. Other authors provided analytical results for samples of mineralization from various locations, with widely varying results (e.g. Cordella, 1869; Potier, 1880; Marinos and Petrascheck, 1956; Gale, et al., 1980; Skarpelis, 2007).

The grade of silver at Laurion has been commonly expressed as ppm silver/tonne of lead (ppm Ag/t Pb)[1], a calculation that exaggerates the grade if samples with low levels of lead also contain separate sulphosalt minerals rich in silver (Voudouris, 2008b). Therefore, we believe that selection of samples that may represent what the ancient miners selected should be restricted to those containing at least 5% lead to ensure adequate dilution of any accessory silver rich sulfosalts. Furthermore, if samples from the third contact are to provide an indication of what was mined, they should contain at least 10% lead to approximate the cut-off grade thought to be used by the ancient miners (Ardaillon, 1897).

Conophagos (1980), noted that the lead content of mineralization varied across the district, and also within single ore bodies, ranging from <10% up to 40–50%lead, but with an average of about 15%. He also believed that the silver content was directly related to the lead content and that in the ancient mines it varied from 1,000 to 4,000 ppm Ag/t Pb. After considering the various processing steps at Laurion that were applied in the Classical period, Conophagos (1980), concluded that the average silver content of mined and processed ore was about 2,000 ppm/t Pb. This figure was based on the silver content of the ecvolades, i.e. the discarded lower grade waste from washeries and mining. It has been widely adopted in historical studies of Laurion.

A total of 29 eligible analyses have been compiled in Table 1. Thirteen are from the first contact, eleven from the third contact and five from the Filoni 80 vein, near Plaka. They are plotted in Fig. 10 as ppm Ag/t Pb against wt.% Pb. The 13 first contact samples include three from Plaka, that were collected by Gale, et al. (1980), from modern workings in primary mineralization. They average 2,114 ppm Ag/t Pb and 46.0% lead and may include some mineralization from the second contact. But the more important issue is that: did mining of the deeper, primary mineralization at Plaka occur in ancient times? Ardaillon (1897), refers to very little silver at Plaka and there appears to be no evidence for ancient working of the deeper sulfides. Huet (1879), provides evidence of grades of about 1,000 ppm Ag/t Pb in strongly oxidised mineralization with about 8% lead at the first and second contacts at Plaka, which he refers to as “leaded iron, manganese iron and dry iron” and suggests it may have value as flux. To avoid doubt, we have deleted these three Plaka samples from our estimation of the grade of first contact mineralization exploited by ancient miners.

The remaining ten samples represent six first contact deposits with grades ranging from 509 to 4,000 ppm Ag/t Pb with an average of 1,120 ppm Ag/t Pb and 31.8% lead. References to Table 1 and Fig. 10 shows that nine of these samples range from 509 to 1,500 ppm Ag/t Pb, and average 800 ppm Ag/t Pb, with only Trachynkera, at 4,000 ppm Ag/t Pb, as the outlier. Although the sample size is small and the data imperfect, they do show some coherence. They also support the widely held belief that

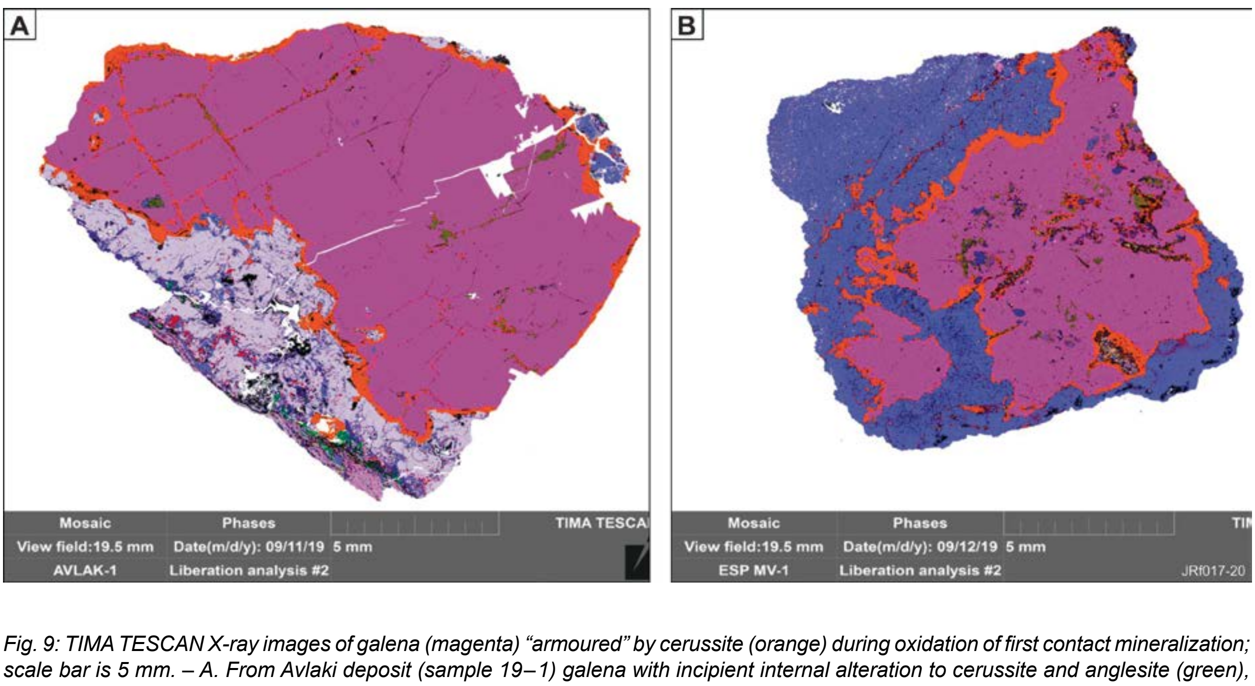


Fig. 9: TIMA TESCAN X-ray images of galena (magenta) “armoured” by cerussite (orange) during oxidation of first contact mineralization; scale bar is 5 mm. – A. From Avlaki deposit (sample 19–1) galena with incipient internal alteration to cerussite and anglesite (green), rimmed by up to 1 mm of cerussite and bordered by iron-manganese-lead oxides (mauve). – B. From Esperanza deposit (sample ESP MV 19–1), galena enclosed within hematite (blue) with more advanced internal alteration to cerussite and anglesite and a narrow rim of cerussite up to 0.5 mm wide. (Images from John de Laeter Centre, Curtin University).

first contact mineralization was lower grade than the third contact. Oxidation may explain the difference, but a sample from Sounion, analysed by Gale, et al. (1980), contains 86.3% Pb and is essentially pure galena, yet only contains 579 ppm Ag/t Pb. A result which suggests that the grade of primary mineralization at the first contact, at least at that location, may have been lower than at the third contact.

Results for eleven samples of third contact mineralization containing at least 10% lead are also shown in Fig. 10. Ten of these samples are from the Kamariza area and average 2,917 ppm Ag/t Pb and 71.2% lead. They include seven samples of almost pure galena concentrate from Skarpelis (2007), which average 2,864 ppm Ag/t Pb and 82.2% lead. The eleventh sample is from Agrileza and contains 2,500 ppm Ag/t Pb and 10% lead. The ten samples from Kamariza average almost 3,000 ppm Ag/t Pb, much higher than first contact mineralization, and significantly higher than the estimate of Conophagos (1980). Whilst this small population should not be considered a reliable guide to the grades of silver exploited by the ancient miners at Kamariza, the higher values of silver are consistent across the range from 10% lead to almost 83% lead in individual samples. Furthermore, these results are broadly consistent with results of early sampling of mineralized support pillars in the Kamariza workings, which often included lower grade sections of mineralization. According to Cordella (1869), this sampling gave results ranging from 35–60% lead and 1,200–3,500 ppm Ag/t Pb.

The narrow, shallow dipping and high grade Filoni 80 vein at Plaka was not discovered by the ancient

Sample	Location / deposit	Contact	Source	Pb (%)	Ag (ppm)	ppm Ag / t Pb
–	Daskalio-Dardeza	First	Marinos and Petrascheck (1956)	5[1]	–	1500[1]
–	Vromopoussi	First	Potier (1880)	22.5	–	750
–	Vromopoussi	First	Marinos and Petrascheck (1956)	8[2]	–	605[2]
–	Turkolimani	First	Potier (1880)	15	–	1200
–	Trachynkera	First	Potier (1880)	9	–	4000
–	Villia	First	Potier (1880)	12.7	–	900
A4	Plaka-North	First	Gale, et al. (1980)	68.7	350	509
A5	Plaka-North	First	Gale, et al. (1980)	31.4	200	637
A6	Plaka-North	First	Gale, et al. (1980)	59.5	310	521
S12	Sounion	First	Gale, et al. (1980)	86.3	500	579
B2	Plaka	First	Gale, et al. (1980)	38.0	1240	3263
B4	Plaka	First	Gale, et al. (1980)	43.0	720	1674
B5	Plaka	First	Gale, et al. (1980)	57.0	800	1404
PLK1/1	Filoni vein		Skarpelis (2007)	84.8	5537	6529
PLK1/2	Filoni vein		Skarpelis (2007)	82.6	4932	5971
PLK1/3	Filoni vein		Skarpelis (2007)	83.1	5754	6924
E7	Filoni vein		Gale, et al. (1980)	84.6	4400	5201
W110	Filoni vein		Gale, et al. (1980)	80.4	4760	5920
–	Kamariza	Third	Cordella (1869)	32[3]	–	3250[3]
_	Agrileza	Third	Marinos and Petrascheck (1956)	10	–	2500
D1	Kamariza	Third	Gale, et al. (1980)	22.1	790	3575
TG60A–1	Kamariza	Third	Gale, et al. (1980)	82.5	1900	2303
SUB1	Kamariza	Third	Skarpelis (2007)	82.1	2440	2972
SUB2	Kamariza	Third	Skarpelis (2007)	82.3	2606	3166
ILA3/1	Kamariza	Third	Skarpelis (2007)	81.6	2234	2738
Serp3/4	Kamariza	Third	Skarpelis (2007)	81.7	2375	2907
ILA4	Kamariza	Third	Skarpelis (2007)	82.1	2157	2627
SUB2	Kamariza	Third	Skarpelis (2007)	82.8	2453	2962
Serp3/3	Kamariza	Third	Skarpelis (2007)	82.3	2200	2673

Tab.1: Silver contents of Laurion mineralization. 1) Midpoint of range: 4–6% Pb; 1,000–2,000 ppm Ag/t Pb; 2) Midpoint of range: 7–9% Pb; 550–660 ppm Ag/t Pb; 3) Midpoint of range: 20–44% Pb; 3,000–3,500 ppm Ag/t Pb.

Greek miners. It is up to 2 m in thickness (Voudouris, et al., 2008a) and hosted mainly in the Kamariza schist hornfels, therefore it is neither first nor third contact. Five samples of almost pure galena from Gale, et al. (1980), and Skarpelis (2007), average 6061 ppm Ag/t Pb and 83.1% lead. According to Voudouris, et al. (2008a), galena from the Filoni 80 vein is rich in silver and contains small inclusions of silver sulphosalts, such as argentian tetrahedrite and miargyrite.

These small populations of available analyses for the first and third contacts are insufficient to draw firm conclusions. Nevertheless, they do indicate that third contact mineralization is much higher grade and provide a hint that this difference may originate in the primary mineralization, rather than result solely from stronger oxidation at the first contact. A curious feature of the available analytical results are the higher grades at Plaka and Filoni 80 vein. Both deposits are close to the Plaka granodiorite and the possibility that this intrusion may have influenced mineralization at the first contact is supported by the data of Fig. 11. It shows the distribution of anomalous concentrations of accessory non-sulfide minerals in first contact mineralization as recorded in the Mining Map of Marinos and Petrascheck (1956). Notable concentrations of fluorite, iron-manganese and iron ores occur near the extremities of the district, implying a more centralised source for the first contact mineralization. The anomalous concentrations of barite may appear closer in plan view, but they occur at significantly higher stratigraphic levels, in association with Pounta marble above the SAD.

The archaeological implications

The archaeological implications of the geological and geochemical data presented above, are best considered in the context of current archaeological knowledge about early mining at Laurion. Firstly, the oldest direct evidence is that from Mine 3 at Thorikos (Fig. 1), where pottery sherds were recovered from a thin, undisturbed clay covering of stone tool marks at the base of an exploited vein of mineralization, a few metres within the modern opening. These have been dated as late Early Helladic II (2200–2150 BC; Manning, 1995) by Spitaels (1984). The extensive investigations at Thorikos by the Belgian Archaeological School at Athens also recovered a few sherds of Neolithic and Early Bronze Age pottery associated with tool marks of stone hammers both outside the modern mine entrance and within the ancient underground gallery (Spitaels, 1984; Nazou, 2014; this vol.). Whilst these older sherds lacked precise stratigraphic context, they do indicate that mining may have commenced in the 4th millennium BC on oxidised mineralization exposed at the surface, before following the veins several meters into the hillside.

Secondly, there are three examples of indirect evidence for early mining at Laurion that support these early dates. The first are finds of litharges on the Mesogeia plain just to the north of the Laurion district which have been dated to the Early Helladic period (c. 3100–2650 BC) at Lambrika, and those dated to the middle of the 4th millennium BC at Merenda (Kakavogianni, et al., this vol.). It is not surprising that these metallurgical finds may be the only evidence of

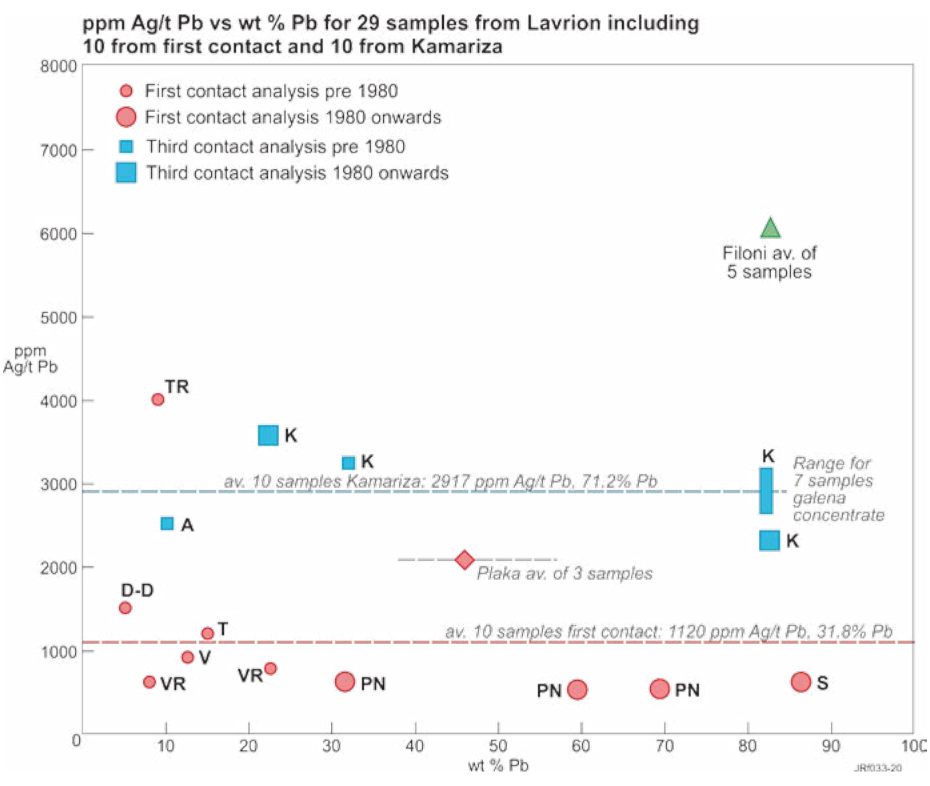


Fig. 10: Plot of wt.% Pb versus ppm Ag/t Pb for 29 published analyses from the first and third contact mineralization, and the Filoni 80 vein, at Laurion. Data includes analyses derived from 19th century publications and Marinos and Petrascheck (1956), in addition to "modern" analyses published from 1980 onwards (preparation: by J. Ross).

very early mining activities, because the reworkings of the Laurion landscape and metallurgical residues that occurred from the Classical period onwards, including the modern period, are likely to have swept up and reprocessed any older residues containing silver and lead.

The second indirect evidence are copper slags from the Early Helladic II (c. 2650–2200 BC) found at the coastal site of Raphina, located about 20 km north of the Laurion district. They have a lead isotope signature consistent with a Laurion source (Gale, et al., 2009). The third example are lead isotope data of silver, lead and copper artefacts found on mainland Greece and the Aegean islands. These results extend from the Final Neolithic silver and copper artefacts discovered in the Alepotrypa cave (Gale and Stos-Gale, 2008) through the silver, copper and lead artefacts of the Bronze Age (Gale and Stos-Gale, 2008; Kayafa, 2020; Ross and Kayafa, forthcoming). They are far too numerous to ignore in any assessment of the mining history of the Laurion district.

Laurion also had significant resources of iron ore within hematitic gossans, which were exported to Europe during the modern mining era. According to Marinos and Petrascheck (1956), about 1.5 million tons of iron ore were exported between 1864 and 1950 (sourced from Argyropoulos, 1955). With such resources available within an established mining district it seems unlikely that some iron was not sourced from readily available surface deposits to provide tools for mining, agriculture, and weapons during the first millennium. However, besides ample evidence for iron smithing (Photos-Jones and Jones, 1994, p.355) so far no evidence for iron smelting in the Classical or Hellenistic period was ever recorded from Laurion, but only from Late Antiquity (Varoufakis, 2014).

In a series of papers Conophagos and Papadimitriou (1981) concluded that iron and steel clamps used at the Erechtheion were sourced from Laurion iron. They also suggested that a local iron industry at Laurion would have produced the essential iron tools, used by the ancient miners in the Classical period. Iron hammers and high purity, tempered chisels and picks (Ardaillon, 1897) must have been a key factor in the sinking of numerous shafts to access and ventilate mining of the third contact. Varoufakis

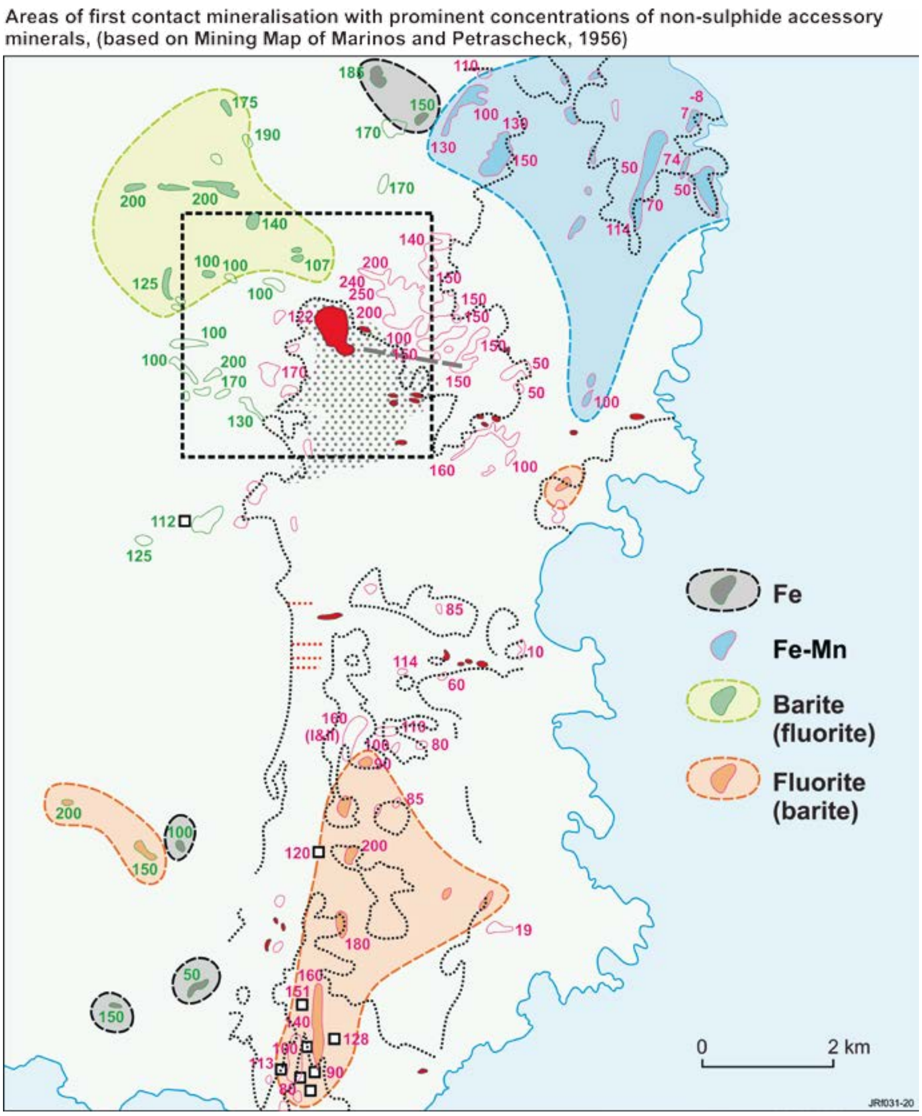


Fig. 11: Plan of first contact mineralization within the Laurion district highlighting those occurrences with anomalous concentrations of accessory minerals of iron, iron and manganese, fluorite, and barite. Base map is from Fig. 4A and information was compiled from annotations on the Mining Map of Marinos and Petrascheck (1956) (preparation: by J. Ross).

(2014), provided compelling evidence that smelted iron ore had been sourced from Laurion, based on analyses associated with a Late Roman furnace at Thorikos.

The gradually mounting archaeological evidence associated with the Laurion district encourages the conclusion that surface mining and processing commenced no later than the 4th millennium BC and continued, albeit intermittently at times, until the Christian era. Early mining was most likely focussed on silver and copper, with lead as a by-product from either reduction of argentiferous litharge, or as a commodity when the silver content was insufficient to justify cupellation (Stos-Gale and Gale, 1982). Secondary lead minerals would have been common within oxidised first contact mineralization and, when they had insufficient silver to justify cupellation, it was an opportunity to produce lead and generate additional income. This possibility is supported by the lead isotope data which indicates that Laurion was the principal source for Aegean lead artefacts during much of the Bronze age (Gale and Stos-Gale, 2008; Kayafa, in prep.; Ross and Kayafa, forthcoming).

The geology and geochemistry of the Laurion mineralization has significant potential to advance our understanding of the archaeology of the district and its mining history. Of most significance is the contrasting character of the mineralization at the first and the third contact. Whilst they share essentially the same primary mineralogy, the former is more widespread, thinner, less continuous, and lower grade, at least in most areas mined by the ancient Greeks. Stronger oxidation of the outcropping and shallow first contact mineralization amplified its difference from the third contact and contributed to its lower grade. Systematic exploitation of first contact mineralization would have often been difficult because of variable oxidation (Fig. 5A, B) and its irregularity. Therefore, it is likely that much of the mining was focussed on seeking out patches of residual galena (see Fig. 9), and cerussite and anglesite, with mineable concentrations of copper oxides being a welcome bonus.

This interpretation of the first contact mineralization at Laurion is in sharp contrast to the character and form of that at the third contact, which comes to us from 19th century records and maps of the main Kamariza area. They describe thick lenses of mineralization up to 1,500 m long, 11 m thick and ranging from 30–50 m wide. These continuous lenses of less oxidised mineralization enabled systematic mining at much higher production rates and they must have been bonanzas for the ancient Greek miners. Their discovery would have left an indelible mark on the mining history of Laurion, particularly when placed in the context of a long preceding period of mining less profitable first contact deposits.

Initial exploitation of the Kamariza deposits, and the resultant surge in silver production, would have been an exceptional event in the history of Laurion and ancient Athens. Undoubtedly, there is a strong case for linking their discovery and initial development to the account by Herodotus (*7.144*) of a windfall surplus to Athens from the mines at Laurion, and the dating of this event to 483/2, by Aristotle (*Ath. Pol. 22.7*). Systematic exploitation of these thick, rich Kamariza lenses after 480 BC would have provided an almost continuous flow of wealth to the city and its residents for much of the 5th century BC and underpinned the dominance of the Athenian owl in Aegean commerce and trade.

Conclusions

This reassessment of the mining history of the extensive lead-zinc-copper-silver deposits of the Laurion district integrates the observations of scholars and mining professionals in the 19th century, when much of the evidence of ancient mining and processing was still preserved, with the substantial body of more recent geological and archaeological research at Laurion and adjacent areas. The most significant outcome is the contrasting character of mineralization at the first and third contacts.

The first contact mineralization is more widespread, thinner, less continuous, and lower grade, at least in the areas mined by the ancient Greeks. Oxidation of the outcropping and shallow first contact mineralization amplified its difference from the third contact and contributed to its lower silver grade. It is likely that oxidation also favoured mining of secondary copper and led to significant production of copper at Laurion during the first 3,000 years, as noted by Gale, et al. (2009) and shown by Ross and Kayafa (forthcoming).

Third contact mineralization at Laurion, as represented by the core area of Kamariza, was higher grade, thicker and more continuous. These lenses of less oxidised mineralization were bonanza zones, when compared with the first contact, and their discovery would have left an indelible mark on the mining history of Laurion. The contrast between first and third contact mineralization is sufficiently strong to closely link discovery of the latter with the windfall surplus received by Athens, according to Herodotus, and dated to 483/2 BC by Aristotle.

Before that momentous discovery, mining must have been focussed on the numerous, small, discontinuous and lower grade deposits in the district. During that period the economics of mining were probably assisted by opportunistic extraction of secondary copper and production of lead. It is likely that iron became another by-product at Laurion in the first millennium, a development that provided the essential tools for shaft sinking and may have enabled the discovery of the Kamariza deposits.

The different character of first and third contact mineralization determined their different capacities to produce silver. At the first contact the numerous small deposits spread throughout the district favoured small scale, individual mining operations. Aggregate silver production may have been significant, but it is likely to have fluctuated. In contrast, the much larger third contact deposits at Kamariza were concentrated in a relatively small area and their character favoured relatively large scale, systematic, and continuous mining and processing operations. These operations would have been capable of providing a substantial and continuous output of the silver that first transformed the mining history of Laurion and then, inevitably, assisted the transformation of Athens.

Notes

1 When the recovery of silver depends on prior concentration of a particular host mineral (in this case galena) then the silver value of any area of mineralization is determined by both its Pb content (with galena the dominant source of Pb and silver at Lavrion), and the silver content of that Pb (which can vary considerably). Silver-rich galena in an area of mineralization with relatively low galena content may be equally valuable to mine and concentrate as another area of higher galena content but lower silver. For this reason, the 19th and 20th century authors who studied the Laurion mines used grade (g Ag/t Pb) rather than ppm when discussing the operations and treatment processes. We also prefer to adopt this convention because it tells us something about the ancient economics of mining at Lavrion and the relative values of the shallower and deeper ores, which are fundamental aims of our work. Nevertheless, the ppm Ag data is included in Table 1 for comparison.

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Mapping the shafts of Laurion – Contribution to a new geological stratigraphy

ABSTRACT: *The mining territory of Laurion in Attica-Greece comprises a great number of shafts constructed since antiquity in order to exploit the silver bearing ore deposits. These vertical constructions have presumably served a multipurpose role as artificial conduits for uplifting the extracted material, exploration shafts as well as ventilation chimneys. They are situated in an area of 70 km² and their depth varies from a few meters to over 100 m. The different contacts of the Laurion rock sequences, where the ore mineralization was deposited, are visible in the majority of the shafts. The main extracted minerals found in the primary and oxidized carbonate replacement deposits are galena, cerussite and anglesite. The ore mineralization is hosted in mantos and chimneys clearly visible in the shaft's interior.*

This study presents the results of the "Laurion Shafts Project" that took place during 2018 with its primary objective the description of the stratigraphy in selected mining shafts at Laurion. During the research, 284 mining shafts were located, and 10 of them were speleologically explored and topographically mapped with the use of the laser meter Disto-X2. Geological mapping was also performed at the inner part of the selected shafts. The gained stratigraphic data provide enough information for a general stratigraphic column and will contribute to the future construction of a 3D geological model of the Laurion mining district.

KEYWORDS: MINING, ORE MINERALIZATION, DISTO-X2 MAPPING, SILVER

Introduction

Laurion constitutes the most famous mining and metallurgical site in Greece. The mining area of about 70 km² comprises numerous horizontal mines, vertical mining shafts, and metallurgical installations such as cisterns, washeries and furnaces. Mining for metals and intense metallurgical activity at the southeastern part of Attica are recorded since prehistoric times (Conophagos, 1980; Kakavogianni, et al., 2008). According to ancient writers (Herodotus, 7.144; Thucydides, 2.55; Strabo, 9.1.23) and published data by modern researchers (Cordella, 1869; Ardaillon, 1897; Conophagos, 1980) silver was the main extracted metal, while lead and iron were also exploited providing remarkable revenue to the Athenian polis. Copper was also extracted from Laurion ores as shown by lead isotope results of Bronze Age artifacts (McGeehan-Liritzis and Gale, 1988; Gale, et al., 2007; Asderaki, et al., 2017).

There have been several attempts to map the entrances and interiors of shafts (Cordella, 1869; Ardaillon, 1897; Marinos and Petrascheck, 1956; Conophagos, 1980; Kakavoyannis and Koursoumis, 2013; Morin, et al., 2012). According to Conophagos (1980), the vertical shafts were mainly used as ventilation chimneys, for exploration to define the limits of the ore and to bring mined ore to the surface. Cordella (1869) claims that their depth varies from a few meters to 110 m while their number is generally assumed to be over 1,000.

Most of the modern vertical shafts represent ancient shafts enlarged and deepened by modern exploitation carried out in the late 19th and 20th century. Serpieri-1 shaft in the core of Kamariza mining territory was described as an ancient shaft with a depth of 66 m when the French Mining Company enlarged and deepened it to 170 m during the 19th century (Cordella, 1869; Marinos and Petrascheck, 1956). The few comprehensive studies that have been carried out at the mines and shaft interiors have left a number of questions unanswered. For example, the use of the remarkably constructed twin shafts remains indeterminable. However, recent studies do provide answers to air circulation dynamics at the area of Spitharopoussi where ancient mining shafts have depths between 25 m and 105 m (Morin, et al., 2012).

The present study introduces a detailed stratigraphic view of the Laurion mining district based on surface survey and thorough study of several vertical mining shafts. The emphasis of this investigation was on the geological features of the shafts and not their technical characteristics or their archaeological contribution. A complete up-to-date recording of the shafts stratigraphy will be integrated in a future 3D geological model of the Laurion mining district.

Geological setting

The Laurion area is located in the northwestern part of the Attic-Cycladic Metamorphic Complex. Oligocene-Miocene extension in Aegean caused the exhumation of several metamorphic units (Altherr, et al., 1982; Okrusch and Bröcker, 1990; Avigad and Garfunkel, 1991; Jolivet, et al., 2004a; 2004b). The stack of metamorphic nappes in the Laurion peninsula is dominated by the Laurion schist, and Mavrovouni and Pounta marble at the top (Fig. 1), which overlie the Kamariza Unit (Lekkas, et al., 2011). These two units are separated by the South Attica detachment fault (Lekkas, et al., 2011), which represents the northern

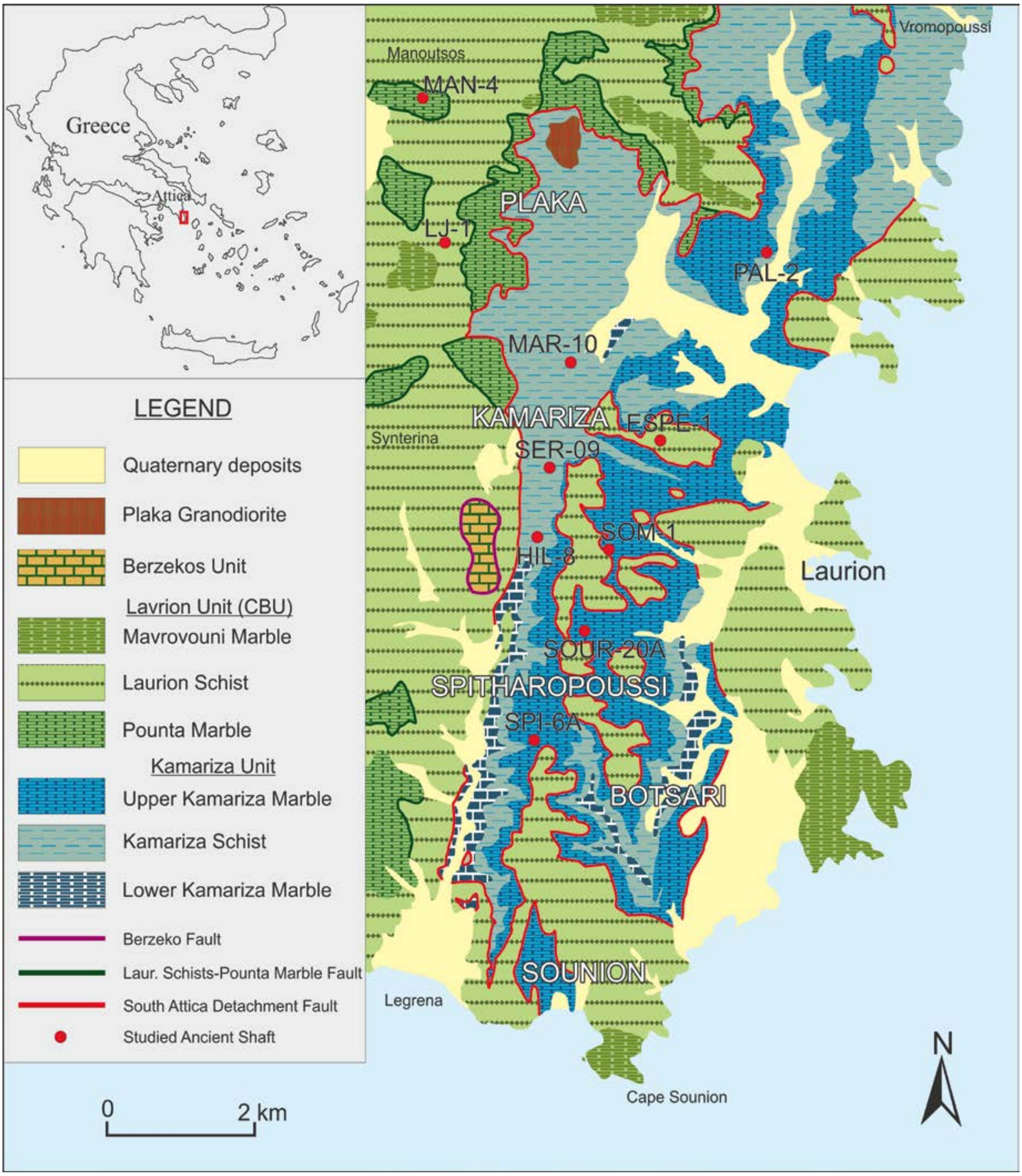

Fig. 1: Geologic map of the Lavreotiki area in Greece (illustration modified from Lekkas, et al., 2011).

extremity of the Western Cycladic Detachment system in the Laurion area (Berger, et al., 2013; Scheffer, et al., 2017; 2019).

The Kamariza unit comprises three different lithological facies; the ultramylonitic Upper Kamariza marble, the Kamariza schist and the Lower Kamariza marble (Fig. 1). These rock series used to be referred as the “autochthonous” tectonic unit (Lepsius, 1893; Kober, 1929; Marinos and Petrascheck, 1956; Photiades and Carras, 2001) or “para-autochthonous” (Scheffer, et al., 2016; Coleman, et al., 2019). The Kamariza schist and the Laurion schists are often referred by Laurion researchers as lower (Kaesariani) and upper schists respectively (Marinos and Petrascheck, 1956).

The Laurion schist and Pounta marble form the dominant outcrops immediately west of the South Attica detachment fault (Fig. 1). To the east of the detachment the Upper Kamariza marble consists of white to blue-gray ultramylonitic marble. The Kamariza micaschists are generally dark (graphitic) and contain marble intercalations. Their thickness ranges between a few meters in the south and southeast to 300 m or more in the north (Marinos and Petrascheck, 1956). The Lower Kamariza marble thickness reaches ≥150 m (Lekkas, et al., 2011).

In Plaka a more or less undeformed granodiorite intrusion is exposed (Marinos and Petrascheck, 1956), and appears to have been emplaced during the last stage of the Miocene extensional detachment faulting. The granodiorite is of late Miocene age (8.34± 0.20 Ma, Liati, Skarpelis and Pe-Piper, 2009).

The Laurion mineralization includes a variety of ore types such as carbonate replacement, vein-type, skarn and porphyry ores (Marinos and Petrascheck, 1956; Economou, et al., 1981; Skarpelis, 2002; 2007; Voudouris and Economou-Eliopoulos, 2003; Solomos, et al., 2004; Voudouris, 2005; Voudouris, et al., 2008a; 2008b; Bonsall, et al., 2011; Scheffer, et al., 2017; 2019). Carbonate-replacement mineralisation by Pb-Zn-Ag±Au deposition is mainly localized at the interfaces between the Lower Kamariza marble, the Kamariza schist, the Upper Kamariza marble, the Laurion schist and the Pounta marble, and in the form of carbonate replacement ore bodies (e.g. mantos and chimneys). The South Attica Detachment fault was active in mylonitic to cataclastic tectonic conditions, accommodated exhumation of metamorphic unit under syn- to post-orogenic conditions and also facilitated enhanced hydrothermal fluid circulation and ore deposition (Berger, et al., 2013; Scheffer, et al., 2017; 2019).

Materials and methods

The surveyed area is situated at south-eastern Attica from Legrena bay and Sounion cape in the south to Vromopoussi and Manoutsos areas in the north (Fig. 1). An area of almost 70 km^2 was explored, which represents the ancient Laurion mining territory. Sparse mining works found outside this area were not included in this study. Shaft entrances were located in the field from April to December 2018 based on international bibliographies, personal archives, local informers and the maps of the French Mining Company (CFML). All geographic information on shafts was verified in the field. The in situ research included recording of each shaft's entrance geographical features, dimensions of the opening, its depth where possible and detailed geological mapping of the adjacent area.

From this initial group of 284 shafts, ten mining shafts were selected and speleologically explored and mapped. A laser meter Disto-X2 was used for topographical mapping of the shaft interiors. Each shaft was then geologically mapped to establish the different stratigraphy intersected, any evidence of mineralization and tectonic features.

Results

During the survey 284 vertical shafts were located: 137 are situated in the Kamariza area, 21 in Plaka, 41 in Botsari, 51 in Spitharopoussi and 34 in Sounion. It is important to note that the borders of each of these areas are not well defined. Regarding the geological features of each shaft entrance, six of them are opened in the Pounta marble, 25 in the Laurion schist, 141 in the Upper Kamariza marble, 100 in the Kamariza schist and twelve in the Lower Kamariza marble. The majority of the shafts recorded explore the well-known “third contact” with 146 shafts reaching the Kamariza schist and the Lower Kamariza marble. The contact between the Upper Kamariza marble and the Kamariza schist (second contact) has been explored by 133 shafts. The contact of the Upper Kamariza marble and the overlying formations (Pounta Marble/Laurion schist) has been considered as the “first contact”. This contact was explored by 31 shafts. Several shafts cross both the second and third contacts.

The selection of the ten shafts for further research was made according to their spatial separation, depth and safety. The deepest shafts were selected to include more stratigraphical units, but in most cases mining debris, collapsed material, or even garbage at the bottom of the shafts made it impossible to map their full depth. The depth of mapping varied from 21 to 93 m and the results are shown in Figs. 1 and 2. The results are described below from North to South of the mining area.

The Manoutsos-4 shaft

The Manoutsos hill is situated at Ari in the northwestern Lavreotiki covering almost 0.6 km^2. It hosts eleven horizontal mines and five vertical shafts. Manoutsos-4 ancient shaft (MAN-4) has a depth of 46.5 m (Fig. 2) with its entrance lying on the north slope of the hill at an altitude of 167 m. Notches at both sides of the shaft's walls imply internal partitioning (Fig. 3a). At the depth of 22 m the shaft becomes narrower. This vertical shaft is entirely constructed within Pounta marble. Oxidized vein mineralization, mainly goethite, is observed in the marbles at the shaft's walls. At depths of 11.7 m and 29.6 m respectively, ancient horizontal drives follow the mineralization in the Pounta marble. Most of the walls of these horizontal galleries are covered with calcitic crust and speleothems.

The Louis Joseph shaft

At the area of Dimoliaki numerous water cisterns and other metallurgical remains are found. The Louis Joseph (LJ) shaft is located near the road leading from Synterina to the Manoutsos area (Fig. 1). Ardaillon (1897), included this shaft in his map of the ancient mine of Dimoliaki. This mine is described as a network of horizontal galleries with two vertical shafts at its southwest edge, named Louis-Joseph and Jupiter and two vertical shafts at its Northeast edge named No 3 and No 4. Ardaillon's map is very detailed, providing altitudes of the shaft entrances and the galleries. During fieldwork in the area only the shafts Louis Joseph and No 3 were discovered, but the latter had partly collapsed and its walls were unstable. Exploration and research were therefore carried out in the Louis-Joseph shaft.

According to Ardaillon (1897), the altitude of the Louis Joseph shaft entrance is 182.10 m and the altitude of the horizontal gallery at its bottom is 154.62 m. The resulting depth of the shaft is 27.48 m. Our exploration and mapping of this shaft showed that it has been enlarged by modern exploitation since the time of Ardaillon. The current depth of the shaft is 28.5 m and the modern dimensions of the entrance are 1.5 x 2.8 m. It has been opened in Pounta marble and crosses the contact between the overlying Laurion schist and the Pounta marble (Fig. 3b) at the depth

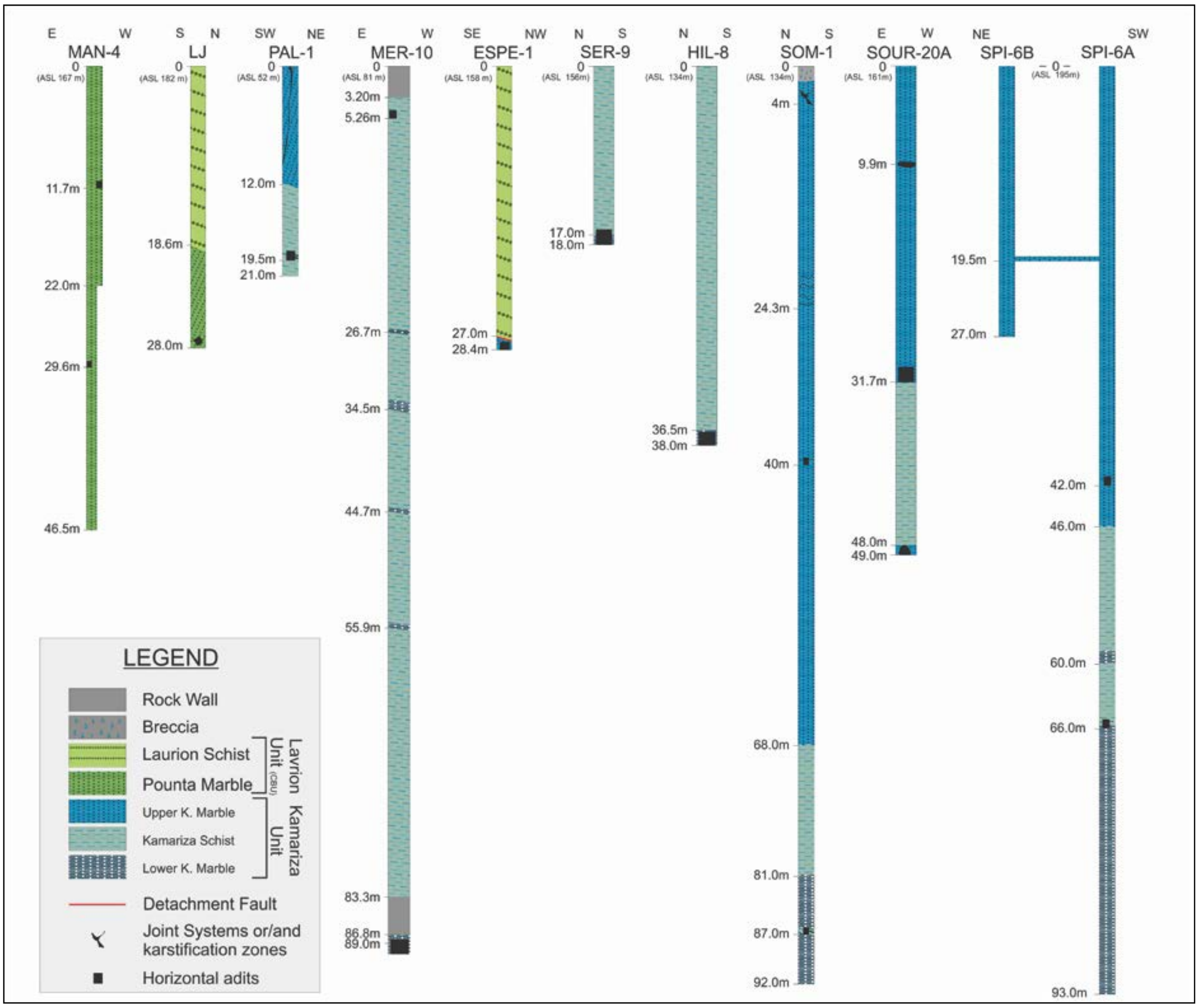

Fig. 2: Stratigraphic columns of the ancient shafts mapped during the "Laurion Shafts Project". From left to right depicted the shafts Manoutsos-4 (MAN-4), Louis Joseph (LJ), Palaeokamariza-1 (PAL-1), Mercati-10 (MER-10), Esperanza-1 (ESPE-1), Serpieri-9 (SER-9), Hilarion-8 (HIL-8), Sommet-1 (SOM-1), Soureza-20A (SOUR-20A), twin shafts of Spitharopoussi-6 (SPI-6A and SPI-6B).

of 18.6 m. The stratigraphic dip is north at 20-30°. The oxidized mineralization occurs at the contact of Pounta marble and Laurion schist, forming a zone with a mean thickness of 5m below the contact. Goethite, limonite, hematite and other iron oxides and hydroxides are the main minerals of the supergene ore. Most sulfides have been weathered, apart from rare occurrences of galena found in small carbonate-replacement deposits.

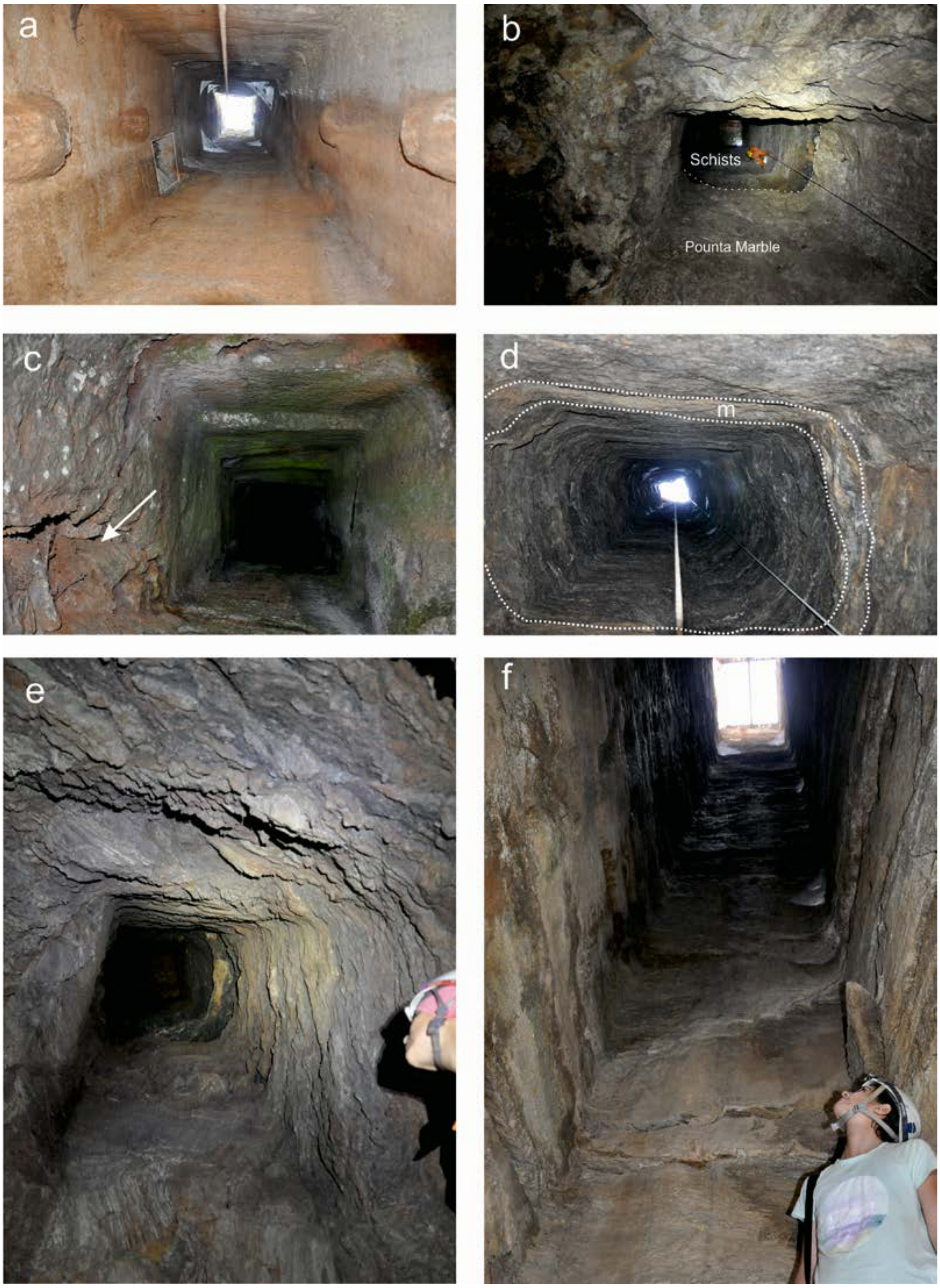

Fig. 3: a. View from the internal part of the MAN-4 shaft. Notches at both sides of the shaft's walls and the position of the horizontal openings imply an internal partitioning. – b. The contact between the Laurion Schist and the Pounta Marble at the depth of 18.6 m. – c. The NNE-SSW joint system was followed by the miners in the construction of the PAL-1 ancient shaft. – d. Marble intercalations (m) in the walls of the shaft MER-10. – e. The inner part of the vertical shaft ESPE-1. f. View from SER-9 shaft's bottom. (Photos: Markos Vaxevanopoulos).

The Palaeokamariza-1 shaft

At the area of Palaeokamariza two shafts PAL-1 and PAL-2 were discovered and PAL-1 with a total depth of 21 m was geologically mapped. The entrance is located in the Upper Kamariza marble characterized by a NNE-SSW karstic joint system explored by the miners (Fig. 3c). The transition from marbles to Kamariza schist (the second contact) is located at 12 m where no mineralization is recorded, while at the depth of 19.5 m a small horizontal gallery has been opened in the schist. Minor mineralization is hosted in the sparse joints of the schist with goethite, limonite and malachite being the main minerals observed in the walls of the gallery. An oil lamp of the Classical period was found at the end of this gallery and was delivered to the Ephorate of Antiquities of east Attica.

Mercati-10 shaft

The Mercati-10 shaft (MER-10) is located 980 m northeast of the Kamariza village. It is 89 m deep and has been opened in the Kamariza schist. At the depth of 5.26 m two small galleries in the schists were mapped. Many marble intercalations were recorded in the walls (Fig. 3d). The contact of the schists and the Lower Kamariza marble (the third contact) is situated at 86.8 m. A large amount of garbage has closed passages to the horizontal network of galleries at the third contact, and the access was limited via narrow fissures. The modern horizontal galleries have enlarged the ancient workings and are characterized by oxidized mineralization, consisting mainly of iron oxide-hydroxide minerals.

The Esperanza-1 shaft

The Esperanza-01 mine (often mentioned as Esperance or Esperantza) is located 2 km northwest of the town of Laurion. It constitutes one of the most representative examples of mining works with over 2,000 m horizontal galleries at the first contact. Two horizontal entrances have been discovered and another collapsed horizontal entrance was revealed during the detailed mapping. The bottom of a 27 m vertical shaft was located at the inner part of the mine (Fig. 3e). Whilst the entrance of the shaft is closed with a big plate of schist, it was located at the surface only with the assistance of the 3D mapping of the mine.

Ancient mining in Esperanza focused in silver-bearing mineralization (galena, cerussite, anglesite). Numerous exploitation phases have been recorded at the inner part of the horizontal mining system. The first exploitation phase has confirmed dates to the 5th century BC and diachronic use is assumed until the 19th century.

The Serpieri-09 shaft

The Serpieri-09 (SER-9) shaft is located very close to the horizontal entrance of the mine named “Paron”. The depth of the shaft is 17 m and it was opened in the Kamariza schist. The contact between schists and Lower Kamariza marble (the third contact) is recorded at the bottom of the shaft (Fig. 3f). The Serpieri-09 shaft is connected to the network of modern horizontal galleries attached to the “Paron” entrance. The mineralization is partly oxidized and characterized by the presence of goethite, galena, cerussite, fluorite and ankerite.

The Hilarion-8 shaft

The ancient shaft Hilarion-8 (HIL-8) is located 980 m south of the Kamariza village. A strong wind current comes out of this shaft implying an extensive horizontal network. The entrance (1.2 × 1.3 m) has been opened in Kamariza Schist and its depth is 38.0 m. The shaft's width varies from 1.2 to 1.4 m and its cross section is progressively rotated clockwise with increasing depth (Fig. 4a). Thin calcareous crust covers the walls and is more concentrated at depths of 18.5–22.0 m. The contact between the Kamariza schist and the Lower Kamariza marble is at 36.5 m. The marble is banded with white to gray colour. At the bottom of the shaft a modern extended network has enlarged the ancient galleries (Fig. 4b). The main minerals observed are goethite, cerussite and sparse malachite.

The Sommet-1 shaft

In the Elafos area two shafts named Sommet-1 and Sommet-2 are recorded in the maps of the French Mining Company of Laurion. The abbreviations SOM-1 and SOM-2 are used respectively in the present study's maps. The ancient shaft SOM-1 was sunk in the ultramylonitic Upper Kamariza marble and it has been intensively explored and mapped to a depth of 92 m. Marble debris, confined by a modern drystone wall, characterizes the first 2 m of the shaft. From 2.0 to 4.0 m a karstic zone occurs. At depth between 21.0 and 24.3 m the marbles are sheared with iron oxides in the voids. At a depth of 40 m an unfinished gallery in the marbles has been recorded (Fig. 4c). The contact of marble and Kamariza schist is located at a depth of 68.0 m with minor mineralization hosted in small joints. The Lower Kamariza marble is intersected at 81 m, however, a lens of schist with a mean thickness of 0.9 m is intersected at 86.1 m within the marble. At this level, the four sides of the shaft have been exploited in antiquity with horizontal openings. Curved traces of chisel are observed at the corners of the ancient shaft, whereas cylindrical holes evincing modern exploitation

Fig. 4: a. HIL-8 twisted cross-section. – b. Contact between Kamariza Schist and Lower Kamariza Marble at the HIL-8 horizontal part. Carbonate replacement deposition is depicted. – c. Unfinished gallery at the depth of 40 m in the SOM-1 shaft. – d. The lowermost part of the SOM-1 shaft at the contact of Kamariza Schist and Lower Kamariza Marble. Ancient curved traces of chisel are observed at the corner of the shaft (black arrow), whereas cylindrical holes from modern exploitation are also found (white arrow). – e. The entrance of the SOU-20A shaft. – f. Modern galleries enlarged ancient works at the depth of 31.7 m in the SOU-20A shaft. – g. Void at the intersection of two distinct tectonic joints of the Upper Kamariza Marble at the inner part of the SPI-6A shaft. The void is filled with iron oxides mainly goethite. – h. Kamariza Schist-Lower Kamariza Marble contact crosscut by small subvertical faults in the SPI-6A shaft. (Photos: Markos Vaxevanopoulos).

are also found (Fig. 4d). A modern horizontal mine has enlarged previous ancient workings. Numerous layers of mineralization up to 1 cm in width are recorded along the contact of the schist lens and the Lower Kamariza marble at the bottom of the shaft. The main minerals are goethite, cerussite, galena, fluorite and ankerite.

The Soureza-20A shaft

Soureza-20A shaft (SOU-20A) is situated 2.8 km southwest of Laurion town and is 49 m deep. Its twin shaft SOU-20B is located 4.9 m north and is 5.6 m deep. Two different phases of construction can be seen in the entrance of the shaft SOU-20A (Fig. 4e), which may be connected to the existence of a natural karstic cave at 9.9 m. At a depth of 31.7 m a horizontal development is located (Fig. 4f) with exploited mineralization along the contact between the ultramylonitic Upper Kamariza marble and Kamariza schist. Modern horizontal adits have enlarged ancient workings. At the depth of 48 m the contact of the Kamariza schist and the Lower Kamariza marble is observed. Ancient development at this contact has also been enlarged by modern mining activity, which follows the mineralization in the Lower Kamariza marble beneath the schists. Several lenses of oxidized ore are found in the horizontal parts of the mine. The mineralization at both contacts consists of goethite, galena, cerussite, while ankerite and fluorite are also found as gangue minerals.

The Spitharopoussi-6A shaft

SPI-6A and SPI-6B are known as twin shafts and are located at the Spitharopoussi area (Conophagos, 1980; Morin, et al., 2012). Their entrances lie in the ultramylonitic Upper Kamariza marble. Small veins filled with iron-oxides and -hydroxides, such as goethite/limonite and hematite, crosscut the main foliation of the Upper Kamariza marble in both shafts. Small pods of mineralization are formed in the intersections of the veins with the marble foliation (Fig. 4g). The shaft SPI-6B is entirely constructed in the upper marbles. It has a depth of 27 m and connects with SPI-6A via a narrow passage at 19.5 m. Shaft SPI-6A has a total depth of 93 m and intersects the Kamariza Schist at 46 m and the Lower Kamariza Marble at a depth of 66 m. An unfinished horizontal adit is located at the depth of 42 m and a lens of marble occurs within the schists from 58.6 to 60 m. Mineralization was recorded at the second contact at 66 m where a small horizontal gallery is located. This contact is crosscut by subvertical normal faults (Fig. 4h).

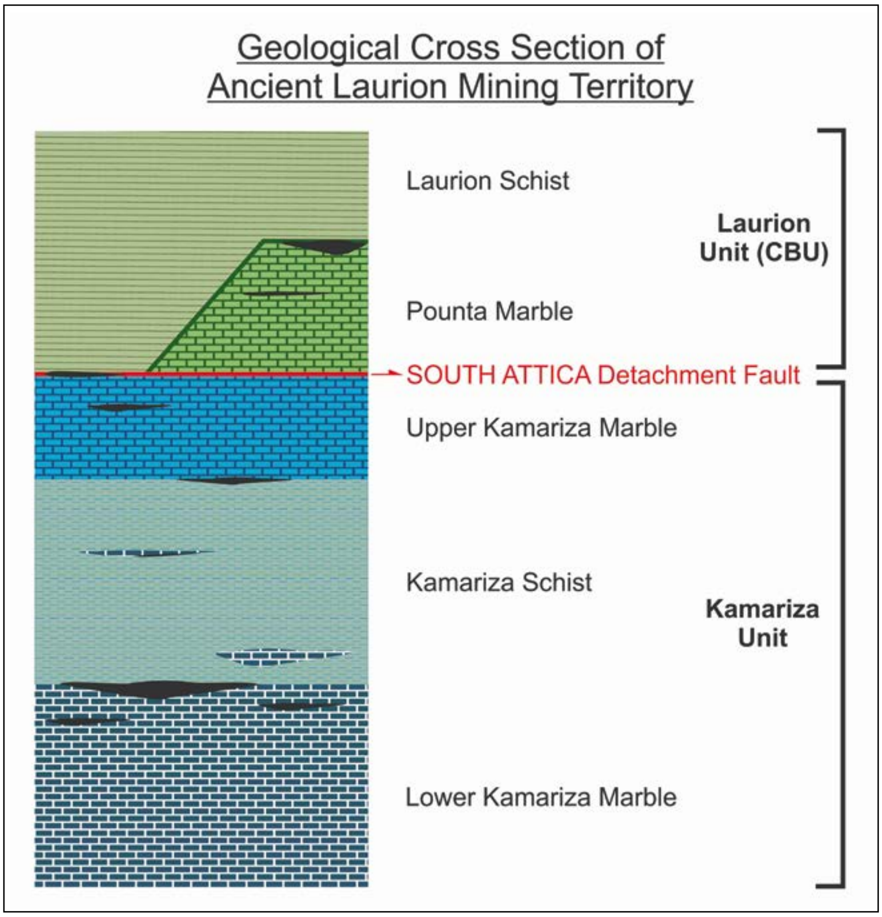

Fig. 5. Generalized stratigraphic column of the ancient Laurion mining territory. Mineralization zones are noted with black color (illustration modified from Lekkas, et al., 2011).

Stratigraphic column

The stratigraphic data gained through the mapping of the Laurion shafts (Fig. 2) are in accordance with those presented by Lekkas, et al. (2011), in the indicative stratigraphic column of the ancient Laurion mining district in Fig. 5. The Laurion Unit schists lie at the top of the stratigraphy of the mining area and directly on Pounta marble or on the formations of the Kamariza Unit. Pounta marble also overlies the Kamariza lithological units. The South Attica Detachment fault constitutes the tectonic contact among the overlying formations and Kamariza Unit. The ultramylonitic Upper Kamariza marble underlies the South Attica Detachment fault. Kamariza schist lies between the Upper and Lower Kamariza marble and includes numerous marble intercalations. The number and dimensions of these marble intercalations increase at the contact with the underlying Lower Kamariza marble.

Ore mineralization occurs in or near the contacts of the lithological units. The marble intercalations in the Kamariza schist present minor mineralization. Carbonate-replacement and vein-type mineralization, mostly oxidized, is found in the marbles.

Conclusions

During the "Laurion Shafts Project" 284 ancient shafts were located during an extended survey within an area of about 70 km^2.

The results show that most shaft entrances were opened in the ultramylonitic Upper Kamariza marble (141 shafts) and the Kamariza schists (100 shafts) to access or explore the contacts of the Upper Kamariza marble-Kamariza schist (second contact) and Kamariza schist-Lower Kamariza marble (third contact). Ten of these shafts were selected on the basis of spatial distribution, depth and safety, before being surveyed and geologically mapped.

The stratigraphic data gained from mapping these shafts is in accordance with those presented by Lekkas, et al. (2011). In addition, they clearly show that in general, the richest mineralization is hosted at the lithological contacts of five different lithological units, the Laurion shist, the Pounta marble, the Upper Kamariza marble, the Kamariza schist and the Lower Kamariza marble. This mapping also showed that the barren or weakly mineralized second contact was often crossed by the ancient miners in their effort to reach the more promising third contact, as for example at the shafts SOM-1 and SPI-6A. Apart from exploring these contacts, ancient miners appear to have also prospected underground by following mineralized joint systems, marble intercalations in schist and in karstic voids in marbles as shown in PAL-1, MAN-4 and SOM-1 shafts.

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Keratea, Attica: Early Helladic silver-lead metallurgy and its pottery context

ABSTRACT: *At Zapani at Keratea region, Attica three Early Helladic sites were excavated in 2006 – 2008 during the construction works of the new Industrial Area of Keratea. All three sites yielded litharge items. The preliminary study of the pottery indicates that habitation started in EH I, but the main bulk of it dates to the EH II phase.*

The density that the litharge items presented at Site 1 is only comparable to their density at the EH I Lambrika cupellation workshop. Although no installations similar to those at Lambrika were found, the site should be connected to silver production. Site 2 was most probably an area for open-air communal activities comprising eating and drinking and Site 3 was a settlement area. The presence of litharge items on these latter sites is compared to this in other EH settlements in the Mesogeia plain. The distribution of the sites which yielded litharge items in east Attica implies that silver-lead metallurgy developed on a peripheral pattern around the mining area of Lavreotiki.

KEYWORDS: LITHARGE, CUPELLATION, LAVRION, LAMBRIKA WORKSHOP

Introduction

At the area Zapani in the region of Keratea (Fig. 1), rescue excavations were conducted in 2006 – 2008 due to the development of the new Industrial Area of Keratea (IAK). At the east part of the IAK three Early Helladic sites were excavated (Fig. 2).

Site 1 lies on the north-northeast slope of a hill 147 m high, just below the flat top. It was discovered during the construction of street B25 around the hill (Ανδρίκου, 2007, pp.206 – 208, figs.159 – 163). *Site 2* is located in the plain (124 m) at a distance of about 350 m southwest of Site 1 and was discovered during the construction of a water pipe along street B20 (Ανδρίκου, 2007, p.208). *Site 3* lies at the foot of the hill (135 m) south of Site 1 and approximately at equal distance (200 – 250 m) from Sites 1 and 2. The excavation was very extensive since it just preceded the construction of an industrial building. In an area of around 300 m^2 (Fig. 3), remains of a settlement were excavated. A sunken floor of at least one hut and auxiliary spaces around it and a pair of storage pits with stone-built mouths were discovered. In Site 3 fourteen specimens of litharges have been found in the area around the hut and twenty more were discovered further to the southwest in the area of the LH III settlement. The study of this site has not yet processed (Ανδρίκου, 2010, pp.181 – 182, figs.118 – 119). Emphasis has been placed on the study of Sites 1 and 2. Special attention was paid on the silver and lead metallurgy, since at Site 2 two hundred fifteen litharge specimens and Site 1 more than 700 pieces were found. The number of litharge specimens from Site 1 can only be compared to the nearly 1,400 pieces from the Lambrika workshop.

Site 1

Site 1 was found during the construction of street B25, just below the surface. It was a trench of 10 or 5 m wide, around and below the top of the hill. The length of the site, approximately on east-west axis was 95 m, but its width remains unknown. Under the dark brown earth of the surface layer most of the site was covered by more or less extended heaps of stones. Below these heaps the architectural relics, the stone packed areas and the pits were uncovered (Fig. 4). At the west part of Site 1 (sectors B – Z, c. 325 m^2) lie the best-preserved architectural relics. An elongated construction is thought to be part of a road leading to the top (sectors B – Γ). It consists of two parallel walls. The surface between them is coated with hard whitish-yellow material, reminiscent of the material on the surface of a main street at the EH II settlement at Koropi (Ανδρίκου, 2007, p.202; 2013, p.92). Later, the circular pits 1 and 2 were carefully dug on this surface. Further to the west (sector Δ) a tower-like circular construction, 2 m in diameter, preserved at the lower part, is hard to interpret, since it yielded no other finds than pottery. Between these two constructions the natural schist rock was extending levelled and interrupted only by the circular pit 3, a shoeshaped area covered with stones, probably a working table, and further to the south by an irregular surface (12 × 6 m) covered with stones. In this west part of the site, seven litharge specimens were found.

In the middle part of Site 1 (sectors H – IB, c. 125 m²), the excavated area is bordered to the south by the rocky hillside which rises abruptly. In front of this, the northeast-southwest Walls 3 and 4 (sectors Θ – I) of medium and big size stones are running almost parallel, founded on the rock. They were heavily disturbed, most probably by ploughing. The longest and curved Wall 3 forms a kind of enclosure in front of the rocky hillside. At this area, Wall 4 extends straight and partly undisturbed. The space between the two walls was packed with small stones. North of Wall 3 slabs of schist and limestone define a floor level which continues further to the west, with a layer of tightly packed small stones. To the southeast, a ditch curved on top of the rocky hillside was unearthed (sectors IA – Γ), running northeast-southwest on a parallel line to Walls 3 and 4. In the middle part and especially close to the Walls 3 and 4 and the packed stone-floor, the number of litharge items (376) was very high, while they are becoming sparse (60) further to the east.

At the east part of the site (sectors IΔ – Θ, c. 200 m²), a second ditch (14 m long, 0.60 – 0.80 m wide and 0.40 m deep, sectors IΔ – IΣT) similar to the one previously mentioned came to light but with northwest-southeast alignment. Both ditches contained fallen big stones. Walls 3 and 4 and the ditches, if they are understood as foundation trenches, imply that an effort was made to restrict and possibly organize the space in front of the rocky outcrop. Filling gaps and cavities with packed stones constitutes a further effort to level the natural bedrock and create space for various activities, as it was clearly observed at the lower side in front of the ditch. Toward the east end of the site only stone heaps were excavated notably smaller and fewer in number in comparison to the rest of the site. Again, litharge specimens (120) appeared more densely on the stone packed level and the stone heaps.

The litharge specimens started below the surface layer in a moderate number. The peak of their density was in the 1 m thick layer with the architectural relics and the stone heaps (at 141 – 140 m). Below this and over the rock surface they were found sporadically. Apart from the litharge specimens, no slags, silver or lead objects were present. Most pottery is coarse ware, but fine ware is also present. Despite the bulk of sherds few joints were found. Among the other finds obsidian (blades, flakes, two cores) is present in a moderate quantity and even lesser flint (blades and a lump). Other stone tools are scarce including two fragmentary mortars, as also clay spindle whorls (8 examples). The east part yielded a tiny piece

Fig. 1: The Industrial Area of Keratea, Attica. Sites 1 – 3 (source: the author).

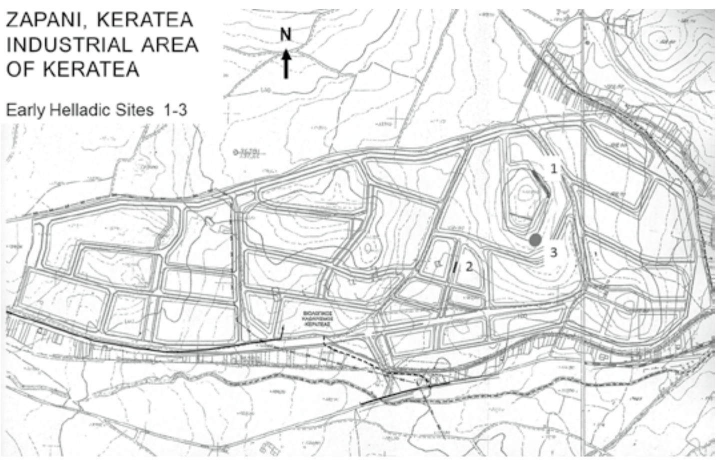

Fig. 2: Ground plan of the Industrial Area of Keratea, Attica. Sites 1 – 3 (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

and a possible wire of bronze and a marble head of a human figurine of the FN type (ΜΛ 1515, Ανδρίκου, 2020, pp.163 – 164, fig. 3α-θ.). Considerable was the number of limpet shells (patellidae), and smaller the number of land snails. No animal bones were found. The great quantity of litharge recovered contrasts, with the exception of the pottery, to the restricted variety and quantity of the other finds, which are consistent with settlement contexts. The pottery is of the usual character found in settlements without any special type for other than everyday use. Some obsidian tool production should also be assumed on the spot, but in a limited scale. Consequently, the abundant presence of the litharge items is a substantial element for the identification of the site.

The pottery indicates that Site 1 was used in EH I and EH II, but the two phases are stratigraphically not separable. It is difficult to explain its character. The west part seems to be a residential area. The extended flattened area most probably accommodated special activities that have not left any signs but certainly were not connected to litharge items. In the middle and east parts, where the great concentrations of litharge items are attested, a craft activity is implied. On the grounds of the great bulk of the litharge items and the absence of slags, it has already been suggested (Georgakopoulou, et al., 2020, pp.187, 190) that production of silver and lead was exercised by applying the cupellation method, like in the Lambrika workshop (Kakavogianni, et al., 2008, pp.47 – 48). Although no pits or cavities similar to the Lambrika workshop were found, the whole arrangement of the area with Walls 3 and 4, the stone packed areas and the ditches should somehow be connected to the litharge items. Future discoveries or detailed examination of previously excavated sites, if studied comparatively, may shed more light.

Site 2

Site 2, located in the plain, was detected over a length of 33 m in a 1.50 m wide trench running from north to south, dug for a modern pipe (Fig. 5). The archaeological layers rested in a cavity of the schist stratum. The schist sloped from both the north and south end of the excavated area towards the middle to a depth of 2.90 – 3.10 m from the soil surface. The width of the cavity towards the east and west is unknown. Excavation has been difficult because of ascending aquifer water at that time of the year (December) and a pump was indispensable when digging the lower levels. The earth was sandy, grey in colour at the upper level and yellowish with small gravels at the lower layer (0.40 – 0.90 m thick) above the rock surface. The sandy texture of the earth deprived from stones, suggests that the area was flooded in antiquity as at present. The architectural relics were humble. An ellipsoid with a well-built stone border and a lot of fragmentary pottery inside was the best-preserved construction. This was one of the pottery clusters found isolated in the excavated area and at different depths. Similarly, obsidian (blades, flakes and cores) and snails and limpet shells (patellidae) were found in clusters. Animal bones were scarce. Few spindle whorls must be added to the finds. On the contrary, a great number (215) of litharge specimens was scattered mainly in Zones II-IV and more densely in the lower yellow layer. Although the range of the finds is similar to the one at Site 1, Site 2 seems to have been an open-air space used for a specific function in EH II period. This is evoked by the fact that most of the pottery was concentrated on flat paved surfaces in different layers. It comprises tableware vases in good preservation, most probably due to

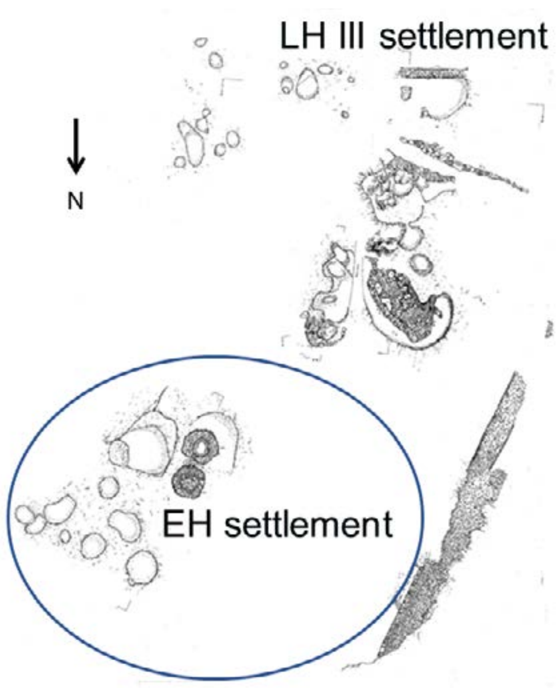

Fig. 3: Site 3. The EH settlement and litharge bowl fragment (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

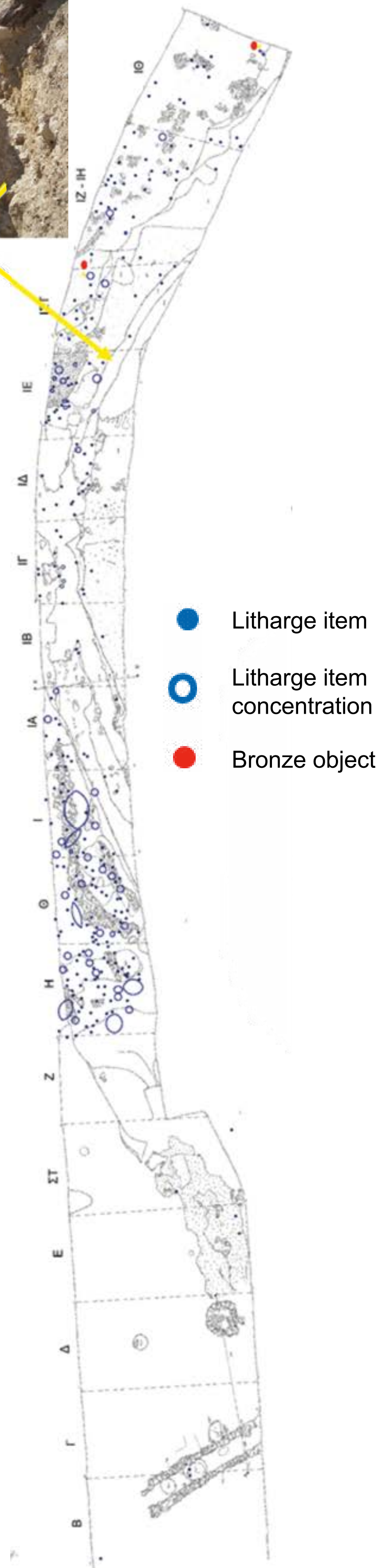

Fig. 4: Site 1. Ground plan, dispersion of litharge items, details of the excavation (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

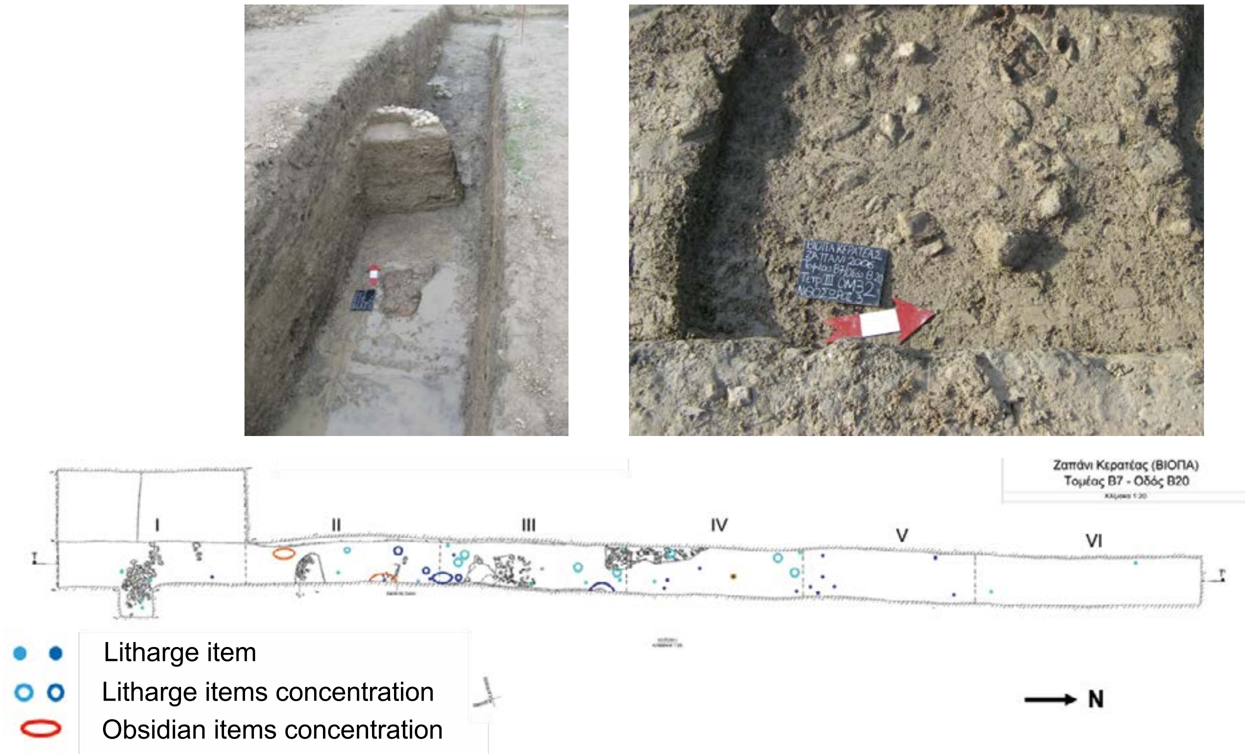

Fig. 5: Site 2. Ground plan, dispersion of litharge items, details of the excavation (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

the short period of use, and cooking pots that present a long-term use. Many small cups, an uncommon shape in domestic contexts but in abundance at the cemetery of Ayios Kosmas, indicate the special character of Site 2. Sauceboats are also frequent, while closed shapes and storage vessels are rare. Site 2 is suggested to have been used for open air communal activities comprising eating and drinking, repeated most probably periodically in the dry months of the year. In this context, the presence of the litharge specimens can hardly be explained as waste products of cupellation. Presumably, it is material thrown away from a nearby workshop, probably the one in the area of Site 1. Site 2 was occupied in EH I, but the main bulk of the otherwise small quantity of pottery is EH II.

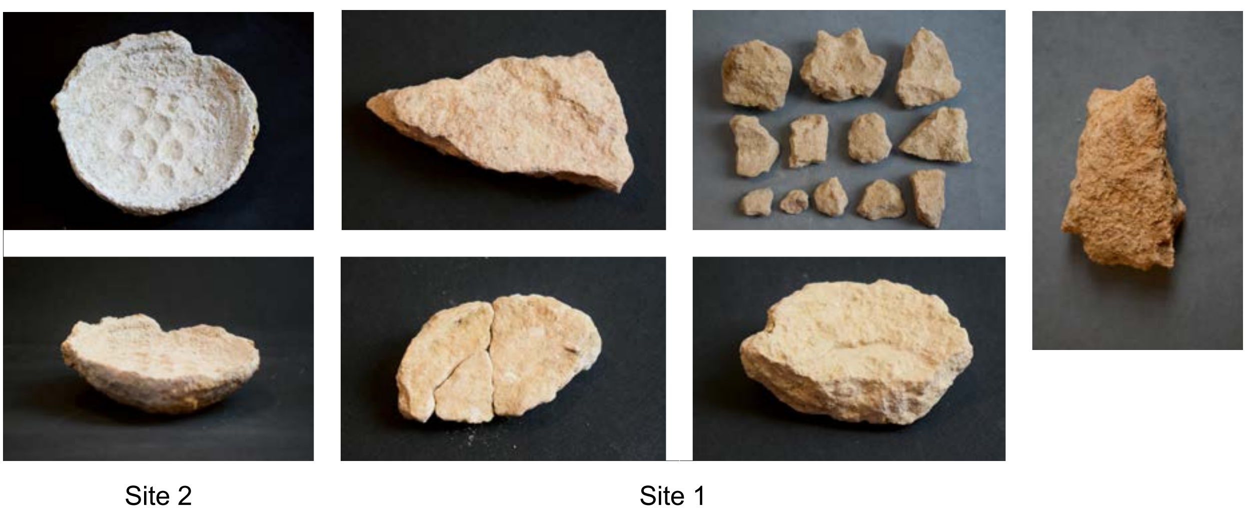

Fig. 6: Site 2. Litharge bowl (ΜΛ 1351). Site 1: Litharge fragments (bowl-shaped, plate-shaped, lumps). (Source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Site	Area m²	No. of litharge specimens	Litharge specimens per m²
Lambrika workshop	70	1400	20
Zapani, Site 1 - middle part (sectors H – IA)	75	376	5
Zapani, Site 1 - east part (sector IE)	12	150	12.5
Zapani, Site 2 - Zones II – IV	25	198	8

Tab. 1: Finds of litharge specimens at Zapani Sites 1and 2 and Lambrika workshop.

The litharge from Zapani as evidence for early metallurgy in the Lavreotiki

The litharge specimens from Zapani (Fig. 6) are classified (Kakavogianni, et al., 2008, pp.51 – 54) mainly as bowl-shaped (roughly 60%) and lumps (35%) while plate-shaped are rare (4%), although the percentages may be slightly differentiated when registration of the items will be completed. They are all fragmentary. Their preserved size ranges mainly from 0.05 to 0.07 m, while many of them are smaller (0.02 – 0.03 m). The only almost intact litharge bowl from the deepest layer of Site 2, bears 10 shallow depressions in the interior arranged in three lines (3 – 4 – 3), a feature restricted so far to Attica specimens (Kakavogianni, et al., 2008, p.55; Georgakopoulou, et al., 2020, pp.189–190). The majority of litharge bowls at Zapani bear these depressions, while the examples with plain interior are occasionally found. As it is the case at Lambrika, the Zapani specimens occurred when the litharge was absorbed during the cupellation by a porous container (Κακαβογιάννη, et al., 2006, pp.80 – 81; Georgakopoulou, 2007, p.394).

Early mining of silver-bearing ores at Lavreotiki has already been suggested by small galleries on the slopes of Ovriokastro (Κακαβογιάννης and Κακαβογιάννη, 2001, pp.56 – 57) and other sites in Lavreotiki (Lohmann, 1993, pp.476 [TH32]; 486 [TH49]; 505 [AN26]; 520 [LE22]), which are related to the uppermost 1st contact and to FN / EH I pottery fragments scattered on the soil surface around. Mine gallery 3 at Thorikos was active at least in EH II (Spitaels, 1984, Νάζου, 2013). A fragment of a litharge bowl was found at the entrance of an EH I cist grave at Tsepi, Marathon (Pantelidou, 2005, pp.68. 323. 345 – 349, pl.8.7,3). Some examples are known from Makronessos (Spitaels, 1982, pp.155 – 158; Lambert, 1972, p.879) and the major EH II settlement at Koropi (Georgakopoulou, et al., p.187) where evidence (slags, moulds) of copper metallurgy was found too. (Kakavogianni, et al., 2008, p.50; Ανδρίκου, 2013, pp.179 – 180, fig.17). One litharge fragment is known from Melissourgos, Kalyvia. An isolated litharge bowl has also been found in a MH house at Velatouri, Thorikos (Servais, 1967, p.22, fig. 16) and two others in later (4th century BC) contexts (Lambert, 1981, pp.422 – 424, figs. 285, 287(2); Οικονομάκου, 1997, p.88). Three stray finds are known from Lavreotiki (Conophagos, et al., 1976, pp.12 – 16, figs. 8 – 10; Conophagos, 1980, p.367, fig. 16 – 4; Κακαβογιάννης, 2005, pp.277 – 280, pl. 24β). Recently, litharge fragments have been reported from the Saronic gulf shore, in the *Asteria* property at Glyphada, from the ongoing excavation of an EH I workshop used for burials in EH II (Καζά-Παπαγεωγίου, 2016, pp.1 – 2, 10, fig. 3b; 2017, pp.1 – 2).

A substantial impetus for the archaeology of silver and lead metallurgy was the discovery of the cupellation workshop at Lambrika, which extended over 70 m² and yielded nearly 1,400 litharge specimens. Besides of these finds, three more pieces came from a neighbouring EH I house and 117 more, including the only intact bowl, were discarded in a wide nearby ditch (Kakavogianni, et al., 2008, pp.47 – 49; Kakavogianni, Douni, Georgakopoulou, this vol.).

In Table 1 the density of the litharge items at the Zapani sites and the Lambrika workshop is compared.

At Zapani, in the sectors of Site 1, which are not mentioned in Table 1, the density is 1 litharge specimen/m². The only almost completely preserved litharge bowl from Site 2, Zone IV, measures 0.14 m in diameter and has a weight of 1,325 g. It is therefore bigger and heavier than the ones from Lambrika (Kakavogianni, et al., 2008, p.52), but still of the same type. Although Zapani lags behind Lambrika in terms of absolute number and density per square metre concerning the litharge specimens, it must be stressed that it is the only place so far that can be compared to Lambrika. At other sites, the number of litharge specimens is lower, and they form smaller groups within the settlement. For comparison, ten small amorphous pieces were excavated at the Mokriza hill (Παρράς, 2010, p.143). At EH I Merenda 80 pieces of litharges were found, and at FN/EH I settlement at Gialou, north of Spata, only several fragments were found in a pit (Kakavogianni, Douni and Georgakopoulou, this vol.). Based on these finds, we suggest that the litharge specimens at Zapani are evidence of production of silver from argentiferous lead by cupellation. This activity should be restricted to the area of Zapani, Site 1, since the context at Site 2 leads to a different interpretation and the few pieces at Site 3 should be compared with those at Merenda and Lambrika settlement.

This is additionally supported by the vicinity of Zapani to the hill of Ovriokastro, where early exploitation of the 1st contact has already been suggested. The site is located on a high spot open to north winds. Similar topographical features of metallurgical workshops have been

Fig. 7: Site 1. "Cheese-pot", rim fragments (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

observed close to coastlines of Cycladic islands, and at Crete (Broodbank, 2000, p.294; Betancourt, 2006, p.180). Here, primarily smelting of copper ores was practised. At Akrotiraki (Siphnos), "domestic site related to silver/lead production (Papadopoulou, 2011, p.150)", secondary processing of metal cannot be excluded. Zapani, of course, is not coastal, neither is Lambrika, where the EH I workshop was installed on a smooth slope higher than the nearby EH I house, facing south. The argentiferous lead used at Lambrika and Zapani should have been extracted from the ores at the mining area, and then transported to these sites where cupellation was practiced. Evidence for secondary melting for making artefacts using, e.g. moulds, is only known from the major settlement of Koropi in a distance of 5 km from Lambrika, a situation observed also in Cyclades (Broodbank, 2000, p.294).

Lambrika and Zapani indicate that cupellation workshops operated on the periphery of the main ore extraction area of Lavreotiki peninsula. However, the recent evidence from Glyphada implies a further expansion of the activity on the coast to the west, where the ore was probably transported by sea, a common practice in the Aegean (Broodbank, 2000, pp.293, 296, 298; Betancourt, 2006, p.180). The minor presence of litharge fragments at the other sites mentioned above may suggest that a process aiming to lead production took place or that litharge specimens were used for other purposes not connected to metallurgy. However, neither of these alternatives is supported by EBA evidence (Georgakopoulou, 2007, pp.394–395; Sotiropoulou, et al., 2010).

The Aegean island sites where litharge fragments were found are few. At Ayia Irini, Kea, four lumps were found (Wilson, 1999, p.146, pl. 94), at Daskalio-Kavos and Daskalio, one example at each site (Georgakopoulou, 2018, p.530), and few pieces from FN/EH Limenaria, Thasos (Papadopoulos, 2008, pp.62. 64–65, fig. 5a-b). Only Akrotiraki, Siphnos yielded 46 fragmentary bowl-shaped litharges and some lead slags of EC date, while the date of the examples from Ayios Sostis and Kapsalos is not clear (Papadopoulou, 2011, pp.149–150). The comparison between the Attic and the Aegean evidence suggests, that the silver-lead metallurgy in Attica strongly developed on a peripheral pattern around the mining area of Lavreotiki, probably due to topographical parameters.

The Pottery

The pottery groups from the EH Sites 1 and 2 at Zapani, Keratea, present several similarities to each other. This indicates that both sites were in use in the same time period. The differences exhibited in types and forms of the vases are attributed to the different nature of each site. This is a preliminary report based on the ongoing study of the ceramic material.

Early Helladic I

Quite a few EH I sherds came to light at Site 1, mixed in some cases with EH II pottery. The fragmentary state of preservation of the material, which was abundant, has not allowed mending of vases or even bigger parts of them. The most common shapes were large open ones, such as basins and bowls. Most of the pots bear a slightly incurved rim and curved walls. At Site 2, the material dating to EH I, is limited and comes from the lower layers of the cavity.

Tubular horizontal handles below the rim of open vessels were found at Site 1, which is a common trait of the period in Attica at the sites of Lambrika (Kakavogianni, et al., 2008, p.50, fig. 6a; Κακαβογιάννη, et al., 2009, p.238, fig. 2, p.243, fig. 10a) and Artemis (Ευστρατίου, et al., 2009, p.226, fig. 7b) and elsewhere as at Eutresis (Caskey, 1960, p.135, pl. 45 II.30), Ayia Irini (Wilson, 1999, pp.16–17,19, pl. 40) and Lerna (Wiencke, 2000, p.329, fig.II.1). Some of the larger and coarser handles could be attributed to vases, similar to the ones from an EH I house at Artemis, mentioned above.

Flat bases possibly belong to deep bowls or basins. Parallels have been found at Kontra Gliate in the area of Koropi (Nazou, 2017, p.123, fig. 6), Artemis (Ευστρατίου, et

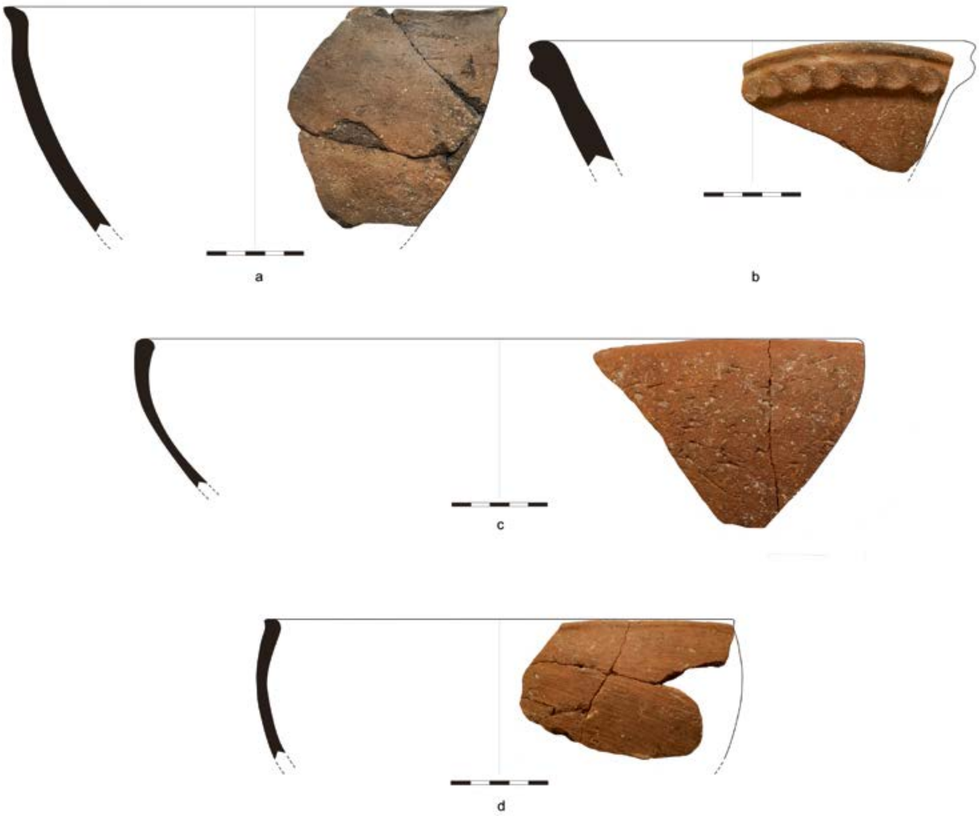

Fig. 8: Site 2. Basins. – a–b. Type1; – c. Type 2; – d–e. Type 3 (ΜΛ1343). (Source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

al., 2009, pp.227, 229, fig. 10), Tsoungiza hill (Pullen, 2011, p.98, fig. 3.10:31; p.99, fig. 3.11:32, p.101, fig. 3.13:40, p.123, fig. 3.29:123, p.133, fig. 3.35: 168. 169. 175). Apart from these, some flat bases belong possibly to cups.

A basin fragment with applied band decoration below the rim resembles an EH I sherd found at Lambrika (Κακαβογιάννη, et al., 2009, p.238, fig. 2). Goldman (1931, pp.92–93, fig. 116:1,4.) characterizes similar decoration at Eutresis as false or imitation handles. A few sherds of basins are covered with a thick red slip, which is one of the most characteristic features of this period. It has been noticed on EH I pottery at Lambrika (Kakavogianni, et al., 2008, pp.48, 50, fig. 6b), Artemis etc. Another fragment that possibly belongs to a red slipped jar bears incised decoration, as it has also been observed at the Koropi pottery (oral information by K. Ntouni). In the lower layer at Site 2, where the almost intact litharge bowl was found, a fragmentary basin scored inside and with applied decoration on the rim was found. Moreover, two incised examples, one rim and one body fragment with a combination of incised lines and a circle.

The open vessel known as "cheese-pot" is represented by many plain rim fragments with a horizontal row of holes just below it (Fig. 7). They were retrieved from various depths of the excavation at Site 1. Four more sherds were found in the lower layers at Site 2. A few bear traces of polishing on the inner surface. None showed traces of burning, which confirms that they were not used as cooking pots. The vessel was common in settlements, in large or small quantities, from Late Neolithic until EH I. Recently the shape was thoroughly discussed by Pantelidou (2016, pp.227–232), who refers to several examples from Attica. To

Fig. 9: Site 2. Basins. Various types of rims: – a. rounded, – b. rounded hastily made, – c. rounded with groove below, – d. T-shaped, – e. canted. (Source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

these an example from Artemis can be added (Ευστρατίου, et al., 2009, pp.226–227, fig. 7στ). The fragmentary state of the examples from Zapani prevents the attribution to either Type 1 or 2 of the Pantelidou classification. The use of the vessel has not been confirmed. Pantelidou suggests for her Type 2 that it forms a boat model.

Early Helladic II

In this phase four broad categories of pottery fabrics are discerned: fine, medium fine, medium coarse and coarse. Coarse and medium coarse pottery from Site 1 was found in large quantities while at Site 2 the majority of vases is of medium fine/medium coarse clay and very few coarse ones. The ceramic evidence from Sites 1 and 2 is mainly comparable to material from Attica, according to Ntouni's classification (2015), and from Lerna III, Peloponnese, according to Wiencke's (2000).

The coarse/medium coarse pottery from Site 1 represents mainly large open vessels. Body sherds of talc-ware vases are present in Site 1, but they are uncommon in Site 2. Talc-ware appears in Attica (Thorikos: Νάζου, 2013, pp.51–52), the Cyclades (Caskey, 1972, p.373; Wilson, 1999, pp.8, 130–131; Σωτηρακοπούλου, 1999, pp.76–78) and is recognizable by touch, as it feels as if coated with talc. Scored-ware sherds were found in large quantities all over the excavated area at Site 1 and 2. At both sites this surface treatment is noticed on the inner surface, while at Site 2 it also occurs on the outside (Fig. 8d). Scoring is a technique of smoothing the surface of the vases with some means (e.g. dry greens) and it is attested in various sites

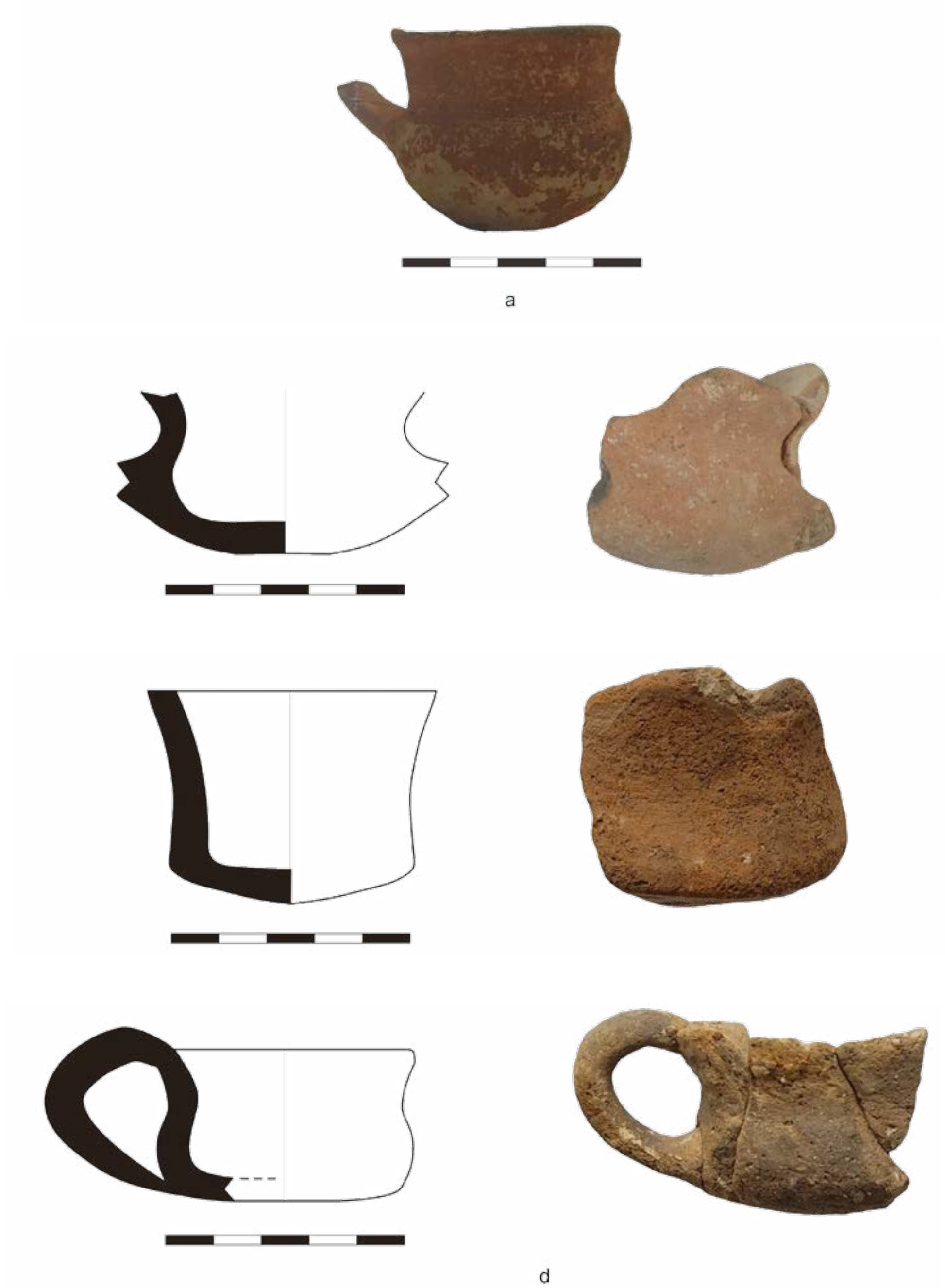

Fig. 10: Site 2. Small cups. a. Type 1 (ΜΛ 1336); – b–d. Type 2 (ΜΛ 1335a, 1338a, 1342a). (Source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

(Akrotiri, Thera: Σωτηρακοπούλου, 1999, pp.80–81; Ayia Irini: Caskey, 1964, pl. 47g; Caskey, 1972, pp.360, 366, fig. 79. B41c, B56-B7, pl. 76. A43-A46; Raphena: Θεοχάρης, 1951a, p.91, fig. 17δ; Thebes, Lefkandi, Macedonia: Σωτηρακοπούλου, 1999, pp.80–81).

Coarse/medium coarse open vases

To basins, broad bowls with a rim diameter over 20 cm are ascribed. It is a very common shape on both sites. Since no complete profile exists, it is quite insecure to determine the typology and to allot individual sherds to basins or bowls. At Site 1, basins are of coarse unpainted fabric, with a plain or T-shaped rim (Wiencke, 2000, p.539, fig. II.76, types 4, 7). At Site 2, they are always dark, unpainted, of medium coarse fabric (Fig. 8, 9). The main bulk of them had been used for cooking. The total absence of baking pans can only be explained by the population's preference for specific kind of food and cooking procedure. Bases corresponding to basins are mostly flat (Ntouni, 2015, p.203, tab. 14.A1-A2) or convex (Ntouni, 2015, p.203, tab. 14.A3). The sides curve gently

Fig. 11: Site 1. Frying pan fragment with stamped decoration (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

inward (Wiencke, 2000, pp.538–542, fig. II.75, type 1–3) or are rather flaring (Wiencke, 2000, pp.542, 544, fig. II.75, types 4, 7). The rim is usually rounded (Ntouni, 2015, p.195, tab. 5.2) or less often thickened out (Ntouni, 2015, p.195, tab. 5.5) and canted (Ntouni, 2015, p.195, tab. 5.4). Rounded rims are hastily made and finished. A groove marks sometimes the transition to the body. Only few examples of T-shaped rim were noticed. (Ntouni, 2015, p.195, tab. 5.6; Wiencke, 2000, p.540, fig. II.76, "type m"). Handles are almost absent, while flat lugs/handles are not uncommon.

Bowls are another open shape that stands out at Site 1, with plain incurved rim. Many of the flat bases as well as of the pedestal ones (Ntouni, 2015, p.254, tab. 22. IV, fig. 12.K98) could be attributed to bowls, with parallels at Koropi, Lerna and elsewhere. The bowl is a common shape found in all the known EH sites (Ntouni, 2015, p.252). Bowls form a wide group in Site 2 as well. Those made of medium coarse fabric are usually cooking vessels and in that case their manufacture, surface treatment and shape are similar to basins. Consequently, it is impossible to distinguish them in fragmentary state.

Only one example of a plate has been recognized from Site 2. It is a very shallow vessel, 8 cm in diameter, with heavily curved walls. It falls into the Attica type III (Ntouni, 2015, pp.208–209, tab. 17, fig. 2.K16).

The specific function of Site 2 is confirmed by the concentration of fifteen small cups – an uncommon shape in a domestic context – lying on top of a stone-laid area (Fig. 10). They are made of medium fine or medium coarse fabric. They are 3.5 to 6 cm in height and diameter. Two types are recognised:

- Type 1: Only one specimen, with rounded bottom bearing a small depression for greater stability (Ayios Kosmas,Type C–13a: Mylonas, 1959, pp.69–70, pl. 57, Attica type I: Ntouni, 2015, p.280. tab. 25).
- Type 2: with an S-shaped profile and rounded bottom. The cups of this type are hastily made with thick walls and cruder than these of the previous type. (Ayios Kosmas, Type C–13c: Mylonas, 1959, pp.69–70, pl. 57, Attica type III: Ntouni, 2015, p.280, tab. 25, fig. 18.K158).

Tactile decoration on open vases was typical in prehistoric Greece from the Neolithic period on (Kefala on Kea, Saliagos, Antiparos and elsewhere, Γιαννακάκης, 2015, p.56). It appears on coarse utilitarian pottery at Ayios Kosmas (Mylonas, 1959, pp.24–25, fig. 118), Raphena (Θεοχάρης, 1951a, p.89. fig. 16), Koropi (Ανδρίκου, 2013, p.176, figs. 4–5), the Cyclades (Kea: Caskey, 1972, p.366, pl. 76), Lerna (Wiencke, 2000, p.619, fig. II.102), Tsoungiza hill (Pullen, 2011, p.169), etc. At Site 1, it was commonly found in the total area of the excavation, on pithoi or basins with plain or T-shaped rim. The motifs applied coincide with the types recognized for Northeast Peloponnese (summarized by Pullen, 2011, p.170, fig. 4.15): raised band with finger impressions (type c), formed by overlapping disks set at an angle to imitate rope (type e), formed by closely (type b1) or more widely (type b3) spaced applied disks, and with diagonal incisions (type d). At Site 2, apart from types c (Fig. 8b) and d, type b2, raised band with tangent disks, is also met.

Impressed decoration is attested on a frying pan fragment bearing four stamped concentric circles found at the south part of the excavated area on Site 1 (Fig. 11). This kind of decoration is well-represented at several sites, in the Cyclades (Akrotiri: Σωτηρακοπούλου, 2009, p.325, dr. 47ε, fig. 184 Δ201; Ayia Irini: Caskey, 1972, p.365, pl. 77 B21; Wilson,1999, pp.325–326, pls. 54–57); Boeotia (Caskey and Caskey, 1960, p.156, pls. 48 VIII. 52. 54); Attica (Ayios Kosmas: Mylonas, 1959, p.300, fig. 159; Palaia Kokkinia: Θεοχάρης, 1951b, pp.111–112, fig. 26; Koropi: Ανδρίκου, 2013, pp.178–179, figs. 10–11); Argolis (Tsoungiza hill: Pullen, 2011, p.221, fig. 4.26). Impressions are considered a mainland characteristic in contrast to incisions that are typical for the Cyclades (Coleman, 1985, p.201). From the same context, part of a hearth rim is decorated with alternating stamped triangles. This motif was quite common in the Aegean (Raphena: Θεοχάρης, 1951a, p.89, fig. 15; Lerna: Wiencke, 2000, p.557, fig. II.84). Incision is used for a fishbone-like motif on a polished fragment from a frying pan. These vessels speak for cycladic connections.

Matt-impression appears on the legs of stands from Site 1. Impressions of matt, leaves or even cloth on pots, mainly on their standing surface, were quite common during the EH period (Raphena: Θεοχάρης, 1951a, p.90; Marathon: Παντελίδου, 2016, pp.297–309, fig. 18; Eutresis: Caskey and Caskey, 1960, p.142; Lithares: Tzavella-Evjen, 1985, pl. 54; Argolis, Tsoungiza hill: Pullen, 2011, fig. 5.109, 126) and continued in the MH period too (Παντελίδου, 2016, p.306).

Coarse/medium coarse closed vases

The jar and the askos are identified in the pottery of Site 1. Many cylindrical/elliptical, and ribbon handles could have been parts of jars, which resemble examples from Lerna

(Wiencke, 2000, pp.559–569, fig. II.86). Such handles from jars, incised with diagonal lines can be dated in EH II (Σωτηρακοπούλου, 1999, pp.210–211, figs. 302–308), with parallels at Ayia Irini and elsewhere in the Cyclades (Caskey, 1972, p.358). A body sherd with part of handle may have belonged to an askos (Ntouni, 2015, p.332, tab. 30).

Although closed vases are infrequent and fragmentary at Site 2, they are assumed to be of medium size. No classification is possible. However, some similarities to examples of Lerna III can be noticed. An example of a low neck perhaps suggests a globular jar, like type 3 (Wiencke, 2000, pp.563–564, fig. II.85, cf. Koropi: Ανδρίκου, 2013, p.177, fig. 6b-c). As another example the neck is of medium height and breadth and flares slightly outward like type 6 (Wiencke 2000, pp.561, 564–565, fig. II.86).

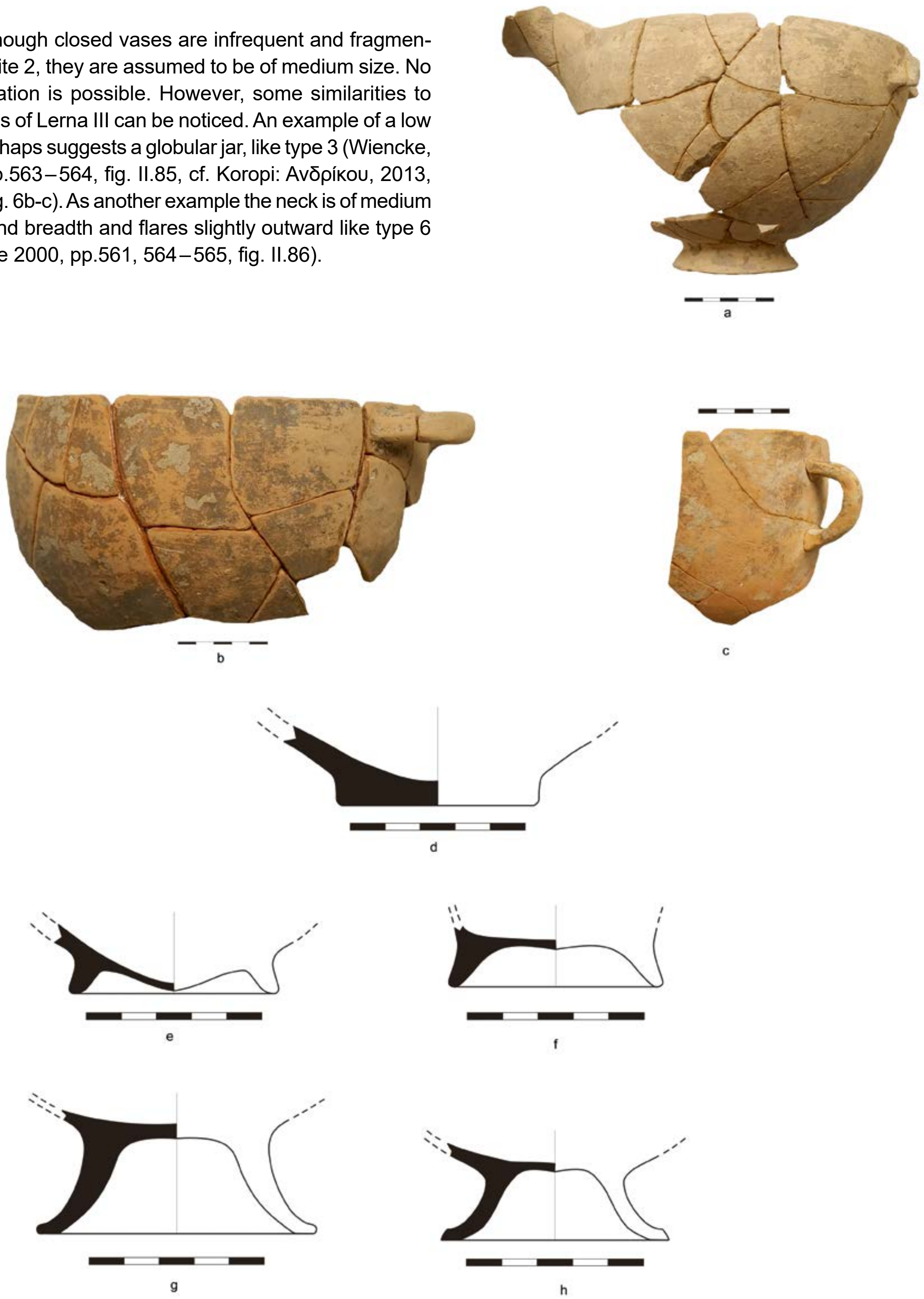

Fig. 12: Site 2. Sauceboats. – a. Type Ia (ΜΛ 1332); – b–c. Urfirnis: Type Ib (ΜΛ 1345), Type Va (ΜΛ 1344); – d – h. Various base types. (Source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Fig. 13: Site 2. Pyxis fragments with patterned decoration (ΜΛ 1349). (Source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Fine pottery

EH II fine pottery from Site 1 is estimated from 25% to 30% of the total quantity of pottery. Sauceboat is the dominant shape, as observed in other EH II fine pottery assemblages in Attica. Following the typology of the Koropi settlement, the majority belongs to type Ia, with conical bases rather widened towards the standing surface (Ntouni, 2015, p.308, tab. 29). It is the most common type in the area, with parallels at Merenda, Ayios Kosmas and Asketario. Yellow-blue mottled sauceboats (Ntouni, 2015, fig. 24.K.189–190; Ανδρίκου, 2013, pp.176–177, fig. 6e-g) or black and red Urfirnis have been found at Site 1 in almost equal percentages. The red or black Urfirnis examples comprise rims, horizontal handles and a few vertical ones of Attica type Va (Ntouni, 2015, p.309, tab. 29). At Site 2, even though sauceboats are in abundance, they are not preserved in their entirety (Fig. 12). The majority of the examples corresponds to Attica type Ia and a good number resides in Type Ib (Ntouni, 2015, p.308, tab. 29). The difference between Type Ia and Ib is the position of the horizontal handle and the ring base. Finally, Attica type Va comprises fewer and more fragmentary examples. In the absence of complete profiles we cannot be sure whether individual body sherds, bases or handles made of fine fabrics should be recognized as belonging to sauceboats, bowls, or cups. Two methods of surface treatment are noticed: either the surface is covered with a thin light slip – often yellowish – or with a dark brown or black one in the 'Urfirnis' technique.

Pyxis is recorded only with few sherds all made of medium fine yellowish clay and only from Site 2. The sole almost complete example is assigned to Attica type IIb (Ntouni, 2015, p.361, tab. 32, pp.364–365, fig. 44.K341). Dark-painted hatched triangles (Ntouni, 2015, pp.388–389, tab. 36. Motif 3d) decorate the upper part of the body (Fig. 13). Dark-on-light decoration is preserved on a probable sauceboat rim fragment from Site 1 (Fig. 14). The motif, a horizontal band with vertical lines, is known from Koropi (Ntouni, 2015, p.388, tab. 36. Motif 1d/1e, fig. 34.K264-K267).

Thin incised lines run along the fragmented handle of a ladle from Site 1. It belongs to the common Attica type 1 (Ntouni, 2015, pp.382–383, tab. 34). Incised deco-

Fig. 14: Site 1. Sauceboat rim fragment with patterned decoration (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Fig. 15: Site 1. Fragment with incised decoration of alternating oblique lines (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

ration of alternating oblique lines reminding fishbone motif appear on an unidentified sherd from Site 1 (Fig. 15). This type of decoration has several parallels, from Koropi (Ntouni, 2015, p.412, Motif 2b, fig. 42.K317), Ayia Irini, Kea (Wilson, 1999, pl. 49:II – 180, pl. 70:II – 746, pl. 76:II – 122), Eutresis (Goldman, 1931, p.113, fig. 150:1), Lerna (Wiencke, 2000, p.465, fig. II.58: P953) as it is widespread during the EBA II.

Conclusions

The EH I pottery from Sites 1 and 2 at Zapani, Keratea is restricted in quantity and variety of shapes, mainly open vases and “cheese pots". Best parallels are recognized in the EH I pottery of Lambrika.

The pottery assigned to EH II presents variety in shapes, with most prominent the sauceboat at both sites, plain, ‘Urfirnis’ or yellow-blue mottled. Dark on light decoration is attested on a pyxis and a probable sauceboat fragment. Talc-ware and frying pans suggesting Cycladic contacts are only found at Site 1. Incised decoration is preferred on fine and semi-coarse vases and tactile decoration on coarse ones. The pottery assemblage from Zapani, Keratea falls within the mainland pottery tradition and presents clear similarities to the pottery of other EH II sites in Attica, like Koropi and Merenda, and to Lerna III.

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The cupellation of argentiferous lead in Mesogeia, East Attica, during the Final Neolithic/ Early Bronze Age periods – The cupellation workshop at Lambrika

ABSTRACT: *Excavations in southeast Attica have uncovered a wealth of metallurgical finds relating primarily to cupellation and to a lesser extent copper working. Workshop installations were only identified at Lambrika, but significant quantities of litharge are also known from the sites of Merenda, Gyalou and Zapani. Litharge is characteristically scarce at the extensive, nodal settlement of Koropi. The finds from Merenda and possibly Gyalou place the beginnings of cupellation in this region at least to the mid-4th millennium BC, extending continuously among the different sites to the EHII phase. The bowl-shaped litharge is the most common type of litharge identified here with the characteristically arranged ten depressions on the top surface appearing to be a chronologically later (mature EH I/EH II) feature, possibly also spatially restricted to the Laurion/Lambrika zone. The identification of litharge does not intrinsically testify to in situ practice of cupellation, as the material is known to have had secondary usages in antiquity, not least as a raw material for lead production. The quantity of finds and other considerations, however, suggest that cupellation workshops existed on almost all the sites considered here, even if actual remains of installations have only been identified at Lambrika. The finds from southeast Attica testify to the significance of the Laurion deposits already for the earliest Aegean silver production and allow for direct study of this technology.*

KEYWORDS: PREHISTORIC, SILVER, BOWL-SHAPED LITHARGE, LAMBRIKA, LAURION, TECHNOLOGICAL CHANGES

Introduction

The earliest evidence for metals and metallurgy in the Aegean dates at least back to the 5th millennium BC and involves the production of a few copper-based artefacts, primarily known from Northern Greece, for example from Promachonas, Servia, Sitagroi, Dikili Tash and Makrygialos (Zachos, 2010, p.81; Tsirtsoni, 2016, p.21; Malamidou, 2016, p.311, fig. 26). Apart from copper-based artefacts, excavations have also uncovered remains of extractive metallurgy such as slags and metallurgical ceramics. On the contrary, finds from Southern Greece are fewer for these periods, examples including a copper needle from the Kitsos Cave dating to the middle of the 5th millennium BC (Bourhis, et al., 1981, p.425 no. 4, fig. 288) as well as the copper axe from Spata (Phelps, et al., 1979, p.176, no. 120, pl. 22.1; Ζάχος, 2010, figs. 6 – 6β, cat. no. 70) which is a chance find or the result of looting.

Regarding silver, the earliest known artefacts are also dated to the 5th millennium BC and are items of jewellery finds found primarily in Southern Greece (Ζάχος, 2010, p.88); for example in Salamina (Dimakopoulou, 1998, p.64, no. 62), Alepotrypa, Diros (Papathanassopoulos, 1996, p.227, nos. 41 – 43); Παπαδημητρίου and Τσιρτσώνη, 2010, cat. No.51), Amnissos, Heraklion (Μαρινάτος, 1930, p.97, fig. 9). Compared to copper, the earliest extractive metallurgy of silver in the Aegean is presently attested a little later towards the end of the Neolithic period in the mid – 4th millennium BC. It is at this period that the earliest known mining galleries are dated in the Lavreotiki (Lohmann, 1993, p.75, pl. 72.3 [Mokriza], p.88, pl. 76.4 [Rimpari], p.486, pls. 129.2,3 [Kastela TH 49]; Lohmann, et al., 2002; Lohmann, 2005, p.128) and at Ayios Sostis, Siphnos (Gropengiesser, 1986; 1987).

Prehistoric remains of silver production from the immediate vicinity of the extensive Laurion metalliferous zone are understandably very rare. Later, intense activities in antiquity and primarily in the modern period at Laurion will have largely destroyed this evidence (Κονοφάγος, 1980; Κακαβογιάννης, 2005). As such, the finds discussed

Fig. 1: Map of Attica presenting sites discussed in this paper (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

in this paper, discovered mainly in the nearby Mesogeia region, constitute an important witness to the technology of silver production in this period as well as the spatial and overall organization of these activities.

The finds presented here relate to the last step of silver production, the cupellation, where the silver is separated from the argentiferous lead metal, with lead being oxidized to litharge, the main by-product of this procedure (Κονοφάγος, 1980, p.304). Litharge is by far the main type of metallurgical find we come across in prehistoric contexts from southeast Attica. Lead slags or other relevant remains of smelting are essentially absent. We discuss primarily the finds from four sites from the broader Mesogeia area, (Fig. 1), Lambrika, Merenda, Gyalou and Koropi while we consider also comparatively the finds from the site of Zapani (Ανδρίκου, 2010; Andrikou, et al., this vol. pp.57–72). We present first the archaeological evidence for these sites and subsequently discuss the characteristics of the litharge fragments and other relevant finds in each case.

Lambrika

The discovery of the Lambrika workshop during rescue excavations in 2002[1] (Douni and Kakavogianni, 2002, p.195), opened the way to the direct study of prehistoric silver production in the Mesogeia plain and more broadly in the region of southeast Attica. Lambrika constitutes to this date the only clear cupellation workshop in Attica (Kakavogianni, et al., 2006; 2008; Κακαβογιάννη, et al., 2009) up to the Classical period. Together with the plethora of other finds coming from the other neighbouring sites, they allowed us to recognize and study new types of litharge, particularly the bowl shaped with or without depressions, as well as to trace a chronological evolution or change in the technology of cupellation in the region.

Lambrika is situated in the southeast foothills of Hymettus (Fig. 1), in the site of the ancient demos Lamptrai *Καθύπερθεν*. Lamptrai means shiny. Could the toponym have its roots in a very old memory of the shining silver which was produced here? The site is located at a

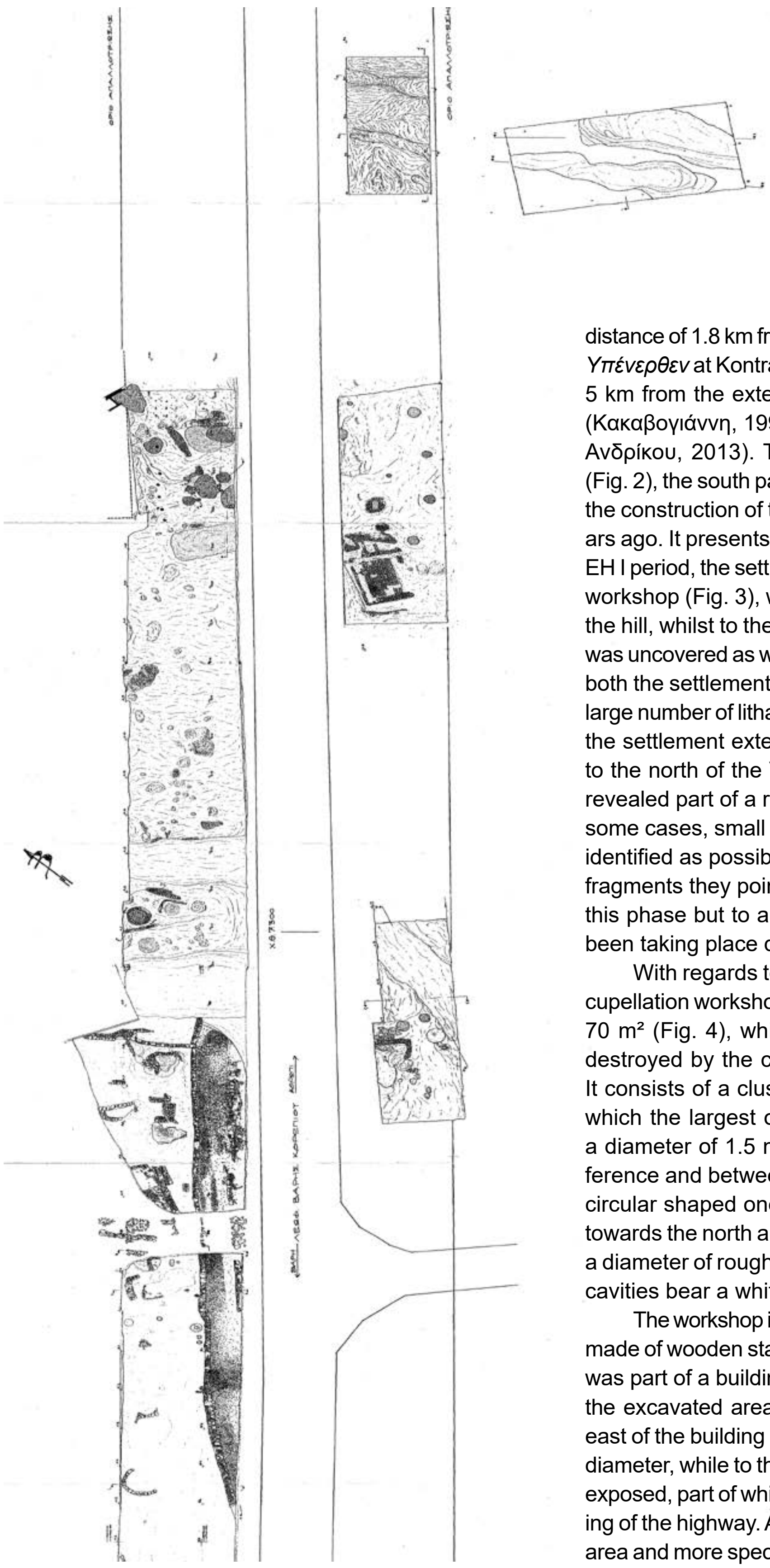

Fig. 2: General plan of the EH settlement at Lambrika (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

distance of 1.8 km from the other EH settlement of Lamptrai *Υπένερθεν* at Kontra Gliate (Kiafa Thiti) (Lauter, 1996) and 5 km from the extensive nodal EH settlement of Koropi (Κακαβογιάννη, 1993; Κακαβογιάννη and Ντούνη, 2009; Ανδρίκου, 2013). The settlement extends on a low hill (Fig. 2), the south part of which has been destroyed during the construction of the Vari – Koropiou highway, many years ago. It presents two chronological phases. During the EH I period, the settlement encompasses the metallurgical workshop (Fig. 3), which is found in the southeast part of the hill, whilst to the south of the workshop a small house was uncovered as well as ditches with refuse deposits from both the settlement and the workshop, as attested by the large number of litharge fragments. During the EH II period the settlement extends to the west of the workshop and to the north of the Varis Koropiou highway. Excavations revealed part of a road, as well as remains of houses. In some cases, small cavities carved into the bedrock were identified as possible hearths and along with the litharge fragments they point to the practice of cupellation during this phase but to a smaller extent than appears to have been taking place during the EH I.

With regards to the EH I period finds, the excavated cupellation workshop extends to an area of approximately 70 m² (Fig. 4), whilst it seems that part of it had been destroyed by the construction of the adjacent highway. It consists of a cluster of three pits of circular shape, of which the largest one is located in the middle and has a diameter of 1.5 m and depth of 0.5 m. On its circumference and between this largest pit and the two smaller circular shaped ones, are two clusters of cavities, three towards the north and two towards the south. These have a diameter of roughly 17 cm and a depth of 10 cm. These cavities bear a whitish coating (Fig. 5).

The workshop is defined from the north by an enclosure made of wooden stakes, while north of the largest pit there was part of a building that continued to the north, outside the excavated area. Northeast of the cluster of pits and east of the building there was a large ellipsoidal pit, 5 m in diameter, while to the northeast a natural submersion was exposed, part of which had been cut during the initial opening of the highway. At the surface of the broader workshop area and more specifically within the large ellipsoidal pit, at its northeast part, hundreds of fragments of bowl-shaped litharge were collected (Fig. 6), obviously waste coming from the workshop activities, together with pottery of the EH I period (Fig. 7) and fragments of grinding stones.

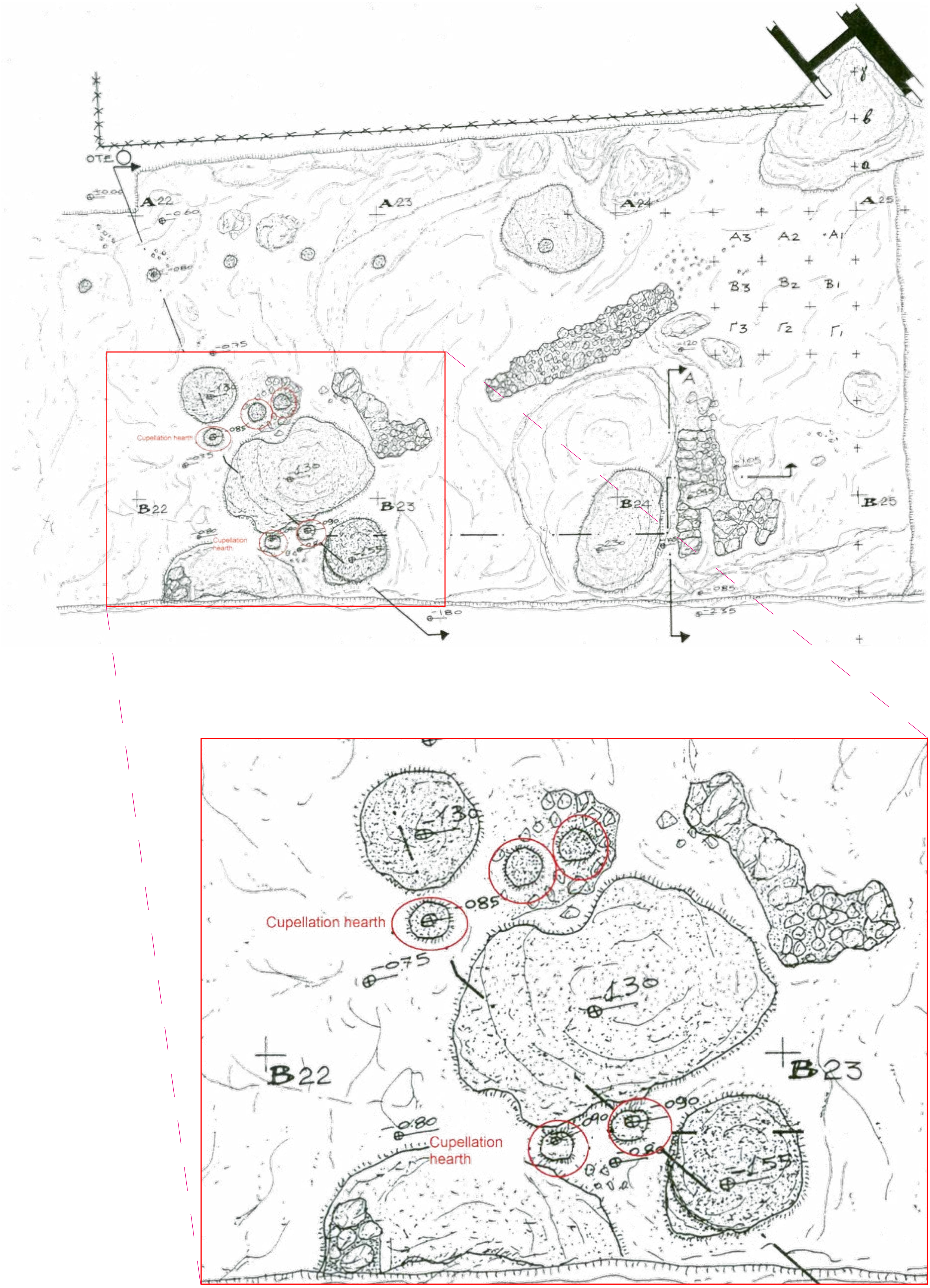

Fig. 3: Plan of the workshop at Lambrika (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Fig. 4: Photo of the workshop at Lambrika (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Fig. 5: Cupellation hearth from Lambrika (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Fig. 6: Litharge fragments exposed during excavation of the workshop (marked with yellow labels) at Lambrika (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Fig. 7a: EHI pottery from the workshop at Lambrika (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

The small house found 15 m to the south of the cupellation workshop (Fig. 8) also dates to the same period. The building had well-built walls, a paved floor and special care had been taken to protect the foundations of the building externally from the rainwater. A large quantity of pottery of various shapes and types (Fig. 9) was collected from the house, as well as many other finds (5 spindle whorls, obsidian tools and grinding tools, animal bones) that relate to the habitation of the building (Κακαβογιάννη, et al., 2009, fig. 5). In the southeast part of the EH I settlement and at a small distance from the above remains, at least two large ditches were exposed, 15 m in length, 4 m in width and 3 m in depth. Their original use possibly relates to collecting water from the small streams of the area. Large quantities of EH I pottery sherds (Fig. 10**)**, stone tools, one intact bowl-shaped litharge (Fig. 11) and many litharge fragments were found in their fills.

Fig. 7b: EHI pottery from the workshop at Lambrika (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Fig. 8: Photo of the EHI house at Lambrika (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Fig. 9: Large part of pithos from the EHI house at Lambrika (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Fig. 10: EHI pottery from ditches at Lambrika (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Therefore, it is worth highlighting, that litharge fragments were concentrated in special parts of the settlement and were not found scattered throughout. Apart from the area of the metallurgical workshop, litharge was also found in the ditches. It seems that inside these ditches, inhabitants have discarded the material from the workshop (litharge, stone tools, and sherds of pottery). On the other hand, it is noteworthy that, despite the proximity of the EH I house to the metallurgical workshop, no litharge fragments were found within or in the immediate vicinity of the former.

The litharge fragments

There are about 1,500 litharge fragments (or 160 kg) from Lambrika and by far the most common type is the so called bowl-shaped with the characteristic ten depressions on the upper surface. Similar finds were recovered from Zapani (Andrikou, et al., this vol.). The bowl-shaped type, with or without depressions, was known before from a few examples (Kakavogianni, et al., 2008, fig. 15) but the contexts were always either unknown or unclear and the finds had been thought of as belonging to the classical period (Κονοφάγος 1980, pp.367 – 369, fig. 16 – 4, 16 – 5). The finds from Lambrika and subsequently from Zapani place this type of litharge with certainty to the EH I and EH II periods in southeast Attica.

The preservation state of the Lambrika litharge finds varies. The average size of the fragments is 6 by 4 cm, while the largest fragment measures 11 by 8 cm. The intact bowl (Fig. 11), as well as several others large enough, allow us to reconstruct with confidence the original shape of these remains. Their diameter varies between 6 to 12 cm and the height of their walls between 1 and 2 cm. The weight of the intact litharge is 500 g. Very characteristic are depressions found on their upper surface. It is obvious that each bowl had always 10 depressions arranged in three parallel rows of three- four- three depressions and the dimensions of these were 0.6 – 1.6 cm diameter and 0.01 – 0.08 cm depth.

The dimensions of the bowl-shaped litharge finds correspond very well to the dimensions of the small coated cavities cut into the bedrock surrounding the large pit in the Lambrika workshop area. Furthermore, the analytical data suggest a close relationship between the chemical composition of the lining of these cavities with the bowl-shaped litharge fragments (Georgakopoulou, et al., in

Fig. 11: Bowl-shaped litharge from Lambrika (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Fig. 12: Bowl-shaped litharge with flat rectangular shape from Lambrika (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

prep). The litharge bowls should thus more correctly be identified as litharge-impregnated hearth lining, as proposed by E. Pernicka and his colleagues on the basis of similar finds from Habuba Kabira in Syria (Pernicka, et al., 1998). The process they described was relatively simple and certainly different to what we encounter in the case of Classical Laurion. A well-formed calcium- and silica-rich lining, leaving, at the end of the process, the less reactive silver metal to collect on the top, was applied, or was placed internally to the rock-cut cavities. The ten depressions must have been pre-formed on this lining or the cupel prior to firing. The solid silver-rich lead metal was subsequently placed within these cavities along with the fuel and heated under an oxidizing atmosphere. The forming litharge was continuously absorbed by the lining leaving, at the end of the process, the less reactive silver metal to collect on the top, most likely concentrating within the ten depressions. There are no ceramic or other finds with evidence for a lead-rich coating to suggest that any other vessels were involved in the process.

It is noteworthy, that among the bowl-shaped fragments, there is additionally a unique specimen (Fig. 12) that has a flat and rectangular shape. It has eight shallow depressions in two series of four, and another less clear one below. In at least five of these depressions there are smaller rounded depressions marked by a litharge rim at its inner side This is a peculiar and so far unique find. A possible interpretation is, that these depressions which must have been formed naturally are the imprints left by the separated silver globules, which were too small to fill the entire space of the pre-formed depressions on the lining(see also below for the single depressions noted on the Merenda and Gyalou finds).

It is evident that at Lambrika there was an outdoor cupellation workshop. The large amount of metallurgical remains (roughly 160kg in weight) suggests that the primary aim of the workshop was the production of silver by cupellation. On the basis of the workshop layout (Fig. 4), we propose that the metallurgists were standing in the large pit in the centre, to facilitate their work within the small cavities. Preliminary calculations have shown that despite the extent of the Lambrika workshop and the large amount of litharge recovered, so far unparalleled anywhere else in the Old World, the final product of silver from several centuries of production may be impressively small, even if we accept a large error margin (Georgakopoulou, et al., 2020). This observation certainly highlights the significance and value of silver in prehistory.

Merenda

Between 2000 to 2004, extensive archaeological research at the nearby site of Merenda, Markopoulo (Fig. 1), brought to light another interesting metallurgical assemblage, that includes the earliest securely dated litharge fragments known to date from southeast Attica. The prehistoric settlement of Merenda (Κακαβογιάννη, 2009, pp.55 – 57, fig. 2 (no. 2); Κακαβογιάννη, et al., 2009) is dated from the FN to the EH II period (Kakavogianni, et al., 2016, pp.442 – 443). In the first two occupational phases assigned to the FN/EH I and the EH I period, the settlement is characterised by underground chambers cut into the soft bedrock, organised in six clusters (Α – ΣΤ), which were used as residences (Κακαβογιάννη, et al., 2009, figs. 1 – 3, 7, 8, 12, 14; Kakavogianni, et al., 2016, figs. 6, 7). During the third phase, in the EH II period, habitation was limited to few underground chambers and to two small free-standing buildings, built above ground (Κακαβογιάννη, et al., 2009, pp.169 – 171, figs. 1, 15).

Eighty litharge fragments (in total 9 kg) were recovered from the entire Merenda settlement. However, the vast majority of the material is dated to the FN/EH I and EH I phases. A large number (34) were found in the fills of chambers A, B, Γ, Δ and E. Following their use, these chambers had been filled with waste from the settlement and among these materials also the litharge fragments were found, which were mainly bowl-shaped.

Amongst the material discovered in the chambers, particularly important is the identification of litharge fragments in a closed context from cluster B of the subterranean chambers (Kakavogianni, et al., 2016, pp.445 – 447), which, according to the latest evidence from radiocarbon dating, date to the middle of the 4th millennium BC (Maniatis, et al., 2016, p.58; Tsirtsoni, 2016, p.454). These are the earliest securely dated litharge fragments known to date and constitute the earliest direct evidence for silver production through cupellation in the Aegean. Furthermore, a small fragment of a flat litharge was found in a small, isolated building in close vicinity to the settlement, which was characterized as a small 'workshop' due to the nature of the finds that included a large number of stone tools.

In the third phase of the settlement (EH II period), in close vicinity (northeast) to a small free-standing house, an important obsidian and flint tool production workshop (Spiliotakopoulou, 2020) was brought to light. In the same context, several metallurgical remains were uncovered relating mainly to copper (clay moulds and copper slags) as well as a lead clamp, a small amorphous lead fragment and few fragments of litharge. The latter are all very small and fragmentary and their original shape cannot be reconstructed.

At the Merenda settlement we recovered primarily bowl-shaped litharge fragments (76 out of 80) and a small number of flat fragments. Intact bowl-shaped litharge examples were not found at Merenda; the largest preserved fragment measures 9 by 6 cm and provides substantial information concerning its original shape – its diameter would have been approximately 10 cm and its height about 2 cm. The average size of the litharge fragments is relatively small, roughly 4 by 3 cm. The vast majority of the fragments has a flat upper surface (Fig. 13), with no evidence for the characteristic depressions, which, as was outlined before, is a distinctive element of the finds from the nearby workshop of Lambrika. In three cases, however, the litharge fragments display a single large depression on their upper surface (Fig. 14). Contrary to the multiple depressions seen in the litharge fragments of Lambrika, these single depressions on the Merenda specimens could be a natural result of the cupellation process, marking the spot, where the silver was concentrated at the end of the process (see for example Bayley and Eckstein, 1997; Renzi 2013, p.54, fig. 4.1) or performed to collect the silver during the process of cupellation.

In the flat litharge fragments, a different type, or a different procedure cannot be distinguished, as their number and their state of preservation is poor. It is noteworthy that their thickness, which is less than 1 cm, is smaller than that of the bowl-shaped litharge of Lambrika and of some small pieces of so-called plate-shaped litharge known from other sites (Kakavogianni, et al., 2008).

The archaeological context of the litharge fragments in the excavated area at Merenda do not allow for identifying a particular workshop area, as diagnostic installations were not recognized and there were no particular concentrations of these waste materials that stood out, as is the case with Gyalou, discussed below. Litharge fragments at Merenda are found dispersed throughout the excavated area and across all chronological phases.

Fig. 13: Fragments of bowl-shaped litharge from Merenda (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Fig. 14: Fragment of bowl-shaped litharge with a single depression on upper surface from Merenda (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Their poor preservation in comparison to the other sites discussed here is also noteworthy. Nevertheless, the number of specimens is substantial, particularly if we compare it to the small number of litharge from the large settlement of Koropi (see below).

We therefore suggest, even in the absence of clear installations, that towards the middle of the 4th millennium BC, there was another cupellation workshop in the broader area of Merenda, whose litharge finds differ from those of the workshop of Lambrika. Although the litharge at Merenda is also bowl-shaped, the characteristic depressions are absent. The significantly smaller amount of litharge found here, may reflect the fact that the actual workshop area has not been identified, or alternatively, might indicate a smaller scale of production, possibly only serving the needs of the settlement itself.

Gyalou

The settlement of Gyalou at Spata (Fig. 1) is a small, flat settlement of approximately 3 acres, dating to the FNL/EHI period (Γκινάλας, Στάθη and Ζγουλέτα, 2015; Georgakopoulou, et al., 2020). In the western part of the settlement, excavation revealed mainly groups of pits which were used as storage areas, refuse pits etc.. Aside from stone tools and pottery, several litharge fragments were recovered from some of these pits.

Fig. 15: Fragments of bowl-shaped litharge from Gyalou (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Fifty-one litharge fragments (8 kg) were recovered in the Gyalou settlement and all were found in the western nuclei and particularly its northern part, in Sector 14. Excavations in this sector revealed a complex of six pits of different sizes. The largest is Pit 6 of ellipsoid shape and large dimensions (2 by 2.3 m), but relatively shallow depth (0.66 m). In its interior there was a grey-brown fill, whilst on its sides there was a groove, perpendicular to them. The largest number of litharge fragments was collected from the interior of this pit together with masses of clay, pottery, stone tools (obsidian and grinding tools) and animal bones. Pit 1, of approximately circular shape and smaller dimensions (diameter of 1 m), had at its bottom a floor made up of semi-worked stone. Initially it probably served a storage use, but subsequently became a refuse pit filled with pottery, stone tools and a few litharge fragments.

All litharge fragments from Gyalou are of the bowl-shaped type (Fig. 15). Their preservation is quite good. Although there are no completely preserved pieces, the average size preserved is quite large around 7 by 5 cm. The largest preserved fragment measures 12.3 by 9.8 cm. Their estimated diameters range between 11 – 22 cm, whilst their height is approximately 2.5 cm. They have a flat upper surface (Γκινάλας, Στάθη and Ζγουλέτα, 2015,

Fig. 16: Fragments of clay moulds from Koropi (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

Fig. 17: Fragment of bowl-shaped litharge from Koropi (source: Archive of the Ephorate of Antiquities of East Attica, Copyright © Hellenic Ministry of Culture and Sports).

p.344, fig. 23), whilst their bottom surface is rough with evidence of burning and attached soil. Approximately one third of these (15 examples) bear on their upper surface a single central depression, similar to that seen in some cases at the Merenda material. The central depression has a diameter that ranges between 1.4 – 3.8 cm and a depth of 0.2 – 0.3 cm. As in Merenda, this could be the negativeprint of the silver which agglomerates by cupellation, rather than pre-formed depressions on the cupellation hearth lining, as proposed for the case of Lambrika. The excavations at Gyalou did not bring to light a single example with multiple depressions, as known from Lambrika and Zapani.

Although, similarly to Merenda, clear workshop features were not identified in the excavated settlement, the evidence for *in situ* cupellation is substantial. It includes a large number of litharge fragments and their concentration in a single part of the settlement, specifically its northern side, as well as their spatial connection with a group of pits, which might be connected to the metallurgical activities based on the associated finds and evidence for burning.

Koropi

The extensive and nodal settlement of Koropi, situated at a distance of 5 km from Lambrika (Fig. 1), shows a different picture in terms of the presence and distribution of metallurgical remains. Such finds were retrieved from the earliest strata dating to the EH I period (western part of the settlement) (Kakavogianni, et al., 2008; Κακαβογιάννη and Ντούνη, 2009, p.392). They include a fragment of a bowl-shaped litharge without depressions, a few copper slags and 23 clay moulds (Fig. 16). They were mainly found in secondary deposits in the filling of a room together with a great quantity of pottery, animal bones, shells and stone tools.

Metallurgical finds dating to the subsequent EH II period were recovered from the western, eastern and northern nuclei of the settlement. In the filling of the subterranean chambers (northern nucleus), three small fragments of plate-shaped litharge were collected, as well as clay crucibles, clay moulds and two large copper slags, one of which is rounded and appears to have been used as a pestle (see for comparison Georgakopoulou, 2013, p.672 and references within). A copper slag and a clay mould were collected from the eastern part of the excavated street.

Several clay moulds and two litharge fragments were found scattered in the eastern and western part of the settlement, where complexes of streets with adjacent houses were discovered as well as a large communal building and areas for the processing and production of stone tools.

In total six litharge fragments were found in the excavated area, a number surprisingly small compared to the previous sites, especially if the large extent of the excavated area is taken into account (Georgakopoulou, et al., 2020). Only one of them is clearly of the bowl-shaped type (Fig. 17), most probably without the characteristic depressions. In contrast to the surprisingly small number of litharge fragments, evidence for copper working activities is particularly striking at Koropi, mainly at the early phase of the settlement (EH I period).

Discussion

From simple bowls to bowls with depressions – an Attic/Lavreotic innovation

Similar to the scanty early lead-silver mining evidence in the Lavreotiki region, the earliest litharge fragments known from southeast Attica date to the Final Neolithic period, in the middle of the 4th millennium BC and were found at Merenda (Tsirtsoni, 2016, p.450, n. 113). Perhaps the material from Gyalou dates to the same period. However, the only clear cupellation workshop known presently, at Lambrika, is dated to the following period, the EH I, at the end of 4th/beginning of the 3rd millennium BC. Its discovery in 2002 opened a new chapter in the study of archaeometallurgy in Attica. The earliest litharge finds from the extensive Koropi settlement also date to the EH I, as does the single example from the cemetery of Tsepi, Marathon (Παντελίδου-Γκόφα, 2005, pp.68, 323, 345 – 349, pl. 8) as well as all the litharge fragments recovered from Asteria, Glyfada (Καζά-Παπαγεωγίου, 2014, fig. 6). The dating of a second potential cupellation workshop found at Zapani (Andrikou, et al., this vol.) also seems to extend back to this period. So far, it constitutes the earliest preserved workshop from within the Lavreotiki.

The EH I thus emerges as a period of intense silver production activity in southeast Attica. This picture somewhat changes in EH II. Aside from the possible workshop at Zapani, which continues to operate, evidence from the settlement of Lambrika, suggests that metallurgical activities also continue there, but on a much smaller scale. Remains associated with lead-silver metallurgy of this period have also been discovered in different areas in Attica: litharge fragments in Koropi, Ayia Marina at Koropi, Provatsa on Makronissos (Spitaels, 1982, p.158), Kalyvia Melissourgou (Τσαραβόπουλος, et al., 2001, p.186), two so-called lead ingots from Rouf (Πετριτάκη, 1980, p.174, pl. 48a) and the leaf-shaped lead object from Askitario at Raphina (Θεοχάρης, 1953 – 1954, p.75). The earliest exploitation of Mine No. 3 at Thorikos has been dated to this period, although the ceramic evidence suggests possibly earlier works (Spitaels, 1984, 166; Νάζου, 2013).

During the following Middle Helladic period, litharge fragments have been found in settlements such as Velatouri at Keratea (Kakavogianni, et al., 2008, p.50, fig. 10; Κακαβογιάννη and Ντούνη, 2009, pp.393–395) and Velatouri at Thorikos (Servais, 1967, p.22, fig. 16). Perhaps the examples mentioned above found in private collections or in classical contexts also date to prehistoric periods.

With reference to the morphological aspects of litharge, the bowl-shaped type is by far the most abundant and characteristic type of the prehistoric period. It is related to a specific technological process that becomes evident in the Lambrika workshop. All the other types, like plate-shaped litharge, flat litharge or lumps are so few that we cannot draw any conclusions concerning the technology involved (Kakavogianni, et al., 2008). As for the morphology of the bowl-shaped litharge, in the light of the present finds, we can distinguish two categories: bowl-shaped without depressions (*Merenda type*) and with multiple shallow depressions on their upper surface (*Lambrika type*). In the first category, some specimens bear on their upper surface a single central depression. The archaeological evidence proves that there is a chronological difference between the two categories, at least between the material discussed in this paper; the bowl-shaped specimens without depressions being older than the Lambrika type. It seems that the older material (FN) in Merenda and Gyalou is always without depressions, while the depressions appear from the more mature EH I phase, attested at Lambrika. However, the appearance of depressions may also have a restricted spatial distribution within Attica, concentrating primarily in the Lavreotiki and extending to Lambrika. This would be supported by their absence not only from adjacent sites such as Merenda and Koropi but also from other sites at a longer distance such as Tsepi or Asteria.

Bowl-shaped litharge cakes are also known from Aegean sites outside Attica such as at Final Neolithic Limenaria on Thasos (Papadopoulos, 2008; Neranztis and Papadopoulos, 2013; Νεραντζής, 2017; Bassiakos, et al., 2019) and EBII Akrotiraki on Siphnos (Papadopoulou, 2011; Μπασιάκος, et al., 2013; Παπαδοπούλου, 2013). None of these show any evidence for the multiple depressions on the upper surface, proving that these are so far at least a regional, Attic/Lavreotic innovation. The reason behind the clearly deliberate presence of these depressions leaves many open questions. Was the aim to recover silver in small globules of specific sizes? This is a tempting suggestion with interesting implications for early systematic recovery and distribution of precious metals in specific weights and sizes. Presently we have no evidence for the existence of such small silver globules in the prehistoric Aegean, however, this cannot be considered negative evidence, as these could have been remelted to make artefacts. Alternatively, or additionally, would these depressions have improved silver recovery by exposing slightly more lining surface and promoting the soaking of the lead oxide (Rehren and Klappauf, 1995)? Or finally, is this Attic technological particularity not driven at all by functionality, but rather reflects an attempt at a distinctive cultural differentiation by the Attic metalsmiths? Planned future systematic experiments will attempt to address these questions.

Presence of litharge in the sites mentioned above – identification of cupellation workshops

Litharge may be present in an archaeological context either as waste, or as raw material for secondary use, with several instances known from antiquity (see discussion and references in Georgakopoulou, 2007, pp.394–395). Specifically in the Aegean, there is clear evidence that litharge was used as a pigment at the site of Akrotiri on Thera, based on remains of the material identified on a significant number of stone tools dating from the Early to the Late Bronze Age (Sotiropoulou, et al., 2010). Similar evidence has not been identified in Attica, but a systematic study remains to be done. Earlier analyses of litharge and lead and silver artefacts from the Bronze Age Aegean have not favoured the idea that litharge was recycled back to lead metal in the prehistoric Aegean (Gale and Stos-Gale, 1984; Pernicka, et al., 1983). The relatively high silver content of the analysed lead artefacts (above 0.01%) compared with the analyses of contemporaneous litharge finds suggested that lead was produced by smelting separate batches of silver-poor lead ores, rather than by reduction of the litharge produced as a by-product of silver production from silver-rich lead ores. It should, however, be noted that published analyses of lead, silver and litharge finds from the Attica region are so far scarce and the pattern remains to be tested here.

Thus, the identification of litharge fragments on a site does not necessarily suggest *in situ* cupellation, but the possibility that these have been transferred there for secondary usage needs to be considered. Useful deductions are to be drawn when considering the archaeological contexts of these finds. The quantity of litharge and the workshop installations at Lambrika leave no doubt that a cupellation workshop existed on the site during the EH I and possibly during the EH II. Similarly, Zapani also stands out as a cupellation workshop, based on the high relative number of litharge compared to the excavated area (Georgakopoulou, et al., 2020), despite the lack of identified installations so far. In any case, the unsophisticated nature of these installations means that their preservation in most cases is rather unlikely. Although significantly less, both in absolute terms and relative to excavated areas, the amounts of litharge from Merenda and Gyalou are substantial and were most likely disposed of from a nearby cupellation workshop, as yet unidentified. The smaller quantities suggest activities on a much smaller scale or perhaps carried out at a longer distance from these settlements or over a shorter period than those of Lambrika or Zapani.

The situation at Koropi is, however, somewhat different and the strikingly small number of litharge compared to the size of the excavated settlement could either suggest that cupellation was practiced rarely and in a very small scale here, or alternatively that the litharge was present as raw material for other uses. What these possible uses may have been remains to be addressed through the thorough study of the range of finds from the settlement. Regarding the possibility that the litharge fragments served there as raw material for recycling and re-melting back to lead metal, another parameter should be noted. The analysis of litharge fragments from Attica, undertaken so far (Georgakopoulou, et al., in prep) showed that these are not composed of pure lead oxide but bear a significant content of other gangue oxides. In principle pure re-melting of these materials under a reducing atmosphere would not produce pure metallic lead unless they were properly smelted removing the gangue oxides by slagging. The lack of such slags from the excavated sites in southeast Attica may constitute an additional argument against the proposal that litharge was re-melted back to lead metal during this period.

The wealth of finds from southeast Attica testify to the significance of the rich metalliferous deposits of Laurion already from the earliest stages of silver production in the Aegean. The inhabitants of this region not only knew of these resources, but also systematically exploited them, as is clearly evident from the organized Lambrika workshop. It seems that Lavreotic silver and lead were distributed across the Aegean. The finds discussed here illustrate a unique Attic/Lavreotic technological trajectory which is currently being defined more specifically both temporally and spatially.

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We mourn the sudden loss of our colleague Myrto Georgakopoulou. She was an eminent scientist and her work has had a transformative effect on our understanding of prehistoric metallurgy and Laurion's important role in prehistoric and later periods.

Notes

1 The archaeologists K. Douni, P. Michailidi and F. Nezeri participated in the excavations at Lambrika. The archaeologists M. Nazou and Efth. Kakavogiannis catalogued the litharge and other finds.

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Cupellation and litharge in their technological context at Laurion, Attika (Greece) – From Prehistoric to Hellenistic and early Roman periods

ABSTRACT: *The extraction of silver and lead at Laurion started in prehistoric times and reached its peak in the classical period, it passed through crises and recoveries during the Hellenistic period and finally ceased permanently in the beginning of the Roman period. During this long period of time, the techniques used for silver extraction were adapted to the raw material available and the production scale. Among them, cupellation variants of argentiferous lead for silver production were evidenced at many locations of the wider area of Laurion, as it is shown from findings of different types of litharge and cupel forms and sizes, located close or at a greater distance from the source of the ore.*

In the present work, the process of cupellation is described from a scientific and technical point of view and an attempt is made to interpret the remains that were preserved on the surface or found in excavations, with regard to their technological context. The technology of the cupel of the classical period at Laurion is examined and compared with the corresponding technology of the prehistoric period and with cupels made from porous ceramics of the Middle Ages in Europe. Litharge, the waste of the cupellation process, is also thoroughly examined, since it plays a key role in the performance of the process for minimizing silver losses. But this material, even after its removal from the furnace, remained still useful in applications of technological or economic importance, to which reference or brief description is also made in the text.

KEYWORDS: CUPELLATION, LITHARGE, FURNACES, LAURION, ANCIENT METALLURGY

Introduction

The old-world mining and metallurgical history of the wider area of Laurion, also known as Lavreotiki, extends from the Late Neolithic to the Roman and early Byzantine period. In recent times, after a long period of inactivity, mining and metallurgy have been resumed from about the middle of the 19th to the middle of the 20th century AD. (Kordellas, 1867; Ardaillon, 1897; Conophagos, 1980).

In the old technological history, there are, however, intermediate gaps, most probably due to lack of evidence as opposed to the absence of activities in the corresponding periods.

The most imperfectly known aspect of Laurion is its technological path through prehistoric times, which extends further until the end of the Archaic period. This is due mainly to the rarity of relevant findings. The failure to find prehistoric metallurgical remains inside the central mining zone of Laurion, has been attributed to the fact that older residues were recycled, moved or covered with newer ones during periods of intense mining and metallurgical activity, so that today it is difficult to isolate and identify them. Nevertheless, it is now confirmed that copper, silver and lead had begun to be produced at Laurion since the end of the Neolithic era, thanks to the isotopic analysis of lead contained in prehistoric metal objects, which proved that a significant number of them had been produced from silver and copper from Laurion (Gale and Stos-Gale, 1981, p.211 – 13; Stos-Gale, 1989, pp.287 – 88).

Prehistoric remains of silver metallurgy (mainly litharge and lead pieces, fragments of cupels and smelting slags) associated with Laurion, have been identified at Thorikos, in a settlement near the top of Velatouri hill, where silver production was evident from cupellation residues (Servais, 1967, pp.24 – 7) and on the islands of Makronissos (Spitaels, 1982a, p.158) and Keos (Gale and Stos-Gale, 1981, p.191; Gale and Stos Gale 1984). Significant concentrations of litharge and other residues of the prehistoric period that are clearly related to silver production were found more recently in Mesogeia, at the site of Lambrika-Koropi, at Koropi and other nearby areas (Kavogianni, et al., 2008, p.58 – 62). In particular at Lambrika, along with pieces of litharge, a large number of broken shallow bowls were discovered and have been characterized as a particular type of litharge, but in my opinion are certainly prehistoric cupels. These indicate the existence of an argentiferous lead cupellation workshop which, according to the dating, was active in phase I of the Early Bronze Age (Kakavogianni, et al., 2006).

Findings concerning copper metallurgy have been identified at Raphina (Theocharis, 1952; Theocharis, 1954) and on the island of Keos (Coleman, 1977).

The sites above are located at the wider periphery of the mining zone, with the exception of Thorikos and Makronisos which are close to Laurion.

Mining activity in Lavreotiki during the prehistoric era is known from the hill Ovriokastro of Keratea, on the southern slope of which there are mining traces in the first metalliferous contact, outcroppings on the surface, as well as obsidian blades and fragments of vessels of the Final Neolithic period (3500 – 3000 BC) and from the Early Bronze Age I (3000 – 2800 BC) (Kakavogiannis and Kakavogianni, 2001, pp.55 – 85).

But the only prehistoric mining work that has been thoroughly studied so far is the Mine 3 at the foot of Velatouri hill, west of the Thorikos Theatre (Spitaels, 1984). It dates back to the 3rd millennium BC and was opened for the extraction of lead ore from a vein outcropping on the surface. There have not been remains of silver metallurgy at this place, but fragments of litharge of the same period, were found in the prehistoric settlement of Provatsa in the near-by Makronisos island (Lambert, 1972; Spitaels, 1982a).

In Thorikos the production of silver continued during the Late Bronze Age (Mycenaean period), as evidenced by the presence of fragments of Mycenaean vessels in Mine 3 (Spitaels, 1982b).

During the Classical period, well organized mines, ore dressing plants and metallurgical furnace compounds were active, producing silver and lead. The relevant technology is mainly known from archaeological excavations (Conophagos, 1980; Jones, 1982; Tsaïmou,1988; Kakavogiannis, 2001) as well as from an important number of archeometallurgical studies. Iron production from local ores has been, also, documented in the same period (Conophagos and Papadimitriou 1982, p.363).

During the Hellenistic times the number of active mines was reduced, due to political instability. Mining experienced long periods of crisis, but during the 2nd century BC mining activities resumed. During this period the exploitation of ores in deeper horizons (the so called “third contact”) was intensified by means of mining shafts. The ores extracted from them included sulphides very rich in silver; for example in the regions of Ari and Soureza contents up to 5,000 g Ag/t Pb were found. At Demoliaki, which is situated near to Ari, Hercules Katsaros located a few years ago, the first roasting furnace for sulphides (Papadimitriou and Katsaros, 2019) which allowed roasted sulphides to be smelted in the conventional smelting furnaces. In the same period, a new technology for recycling of old stocks of litharge was developed due to the discovery of, high productivity, circular mills, which enabled fine and uniform grinding of the material (Papadimitriou, 2015, 2016).

There is no information on possible production of silver at Laurion after the Hellenistic era, except from Strabo (9,1,23), reporting on recycling of old waste stocks for production of silver. Then the eclipse of Laurion is attested by Pomponius Mela (II,3,46) in 40 AD and is confirmed by Pausanias in the 2nd century AD (1,1,1). However, some activities are confirmed later, at the beginning of the Byzantine period, as evidenced by the discovery of coins of the 4th century AD (Cordella, 1894, p.239; Conophagos 1980, p.385). There is, also, a reference by Silentarius Paulus to the Inauguration of the church of Hagia Sophia in Constantinople in 563 AD, according to which the decoration of the church was made with silver from the Mines of Pangaion and Laurion (Corpus Scriptorum Historiae Byzantinae, 26, pp.679 – 80).

From the previous review it is clearly seen that cupellation was the technique continuously employed, from the Final Neolithic period and onward, since remnants of litharge have been identified in sites of either period of prehistoric and then of historical times until the end of the Hellenistic period. Furthermore, the cupellation findings scattered across various locations, near or in the periphery of the source of the ore, are an indication that the process of cupellation was practiced also as a small-scale metallurgical process, independent of smelting and mining. These reasons could justify possible local variations of the process, and adaptations to the production scale. Unfortunately, no place is known until now where a cupellation furnace along with its workshop and relevant remains are still preserved and studied. For this reason, many issues of cupellation of argentiferous lead remain open, so that discussion continues with much interest, especially for the prehistoric period, where the interpretation of some archaeological findings, still remains controversial.

In the present paper the cupellation process is described and discussed, with emphasis given to its operation at Laurion, based mainly on the study of local findings. In the same context a brief description is given for the roasting and smelting processes which are stages of the production chain of silver and lead, prior to cupellation.

Special sections are devoted to the technology of cupels and to the metallurgical properties of litharge, since both of them are of main concern for the good performance of the process for avoiding/minimizing silver losses. A particular section is also devoted to the cupellation process of the prehistoric period attempting to interpret the exact role of the cupels in the form of shallow bowls with depressions at their bottom, which were found at many places of Laurion and more recently in a large number at Lambrika-Koropi.

Litharge, after it was discarded from the cupellation furnace, was not a real waste, since it became later a source of revenues from production of silver and commercial lead after recycling. Furthermore, due to its special properties it was used in many different applications such as waterproofing mortars for cisterns (Conophagos and Papadimitriou, 1978; Papadimitriou and Kordatos, 2001) and ceramic fabrics for making cupels. These issues are also mentioned or briefly described.

The present work is limited as far as possible to technological issues, without extending to archaeological ones, for which there is a significant number of archaeological studies available (see Andrikou, 2015, Kakavogiannis, 2005).

Ore smelting

The first stage of silver production process from ore at Laurion was smelting. The charge smelted comprised mainly cerussite with possible addition of galena up to 20 percent (Conophagos, 1980, pp.278 – 79). It is of course known that there is a possibility of a combined process of roasting and reduction of the ore in one single stage in the reduction furnace, as described by Hauptmann, et al. (1988, p.110 – 11) for Thassos, but so far it remains open whether it was used at Laurion (Bachmann, 1982, pp.248 – 51). In any case, the product obtained from smelting was argentiferous lead, an alloy of lead containing silver at a ratio varying between 1,000 and 4,000 g Ag/ t Pb, depending on the ore used. The most common average silver content was around to 2,000 g Ag/t Pb.

Fig. 1: Remains of the Megala Pefka smelting furnace at Legrena, Laurion). The semi-circular supporting wall of the furnace shaft with the air inlet stone-built channel at its base. (Photo: G.D. Papadimitriou).

Fig. 2: Remains of a smelting furnace at Ari (Laurion). The shaft was based on two stone boulders, carved internally in a circular cross-section of 1 m diameter. The air inlet was through a vertical stone-built channel at the back of the furnace. (Photo: G.D. Papadimitriou).

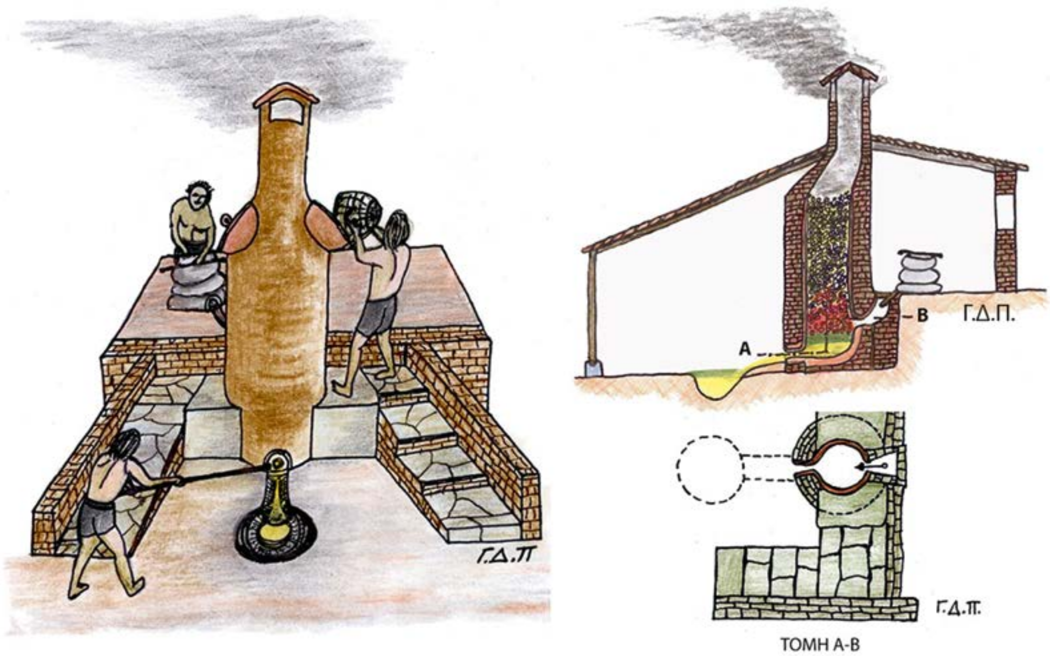

Fig. 3: Schematic representation of the smelting furnace at Ari (Laurion). (Drawing: G.D. Papadimitriou).

Smelting was done in shaft furnaces using charcoal as heating and reducing agent. Photographs of remains of smelting furnaces at Laurion in the areas of Megala Pefka and at Ari are shown in Fig. 1 and 2. A schematic reconstruction of a typical smelting furnace, based on the previous remains, ancient texts (Diosc. 5,85) and Attic vase paintings (Chatzidimitriou, A., 2005, tab. X2, X12, X13) is shown in Fig. 3 (Papadimitriou, 2018).

The internal diameter of the furnace is about 1m and the height is estimated at 2 – 2.3 m. Three consecutive levels serve the operation of the furnace: the ground level, where the furnace is based and where liquid lead and slag are concentrated in a pit, the second level accessible by a staircase, from which a worker charged the furnace with ore and charcoal and the upper level, behind the furnace, where one or two workers operated skin-bellows for furnace blowing, Fig.2. The air blown was directed through a vertical stone-built channel and entered at the back of the furnace. No residues of ceramic channels were found during excavations.

In order to have a proportion of sulphides higher than 20 % in the charge, the miners had to expose the sulphides to an oxidizing roasting environment, in order to convert them to oxides before smelting.

Roasting was certainly known and practiced in the antiquity using stalls or roasting furnaces, however, only one

Fig. 4: Remains of a roasting (or calcination) furnace for galena (PbS) at Demoliaki (Laurion). (Photo: G.D. Papadimitriou).

Fig. 5: Schematic representation of a roasting furnace during the charging phase with galena and a small proportion of charcoal. (Drawing: G.D. Papadimitriou).

roasting furnace has been discovered so far. This furnace has been at Dimoliaki and discovered by Hercules Katsaros.The furnace is contemporary to the smelting furnaces at Ari (Papadimitriou and Katsaros, 2019), belonging to the Hellenistic period (Tsaimou, et al., 2015). It is a strong construction with 0.9m thick stone-walls, having the form of an inverted truncated cone, broadening upward with a slope of about 10 degrees, with a height of 2.2m and, an unusually large, diameter of about 2.5m, compared to the smelting furnaces which had an internal diameter of only 1m. Few slag foams remain attached on the wall near the furnace mouth, indicating that during operation the furnace was filled up to its top and that temperatures of 800 – 900 °C prevailed, locally, at this uppermost zone, leading to melting of the most fusible ore components. This is certainly due to the abundance of free air available near the wide furnace mouth.

A photograph of the remains and a reconstruction of the roasting furnace are presented in Fig. 4 and 5 respectively.

If the ores containing silver (or in other cases gold) were not ores of lead, but –for example- oxidized ores of iron, then they were subjected to leaded smelting (Hauptmann, 2020, p.338). They were smelted in the presence of a quantity of lead, so that silver was again dissolved in lead, giving argentiferous lead from which the precious metals were extracted by cupellation. As a matter of fact, lead is an extremely efficient scavenger of silver and gold. This technique was probably used in ancient times in the region of Pangaion mountain in Macedonia and in Chalcidique during the Byzantine period but nothing so far indicates its application at Laurion.

In 1864, about 30 heaps of ancient smelting slags were identified at different mining locations of Laurion by Kordellas, who recorded them on behalf of the State. About half of them were by the sea and the rest in the hinterland. Their reserves amounted to 1.5 – 2 million tons and were smelted by the Greek Metallurgical Company for lead production between 1865 and the beginning of the 20th century.

Assuming that each heap of slags was created from one complex of furnaces, we must accept the existence of at least 30 furnace complexes active in antiquity (from the Archaic to the Hellenistic period). However, only in six places remains of furnaces have survived and four of them have been excavated. Most furnaces were probably constructed during the Archaic and Classical period for the production of argentiferous lead intended for production of silver by cupellation, but their last period of operation should be placed in Hellenistic and Roman times. These were mainly used for the production of commercial lead from litharge and low content ore wastes (ekvolades), possibly aided by the addition of a small quantity of old slag relatively rich in lead. This was the case with furnaces at "Ari", as confirmed by radiocarbon dating of charcoal samples that gave a calibrated date (2σ) of 246-03 BC (Tsaïmou, et al., 2015, p.118).

Cupellation at Laurion in the Classical period

In order to separate and recover silver from argentiferous lead produced in the smelting stage, only a unique method was known: "cupellation".

Cupellation is a process separating silver and lead by the selective oxidation of lead from an alloy of predominantly lead and silver composition (argentiferous lead).

The method consists in melting the argentiferous lead in a cupel placed inside a reverberatory furnace by burning wood or charcoal and blowing air on the surface of the bath by means of bellows (Fig. 6).

During this process lead is selectively oxidized to form litharge (lead oxide, PbO) which is immiscible with lead and has a lower density, so it floats as a thin liquid layer on top of the bath of lead.

As soon as the layer of litharge reaches a thickness of about 1 – 2 mm, it is somehow removed from the surface of the melt, so that, by continuing air blowing, the quantity of lead in the cupel diminishes and silver content increases progressively in the bath. The temperature should be maintained around 900 °C, given that litharge melts at 880 °C. Pure silver melts at 962 °C, but remains in solution in the liquid alloy almost to the end of the process, namely until the liquid alloy content reaches 90 % of silver. Then it begins to solidify and, therefore, the temperature should be increased to about 1000 °C, so that the alloy remains in a liquid state for as long as necessary to complete the removal of lead and impurities.

When almost all lead is oxidized and removed, silver remains in the bottom of the cupel, as an alloy of silver containing mostly lead and copper as impurities (in actual metallurgical jargon this alloy is called a "doré"). Then with further oxidation of the last impurities, silver becomes superclean, its melting point increases sharply leading, eventually, to its solidification. This is the end of cupellation

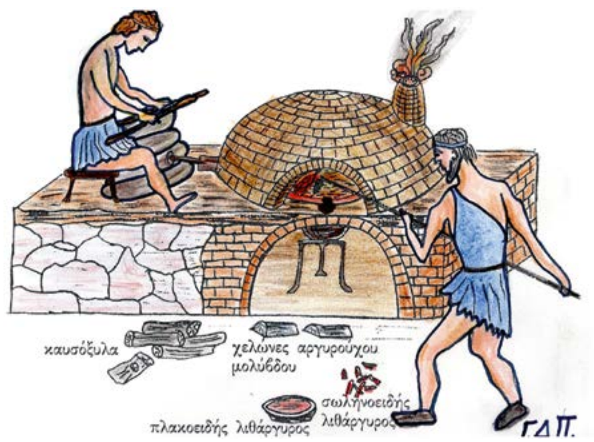

Fig. 6: Virtual reconstruction of a cupellation furnace of the classical period at Laurion. (Drawing: G.D. Papadimitriou).

Fig. 7: Very shallow cupel of the classical period at Laurion, from the collection of K. Konophagos (Author's modification from Conophagos, 1980, p.315, fig.12-4).

Fig. 8: Deep Cupel of conical form from Megala Pefka (Legrena, Laurion), Classical to Hellenistic period. (Photo: G.D. Papadimitriou).

and it is clearly perceived from the characteristic "glancing of silver". This is attributed to the latent heat that is abruptly released from the solidification of silver.

However, the description above is rather simplified from a technical point of view. In practice, the process of cupellation was certainly done in two successive stages in order to limit losses of silver withdrawn inside the rejected litharge. This issue is described below.

It should not be disregarded that during cupellation a small fraction of silver oxidizes as Ag_2O and dissolves into the mass of liquid litharge. As a matter of fact, liquid litharge which forms on the surface of the metallic bath is a sort of slag and chemical elements and oxides such as CaO, SiO_2 and Cu/Cu_2O, including silver, are partitioning between the metal and the slag. Modern experiments show that the quantity of the silver lost in litharge as silver oxide, would cause silver losses of the order of 1 – 3 % (Swinbourne, et al., 2003, C73; Ulseth, et al., 2015, p.269). It is not possible to avoid completely these "chemical" losses, but it is possible to reduce them by applying cupellation temperature which is as low as possible. The control of this process requires however a deep metallurgical knowledge and a strict control of temperature, something that was certainly beyond the skills of ancient metallurgists. However, a more practical means for reducing this kind of losses is by removing the litharge as soon as possible from the surface of the bath, before it becomes saturated in Ag_2O. Removal of litharge from the surface of the bath is also advantageous because it allows direct contact of air with the lead, accelerating thus the oxidation process.

In the Classical period, litharge was aided to flow over the rim of the cupel and run out of the furnace, by the impact of the air blown on the bath. Alternatively, it was removed from the surface of the cupel by means of a scraper. At the same time, the volume of litharge removed was replaced by a corresponding addition of argentiferous lead in the form of ingots. During the removal of litharge from the cupel, small masses of liquid argentiferous lead were inadvertently entrapped in litharge and were carried away, forming solid inclusions inside the litharge mass after its solidification. This was a second type of silver loss, a "mechanical loss", which was more important than "chemical loss" described above, in particular, when the cupellation process had advanced and the lead bath had become very rich in silver.

For resolving this problem, the metallurgists conducted cupellation in two successive stages. Between the two stages, they probably transferred the content of the cupel in use to a second one. The technique of using two cupels is mentioned by Pliny, but it is not quite clear how it was practiced, in the case it was actually applied during the classical years at Laurion.

Nevertheless it is certain that in the second stage of cupellation, the removal of litharge from the cupel was no longer done as previously, but by dipping in the bath the edge of iron rods, on which litharge was selectively attached and drawn out of the furnace. After solidification it had the form of small tubes, Pliny (n.h. 32) and is known as tubular litharge. Argentiferous lead was not attached on the iron rods, since there is neither wetting, nor reaction between iron and lead.

The application of this method was confirmed after identification of tubular litharge pieces at Laurion. This was a very smart technique, but since it suffered from low productivity, it was applied only as a second stage, when lead had become relatively rich in silver. This technique was shown to be applied during the classical years in Laurion during excavations (Conophagos, 1959), but it was also applied industrially in the 19th century AD, for example at Kongsberg (Girardin and Lecoq, 1826, pp.280 – 82).

Two cupels were identified at Laurion so far (Fig. 7. 8). They have not exactly the same form. The first one (Fig. 7) from the collection of K. Konophagos (Conophagos, 1980, p.315, fig. 12-4) was shallow with a large surface area in relation to its depth, in order to accelerate the cupellation process. The form of this cupel seems quite adapted for the first stage of cupellation, when the silver content of the bath was still relatively low and the removal of litharge from the cupel was done in one of the ways described earlier in this section. Then litharge was poured out of the furnace, either on the ground or in molds with a flat bottom, where it solidified taking the form of lumps or plates a few centimeters thick, respectively.

The second cupel (Fig. 8) was like a cone with a large surface area, but it was deeper than the previous one and therefore it was more convenient for dipping the edge of the iron bars into the bath. (Papadimitriou, 2012, p.810, fig. 3).

An estimation of the silver content in argentiferous lead, at the time when the removal of litharge started using iron rods, was done by examining an important number of samples of plate litharge using EDS microanalysis in Scanning Electron Microscopy (SEM). It was found that the inclusions of argentiferous lead in litharge contained usually 2.5 – 2.8 % Ag and in some cases up to a max. 5 %. Tubular litharge produced in the next stage of cupellation was practically exempted of measurable argentiferous lead inclusions.

Our knowledge on the form and size of the cupellation furnaces of the classical period at Laurion is limited. The only authentic testimony available is due to Kordellas, who wrote that: “Tracks of cupellation furnaces found at Lavrion testify that they were round, low, hollow in their middle and made of clay materials full of litharge” (Cordellas, 1890). This description clearly suggests that they were vaulted furnaces and that at least a portion of litharge was raked from the cupel on the bottom of the furnace. Conophagos represented a cupellation furnace as a vaulted furnace (Conophagos, 1980, p.307, fig. 12-1; p.315 fig. 12-4) in agreement with Agricola's depictions (1950, p.481) and in accordance to verbal information of old miners who had seen remains of ancient cupellation furnaces in the early 20th century.

Many years ago, I saw a vaulted cavity in the area of Bertseko, near the so-called “archaic washeries” of the excavations of E. Kakavogiannis. It had a diameter of about 0.8 m and was dug on a slope of the ground, inside a circular stone-walled enclosure of about 2.5 m diameter (Fig. 9). I considered it to be most likely a cupellation furnace, because of glazing and soot evidence on its vault and of its location in an area rich in metallurgical remains (lead smelting slags, fragments of litharge and burnt ceramic pieces. H. Katsaros, a resident of Lavrio, and passionate explorer of the mining area, found recently one similar furnace close to the previous one inside a rectangular enclosure of about 2×2.5 m, and probably another hidden in vegetation.

The presence of these furnaces situated close to each other, in an area where smelting and cupellation activities certainly took place, suggests that they are actually cupellation furnaces. However, it is astonishing that their construction looks like primitive, compared to smelting furnaces, washeries and other industrial constructions of the classical period that have been found so far at Laurion. In particular, it seems that they were fully operated by the door and neither chimney nor inlet for air blowing are present. It is thus probable, that they are older than classical, taking also into account that they are in proximity of the so-called archaic washeries, which according to Kakavogiannis (2001) are dated to the end of the archaic period. These washeries are also dug into the ground, their channels and water tanks have no waterproof lining and are irregular in shape and rather irrational from an ergonomic point of view.

Fig. 9: Cupellation furnace from the area of Bertseko (Legrena, Laurion) near the so-called “archaic washeries of Kakavogiannis" at Vrissaki of Kamariza. (Photo: G.D. Papadimitriou).

I suppose that cupellation furnaces attached to the Classical and Hellenistic furnace complexes were built more diligently, resembling rather to those of Agricola (Agricola, 1950, p.481). In this respect, it is worth noting that in the areas of “Oxygen” and “Megala Pefka” at Laurion, where the remains of important complexes of smelting furnaces survived, conical piles of stones are present, for which the most probable interpretation based to their shape and position is that they were once bases of stone-built cupellation furnaces.

Litharge

The oldest litharge pieces in the Helladic space and in particular at Laurion go back to the Late Neolithic and Early Bronze Age (Lambert, 1972; Spitaels, 1982a; Servais, 1967; Kakavogianni, et al., 2008; Papadopoulos, 2008). Then litharge is found in much more important quantities until the classical and Roman years. Although its persistence may seem singular, it is not unexpected, considering that cupellation was, in a global scale, the unique technique used for the extraction of precious metals from a melt of lead from the prehistoric through the classical, Roman, Byzantine and medieval times, until the early 19th century, when it was replaced by Pattinson's more economical method. But even today, although the industrial application of cupellation has ceased, the method continues to be used by goldsmiths for refining

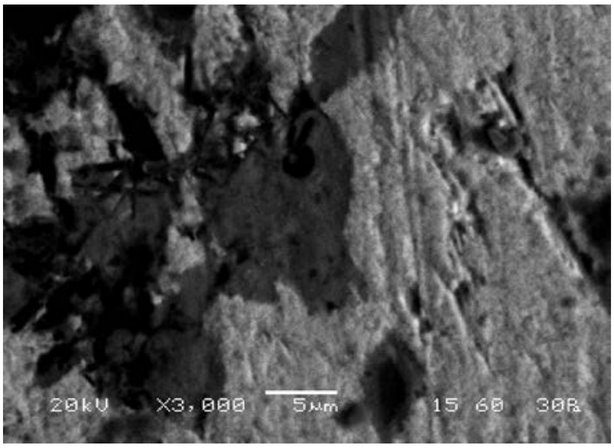

Fig. 10. Backscattered electron image from a section of a fragment of a platy litharge. Yellow litharge in light grey, red litharge in dark grey. Black needles are calcium-magnesium silicates, probably merwinite ($Ca_3Mg[SiO_4]_2$). (SEM micrograph: G.D. Papadimitriou).

and controlling the purity of gold, as an analytical tool for gold and silver determination, as well as in some special technological applications. Cupellation is thus, among the most resisting metallurgical techniques throughout the time. This allows us to deal with cupellation and litharge as a global issue, since the basic fundamentals of the method remain unchanged with the exception of technological details.

The name of litharge comes from the Greek λιθάργυρος, given by Dioscorides (50 AD) to a material obtained in the process of separating lead from silver. Litharge, in Greek, means literally "stony silver", certainly implying a useless form of silver, as if it was a "poor" stone. In Latin it is referred to by Pliny as spuma argenti, i.e. "silver foam" (Plin. n.hg. 32,106), a name that refers to the way it is produced, because during cupellation it floats on the bath from which it is removed by skimming. It is also mentioned by the name galena, essentially identified by Pliny with (non-silvery) galenite, i.e. an ore that can be used solely for lead production (Plin. n.h. 34,159). Therefore, all three names – Greek or Latin – are very expressive and contain important technological information.

Litharge (lead II oxide, lead monoxide, PbO) occurs in two crystal forms. The first one, massicot, has an orthorhombic structure, is yellow, and is stable at high temperatures. The rsecond crystal form has a tetragonal structure, is red in colour and is stable for $\theta < 540\,°C$. With rapid cooling from high temperature, the yellow form is maintained at the ambient temperature, but with even faster cooling the amorphous (glassy) state can be also obtained. Red litharge is obtained by slow cooling down to the temperature of the environment. All forms of litharge have a high specific gravity, the yellow 9.53 t/m^3, the red 8 t/m^3, and the amorphous 9.2 – 9.5 t/m^3, versus 11.34 t/m^3 of lead.

The chemical composition of litharge corresponds to 92.8 % lead and 7.2 % oxygen, so it can be considered as an extremely rich material for commercial lead production. Litharge obtained as a by-product of lead metallurgy in Laurion contained various impurities, mainly Fe, Ca, Si, As, etc. Among them the silver content ranges from 20 to 100 g Ag/t Pb (0.002-0.01 %), while the rest of metallic elements do not exceed 0.5 – 2 % in total. However, the silver content may reach 800 – 1,000 g/t Pb if many inclusions are present.

By examination of litharge samples from Laurion by means of X-ray diffraction and scanning electron microscopy associated to EDS microanalysis it is found that they consist mainly of a mixture of red and yellow litharge. Over time, a quantity of these was converted into lead carbonate (cerussite) and hydrated lead carbonate (hydrocerussite) under the influence of carbon dioxide and atmospheric moisture. Lead silicates and calcium-lead silicates that also contain magnesium, are also recognized either in massive or in needle-like form (Fig. 10).

Fragments of litharge of Laurion exhibit three different forms in terms of shape: plate litharge as slabs, a few centimeters thick, tubular pieces 3 – 5 cm long and 2 – 3 cm in diameter and lumps, i.e., masses without any specific shape. Their particular forms depend on the way litharge was extracted from the cupel and to subsequent solidification. It should be emphasized that litharge is also found at Laurion as residue of fine-ground material, usually of grain size either under 2mm or under 0.5mm. Their difference of fineness is due to the grinding equipment which was used in each case, namely reciprocating Olynthus mills in the old ore washery compounds and circular mills in the corresponding compounds, respectively. This issue will be addressed further in the section "Litharge during the Hellenistic period at Laurion".

The reason why litharge flowing out of the furnace was poured into molds with a flat bottom is, in my opinion, the following: during cooling and before solidification, the inclusions of argentiferous lead contained in the melt, settled near the bottom due to their higher specific gravity. After solidification many of them were visible on the outer surfaces of the plate and their concentration allowed metallurgists to judge which of the plates were rich in silver. Such plates were redirected in the smelting furnace to recover the metal. In the photograph of Fig. 16, a piece of litharge with many inclusions visible near their bottom is shown. The pieces of litharge in the form of lumps may have come from the earliest stages of the cupellation process, when the bath was still poor in silver. They were therefore poured into the ground or into small cavities before being disposed or stored for some other use. As a matter of fact, litharge could be used for the production of commercial lead, for the preparation of medicines, for the production of the waterproof coatings of water cisterns and possibly for other special applications.

Cupels

Two technical issues are directly related to the construction of a cupel: its shape and the material. Both of them

Fig. 11: Optical micrograph of the material of the cupel of Fig. 8, showing a kind of breccia microstructure characteristic of material produced by a mortar. It consists of angular fragments of broken litharge embedded in a fine-grained matrix. (Optical micrograph: G.D. Papadimitriou).

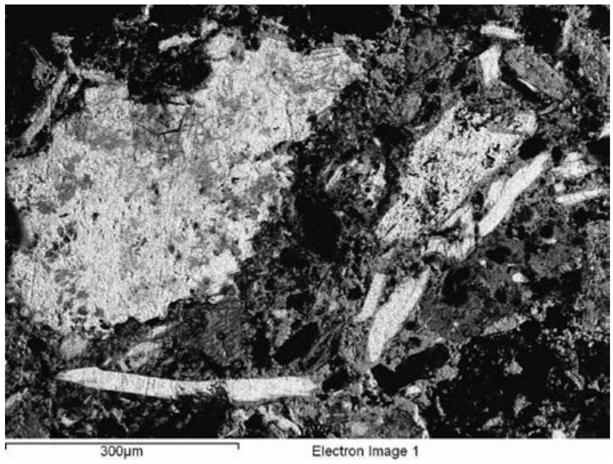

Fig. 12: Scanning electron micrograph of the material of the cupel of Fig. 8. Angular fragments of ground litharge are readily recognized. Light grey grains are PbO-yellow, dark-grey material is PbO-red, whereas grains of black material are mainly calcite, kaolinite and illite. (SEM micrograph: G.D. Papadimitriou).

are crucial in limiting silver losses during cupellation. The material of the cupel should not be wetted by liquid silver, otherwise some silver would be absorbed and lost in cracks and pores of the cupel.

The first choice of material that was most probably used for making cupels in prehistoric times at Laurion should be clay, since metallurgists were already familiar with clay from their standard metallurgical practice, namely for making ceramic walls of furnaces, refractory linings, crucibles and molds for casting. But clay was certainly judged not quite satisfactory in the case of cupellation, since it might absorb silver (Nezafati and Pernicka, 2012, p.41) leading thus to losses. In fact, wetting of ceramic materials from silver is a well-known physical property and is for example applied in modern technology brazing of ceramic materials, such as alumina and quartz, by means of silver as a filler metal. With regard to cupellation, it is known that materials consisting mainly of SiO_2 and CaO with some Al_2O_3 and minor concentrations of MgO, K_2O and P_2O_5, but without using bone ash, were used from the 4th millennium BC in East Anatolia for making cupels (Hess, et al., 1998, p.63–64). Also cupels made of ceramic materials were used in the Middle Ages before the 13th century, but there were not satisfactory, because litharge reacted with the silica contained in them, forming a glassy layer to which silver was mechanically attached (Bayley, 2008, p.138).

Prehistoric metallurgists certainly noticed the penetration of silver in cracks and pores of clay materials in their cupellation furnaces, and that's probably why they turned to the use of litharge for the manufacture of cupels, since they knew from experience that litharge and silver are not mutually wetted. For making cupels, the well-known technique used for ceramics was certainly applied. Litharge was ground to fine powder and mixed with the appropriate amount of lime as binding material and a small amount of clay as plasticizing agent with the necessary quantity of water for making a plastic mass. Then the cupels were shaped manually, from the plastic mass obtained.

Fig. 11 is an optical micrograph of the material of the cupel of Fig. 8, showing a kind of breccia microstructure consisting of angular fragments of broken litharge embedded in a fine-grained compact matrix.

The scanning electron micrograph (SEM; Fig. 12) shows that the mass of the cupel is compact and consists of rather angular grains of yellow litharge (light grey) and red litharge (dark gray), bound to each other with clay and calcium and lead carbonates that formed respectively from lime and PbO, under the influence of carbon dioxide and moisture of the atmosphere. The clay minerals are identified as kaolinite, illite, chlorite and quartz by means of EDS microanalysis and x-ray diffraction (Fig. 13). It is clearly seen that all of them serve as binding agents and form an almost continuous network around the grains of litharge (materials in black in the SEM photograph (Fig. 12). They also fill the voids of the material. The presence of other secondary minerals which usually accompany lime and clay are present in small quantities (dolomite, magnetite).

This form of microstructure clearly proves that the material was produced in the way we described earlier.

Similar results are obtained with a fragment of another broken cupel. Somewhat different was the x-ray diffraction spectra of powder taken from the inner surface of the cupel, showing the presence of an increased quantity of lead carbonate and kaolinite, meaning probably that a plaster of clay was applied on the internal surface of the cupel.

A question arises, however, for what reason ground litharge has been used for making cupels, since litharge could eventually melt in the temperature of the cupellation. At first, it should not be disregarded that the binding material used to consolidate litharge is refractory and should encompass the low melting point of litharge. On the other hand, one could object that during most of the time of the cupellation process the bath remains at temperatures around 900 °C and therefore the underlying wall of the cupel remains unaffected. The real problem could arise only at the final stages of cupellation, when the silver content in the bath reaches about 90 % Ag. Above this content, temperatures up to 960 °C are needed to melt the alloy which becomes progressively richer in silver. Even in this case, the presence of impurities lowers the melting point of silver. In the extreme case where some melting of the cupel would occur, this melting would be only at the surface and the underlying mass of the cupel would remain intact.

Positive arguments for using litharge are that it is a clean material and does not cause contamination of the bath, as it would, certainly, occur if the cupel was made of clay. Silver does not wet litharge and is not absorbed by it, contrary to the ceramic materials known at the time. The cupels produced by mixing litharge with refractory binders are strong and resist thermal shocks without cracking, as opposed to the common ceramics. Lastly, one may wonder, what other choices of materials could be available, taking into account the limited number of materials available at that time?

It is worth noting that with an almost identical material was produced the water proofing plaster of the ancient water cisterns, during the Classical period at Laurion, having excellent water proofing properties as well as an astonishing strength and resistance to time (Conophagos and Papadimitriou, 1978; Papadimitriou and Kordatos, 1995). Its composition in a number of samples from Soureza was found to contain 30 – 40 % CaO, 45 – 53 % PbO, 10 – 13 % SiO_2, 0.80 – 1.70 % FeO and 2 – 2.4 % Al_2O_3. It was applied on the walls of the cisterns in multiple layers, as a suspension of very finely ground litharge in lime, by means of a brush. Litharge grains were in an amorphous (glassy) condition bound with lime, which after drying transformed to calcite, as it was confirmed from relevant micrographs and X-ray diffraction. The excellent water proofing properties of the material were confirmed by standard hydraulic tests (Conophagos and Badekas, 1974)

During the Middle Ages, a completely different logic prevailed in Europe for removing litharge from the cupel. Instead of discarding litharge out of the furnace, they left it in the cupel, until it was absorbed completely from the porous material of the cupel. For this purpose, highly porous materials were needed, which were able to selectively absorb in their mass the entire amount of litharge as well as the base metals carried in solution (Martinon-Torres, et al., 2008; Ulseth, et al., 2015). These cupels were formed from a mixture of marl with wood and bone-ashes. They are readily recognized from the presence of fragments of bones and by their high content of phosphates. Their manufacture strictly followed specific recipes, because it was not enough for the cupels to simply absorb litharge, but they had to be able to absorb the entire quantity of litharge produced during the cupellation process. That's why they had to have a large and open porosity, so that

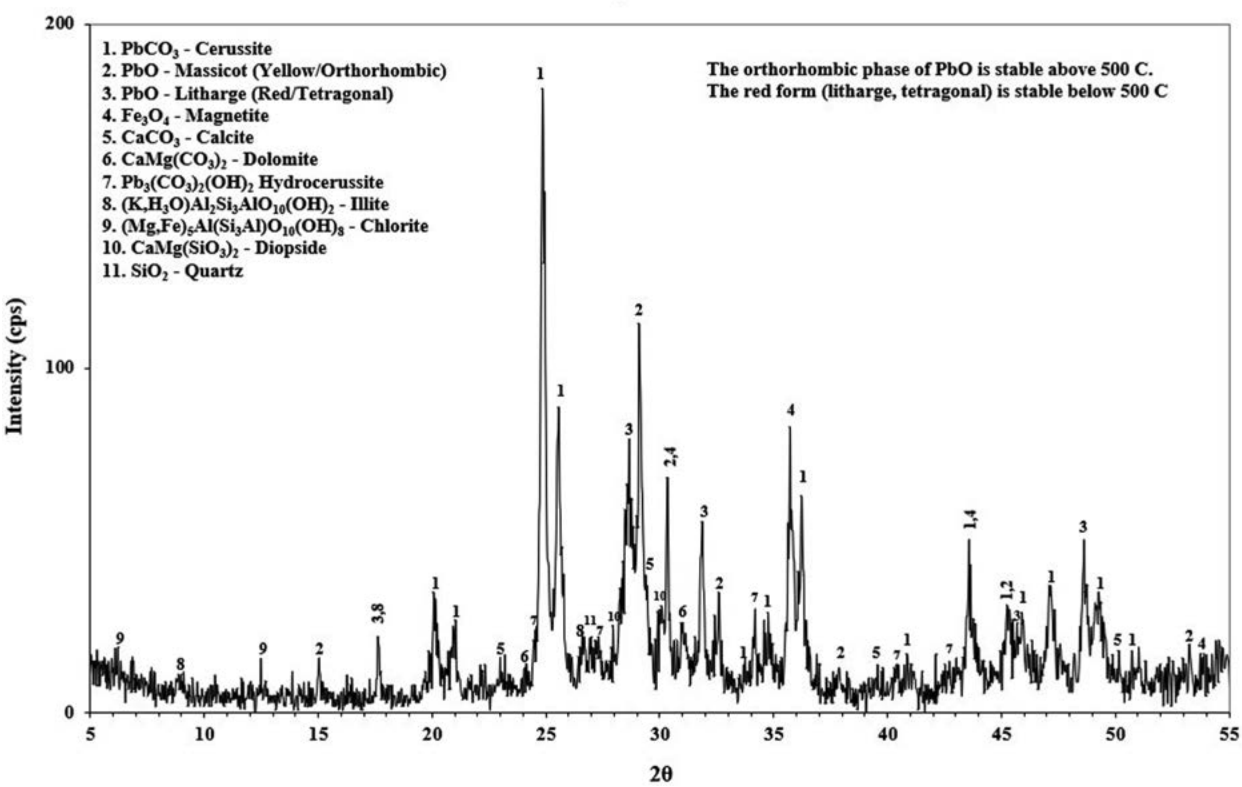

Fig. 13: X-ray diffraction diagram of a sample from the cupel of Fig. 8. The most frequent phases identified are listed in the diagram. (X-ray diffraction diagram: G.D. Papadimitriou).

litharge could penetrate to a great depth from the bottom of the cupel by capillary action. Simple clay did not have this capability, so suitable mixtures had to be used, mainly from calcium-rich marl mixed with wood ash and bone ash.

With regard to Laurion, there has not been any indication of using this kind of porous cupels so far. It is not excluded, however, that they have been used in some period of time, for example for cleaning of the bullion to make blanks for coining.

Prehistoric Cupellation

Prehistoric sites in the area of Laurion, where pieces of litharge were identified, have so far been characterized as potential metallurgical sites for production of silver from argentiferous lead by means of cupellation, considering that litharge is the characteristic by-product of the process. In some of these places were also found fragments of shallow bowls with a flat or slightly concave surface at their bottom, whose role was not obvious and became, therefore, the object of discussion and conjectures. Similar bowls have been found previously in other prehistoric areas of Greece, for example in Thasos (Papadopoulos, 2008) and more recently at Lambrika-Koropi and other places in Attika, as cited in the introduction.

A second variant of bowls very similar to the previous one, but having multiple small depressions at the bottom was identified only at Laurion (Fig. 14). C. Conophagos first investigated this type of bowls with depressions and interpreted them as small cupels serving for melting and refining weighted silver quantities for silver coining in the classical years (Conophagos, 1980, p.367, fig. 16.4; p.369). Since then, these findings have been characterized unambiguously as belonging to prehistoric times (Papadopoulos, 2008, p.64; Kakavogianni, et al., 2008, p.47), therefore this observation needs now to be revised with regard to coining. Nevertheless, the statement of Konophagos that it is a cupel remains valid. As a matter of fact, the chemical analysis performed on a dozen of similar objects coming from Lambrika (Kakavogianni et al, 2006, p.81, Tab. 1) along with careful visual observation of their form and shape suggest that they are made just like the cupels of the classical period, i.e. modeled as ceramics, from a plastic mixture consisting of finely ground litharge mixed with a quantity of lime as binding agent and a small amount of clay as plasticizing additive. As a matter of fact, analyses of twelve samples gave the following results: PbO ~83 %, CaO ~4 %, Al_2O_3 ~2 %, SiO_2 ~7 %, FeO ~1 % and MgO = 1.5.

In terms of their shape, they have a large area compared to to their depth, but, as it is expected, they have much smaller dimensions and capacity in comparison to cupels of the classical period.

These characteristics suggest that the bowls represent actually cupels which were in use during the prehistoric era and their size was adapted to the scale of production of the corresponding period. This is confirmed by the fact that no function other than a cupel could be attributed to this kind of bowl and inversely no other sherds with geometrical characteristics required for a cupel have been identified in the areas, where pieces of litharge and other findings characteristic of lead and silver metallurgy are present.

It is worth mentioning that the large number of litharge lumps and fragments of plate-shaped litharge found at Lambrika suggest clearly that the well-known technique of cupellation, as it was practiced during the classical period at Laurion, was already in use since the prehistoric times. Namely, litharge, was removed from the cupel and was cast out of the cupellation furnace in cavities on the ground or in molds, where it solidified forming lumps and pieces of plate-like litharge respectively.

According to Papadopoulos (2008, p.64), the remains of the bowls found at Limenaria, which seem to be among the oldest ones in the Aegean (Final Neolithic), have a diameter of about 15 cm and a depth of 1 – 2 cm and do not have depressions. In Lambrika their diameter varies between 10 and 14 cm and their height between 1 and 2 cm. The depressions have a diameter of 1 – 2cm. and a depth from 2 – 4 mm. The sole intact example found at Lambrika weighs 500 g.

Now, since the silver content in the argentiferous lead is extremely small (in the best case it could be about 5,000 g Ag/t Pb, but it was usually 2,000 g Ag/t Pb or lower at Laurion), in order to obtain on the bottom of the bowl a quantity of silver of about 15 g at the end of the process, one should treat at least a quantity of 7 – 8 kg of argentiferous lead. This quantity of lead could not be added in the cupel at once, but progressively, as the lead was oxidized and skimmed out. Therefore, repeated removal of litharge from the cupel was necessary, as in the case of cupellation in the classical period. Since the cupel with its content was not too heavy, it was drawn easily out of the furnace and liquid litharge was poured out by slightly tilting the cupel. Litharge was possibly poured straight into a cavity in the ground, in front of the cupellation furnace. Such cavities were found in the excavations of Lambrika, covered internally with a white layer of lead carbonate ($PbCO_3$), which came over time from transformation of litharge under the influence of the CO_2 of the atmosphere. These cavities had the form of a funnel to collect at their bottom any argentiferous lead that was inadvertently carried away with litharge from the cupellation furnace.

A practical problem relevant to the small quantity of silver obtained in the cupel should occur at the end of the process, when the last litharge formed should be removed, leaving the quantity of silver free at the bottom of the cupel. This was most probably done by tilting slightly the bowl and paying attention to avoid withdrawal of silver along with litharge. It was, certainly, a difficult task and the presence of a rim of semi-circular cross section on the bowl, reported by Papadopoulos (2008, p.64), is an argument for the actual existence of the problem. But a more efficient way to avoid loss of silver, was certainly the presence of depressions in

Fig. 14: A prehistoric cupel in the form of a shallow bowl, with multiple depressions at its bottom, from the collection of K. Konophagos (Author's modification from Conophagos, 1980, p.367, fig.16-4).

Fig. 15: A prehistoric cupel fragment from Lambrika-Koropi (Author's modification from Kakavogianni et al., 2008, p.54, fig.14).

the bottom of the cupels, that is probably an invention of the metallurgists of Laurion. In this case it is evident that the mass of silver was divided into a number of individual spherical bodies lodged in the depressions and this way impeding them to run out with litharge, when the bowl was tilted (Papadimitriou, 2012). This remark seems to be confirmed by the photograph of a small cupel (Kakavogianni, et al., 2008, p.54, fig. 14 here fig. 15). This photograph shows clearly the local melting in the form of craters, which has been produced by the hot silver spherulites lodged in the depressions on the underlying litharge. This local surface melting, is however not a problem for the cupel as a whole. One may also observe that the silver spherulites are not of the same size, as they certainly come from coalescence of very small drops of silver.

In addition, splitting the mass of silver to small usable quantities could be practical, avoiding cutting (Papadimitriou, 2012). Furthermore, one could speculate that the division of silver to flans of equal mass could breed later the idea of coins and in this respect, the hypothesis of Conophagos about the use of the shallow bowl with depressions for melting silver and preparing blanks for coining appears valid.

It is interesting to know how much silver was produced in a cupel during a complete cupellation cycle as well as the corresponding amount of argentiferous lead used for it. An approximate estimate of these quantities was possible thanks to the cupel (Fig. 15) accompanied by its scale. The cupel has a diameter of about 10 cm and is broken, but missing parts are located along its periphery, so that probably only one cavity is missing. The cupel was slightly overheated during its use, so that it was softened and slightly deformed. At the same time, the silver beads that had settled on its bottom caused local melting of the substrate and sank to some extent in its soft mass, leaving behind them clearly visible imprints. The imprints of twelve silver beads were detected after magnifying the photograph, of which ten were inside the cavities of the cupel and two outside. After measuring their diameter, their volume and then their weight was calculated, as it is seen in Table 1. Finally, their total weight was found to be 11.09 g.

From this quantity of silver, the quantity of argentiferous lead used during a complete cupellation cycle could be estimated. For the value of 2000 g Ag/t Pb which is usually considered as most representative for the silver content in argentiferous lead, a quantity of 6 kg of argentiferous lead was found.

Furthermore, given that a cupel with a diameter of 10 cm and a depth of 2 cm has approximately a capacity of 155 cm^3, which can accommodate only 1650 g of melted lead, the quantity of argentiferous lead used in one cupellation cycle (i.e., 6 kg), could not be added at once in the cupel. This means that the well-known technique of removing litharge from the cupel and replacing it progressively with argentiferous lead was actually practiced and confirmed from the presence of lumps and plate litharge pieces in the workshop. From the above it is concluded that the design of the cupel was made in such a way that the depressions help to coalescence the silver droplets into larger coarse drops, so that they could not be scattered again and to fit 10, maybe 20 g of silver in the cupel at the end of a cupellation cycle.

The form and size of the cupel changes with time as the production scale increases. As a matter of fact,

No of cavity	Spherulite diameter mm	Spherulite volume mm^3	Spherulite weight g
Mean value		88.0	0.92
1	7.5	220.9	2.32
2	6.65	154	1.62
3	4.15	37.40	0.39
4	5.81	102.7	1.08
5	6.64	153.3	1.61
6	4.15	37.4	0.39
7	3.32	19.16	3.85
8	7.47	218.25	2.29
9	4.15	37.42	0.39
10	4.15	37.42	0.39
11	3.32	19.16	0.20
12	3.32	19.16	0.20
Sum		1056.27	11.09

Tab. 1: Calculation of the quantity of silver produced in a complete cycle of cupellation. (Measurements and calculations: G.D. Papadimitriou).

in prehistoric years mining was limited and the furnace size for the extraction of the argentiferous lead from ore was certainly small, producing perhaps some kilograms at most. For the cupellation of such quantities of lead the cupels in the form of small shallow bowls were sufficient. In the classical years, however, and possibly even earlier, a change in the scale of production has occurred. Systematic underground mining, ore dressing plants and high-capacity reduction furnaces have emerged. Under these circumstances the cupel could not be anymore the small shallow bowl, which continued probably to exist only for assaying purposes. To the opposite, a sizeable recipient with a capacity of the order of 100 kg of lead, as the one shown from the collection of Konophagos (Fig. 7) or the one whose bottom is examined in this investigation (Fig. 8) should be needed. These cupels may have a diameter of at least 0.5m and do not bear depressions any more, but the principle of protecting silver in a depression is preserved as a narrow bottom, away from the surface.

With regard to the prehistoric cupellation furnaces, nothing is known. It is, however, most probable that they were of the type from the region of Bertseko (Fig. 9).

Concluding some discussion should be made relevant to the interpretation that has been proposed by Kakavogianni, et al. (2008) and Georgakopoulou, et al. (2020) for the cupellation technique used in the excavated cupellation workshop at Lambrika and for the origin of the shallow bowls with impressions at their bottom, that were characterized as a new type of litharge and named “bowl shaped litharge”.

With regard to the cupellation method, Georgakopoulou, et al. (2020, p.188–89) stated that “the cupellation technology of Prehistoric Attica is different from that of Classical Laurion, at least on the basis of how litharge was removed from the melt” and suggested that the removal of litharge was done by absorption from the lining of the cupellation hearth, i.e the bowls were “litharge-impregnated cupellation hearth linings” as those studied from Pernicka, et al. (1998) at Habuba Kabira Syria and from Hess, et al. (1998) at Fatmali-Kalecik, East Anatolia. For this hypothesis they were based on the presence of a number of cavities of conical form carved in the ground (Kakavogianni, et al., 2008, p.49, fig. 5), having a diameter of 19 cm on the surface and a depth of 10 cm, and bearing remains of a white lining in their interior (Kakavogianni, 2005, p.46). According to them, the dimensions of intact shallow bowls (10–14 cm diameter) correspond to the dimensions of the above cavities (19 cm diameter at their upper end on the surface), and therefore they should be considered as cupellation hearths. Clearly, the presence of these cavities alone is not a strong argument, since there are no indications suggesting that these cavities were actually cupellation hearths, but could be probably used for pouring litharge extracted from the cupel. Moreover, this assumption conflicts with the actual fact of the presence of a significant number of pieces of plate litharge and lumps at Lambrika and other places, suggesting that the only technique for which we can safely claim that it was applied at Lambrika is the technique of the classical period, in which litharge was discarded from the furnace and cast in molds or poured into cavities on the ground, giving after solidification, pieces of plate -shaped litharge or lumps, respectively.

Furthermore, shallow bowls found at Lambrika are not pieces of litharge solidified after absorption from a porous material, but they are actually cupels, i.e. handmade artifacts modeled like a ceramic vase from a plastic mass, as evidenced by their net contours and strictly symmetrical shape, reproduced as a standard form in all cupels. This is also confirmed from the smoothness of their surface, and from fine details, such as the uniform rim on the periphery of the bowl and the depressions in their bottom. It is, certainly, possible to obtain a crude bowl form by absorption of litharge into a porous cupel having a hemispherical bottom, like those used for cupellation in the Middle Ages, but it is quite unlikely to obtain a perfect shape from the spontaneous penetration of litharge into a porous material.

It is also worth repeating that a shallow bowl, found intact at Lambrika, had a weight of 500 g (Kakavogianni, et al., 2006, p.79, fig. 3).

If we accept as a hypothesis that litharge was removed by absorption from the hearth material and that the weight of litharge absorbed during a cupellation cycle was about 500 g, then this would correspond to about 375 g of argentiferous lead, from which – for a silver content of 2,000 g Ag/t Pb – only 0.75 g of silver could be produced. This quantity is far less than the quantity of 11 g which, according to a previous calculation, had been concentrated in the cavities of the cupel (Fig.15). The limited ability of

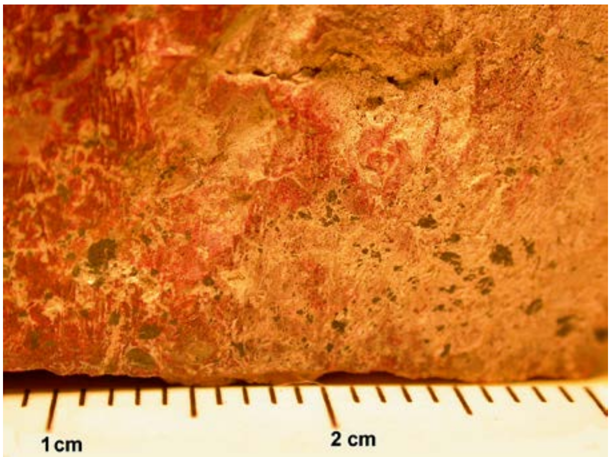

Fig. 16: Macrograph of plate litharge containing inclusions of a lead-silver alloy with impurities near its bottom. The matrix is mainly red litharge, whereas some yellow litharge is also present at some places. (Macrograph: G.D. Papadimitriou).

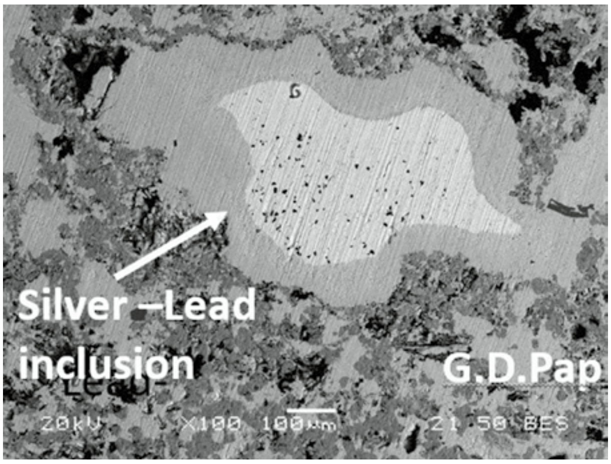

Fig. 17: Scanning electron micrograph of a lead-silver inclusion in a matrix of yellow and red litharge. (SEM micrograph: G.D. Papadimitriou).

Fig. 18: A pile of finely ground litharge in the corner of the enclosure of a circular mill at Ari-Lavrion and in the embedded photo a piece of agglomerated ground litharge, certainly serving as a feed material for the smelting furnaces producing commercial lead. (Photo: G.D. Papadimitriou).

the cupel to absorb more than 500 g of litharge, brings us back to the assumption of the classical technique, characterized by repeated removal of litharge from the cupel and simultaneous replacement by a corresponding amount of argentiferous lead, until a significant amount of silver was concentrated in the depressions of the cupel.

Litharge during the Hellenistic period at Laurion

During the Hellenistic and early Roman period (3rd to 1st century BC), the operation of the mines fell into decline mainly due to political instability. As a solution, production of silver and lead from ores was partially substituted from recycling of stocked mining and metallurgical waste materials of the classical period (Strabo 3,2,9). Among these materials, was litharge, which was recycled for its rich-in-silver, lead-silver inclusions (Papadimitriou, 2020).

Mechanical inclusions consisting mainly of lead and silver with some impurities, such as Cu, Ca, and As are the most important ones and are present in lumps and plates of litharge. Some of them are observed by naked eye as dark grey particles inside red litharge near the bottom of the plates (Fig. 16). Apparently, they precipitated to the bottom of the plate, while litharge was still in the liquid state, due to their higher density. Some of them have an equivalent diameter of 1 mm or even higher, but most of them are smaller than 0.5 mm. These inclusions, were certainly perceived by the ancient metallurgists on the surface of litharge or of broken pieces. Actually, not all pieces of plate litharge contained important inclusions, and this was presumably depending on the skill of the metallurgists in removing effectively litharge from the bath of argentiferous lead.

Tubular forms of litharge are free of mechanical inclusions, and this seems plausible with regard to the corresponding separation technique by means of iron bars.

Inclusions in plate litharge are shown in the SEM micrograph (Fig. 17) and in most litharge samples contain 2.5 – 5 % silver in lead.

For recovering inclusions, the ancient metallurgists followed the same technique, as for beneficiation of silver bearing lead ores in the washeries, namely they subjected the litharge pieces to fine grinding (in the present case under 0.5 mm), in order to liberate the inclusions from the surrounding mass and then recovered them by hydromechanical processing in the washeries as a concentrate (heavier fraction). From this concentrate, silver was presumably obtained by means of cupellation, after eventual addition of a quantity of lead and some charcoal powder in order to reduce any silver oxide which was eventually present. The lighter fraction of the separation in the washery consisted of the mass of ground litharge having a low silver content (called for brevity desilvered litharge).

This fraction was subjected to agglomeration and then smelted in shaft furnaces for production of commercial lead, which was in great demand at the time.

Initially the processing described above was certainly done in the old ore washery compounds of the classical period, where crushing and grinding equipment was available. This is evidenced by the presence of ground litharge residues identified in many of them (Conophagos, 1980, p.273; Rehren, et al., 1999, pp.299 – 308). Finally, it was found associated with the circular mills of Laurion (Papadimitriou, 2015; Papadimitriou, 2016; Nomicos, 2021, p.50 – 57) (Fig. 18).

In particular, during excavations in the Asklipiakon washery at Soureza, residues of ground litharge from both a) a quantity stocked in a room adjacent to the washery and b) a small pile abandoned just outside the washery were identified. After sampling and chemical analysis, it was found that the first sample contained 65.75% Pb and 601 ppm Ag, whereas the second one contained 66.6 % Pb and only 134 ppm Ag. These figures suggest that ground litharge was processed in the washery for recovering silver inclusions and that the first sample belonged to the feeding material, whereas the second one was the waste (light fraction) of the concentration process. Unfortunately, we do not have any evidence of the concentrate (heavy fraction of the separation), but we may assume that it consisted from a fine powder of lead-silver inclusions with some middlings and that about 470 g of silver had been recovered in the concentrate from each ton of ground litharge processed.

In a later period, during the 2nd century BC, when mining and metallurgical activities resumed, new workshops for the recovery of silver from litharge were already in operation near old furnaces. In these workshops grinding of litharge was performed by means of the "circular mills of Laurion", which had been discovered in the meantime. A circular mill consists of a vertical millstone, freely mounted on a long horizontal axle which turns around a vertical shaft in the center of the structure. The millstone revolves in a circular path inside a trough, crushing the material which should be reduced in size. The mill is driven manually or most probably from a donkey (Fig. 19 – 20).

Fig. 20: Representation of a circular mill in operation (Drawing: G.D. Papadimitriou).

It should be emphasized that the circular mill of Laurion was the ideal device for grinding litharge, due

Fig. 19: A well-preserved circular mill at Ari-Lavrion (Ari-II), used for fine grinding of litharge. (Photo: G.D. Papadimitriou).

to its high productivity and strict control of the fineness of the material produced. The older attrition devices of Laurion, i.e. boulders on which crushing was done by means of hammers and reciprocating Olynthus mills for grinding were not satisfactory, due to their inability to grind the material finer than 0.5 mm and to their low productivity. Yet, large quantities of litharge, of the order of 1 – 1.5 million tons, had probably been abandoned in more ancient times near the furnaces as waste, so that high-capacity grinders were necessary for their treatment.

To date, remains of eleven circular mills have been identified, considered previously as helicoidal washeries or mixing devices of ore (Tsaïmou, 2005). All of them are near old stocks of smelting slag and one of them at Ari which is preserved in a good condition, is representative of an integrated recycling compound, comprising one circular mill, one washery and five or six smelting furnaces. It was still active in the Hellenistic or Early Roman period, as shown by radiocarbon dating of charcoal samples coming from the furnaces of the compound that gave a calibrated date of 246-03 BC (Tsaïmou, et al., 2015, p.118).

The operation of the circular mills was apparently very successful. Certainly, for this reason, their technology was transferred to the gold mines of the Eastern Desert of Egypt in the time of Ptolemies (Klemm and Klemm, 2013, p.167, fig. 5. 109), where they probably served in the process of recovering gold from old waste of gold bearing quartz (Papadimitriou, 2020)

Conclusions

The subject explored in this paper is cupellation, as a silver production technique in Laurion. The conclusions we reach are the following:

In Laurion the production of silver lasted from the Final Neolithic until the end of the Hellenistic period, with a production scheme that includes two basic metallurgical processes: smelting and cupellation.

For all phases of this long period of 3000 years, the main evidence, and at the same time source for studying the early technology, are fragments of cupels and pieces of litharge, which prove that the technique of producing silver from lead was steadily cupellation. In particular, the common presence of two typical forms of litharge, in lumps and plates, proves that the basic technique of using a cupel from which litharge was mechanically removed and solidified outside the furnace, was applied throughout the aforementioned time period.

The study of cupels in terms of form and size proves that the technology of both the prehistoric and the Classical-Hellenistic periods is determined by the scale of production. In terms of material, it turns out that the cupels were made with the technique of ceramic materials from ground litharge to which a small amount of lime and clay had been added.

The main concern of the metallurgists of all times was to limit the losses of silver during the removal of litharge from the furnace, along which a quantity of argentiferous lead was carried away. In prehistoric times at Laurion this problem was resolved by printing hemispherical cavities at the bottom of the cupel, where silver was concentrated in thick drops, and its re-dispersion was prevented when the cupel was tilted. During the classical period, large cupels of conical form were used and a technique for removal of litharge in two stages was adopted. During the second stage, the removal was done by immersing the end of iron rods in the cupel, where litharge was selectively attached forming a short tube around the bar. This is evidenced by the existence of tubular litharge pieces.

During the Hellenistic and early Roman periods, litharge stocks were recycled in order to recover silver from the silver inclusions they contained. The litharge was ground into very fine material on the circular mills and inclusions were recovered in the washeries. Silver was finally obtained from the concentrate by cupellation, whereas the desilvered litharge was driven to the smelting furnaces for production of commercial lead.

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The prehistoric finds from Mine 3 and their relationship to the Thorikos mining community

ABSTRACT: *This chapter discusses the earliest prehistoric pottery excavated from Mine 3 at Thorikos, the most ancient mine gallery in the Laurion so far known. The mine was discovered in 1975 and was excavated from 1976 to 1981 by a team led by H.F. Mussche and P. Spitaels; a preliminary report by P. Spitaels appeared in 1984. This study of the Mine 3 assemblage presents the macroscopic fabrics, shapes and surface treatments/decorations of the Neolithic and Early Bronze Age diagnostics. A preliminary distinction between local and imported pottery was possible through macroscopic fabric group analysis. The typological study refers to parallels from other prehistoric sites in the southern Aegean. In the conclusions, the controversial issue of the chronology of the earliest exploitation of the Thorikos ores is reviewed. The excavation data is not sufficient for a systematic investigation of taphonomic processes of the finds, which could have been associated with phases in mining activities. Yet the recovery of Late Neolithic, Final Neolithic and Early Bronze Age I pottery from the excavated area of the mine could be used as evidence for opencast mining in these periods (the 4th and early 3rd millennia BC), before the gallery was dug into the Velatouri hill in the Early Bronze Age II period. In conclusion, the Mine 3 prehistoric pottery offers insights into ceramic production and consumption in the Laurion and helps us unravel the history of a prehistoric mining community.*

KEYWORDS: AEGEAN NEOLITHIC/EARLY BRONZE AGE POTTERY, MACROSCOPIC FABRIC GROUP ANALYSIS, PREHISTORIC MINING

Introduction

Thorikos benefits from its crucial geographical position in the eastern Mediterranean, in the centre of the Aegean and on the coast of south-eastern Attica and the Laurion. The site is a double hill, called the Velatouri, next to a double port. The Adami and the Potami valleys offered arable land in prehistoric times, but it was most likely the rich metal ores that attracted settlement since the Neolithic period.

With about 700 minerals recorded so far, the Laurion is ranked amongst the mineral-richest areas of our planet. Many of these minerals occur at Thorikos; the most important are galena and ceroussite, exploited for lead and silver. Gale, et al. (2009) have suggested that copper ores were most likely mined in the Laurion in prehistory, perhaps also at Thorikos, while there is yet no evidence for the mining of iron.

The first excavations of prehistoric finds at Thorikos were conducted by the Greek archaeologist V. Staïs in the late 19th century; Staïs investigated the tholos tombs 3 and 4, a construction that he named the 'bothros' and the prehistoric settlement at the top of the acropolis (Staïs, 1890; 1893; 1895). The pottery from Staïs' explorations at Thorikos, now located at the National Archaeological Museum in Athens, has been studied in detail and was recently published (Papadimitriou, 2020; Nazou, 2020).

Since the 1960s, the site's rich archaeology is under investigation by international teams led by archaeologists affiliated with Belgian Universities[1]. The prehistoric remains on the acropolis were investigated by Servais in the 1960s and 1970s (Servais, 1967; 1968; Servais and Servais-Soyez, 1984). Servais re-investigated the tholos tombs excavated by Staïs and also three more tombs. In terms of settlement, the floor of a Middle Bronze Age house was excavated in square I 53 (Fig. 1), where also a fragment of litharge was recovered and interpreted as the earliest evidence for cupellation at Thorikos (Servais, 1967, pp.20 – 24). Below the foundations of this house an assemblage of Final Neolithic pottery was recovered and published by Spitaels (1982).

Until the early 1970s, the concentrations of prehistoric remains were mostly on the Thorikos acropolis, with settlement as well as burial remains dated to different periods in prehistory, providing a patchy, yet important picture of prehistoric activities. This picture changed in 1975, with the discovery of Mine Gallery 3 that was dug into the Velatouri (Spitaels, 1984); it is located only 30 m west of the Classical theatre (Fig. 2).

The author's involvement in archaeological research at Thorikos started in 2007, with the study of the Neolithic pottery recovered at the acropolis in the context of a PhD thesis (Nazou, 2014). In 2008 with the kind permission

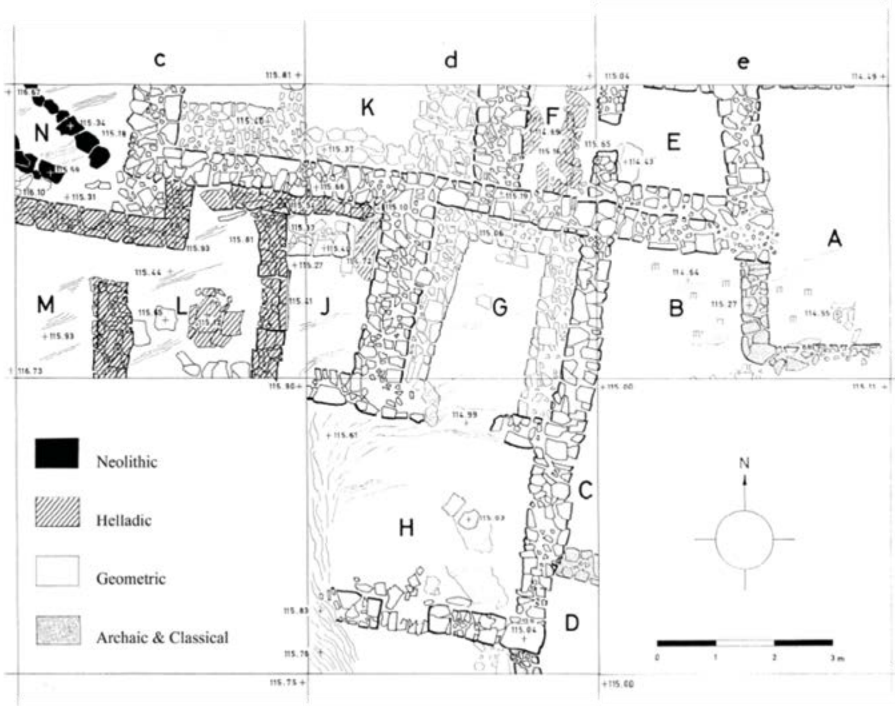

Fig. 1: The central trench on square I 53 on the acropolis (after Van Gelder, 2013, p.17, fig.2).

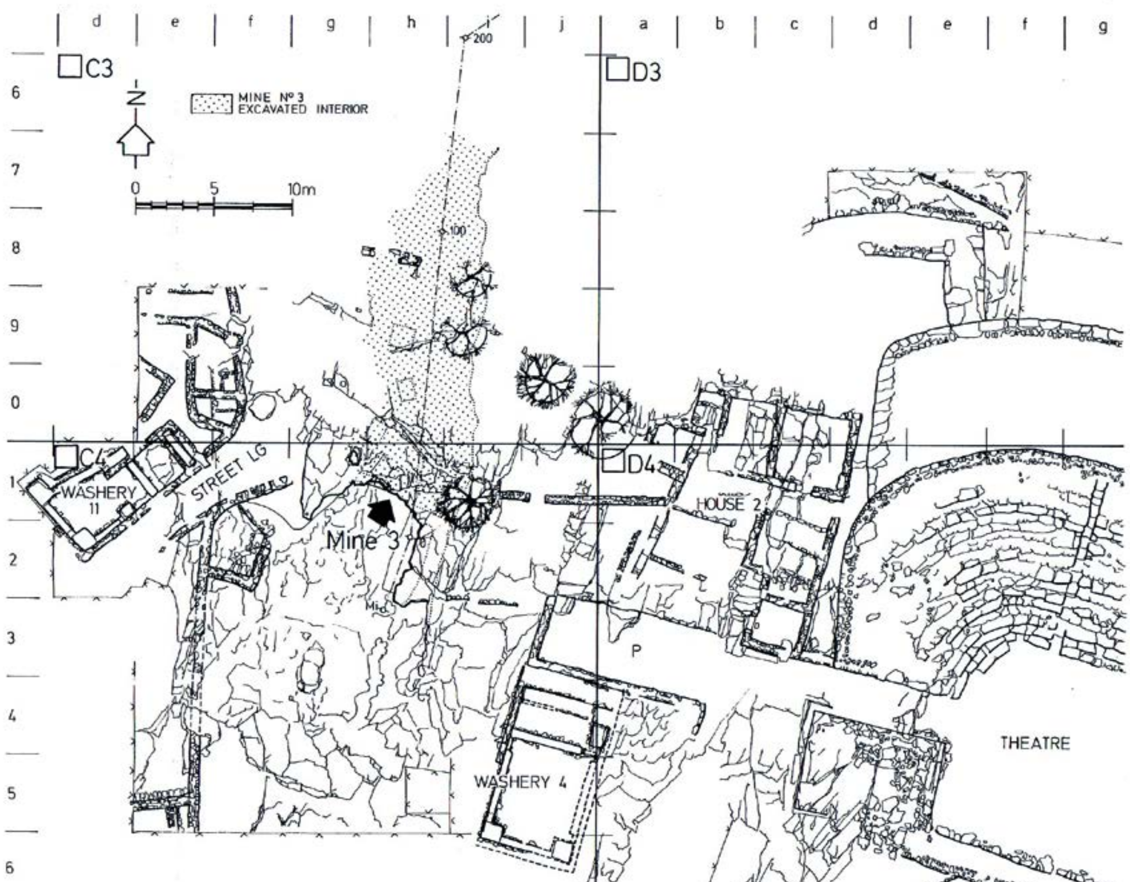

Fig. 2: Plan of Thorikos grid squares C3, C4, D3 and D4, indicating the location of Mine 3 (after Spitaels, 1984, p.155, fig.97).

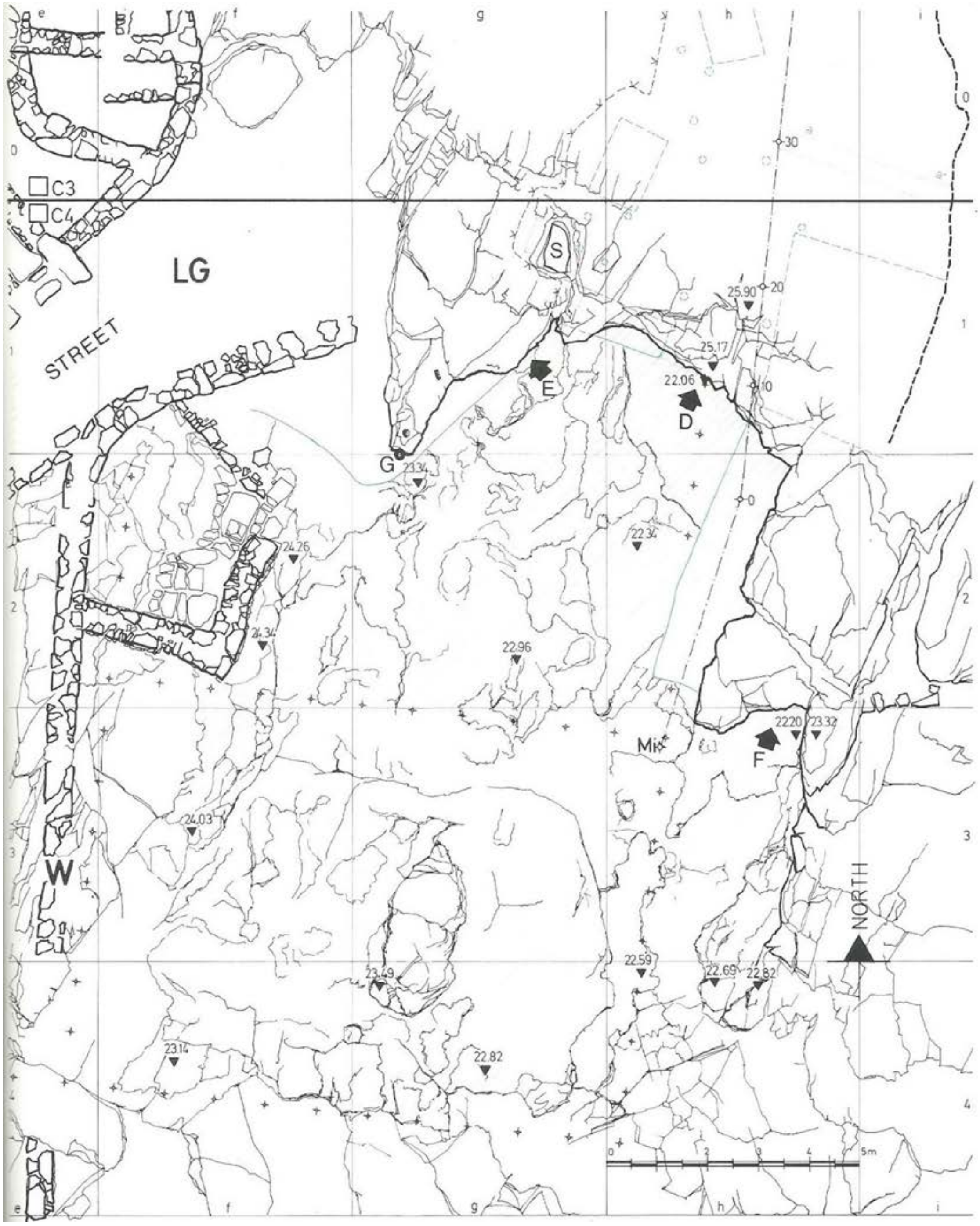

Fig. 3: Plan of the exterior of the mine (after Spitaels, 1984, p.157, fig.98).

of the site director R. Docter the author undertook the study and final publication of the Mine 3 prehistoric pottery. This chapter discusses the Neolithic and EBA pottery from Mine 3 and its relationship to the Thorikos mining community. The preliminary results of the study of the EBA III, MBA and LBA pottery from the mine, still in progress, will also be briefly discussed.

The earliest prehistoric pottery is important for two main reasons: first, it is a very large assemblage that has been studied in detail and can offer unique insights into ceramic production, consumption and exchange at Thorikos. Second, the context of the pottery is unusual, since it was excavated from a prehistoric mine; therefore, the new evidence could contribute to the investigation of prehistoric mining activities in the Laurion.

In order to contextualize the study some essential excavation information will be provided and the history of previous research will be presented. The methodology of this study will be explained. The main part of the chapter is a discussion of the material. Finally, the intriguing issue of the relationship of the pottery with the Thorikos community and prehistoric mining in the Laurion will be considered.

Excavation information on Mine 3

According to the excavation's diaries, Mine 3 was initially thought to be a cave but soon it was realised that the cavity was in fact a mine gallery that had escaped re-working during the modern resumption of mining in the Laurion (Spitaels, 1984, p.153). Mine 3 was further excavated in the late 1970s and early 1980s (Mussche, 1998, p.36).

In her preliminary report, Spitaels provides information on the excavation methods and stratigraphy of the mine[2]. The excavations established that in antiquity the entrance of the gallery was probably 5m further south of the current entrance and it evidently collapsed (Fig. 3). Therefore, the reference to the exterior and the interior of the mine refers to the state of the mine at the time of its excavation and not its ancient state.

The excavation investigated the exterior of the mine and defined the limits of opencast working to the south and to the east of the present entrance. In this area, the marble bedrock is penetrated by a rich rust-coloured zone of haematite and limonite mineralisation, about 15m long and up to 13 m wide (Fig. 4). Worked-out veins of the ore and toolmarks are scattered all over this area but cease abruptly beyond it. Spitaels therefore suggested that there must have been an outcrop of the ore on the hillside, which would have attracted the attention of the first miners. In the rest of the exterior area there were later constructions, but the possibility that the ore outcrop extended further west should not be excluded. This area is now covered by 4th century BC remains of a guard room and a peribolos (Mussche, 1998, pp.37, 124, fig.63). The deposits of the exterior of the mine were very thick, and they increased progressively from south to north, reaching more than 2 m at the present entrance. They consisted mainly of the refuse of extraction and collapse, from both outside and inside the mine. This observation was confirmed by the many sherd joins from the exterior and the interior of the mine. Spitaels suggested that the disturbances, which resulted in the recovery of archaeological materials from different periods at the exterior of the mine, occurred mainly from four activities: continuous extraction of the ore during the prehistoric and later periods, collapse of the entrance, later levelling and modern agricultural operations.

The investigation of the interior of the mine required different excavation techniques. A geological examination proved that the cavity was completely man-made. Potential hazards were erosion, danger of roof collapse and especially flooding in case of heavy rain. It is likely that continuous flooding would also have occurred in antiquity. This could also explain the stratigraphic disturbances in the interior of the mine. The first few metres of the interior were cleared in 1976 and the roof was supported by wooden props and by stone pillars. Due to practical reasons, the method of excavation did not follow the grid system of excavation and recording used outside the mine. Instead, a base-line, established by theodolite, was marked on the roof. A point of reference at the exterior was used to mark a line approximately north-south, which extended into the interior of the mine. Points on this line were used to record the finds and to draw the plan of the interior. The gallery was found to be at least 120 m long, even though

Fig. 4: Photo of the area on the exterior of Mine 3, indicating the rust-coloured zone of haematite and limonite mineralisation (photo: M. Nazou).

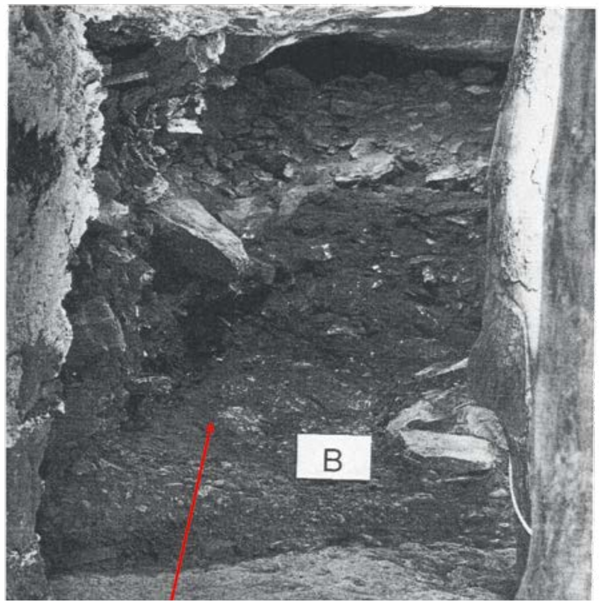

Fig. 5: Left: Photo of the EBA stratum inside Mine 3 (after Mussche, 1998, p.128, fig.68). Right above: Photo of the red filling B below disturbed layers (after Spitaels, 1984, fig.102). Right below: Soil sample from the EBA stratum at the Museum of Lavrio (photo: M. Nazou).

its furthest part is most probably post-Bronze Age. It was suggested that the Bronze Age gallery probably did not exceed 20 m. The height of the gallery varied from 0.5 to 1.5 m, decreasing towards the interior.

The initial hope that the interior of the mine would provide better stratigraphy than the exterior proved to be false. Inside the gallery, severe disturbances were identified. These were probably created by subsequent mining, during prehistoric and historical periods (Waelkens, 1990, pp.136, 138). Moreover, during the Archaic and Classical periods, shafts were dug to haul out the ore. Post-Early Bronze Age miners had moved the Early Bronze Age material in the interior from the west to the east during the re-working of certain veins with metal tools. The Bronze Age material was moved for a short distance, in the first 7 m of the interior, and beyond this area a large quantity of Mycenaean pottery was excavated.

It becomes evident that, even though the excavators of Mine 3 provide some stratigraphic information, the formation processes of the debris from the mine were not fully investigated. The stratigraphic details were not analysed systematically, and the precise stratigraphic context of the pottery from Mine 3, except for few sherds, was not recorded. Therefore, most of the pottery cannot be linked with specific locations inside or outside the gallery. This is very unfortunate, as a detailed study of the mine's topography along with the excavated finds could have established whether the debris was the result of disturbance and collapse, or it was intentionally and carefully placed as filling, also known as ‘deads’ in mining terminology. Deads are frequently used in mining to channel air to the working face or to direct the exit of the fumes from fire setting (Craddock, 1995, p.8). Occasional suggestions on this matter are made by the excavators, but a detailed study was not published. Therefore, the pottery from Mine 3 must be considered out of context, in the sense that most of it cannot be related to detailed excavation and contextual information.

The only exceptions to the lack of stratigraphic information from the mine are two retained excavation units. These constitute the only undisturbed deposits identified in the interior of the gallery. The deposits, patches of red soil covering an area of 1 m, were located on the rock floor, at the western part of the interior and within the first 2 m from the entrance (Fig. 5). They proved to be fillings of the depressions left by the working of two ore-bearing veins. Toolmarks from stone tools were identified at the base of these veins, preserved under the red fillings. The fillings, which varied in thickness between 5 and 12 cm, consisted of reddish clay, greyish towards the base, compact and very hard, mixed with very small fragments of schist and marble.

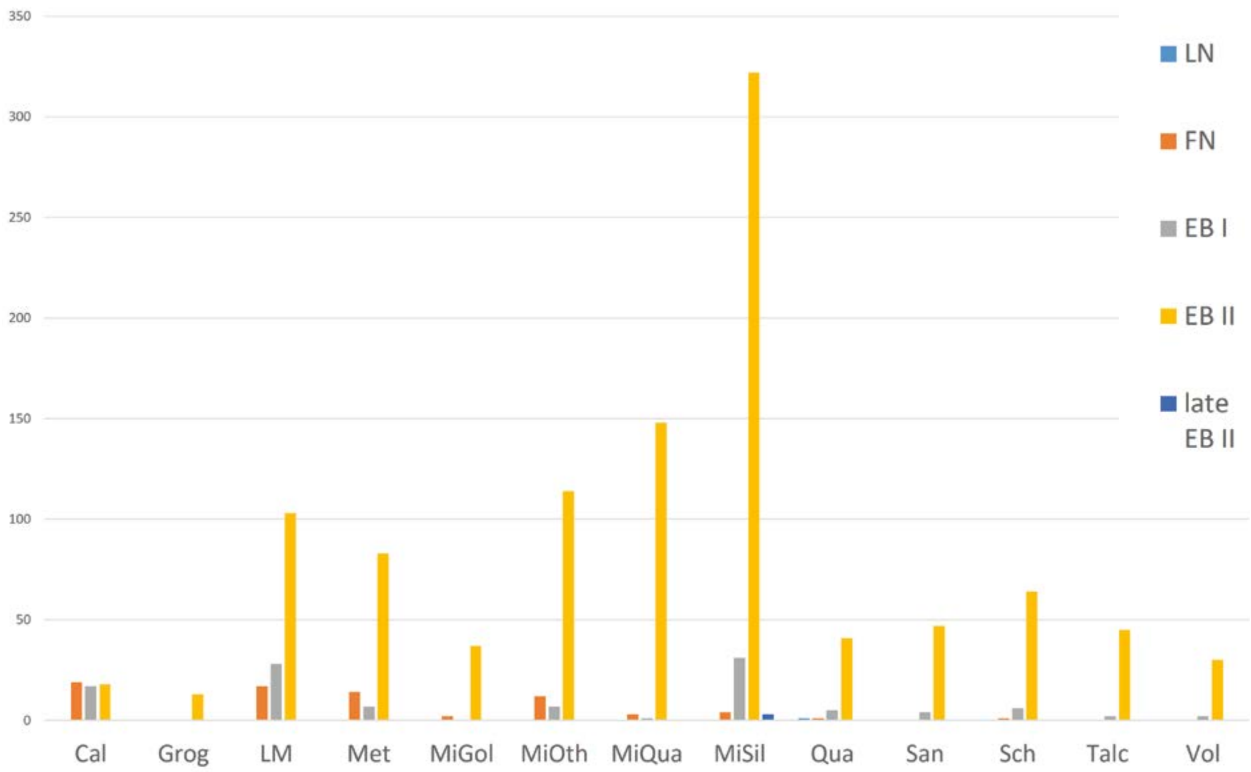

Fig. 6: The distribution of coarse and medium macroscopic fabrics by period (photo: M. Nazou).

The archaeological materials recovered in these excavation units were few: an obsidian flake, a few fragments of shell and bone and 35 small EBA II sherds. This pottery will be further discussed towards the end of the chapter.

The prehistoric pottery

The study of prehistoric pottery offers great potential for exploring a variety of research questions: chronology, function and activities, local production, consumption and imports, ancient exchange and networks, settlement size and nature, technological choices and last but not least, the most intriguing issues of culture and identity (Orton, et al., 1993, pp.23 – 35).

At Thorikos, the first systematic study of prehistoric pottery was conducted by Spitaels (1982), in her publication of Final Neolithic pottery from square I 53 on the acropolis. This pottery was dated to the so-called Attica-Kephala phase of the Final Neolithic, with pattern-burnished ware, red burnished bowls with elephant-head lugs, incised scoops and cheese pots. The phase dates to the 4th millennium BC and it is well documented at other Attic sites such as the Agora of Athens, Kiapha Thiti (Kontra Gliate) and the Kitsos Cave as well as neighbouring islands such as Kephala on Kea, Plakari on Euboea and Kolonna on Aegina (Nazou, 2014, pp.299 – 303).

The pottery from Mine 3 was washed, conserved and preliminary recorded. Spitaels (1984, pp.166 – 170) presented only a small selection of late EBA II and EBA III sherds, as she intended to publish this material at a later stage, but due to her untimely death she did not complete her study. Mountjoy (1995) published a selection of Mycenaean pottery from the mine.

The author's methodology for studying the Mine 3 pottery is described below. Three key aspects were examined in detail: fabric, form and surface treatment/ decoration. For the study of the fabrics the method of macroscopic fabric group analysis was used, a quick and inexpensive technique for designating potentially local and imported fabrics. The ceramic shapes were recorded with a formal and measurement-based classification system. Surface treatment and/or decoration groups were designated. Finally, the pottery was quantified in sherd count and weight.

Spitaels had pre-sorted about 132 kg of pottery from Mine 3, which the author sorted into diagnostic pottery, namely feature and decorated sherds and non-diagnostic body sherds. Most of the pottery is dated to the Neolithic and the Early Bronze Age, but there is also later prehistoric pottery dated to the Middle and Late Bronze Age, and also a few sherds dated to the historical periods.

The identification of macroscopic fabric groups was done following the recording system suggested by Orton, et al. (1993, pp.231 – 242), with ideas from recent work

Chronological period	Date BC
Late Neolithic	5300–4100
Final Neolithic	4100–3100
Early Bronze Age I	3100–2650
Early Bronze Age II	2650–2200/2150
Early Bronze Age III	2200/2150–2050/2000
Middle Bronze Age	2050/2000–1700/1675

Tab. 1: Absolute chronologies for the periods of pottery studied from Thorikos (source: https://sites.dartmouth.edu/aegean-prehistory/chronology/, with additions by M. Nazou).

on macroscopic classification in the Aegean (Broodbank, 2007; Broodbank and Kiriatzi, 2007; Kiriatzi, 2003; Moody, et al., 2003; Pentedeka, et al., 2010).

For the designation of local and imported fabrics, the information from the macroscopic fabrics and the geological maps was combined. To be more specific, the geology around the Velatouri comprises mainly various types of schist and marble (Marinos and Petrascheck, 1956; Scheffer, et al., 2007). The schist, limestone/marble and micaceous silver fabrics identified at Mine 3 are compatible with local geology (Fig. 6). However, these rocks are very widely distributed not only through the entire Laurion, but also on the neighbouring islands of Southern Euboea and Kea. In fact, they have a wide distribution within the Attic-Cycladic massif. Therefore, these fabrics could have been produced locally or elsewhere within Attica and the Cyclades. This was first noted by P. De Paepe (1982), who thin-sectioned the Final Neolithic pottery from the acropolis. Further technological analyses could provide more answers on provenance.

At Mine 3 the fabrics, which are compatible with local geology, such as for example the limestone/marble, the calcite-tempered, the micaceous quartz and the micaceous silver are encountered throughout the Neolithic and the EBA; they are the most likely candidates for local fabric recipes, since they occur in relatively large quantities. On the contrary, the fabrics that are incompatible with the geology of Thorikos, such as the volcanic and the talc, are most likely imports.

Dating the pottery was possible through a detailed typological study and comparisons with Neolithic and EBA ceramics from other sites in Attica and the Aegean. Several chronological phases are represented in the assemblage (Tab. 1).

The earliest sherd from Mine 3 dates to the Late Neolithic. It is an incised scoop handle in the medium quartz fabric (Fig. 7). The type has parallels at the Kitsos Cave (Lambert, 1981, pp.290–291, 306).

The Final Neolithic assemblage associated with the Attica-Kephala phase comprises mostly convex bowls (Fig. 8), with parallels from the Thorikos acropolis (Spitaels,

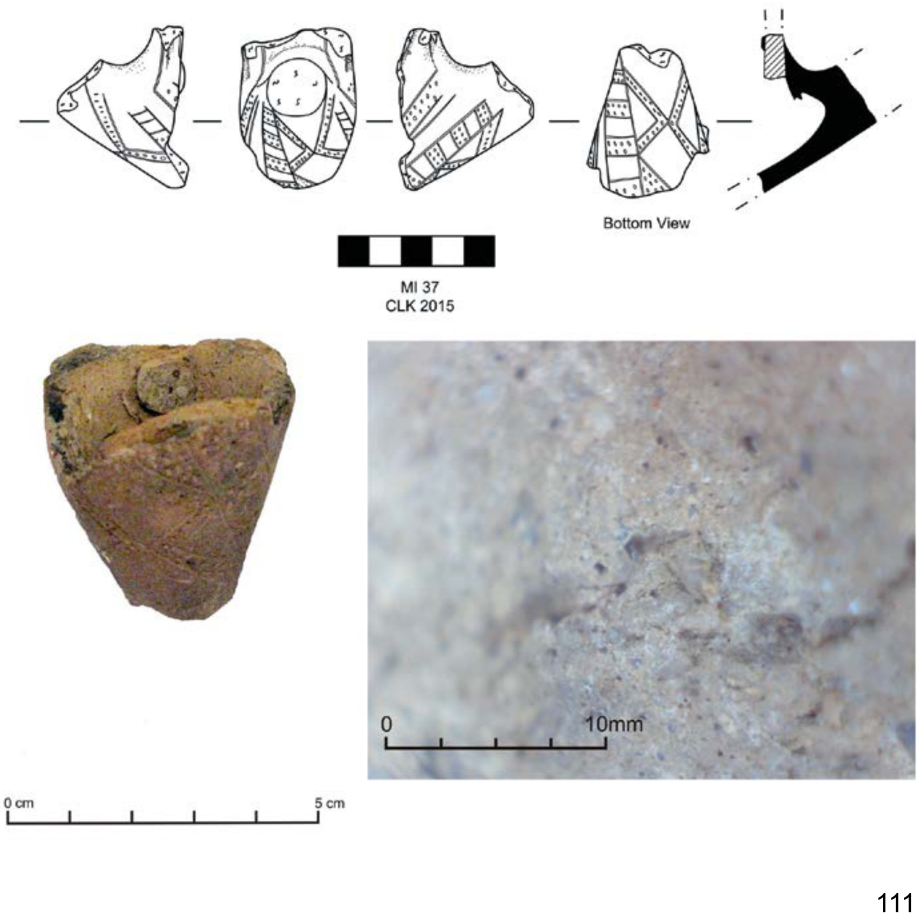

Fig. 7: A LN handle, the earliest sherd from Mine 3 (drawing by C. Kolb, photo and microscope photo by Emilio Rodriguez-Alvarez).

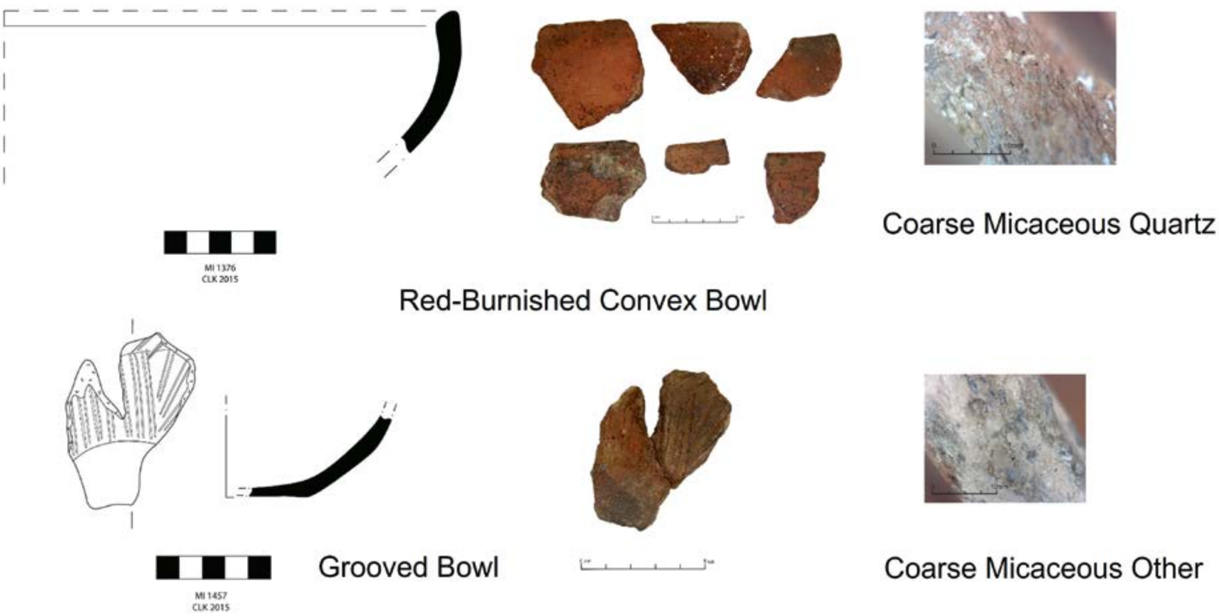

Fig. 8: Examples of FN bowls (drawings by C. Kolb, photos and microscope photos by Emilio Rodriguez-Alvarez).

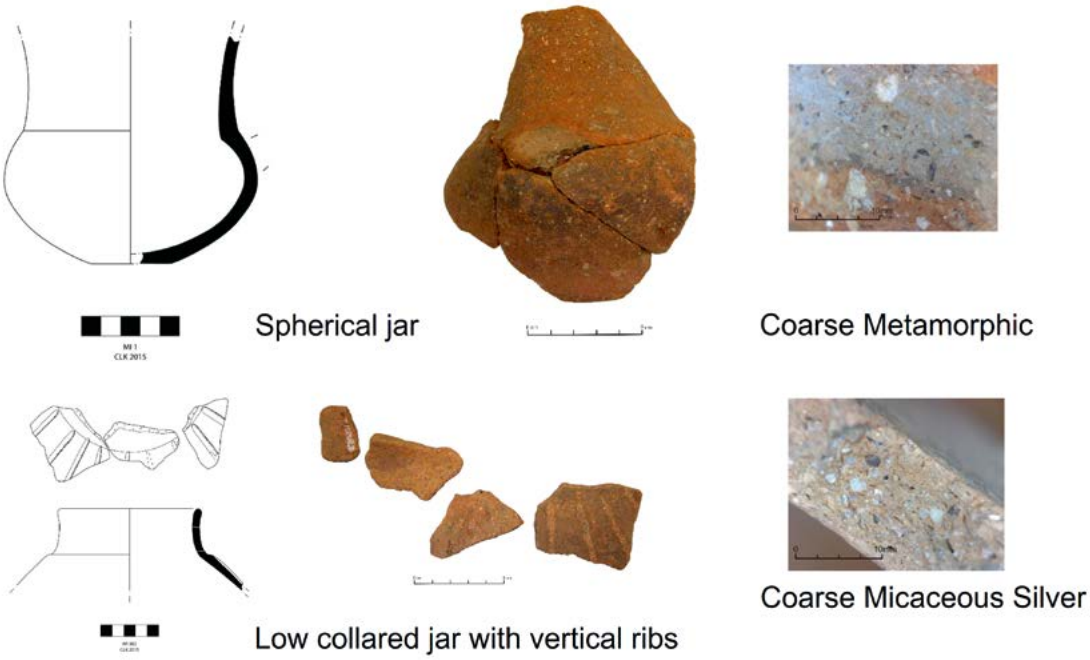

Fig. 9: Shapes of the 'North Slope' phase (drawings by C. Kolb, photos and microscope photos by Emilio Rodriguez-Alvarez).

1982, p.24, fig.1.9 nos 28. 30) and the Kitsos Cave (Karali, 1981, p.354, fig.239.1, CP45). At Mine 3 there is also pottery of the so-called 'North Slope' phase, named from the North Slope of the Athens acropolis. This phase is now better understood in Attica after the recent publication of Deposit 39 from the Tsepi cemetery in Marathon by Pantelidou-Gofa (2016). It comprises two very characteristic closed shapes: the spherical jar and the low collared jar with a decoration of vertical ribs (Fig. 9). In Attica, the North Slope phase is dated to the second half of the 4th millennium BC based on radiocarbon data from Marathon (Facorellis, 2016) and Merenda (Kakavogianni, et al., 2016).

The EBA I repertoire is represented mainly by straight and convex bowls (Fig. 10). The pyxis shape is in local

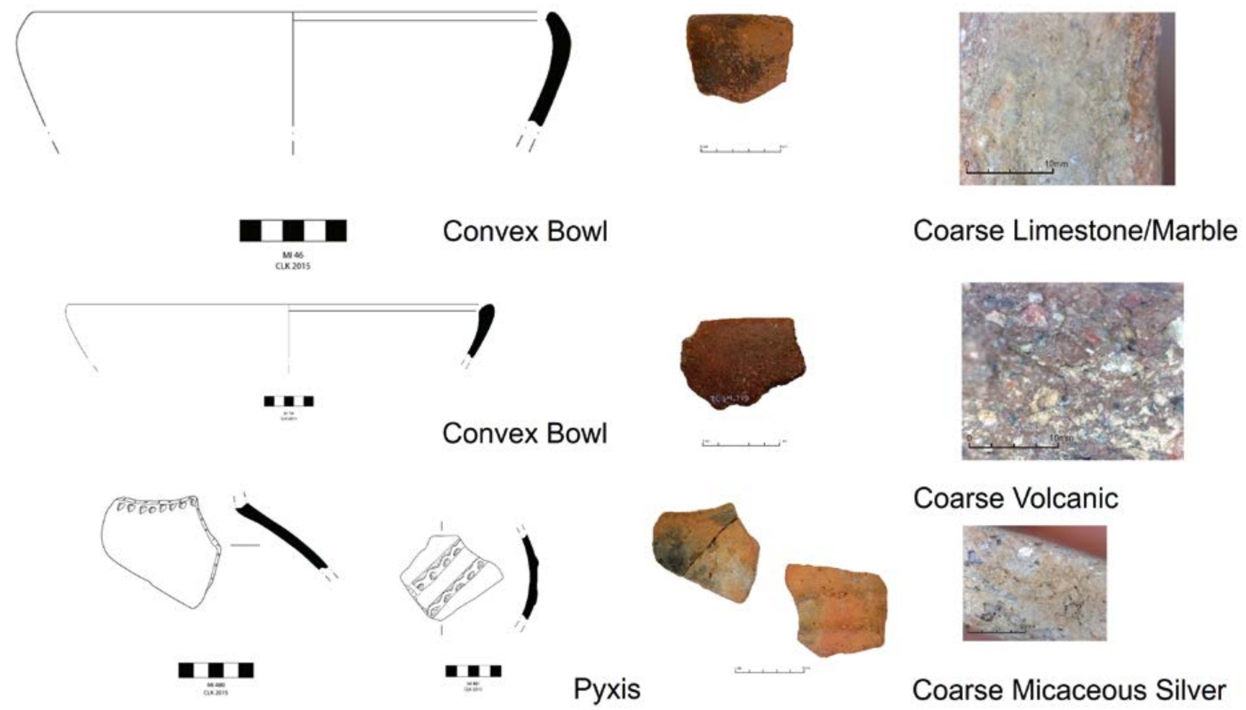

Fig. 10: EBA I pottery (drawings by C. Kolb, photos and microscope photos by Emilio Rodriguez-Alvarez).

and imported examples. Most forms have their closest parallels within Attica, such as Tsepi (Pantelidou-Gofa, 2005, pp.306 – 307, pl.12, Tomb 11.1) and Palaia Kokkinia (Theocharis, 1951, pp.106, fig.18 α. β).

Turning to the EBA II, it can be argued that the Mine 3 assemblage is one of the richest repertoires documented from Attica so far. Tableware is particularly well represented, and its eclectic range indicates stylistic affinities with different areas (Fig. 10, Tab. 2). Some forms, such as the cups, the sauceboats and the collared bowls, have typological similarities within Attica, at Ayios Kosmas (Mylonas, 1959, pls.116. 17. 19; 117, 1. 3. 4. 6. 7, drawing 54, S-3, 7-9) and Koropi (Ntouni, 2014, pp.305 – 330). However, the closest parallels for most of the tableware are reported from Ayia Irini II and III on Kea. Several types of handles from askoi or jugs, the jugs with constricted neck and the three shapes of the Lefkandi I / Kastri group, namely the shallow bowl/plate, the neck-handled tankard and the depas cup, are strikingly similar to examples from Ayia Irini (Wilson, 1999, pp.120 – 121). The stylistic affinities with Ayia Irini are also evident in the case of closed shapes, such as the collared jars, the jar with the exterior flange and the squat pyxis. In terms of absences, no pithoid jars were identified, but the collared jars and the largest bowls or basins could have been used for storage. Finally, the pan and the frying pan occur in small numbers.

The presence of talc ware at Mine 3 (Fig. 11) was first reported by Vaughan and Wilson (1993), who argued that its distribution coincided with the major metal sources in the western Cyclades. At Mine 3, the bulk of the talc sherds were out of context, but several sherds, most

EB II shapes	**Sherd count**
Askos/Jug	21
Bowl, Collared	3
Bowl, Convex	176
Bowl, Pedestalled	3
Bowl, Shallow/Plate	6
Bowl, Straight	84
Cup, Depas	1
Cup, Type a	16
Cup, Type b	14
Jar, Collared	125
Jar, exterior flange	2
Jar, squat (Pyxis)	5
Jug, constricted neck	2
Lid/Frying pan	1
Pan	4
Sauceboat	121
Tankard, neck-handled	2
Tankard, Wavy rim	1
Wheelmade Plate	2
Total	589

Tab. 2: Quantities of EBA II shapes at Mine 3 (author: M. Nazou).

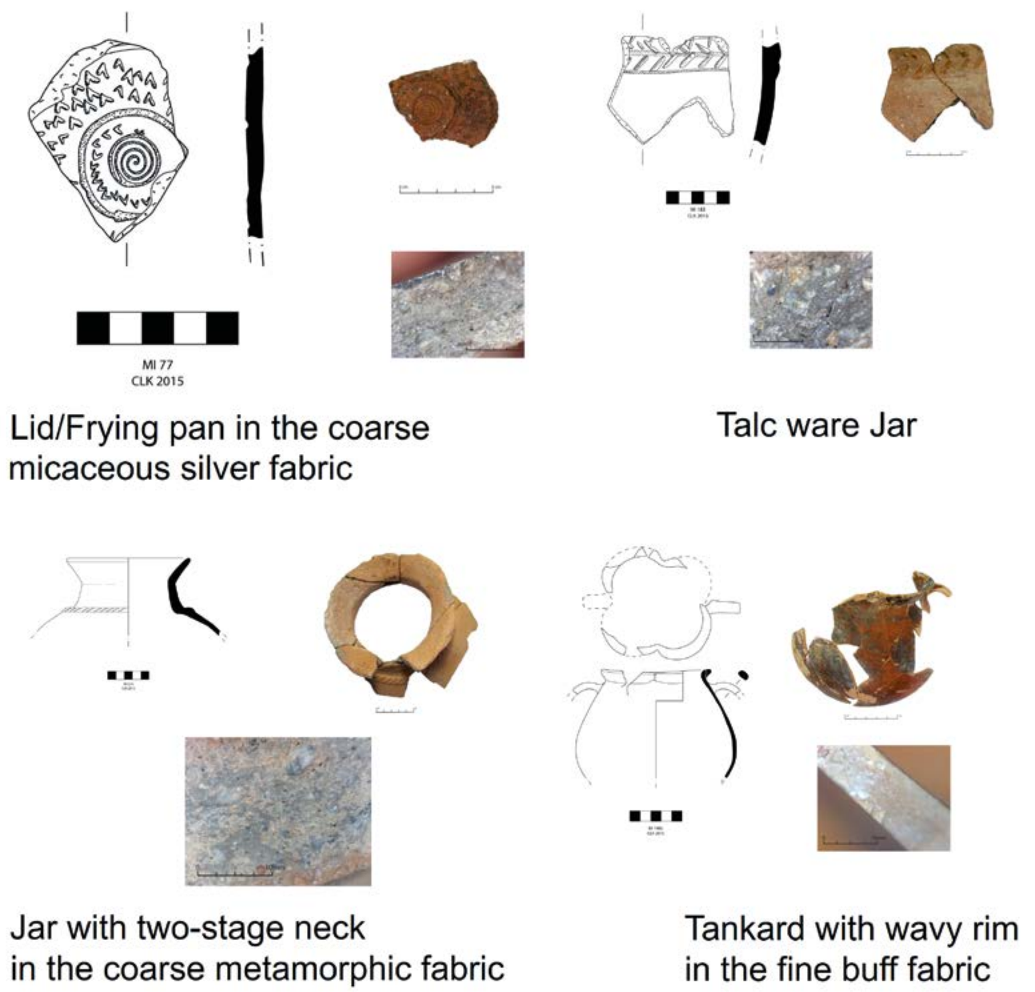

Fig. 11: EBA II pottery (drawings by C. Kolb, photos and microscope photos by Emilio Rodriguez-Alvarez).

likely belonging to the same deep bowl, were excavated together with sauceboat sherds from the red soil deposits at the interior of the gallery, interpreted as undisturbed deposits of mining activity (see above). The imported talc ware vessel recovered in the red soils could be considered evidence strengthening the hypothesis of Vaughan and Wilson, that there is some link of the talc fabric with metallurgy or trade among communities practising metallurgical activities. It is also surprising to encounter sauceboat sherds inside Mine 3, in deposits related to mining activities. The use of this vessel is still controversial. The predominant view considers the sauceboat a tableware shape used for pouring liquids, perhaps wine (Renfrew, 1972, p.284). Theodorou-Mavrommatidi (2007) has refined this interpretation by arguing that sauceboats were used both as ladles and as jugs for pouring wine. It should also be noted that the occurrence of tableware shapes is a long-term phenomenon in Mine 3; Mountjoy (1995, pp.204 – 205) reports that cups occur in the mine during the Mycenaean period.

The EBA III shapes identified so far are bass bowls, ouzo cups and a wide mouth jar, with close parallels at Lerna IV. Incised pyxis lids are also common, with parallels at the Athenian Agora. The study of the Middle Helladic pottery from Mine 3 is still ongoing, but there are several well-known categories such as grey minyan and incised wares together with coarse wares such as pithoi.

A scheme of ceramic phases for the earliest parts of the Thorikos prehistory can be constructed with all the data available (Tab. 3). The Neolithic has so far three ceramic phases, while the EBA has 3 phases, but the Lefkandi I/Kastri phase of the late EBA II period is also present. Due to the problems in the Mine stratigraphy, we cannot separate an early from a late EBA II phase.

Concluding the discussion of the ceramic data from Mine 3, it is now clear that pottery consumption was restricted during the Neolithic, increased in the EBA I, and reached an impressive peak during the EBA II period. The large EBA II assemblage comprises locally produced and imported shapes, mostly tableware. It is evident that Thorikos was actively participating in an exchange network for pottery, extending as far as Siphnos in the South, indicated by the presence of talc ware, the Saronic Gulf in the West, as suggested by the occurrence of the volcanic fabrics, and the Mesogaia, which is a possible production centre for fine buff yellow mottled sauceboats

Thorikos 1	Late Neolithic
Thorikos 2	Final Neolithic – Attica-Kephala phase
Thorikos 3	Final Neolithic – North Slope phase
Thorikos 4	Early Bronze Age I
Thorikos 5	Early Bronze Age II
Thorikos 6	Early Bronze Age III

Tab. 3: The ceramic phases identified at Thorikos (author: M. Nazou).

(Ntouni, 2014, pp.501 – 502). Except for the talc ware, which could have been imported due to its superiority in resisting thermal stress in cooking (Wilson, 1999, p.235), the rest of the imported shapes are mostly fine tableware, and only a few jars. The jars could have been exchanged for their contents, but tableware forms would have been selectively imported as additions to the locally produced eating and drinking sets. The overwhelming stylistic similarities with Ayia Irini II and III suggest that Thorikos and Ayia Irini are in close contact. Finally, the presence of the EBA III pottery indicates activities at Thorikos at a period that is not well documented in Attica.

Early mining at Thorikos

There are several difficulties in the interpretation of the Neolithic and the EBA pottery excavated from Mine 3. At least some of the pottery recovered in the mine could be associated with mining activities. Some could argue, however, that Mine 3 was used as a dump for a nearby settlement (Spitaels, 1984, p.173). Final Neolithic pottery was found about 50 m higher than the mine entrance on top of the Velatouri acropolis (Servais, 1967, pp.24 – 27; Spitaels, 1982). If indeed there was a Final Neolithic settlement on the Velatouri, pottery may have eroded down from the top. That being said, there is a sharp contrast between the very few and sporadic Final Neolithic to EBA finds recognised to date from the entire Velatouri hill and the impressive amount of pottery recovered from the restricted area of Mine 3. Another possibility is that a Final Neolithic to EBA settlement may have been destroyed by later buildings and activities in squares C3, C4, D3 and D4 (fig.4). This area has many later constructions, such as the theatre, a few Classical / Hellenistic houses and the washeries 4 and 11. Bronze Age sherds were indeed recovered in the construction fillings of these buildings (Spitaels, 1984, pp.158, 173).

New evidence on prehistoric settlement on Thorikos, which may be produced by future investigations at the site may shed some light on the history of mining activities. With the existing data, an interpretation of the Mine 3 pottery is inevitably linked to the question of dating the earliest mining activities in the Laurion. The chronology of the first extraction of metal ore from Mine 3 is very controversial. The scenario of Neolithic exploitation would appear reasonable to many researchers, as analyses of Neolithic silver objects have pointed to the Laurion sources (McGeehan-Liritzis, 1996, pp.233 – 234, tab. 4.5.1.1a). Arguments in favour of mining at Thorikos already from the Late Neolithic suggest that the first miners did not need to dig for the ore: it was readily available as natural surface outcrops (Krysko, 1988; Mussche, 1978, p.70). Krysko's research supports the case for opencast exploitation at the initial stages before the Gallery was dug into the Velatouri. Waelkens' study of the toolmarks also argues for opencast exploitation, since the toolmarks outside the Gallery match the ones associated with the undisturbed EBA II layers of red soil in the interior (Waelkens, 1990, p.118). The recovery of stone hammers is further evidence for mining (Fig. 12), since similar stone hammers are found in many early mines (Craddock, 1995, pp.37 – 47), but they cannot be dated with precision. Among the excavation data, the interpretation of the large quantity of pottery recovered from the mine is the most problematic; ceramic specialists world-wide know that pottery use can be difficult to infer from excavation data and that secure stratigraphy, contexts and associations are needed to support the use of pottery in specific activities. Perhaps this scepticism led Spitaels to take a ‘safe approach’ to the matter of the early chronology of activities in Mine 3. She discussed only the late EBA II and EBA III types, leaving the earlier pottery for a later stage of publication.

The possibility that some of the pottery, especially the bowls, could have been used in ore processing, cannot be excluded. Only a limited number of physical manipulations is effective for separating ores, because of the physical properties of components of the ore, and what physical transformation needs to take place, and bowls could have been used in this process. Ethnoarchaeological studies suggest that panning is a technique developed by many cultures world-wide for separating metals from ores. Kakavogiannis (2005, pp.236 – 238) has suggested that

Fig. 12: Stone hammers excavated from Mine 3 (photo: M. Nazou).

during the Classical period the metallurgical workshops in the Laurion used bowls for the same purpose. The direct comparison of the Mine 3 pottery with contemporary sherds found as strays in the later Classical levels in areas surrounding the mine or in other deposits on the Velatouri, potentially relating to nearby domestic activity, might someday highlight any specialised characteristics of the Mine 3 assemblage.

To conclude, there is circumstantial evidence to associate the EBA II pottery from the red soils with the use of the mine. However, with the existing data, the unstratified Neolithic and EBA pottery assemblage excavated throughout the area of the mine cannot be used with certainty to re-date the earliest mining activities at Thorikos, since the excavation did not clarify whether this material was introduced into the reworked fills in the mine all together at a subsequent date or it was originally deposited in sequence, representing different phases of activities in the mine, and later mixed *in situ*.

Conclusions

Summarising the findings we have from prehistoric pottery so far, we can make the following observations. Mining at Thorikos could have started as early as the Late Neolithic (5th millennium BC) and continued during the Final Neolithic and throughout the Bronze Age. The impressive peak in ceramic consumption at Mine 3 during the EBA II could indicate intense mining activities. The preliminary examination of the survey pottery from the southern slope of the Velatouri, a project conducted under the directorship of R. Docter from 2012 – 2017, suggests a relative scarcity of EBA II pottery compared to the Final Neolithic and Middle Bronze Age finds. Lacking data from Thorikos itself, we can argue that the EBA II settlement is most likely located on the coast. In support of this hypothesis, rescue excavations by O. Kakavogianni (1985, p.51) yielded EBA II pottery in the DEI power plant building plot. The Middle Bronze Age is an especially flourishing period, associated with settlement remains on the acropolis (Servais, 1967, pp.20 – 24). There is evidence for the development of a local elite and hierarchies during the late Middle Bronze Age to the early Late Bronze Age, when the monumental tombs are built (Laffineur, 2012). The site seems to decline during the late stages of the Mycenaean period, yet mining at Mine 3 may have continued in the LH IIIC (Mountjoy, 1995, p.197).

Some last observations can also be made on the position of Thorikos in prehistoric metal exchange networks in the Mediterranean. Early seafaring may have been triggered by the search for metal ores in the Aegean and the Mediterranean, and the strategic and easily accessible position of Thorikos cannot be overlooked. The social context of early mining and metallurgy was most likely different than later phases in prehistory, when palatial centres were consuming large amounts of copper, gold and silver.

Kassianidou and Knapp (2005, p.231) have highlighted that early mining and production sites in Cyprus were relatively isolated from the large Bronze Age coastal centres. Thorikos and its place in the Laurion provides a different picture, since it is an important coastal site, which combines evidence of mining, metallurgy and the presence of hierarchies and elites profiting and perhaps controlling its metal sources. There are also other mines in the Laurion that have been preliminary dated to the Final Neolithic and the Early Bronze Age: Vigla Ribari, Kastella-Thymari and Souvlero near Anavyssos (Lohmann, 1993, pp.87 – 88, 244) and Ovriokastro near Keratea, (Kakavogiannis and Kakavogianni, 2001, pp.56 – 57). Their systematic investigation could provide some comparative information in order to better understand early mining in the Laurion.

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Notes

1 The Belgian School at Athens was instituted in 1985. Back in the 1960s, Thorikos was being excavated under the directorship of Herman Mussche of Ghent University, who worked through the so-called Committee for Belgian excavations in Greece. For the history of investigations and excavations at Thorikos see Mussche (1998, pp.5 – 8) and Webster (2018, pp.11 – 12).

2 The section on the Mine excavation is based on the information provided by Spitaels (1984, pp.151 – 164), unless otherwise mentioned.

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Ancient Laurion: Stages, phases and landscape

ABSTRACT: *Where do we stand 160 years after the first systematic exploration of the Laurion district? This paper attempts to assess the overall picture of our progress in solving the great puzzle presented by the main distinctive characteristic of the Laurion Peninsula: its very large scale. It sets off by pinpointing the main pending questions linked to the interpretation of the area's material culture and its landscape; it proceeds to organize them in an intra-referenced sequence of stages and phases. Materials and structures related to mining and metallurgical technology are targeted. For example: how did the ore washeries evolve, how did this evolution participate in structuring the landscape? How did human collectivities co-evolve as to their internal structure? How was this reflected on changes in their landscape organization principles? The major problems of chronology are tackled by sequencing each class of material evidence (katharistêria, hydraulic technology, mining galleries and shafts)*[1]*, independently, based on purely archaeological data. A seven-phase scheme is proposed and compared with established historiographic sequences for a Laurion relative chronology to emerge. The whole network of identifiable evolution lines is proposed to be understandable within a large-scale landscape perspective and this is exemplified in the case of a suggested triggering of urbanization processes within the Athenian Chora. These large-scale dynamics are made visible in structuring power relations which control land (surface and underground), water and human labour.*

KEYWORDS: ATHENS, LAURION, ANCIENT MINING, ANCIENT METALLURGY, SETTLEMENT PATTERN, LANDSCAPE ARCHAEOLOGY, CLASSICAL ARCHAEOLOGY, CHRONOLOGY.

Introduction

It has been almost 160 years since the first systematic exploration of the Laurion district (for place names cited in the text see Fig. 20)[1] as to its link to the material and social dimensions of an emblematic ancient political society, i.e. the Athenian Polis (Cordella,1869; Négris, 1881; Ardaillon, 1897). And almost 2,500 years since the writing of the first known socio-economic analysis on the same region (Xen., Poroi, 4). How have we progressed to date? Even though an impressive amount of work has been done, it seems that essential questions, originally set, remain unanswered.

An overview of such questions inevitably has to address the evolution of ore-processing related structures typologies and their chronologies, the understanding of the entire chaîne opératoire involved, as well as the decoding of the topography of the Laurion Demes and its spatial organisation throughout antiquity.

Persistent questions and yet an overwhelming corpus of data. The comprehensive understanding of Laurion has fallen victim to its unusually large scale: multidisciplinary research remains dispersed and in need for a constant, in-depth dialogue and cooperation between disciplines. There is the necessity to collectively focus on describing and trying to resolve problems and questions that will allow us to achieve an understanding and a synthesis at this large scale.

Methodological framework

The present contribution embarks onto an effort to establish a comprehensive relational phasing scheme for ancient Laurion, setting off from problems in our current state of research, with dating considered as an axial issue. In the present occasion, prehistoric and protohistoric periods are not dealt with and a background knowledge for the following periods is considered as known. This is a five-fold effort:

1. The phasing scheme is aimed to be structured independently, based on purely archaeological data, interweaving evolution sequences, which correspond to discrete practices (mining/ore processing/water management), all tightly linked together within the Laurion mining-metallurgy *chaîne opératoire*.
2. By sequencing each class of material evidence considered (e.g. *katharistêria*[2], hydraulic technology, mining galleries and shafts[3]), their evolution is structured

Fig. 1: Distribution of stage K–1 FBW (Google Earth with additions by A. Kapetanios).

in stages. Synchronisation between stages is then attempted, which produces a seven-phases scheme.

3. In parallel, as archaeological data is compiled and organised in the above manner, important pending questions are highlighted, and suggestions are made on planning further research.
4. The scheme is then juxtaposed to the established historiographic/epigraphic sequences and the result of their superimposition is discussed.
5. Besides its self-evident significance in sequencing archaeological material assemblages, the proposed scheme is applied here heuristically to unravel principles structuring ancient communities in the Laurion peninsula landscape, outlining what I consider the Laurion landscape dynamics. Scale issues prove to be crucial in developing such an understanding.

Problems of chronology

One of our main problems, as regards the bulk of Laurion material remains, which densely cover 25 km² of its valleys, is chronology. This is due to a spectrum of both taphonomic and operational factors:

As to taphonomy, datable archaeological finds rarely derive from undisturbed fillings; the architectural remains of the *ergastêria* have been visible on the land-surface for thousands of years and were intensively exploited in the second half of the 19th century for metallurgical remains employing heavy industrial machinery. Furthermore, these finds are related to the use of the installations and thus provide *terminus ante quos*. To date, we lack direct and safe dates for the construction of mining works and ore processing installations. In the rare occasions that foundation trenches were identified and systematically excavated, as in the trial excavation at Ary 63 in the framework of the Ary project (Lohmann, 2020; Hulek, this vol.), no datable material has been retrieved so far.

Taphonomy is also relevant in the case of surface finds. The pre-eminence of the 4th century pottery is often referred to as conspicuous on the surface of the workshop valleys. This is certainly an important observation, but still an impression rather than the product of a systematic survey, with the exception of those undertaken at Ary (as in the Ary project, Lohmann and Kapetanios in prep.) and at Thorikos (van den Eijnde, et al., 2018). Taphonomic factors should be assessed before such a general picture becomes an argument. For example, the industrial character of the installations involves coarse pottery of long-lived types, such as the lekanai. Lekanai rims, besides being easily recognisable, are exceptionally strong and resist breaking into small fragments. There is thus a strong recovery bias in favour of lekanai, which, even in the light of G. Lüdorf's (2000) seriation, can hardly provide the chronological resolution needed.

These being said, the results of the extensive and partly intensive Ary survey draw an interesting outline, even though the assemblage of datable surface pottery is rather small: there is a peak at Classical times (80 %), with 4th century clearly recognizable; the next peak, though very much lower (5,5 %), falls into the Late Roman/Early Christian period; Hellenistic sherds come third and last with a very low representation (1 %) (Lohmann, 2020; Lohmann and Kapetanios, in prep.).

Fig. 2a: K–1 FBW, Haghia Triadha, Souriza (photo A. Kapetanios).

A way to answer the above mentioned methodological problems is to carefully plan a combination of systematic, extensive and sampling-intensive surveys, which will allow statistical assessment of surface pottery in the Laurion valleys.

As to operational factors, the majority of the cases of archaeological investigation at *ergastêria* have been conducted in the context of salvage excavations. Their priority has been to identify ancient material remains and thus to protect them from destruction in the context of modern developing works. The massiveness of the surviving installations, their state of preservation and the intrinsically urgent character of the investigation have scarcely allowed for trial excavation beneath them.

Besides, we lack detailed published data on pottery deriving from well documented *ergastêria* contexts related to stratigraphy, which could contribute immensely, unraveling issues of chronology.

On the one hand, salvage excavations results have been published only preliminarily in reports[4] their pottery assemblages awaiting thorough study and publication. In the reports, the excavators give an overview of the pottery chronology in order to date the structures. In the case of two *ergastêria* excavated within the Thorikos valley complex, their pottery is summarily described (Saliora-Oikonomakou,1997a) assigning their foundation and use to the 2nd half of the 4th / first half of the 3rd centuries BC, and a revisit, to exploit metallurgical by-products, to Late Roman times.

It is imperative, then, that a wide collaborative project, focusing on the study and publication of contextualised pottery from the numerous *ergastêria* salvage excavations should be initiated.

On the other hand, similar issues are not absent in systematic investigations. Indicatively, the pottery assemblages deriving from the systematic excavations carried out by the late K. Tsaïmou at Ary I, II, III (Τσάϊμου 2006, 2008; Τσάιμου and Τσάιμου 2010) have just been presented by Nomicos and Tsaïmou (in prep.) and should contribute decisively towards a sound documentation of these very important installations as to their chronology. The other systematic excavation on the South slope of Mihales hill, focused more on metallurgy and, apart from an overall dating of the pottery to the 4th century BC, it provided few data on datable pottery in context, which remains unpublished (Jones, 2007, p.275; Photos-Jones and Jones, 1994) and therefore urgently needs to be revisited and studied. The Thorikos Project's (Docter and Webster, 2018) systematic excavations and survey reports, spanning over more than four decades, are the standard source for pottery data, even if preliminarily. Research at Ary II, i.e,. an ergastêrion with circular mill (formerly helicoid washery – see below), a type I “flatbed washery” (hereafter, FBW) and a row of smelting furnaces (*káminoi*), provided the only, so far, absolute dating for archaeo-metallurgical materials but with low chronological resolution: radiocarbon dating of litharge slags retrieved from the *káminoi* gives low resolution calibrated dates

Fig. 2b: K–1 FBW beneath a tower from the 4th century BC, Souriza Valley (photo, information leaflet for the archaeological site, Ephorate of Antiquities in East Attica)

for two samples, falling with a certainty of 95,4% within 203–46 BC and 198–47 BC respectively (Tsaïmou, et al., 2015, p.118, tab.1). If taphonomy is straightforward, these dates probably refer to the module's latest operating years.

In the face of lacking reliable and numerically sufficient direct archaeological chronologies, indirect dating based on historiography[5] was used to provide the canvas for developing synchronies. This is examined further below.

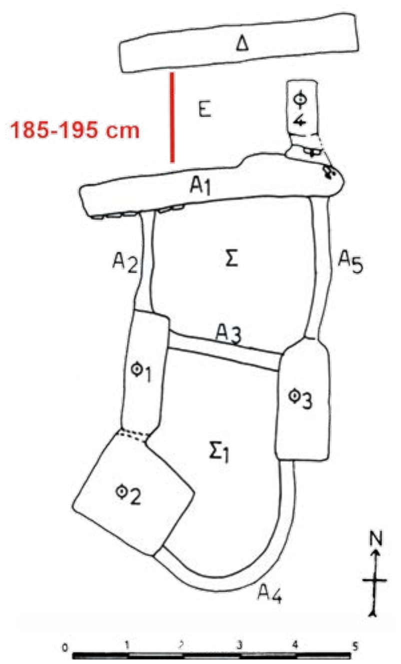

Fig. 3: Layout of a K–1 FBW at Bertseko valley (after Kakavogiannis 2001, with additions by A. Kapetanios).

Relational sequencing

In this section, we may try to compensate the scarcity of meaningful relative or absolute dating by systematising our current knowledge within relational sequencing instead of calendric dating, as prescribed above.

Katharistéria

The evolution of silver extraction technology in Laurion, can lay the warp to weaving such a phasing, starting with the relational arrangement of technological attributes and features of the *katharistérion*, the main structure of the ore cleaning (to enrichment) *ergastêria*, known as "flatbed washery" (FBW Παπαδημητρίου,1992; Kakavogiannis, 2001).

Stage 1

There is certainly an early stage in the evolution of the FBW, prior to the vast majority of standardised *katharistéria* spread all over the Laureotike peninsula (Figs. 1, 2a, 3).[6] Besides the purely formal attributes assigned to the early type, characterising it as experimental and thus irregular (Kakavogiannis, 1989; 1991, p.369), there is direct relational evidence in the case of one such *katharistérion* excavated by E. Kakavogiannis beneath a definitely classical-late classical tower in the Souriza complex (Fig. 2b).

However, datable material related to these early structures is poor (Kakavogiannis, 2001, p.369) and certainly not linked to their construction phase. Consequently, we can only refer to them as early, or stage 1, *katharistéria*, rather than pre-classical ones.

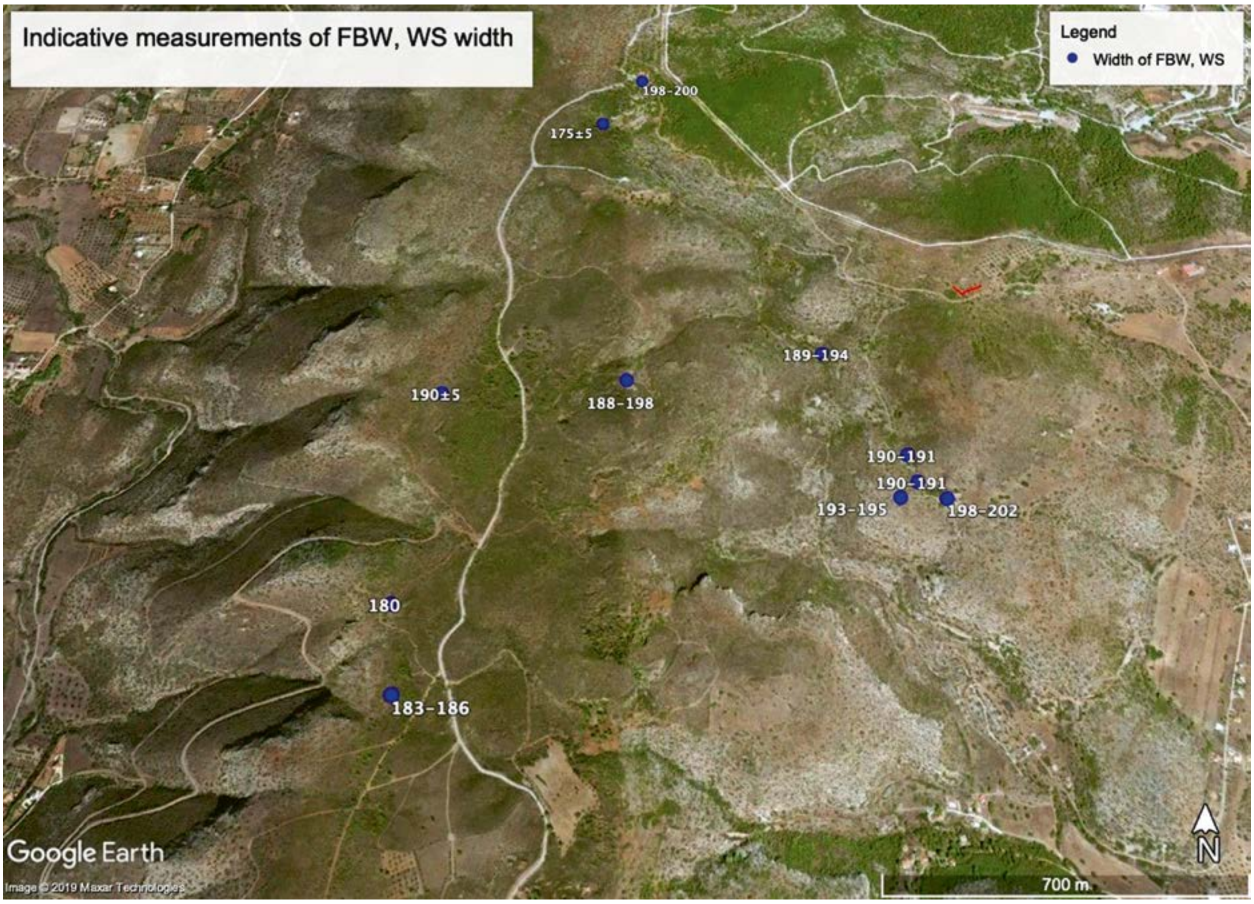

Fig. 4: Indicative example of the spatial distribution of the FBW standardised dimensions as to working space width (Google Earth with additions by A. Kapetanios).

Stage 2

This stage corresponds to the typical "type I" FBW which has been widely discussed (Cordella, 1869; Négris, 1881; Παπαδημητρίου, 1992; Photos-Jones and Jones, 1994; Kakavoyannis, 2001) and there is no need to comment upon it on the present occasion.

In stage 1 *katharistéria*, even if considered experimental, ore-processing in the context of silver production had already entered a "standardisation mode", as evidenced by the dimensions of the working spaces (c. 185–195 cm, taking into account erosion and ware, Fig. 3), which, as aptly expressed by Papadimitriou (1992, p. 193), were kept in "religious piety" for as long as any stage/type of *katharistérion* was constructed (Fig. 4). Standardisation is, of course, appropriate for large-scale massive processing. Then, if experimental, what did ancient metllurgists experiment for?

The significant differentiating structural characteristic between the stage 1 and 2 structures is that:

- in stage 1, *katharistéria* are adapted to an existing geomorphology, hence the irregular distribution of their components, usually hewn into the bedrock, whereas
- in stage 2, *katharistéria* are constructed after the existing geomorphology has been transformed by digging and building in order to be adapted to a preconceived standardised type.

The emergence of stage 2 *katharistéria*, in my opinion, seems to be the result of an effort to achieve the greatest possible standardisation for all parameters related to the process of ore cleaning – i.e. enriching – using water. This affects all practices linked with the Laurion metallurgy chaîne opératoire, i.e. practices and actions undertaken at the spot, as well as others involving large-scale landscape structuring such as water-management. High standardisation could allow consistency in the procession time for certain quantities of certain ores, ground to a certain particle-size. This means labour-cost efficiency and production optimisation. Standardised orientation, plus standardised distribution of FBW and their cisterns within a valley optimises water-flow control, water distribution, evaporation rates and, therefore, water-management on a very large scale.

In brief, the transition from stage 1 to stage 2 *katharistéria* reflects a movement towards great standardisation, optimising the exploitation of scarce water resources and of manpower, and thus reducing the need for highly specialised personnel; only a few of high-value-specialised

Fig. 5: Distribution of stage K–3 (type II) FBW and G–2 Circular Mills (Google Earth with additions by A. Kapetanios).

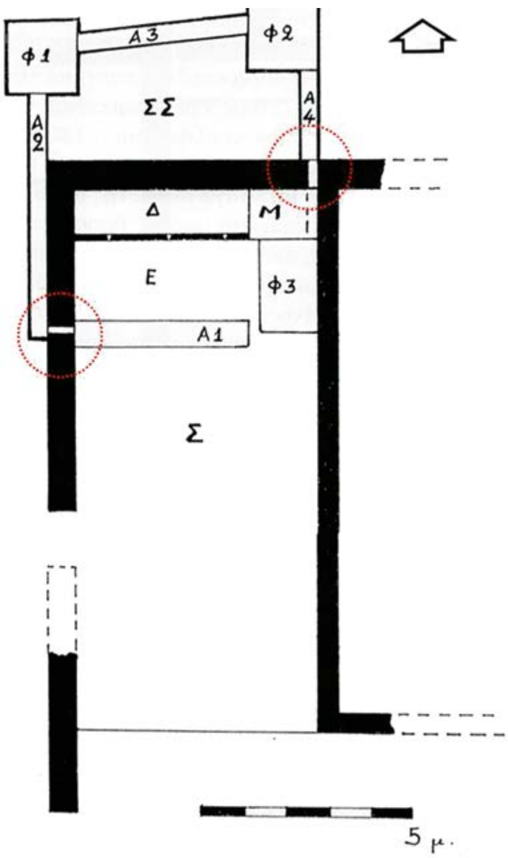

Fig. 6: Variations of the K–3 (type II) layouts (Spitharopousi II and III, after Kakavogiannis 1991); red circles mark tubularopenings (additions by A. Kapetanios).

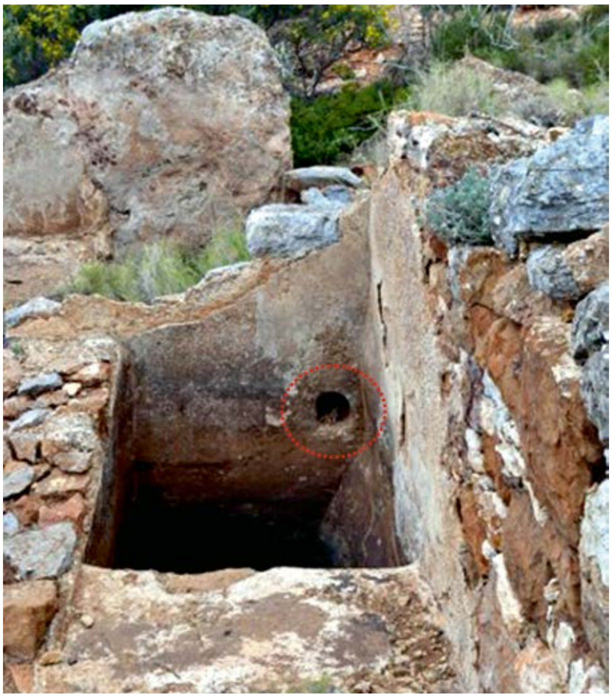

Fig. 7: K–3 (“type II”) tubular opening marked by red circle; Katharistério Spitharopoussi IVb (photo and addition by A. Kapetanios).

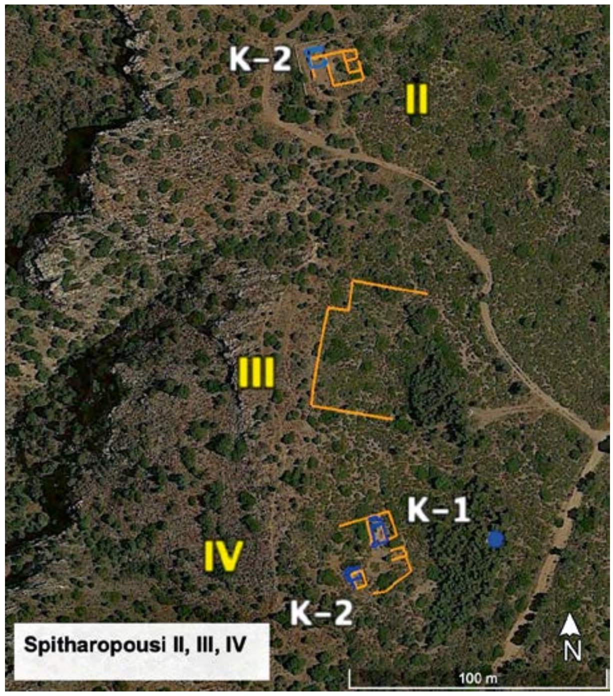

Fig. 8: Spitaropoussi sites, katharistéria II, IV (K-2/“type I” and K-3/ ”type II” in the same anclosure) and building III (Google Earth with additions by A. Kapetanios).

slaves, such as the famous one talent-worth Sosias from Thrace, owned by Nikias Nikiratou (Xenophon, Poroi IV.14), would suffice to orchestrate many groups of unspecialised workers/slaves. And the *katharistéria* would still work with high precision.

In this context, control over manpower and water, through standardisation of structural features and processes, implements effective mass-production and establishes well defined power relations.

Stage 3

The few specimens (ten identified to date, Fig. 5, blue disks) of the so-called type II FBW seem to be rather idiosyncratic as each one presents a different layout (Kakavogiannis, 1991); they do share, though, the same standardisation with type I, as regards working space dimensions. Its interpretation as a predecessor of type I FBW has been criticised.[7]

All type II FBW share two features which differentiate them from the typical type I FBW:

- an extreme variation in positioning the sedimentation tanks (no pair bears the same positioning (Fig. 6).
- tubular openings interconnect channels and sedimentation tanks in a variety of ways (Fig. 7).

It is possible that these two are causally linked. There seems to be an effort to deal differently, but in a systematic way, with subsurface dilution as opposed to its surface, allowing for the first to move on in the circuit, while keeping the second, or the reverse. The resulting non-standardised (as to outline) type, may reflect experimentation to optimise such a process. Taking into account Papadimitriou's scheme, which describes a shift in practices by assigning significant part of the production processes to the exploitation of accumulated by-products, mainly litharge (Papadimitriou, 2008; 2018), type II FBW may indeed place themselves at the dawn of such a transition, even though we cannot decode, yet, their functional purpose. Their small number (relatively to the widespread type I), the general co-existence of both type I and II FBW in the landscape as remains of the last period of the *ergastêria* use (Kakavogiannis, 1991, p.16) and, more significantly, their co-presence in the same *ergastêrion* defined by its enclosure (Fig. 8) corroborate to placing type II in a third stage in the evolution of FBW, co-functioning with the earlier type I (stage 2).

Stage 4

A series of alterations by additional elements (slabs, stones, etc) have been described in various cases by the excavators of *ergastêria* (Zorides, 1980; Oikonomakou, 1979; 1991; 1997; Kakavogiannis, 1995). They are defined by various, rather coarse modifications of the existing type I and II FBW components. Even if not reported in detail, it seems safe to suggest that they are mainly associated with arrangements in channels of the *katharistérion* circuit.

I would divide these post-construction additions into two kinds:

- First, there is a single slab dividing the first (“collection”) channel (parallel to the feeding tank, in front of the

Fig. 9: (a) A slab dividing the feeding tank in two (K–4a, Souriza). (b) Slab with U-notch in situ, held in position by lining slabs (K–4b, Spitharopoussi, ergasterion "Kordella"). (c) Vertical slabs dividing the first (collection) channel in four; notch is visible at the upper left corner of the slab (K–4b, Spitharopoussi, ergasterion "Kordella"). (d) A slab with the typical notch found as one of a tomb's covering stones (Late Hellenistic Cemetery at Limani Passa), (photos and additions by A. Kapetanios).

working space), or the feeding tank itself into two compartments (Fig. 9a). In the first instance, this has been interpreted as a device to process separately powdered litharge and ground tailings, but within the same FBW, aiming at keeping the litharge washing residues in the first compartment, while allowing water to overflow to the second compartment, where the tailings' washing residues were driven into (Papadimitriou, 2018, pp.194 – 195, fig.6).

- Second, roughly hewn slabs are placed vertically in the *katharistérion* channels (the first channel so far), dividing them into more than two compartments[8] (Fig. 9b,c). Schist is almost exclusively used, probably due to its naturally impermeable quality. These slabs are set in place and stabilised by other slabs lining the channel's walls (as a second layer, Fig. 9b,c). They allow overflow through roughly shaped notches, either as a cut at one of the upper corners (Fig. 9c), or, most commonly, as a U-shaped notch at the centre of the upper side of the slab (Fig. 9b). Such notches are not present in the slabs of the first kind, above. The setting could be interpreted as a device for producing gradually higher concentrations of light material, the highest accumulated in the last compartment, a technique which is known to have been applied widely as, for example, in the extraction of clay. Schist slabs of this type, bearing the characteristic notch, have been recorded astray on the surface, in various locations in the Laurion area.

Are these two classes synchronous? They could be, as they both have been found standing in position, as the last phase of use of *katharistéria*, prior to their abandonment. They seem, though, to address different processual targets. For the present classification, I will consider them as stage 4a and 4b, respectively. Can they be dated?

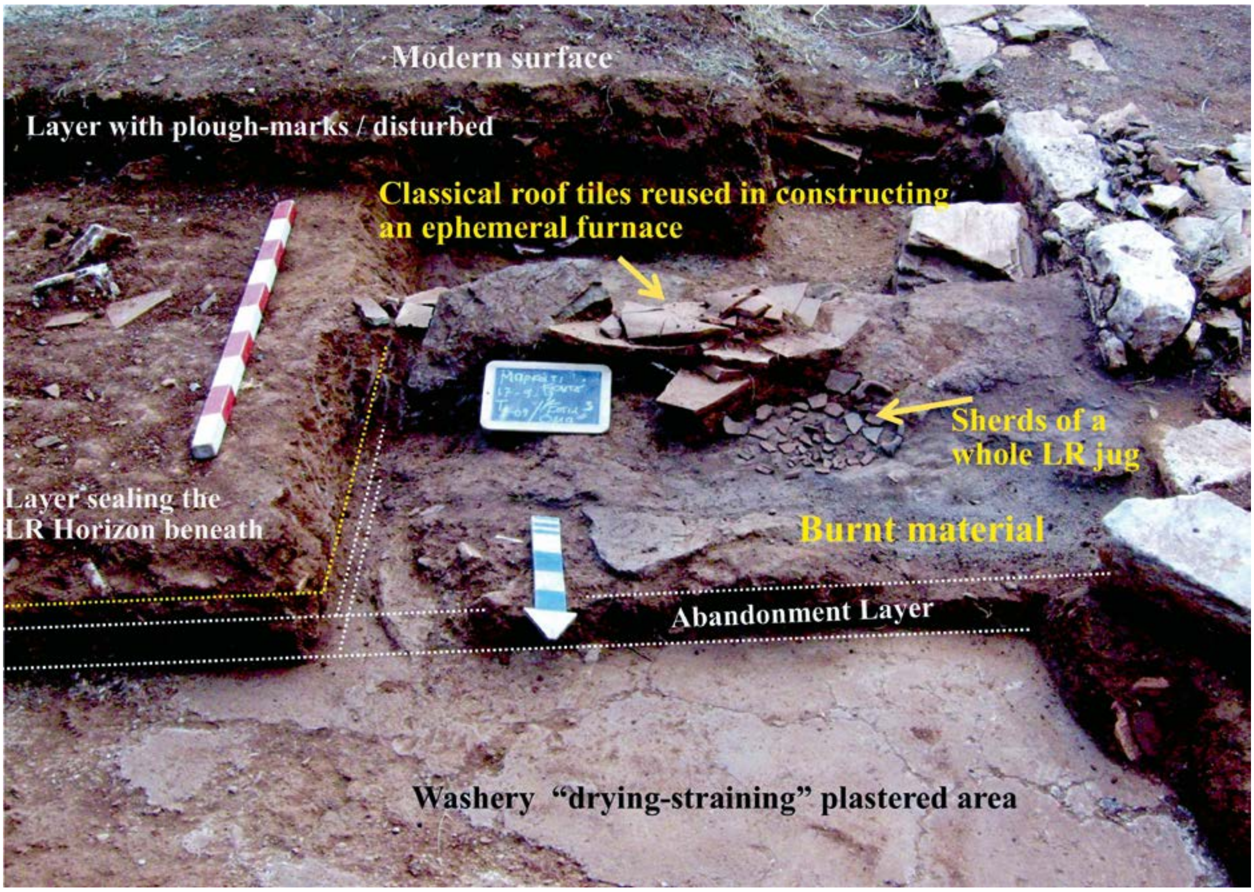

Fig. 10: Remains of short-scale and short-term metallurgical activities, with a broken LR jug, on top of the abandonment layer covering a K-2 (type I) FBW, at Merkati-Stephani, Thorikos (photo and additions by A. Kapetanios).

Again, direct dating of their placement in the channels has not been possible yet. A slab, characteristic of the stage 4b alterations, was found among those covering a pit grave (Fig. 9d) excavated in a late Hellenistic cemetery at Limani Passa (Kapetanios, 2010, pp.150–155; 2013, pp.193–196). The tomb is dated by its grave goods to the late 2nd/early 1st century BC. Therefore, for the time being, we may consider this date as a *terminus ante quem* for the stage 4b rearrangements in FBW being introduced and operating.

Stage 0

To the stages described above I should add one more in the beginning: What was there before the invention of FBW? Wooden versions, or simply nothing? Or both? The possibility that prior to FBW, people were directly smelting high-grade ore and that *kataristéria* came about when the processing of low-grade ore became necessary was put forward in the past (Kakavogiannis, 2001, pp.336–337); current geological and mineralogical research in Laurion (Ross, et al., this vol.) seems to support the availability of high-grade mineralisation, suitable for direct smelting (Ross, et al., this vol.; personal communication). This stage should be included as stage 0.

Stage codification[9]: K–0, K–1, K–2, K–3, K–4a, K–4b

Stage of post-abandonment (PA) alterations in ergastêria

This is an 'interposed' stage, only indirectly linked to the *Katharistérion* itself. It is inserted here, because it has been identified in *ergastêria* excavations as a post- abandonment horizon, usually close or over the katharistéria structures.

Small-scale metallurgical activities have been identified on top of abandonment layers (Fig. 10) in *ergastêria* or as intrusions to these layers; a small roughly shaped furnace, metallurgical residues and a broken pot (in the best instance) seem to form a pattern of a certain practice which could be read as scavenging ancient plynites, litharge fragments, scoriae, or whatever could be re-smelted to produce even small quantities of, possibly, lead. In two examples of such cases, at Skitzeri and Markati, in the wider area of Thorikos (Salliora-Oikonomakou, 1997b, p.127; Kapetanios, 2013, p.187) direct dating is achievable, as they represent small closed contexts, in which pottery is of Late Roman date. At the *ergastérion* Ary 63, people dug into the abandonment / destruction layer

Fig. 11: Two phases of the ultimate waterproof layer of the hydraulic mortar/plaster lining in a cistern (Haghia Triadha, Souriza); Pl–1: the reddish ("litharge") lower layer; Pl–2: the blackish ("manganese") upper layer (photo by A. Kapetanios).

accumulated above its *katharistérion*, probably looking for exploitable residues, and left a broken pot which dates this one-off action again to Late Roman/Early Byzantine times (Hulek, this vol.).

For the sake of the present classification, I will consider this stage as PA-stage.

Stage codification: PA

Hydraulic plasters and mortars

Hydraulic mortars and plasters, being crucial and characteristic components of the sophisticated hydraulic technology applied in the huge network of Laurion *ergastêria*, seem suitable for stages in their evolution to be traced.

As to the substrate mortar, ongoing research building upon earlier studies, suggests that it is actually a hydraulic concrete with extraordinary properties such as high compressive strength, high density and low porosity (Meimaroglou, et al., this vol.). No stages as to the evolution of this technology have been identified so far. A future analytical comparative study between the Laurion mortars and those discovered recently in the well dated water supply system in Piraeus (Chrysoulaki, et al., 2017) could reveal possible technological evolutionary steps.

On the other hand, a twofold variation of the finest waterproof film covering the *katharistéria* and cistern's hydraulic mortar substrate (concrete) has been recognised (Papadimitriou and Kordatos, 1995, p.283; Papadimitriou, 2008, p.116). The two versions differ in that litharge is exclusively present or conspicuously prevailing in one of them, whereas manganese with a lesser presence of litharge characterise the other. It has been proposed that the second version is linked to the period of the cistern's construction, on the basis that litharge would have had been in high demand (and thus scarce) at those times (Papadimitriou, 2008, p.119). This association places the manganese-based layer earlier than the litharge one. Within a small-scale pilot survey employing a portable XRF device to examine in situ hydraulic plasters in the area of the Haghia Triadha-Soureza-Spitharopoussi[10], it was found that in some cisterns the two versions coexisted and quite clearly the one containing manganese had been applied atop the litharge-version as to repair it (Fig. 11). This observation reverses chronological sequencing and places the recipe employing manganese at a later stage than that of the litharge-layer (stage 1 – "litharge", stage 2 – "manganese"). The reasons behind such a shift in the ingredients of the waterproof film remains to be investigated. It is apparent that we need to extend and expand in situ measurements with portable XRF and other non-destructive methods (e.g. photography in various spectrum frequencies, in situ microscopic observation and photography) and keep on documenting hydraulic plasters, mortars and their constituent elements which, macroscopically, do present observable differences. After statistically significant numbers of discrete measurements will be accumulated in a database, we might start developing detailed sequencing by comprehending technical details linked to the evolution of this hydraulic technology.

The exceptional "hi-tech" characteristics of these materials, applied to such an extraordinarily large-scale, result to high-standard, accurate and optimised management of the water resources available in a dry area. This management takes equal care to handle effectively the large scale hydrological networks (catchments and ravines, geology and geomorphology) and the small-scale water use within an *ergastêrion*, through recycling. *Katharistéria* and cisterns covered with these materials make feasible water management that certainly well exceeds the annual cycle.

Stage codification: Pl–1 (litharge), Pl–2 (manganese)

Circular mills

These few (eight identified so far) structures (Fig. 5), initially considered as "helicoid ore-washeries" (Konophaghos and Mussche, 1970; Tsaïmou, 1979), or devices for the homogenisation of ore to achieve effective briquettes for smelting (Tsaïmou, 2008), are now proven beyond doubt to be circular mills (Papadimitriou, 2015; 2016; Nomicos, 2021). Their interpretation as such has been linked to a shift in production towards the exploitation of metallurgical by-products and especially litharge (Papadimitriou, 2008; 2012; 2018, pp.192 – 197). We cannot be sure whether grinding litharge was the purpose of these structures originally; we are definite, though, that this was their use at the time of their abandonment as, at least in the case of Ary II, litharge can be still seen almost embedded into the mill's channel, and accumulated at one of the corners of its square enclosure (or room-walls?) (Papadimitriou, 2016, p.115).

Corroborative argument derives from the gold-mining sites of Samut and Compasi in Egypt's Eastern Desert.

Corresponding structures – one of them almost identical to the Laurion examples – have been identified there, and their use as mills to achieve powder-like ore is attested (Redon-Faucher, 2015; 2016). In a manner reminiscent of Laurion, their dating is uncertain, as these mines were operating almost constantly from the middle Kingdom era down to Roman times and their by- and sub-products were re-exploited in the 20th century.

Direct dating of these mills is (again) currently not possible (cf. Konophaghos and Mussche, 1970). K. Tsaïmou links these constructions with the pottery retrieved from excavations at Bertseko and Ary, ranging from late Classical to Roman times (Tsaïmou, 2008). However, this is just an estimate on the basis of a general overview of the excavated pottery and no detailed pottery data has been available, as yet. In any case no datable finds have been linked to the construction of the circular devices. Papadimitriou infers a similar date range (early 3rd century to Roman times) on the basis of his chronological scheme (see further below) for the emergence of the intensive exploitation of secondary (by) products and especially of the litharge (Papadimitriou, 2018).

Circular mills have been found close to type I (stage 2) FBW but not to type II (stage 3). This has probably no chronological significance but hints to operating and processual differences between all these devices: Circular mills have been found attached to smelting furnaces, whereas K-3 FBWs not (Fig. 5). Furthermore, we do know that, for some period of time, all three did operate simultaneously.

In the context of the present classification, I will consider all pre-existing grinding techniques as G–1 and the introduction of the circular mill as G–2. G–1 techniques kept on being employed contemporarily with G–2 mills.

Stage codification: G–1, G–2

Mines and shafts

The construction (digging) of these extensive works cannot be dated directly, so far. Systematic investigation of mine galleries and shafts is currently at an apex. New data are being accumulated, among which the recording of toolmarks and digging techniques. A study of toolmarks and quarrying techniques towards developing an evolutionary typology, which could contribute to direct dating, is still in the very beginning (Tziligkaki-Stamatakis, 2018). First, we should investigate whether there are intra-site differences (i.e. differences in toolmarks and techniques between different Laurion galleries and shafts).

Currently available datable material retrieved from mines is almost exclusively lamps, found on top of the exposed surface; even if no stratigraphic contexts have been available as yet, these finds are quite safe as *termini ante quos,* being found deep in the galleries; they present two chronological peaks: one in classical times and one in Roman to Late Roman times. Classical lamps of an exclusively and definite 5th century BC date are not known so far. In contrast, the most common finds are the fourth century “inkwell-type” lamps and especially those considered late versions of the type (there is, however, uncertainty as to such a distinction being possible; Blondé, 1983, pp.25 – 26). Such peaks are also visible in material related to mine III at Thorikos (Blondé, 1983, p.170). The same pattern emerged during the exploration of the Esperanza mine near Kamariza (Vaxevanopoulos, et al., in prep.).

The presence of lamps cannot automatically be translated as mining activities. For example, it is very well documented that in periods of great danger due to warfare or piracy and raids, people sought occasional or even lengthy refuge in such places; a good example comes from the Eupalinos aqueduct in Samos (Kienast, 1995). If for the 4th century BC it is almost self-evident that mining activities occurred, it is not for the Roman/Late Roman times. Certain sets of silver jewellery retrieved from 39 out of the 84 excavated tombs in the extensive Late Roman cemetery, at Panormos (Oikonomakou, 1999) could be considered to corroborate primary silver production for this period. The question here is, whether this clear whitish silver could, alternatively, be derived from the liberation of pure silver from within litharge (Papadimitriou, 2008; 2012). Further analytical studies of these artefacts as well as of the differentiating characteristics of the litharge deriving silver (if there are such to be found) seems to be a way to follow, in order to answer such questions.

Summarising, with the exception of the disturbed, mixed filling at the entrance of Mine III (from EH to Archaic and later), which includes late archaic lamps, mine galleries and shafts could be arranged in four stages: stage 1 – construction; stage 2 – 4th century BC use; stage 3 – unknown; stage 4 – Roman/Late Roman presence.

Stage codification: M–1, M–2, M–3, M–4

We should keep in mind that these works are products of very hard and time-consuming human labour; the tens of kilometres of the gallery networks and the hundreds of shafts cannot be all synchronous; what is the time span of their construction? Was there an apex? Besides surveying galleries and shafts, detailed investigation of contextual information regarding, for example, the peak of slave population in the area may contribute to seeking answers for these questions; further landscape survey combined with mortuary and bioarchaeological studies are needed for such a task.

Synchronisations – phasing

Phasing A – independent sequence

An effort to draw correspondences between all stages described above, and to outline seven successive phases is presented in Fig. 12a.

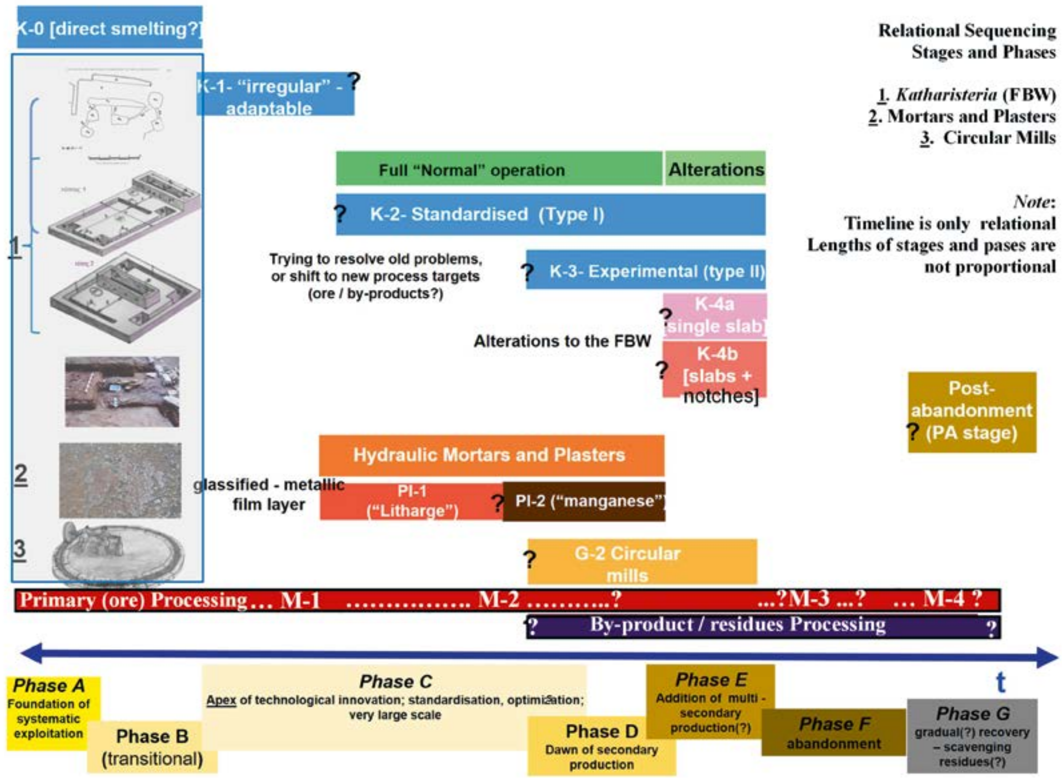

Fig. 12a: Relational Sequencing of archaeological features. Question-marks signify chronological uncertainty as to the beginnings and ends of stages (chart by A. Kapetanios).

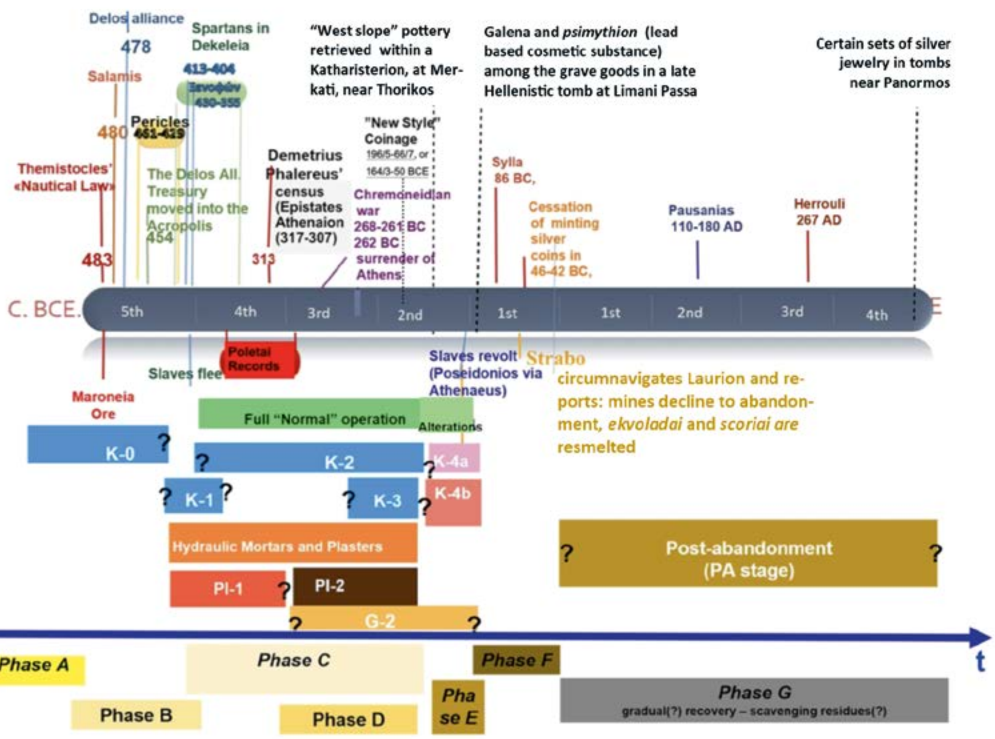

Fig. 12b: Timeline juxtaposing indicative historiographic / epigraphic and archaeological data with the relational sequencing of Fig. 12a. Question-marks signify chronological uncertainty as to the beginnings and ends of stages (chart by A. Kapetanios)

From phase A to C we may discern the formation of suitable contextual conditions for the emergence (with the contribution of technological innovation) and sustainment of an intense interplay between three basic concepts:

- Standardisation,
- Large scale production,
- Control over water, land and human labour.

The way, in which these concepts participate in structuring the Laurion landscape, is examined further below.

Phasing B – indirect dating-links

Next to building an independent sequence, comes the introduction, in it, of links to other "external" datable data, which are presented in Fig. 12b on a timeline.

Indirect dating via available historiographic and epigraphic data[11] still provides the primary chronological thread and the basis for developing synchronies, contextualising, thus, the Laurion mining and metallurgy.

However, establishing synchronies between the historiographic canvas and stages in the evolution of the Laurion economic and social landscape, is not a straightforward process. Let us examine, for example, the suggested linkage between Demetrius Poliorketes's naval blockade of the Athens Asty in 296/5 BC, an assumed banning of silver minting by Antigonos Gonatas – after prevailing in the Chremonidean war defeating the Athenians in 262/1 BC – and the rapid decline, to abandonment, of the Laurion metallurgical and/or mining activities by mid – 3rd century BC (Papadimitriou, 2018, 186). How did such an interpretation emerge? How valid is it? Ferguson (1911, pp.182 – 184) argued that Athens lost the right to issue money, based on inscriptions, which inventory the votives at the Athenian *Asklepeiion* and record "τετράδραχμα αντιγόνεια"[12]. However, as Shear remarks (1933, p.253), (a) there is no evidence that Gonatas confiscated Demosia property such as the Laurion silver mines and (b) these tetradrachms were probably "made in the Athenian mint, but belonged to the Macedonian monetary system", an argument confirmed by the type of the bronze coins issued in the same period (Shear, 1933, pp.253 – 254). It seems thus that, very early on in the debate, a 'pause' in mining at Laurion is far from proven. Furthermore, mines and metallurgical workshops provided metal, not only for coins to be made, but also to be forwarded to the markets as raw material for the production of prestigious artefacts (vessels, arms, jewels) (Kremydi, 2011, p.160). On the other hand, warfare, when raids, land sieges and naval blockades are taking place – as is the case (also) in the 3rd century BC – does affect production, especially when it is implemented in such a large-scale and it is integrally interwoven within such extensive trade and financial networks, as with Laurion. In which manner, though? Indicatively, I refer to trading silver for shipbuilding timber and facilities between the Athenians and the Macedonians, respectively, in the 4th century BC, at least. It has been argued that, in this context, Archelaos, honoured as proxenos and euergetes in Athens, obtained silver for his coinage from Athens so that the Athenians would rebuild their fleet after its destruction at Syracuse in 413 BC (Lykiardopoulou and Psoma, 2000, p.325; Kremydi, 2011, p.164). If we add to such networks that of slave-trade (being highly skilled or not) we may get an idea as to the complexity and extent of these networks.

Material evidence may, nevertheless, hint to some aspects of these effects. The Thorikos hoard (Bingen, J., 1973), for example, buried in 295/294 BC, probably records a response by a certain person or persons to the perilous situation of those years. Does it signpost the desertion of Thorikos, though? A hiatus as to pottery assemblages datable to the second half of the 3rd century, observable in the contexts of cistern 1 and in the so-called industrial quarters (Docter, et al., 2013, p.119; Mortier, 2013, pp.132 – 133, 136, fig.6), seems to correspond to such a narrative. However, in the wider area of the insulae and the theatre, there are pottery types – such as megarian bowls and Coan amphorae – that span over the second half of the 3rd and the 2nd century BC (Mortier, 2013, p.132); the 3rd and 2nd century BC pottery in the ergasterion at Skitzeri (Oikonomakou, 1997, pp.125 – 133) could be a hint that people were relocated to another site (or sites) within the Thorikos valley system and the surrounding slopes (Mortier, 2013, p.138). If this is the case, soon they prospered again as suggested by the 2nd century increase in pottery frequencies at the cistern 1. Besides, this is the century, being its beginnings or its middle, that the "New Style Silver Coinage" was introduced (Shear, 1933, p.252; Thompson, 1961, p.464 – 67; Lewis, 1962, p.275; Kleiner, 1975, p.326; Boehringer, 1972, pp.200 – 204; Mørkholm, 1984, p.38). Furthermore, it is the second half of the 2nd century BC, when a "flood of Athenian tetradrachms" into Macedonia is attested to answer deficiencies of local production due to political and strategic circumstances at that time (de Callataÿ, 1998, p.18).

It is most probable, then, that immediate repercussions of the Chremonideian war are readable in the Laurion material record, further to the military installations at Hárakas and on the Pátroklos island (Lohmann, 1996). What needs further investigation is the spread, the duration and the kind of its impact.

The aforementioned late Hellenistic cemetery at Limani Passa marks the next turning point in a period of change: a shift to Roman trade-routes networks, centred on Delos, which was administered by the Athenians, coincides with political turmoil and the slave revolt in Laurion (Kapetanios, 2013, pp.193 – 196), as reported by Poseidonius, via Athenaeus (Athen. 6,104, 7 – 15). In this account, we learn that the slaves seized the Sounion fort and lived in there, raiding rural Athens "for long". Consequently, there is abandonment of the *ergastêria;* but there is also sporadic scavenging of metallurgical residues visible by Strabo[13] a process to culminate when the Late Roman material culture becomes observable in the archaeological record.

The archaeologically visible and rather opportunistic practice of stage PA, outlined above, is perhaps one of the facets of the Roman to Late Roman revival of human presence in Laurion (i.e. the observable LR presence in the material record), closely related to re-smelting ancient *ekvoládae*, *scoriae*, and *litharge* (Kakavogiannis, 2013; Papadimitriou, 2008; Lagia, et al., 2015). The other, more systematic facet is echoed in the text of an inscription where Ianibelos is hailed as master of furnaces (ἀρχικαμινευτής; IG II² 11697; SEG 13, no. 207; 26, no. 365; Kordellas and Wolter, 1896; Lauffer, 1979, pp. 125. 133 – 135. 168. 175. 178 n.1, 200. 203s.), in the excavated parts of an extensive cemetery with more than a hundred pit graves of this period at Panormos (Oikonomakou, 1999; Parras, 2010), in the foundation of a sanctuary dedicated to Men Tyrant by a slave, overlooking the cemetery (Koumanoudhis, 1898; Kloppenborg, 2012; Lane, 1971, pp.7 – 10), and in the nuclear settlements of the same period at Sounion Plakes (Kakavogiannis, 1977, p.212; 2013, pp.162 – 168; Gikaki, 2015) and at Koulocheri, close to Anavyssos, which seem to specialise in reprocessing ancient metallurgical residues.

We may seek for comparative material in another, purely agricultural area. The seminal Aténe survey (Lohmann, 1993), covering the areas of Legrena, Charaka, Hagia Photini, Thymari and Gaidouronisi to the West and South of the densely built *ergastêria* valleys, revealed and recorded a large-scale agricultural landscape of the apparently agropastoral deme of Atene.

The available data from the surface intensive survey, conducted in the areas of the located farmsteads and small rural sanctuaries, suggest a peak in the Classical period, a dramatic drop (interpreted as abandonment of the farmsteads) c. 300 BC, with the exception of a small metallurgical site on the Legrena coast (recycling metallurgical residues); absence of material culture follows, until another peak from the 4th to the 6th century AD, the latter related to a significant number of sheepfolds and corals (Lohmann, 1993, pp.264 – 266, fig.8, pl.3). This picture corresponds to that of the Laurion mining Demes with the exception of the 2nd century BC ‘revival’.

Besides the chronological implications of the discussion so far, it becomes tangible that practices of scale, which feed economic networks of scale – as were these of the 5/4th century BC Laurion – are conceivably sensitive to scale events, such as warfare and political upheaval. The strength of their impact is not, however, predictable nor it is its outcome.

Phasing C – juxtapositions

In Fig. 12b it becomes clear that overlapping of many different evolutionary stages which were sequenced independently, coincides with the density peaks in the material record and potentially linked to some chronologies deriving from written sources, the famous Poletae Records (Crosby, 1941; 1950; Lalonde-Langdon-Walbank, 1991) among them.

Can we employ these relationships that we have established so far to decode further the observable Laurion? At this point we need to revisit the aforementioned three basic concepts: Standardisation – Large scale production – Control over water, land and human labour.

Laurion landscape dynamics: The Demes' spatial organisation model

The structuring principles of the settlement pattern of the Laurion peninsula Demes are the clustering – or dispersion – of habitation/production modules and their linkage and cohesion as a network. Each module encompasses rooms/buildings for people to live in as well as structures and built space to produce. There are two such modules: the *ergastêrion* and the *farm* or farmstead (Kapetanios, 2013, p.189).[14]

The *ergastêria* known in Laurion, so far, are almost exclusively metallurgical (*katharistêria* and *káminoi*), entailing the ‘industrial’ built components (adequately discussed) plus living quarters (Jones, 2007; Tsaïmou, 1979); in the case of *farms* there are corrals, terraces, threshing floors, wine/olive presses, storerooms, plus the living area, the oikia, (Young, 1956; Langdon and Watrous, 1977; Lohmann, 1993; Goette, 1994). Clustering seems a result of production practices (Fig. 13): *farms* are dispersed as they need cultivable (organised by terracing) and grazing (punctuated by pens and corrals) land; *ergastêria* cluster where the resources needed for their operation were best accessible. Multifunctional *towers* commonly are attached to farm modules and to groups of *ergastêria.* State defence was provided by the Thorikos and Sounion forts[15]. Roads and collective centres – such as sanctuaries and *agoras* or the theatre – provided the cohesive force for a society of people living and working in the clustered *ergastêria* or in the dispersed farms. Harbours (Thorikos, Panormos, Sounion) and anchorages were links to sea-route networks. Then there are dispersed tombs, tomb clusters and cemeteries.

This scheme (Kapetanios, 2013, pp.189 – 193) bears in its core the understanding of a deme, not as a nuclear settlement with satellite sites, but as a network of clustered or dispersed modules of habitation / production plus collective foci and it could be considered a model applicable to other Athenian rural demes as well (Lohmann, 1993, p.124; Steinhauer, 2012, p.51).

The clustering of Ergastêria: Metallurgic or hydraulic societies?

The location of *káminoi* on promontories, or on flat land (lowland/coastal valleys or plains) facilitated their supply with fuel (mainly charcoal?) by sea.

Katharistêria had to be near the mines to reduce, by enrichment, the volume and weight of ore to be carried to furnaces; the evolution of water management technology, as described above, clustered the *katharistêria* in the valleys*,* producing a network of dense linear settlement

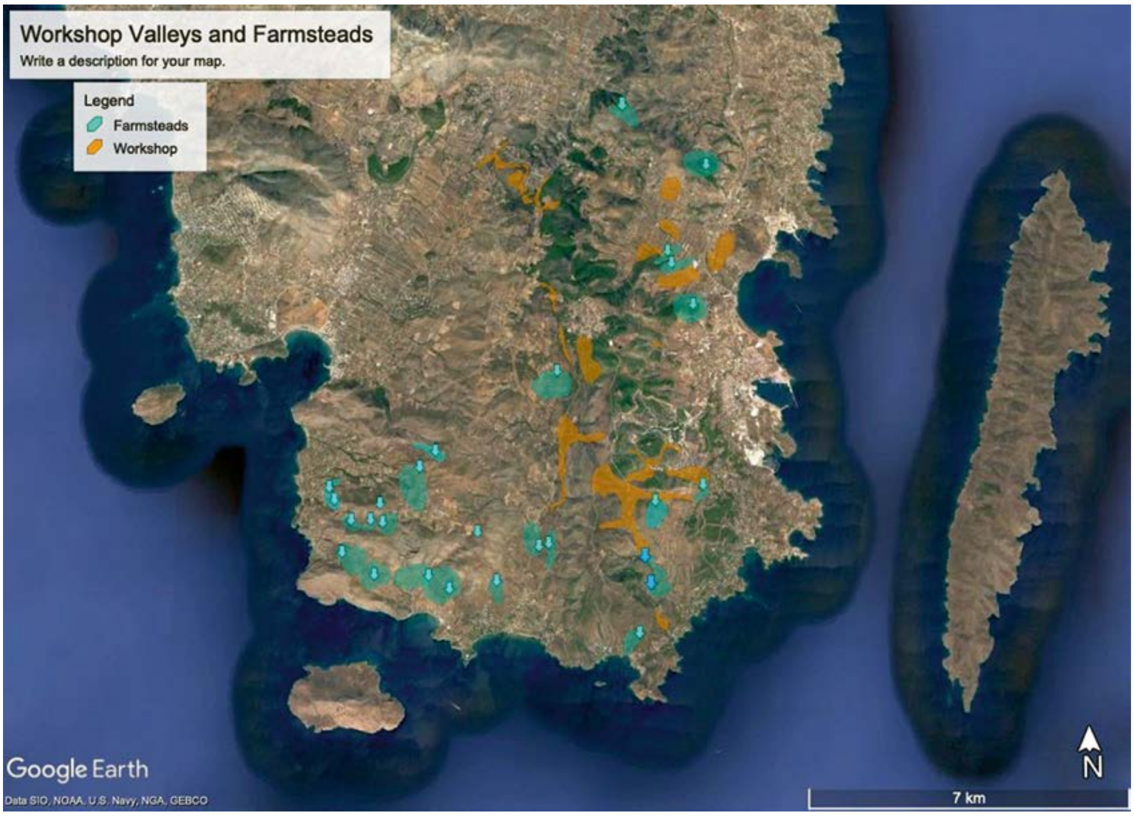

Fig. 13: Dispersion and clustering: the distribution of farms and ergastéria (Google Earth with additions by A. Kapetanios).

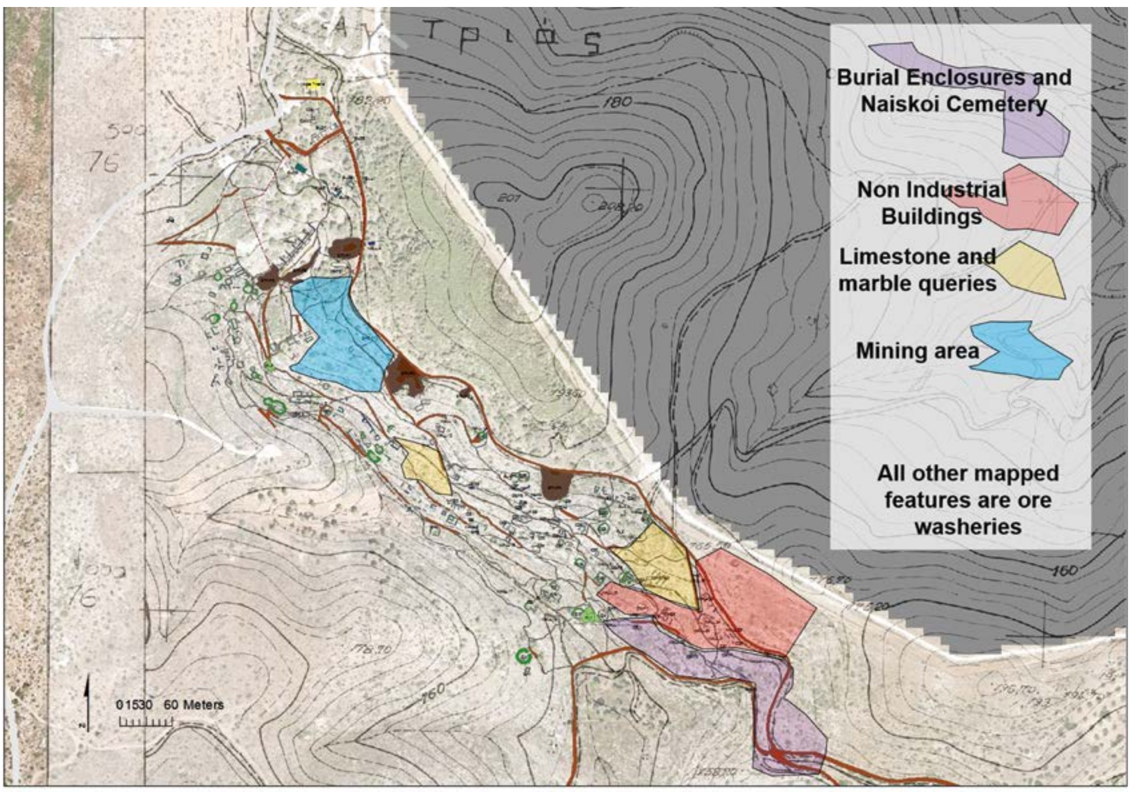

Fig. 14: Typical structure of a valley clustering ergastéria (N branch of Souriza valley system) (compiled basemaps provided by the Hellenic MGS and National Cadastre Service with sperimposed topographic plan and additions by E. Farinetti, L. Koutsoumbos and A. Kapetanios).

Fig. 15: Enclosure on the flat area of the col between Mihale Hill and Botsari (photo by A. Kapetanios).

foci; standardisation and precision boosted production to a very large scale; the largest the scale the greatest the density of the linear valley settlements.

In this manner, the organisation of human built space in certain valleys moved towards ‘urbanisation’. Indications for such an emerging urbanisation can be traced in the archaeological remains of the complex internal valley system of Souriza – Agrileza and its surrounding hills (Fig. 14, 16). Two parts of the densely built space do not present industrial characteristics; the north one, extending around a crossroad, with rows or groups of burial enclosures and *naiskos* tombs along all of its branches and an open-air enclosed, probably unbuilt area (Figs. 15, 16) at the flat level of a col overlooking the Laurion East coast and Makrónêssos; the southern one, on the southern and south-western slopes of hill Michális, is built on a terrace created by an impressive ashlar retaining wall with an additional probable defensive role as part of it is structured in a bastion-like manner (Fig. 17).[16] These are hints to central (collective?) foci of the valleys' cluster network (Fig. 16). The well-known Leukios's agora inscription (IG II² 1180) and a *herm* were reported to be retrieved from a stack of tailings somewhere between the two locations (Kordellas and Wolters, 1894, pp.241 – 243).

It is evident, then, that the observable material record is not merely an imprint on the landscape of the socio-economic activities, but it is actively involved, restructuring the landscape via clustering of buildings in ravine valleys, and leading to the emergence of social phenomena such as urbanisation.

It is also active in shaping ideological aspects of the communities involved: If on the map (Fig. 13), depicting the distribution of production / habitation modules (i.e. farmsteads and *ergastêria),* we add the burial enclosures, we will see that there is a corresponding clustering (Fig. 18). This correspondence seems to be linked to issues of ownership and especially land (farm or *ergastêrion*) ownership. Regardless, whether the owner lived in the estate or not (Steinhauer, 2012, pp.50 – 51), the burial enclosure has to be there, as the material manifestation of the lineage, a constant tangible and ideologically laden reminder of landownership and thus its re-affirmation, or, in other words, its legitimation (cf. Snodgrass, 1998, 37,40).

Conclusions

Even if high-resolution chronological sequencing is not currently feasible, due to lack of direct dating of many of the crucial components structuring the Laurion landscape, there is indeed clustering of material evidence to certain periods. This material record is intrinsically linked to the restructuring effect of technological advances, such as hydraulic works and inventions and metallurgical innovations, illustrated in the comparative chart.

The overall phase-scheme presented here seems to largely confirm, by qualifying them, the coarse lines of the chronological framework we have been familiar with for some time now:

- *Phase A*: Indirect echoes of the 6th century BC; direct smelting(?); the landscape probably dominated by farms, roads, cemeteries, sanctuaries.
- *Phase B*: 5th century BC, obscured (probably due to the overwhelming material presence of the following century); in coarse terms, things proceed with production and landscape organised as in Phase A; the rich Marôneia deposits probably intensified exploitation; large scale mining works; probably large numbers of slaves; high grade mineralisation gradually moves to exhaustion(?) which coincided(?) with the Dekeleia events and the fleeing of slaves. Questions that arise: when did Athenians move from exploiting visible deposits (even some 3rd contact deposits were visible on the slopes of the hills) to underground prospection?
- *Phase C*: most conspicuous peak in the 4th century BC (probably 2nd half); triggered by Xenophon's plan(?); *Poletae* records document administrative meticulousness; intensification of the exploitation of low-grade mineralisation(?); very large numbers of slaves (Demetrius Phalereus's census[17]);

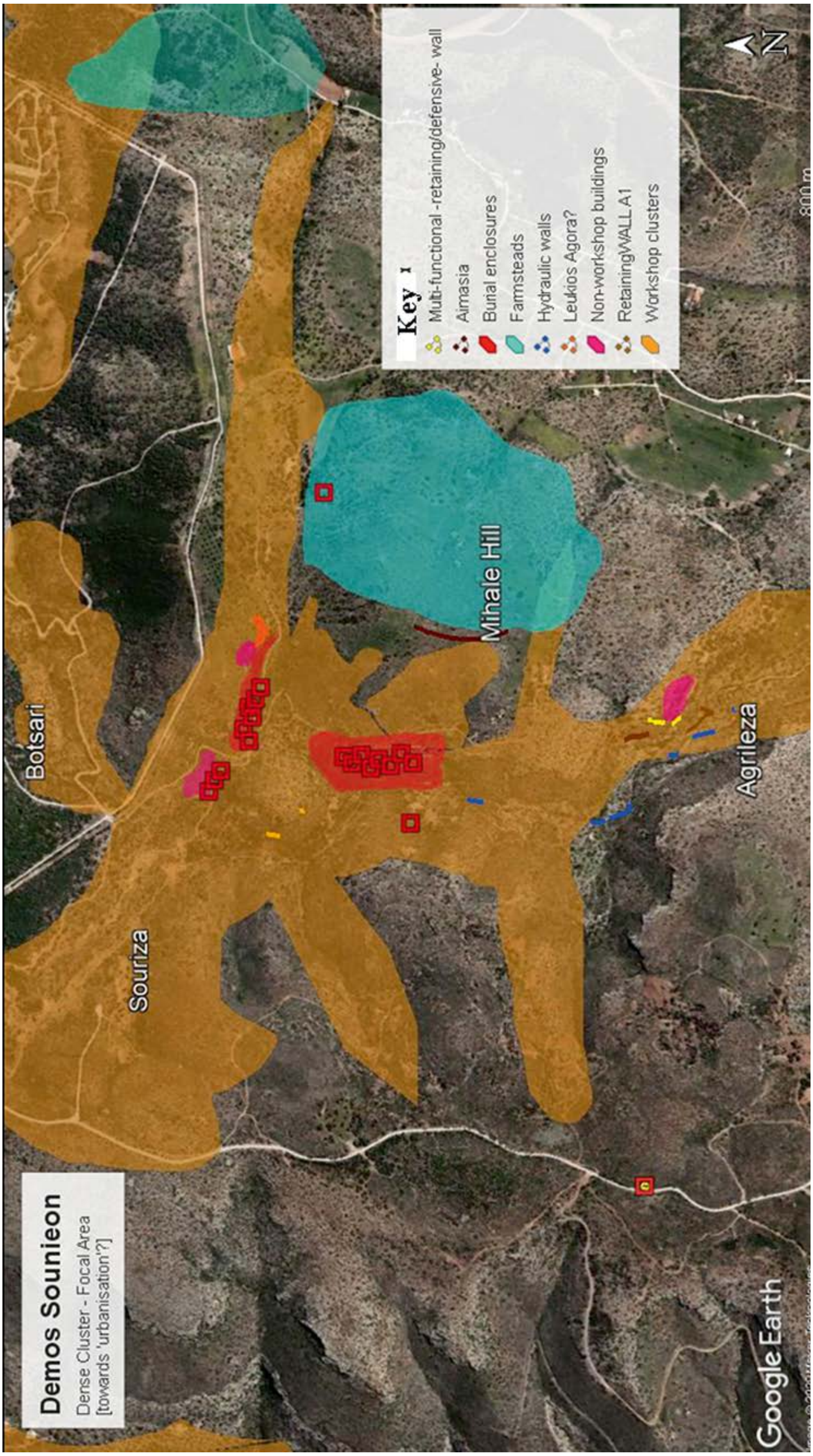

Fig. 16: The area presenting characteristics of a collective locus (Vouno Michali col and its southwest slope) (Google Earth with additions by A. Kapetanios).

technological breakthroughs – the 'hydraulic revolution'; reorganisation of the landscape; dawn of urbanisation; huge quantities of tailings and by-products have already been accumulated; the dawn of metallurgical exploitation of by-products (?).
- *Phase Da-b*: an apparent rapid decline in the 3rd century BC (esp. its second half); metallurgical exploitation of by-products (?).
- *Phase E*: a revival in the 2nd century BC; intensification of the metallurgical exploitation of by-products (tailings, litharge); large number of slaves.
- *Phase F*: (Fa) a rapid decline at the beginning of the 1st century BC; shift in economic orientation/investments; slave revolt (myriads says Poseidonius via Atheneus[18]); (Fb) abandonment to sporadic or less sporadic presence (cf. the Ianibelos inscription) for the centuries to come.
- *Phase G*: another peak around 4th to 6th century AD; both haphazard, small-scale scavenging and large-scale systematic metallurgical exploitation of by-products (tailings, litharge and scoriae); a slave founds a sanctuary; extensive cemeteries; nuclear settlements.

This pattern is certainly present in the basic threads of the chronological scheme proposed by Papadimitriou (2018) for the evolution of the Laurion mining/metallurgical activities.

Further to chronology, the approach adopted here allowed us to delve into fundamental causal relationships and structuring principles in the history of human societies in Laurion:

All stages and phases share the inevitable material presence of the very large-scale works, constructions

Fig. 17: The ashlar multifunctional wall at the SW slope of Vouno Michali (photo by A. Kapetanios).

and technological methods. Their impact in structuring the regional landscape and organising habitation and production (being metallurgical or agricultural) is significant and augmented in the progress of time through the triptych *standardisation – large scale production – control over water, land and human labour.* The exceptional importance of the water-management concepts, practices and built constructions, is conspicuous. It is manifested especially through the 'clustering effect' in structuring the material dimension of the Laurion landscape, but, also, social relations (urbanisation, control) and aspects of ideology (mortuary landscape, 'legitimisation' and sustainment of ownership relations). The certain hydraulic works have landmarked the Laurion landscape palimpsest which is not a passive synchronic presence but constantly and diachronically active. When comparing, for example, the

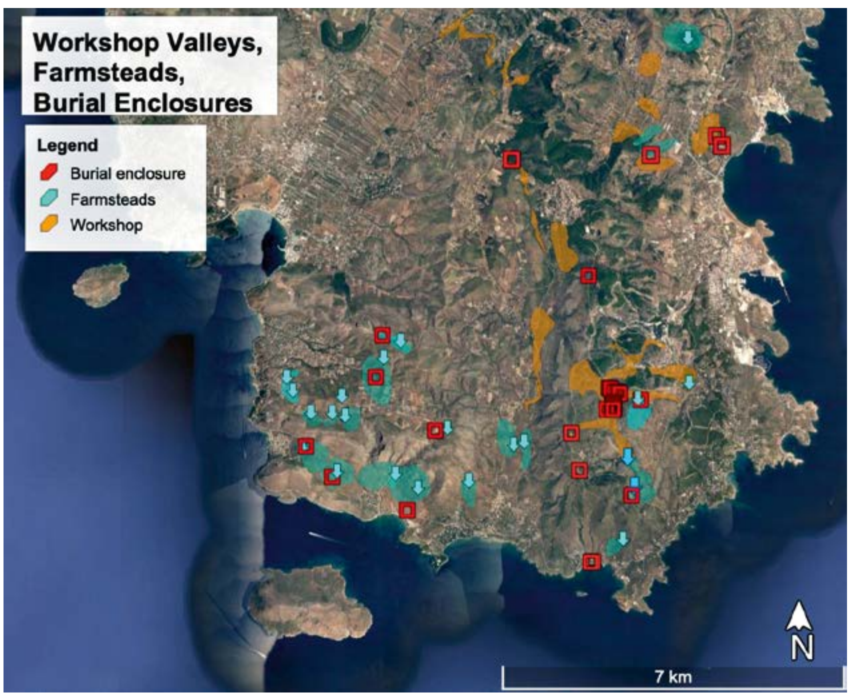

Fig. 18: Farmsteads, Ergastéria, Burial Enclosures (Google Earth with additions by A. Kapetanios).

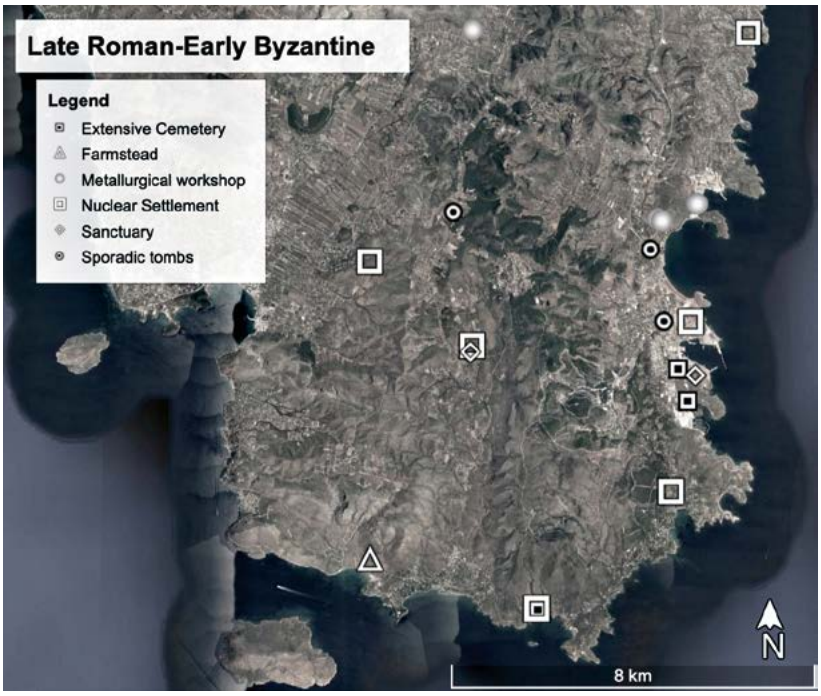

Fig 19: The LR settlement pattern (Google Earth with additions by A. Kapetanios).

agricultural and mining / metallurgical dimensions of the landscape, or Taskscapes according to Ingold (2016), as in the case of Aténe and Laurion, it becomes evident that these large-scale formations produced a landscape which provided the scope for the development of multitudinous communities, via the exploitation of their own past residues, to work, to survive, to prosper, to develop power relations, to collide, to revolt; more than once: 4th century, 2nd – 1st centuries BC and 4th – 6th centuries, 19th – 20th centuries CE. One may even wonder whether we should keep on talking about the Laurion mining and metallurgical societies or the Laurion hydraulic societies.

Except for continuity, as regards the relationship between social groups and metallurgy, economic and political change is also engraved into the landscape: the new trade routes and economic arenas of the Roman world and the shift to secondary (by-product) exploitation in metallurgy, produced *a complete reversal of the settlement pattern model*: the *Demoi* spatial organisation described above as *networks* of clusters dispersed everywhere in the landscape, is replaced by *nuclear* settlements in the Late Roman period, at the perimetry of the Laurion Hills and Valleys (Fig. 19, Lagia, et al., 2015, pp.578 – 579).

In terms of methodology, the present contribution argues that a certain landscape-archaeology approach may function as the cohesive framework for an integrated, consciously interlinked, question-orientated, multidisciplinary research.

Geology, geomorphology, topography, hydrology, technology and humans interact constantly. Communities are organised in space curving the landscape with tools of control, perceiving it and employing its qualities to manifest – impose – negotiate – dispute and rearrange their societies, mainly through power relations. In this context, landscape, surface or underground, is always active. So are all its anthropogenic features: once there, always there, to act!

Acknowlegements

I would like to thank Hans Lohmann, Frank Hulek and Sophia Nomicos for organising the Bochum conference which initiated a much needed, closer interdisciplinary collaboration, opened up fruitful discussions and set the example for keeping on working together to achieve an essential understanding of the complex ancient Laurion. I thank them also for years of cooperation and friendship. Thanks are due to Dr Eleni Andrikou, director of the Ephorate of the Antiquities of East Attica for her encouragement and cooperation for more than a decade at Laurion. The Laurion Archaeological Museum Staff (F. Spanou, P. Makris, M. Athenaeos, G. Andritsakis, M. Tsagifidis, A. Georginakis) has provided a constant support and I am grateful. Special thanks to the conservator of the Ephorate at Laurion open air sites, Yannis Liapis.

Notes

1 All distribution-maps of sites, specific structure-types or features included here, are based on published information, as cited in this contribution, supplemented by primary extensive survey data conducted by the author within a decade (2007 – 2017).

2 The term, literally translated as “cleaning installations”, is applied here to denote the Laurion ancient metallurgical workshop modules (= *ergastêria*), known also as washeries,

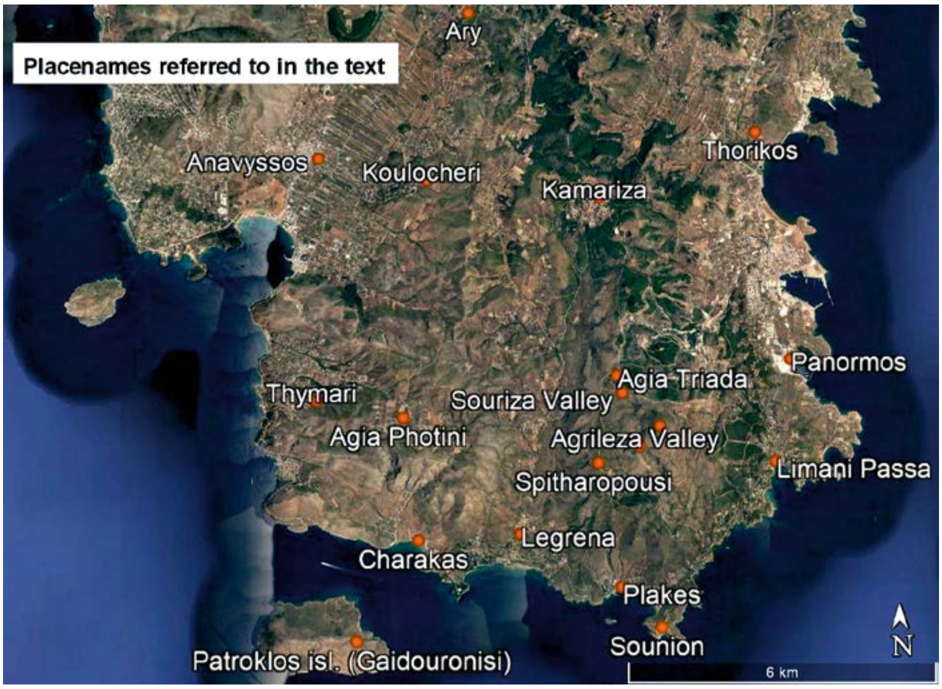

Fig 20: Map of the placenames cited in the text (Google Earth with additions by A. Kapetanios).

which operated with water to produce concetrated ore by washing away lighter material. The alternative term "κεγχρεών" (*kenchreôn*, = locale with pulverised material) is employed by Desmosthenes (Contra Pantaenetum, 26.10 – 11), but according to Harpocration (Kappa, lemma 33) Theophrastus suggested that *katharistêrion* is the proper term to denote the certain Laurion installations.

3 The evolution of smelting and cupellation are not considered in the present occasion as it would demand a significantly more extended version. Furnaces and smelting practices are only indirectly discussed.

4 Indicatively, Kakavogiannis, 1977; 1989; Zoridis, 1980; Kakavogiannis-Oikonomakou, 1995; Saliora-Oikonomakou, 1979; 1985; 1995; 1997a; Oikonomakou, 1991; Kapetanios, 2010; Parras 2010.

5 For a discussion on such indirect dating see Hopper (1961, pp.140 – 147).

6 There is no need for detailed description of the standard FBW characteristics here as they have been extensively analysed and discussed.

7 This interpretation (Papadimitriou, 1992, p.188) was based on assessing type II as being less effective in facing scarcity of water and rudimentary as to its layout. Kakavogiannis (1991, p.16) countered these two arguments in light of further discoveries of type II FBW, suggesting that we cannot conclude on the type's dating.

8 Multiple compartments have been interpreted as interventions to optimise washing by assigning each to a nozzle of the water-feeding tank; however, there is no one-to-one correspondence evident in all cases and one would expect that such a fine tuning would be an integral part of the FBW (Kakavogiannis, 1991, p.17), especially given its meticulous standardisation to optimisation plan.

9 Stage codification provided is employed in the charts of Figs.12, 14.

10 The survey was conducted in 2016 with Dr Anno Hein (NCSR Democritus) aiming to assess the effectiveness of using portable XRF in the field in trying to resolve archaeological questions. The report on the results of this short investigation is currently in preparation for publication.

11 For a discussion on such indirect dating see Hopper (1961, p.140 – 147).

12 Today these inscriptions are catalogued and dated as: IG II² 1534 (c. 275 a), IG II³,1 1010 (248/7 BC) and Aleshire 1989, p.249 (244/3 BC), SEG 39:166 (244/3 BC). These dates are lower (up to a decade) than those mentioned in Ferguson (1911, p.184) and Shear (1930, p.253).

13 Strabon (Geogr., 9,1,23): τὰ δ᾽ ἀργυρεῖα τὰ ἐν τῇι Ἀττικῇι κατ᾽ ἀρχὰς μὲν ἦν ἀξιόλογα, νυνὶ δ᾽ ἐκλείπει· καὶ δὴ καὶ οἱ ἐργαζόμενοι, τῆς μεταλλείας ἀσθενῶς ὑπακουούσης, τὴν παλαιὰν ἐκβολάδα καὶ σκωρίαν ἀναχωνεύοντες εὕρισκον ἔτι ἐξ αὐτῆς ἀποκαθαιρόμενον ἀργύριον, τῶν ἀρχαίων ἀπείρως καμινευόντων. (The silver mines in Attica were originally valuable, but now they have failed. Moreover, those who worked them, when the mining yielded only meager returns, resmelted the old slug and tailings, and were still able to extract from it pure silver, since the workmen of earlier times had not been very experienced as to smelting in furnaces.)

14 One hybrid case has been documented: an epikleros (Euthidike) boundary stele inscription, excavated at Kavodhokano, Thorikos, refers to her property as "ergastêrion and orchard" (Oikonomakou, 1991).

15 The Anavyssos fort, the existence of which has been attested to by Xenophon, (Poroi, IV,.43 – 44) has not been located, as yet. A possible location beneath the thick alluvium of the Anavyssos coastal plain, next to the harbour, would fit the 'fort-harbour' model of Thorikos and Sounion.

16 Masonry and layout of this structure is very similar to the one in Megala Pefka functioning as a retaining and perhaps defensive wall (similar bastion-like features) as well as ahydraulic work controlling the watercourse.

17 Athen. 6,103: Κτησικλῆς δ᾽ ἐν τρίτῃ Χρονικῶν κατὰ τὴν ἑπτακαιδεκάτην πρὸς ταῖς ἑκατόν φησιν ὀλυμπιάδα Ἀθήνησιν ἐξετασμὸν γενέσθαι ὑπὸ Δημητρίου τοῦ Φαληρέως τῶν κατοικούντων τὴν Ἀττικὴν καὶ εὑρεθῆναι Ἀθηναίους μὲν δισμυρίους πρὸς τοῖς χιλίοις, μετοίκους δὲ μυρίους, οἰκετῶν δὲ μυριάδας μ'. (But Ctesicles, in the third book of his Chronicles, says that in the hundred and fifteenth Olympiad, there was a census conducted at Athens by Demetrius Phalereus as to the inhabitants of Attica, and the Athenians were found to number twenty-one thousand, the metics ten thousand and the slaves four hundred thousand.)

18 Athen. 6,104: καὶ αἱ πολλαὶ δὲ αὗται Ἀττικαὶ μυριάδες τῶν οἰκετῶν δεδεμέναι εἰργάζοντο τὰ μέταλλα· Ποσειδώνιος γοῦν, οὗ συνεχῶς μέμνησαι, ὁ φιλόσοφος καὶ ἀποστάντας φησὶν αὐτοὺς καταφονεῦσαι μὲν τοὺς ἐπὶ τῶν μετάλλων φύλακας, καταλαβέσθαι δὲ τὴν ἐπὶ Σουνίῳ ἀκρόπολιν καὶ ἐπὶ πολὺν χρόνον πορθῆσαι τὴν Ἀττικήν. οὗτος δ᾽ ἦν ὁ καιρὸς ὅτε καὶ ἐν Σικελίᾳ ἡ δευτέρα τῶν δούλων ἐπανάστασις ἐγένετο. (and

these certain Athenian myriards of slaves shackled worked in the mines; at all events Poseidonius, whom you are often quoting, the philosopher I mean, says that they once revolted and put to death the guards of the mines; and that they seized on the Acropolis on Sunium, and that for a very long time they ravaged Attica. And this was the time when the second revolt of the slaves took place in Sicily „[104 – 101 BC].)

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The diachronic development of the Laurion mining landscape and its relation to process optimization in mining

ABSTRACT: *This article summarises the main results of my PhD thesis on silver mining in ancient Laurion. In the first part, the development of mining in Laurion is examined against the backdrop of the mining landscape model developed by Th. Stöllner. A correlation between mining activities and settlement development in the region is suggested. The second part discusses different theories concerning the main steps of the chaîne opératoire of silver production. It is argued that process optimization strategies can be detected in the ancient Athenian silver "industry".*

KEYWORDS: ATTICA, ANCIENT TECHNOLOGY, MINING LANDSCAPES, CHAÎNE OPÉRATOIRE

Introduction

In recent years, the reconstruction of the history and development of ancient mining landscapes has increasingly attracted scholarly attention (see e.g. Kassianidou and Knapp, 2005, pp.233 – 235; Bartels and Küpper-Eichas, 2008; Eisenach, et al., 2017; García-Pulido, et al., 2017, Nomicos, 2021; Hulek and Nomicos, 2022). In several articles, Th. Stöllner (2003; 2008; 2014) proposed a structured approach to the analysis of such "specialized region[s], whose primary economic structure is focused on the exploitation of (mineral) resources" (Stöllner, 2008, pp.76 – 77 fig. 4). These regions can be subdivided into *mining districts* (= a centre of production within the larger region) and even smaller *mining ensembles* which, for example, consists of a mine, a smithy and a smelting place (Stöllner, 2004, pp.429 – 430; 2008, 76 – 77 fig. 4). In mining landscapes, the development of human settlements can be closely interconnected with the mining activities (see Stöllner, 2003, pp.420. 433 – 435. 436).

The model is based on two columns: 1) Components of past mining economies that contributed to successful/unsuccessful mining operations and 2) the temporal development of mining landscapes. The factors that should be considered when analysing past mining landscapes are: the natural landscape, the cultural landscape, the mode of production, the social and cultural tradition, and trading modes and historical processes (Stöllner, 2008, pp.72 – 75 tab. 2). Concerning the temporal development of mining, Th. Stöllner differentiates between Phases of *extensive exploitation* (= sporadic, seasonal grasp of the resources) and phases of *intensive exploitation*. This second category, he subdivides into an *anterior phase*, an *initial phase*, a *consolidation phase* and an *industrial phase* (Stöllner, 2004, pp.430 – 439; 2008, pp.77 – 80). Based on the adaptive cycle model (Holling, Gunderson and Peterson, 2002), Stöllner suggests a final *phase of collapse* and *reorganization* (Stöllner, 2014, pp.138 – 140 fig. 7.3).

This methodological approach has not yet been applied to the Laurion. Despite serious destructions of the ancient remains by various activities since the 19th century AD, it is the widest studied and therefore best known pre-modern mining area (Fig. 1), and it provides a particularly suitable testing ground.

I begin by reviewing the development of mining at Laurion in the light of the different phases of the mining landscape model. This is followed by a brief examination of the decisive factors in this development. In the second part of the paper, I discuss to what degree process optimizing strategies can be detected in the ancient mining "industry".

The development of mining and habitation in ancient Laurion

At what time exactly the metal ores of Laurion were first exploited is still unclear. Possibly, the first resources to be exploited at Laurion were the hematite and ochre deposits for the production of pigments (see Rihll, 2001, pp.129 – 130; Nomicos, 2021, p.34). The earliest traces of underground pigment mining in Europe have been detected on the island of Thasos and dated to the Paleolothic (Koukouli-Chrysanthaki, Weisgerber, Gialoglou and Vavelidis, 1988, pp.241 – 242). Despite evidence for anthro-

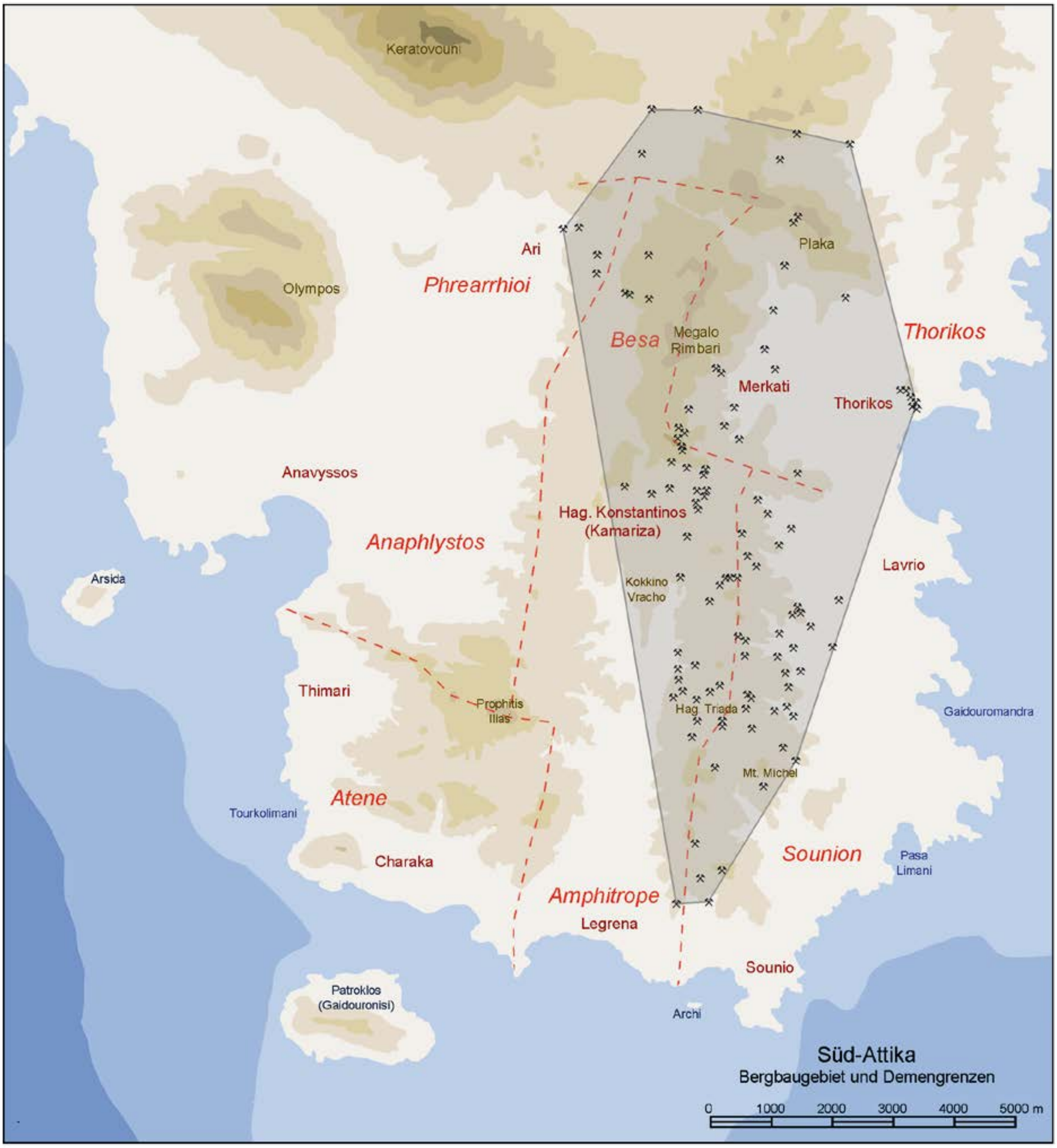

Fig. 1: Map of South-Attica with mining area and deme boundaries; scale ca. 1 : 100,000 (map by S. Nomicos, Ö. Özgül; distribution of mines after Konophagos, 1980, map; deme boundaries after Lohmann, 1993, p.109 fig. 12).

pogenic presence in Paleolithic Laurion ("Kitsos I", Lambert, 1981; Andrikou, 2020, pp.19–20) and the existence of ochre deposits (von Ernst, 1902, p.480), archaeological evidence for their exploitation at any period is missing.

The earliest evidence for metal mining at Laurion dates to the Late Neolithic/Early Bronze Age. There is indirect evidence in the form of cupellation residues from several sites in South Attica (Kakavogianni, Douni and Nezeri, 2008, pp.45–57; Kakavogianni, et al., 2009, pp.237–248; in this vol.; Georgakopoulou, et al., 2020). The earliest direct evidence from the Laurion are the traces of mining in Mine 3 that have been known for a while (Spitaels, 1984) and have recently been dated more securely to the Early Bronze Age II (Nazou, 2013; 2018; 2020; see also the comprehensive discussion in Kayafa, 2020). The litharge in a Middle Helladic stratum at Thorikos (Servais, 1967, p.23) is still the only evidence of mining activities in this period. Mycenean Laurion has been identified as a major silver supplier of the Aegean. This however is solely based on the indirect evidence of lead isotope studies (Stos-Gale and Gale, 1982). Despite the fact that (in view of the importance of Thorikos in the Mycenaean era see Laffineur, 2010; 2020;

Lohmann, 2005, pp.129–130; see also Papadimitriou and Cosmopoulos, 2020) this seems a very plausible theory, mining archaeological evidence to support these results is still lacking. Many questions concerning prehistoric mining in Laurion remain unclear; did mining take place only at Thorikos or were other deposits in the Laurion mined as well? Although several prehistoric sites in South-East Attica have been identified (see Salliora-Oikonomakou, 2004, pp.32–33; Oikonomakou, 2010; Papadimitriou, et al., 2020, pp.vi-xv nos. 77, 87, 90, 127, 172, 185, 196, 197, 198; Andrikou, 2020; Syrigou, 2020; Philippa-Touchais and Balitsari, 2020, pp.390–392), with the exception of the hillsite of Mokriza (see Lohmann, 1993, p.505, pl.72,1. 2 (AN 25); Parras, 2010, p.143, fig.4; Andrikou, 2020, p.22), their relation to mining activities remains hitherto unknown. Another unsolved question is the role of the Laurion as a copper deposit for the Bronze Age Aegean. Even today, copper minerals are known in the Laurion (Cordella, 1901, p.360; Kakavogiannis, 2005, p.92), but if and to what extent they were exploited is debated (see Nomicos, 2021, p.34 n.283). All in all, the evidence for prehistoric mining in Laurion is still scarce. It is in fact not even clear if the term “mining landscape/area” in the sense defined here can be applied to prehistoric Laurion.

Archaeological finds from geometric Laurion are scanty. The evidence for mining is inconclusive and there are hardly any signs for habitation from inland areas (see Nomicos, 2021, pp.77–79). Proof of settlement activity can be found at Thorikos (see Van Gelder, 2010), Anavysso (Kastriotis and Philadelpheus, 1911; Verdelis and Davaras, 1966, pp.97–98; Themelis, 1979, pp.108–109) and other coastal sites (see Nomicos, 2021, p.79). Despite the limited data, there might be an association between the lack of clear evidence for mining and the lack of geometric finds in the off-coast areas, which are not as favourable for human settlement. In terms of Th. Stöllner’s model, this period may be labelled as a period of *extensive mining*.

This situation changes noticeably during the archaic period (Nomicos, 2020; 2021, pp.80–88). Compared to the data available for the classical period, the evidence is still hard to interpret, but some basic observations can be made that attest for a beginning mining activities from the last third of the 6th century BC onwards. First of all, the literary testimony (Hdt. 7,144,1; Arist., *Ath. Pol.* 22,7; Aesch., Pers. 238) suggests increasing mining activities in the late archaic period the latest. This matches with the emergence of the Athenian owl coinage which according to the results of archaeometric studies (Kraay, 1958; Gentner, Müller and Wagner, 1978; Gale, Gentner and Wagner, 1980; Nicolet-Pierre, 1983) and literary evidence (Aristoph., Av. 1106) was made of Laurion silver. During this period, there is a gradual increase of sites in the inland area of the Laurion (Nomicos, 2020) while habitation in Thorikos intensifies (Mussche, 1998, p.62; Docter and Van Liefferinge, 2010, p.55; Bergemann, Klug and Docter, 2018). A connection between the mostly non-mining related archaic sites in the Laurion and intensified mining activities is supported by two observations: 1) the natural conditions – especially the lack of natural water – in the inland areas are most unfavourable for agrarian communities 2) some structures that were excavated, interpreted and discussed by E. Kakavogiannis (1989; 2001; 2005, pp.245–253) resemble the later ore washeries. Despite all the difficulties in their interpretation and dating (Kakavogiannis, 2001, p.369; Van Liefferinge, 2018, pp.539–540; Nomicos, 2021, p.84), they can, as suggested by E. Kakavogiannis, be understood as washeries of an early and maybe experimental stage when methods of exploitation of the ores in that arid and therefore precarious natural environment were tested.

This was mastered impressively as is attested for by the hundreds of large cisterns that can still be found all over the Laurion (see Konophagos, 1980, pp.252–254; Kakavogiannis, 2005, pp.225–229; Van Liefferinge, 2013; 2014; Nomicos, 2021, pp.59–61). As can be deduced from the contemporaneous literary evidence (Hdt. 7,144,1; Arist., *Ath. Pol.* 22,7; Aesch., Pers. 238; Thuk. 6,91,7) and the “almost unbelievable output” (Kroll, 2011, p.17) of Athenian coinage (see also Van Alfen, 2012, p.93), the 5th century saw a boom-phase in mining. This is not equally mirrored in the archaeological record which is dominated by finds dating to the 4th century BC. Nevertheless, there is some evidence to suggest that the main technologies of the Laurion industry (shaft mining, hydraulic mortar, ore washeries, and furnaces) were already developed and employed in the 5th century (see Nomicos, 2021, p.89–93).

After a hiatus of finds and other evidence from the first half of the 4th century, there is overwhelming archaeological evidence to suggest that the largest part of the now visible remains today dates to this period. This conclusion can be drawn from a meta-analysis (see Nomicos, 2021, chapter 3.4) of the results from numerous excavations and surveys. Together with the poletai records (see Crosby, 1941; 1950; 1957; Langdon, 1991) the picture of a densely worked and inhabited mining landscape emerges. This *mining landscape* comprised mines, workshops (Th. Stöllner’s *mining ensembles*), smelting furnaces, infrastructural remains, sanctuaries and burial places. There is reason to suggest that many of the at least 491 “sites” marked on the respective sheets of “Karten von Attica” date to this period (cf. Lohmann, this vol., pp.Seite 153–Seite 174). As the poletai inscriptions record, the 4th century mining landscape was organised in local sub-units, called *mining districts* by Stöllner, some of which can be located with some certainty (see Kalcyk, 1982a, pp.57–95; Lohmann, 1993, pp.89–110). What is unclear, however, is, whether the 4th century should be interpreted as *the* boom phase of mining in the Laurion or as a *second* boom phase. This is because the archaeological picture may be misleading. It is obvious that most of the evidence can be dated to this period. But is this because it really was the most intensive mining phase, or is it, because the area was abandoned around 300 BC and the remains of the 4th century were never "overprinted"? Did the 4th century then almost fully overprint the 5th century remains, and had they originally been equally dense? This at least can be suggested on the grounds of the testimony of Xenophon who around 350 BC refers to a time in which “most people were involved in mining” (Xen., *Vect.* 4,3 – 4). This interpretation also finds some support in the archaeological record since 5th century BC pottery was found in a number of the excavated workshops (evidence compiled in Nomicos, 2021, pp.91 – 93).

Around 300 BC there is a sharp decline in settlement activity in Thorikos and the Laurion. Evidence for habitation can only be detected on some coastal sites. The mining industry clearly collapsed, as can be reasonably inferred from the fact that the workshops are abandoned around this time. Having said that, it may be discussed whether this was a sudden or gradual process. The latter seems possible, as some workshops have yielded 3rd century pottery, mostly plain ware (evidence compiled in Nomicos, 2021, p.108 n.1295). Since the internal chronology of plain ware is not always conclusive, conclusions must be drawn with caution. The reasons for the collapse of the mining industry were, for all we know, quite complex. There is clear evidence that “the mining yielded only meager returns” (Strab. 9,1,23; transl. H. L. Jones, 1924) towards the end of the 4th century. But it should not be overlooked that simultaneously Athenian minting activity came to an almost complete standstill, which will have resulted in a sharp decrease in the demand for silver (Nomicos, 2021, pp.108 – 110).

Renewed and reorganised activity in the Laurion can be detected in the 2nd century BC when older process residues were reprocessed (Lauffer, 1979, pp.165 – 166; Kalcyk, 1982a, pp.144 – 145; Lohmann, 1993, pp.245 – 246; Goette, 2000, p.106; Nomicos, 2021, pp.110 – 112) in what apparently were large-scale operations. Stamped amphora handles from several smelting sites in the Laurion attest archaeologically for this activity (Lohmann, 2005, p.126; Börker, 2018) that has been known for a long time from Strabo’s account (Strab. 9,1,23) of these workings. The purpose of these operations may be found in the renewed Athenian minting activity (Lauffer, 1979, pp.165 – 166; Kalcyk, 1982a, pp.138 – 142; 1982b, p.246; Lohmann, 1993, pp.245 – 246; Börker, 2018, pp.70 – 72; Nomicos, 2021, pp.112 – 113; for the “New Style” Tetradrachms see Thompson, 1961; Mattingly, 1971; Boehringer, 1972; Mørkholm, 1984; Habicht, 1991) that correlates chronologically.

Strabo’s account is somewhat ambiguous on the matter of whether or not the reprocessing of older residues continued in his own time. There is certainly no archaeological proof (compare also the literary sources Plut., *De def. or.* 43,5; Paus. 1,1,1) for any larger mineral processing or mining operations in the Laurion during the first four centuries of Roman Greece. Only a few sites have yielded evidence for small-scale lead production activities (evidence compiled in Nomicos, 2021, pp.118 – 119), although their dating remains difficult. In accordance with the account of Pomponius Mela 2,46, except for some smaller coastal sites (evidence compiled in Nomicos, 2021, pp.119 – 120) there are hardly any traces of habitation in the region.

The Early Byzantine period in the Laurion sees a remarkable increase in human activity even in off-coast areas, and the reprocessing of slags and other residues is intensified (Kakavogiannis, 2013). According to latest mining archaeological results by D. Morin (Morin and Delpech, 2018, pp.44 – 45), mining is taken up again during this period (see Nomicos, 2021, chapter 3.7). This matches the literary evidence (Paul. Sil. 678 – 681) and fits into the picture of the changing resource availability of the Byzantine Empire with the loss of the western half of the empire (Davies, 1935, p.251; Mussche, 1998, p.65; 2006, p.226; Docter, Monsieur and Van de Put, 2011, p.120; Nomicos, 2021, pp.124 – 125). This is remarkable, since it opens up a whole new set of questions to be addressed in the future. These concern not only the technical details of ore extraction but also the organisation of these undertakings. Around 600 AD however, the evidence for human activity in the Laurion declines sharply and remains low until the mining revival in the 19th century.

Discussion of the development of mining in the Laurion in the light of the mining landscape theory

South-East Attica was continuously inhabited with varying intensity from the Late Neolithic Period to Late Antiquity. Direct evidence for prehistoric mining of Laurion ores exists only at Thorikos, to what extent other parts of the Laurion were exploited remains unclear. In view of the lack of finds, only *extensive mining* operations in those parts seem likely, possibly only seasonally during humid parts of the year when water was available. With the emergence of the owl coinage, the first evidence of “workshops” and increasing settlement activity in the inland areas during the late Archaic period, an *initial phase* of mining can be detected. The impetus for this intensification will most probably have been the adoption of silver as base metal in the Greek world ca. 550 BC. A *radiation phase* can be postulated between the *initial phase* and the *industrial phase* during the 5th century, which is reconstructed mainly on the basis of the literary evidence. After a *phase of collapse* during the Peloponnesian War and *reorganisation* around the middle of the 4th century BC, a second *industrial phase* can be clearly detected in the material record. This is followed by another *collapse* by the around 300 BC. A *reorganised* industry with a focus on the reprocessing of older residues in the 2nd century BC can be reconstructed. Possibly in the 1st century BC the system *collapses* yet again. After a period of near standstill during the Roman Imperial Period, mining was resumed during the Early Byzantine Period. So far, the evidence is too scarce to allow for a comprehensive characterization of this phase. It can be observed however that there is another *collapse* around 600 AD that lasts until the 19th century.

The analysis of the settlement development in the Laurion shows that there is a traceable correlation with the mining history, and a causal relationship is suggested (see Nomicos, 2021). This can be deduced, on the one hand, from the changing quantity of finds and, on the other hand, from the fact that in intensive mining phases both the coastal region and the inland areas show traces of settlement, whereas in phases with little or no mining activity the sites are limited to the coastal region. Therefore, mining directly affected the settlement development of the Laurion.

Several factors can be identified that directly influenced the productivity of the mining industry in the Laurion. These comprise especially *the quality and accessibility of the deposit* and the *supply and demand structure*. The former is one way to explain the absence of extensive mining activities in the Laurion outside of Thorikos before the late archaic period. The mining of the inland deposits only really took off, when firstly the so-called third contact, the rich and ca. 100 m deep (Kakavogiannis, 2005, p.92) deposits, could be reached by means of sinking of deep shafts and secondly, when the water-management problem was solved by the construction of countless large cisterns plastered with the distinct hydraulic mortar which made the mining industry independent from seasonal water availability. Only then could the lead-silver ores be effectively and perennially processed in the numerous washing tables, which were also lined with hydraulic mortar. The success of Athenian mining therefore was the result of (and only made possible by) these three technological innovations: deep shafts, large cisterns, and water-proof mortar. Unfortunately, we do not know any details on how these inventions were developed and who was involved. We can only guess that the Laurion attracted “mining engineers” from other regions such as Thrace and Siphnos who contributed to the technological innovations (Kalcyk, 1982a, p.109). The latter factor is not only manifested in Athenian coin production, but later in the Byzantine Empire also, according to Paul the Silentiary, in silver for decorative purposes. The *changing supply and demand structure* was moreover greatly responsible for the standstill in mining in the second half of the 5th and first half of the 4th century which is to be explained by the events and the aftermath of the Peloponnesian War.

The role of process optimization in reconstructing ancient technical processes

With regard to the Laurion, the one component of past mining economies that has attracted much scholarly attention is that of the *mode of production*. Reconstructing the chaîne opératoire of ancient Athenian mining was the aim pursued already by A. Kordellas (Cordella, 1869) and E. Ardaillon (1897). It was the seminal work by K. Konophagos (1980), however, that systematically considered the different steps of the technological process comprehensively. Being a mining engineer himself, much insight was gained by his process-optimising approach. Yet, some of his theories have been questioned, especially by archaeologists (Trikkalinos, 1978; Kakavogiannis, 2005, p.241; Lohmann, 2005, pp.113 – 116). How does this change of perspective help to reconstruct the process chain and to what extent can process optimisation measures be detected in the classical silver “industry”?

The process of silver production in classical Laurion, after prospecting, started underground. The ore was extracted from subterranean chambers which were reached by narrow passages branching off deep shafts. Already A. Kordellas (Cordella, 1869, pp.82 – 86) noted that different types of shafts existed, but it was Konophagos (1980, pp.197 – 206) who described them in more detail and distinguished seven different types (Konophagos, 1980, p.188 fig. 9 – 32). He explained the differences with alternative ways of accessing (“riding”, see Weisgerber, 2005 p.40) the deposits. The examination of the shafts conducted by D. Morin (Morin, Herbach and Rosenthal, 2012; Morin and Photiades, 2012, Morin, in this vol.), however, suggests that the main difference between the shaft types lies in their ventilation techniques. Important new results are to be expected from the current project by M. Vaxevanopoulos (see Vaxevanopoulos, in this vol.).

The topic most widely discussed by engineers, archaeologists and mineralogists alike is ore beneficiation (see Nomicos, 2021, chapter 2.2). Before the ore can be extracted by metallurgical processes, it must be first reduced in size and then separated from the gangue. Different methods of size reduction can be reconstructed in the Laurion. The most ancient method of size reduction of all materials is that of pounding. Such bedrock processing floors are known from all over the world (see for example: Craddock, 1995, pp.159 – 160 fig. 5. 3 – 5. 4; Eitam, 2009; Fig. 2), but they had not been described for the Laurion until 2015, when, during the Survey at Ari several such sites were discovered (one of them additionally comprising bedrock mortars, see Lohmann, this vol., p.161 Fig. 7). Unfortunately, the dating of these features is elusive because they constitute a universal method not restricted to one area or time period. Size reduction was furthermore achieved by grinding the ore either in saddle quern-like devices or hopper querns (compare Lohmann, this vol.). The structures known as “helicoidal washeries”, first observed by Young (1942, p.95 in the footnote) but thoroughly described and reconstructed by Konophagos, can in view of previously unknown in-situ finds be more consistently reconstructed as mills of the kollergang type; there are however contrasting views on their dating and purpose (Nomicos; 2013; 2017; Papadimitriou, 2015; 2016; 2017). A recent find at Ari is interpreted as a part of a stamp mill (see Nomicos, 2021, p.57 – 58 pl. 18,1; Lohmann, this vol.), which could be the earliest evidence of this technology.

Fig. 2: Depiction of stone pounding (after Lynch und Rowland, 2005, p.31 fig. 3.7 (b); digital post-processing L. Hecht).

A much-disputed question (Negris, 1881; Konophagos, 1980; pp.223 – 224, 241 – 246; Kakavogiannis, 1992; Domergue, 1998) is the exact function of the famous ore-washeries, of which hundreds have been preserved in the Laurion. There are arguments in favour of the reconstruction put forward by Ph. Negris (1881; see also Agricola, 1556, p.261 with fig.) in the 19th century with an adjustment concerning the purpose of the basins. In accordance with the results presented by E. Photos-Jones (Photos-Jones and Jones, 1994), these may be understood as means of classification (Nomicos, 2021, pp.67 – 68).

Hardly understood are the smelting, cupellation and lead production techniques employed in ancient Laurion, although different reconstructions have been put forward (Wilsdorf, 1974, p.1758; Konophagos; 1980, p.289 fig. 11 – 1; Papadimitriou, 1995, p.255 fig. 3; Kakavogiannis, 2005, Pl. 18; for a discussion see Nomicos, 2021, pp.69 – 71). Interpreting the material remains from these processes is particularly difficult because of a general lack of archaeological contextualisation. A blind spot of the process chain is the cupellation method employed in ancient Laurion. Although several types of litharge (plate-shaped and tubular), the by-product of cupellation, have been found in great numbers (see Konophagos, 1980, pp.307 – 326; Kakavogiannis, 2005, pp.273 – 281 with pl. 23; see also Papadimitriou, 1995; 2012; for a discussion see Nomicos, 2021, pp.73 – 74), the actual furnaces have not survived. Due to the Laurion's complex mining history, it is hardly possible to contextualise these remnants reliably.

The change of perspective from an engineering to an archaeological/historical point of view leads to different interpretations of the material remains all along the process chain. This is demonstrated by the new interpretation of the different shaft types in the Laurion by D. Morin. It also becomes apparent, when analysing the different means of size reduction. The stone blocks interpreted by Konophagos as pounding tables can in the light of typological parallels be better explained as saddle quern-like mills and the "helicoidal washeries" as kollergang-type mills. Moreover, the material remains of the washeries lack any indication of the sluices proposed by Konophagos and can more consistently be reconstructed in another way.

That being said, the theory of process optimization as implicitly employed by K. Konophagos merits careful consideration. Especially when stratified contexts are missing – as is the case in the Laurion – it proves to be an invaluable tool in explaining the use of different archaeological finds which belong to the same process step but differ in their technical efficacy. The way in which Konophagos repeatedly employed this notion was to reconstruct a several step process: according to him, 1) the ore was first reduced in size coarsely on the stone blocks here addressed as saddle quern-like mills and the finely ground in the hopper querns (Konophagos, 1980, pp.219 – 223); 2) the metal was first handled in a way that produced the plated litharge and then in a way that produced the tubular type (Konophagos, 1980, p.308). These conclusions are consequential when considering all the remains as belonging to the classical period. Since we know today however that the mining history of Laurion was much more complex with different modes of production and uses of the deposit, this one-dimensional view has to be challenged. It can be argued, for example, that the different milling devices represent different steps in a long-term technological development. In this hypothetical scenario the hopper quern could be a technological innovation (of the 4th? century BC) superseding the earlier (?5th century BC) saddle quern. The kollergang-type mills and the newly discovered stamp mill may be understood as even further steps of this mechanization process of size reduction.

Conclusions

Silver mining in ancient Laurion has been the subject of scholarly attention for more than two hundred years. Owing to the results of numerous excavations of the past decades, it has only recently become possible to draw a more differentiated picture of the diachronic development of raw material exploitation. Employing the mining landscape model developed by Th. Stöllner allows for a structured approach in reconstructing different phases of exploitation that furthermore takes into account the various factors of rentability. The discussion of the connection between the settlement and the mining history revealed a close correlation and causal relationship between the two.

The example of Laurion shows moreover that the theory of process optimisation, as implicitly employed by K. Konophagos, helps to better explain ancient Greek technological processes when typological parallels, results of archaeometric analyses, and historical processes are carefully considered. This conclusion is significant because, when employed systematically, it adds a new perspective to the study of technology in ancient cultures in general and technological innovations in particular.

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Laurion – The present state and future scope of research

ABSTRACT: *The mining district of Laurion in Attica (Greece) was doubtless the largest and most important industrial area of ancient Greece. Due to the density, diversity and partly excellent state of preservation of the remains it is also one of the most fascinating mining landscapes of the ancient world. The silver mining at Laurion formed one of three pillars of the Athenian public economy. Although the geological and archaeological exploration of the Laurion has made significant progress over the last few decades, numerous questions concerning its history and topography, as well as its mining archaeology and archaeometallurgy remain unsolved. This paper tries to offer a brief general overview of the outstanding problems and questions, in order to define research fields and to formulate tasks for the future as a matter of priority. The most important task, however, is adding the Laurion to the list of UNESCO World Cultural Heritage sites and to protect it from further destruction.*

KEYWORDS: LAURION, MINING LANDSCAPE, MINING, BENEFICIATION, ARI

Introduction

Attica, comprising about 2,500 km^2, has already for a long time and for good reason been regarded as a ‘central’ landscape of Greece – ‘central’ not in a geographical sense but for the cultural history of Greece as a whole, and likewise ‘central’ for the entirety of ancient studies: Archaeology as well as Ancient History and Classical Philology (Lohmann and Mattern, 2010). There is no other historical landscape of Greece providing a similar quantity of literary and archaeological evidence. It is therefore not surprising that no other landscape and its urban centre were the object of comparable intensive historical and archaeological research from prehistoric to modern times, as Athens and Attica. Not only the number of publications is impressive, but also the number of excavations, mainly by the Archaeological Service, but by the foreign schools as well. Thanks to the substantial works starting already in the 19th century on the Athenian Acropolis, the Athenian Agora and the Kerameikos, Athens stands out as a lighthouse. With the long-term excavations of V. Petrakos at Rhamnous, published only recently in six extensive volumes (Petrakos, 1999a-b; 2020a-d), and the likewise substantial publications of the Belgian School at Thorikos (Docter and Webster, 2018, pp.58 – 69, with ample bibliography) two important country towns, each of them displaying a completely different character, have enormously enriched our knowledge. It is to be hoped that in the future the regrettably much degraded town and sanctuary of Eleusis will gain more attention and a reassessment of the outdated excavation results, especially with regard to the chronology of its fortifications (Hülden, 2020, pp.370 – 377; Lohmann, 2021, pp.78 – 89). The beautifully situated country town of Sounion also deserves further research and it is to be hoped that funds will be found for the restoration of its marvellous 5th century BC city wall before it will collapse entirely (Lohmann, 2021, p.98, fig.54).

On the other hand, there are also enormous deficits. After the Second World War the unrestrained growth of Athens has turned large parts of Attica into an archaeological desert. Hundreds and thousands of ancient sites and monuments – including well-known and published ones – were destroyed in an uncontrolled manner. The vast majority of rescue excavations by the Greek Archaeological Service has never been fully published (Μαλούχου, 2017, p.7). Where the Prussian maps of Attica from the late 19th century[1] show thousands of archaeological sites, concrete is now spreading across the once lovely Attic countryside.

Since the reforms of Kleisthenes Attica was divided into rural and urban demes (‘villages’), which in the 4th century BC numbered 139, and disposed of a differentiated settlement structure, comprising thousands of single farmsteads, as well as hamlets, villages, country towns and an urban centre – Athens –, which itself consisted of approximately 40 ‘city’ demes (Traill, 1975; 1986). According to Thucydides (2,16) down to the outbreak of the Peloponnesian War in 431 BC, the majority of the Athenians lived as farmers in the countryside, which so far has been the object of no more than four survey projects: in Southwestern Attica, in a region identified as

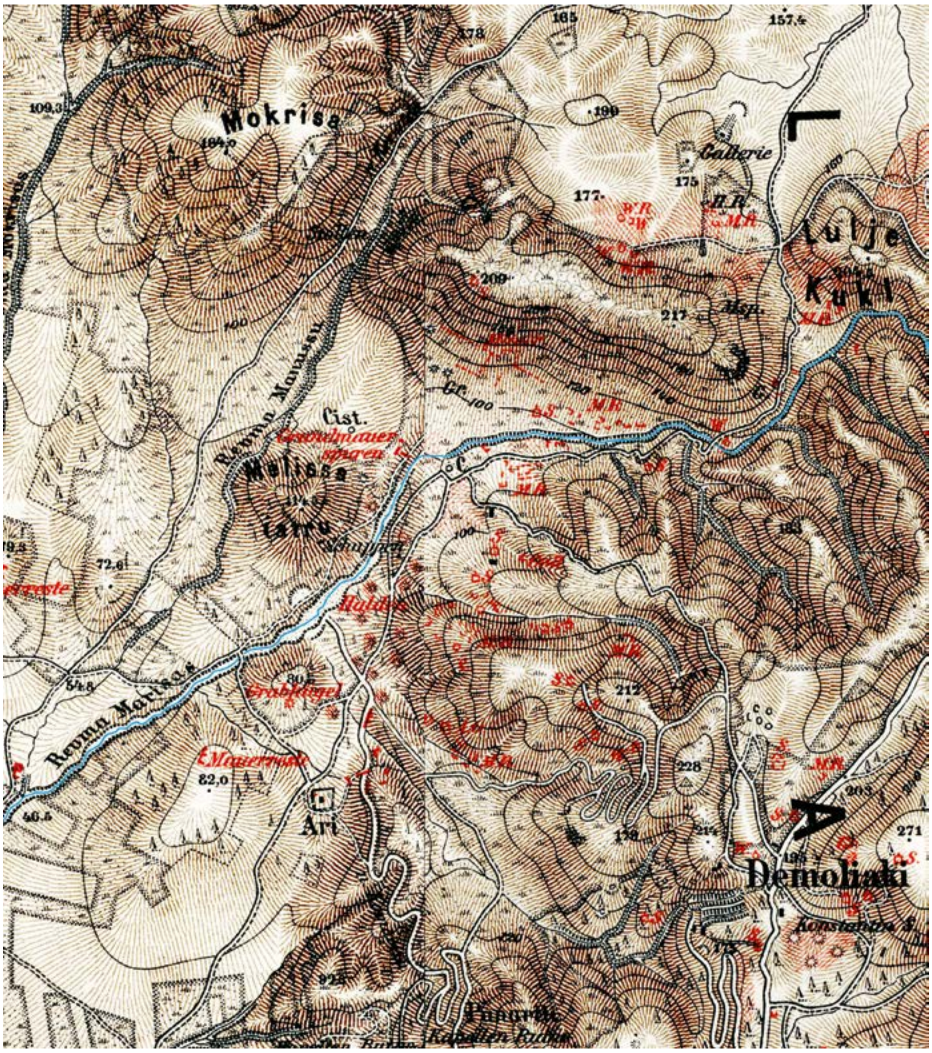

Fig. 1: Map of Ari. Sections of the maps 16 (Lavrion) and 17 (Olympos) of the Prussian Maps of Attica, prepared by Friedrich von Bernhardi from survey in 1882.

the rural deme of Atene (Lohmann, 1993), in the Skourta plain (Munn and Munn 1990; Munn, 2010), in the Oropia (Cosmopoulos, 2001) and only recently in the Mazi plain in Northwestern Attica (Knodell, et al., 2017). Despite the mountainous structure of vast parts of Attica, the land contributed considerably to the wealth of Athens through the efforts of the Athenian farmers, cultivating even the last corner of their homeland (Thuk. 1,82,4; Hell. Oxyrh. 17 (12),5; Audring, 1977, p.20). The extensive exchange of goods between the urban centre and the countryside as well as the mass production of different goods in the town, contradicts the notion of economic historians of the ‘primitivist school’: During the Classical period Athens was instead beyond any doubt the highest developed polis of Greece, economically, politically and culturally.

The second pillar of the Athenian Empire was formed by the contributions of the allies organized in the First Athenian League. While the percentage of the tribute that flowed directly into Athens' treasury seems rather modest (Flament, this vol.), the tribute going into the construction of the Athenian fleet stimulated its economy enormously. The hundreds of shipsheds and shipyards in the Piraeus are witness to this. This vividly calls to mind the USA forcing European states to spend 2% of their gross national product on defence, mainly of course on weapons purchased in the USA.

The third pillar of the Athenian state economy in addition to agriculture and to the Athenian League were the silver mines at Laurion (Flament, this vol.). Although their contribution to the economy of Athens and its hegemonial role during the 5th century BC and at least also during parts of the 4th century BC has regrettably been extremely underrated by many historians, it can – to the contrary – hardly be overestimated. Not to speak of the building of the fleet before the fateful naval battle at Salamis in 480 BC, when the Athenians prevented Greece from becoming just another province of the Persian empire. European history might have taken a completely different turn then. It, therefore, cannot be stressed often enough, that the Laurion in Southeastern Attica was by far the largest and most important industrial area of ancient Greece. It comprises no less than 80 or 90 km^2 stretching from Cape Sounion in the South, to Plaka in the North, and from Thorikos in the East to Ari near Anavysso in the West. Because of its enormous wealth of ancient remains, comprising mines, workshops, smelting places, sanctuaries, graves, towns and farmsteads, it forms a unique fossilised industrial landscape, mainly of the Classical period, the 5th and 4th century BC. It will hopefully finally be listed as world cultural heritage by UNESCO (Voudouris, et al., 2021) – despite the immense damage that, after a first wave of destruction by the mining activities of the 19th and early 20th century, uncontrolled summer house construction and industrial projects have caused since the 1960s.

History of research

The most recent and thorough treatment of the research on ancient Laurion is that by S. Nomicos (Nomicos, 2021, pp.17 – 24). Within the framework of this paper, I can only highlight some of the milestones of past academic research, which started in the early 19th century, more than 200 years ago, when in 1815 A. Boeckh published his paper "Über die Laurischen Silberbergwerke in Attika" (Boeckh, 1815). Only two years later followed his comprehensive work "Die Staatshaushaltung der Athener" (Boeckh, 1817), which made him the father of Economic History as a historical discipline of its own. Due to the great impact of this work, it was translated into English in 1828 (Boeckh, 1842). His writings were created exclusively on the basis of the extant ancient sources. He never personally visited the Laurion.

Early pioneers of the Laurion mining district were the mineral geologist K. G. Fiedler (1840, pp.36 – 79) and the Greek mining and metallurgical engineer A. Kordella (Cordella, 1869). In 1864 the Roux-Serpieri-Fressynet & C.E. started to rework the ancient slags, while since 1870 the ancient mines were reopened. But the mining history of the Lavriotiki during the 19th and 20th century remains still to be written.[2]

Shaped by a foresight in research policy that is all too painfully missing today, were the Prussian maps of Attica of the late 19th century, when modern mining in the Lavriotiki advanced rapidly. For the first time these maps sought a systematic inventory of the whole of Attica, including all ancient remains in the Laurion. In 1882 and 1883 Friedrich von Bernhardi, then Lieutenant in the Prussian army, mapped the whole of Laurion at the scale of 1: 25 000 (Curtius and Kaupert, 1891 – 1900, maps 14, 15, 16 and 17; Fig. 1), within seven months – an almost unimaginable effort (von Bernhardi, 1920, pp.157 – 164; 1927, 92 – 100; Lohmann, 2010, pp.259 – 275), especially regarding the high precision of these maps. More detailed maps of parts of the mining area are to be found in the archive of the CFML (Compagnie Française des Mines du Laurium) and the later Hellenike Hetaireia Lavriou (Ελληνική Εταιρεία των Μεταλλουργείων Λαυρίου) in the Technological Park at Lavrio (Τεχνολογικό Πολιτιστικό Πάρκο Λαυρίου). To date there is no recent mapping of the ancient remains, instead up to the most recent publications maps of the 19th century are reproduced (v. *exempli gratia* Kapetanios, 2010, p.162, fig.27). The maps published by K. Konophagos (Conophagos, 1980) are copied from maps of the CFML. The envisaged project of the Belgian School at Thorikos to map the entire Laurion by means of a LIDAR-drone was, unfortunately, never accomplished.

The scientific commentary on the Prussian maps concerning the mining area by A. Milchhoefer (1889) lags far behind the enormous number of entries they display. Obviously, completely on his own, A. Milchhoefer was overwhelmed with the task of describing the vast area comprehensively. The attempt of W. Wrede, director of the German Archaeological Institute at Athens during inglorious times (Petrakos, 1994), to provide a new commentary, got stuck at the beginning.[3] Plans of some ancient mines made by the Saxon geologist Baldauf in 1935 were lost during the Second World War, before they were published (Wilsdorf, 1952, p.112; Hopper, 1968, p.312, n.159). Among the first authors who tried to provide an overall picture of the ancient mining district of Laurion were A. Kordella (Cordella, 1869) and E. Ardaillon (1900). After the Second World War, interest was primarily directed towards the organization of mining in Classical times, which we are informed about in the ancient mining leases from the Athenian Agora (Crosby, 1941; 1950; 1957; Langdon, 1991; Aperghis, 1997/98). The paper of R.J. Hopper of 1953, working on the extant literary and epigraphical sources is still much appreciated and indispensable for the study of the Laurion mining industry, but is lacking intimate knowledge of the region and the ancient remains existing there. Many publications followed, H. Kalcyk lists in his PhD no less than 180 books and articles (Kalcyk, 1982, pp.226 – 235). But only with the seminal work of K. Konophagos (Conophagos, 1980), former director of the metallurgical plant at Lavrio, then director of the renowned EMP (Εθνικό Μετσόβιο Πολυτεχνείο) / NTUA (National Technical University of Athens) and industry minister of the first democratic government of Greece after the Junta, did there commence a new era of research on the ancient mines at Laurion. His book, therefore, marks in some respects a turning point. It is certainly no coincidence that several attempts to take stock of previous research appeared in the early 1980s (Jones, 1982; Weisgerber and Heinrich, 1983). Since then, the number of publications has more than doubled (Nomicos 2021, pp.139 – 159). Although some ideas of K. Konophagos are now out-of-date, his greatest merit is the stimulation of new research.

Indeed, research on the Laurion has made tremendous strides over the past four decades. The geologists solved essential questions of orogeny and the formation of the polymetallic ore deposit (for an overview see Voudouris, et al., 2021; Ross, et al., this vol.). In the beginning of the 21st century D. Morin, A. Photiadis and their team explored the ancient shafts of Laurion with modern equipment (Morin and Photiades, 2005; Morin and Herbach, 2008; Morin, et al., 2012; Herbach, et al., 2013; Morin, et al., 2020). Only recently the "Lavrion Shafts Project", a survey project by a team headed by M. Vaxevanopoulos (Vaxevanopoulos, et al., this vol.), has for the first time located all shafts in the Laurion area, the number of which has been tremendously exaggerated in former publications: Estimates have reached from 1,000 to more than 2,000.[4] The aforementioned project has put an end to this debate by determining that there were approximately 300 shafts, as I had already suggested long ago on the basis of the mining leases from the Athenian agora and the entries in the Prussian maps nos. 14 – 17 (Lohmann, 2005, p.118). No less than 10 ancient mines were speleologically explored and topographically mapped by M. Vaxevanopoulos and his team. More plans of ancient mines will be provided by D. Morin (Morin, et al., forthcoming). Other plans together with thousands of important documents and maps in the archive of the Technological Parko at Lavrio await intensive study and publication.

Since the 1970s dozens of workshops, so-called *ergasteria*, have been uncovered. K. Konophagos excavated the Asklepiakon of Simos in the Soureza valley (Conophagos, 1980, pp.375 – 389), others were unearthed by the Belgium School at Thorikos, by E. Kakavogiannis and O. Kakavogianni, by K. Tsaïmou and by M. Salliora Oikonomakou, the former director of the Archaeological Museum at Lavrio which opened to the public in 1999. But so far none of these workshops has ever been fully published. Only the publication of a large *ergasterion* on the southern slope of Mt. Michali by E. Photos-Jones and J.E. Jones stands out as an important point of reference (Photos-Jones and Jones, 1995).

Several conferences on the different aspects of the history and technology of the ancient mines in the Laurion at Keratea and elsewhere have brought about many pieces of new evidence and contributed considerably to improve our knowledge and our understanding of this important part of Attica. During the last two decades the question of prehistoric mining in Laurion has gained special attention. Only recently J. Maran has strongly advocated, that in the Aegean the use of silver “can be traced back to the early 4th millenium BC and possibly even earlier” (Maran, 2021, p.197). Thanks to recent findings in Lambrika, Keratea and elsewhere (Andrikou, this vol.; Kakavogianni and Douni, this vol.) it can now be stated safely that mining in the Laurion goes back to the Final Neolithic and Early Helladic I period, although it still remains difficult to pinpoint traces of such early mining works. The discussion of the findings in the famous Mine 3 at Thorikos gives an impression of the problems involved (Nazou, 2018; Nazou, this vol.).

On the other hand, there are also heavy losses to report. Since the 19th century much damage occurred to the Laurion area, first by reworking the ancient slags since 1864, than by reopening the mines since 1870 and within the last decades by various building activities and industrial projects like the EBO (Ελληνική Βιομηχανία Όπλων), which devastated senselessly the valley of Botsari most probably identical with the ancient mining district of Thrasymos, one of the largest and most important ones in the whole Laurion, being part of the deme of Sounion.[5]

Pending problems

Historical topography

The questions of the historical topography of ancient Laurion have been scrutinized by H. Kalcyk (1982) and the author (Lohmann, 1993, pp.98 – 110) with partially diverging results. Since no significant progress on the issue has been made since then, there is no need to go into any detail here. In only six out of the 139 Classical demes of Attica did mining took place. These are (in alphabetical order) Amphitrope, Anaphlystos, Besa, Phrearrhioi, Thorikos and Sounion. Thanks to the discovery of several rock-cut horos-inscriptions in the region, we are able to draw borders between at least some of these ancient demes. In addition to the already known series of horoi on Megalo Baphi and on Spitharopoussi (Lohmann, 1993, p.109, fig.12, pp.447 – 448, PH 62 no.1 – 5; Fig. 4), only recently a rock-cut horos inscription already mentioned by K.G. Fiedler in 1840 has been rediscovered by M.K. Langdon (Fig. 2. 3).[6] Although this inscription to the north of Plaka, in a saddle a little northeast of the Mousaki (H 359), is somewhat smaller than the horoi on Mt. Megalo Baphi

Fig. 2: Rock-cut horos inscription situated North of Plaka (photo: Hans Lohmann).

Fig. 3: Rock-cut horos inscription situated North of Plaka (photo: Hans Lohmann).

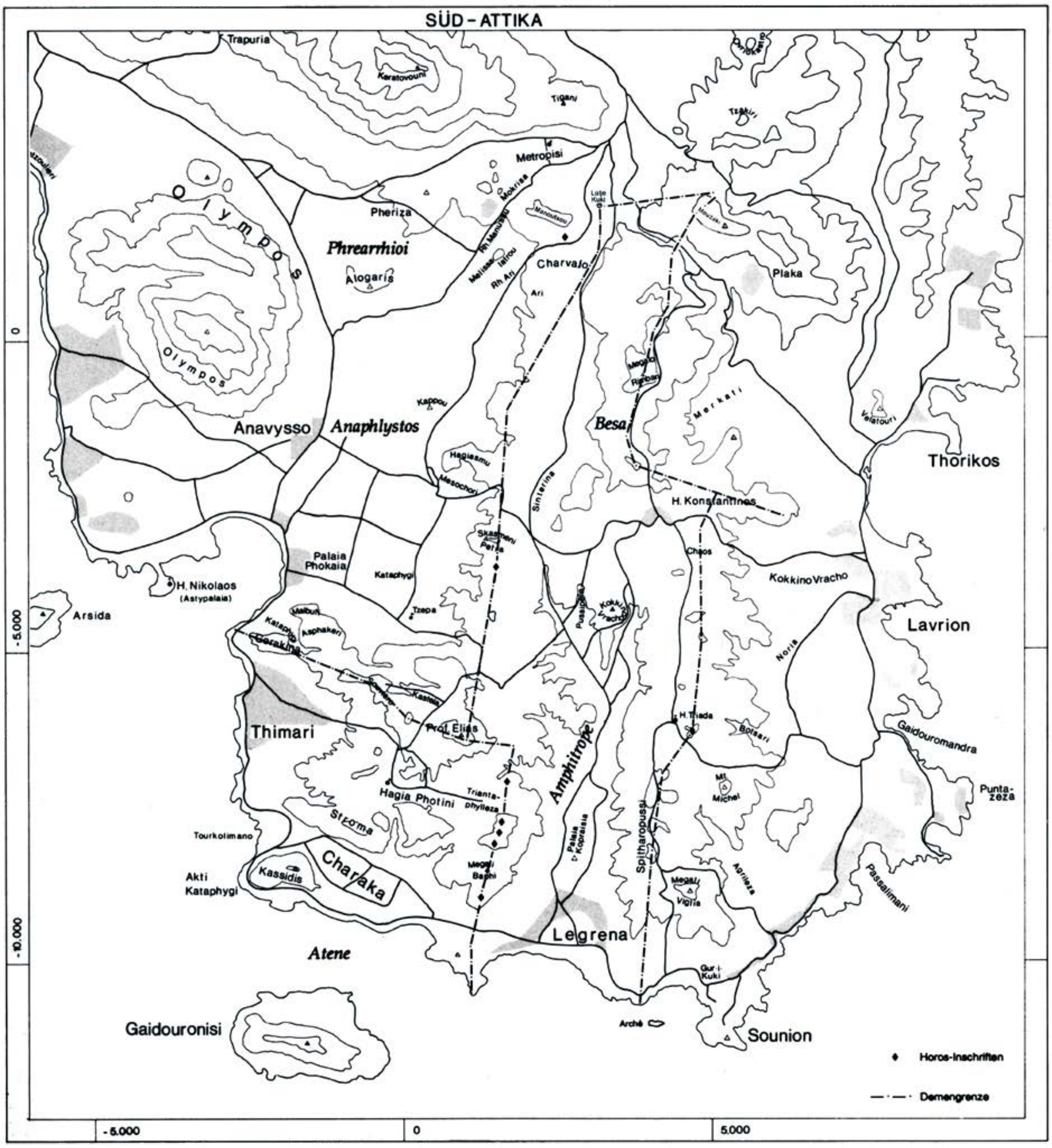

Fig. 4: Map of South Attica with borders of demes (by Hans Lohmann).

and on Mt. Spitharopoussi, it might well mark the border between the demes of Kephale (Keratea) to the north and Thorikos to the south. At the same time, the discovery of four ancient shafts in the northeastern part of the Manoutsou or Koumarodiasello discovered by M. Vaxevanopoulos (this vol.) raises the question, where the valley of Metropissi (miswritten as "Μητροσπίτι" in the Greek Topographical Map Sheet Lavrion, Fig. 5) north of the Manoutsou belonged in antiquity. Since it is by no means identical with the ancient deme of Amphitrope (Lohmann, 1993, p.80) and no mining leases are attested for the closely adjacent deme of Kephale (more or less identical with modern Keratea), it was evidently part of Phrearrhioi.

It is not particularly surprising that in antiquity the mining landscape of the Laurion was made accessible by a dense network of mule tracks and driveways, some of them being the same ones we still drive on today. 'Roads' (ὁδοί), perhaps not always in the strict sense of the English word as driveways but as mule tracks, are often mentioned as borders of mining concessions in the

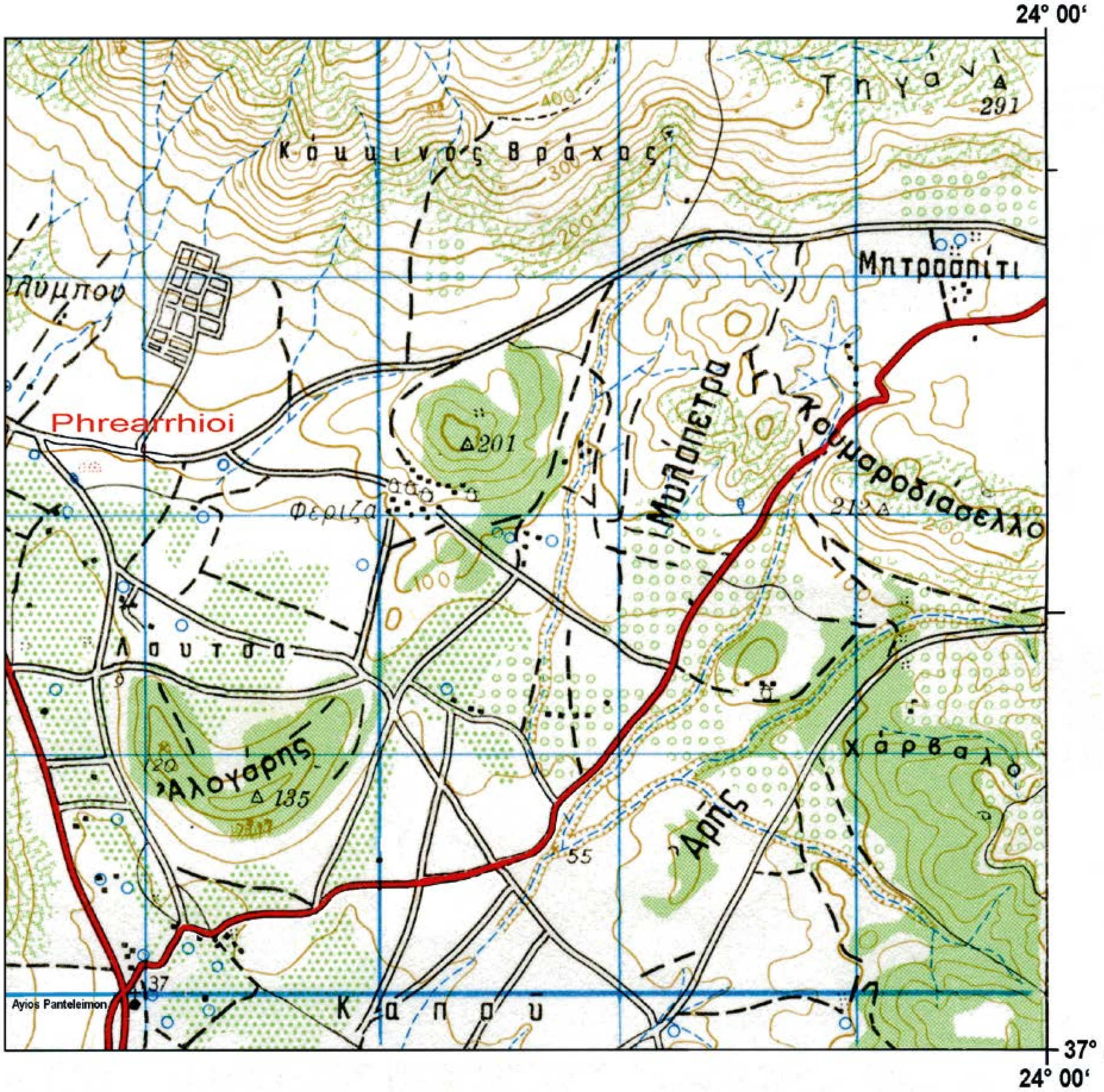

Fig. 5: Map of district of Ari. From Athenai-Koropion 1 : 50 000 (edited by the Geographiki Hyperessia Stratou, 1976; modified by Hans Lohmann).

mining leases from the Athenian Agora. The few remains still existing have been studied previously by J. Young (1956b) and more recently by O. Kakavogianni (2008).

What has been mined?

The question what has been mined in prehistoric and ancient times in the Laurion has been discussed for some time (see Ross, et al., this vol.). For my part I can only offer an archaeological point of view on the topic. Although the Laurion is primarily famous for its silver deposits, it is indeed a polymetallic ore deposit. No less than 700 different minerals are attested there.[7] A significant by-product of the silver was lead, which was obtained in large quantities. But there are also copper minerals. Although the quantitative relationship between copper and lead ores in the Laurion is difficult to ascertain, the copper ores were obviously mined primarily in the bronze age (Gale, et al., 2009). In this context it should be noted that one of the largest Early Bronze Age sites of Southwestern Attica is located on a hill called Mokriza, only about 1.5km Northwest of Mt. Charvalo at Ari.[8] The hill is situated on the 'Phrearrhian' side of the torrent Ari (Fig. 1. 4). On the hilltop traces of a sanctuary were found and remains of a settlement of the Classical period were discovered in the much overbuilt slopes (Lohmann, 1993, pp.75. 505, AN 25. 26). D. Parras discovered fragments of crucibles, slags and litharge, which have not yet been published (Andrikou, et al., this vol; A. Kapetanios, pers. comm.).

Besides, copper zinc minerals may have played a certain role (Hanel and Bode, 2016, p.174). The existence of large zinc deposits has already been pointed out by K. Fiedler (1840, p.71) and A. Cordella (1901, p.353), while the Compagnie Française Minière de Lauréotiké (CFML), founded in 1876, was the first to realize the potential of the deposits of zinc carbonate (calamine) in the Laurion and to mine it. Zinc sulfide (sphalerite, from Greek σφαλερός), which was recognized as zinc mineral only in 1735 (Lüschen, 1979, p.191) and could not be melted before the 18th century seemingly prevails in the Laurion. While it is unclear, to what extent zinc sulfide was mined in modern times in Laurion, since there are still large amounts of it, its use cannot fully be excluded for pre-industrial times. Likewise, there is no evidence for the mining of zinc carbonate (calamine) in ancient Laurion (Nomicos, 2021, p.34). But since brass (Greek ὀρείχαλκος, Latin aurichalcum), an alloy of copper and zinc (Hammer, 2001, pp.609 – 615), was not produced by mixing melted copper and zinc, but by adding zinc ores like calamine or sphalerite to melted copper (Hauptmann, 2020, pp.402. 404), it would be surprising, if brass should not have been produced in the Laurion – be it by experiment or by chance. But once again evidence is totally lacking, especially, since on the basis of the data available, it cannot be decided whether and to what extent the numerous Classical or Hellenistic 'bronzes' in the museums around the world are actually brass.[9] It would, therefore, be fully speculative to claim that the brass ingots from a shipwreck sunk on the Southern coast of Sicily near Gela, allegedly dating back to the 6th century BC,[10] or those from another wreck found near the island of Embiez (Dép. Var, France), vaguely dated between the 4th and the 2nd century BC (Dumas, 1972, pp.181 – 185; Parker, 1996, pp.252 – 252; Hauptmann, 2020, pp.402 s.), originated in Laurion. The Romans, for whatever reasons, did not mine calamine at Laurion, but on Sardinia (Boni and Large, 2003; Boni, et al., 2002; Valera and Valera, 2005; Valera, et al., 2005).

Another major problem is the question, if iron was produced in the Laurion (see Ross, et al., this vol.; Nomicos, 2021, p.34). Certainly, the need for iron in the largest Greek polis besides Sparta was enormous: in architecture, agriculture and warfare as well as for the shipyards and last but not least in the mining district itself. Although iron ore does exist in the Laurion, clear archaeological evidence for mining and smelting of iron is totally lacking. Iron slags are very large and usually occur in huge quantities. So far, no such slag heaps have ever been reported from Laurion, but only forging slags, which sometime were erroneously reported as smelting slags. Huge slag heaps as relics of iron smelting are found in Etruria instead. Was iron the commodity exchanged against Athenian Black Figure and Red Figure vases, which are found in Etruscan tombs in their thousands? But is it even thinkable, that a polis of the size of Athens could cover its need for iron by import only? Unfortunately, the 'fingerprint' of the iron clamps of the Erechtheion (Conophagos and Papadimitriou, 1986, pp.129 – 42) does not point unambiguously to a provenance from Laurion. The methods of analysis applied to them in the 1980s do however not cope with today's standards of provenience studies.

Regarding Laurion, there is much talk about silver in the extant ancient sources, rarely and only in rather unreliable ones about gold, as already A. Boeckh (1842, pp.627 s.) had clearly seen.[11] Only B. Rieck in a regrettably confused passage of his dissertation has claimed the contrary.[12] Still little is known about gold production in 5th century BC Greece. But the literary testimonies do not have Laurion among the few places in Greece where gold was mined in the 5th century BC (Eddy, 1977, pp.108 – 109). This silence of our sources is difficult to explain, since thanks to recent research of P. Voudouris (Solomos, et al., 2004; Voudouris, 2005; Voudouris, et al., 2008; 2018; Rieck, 2012) there are evidently gold containing minerals in Laurion.

In the middle of the 5th century BC Phidias constructed the chryselephantine statue of Athena Parthenos, whose garment consisted of 1.5 mm thick sheet gold weighing 1.150 kg or 44 talents, thereby forming an important part of the state treasury.[13] Where did this huge amount of gold come from? S. Eddy (1977) argued that the major part consisted of melted coins of different, also Persian, origin mainly paid as a tribute by Athens' allies. But in the light of the new evidence mentioned, one wonders if at least part of this gold might originate from Laurion. Unfortunately, so far there is not the slightest piece of evidence for this.

In a polymetallic ore deposit like Laurion, offering hundreds of different minerals, pigments should have been an important by-product of mining. Since the Archaic period a growing need for pigments was fuelled by the practice to colour lavishly not only marble sculpture but whole temples. Pliny (n.h. 33,46) praises the ochre (Greek ὤχρα) of Laurium and indeed in a modern mine at Plaka ochre of the finest quality is present and ready for use without any further processing (Nomicos, 2021, p.34 n.287). Likewise, Vitruvius (7.7.1) describes Attic ochre as the best, thereby stating that it is currently not available. His formulation seems to imply that the supplies are exhausted, which is evidently wrong. The real reason might well be instead that in his times the mines had been long shut down and the Southern part of Attica was depopulated. Presumably for the same reason the extant literary sources offer no explicit evidence on cinnabar (Greek κιννάβαρι) and red chalk (μίλτος) from Laurion, which are to be expected as other significant by-products of lead-silver mining (Lauffer, 1979, p.44). But so far archaeometry and archaeology cannot fill this gap.

Mines and shafts

As already stated above, the "Lavrion Shafts Project" of M. Vaxevanopoulos and his team has clarified the number of ancient mine shafts in the Laurion district. The general correlation between the number of mines rented out, the number of shafts in the Prussian maps and the number of shafts located by the "Lavrion Shafts Project" should not distract from the fact that although almost every shaft indicates a mine, not every mine necessarily disposed of a shaft. The number of mines should, therefore, be higher than the number of shafts.

In times when explosives were not available and galleries as well as shafts had to be hewn into the native rock by hand only, it was more economic to access the ore deposit by a shaft than by a gallery – especially under the aspect, that later on, a shaft allowed for easier access to the mine as well as easier hoisting of the ore by simple lifting devices (Conophagos, 1980, p.163). In a series of articles D. Morin has convincingly shown how the ventilation of a shaft was enabled during the process of sinking it (Morin and Herbach, 2008; Morin, et al., 2012).

The absolute and relative chronology of the ancient mining shafts at Laurion is open to debate. K. Konophagos differentiated nine different types of shafts (Conophagos, 1980, pp.163 – 165. 205 – 207, fig.9 – 32). Since none of the hundreds of shafts can be dated more precisely and since we do not know the reason why different types of shafts exist, it is obviously impossible to establish a relative chronology (Nomicos, 2021, pp.36 – 41). With respect to absolute chronology, so far it is totally unclear when the first shafts were sunk in the Laurion. Some connected the 'invention' of sinking a shaft with the mention of the discovery of an extremely rich ore deposit in 483 BC by Aristotle (Kalcyk, 1982, p.106). This is purely speculative (Nomicos, 2021, pp.90 – 91). An approximate date could perhaps be obtained if one knew the precise age of the oil lamps, which were found in the shafts. Contrary to the 'normal' evaluation of a stratigraphy, in this special case the oldest find dates the shaft. Unfortunately, so far, no evidence of this kind is available.

As far as we know, during the Hellenistic period, when the New Style tetradrachms were emitted, mining was not resumed, but the silver was exclusively won by reworking ancient slags (Lohmann, 2005, p.126; Nomicos, 2021, pp.112 – 113). This is, why in some of the slag heaps in the Laurion, meticulously mapped by Greek mineral engineers Vouyoukas and A. Kordella (Conophagos, 1980, pp.134 – 135, fig.7-3; 7-4) amphora stamps of the first half of the 2nd century BC were found (Lohmann, 2005, p.126; Börker, 2018).

Starting with the Early Byzantine era in the 4th century BC, but especially under the reign of emperor Justinian (527 – 565 AD), a remarkable revival of the Attic countryside can be observed (Mattern, 2010). In many parts of Attica Early Christian churches were established, in their majority rather modest ones, but also some larger three-aisled basilicae like at Brauron, Olympos and Lavrion. In Southwestern Attica a remarkable increase in pastoralism is evident by the number of Late Roman or Early Byzantine sheepfolds, so-called mandras (Lohmann, 1993, pp.254 – 261). Besides these, some of the larger Classical farmsteads have been reoccupied – at Hagia Photini (Lohmann, 1993, pp.145, 207, 431 – 433, PH 33) as well as at Charaka, where a Classical grave precinct served as backwall to a modest house (Lohmann, 1993, pp.126 – 128, 362 – 367, CH 14, CH15). Mining was resumed to some extent too.[14] We are informed that "the veins of Laurion were opened" (Paul. Sil., Ecphr. 678 – 681; Nomicos, 2021, p.121), in order to cover the enormous costs of the Hagia Sophia at Constantinople.

S. Nomicos in her comprehensive work (Nomicos, 2021) has thoroughly collected all available direct and indirect evidence for the revival of the mining district which occurred since the 4th or 5th century AD (Nomicos, 2021, pp.121 – 128). While the large 5th century AD basilica at Lavrio, providing clear indirect evidence for an economic upswing had to give way to modern houses (Nomicos, 2021, pp.126. 206, Kat. 182), a large mosaic from this church is preserved in the archaeological museum at Lavrio (Salliora Oikonomakou, 2007, p.45 fig.49; Nomicos, 2021, pl.40,1). Only little, and sometimes doubtful, direct evidence for Early Byzantine mining in the Laurion has so far been published. A. Milchhoefer (1887, p.302) mentions grafitti "aus christlicher Zeit" (from the christian era) in a shaft at Berseko, K. Konophagos (Conophagos, 1980, p.385) reports coins of the 4th century AD from the Asklepiakon of Simos and in an unstratified context in Mine 3 at Thorikos lamps of the 5th century AD were found (Butcher, 1982). D. Morin saw Late Roman oil lamps in some of the Laurion mines he investigated and a piece of burned wood, dated to the 5th century AD by C14-analysis (pers. comm.).

Evidence that new shafts were sunk during this period is lacking. The hundreds of Classical shafts provided ample and easy access to the mines. But what about enriching and smelting? A single Late Roman water jar found in the workshop at Mt. Michel, excavated by J.E. Jones and E. Photos-Jones (Jones 1984/85, pp.122 – 123), does not testify to any metallurgical activities of the time (Lohmann, 1993, p.260 with n.1810), nor do the few fragments of Late Roman pottery which W. Wrede collected at Megala Pefka (Lohmann, 1993, p.95; Grigoropoulos, 2009, pp.431 – 432 no.11, 15, p.478, FO 070). Among the pottery from the large *kaminos* at Ari excavated by K. Tsaïmou, were some few fragments of the typical Late Roman 'combed ware'. Moreover, in one of the eight furnace chambers (φ 5) charcoal dated by ^{14}C to the 5th century AD might testify to metallurgical activities there (Tsaïmou, 2007, pp.221 – 225; Nomicos, 2021, pp.169 – 170 Kat. 18; Tsaïmou and Nomicos, in prep.).

107 ancient shafts are marked in the map of the CFML published by K. Konophagos (Conophagos, 1980, map). Only a fraction of them was re-used in modern times, some were widened or repaired in order to enable machine hoisting like the Puit Damianos and the Puit Skouzès at Ari, while others were deepened like the Puit Serpieri 1 at Kamareza. But no precise statistics are available for the time being. However, to the best of my knowledge, no new shafts were sunk after the resumption of mining in the 19th century. Many galleries were enlarged by the CFML too. Obviously, a closer study of modern mining in the Laurion and of the archival materials in the Technologico Parko at Lavrio, would contribute considerably to our understanding

Fig. 6: Edge-mill, so-called 'crushing table', in the Asklepiakon of Simos at Soureza (photo: Hans Lohmann).

Fig. 7: Ari, site no. 85. Depressions in the living rock, most probably created by crushing the ore (photo: Hans Lohmann).

of the ancient remains. Unfortunately, interest in this topic seems regrettably low, while the economic policy aspects of 19th century mining at Laurion have been masterly elucidated by K. Schönhärl (2017, pp. 166 – 213).

Besides the questions already mentioned, more research is needed on the tools used for mining in the different periods of exploitation. Obviously, the geology of an ore deposit determines to a certain extent the shape of the tools required for mining. But which tools exactly had been used for the exploitation of the ore deposit and for winning the ore, has not satisfactorily been clarified. Differing from the former view expressed by G. Weisgerber (1988, pp.203 – 205), G. Körlin and G. Weisgerber in a more recent paper hold (2004) that hammer and wedge have been invented in the Middle Ages and were not used in Greek or Roman mines. A closer study of toolmarks might be helpful to solve this question. A pick from Laurion is in the collection of the Bergakademie at Freiberg (Weisgerber, 1988, p.208, fig.249). K. Konophagos published three hammers from Laurion, two of them still preserving their wooden handles. Another one with a wooden handle is said to be in his private collection (Conophagos, 1980, pp.176 – 177, figs.9-8. 9-10). It would doubtlessly be a great advance if the age of these tools could at least approximately be determined by ^{14}C-analysis.

The beneficiation of the ore

At all periods, the workflow from the mine to the metal takes three fundamental steps: mining, beneficiation and smelting or extractive metallurgy.[15] After sorting the mined material roughly underground, the ore underwent a process of beneficiation, which, even after decades of research, still raises many questions. Since the ore was extracted by hand, no large chunks were brought to the surface, only small ones. Nevertheless, these had to be crushed further. Therefore, the beneficiation of the ore before smelting likewise took three steps, namely crushing, grinding and washing.

1. Mining
↓
2. Beneficiation
↓
a. Crushing
↓
b. Grinding
↓
c. Washing
↓
3. Smelting (extractive Metallurgy)

Crushing

The crushing above ground did not take place on the so-called crushing tables consisting of big blocks of limestone, which K. Konophagos discovered in the Asklepiakon (Conophagos, 1980, pp.220, 227, 233, figs.10-3, 10-4, 10-15) and which are also well attested for many other workshops (Fig. 6). They served instead for grinding, most probably under the addition of water, because in most instances the surface of these blocks is extremely smooth and has a shallow circular depression. It is most likely, therefore, that these blocks are to be identified as the stone beds of saddle querns, on which the grinding was achieved by circulating movements with a rounded stone tool (Nomicos, 2021, pp.47 – 48). Since limestone is rather soft compared to basaltic lava, the preferred material of the so-called Olynthian mills, the question arises whether these saddle quern-like mills served for grinding ore or more probably for something else – for instance slags or litharge.

But where did the fine crushing take place instead? At two sites at Ari for the first time groups of round depressions in the living rock have been observed (Fig. 7). I hold that these are not natural. The living rock served here as a processing floor (Nomicos, 2021, p.46 pl.7,1). Similar depressions were found by D. Morin within the mines (pers. comm.). But the date of their use is unclear. Any period from prehistoric times to the Byzantine era and beyond can be considered, as is exemplified by an old postcard (Nomicos, 2021, pp.46 pl.7,2; Nomicos, this vol., fig.2).

Grinding

Compared to the edge-mills (Fig. 6), which are known since Neolithic times, the so-called Olynthian mills mark a significant advancement in grinding technology. They belong to the category of lever mills. K. Kourouniotis (1917) was the first to acknowledge their true function. They owe their name to Olynthos, the destruction of which by Philip II. in 348 BC marks a clear *teminus ante quem* for their invention. Indeed, they existed at least since the early 5th century BC (Amouretti, 1986, p.142). Although at Olynthus these mills served exclusively for grinding grain, K. Konophagos was most probably right in assuming that those found in large numbers in every *ergasterion* of the Laurion, served for grinding ore – be it cerussite or galena (Conophagos,

Fig. 8: Quadrangular block of limestone with recess in the Asklepiakon of Simos at Soureza, serving as support for an Olynthian mill (photo: Hans Lohmann).

Fig. 9: Quadrangular block of limestone with recess at Thorikos, serving as support of an Olynthian mill (photo: Hans Lohmann).

Fig. 10: Ari, site no. 32. Pan grinder or kollergang, excavated by K. Tsaïmou (photo: Hans Lohmann).

1980, pp.220, 228–229, figs.10-6/8; Nomicos, 2021, pp.48–49). Their material, a basaltic lava not available in Attica, is harder than both types of ore. But it is also evident that they likewise served for grinding grain for the nutrition of the numerous workers. Most probably the stator of the mill was positioned on blocks with a rectangular recess, in order to prevent the stator from slipping. Such blocks have been found within the Asklepiakon (Fig. 8) as well as at Thorikos (Fig. 9) and elsewhere. Fragments of Olynthian mills from a recently excavated washery at Ari, which were tested by A. Hein (NCSR Demokritos) by means of an XRF-diffractometer, displayed no traces of lead higher than the surrounding ground, which should instead be the case if they had served for grinding ore (Hein, in prep.). These tests should be continued on as many samples as possible, especially since they are non-destructive. However, the large number of fragments of Olynthian mills found in the workshops clearly hints to their use in metallurgical processes, because by grinding grain only not as many would be broken as by grinding the much harder ore.

It is crucial for our understanding of the enrichment process, if the grist was afterwards ground to a powder-like substance by the saddle quern-like mills, or if they served other purposes as indicated above. There is obviously a need here for clarification.

The claim of M.I. Finley and his school that there was no substantial technological progress made during antiquity (Greene, 2000) is disproved by an even greater technological advancement which was achieved during the second half or near the end of the fourth century BC, when the pan grinder or *kollergang* was invented. They were probably driven by animals. K. Konophagos (Conophagos, 1980, pp.248–252) erroneously identified them as ‘helicoidal washeries’. S. Nomicos first argued that they are neither helicoidal nor washeries, but large *kollergangs* or pan-grinders (Nomicos, 2013; 2021, pp.50–57). Her new interpretation has immediately gained much approval.[16] These *kollergangs* are made from large blocks of limestone which is much softer than the basaltic lava of the Olynthian mills.

It can therefore hardly be assumed that ore such as galena was ground on them. Rather, as G. Papadimitriou has suggested and as analyses of grinding residues confirm, one should think of litharge. Litharge is a by-product from the smelting of lead ores. It still contains high percentages of lead and silver. In order to recycle it, it had to be grounded first before it could me smelted again together with a fresh batch of ore. If the grinding of the litharge happened on these kollergangs, which are attached to the ore-concentrating plants, not to the smelting works, an important conclusion can be drawn about the economic relationships between the operators of the processing plants and the smelter sites. Because it would mean that the lessees or operators of the processing plants did not sell the enriched ore to the operator of the smelter, but that he worked against payment.

And this would also explain, why these pan grinders are so numerous in Ari, where no less than five of them have been found: Three have been excavated in an excellent state of preservation by K. Tsaïmou (Fig. 10), two more are testified by fragments: The smelting place at Ari evidently produced large amounts of litharge which had to be recycled in the nearby ore-concentrating plants. Since the surroundings of the other huge smelting place at Pountazeza excavated by K. Konophagos (1974) was already overbuilt by summerhouses in the 1970s, no evidence for a similar accumulation of *kollergangs* is available there. But at least two of these were testified close to the well-known furnace at Bertseko-Megala Pevka (Mussche and Conophagos, 1973, pp.66–71; Nomicos, 2021, p.178 Kat. 50, for the Kollergang ibid. p.175 Kat. 34).

With regard to the discussion on gold above, it should be noted here, that similar *kollergangs* or pan-grinders served in Egypt for grinding gold-bearing minerals.

The mechanisation of fine crushing by means of a *kollergang* would have brought about a substantial increase in productivity, while additionally saving manpower. This fits perfectly well with the economic situation of the second half of the 4th century BC, when the output of the mines decreased and slave labour was less available. Almost at the same time, the *kollergang* for milling olives was most probably invented by the Athenian mathematician Aristaios (Lohmann, 1993, p.215).

Washing

With respect to washing, it must be emphasized, that under pre-industrial conditions there was no other choice for enriching the ore than by gravity separation with water. The total number of ancient washeries in the Laurion is not

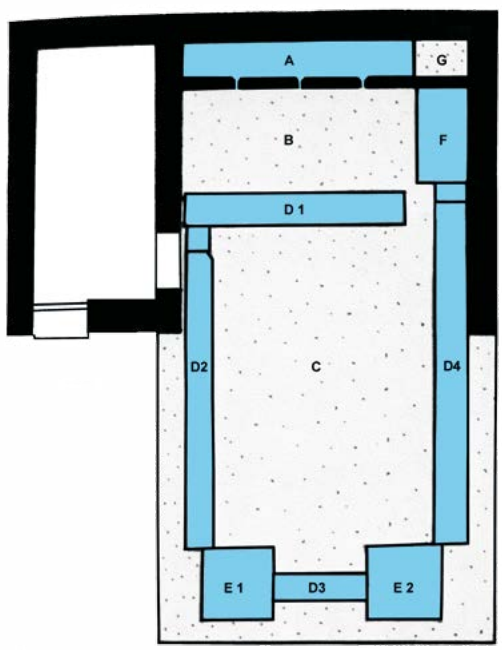

Fig. 11: Canonical type 1 washery at Agrileza, after Travlos (1988, p. 208, fig. 260) (modified by Hans Lohmann).

exactly known, there might have been over 250 (Nomicos, 2021, pp.63 s.), almost as many as shafts. In the mining leases they appear as '*ergasteria*', a general noun for workshops of all kinds.[17] The *ergasteria* or workshops of the Laurion all differ in terms of the arrangement of the rooms, but all have a washery as a central component. These washeries are surprisingly homogenous (Fig. 11). Almost all examples known to date are of a rectangular plan and consist of a tank (A) with four to eight jets in its front, a slightly (8%) inclined area (B) in front of it, and between two and four round or rectangular basins (E1-E4) at the corners connected to each other by water channels (D1-D4). A distinction can be made between type 1 and type 2 washeries, whereas the type 1 washeries form the overwhelming majority. The principle of both types is similar (Nomicos, 2021, pp.63 s.). While the tank and the area in front of it were roofed, the rectangular area (C), surrounded by the channels, which evidently served for drying the enriched ore after washing, was open to the sky. All parts exposed to water are covered with the same hydraulic mortar which was used to seal the cisterns. Because of their homogeneity we call these washeries 'canonical'. They seemingly belong in their majority to the 4th century BC. But what about their forerunners?

Fig. 12: Ari site no. 76, uncanonical washery, probably early 5th century BC (photo: Hans Lohmann).

Fig. 13: Ari site no. 76, uncanonical washery, probably early 5th century BC, detail of channels and tanks (photo: Hans Lohmann).

Fig. 14: Kamareza-Vrissaki, uncanonical washery, most probably unfinished, 6th century BC (photo: Hans Lohmann).

Only very few examples differ from this 'canonical' ground plan by displaying a totally irregular arrangement of tanks and channels (Nomicos, 2021, p.182, no.64, pl.31; p.186, no.77, pls.32, 2. 33). To the already known examples another one excavated in 2016 at Ari (site no.76) might be added (Fig. 12. 13). Of special interest is the example E. Kakavogiannis excavated on the edge of the gorge of Vrissaki below Kamareza, because he dated it back to the 6th century BC (Kakavogiannis, 2001, p.374, fig.8; Nomicos, 2021, p.182, no.64, pl.31; Fig. 14). Unfortunately, he passed away, before he was able to fully publish this most important finding. Tanks and channels have been cut into the extremely hard cemented alluvial fan, but are not coated with hydraulic mortar, even though the ground is permeable to water. Moreover, no remains of any walls have been found. The likewise irregular washery found at Ari (site no.76) is cut into the native bedrock, but channels and tanks display clear remains of mortar, although the washery has been seriously damaged by the activities of the CMFL. The bottom of the tank (Fig. 13 right below) was carved out by treasure hunters, most probably in the Byzantine period. The pottery found in connection with this washery points to a date in the 5th century BC. Another pre-canonical ore-washery was discovered underneath the fourth-century Hilltop Tower at Soureza (Young, 1956a, 129 – 131; Goette, 2000, 86; Lohmann, 2005, 118). The basins and tanks are likewise coated with mortar. The installation at Kamareza-Vrissaki, therefore, seems to be unfinished. Another explanation was kindly brought to my attention by F. Hulek (pers. comm.). He holds that regarding the finds of fine ware of the Archaic period it might be a totally plundered and devastated grave precinct of the time. Be that as it may: evidently an experimental phase preceded the invention of the 'canonical' washeries.

Four different models as to how the 'canonical' washeries were run have been discussed. It seems that already in 1881 Ph. Negris has given the correct answer (Negris, 1881). His model of the functioning of the rectangular washeries is based on Agricola. In his work "De re metallica libri XII" of 1556 he describes seven different types of washeries. The so-called "short herd" equals the 'canonical' rectangular washeries of Laurion in almost every detail (Fig. 15). The tank has several adjustable jets, which can be regulated according to the amount of water needed. In front of them there is a relatively short wooden box, in which the ore is enriched by stirring it by means of a brush. In front of the box runs a channel, gathering the sandy debris. In the rectangular washeries of Laurion such a wooden box was not required, since the ore could be swayed on the slightly inclined area in front of the tank.

As H. Morin-Hamon (this vol.) has convincingly shown in her paper this model was generally accepted until the publication of K. Konophagos (Conophagos, 1980, pp.224, 241 – 247, who suggested sluices in front of the jets instead). Many arguments advocate against this, archaeological ones as well as technical (Lohmann, 2005, pp.114, 130; Nomicos, 2021, pp.64 – 66). Empirically the best results are obtained when the sluices are approximately 2m long (Nomicos, 2021, pl.24,1.3). Should we really assume that over decades the skilled ancient workers never achieved this by experiment? Should we really assume that in all washeries the slightly inclined surface in front of the nozzles is incorrectly oriented because they are always wider than they are deep, allowing for a maximum length of the sluices of 1,10 m? Why, in a period, which displays even in modest buildings or technical installations the highest standards of stonemasonry, was an abutment for the sluices never hewn into the retaining wall with the nozzles? Why, then, were never any sluices found made of stone? Why among dozens of washeries there never occurred any stone support for the sluices, but we are forced to postulate wooden stands instead, although in the 4th century BC the Laurion was already largely deforested and wood as fuel for the furnaces had to be imported?

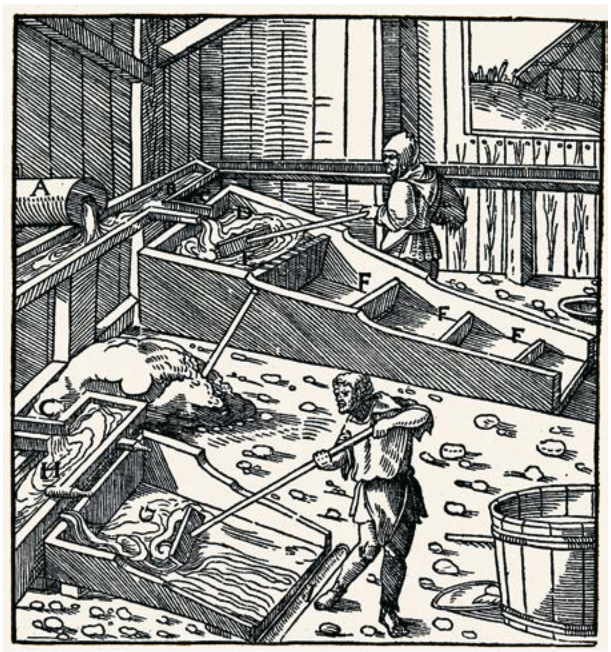

Fig. 15: Georg Agricola (1556, Reprint 1977, p. 261 fig. 11) (modified by Hans Lohmann).

Ockham's razor or law of parsimony perfectly applies to this finding: This problem-solving principle postulates that "entities should not be multiplied without necessity" – or the simplest explanation is usually the right one (Schaffer, 2015).

The model of C. Domergue (1998; 2008, pp.66 – 67), who holds that the ore was agitated within the tank behind the nozzles, does not stand up to any critical examination. When excavating a washery at Ari in 2016 (Lohmann and Kapetanios, in prep.) it became totally obvious, that the hydraulic mortar within the tank, especially its floor, was in excellent condition, just as if it had been made yesterday, while the mortar on the area in front of the nozzles was much worn and displayed clear signs of wear, as we should expect, if the ore is moved in front of the nozzles by means of brushes or wooden pushers.

Likewise panning by means of *lekanai* as prosposed by E. Kakavogiannis (2005) can be excluded. As experiments with modern replicas by K. Tsaïmou have shown, these clay bowls are far to brittle for the heavy ore and far too deep (Tsaïmou and Fragkiskos, 2001; Nomicos, 2021, p.66). For panning, as the name indicates, flat metal pans are required. The considerable number of fragments of lekanai found in every workshop can easily be explained by the often large number of workers, the one-sidedness of nutrition (mainly barley groats with olive oil) and the fragility of clay vessels in general, which are much less durable than modern porcelain, fired at 1400° C.

While the use of sluices in the 'canonical' washeries can safely be excluded and should no longer be discussed, on the basis of the data available it seems uncertain whether the separation of different grain sizes of ore in the channels D1 to D4 and the basins or tanks E1 to E4 respectively was intended and what it might be good for. Anyway, the main purpose of the basins and the connecting channels was to purify and to recycle the scarce water.

Large quantities of water were required to wash the ore. Although according to H. Wotruba, a worldwide renowned expert in beneficiation at the RWTH Aachen, seawater might do (pers. comm.), no ancient washeries are ever found at the coast. In the notorious semiarid climate of Attica with a precipitation of 377 mm per year only, the enrichment of the ore could only be continued during the dry season if enough rainwater was stored in large tanks during the more humid months, i.e. mainly in the winter from December to March. Nowadays – but this situation might slightly differ from antiquity – there is usually no rainfall between mid-April to mid-October. No wonder, therefore, that large to huge cisterns were found all over the Laurion.[18] Every cistern indicates more or less an *ergasterion*, since only very few metallurgical sites are known that had springs, as at Vrissaki near Kamareza or at Palaiokamareza, or groundwater wells as at Ari and at Demoliaki (Nomicos, 2021, p.62). A waterproof mortar was required to seal the cisterns as well as the tanks, channels and basins of the washeries. But when and where was it invented? The enormous boom of mining in the 5th century BC Laurion would not be possible without the construction of the numerous cisterns. As F. Schön has shown in his PhD (Schön, in prep.) there are no cisterns with hydraulic mortar in the Western Mediterranean before the 5th century BC. But what about the Near East?

Thanks to new evidence from Tell el-Burak in Lebanon it has become evident that the Phoenicians, already in the 7th century BC, were able to produce a water-resistant plaster or mortar which closely resembles the mortars of the cisterns at Laurion (Orsingher, et al., 2020, pp.1233–1241) – especially by adding grog (crushed pottery or tiles).[19] Maybe in the Near East the technological achievement of water-resistant mortars goes back to the Bronze Age (Yadin, et al., 1958, pp.118–140, pls. CLXXXII. CLXXXIV). At Hazor in the period LB II (Late Bronze Age II) cisterns nos. 9024 and 9027 have been secondarily used as graves and the burial within cistern no.9027 contained two imported Mycenaean LH II B-pyxides as grave goods. The cisterns, therefore, are undeniably older. The inner lining of the cisterns is described by the excavators as 'plaster'. But to my knowledge no archaeometric analyses were made. Whether and to what extent this 'plaster' was water-resistant and if it contained grog is, therefore, totally unclear. Be that as it may: The mortar used in Tell el-Burak in the 7th century BC fulfils all requirements for water resistance. Since so far, no securely dated cistern of the 6th century BC lined with water-resistant mortar is known in Greece, it remains an open question when this technology was brought to Greece and where it was first applied there.

The cisterns each had sediment traps and a sophisticated rainwater catchment system, remains of which are only seldom preserved, as for instance in the Soureza Valley where a channel served a whole chain of cisterns sunk into the valley bottom (Ardaillon, 1897, pp.66s., pl.3; Nomicos, 2021, pl.21, 23,2). Such catchment systems were not limited to the mining area. They can, for instance, also be found in a purely agrarian environment like for instance in the Mikro- and Megalo Kriftis Valleys in the Megaris (Van de Maele, 1984), which are totally void of springs.

A most interesting phenomenon about the cisterns in the Laurion, is that despite its hilly nature, the cisterns are regularly sunk into the ground at the same level as the washeries. Only in very few instances are they built higher up the hillside so the water could flow by gravity to the washery, while normally their tanks had to be filled by manpower. The operators or *epistatai* of the washeries apparently feared that otherwise the slaves would simply open the tap for convenience and waste the precious water.

Evaporation is another problem connected to the cisterns because of their wide openings and the climatic conditions in Attica. Obviously, roofs were indispensable in order to avoid too much evaporation, which would consequently have lead to an untimely end of the beneficiation process. Burnt-clay roof tiles are heavy and would, therefore, require strong wooden supports. So far, only very few cisterns with a central support pillar are known (Nomicos, 2021, p.61, pl.22), but to my knowledge there have never been found any large amounts of roof tiles within any of the numerous cisterns of Laurion. Many of these are circular and would, therefore, require conical roofs, but the manufacturing of these as a clay roof is extremely demanding. Neither these nor fabric sails are an option for covering, considering the frequent strong storms in Attica. The best thing to think about might, therefore, be thatch roofs (Kakavogiannis, 2005, p.226; Nomicos, 2021, p.61). These may often have been used to roof simple rural buildings and properties, workshops, stables and the like, because too few roof tiles were found during excavations of such buildings. This also applies to the *ergasteria* themselves.

Fig. 16: Megala Pefka in the upper valley of Legrena. Washery, excavated in the 19th century (photo: D-DAI-ATH-Attika-0062. With kind permission of the German Archaeological Institute at Athens).

Smelting

As far as smelting is concerned, I cannot go into any detail here, because the problems involved are far too many. I wish, instead, to touch upon some selected points only. First, the number of furnaces. I am convinced that the number of furnaces existing during the Classical and perhaps the Hellenistic period in the Laurion might be rather precisely calculated on the basis of the slag heaps thoroughly mapped by A. Kordellas and M. Vouyoukas (Conophagos, 1980, pp.134 – 135, figs.7-3. 7-4). Before the ancient slags were reworked at Lavrio during the 19th and 20th century, nobody took the pain to carry slags in large quantities from one point to another. It is, therefore, most likely that the number of slag heaps coincides more or less precisely with the number of furnaces once existing. Although both maps are much distorted and not to scale, they consistently display two slag heaps at Ari-Charvalo, which fits the results of the survey there (see below). A third heap on Manoutsou, shown on the map of Vouyoukas, has completely vanished as well as the furnace, which is indicated by the heap.

The remains of the ancient furnaces became particularly victims of the raging of modern mining companies. So far only at four sites have the remains of furnaces been excavated. All of them had already been looted. The size of the

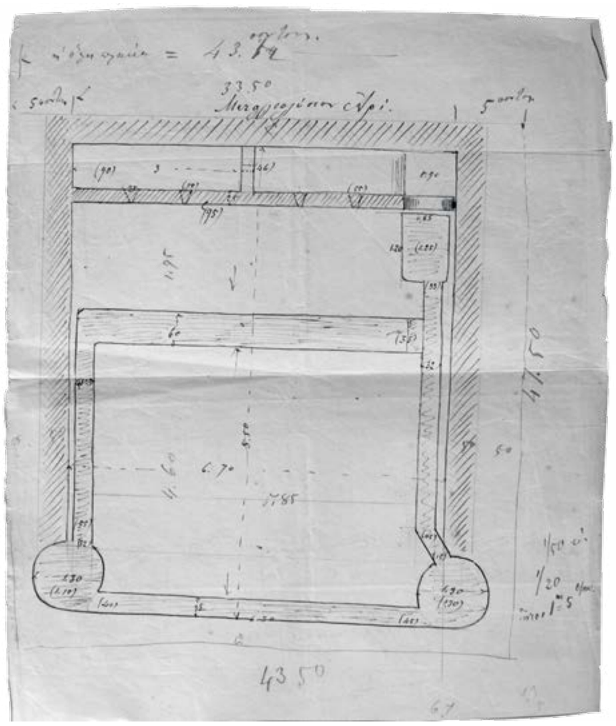

Fig. 17: Rough sketch of an otherwise unknown washery at Ari by A. Kordella (?) in the copy of Cordella (1869), owned by O. Kakavogianni.

smelting works ranges from small ones such as Asimaki or Passa Limani (Nomicos, 2021, pp.178 s., nos.49, 51), to medium-sized ones such as Berseko and Ari (Nomicos, 2021, p.169 s., no.18; p.178, no.50), to very large ones such as Pounta Zeza (Nomicos, 2021, p.179, no.54, pl.27). There might have been another one at Megala Pefka in the upper valley of Legrena, where in the 19th century an excavation took place, which is nowhere documented except for an old photo in the archive of the German Archaeological Institute at Athens (Fig. 16).[20] The most southwestern furnace of Laurion at the bay of Charaka is indicated by a huge amount of slags, sherds of both Classical and Hellenistic age and several Hellenistic amphora stamps (Lohmann, 1993, pp.243 – 246, 248, 396 s., pl.131, 1. 2). This testifies to activities there when during the first half of the 2nd century BC the New Style tetradrachms were emitted.

A survey at Ari

In 2014 at Ari North of Anavysso, ancient Anaphlystos, a survey was started as a *synergasia* or joint venture between the Ephorate of East Attica, represented by Dr. Eleni Andrikou, the German Archaeological Institute at Athens and the Ruhr-University at Bochum. Since a full report on the survey will be published together with A. Kapetanios in a forthcoming volume, devoted exclusively to Ari, I wish to report here only shortly on the topic, thereby highlighting only some of the peculiarities observed there.[21]

Ari is located in the north of the littoral embayment of Anavyssos and forms the westernmost ore deposit of the whole Laurion. It has been chosen for a survey because there, within a limited area comprising no more than 5 to 6 square kilometres, the whole workflow from the mine to the furnace can be studied, especially thanks to the excavations there by K. Tsaïmou between 2005 and 2008 (Tsaïmou, 2005; 2006; 2007; 2010). The enormous density of mining galleries, shafts and workshops at Ari becomes already obvious from the map of F. von Bernhardi, who mapped the region during the winter 1883/84, and was fully confirmed in the course of the survey (Fig. 1). The project at Ari might, therefore, contribute to solving at least some of the questions still pending, although there has been much devastation by the mining companies during the 19th and early 20th century. Another important peculiarity of Ari is its proximity to the important prehistoric site on Mokriza hill.

In antiquity the small mining district of Ari belonged partly to the large ancient deme of Anaphlystos, partly to the deme of Phrearrhioi. Anaphlystos was represented in the *boule* of Athens by no less than ten councillors. But only five to six mining leases out of 289 are testified for Anaphlystos, even less for Phrearrhioi, sending nine councillors to the *boule*. It is evident, therefore, that mining played only a minor role there, while agriculture was predominant. Despite their Greek appearance, the names of both demes derive from the pre-Greek language substrate. “Phrearrhioi”, for instance, has nothing to do with the Greek φρέαρ “well”. The name of Arí (Ἀρί, stressing the last syllable) derives by iotacism from the locative of Phrearrhioi φρεαρροῖ, as I have argued elsewhere (Lohmann, 1993, p.74 with n.568). Since then, this has been confirmed by the best connoisseur of Arvanitic toponymy of Attica T. Jochalas (pers. comm.). All ancient maps of the 19th century as well as a sketch by A. Kordella (Fig. 17), a copy of which I owe to the kindness of O. Kakavogianni, have Ἀρί, not Ary (Ἀρύ).

The torrent Ari, marked in blue in the map Fig. 1, once formed the borderline between the two demes of Phrearrhioi and Anaphlystos. In 1979 students of the American School found a horos-inscription within the rhevma Ari, correctly identified a marker of the border between Anaphlystos and Phrearrhioi by J.S. Traill (Traill, 1986, pp.117. 146, pl.16,4). And in 1970 E. Vanderpool reported finding a cult calendar of Phrearrhioi at km 48 of the road from Anavysso to Kalyvia (Vanderpool, 1970). Although the inscription was not found *in situ*, it was evidently not much dislocated.

Have the rich ore deposits at Charvalo already been mined in the EBA or even earlier? Are among the hundreds of outcrops some of prehistoric age? As already mentioned, there are fragments of crucibles and slags on nearby Mokriza hill. But at Mt. Charvalo prehistoric pottery is almost totally lacking. A total of four fragments of FN-pottery does not make up for intensive prehistoric activities there. Also, the typical grooved mallets are lacking throughout, while in the 1980s a hundred of them were heaped up in front of Mine 3 at Thorikos. They leave very typical tool marks. Whether any of these may be found within the dozens of ancient and modern underground-workings at Ari, is not yet clear.

With the Puit Skouzès and the Puit Damianos two shafts, both originally 80 meters deep, now filled with waste, are still prominent and had in modern times been improved for hoisting by means of a steam or diesel engine (Conophagos, 1980, map). In antiquity, Puit Damianos gave access to one of the largest mines of the whole Laurion, mine Ari 3, which was visited by D. Morin. He will present the results of his research in a forthcoming volume of the present series.

Without going into much detail, it should be emphasized that no less than 17 workshops have been identified on both sides of the rhevma Marisas / rhevma Ari. Some of them are already destroyed and are indicated by a large cistern on the surface only. O. Kakavogianni kindly send me a rough sketch of a washery at Ari she found in her personal copy of the publication of A. Kordella (Fig. 17). It does not display any of the washeries excavated there by K. Tsaïmou and has, therefore, to be considered as destroyed.

Some of the workshops at Ari evidently did not have a cistern. Due to a special geological phenomenon, groundwater wells were used as in Demoliaki. Others may have drawn water from the rhevma, which was retained by a dam. It cannot be ruled out, that in the Classical period at least some streams and rivers like for instance the Ilissos were perennial (Lohmann, 1993, pp.20 – 21). With the discovery of four ancient shafts in the northwestern part of the Manoutsou by M. Vaxevanopoulos (this vol.) it has become evident that the workshops on the east

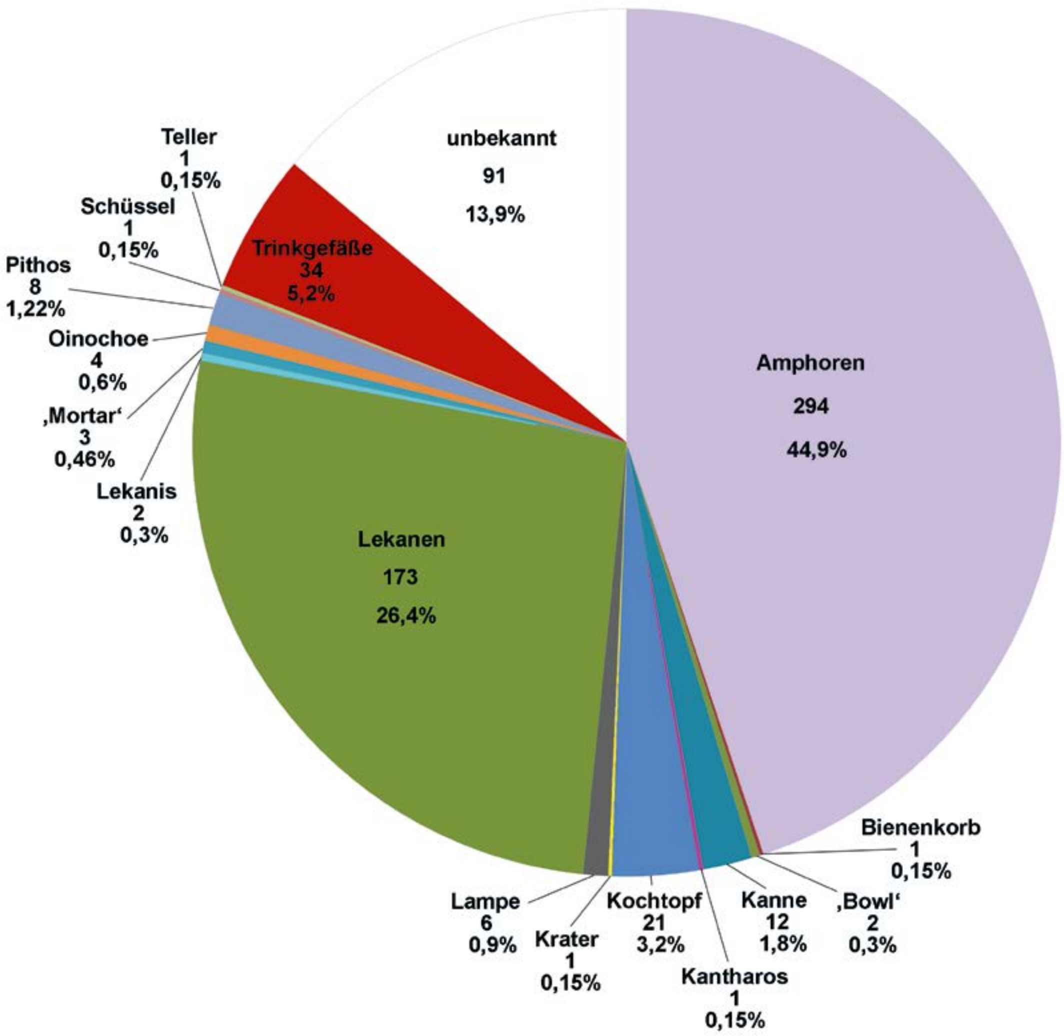

Fig. 18: Pie chart of the shapes of the ancient pottery and their respective percentage found in the survey at Ari. Prepared by Marta Korczyńska.

bank of the rhevma Marisas / rhevma Ari processed ore from these, belonging to Phrearrhioi, while those on the East bank processed ore from Mt. Charvalo.

Besides the local concentration of pan-grinders or *kollergangs* at Ari already mentioned, another important discovery was a stone which looks exactly like the anvil stones, hundreds of which have been found in the Roman mines at Tres Minas in Northern Portugal (Nomicos, 2021, pp.57 – 58, pl.18,1). We should not be too much surprised if the invention of a mechanical driven stamp mill has already been made much earlier in Greece.

The majority of the pottery from Ari dates to the Classical and Early Hellenistic period. It covers the same time span from the early 5th to the early 3rd century BC as the pottery from a Classical workshop at Ari excavated by K. Tsaïmou between 2005 and 2008 (Tsaïmou and Nomicos, in prep.).

Moreover, workshops can clearly be distinguished from farmsteads and other kind of settlements by the percentages of the shapes of vessels. The *ergasteria* of Ari show a very limited range of shapes, dominated by *amphoras* and *lekanai* (Fig. 18). Cooking vessels and Black Glaze drinking vessels are extremely rare, and there are no loom weights or beehives. This does not testify to what we might call a balanced nutrition for the many slaves working in the Laurion. But it might help us in the future, even in cases of much destroyed sites, where only a scatter of pottery can be found on the surface, to distinguish between rural settlements and workshops.

Conclusions

What conclusions can be drawn on the basis of this short overview?

First of all most urgently needed is a record of all surface remains in the Laurion, a complete atlas of the mining area, at least at the scale 1 : 10,000, especially with regard to the entry of the mining area into the list of UNESCO World Cultural Heritage. Together with this inventory, detailed surveys of at least some areas of the Laurion are needed. An initiative should be taken to publish former excavations which so far are only known through preliminary reports or short find notes in Greek periodicals like the Archaiologikon Deltion.

The open questions are numerous and not only concern the whole workflow from the mine to the furnace, starting from the question which tools were used and when sinking of shafts was introduced in the Laurion. But also, the question what has been mined, when and by what means. As has been exemplified regarding gold and pigments, the extant ancient sources are sketchy. Other open questions concern the beneficiation and enrichment of the ore, the precise date of the invention of the pan-grinders or *koller-gangs*, as well as the development from the 'non-canonical' washeries to the 'canonical' and their respective functioning.

Hopefully the close cooperation between geologists, archaeometrists and archaeologists practiced successfully for many decades, will be continued in the future and will help to solve at least some of the problems addressed here.

Acknowledgements

First, I wish to thank Dr. Eleni Andrikou and Prof. Andreas Kapetanios who were my partners in the Ari-Project and supported it more than can be expressed here in a few words. I also wish to thank the members of my team, Frank Hulek, Sophia Nomicos, Hans-Peter Klossek, Hans Marg (†), Achim Dombert and Dietmar Gansera for their constant help. The last-named provided the fabulous aerial photos. Special thanks go to Professor Adonis Fotiadis for providing a new and more detailed geological map of Ari and to Denis Morin and his team for studying at least some of the shafts and galleries within the survey area. Andreas Hauptmann as well as Norbert Hanel, Gabriele Körlin, Sophia Nomicos, Panagiotis Voudouris and F. Schön provided me with helpful information and some of the articles quoted here. Special thanks go to Sophia Nomicos for her constant help in all questions discussed here. Last but not least I wish to thank Theresa Stewart and John Bintliff for improving my English.

Notes

1 Curtius and Kaupert, 1891 – 1900; reprint Korres, 2008.

2 For now, see the overview in Conophagos (1980, pp.35 – 54) and Manthos and Dermatis (2017). For short accounts see also Kalcyk (1982, pp.214 – 219), Rieck (2012, pp.12 – 24) and <https://el.wikipedia.org/wiki/Λαύριο>.

3 His handwritten diaries and notes are, unfortunately, privately owned and currently not accessible.

4 Lauffer, 1979, p.22: "mehr als 2000 solcher Schächte und Stollen sind in einem Gebiet von 2000 ha nachgewiesen" (without testimony); Kalcyk, 1982, p.161; Goette, 2000, p.97. Critically Lohmann (1993, p.80 with n. 617).

5 For Botsari see Ardaillon (1897, pp.66 s., pl. 3), Kakavogiannis (1989a; 1989b), Lohmann (1993, pp.107 – 108); Goette (2000, p.12) and Nomicos (2021, p.176, no.36; p. 193, nos. 110. 111, pl. 21).

6 Pers. communication. geogr. coor. (WGS84): 37° 46' 28,0" N; 24° 01' 25,3" H 265 mamsl. – Fiedler, 1840, p.63; Curtius and Kaupert 1891 – 1900, sheet 16 (Laurion): "Villia, H 285, H.R.". The inscription is cut into a flat, triangular rock slab near a dirt road about 50 m northeast of an abandoned house. Length: 0.445 m. Its position is not on Mouzaki as presumably indicated in Lohmann (1993, p.109, fig.12) but a little bit further to the northeast (see Fig. 4).

7 For a list see Rieck (2012, pp.177 – 180), for brilliant photos see Voudouris, et al. (2019).

8 The name derives from Albanian mókrëze, diminutive of mókërë, hand mill (Lohmann, 1993, p.303). – Early Bronze Age pottery but no architectural remains were discovered during road construction work at the southern foot of the Mokriza hill (Parras, 2010, p.143, fig.4). This confirms Lohmann (1993, p.505, pl.72,1. 2 [AN 25]).

9 For the use of zinc in antiquity see Craddock (1990, pp.1 – 6).

10 So far, only preliminary reports on this shipwreck have been published (Hanel and Bode, 2016, p.168; Caponetti, et al. 2017a; 2017b; Hauptmann, 2020, pp.402). The date seems far from certain: The ship sank while mooring, i.e. close to the harbour of Gela. Pottery of the 6th century BC is said to be found "nearby", whatever this means. During geomorphological drillings in the harbour of Miletus enormous amounts of pottery of all periods after ca. 50 AD have been found. At this date, the harbour basin had evidently been dredged, but afterwards served as a garbage dump again.

11 Boeckh 1842, 627 n. 37; Hesych. s. v. Λαύρεια; Schol. Arist. Eq. v.1091; Souidas s. v. γλαὺ ἵπταται; Harpokr. and Suidas s. v. χρυσοχοεῖον.

12 Rieck, 2012, p.43. He claims that the mining leases explicitly define gold finds as Athenian state property. But such a contract term is nowhere found in the leases. Furthermore, he quotes from a non-existing inscription that a lessee named Hipponikos delivered two talents of gold in addition to the rent. His remarks on several golden statues of Athena in the Parthenon are totally confused, too. – I thank P. Voudouris for providing me a copy of the dissertation of B. Rieck.

13 Paus. 1.25.7 and Plut., Isis et Osiris 71 report that the tyrant Lachares in 296 BC stole the golden robe of Athena. That he minted coins from it is a mere assumption based on a gold coin of Lachares in the collection of the University of Glasgow: <http://collections.gla.ac.uk/#/details/enarratives/311>. King George III of England (not King Otto III of Greece as Rieck, 2012, p.43 holds) presented it to his personal physician William Hunter, who was a famous numismatist. The golden coin published by Rieck (2019, fig.7), had already been recognized as modern forgery by A. Boeckh .– I wish to thank here Frank Hulek once more for his invaluable help.

14 The remarks of Vryonis (1962, pp.1 – 17) on this point are purely hypothetical. On him relies Lilie (1976, p.260 with n. 224).

15 For the terminology see Weisgerber (2005, p.40). Very helpful is also the multi-lingual dictionary of Venator (1905).

16 Papadimitriou, 2016; see also <https://ntua.academia.edu/georgepapadimitriou> (Presentation 8 November 2015) [accessed January 2017].

17 For ample discussion of the term see Hopper (1953, pp.203 – 207).

18 A dissertation by K. van Liefferinge dealing with the cisterns of Laurion has, unfortunately, not been published. So far see Nomicos (2021, pp.59 – 63).

19 The authors are clearly wrong in stating (Orsingher, et al., 2020, p.1240) that "The tradition of mixing crushed ceramic (or tiles) with lime to produce hydraulic plasters … is rarely attested prior to the third century BC", because almost all Classical cisterns and washeries in the Lavriotike are using exactly that kind of mortar.

20 The site has been mentioned as 'fortified deme' by Löper (1892, pp.381 – 382), who does not mention either its name "Megala Pefka" nor the excavation, the photo of which shown

in Fig. 16 has been taken there according to the data in the archive of the German Archaeological Institute at Athens (D-DAI-ATH-Attika 0062). For Megala Pefka see Nomicos (2021, p.173, no.26 [with bibl.]).

21 For a first preliminary report see Lohmann (2015).

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Frank Hulek

The trial trenches at Ari/Charvalo in 2016 and the excavation by E. and O. Kakavogianni at Frankolimano Thorikou 1969/70: Preliminary results

ABSTRACT: *As part of the research project of the University of Bochum at Ari (Lavreotiki/Attica), an ancient ore-washery was excavated there in 2016. According to the findings, it was only superficially disturbed by later activities and is preliminarily dated to the 4th and early 3rd century BC. The findings settle the long-debated question of how the ore washeries worked: They were so-called plain tables or buddles, on which the ore was separated by density on the washing surfaces, using a water film, and without sluices.*

Another project started in 2017 and concerned an old excavation at Frankolimano Thorikou near Lavrio. The archaeological finds from a battery of melting furnaces and other ancient buildings are currently under evaluation. For the time being, they can be dated to the advanced Hellenistic period. Archaeometallurgical investigations are under way in close cooperation with specialists at the NCSR Demokritos.

KEYWORDS: ARCHAEOMETRY, ARCHAEOMETALLURGY, ARI, LAURION, ORE WASHERIES, SMELTING FURNACES

Introduction

In 2014 at Ari to the North of Anavyssos, a survey was started as a joint venture between the Ephorate of Antiquities of East Attica, represented by Dr. E. Andrikou and Dr. A. Kapetanios, the Athens Department of the German Archaeological Institute and the Ruhr University Bochum (Germany), represented by H. Lohmann. For a short preliminary report on the survey see H. Lohmann (2020; this vol.). A full report on the survey will be published in a forthcoming volume devoted exclusively to Ari. Here, I wish to report shortly on a trial excavation in one of the numerous ancient ore washeries at Ari and on the evaluation of material from an old (1969/1970) excavation by O. Apostolopoulou-Kakavogianni and E. Kakavogiannis at Frankolimano near Thorikos.

The trial trenches at Ari 63

The excavation took place in September 2016 under the license of the *synergasia* mentioned above. Prof. A. Kapetanios, representative of the Ephorate and field director, and Prof. H. Lohmann from the Ruhr University Bochum directed the excavation. The first target was a facility that had been cleaned and surveyed the year before and was catalogued as “Ari 63A”. Its rectangular ground plan (Fig. 1) shares similarities with other metallurgical workshops known from the Laurion region which were analysed by J. E. Jones and illustrated by examples from the Agrileza valley and other parts of the Laurion region (Jones, 2007). Rooms of different sizes are arranged around a central courtyard. The excavation site (Lohmann, 2016; 2020, pp.53 – 54, figs.12 – 13; Hulek, 2020) lies on the north-western spur of Mt. Charvalo, on a natural graded terrace at about 120 m above sea-level (Fig. 2). The terrain is rather flat there and thus was convenient for building purposes. Water for an ore washery came from the neighbouring steep slopes and was stored in a cistern, as elsewhere in the Laurion region (cf. Kakavogiannis, 2005, pp.225 – 229; 2013; Van Liefferinge, et al., 2014). A second cistern was left unfinished, but likewise shows the large demand for water.

The amount of debris and the well-built walls suggest that at least part of the complex had an upper, second storey. There are indications, e.g. building joints, that the rooms in the southwest were added later. The building was presumed to be a workshop for ore enrichment, a so-called Ergasterion, due to the ground plan, the two large rectangular cisterns, and the remains of waterproof mortar in one of the rooms (Lohmann, 2020, pp.53 – 54).

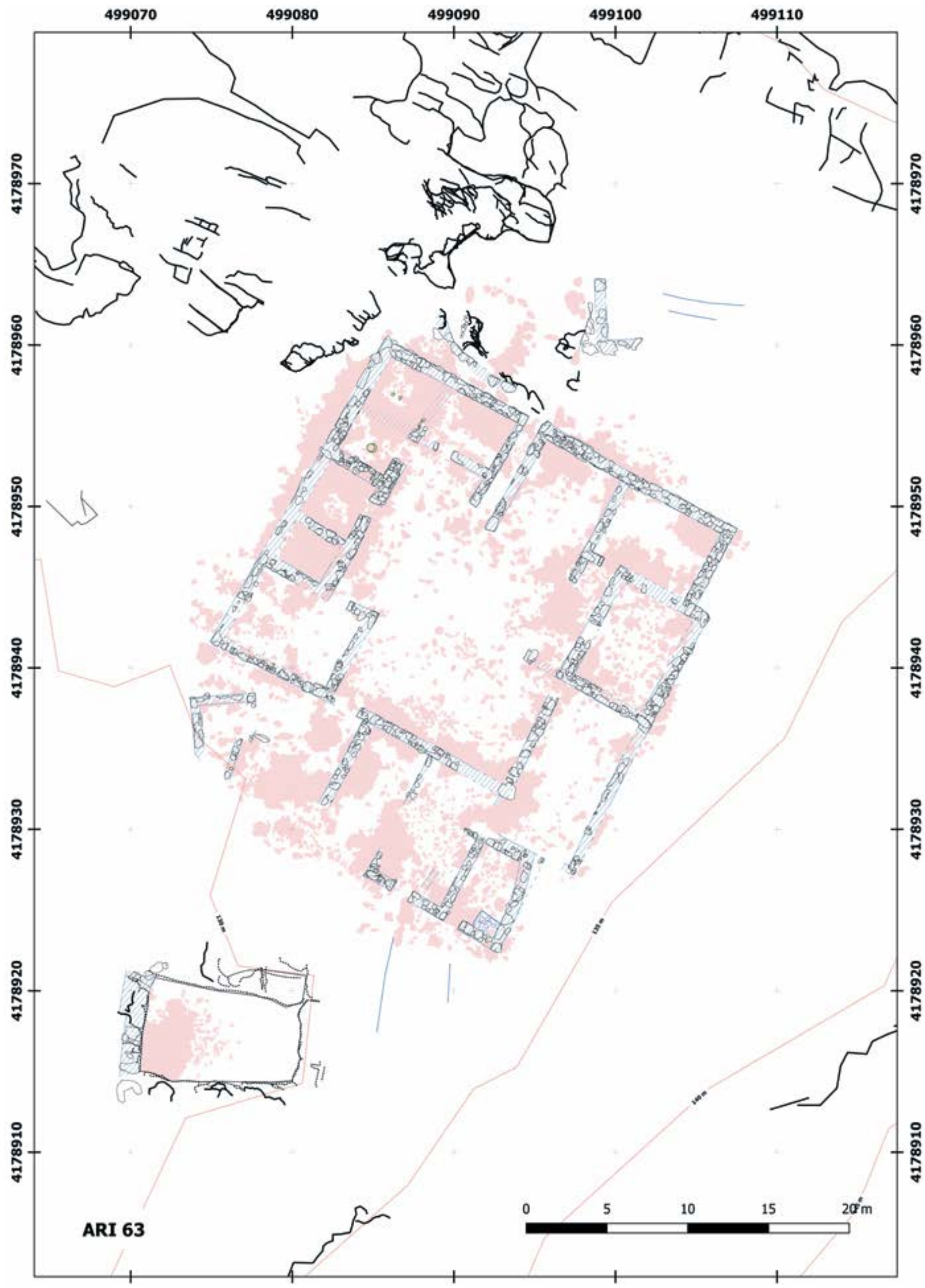

Fig. 1: Workshop Ari 63A, ground plan (Ari-Project, Bochum, drawing: H.-P. Klossek). The rights of the monuments depicted belong to the Greek State and the Ministry of Culture and Sports (Law 3028/2002).

In the room where the ore washery was assumed to have been located, the first trial trench was opened. The other trenches were located in the two neighbouring rooms in the east and the corridor in the west (Fig. 3). During excavation, the complex turned out to be only superficially affected by later activities. The stratigraphic layers showed the expected sequence of top soil, collapse, then the stones of the walls and at the bottom the clay of the mud bricks. Only two areas in the centre of the washery and in its eastern corner had been disturbed. However, this disturbance did not take place in modern times, but according to the ceramics found could be connected to treasure hunters in the early Middle Ages.

As the trench was planned as a trial excavation, we excavated only the south-eastern half of the washery. Its ground-plan corresponds to the well-known type of rectangular ore washeries of the Laurion region (Fig. 4; Negris, 1881; Conophagos, 1980, pp.224 – 247; Domergue, 1998; Rehren, et al., 2002; Kakavogiannis, 2005, pp.229 – 253; Nomicos, 2021, pp.63 – 68). In front of the water tank was the washing area, followed by a channel, which in this type of washery is generally linked to a perpendicular channel. This can therefore be presumed in the unexcavated half of the washery. Generally, the latter runs into a basin linked to a second basin, connected by the third water channel. The second basin is also to be found in the excavated

Fig. 2: Aerial View of ancient workshops Ari 63A (centre right) and Ari 64 (left) on the Charvalo hill at Ari (photograph: D. Gansera, No. DG15_P1070840). The rights of the monuments depicted belong to the Greek State and the Ministry of Culture and Sports (Law 3028/2002).

Fig. 3: Workshop Ari 63A, Orthophoto of excavation trenches in the washery (centre), adjacent rooms 2 (right) and 3 (right down) and the corridor (up left) (Ari-Project, Bochum, processing by M. Korczyńska). The rights of the monuments depicted belong to the Greek State and the Ministry of Culture and Sports (Law 3028/2002).

half of the washery. After another channel, the third and last basin is reached. From there, water could be taken and reused again in the water tank. The channels thus surround a rectangular area, the drying surface.

The washery was about 10 m long and 5 m wide. It is comparatively well preserved; as mentioned before, the late Antique/early Byzantine activities destroyed part of the surface of the drying area and of the wall separating the washery from room 2 on the eastern side. Also, the front wall of the water tank is missing. No observations of reconstruction or repairs of the washery were made. The surfaces, channels and basins were all completely covered by waterproof mortar, which is common in hydraulic installations in the Laurion region. The water channels had been dug into the natural soil, while the slightly sloping surfaces were underlain with medium sized stones in the foundations and small sized stones in the upper layers, mixed with clayey soil.

In ancient Laurion, ore was mined with hammer and pick, coming out of the workings about fist-sized and smaller

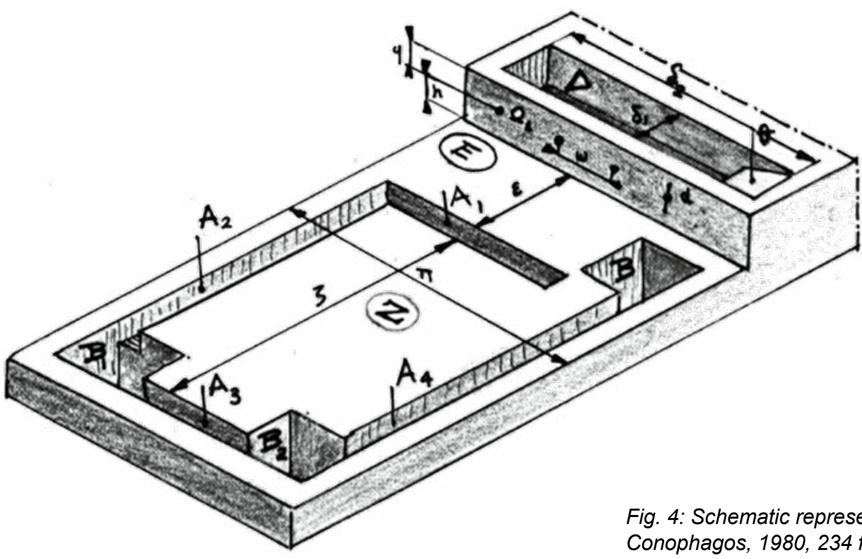

Fig. 4: Schematic representation of an orthogonal washery (after Conophagos, 1980, 234 fig.10-16).

(Conophagos, 1980, pp.166 – 212; Morin, et al., 2013, p.20; Lohmann, this vol.). A coarse sorting by grade took place already underground. Above ground, the ore had to be crushed and enriched. It was first spalled, implying smashing with an iron hammer or stone tools. Rock holes formed by this process were discovered for the first time in the Laurion above ground during the survey at Ari (Lohmann, 2020, p.48, fig.5; this vol.; Nomicos, 2021, p.46, pl.7,1; cf. underground in the mines at Velatouri/Thorikos: Morin and Delpech, 2018, p.44).

In a second step, the spalled ore was ground. The resulting ore grains measured about 1 mm and resem-

Fig. 5: Workshop Ari 63A, Room 3. Grinding table with hollowed-out surface (photograph: H. Lohmann, No. N16_6707). The rights of the monuments depicted belong to the Greek State and the Ministry of Culture and Sports (Law 3028/2002).

bled coarse sand. It can be ascertained that a 1 m wide limestone block with a hollowed-out and smooth surface found in room 3 served to grind the ore (cf. Nomicos, 2021, pp.47 – 48). It is also possible that so-called Olynthian mills, which are ubiquitous in the ancient workshops in the Laurion mining region, were used for this activity, as K. Konophagos has proposed (Conophagos, 1980, pp.220 – 223; Lynch and Rowland, 2005, p.3; Van Liefferinge, et al., 2013, pp.68, 70, 73 fig.18; Nomicos, 2021, pp.48 – 49). Fragments of this type of millstones were found at the Ergasterion Ari 63A and analysed by Dr. A. Hein of the NCSR Demokritos by means of a portable XRF analyser, but their surface showed a lead concentration of 0.7%, equivalent to the lead pollution of the soil (Lohmann, 2020, p.48; this vol.). Thus, the final proof for the use of so-called Olynthian mills for grinding not only cereals but also ore is still missing.

Room 3 was built next to the ore washery on three different levels formed by the terraces of the natural rock. The limestone block mentioned above stood in a corner of the room on the middle terrace, built on a small platform of smaller stones (Fig. 5). A door next to it linked room 3 and room 2. A storage installation in room 3 constructed from fieldstones was found empty, so we do not know its exact use. In room 2, which lies between this room and the washery (Fig. 3), there were no tools or technical installations found during the excavation. However, the floor was lined with the same waterproof mortar that was used in the ore washery. It could be interpreted as a bathroom for the workers or a storage room for the ore powder.

The ore washing process

In many ores, the metals and their compounds are the fractions with the highest specific gravity, such as in Laurion, where argentiferous lead minerals are found in carbonates. They can, therefore, be separated from the gangue material by a density separation in flowing water. According to a thesis put forward by K. Konophagos, the density separation was achieved on sluices, wooden gutters with small hollows, in which the denser material remained, while lighter particles were washed away (Konophagos, 1970, esp. pp.7 – 13; Conophagos, 1980, pp.224 – 245; Rehren, et al., 2002, pp.38 – 40; Mussche, 2006, pp.229 – 230; Papadimitriou, 2017, p.401; cf. Domergue, 2008, pp.150 – 151 fig.95; Van Liefferinge, 2018a, p.91; Hauptmann, 2020, pp.83, 168). There is no archaeological evidence so far, however, as to

Fig. 6: Ari 63A, Washery. Water basin (left), washing surface (centre), last basin (top centre), and first channel (right) both still filled with rubble. The smooth part of the washing surface exactly in the centre, the roughened below, with the folding rule (photograph: H. Lohmann, No. N16_6568). The rights of the monuments depicted belong to the Greek State and the Ministry of Culture and Sports (Law 3028/2002).

Fig. 7: St. Anne's Church, Annaberg-Buchholz (Saxony), altar piece, rear side, detail: Ore washery with plane tables (artist: Hans Hesse, 1522; rights holder: Evangelical Lutheran Congregation Annaberg-Buchholz).

how these assumed sluices were installed on the washing surfaces in front of the wall of the water tank (Lohmann, 2005, pp.114, 130; 2020, p.51; this vol.; Domergue, 2008, p.150; Nomicos, 2021, pp.64–65). Another interesting opinion was put forward by E. Kakavogiannis, who suggested that the ceramic bowls (*lekanai*) found in the ancient workshops may have been used in a similar way to washing pans for washing gold in placer deposits (Kakavogiannis, 2001, pp.367–368; 2005, pp.230–242; but cf. Domergue, 1998, p.39; Tsaïmou and Fragkiskos, 2001; Nomicos, 2021, p.66).

An older thesis was established in the 19th century by the engineer Ph. Negris, who assumed that the ground ore was spread out on the slightly inclined surface of the washing surface in front of the tank and that the water flowing out of the jets in the front wall of the tank then carried away the lighter particles. The medium-heavy particles remained in the channel in front of the washing surface and had to be washed once more. Further medium-heavy particles (so-called middlings) were swept away into the three successive basins. The residues collected there were washed again (Negris, 1881; Ardaillon, 1897, pp.68–70; Wilsdorf, 1951, p.118; Marinos and Petrascheck, 1956, pp.9–10; Trikkalinos, 1978, pp.54–55, 67–68; Kalcyk, 1982, p.187; Photos-Jones and Jones, 1994, pp.353–354; Domergue, 2008, pp.149–150 fig.92; Lohmann, 2020, pp.51–52; this vol.; Nomicos, 2021, p.67; this vol.). The material with the highest density and therefore richest material remained on the washing surface. Regrettably, Ph. Negris did not further elaborate the considerations on which he based this explanation, but he possibly made similar observations as we did during the excavation and additionally had the installations of the early modern ages in mind, the so-called plane tables or buddles (cf. Morin-Hamon, 2013, p.38; in prep.; this vol. p.213; Lohmann, 2020, pp.51–52, fig.11; Nomicos, 2021, p.67 pl.26,1).

At the washing area of Ari 63A, again any evidence for the application of sluices is missing. But one notices that except for a 40 cm wide strip next to the edge of the neighbouring basin, the entire plaster surface is strongly abraded and roughened, as if someone had rubbed or swept something there again and again (Fig. 6). During the excavation, this already brought early modern drawings like one by the mining specialist Georgius Agricola (Agricola, 1556, p.237; Hoover and Hoover, 1950, p.302) or on the Annaberg altar piece in the Saxonian Ore Mountains (Fig. 7) into mind, showing workers in a contemporary ore washery moving the slurry with a horizontal board on a rod. This method, which is not used any more nowadays, is explained in a textbook by the professor of mining science at the Freiberg Mining Academy, E. Treptow (1925, pp.95–100). He describes that in the plane tables, the sand-like fine ground material is first applied to a slightly inclined surface and covered with a flowing film of water. In a further step, one moves it with a broom or a wooden scrubber and sprays fresh water on it again to bring the material into motion, letting the water wash away the lighter particles or buddle waste (Treptow 1925, pp.97–98; cf. the English handbook Le Neve Foster, 1900, p.579). In our opinion, it was precisely this process that caused the wear marks on the washing surface of the excavated ore washery. Treptow goes on to explain that during this process a good part of the richer ore particles remain on the surface, while another part is washed into the basin in front of it and settles there. Yet another part is transported even further, which is why he suggests to add further basins to catch it. Therefore, the basins of the Laurion ore washeries served not only for the settling and recycling of the used water but also to collect ore rich particles that had been washed away (cf. Negris, 1881, pp.160 – 161; Treptow, 1925, pp.97, 174 – 175; cf. Rihll, 2001, pp.118, 137 n.12).

The archaeological finds corroborate the thesis that the washery worked like a plane table: A very fine, sintered layer with a slight metallic gloss has settled at the bottom of the first channel, and a similar residue could be found on the bottom of the basins. A. Hein (NCSR Demokritos, Athens) analysed thin-sections (microsections) of these residues with an optical microscope, a scanning electron microscope and an X-ray spectrometer device (SEM-EDS). They show a layered structure, which actually turned out to be high in lead. However, further analyses are still pending, so that it cannot be completely ruled out that the residues were formed as a result of post-depositional processes after abandonment of the ore washing. Yet, according to A. Hein, the clearly separated layers and the relatively homogeneous grain size distribution within the layers speak against this. Similar results are known from the excavations of E. Photos-Jones and J. E. Jones at Agrileza (1994, pp.331 – 356; Nomicos, 2021, p.64 n.708; cf. already Kordellas, 1888, p.33).

If the number of workmen Treptow states as necessary for the process is applicable to the ancient washeries, this reconstruction of the washing process means that a small workforce did all the ore washing. The mining specialist relates that a single workman could operate two plane tables simultaneously (Treptow, 1925, p.99; cf. Domergue, 1998, p.41). At the Laurion washeries, at least another, but unskilled worker was necessary to scoop the processed water back into the tank. This would be an effective process management, especially when compared to the up to fourteen workers of Konophagos' reconstruction (Conophagos, 1980, pp.345, 237, fig.10-20 as opposed to Domergue, 2008, p.151, fig.94).

Fig. 8: Ari 76, non-canonical ore washery. Orthophoto of excavation in the washery. Areas interpreted as washing surface (up), channels, basins and drying surface (centre) degraded down to the bedrock, and modern tailings pile (right) (Ari-Project, Bochum, processing by M. Korczyńska and F. Hulek). The rights of the monuments depicted belong to the Greek State and the Ministry of Culture and Sports (Law 3028/2002).

Chronology

During the excavation in the three rooms of the workshop Ari 63A, only few fragments of pottery were found. If any conclusions can be drawn based on such a small trial excavation of a minor part of the complex, the small number of finds might be explained by the function of the rooms as workplaces, which had been tidied up regularly during their use and emptied, when the building was finally abandoned. The largest part of the pottery dates from the second quarter to the end of the 4th century BC, while some shapes are extending into the first decades of the 3rd century BC. This corresponds to the pottery finds of the extensive survey and from the excavation of K. Tsaïmou at Ari III (Lohmann, 2020, pp.51, 53; Nomicos, 2021, esp. p.116; this vol.; Kapetanios, this vol.).

Unfortunately, the construction of the complex could not be dated exactly, but the evaluation of the totality of the pottery found will at least give an indication. There are some ceramic bowls, *lekanai*, which according to the parallels offered by G. Lüdorf (2000) might date either to the 5th or the 4th century BC. One of the youngest pieces is a nearly complete one-handler (inv.-no. Ari 63A – 3A – 63:1; cf. Rotroff 1997, p.329 no.864, fig.58: 300 – 275 BC), which was found pressed flush under the debris of the ground floor of room 3 and is therefore to be interpreted as a possible terminus post quem for the abandonment of the workshop. Scattered in the disturbed parts of the washery, some pottery fragments from the 6th or 7th century AD were observed, many of them fragments of one jug.

Trenches at Ari 8 and Ari 76

On the other, south-western flank of Mt. Charvalo, the remains of a smelting furnace battery (Ari 8) and a non-canonical ore washery (Ari 76) were also investigated by two trial trenches. Conspicuously, the ore washery Ari 76 shows non-orthogonal channels. Both objects were unfortunately heavily disturbed by the activities of modern mining activities. The shape of the ore washery,

Fig. 9: Ari 8, Furnace battery. Fragment of furnace wall with lead containing coating (photograph: H. Lohmann, No. N16_6832). The rights of the monuments depicted belong to the Greek State and the Ministry of Culture and Sports (Law 3028/2002).

however, which has been stripped down to the bedrock by bulk earthworks in modern times (Fig. 8), may at least indicate that it could be older than the rectangular ones. The oldest fragments of pottery found there, mixed with modern debris in unstratified contexts date to the late 6th/ early 5th century BC.

At the smelting furnace battery Ari 8, numerous fragments of slabs of volcanic rock were found, each of which had a brownish or yellowish coating on one or more surfaces (Fig. 9). Analyses carried out by A. Hein at the NCSR Demokritos (Athens) proved the coating to be lead-rich slag, thus the stone slabs can be interpreted as walls or floor of a smelting furnace. Close to the furnace battery Ari 8, two worked stone blocks were found which strikingly resemble the anvil stones of Roman stamp mills found at Três Minas in Portugal and in other mining regions within the Roman Empire (cf. Nomicos, 2021, pp.57 – 58, pl.18,1; Lohmann, this vol.; for Roman stamp mills cf. Wilson, 2002, pp.21 – 23 fig.3; Domergue, 2008, pp.144 – 145, fig.87; Wahl-Clerici, 2020, pp.190 – 191, 203 – 208 figs.4.0.8 – 18)

The excavation at Frankolimano in 1969/70

In the summer of 1969, the Public Power Corporation of Greece (ΔEH) started to build a power plant north of the town of Lavrio at a small bay called Frankolimano (for the name, cf. Kakavogiannis, 1985, p.82). The Ephor of Antiquities at the time, E. Mastrokostas, enforced a rescue excavation on the building plot, which was situated close to the archaeological site of Thorikos, against the will of the construction supervision and the authorities (cf. Kakavogiannis, 2005, pp.270 – 271 n.668; Apostolopoulou-Kakavogianni, 2008, p.37).

This resulted in the archaeologists O. Apostolopoulou and E. Kakavogiannis excavating ancient buildings, two cemetries, a rectangular ore washery and above all a battery of five smelting furnaces (Fig. 10) and a presumed cupellation furnace. So far, only brief remarks on these excavations have been published (Liagkouras and Kakavogiannis, 1972, p.150; Konophagos, 1974, pp.268 – 271; 1975, p.344 fig.3, p.361; Trikkalinos, 1978, pp.59, 72 – 73, tab.12; Conophagos, 1980, pp.280 (note), 288; Kalcyk, 1982, pp.144, 149, 208 fig.24, p.211; Kakavogianni, 1985, p.51; Kakavogiannis, 2005, pp.262, 270 – 271 n.668; Lohmann, 2005, p.132 n.69; Nomicos, 2021, pp.114, 117, 179 no.52). O. Apostolopoulou-Kakavogianni kindly allowed me to study and publish the material and the excavation documentation. This, and especially the detailed excavation diaries and photographs by the excavators, will offer the opportunity to explore the smelting of the ore and the production of metallic silver.

The furnace battery (Fig. 10) is located on a small tip of land in the northern part of Frankolimano and consists of the east-west oriented foundation walls of at least five chambers (each about 5.0 m × 3.2 m in size) which open into a walled courtyard facing South. At least a sixth chamber can be assumed, but this side of the complex has been eroded by the sea; it is preserved for a length of 37.5 m and has an overall width of 18 m (Konophagos, 1974, pp.269 – 271, figs.3 – 4; cf. Kakavogiannis, 1988, pp.31 – 32). The foundation walls are made of local limestone and, above all, granite-like stone. On the northern wall of each chamber, traces of the smelting furnace proper have been preserved in semi-circular recesses where the natural rock and stones are reddened by the heat and fired clay and oxidized coatings were observed. The furnaces themselves were built of a thick clay layer, probably in addition to mud bricks. To the north behind the chambers are two parallel corridors from which the charging of the furnaces was carried out. The furnace battery is preserved as a fenced archaeological site within the power plant compound.

Museum Campaigns 2017 and 2019

The campaign in the Archaeological Museum of Lavrio in summer 2017 lasted four weeks. Priority was given to processing finds from the battery of smelting furnaces and a presumptive cupellation furnace.

Based on the pottery, the amphora stamps and some coins, the chronology of the smelting furnaces probably goes back to the first half of the 2nd century BC, the time when the so-called New-Style-tetradrachms began to be issued (early 2nd century BC according to Thompson, 1961, esp. pp.107 – 132; later chronology starting 164/163 BC.: Lewis, 1962, p.275; Boehringer, 1972, pp.28 – 31; van Alfen, 2012, pp.98 – 99; middle chronology Mørkholm, 1984, p.42; cf. Flament, 2007, pp.146 – 147; Börker, 2018,

Fig. 10: Frankolimano Thorikou (near Lavrio), ancient smelting furnaces during excavations 1969. From South (Archives of the Ephorate of Antiquities of East Attica, photograph: E. Kakavogiannis, DEI-excavation No. 8). The rights of the monuments depicted belong to the Greek State and the Ministry of Culture and Sports (Law 3028/2002).

p.70). The same seems to be true for some of the other smelting furnaces on the coast (Konophagos, 1974, p.266: 3rd century BC or later; Salliora-Oikonomakou, 2004, p.62; Lohmann, 2005, pp.127 – 128; Van Liefferinge, 2018b, p.550; Börker, 2018; Nomicos, 2021, pp.110 – 111; Tsaïmou, et al., 2015, p.118 tab.1, p.125 for Ari in the hinterland; but cf. Mussche, 1998b, pp.65 – 66; Conophagos, 1980, p.288; Salliora-Oikonomakou, 2004, pp.70, 74 – 75). In these cases, they are most probably the remains of a later reuse of the Classical slag heaps and washing residues. The finds of the old excavation also include intermediate products of smelting and remains of the furnace walls. Analysing them will make it possible to reconstruct the smelting process.

Another, single furnace, which was labelled as a cupellation furnace during excavation, was located about 30 m north of the smelting furnace battery, where today the cooling water of the power plant is discharged into the sea. According to common opinion, in Antiquity silver was separated from the argentiferous work lead in cupellation furnaces by oxidizing the lead to lithargite and draining it. In a second cupellation step, the enriched argentiferous lead is again oxidized and silver, as the nobler (i.e. more resistant to oxidation) metal, is left behind (Konophagos, 1959, pp.259 – 261; Conophagos, 1980, pp.308 – 327; Pernicka and Bachmann, 1983; Hauptmann, 2020, pp.342 – 343; cf. Nomicos, 2021, pp.73 – 74). However, according to the preliminary analyses by E. Filippaki, the furnace in question could also be related to iron metallurgy, i.e. an iron smelting furnace or a forging furnace. There is a similar finding at nearby Thorikos in the theatre necropolis (Mussche, 1998a, pp.44 – 45, 64 – 65; Varoufakis, 2014). Cupellation furnaces from Laurion have not yet been documented in the literature, probably because they have been destroyed entirely during the 19th and early 20th century, when the workmen of the modern mining companies collected the litharge found within them (Cordella, 1869, p.103; Kordellas, 1888, p.87; Conophagos, 1980, p.308; Mussche, 1998b, p.67; Kakavogiannis, 2005, pp.273 – 274; Nomicos, 2021, p.73).

The chronology of this site remains unclear up to now, as some contexts contain both Hellenistic and early Byzantine pottery of the 6th or 7th century AD. A Hellenistic date of this small furnace together with the smelting furnace would result in a harmonious ensemble of metallurgical installations, while a late Roman or early Byzantine date would illuminate another phase of metal production in the Laurion. D. Morin has observed oil lamps with Christian symbols in the antique shafts at Thorikos (Morin and Delpech, 2018, pp.44 – 45; see also Butcher, 1982; Mussche, 1998a, p.65; Konstantinidou, et al., 2018, pp.53 – 54; cf. Mattern, 2010; Docter, et al., 2013; this vol.; Kakavogiannis, 2013; Lagia, et al., 2016; Nomicos, 2017, p.225; 2021, pp.121 – 127; this vol.; Lohmann, this vol.; Kapetanios, this vol.), which speak for a reopening of mining in the late Antique or early Byzantine period. Finally, Paul the Silentiary claims that the »…veins of the mountains of Sounion had to open again…« for the silver of the Hagia Sophia church in Constantinople, which is another hint to a renewed use of the mine workings in the time of the emperor Justinian I. (Paul. Sil. Ecphr. 679 – 680; de Stefani, 2011, p.46).

The second campaign took place during two weeks in early autumn 2019. The recording of the finds from the old excavation was continued, with priority given to the finds from the so-called “Building 1”. According to the excavator O. Kakavogianni, referring to its ground plan, the building could be an ancient farmstead, but numerous metallurgical finds were also made. It can be hoped that an analysis of the finds will help to determine the function and chronological classification, which will allow us to determine more precisely the relationship with the smelting furnaces.

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Last use and abandonment of the Cistern No. 1 *ergasterion* at Thorikos: Finds from the lowest levels of the cistern's fill

To the memory of Francine Blondé (1948 – 2019)

ABSTRACT: *This contribution focusses on the finds related to the last use and abandonment of Cistern No. 1 and found in its lowest layers during the excavation campaigns of 2011 and mainly 2012. The cistern, partially hewn in the bedrock and partially constructed with massive ashlars, belonged to a silver-working ergasterion that included the newly discovered ore washery W13 and that drew its ores from Mine No. 2. With a calculated capacity of 209.6 m^3, it forms the largest cistern in Thorikos. The ergasterion, which on the basis of finds in the foundation layers of the south wall of the cistern probably came into existence in the late 5th century BC, remained in operation (perhaps with a hiatus after the Peloponnesian War) until it was abandoned in the Early Hellenistic period, ca. 325-275 BC. After having fallen in disuse as a metallurgical cistern and after a process of filling in with mudbrick debris, disintegrated cistern lining and erosion material from around the cistern, the remaining part of the cistern was still able to contain some water. At some point in the Late Hellenistic period (2nd/1st century BC) a limited activity is to be seen around the cistern: a visitor or inhabitant of Thorikos dropped a water jar in the cistern and a fragment of a brown-glazed lagynos (?) dated to the first quarter of the 2nd century BC found its way into the fill. This process of micro-events can be traced in the archaeological record of successive filling layers. The upper layers of this fill were mixed with Late Antique/Early Byzantine pottery and mill stone fragments suggesting some new activities around the cistern and Mine No. 2.*

KEYWORDS: LATE CLASSICAL, HELLENISTIC, LATE ANTIQUITY, EARLY BYZANTINE, WORKSHOP, SILVER, METALLURGY, CERAMICS, HOUSEHOLD POTTERY, STONE TOOLS, ROOF TILES, WATER MANAGEMENT

Introduction

Between 2010 and 2012, a rectangular cistern and its workshop (*ergasterion*), situated within Macrosquare A'51 just above the Industrial Quarter of Thorikos, have been the object of archaeological investigations (Figs. 1 – 3).[1] The excavations were conducted within the framework of the Thorikos Archaeological Research Project (TARP) of the Belgian School at Athens and Ghent University in collaboration with Utrecht University and under the aegis of the then Ephorate of Eastern Attika (ΕΦΑΑΝΑΤ).

Primarily during the Late Classical (400 – 323 BC) and part of the Early Hellenistic period (323 – 290 BC), the Laurion witnessed a true mining boom, with ore processing *ergasteria* being set up all over the area (Conophagos 1980; Jones 1985; Photos-Jones and Jones 1994; Kakavoyannis 2001; 2005). These generally consisted of an ore washery, workspaces, a cistern and living quarters, and were located at a short distance to the mine entrances. As the ores came from the mine, they were purified in the washeries, which were especially designed to recycle water. According to one view (Conophagos 1980, pp.213 – 273; Rehren, et al., 2002; see Mussche 2006, Nomicos 2020, Morin-Hamon, this vol., for a discussion of other theories), the beneficiation or concentration process in these washeries started from water being fed from the main reservoir, through a fixed number of nozzles connected to wooden sluices. This process is based on the gravity of the ore particles: the heavier metal particles more readily sink, while the lighter impurities are swept away by the water flow. Afterwards, the water flowed into a series of channels and settling tanks, where the remaining ore particles could settle, and was recuperated at the end of the circuit. Therefore, an extensive and reliable water stock throughout the year was indispensable, particularly in an area as the Laurion with few permanent rivulets or springs. This was overcome by harvesting rainwater in large cisterns, which are, because of their size and massive walls, often the only evidence of the scale of the industrial activities and the significance

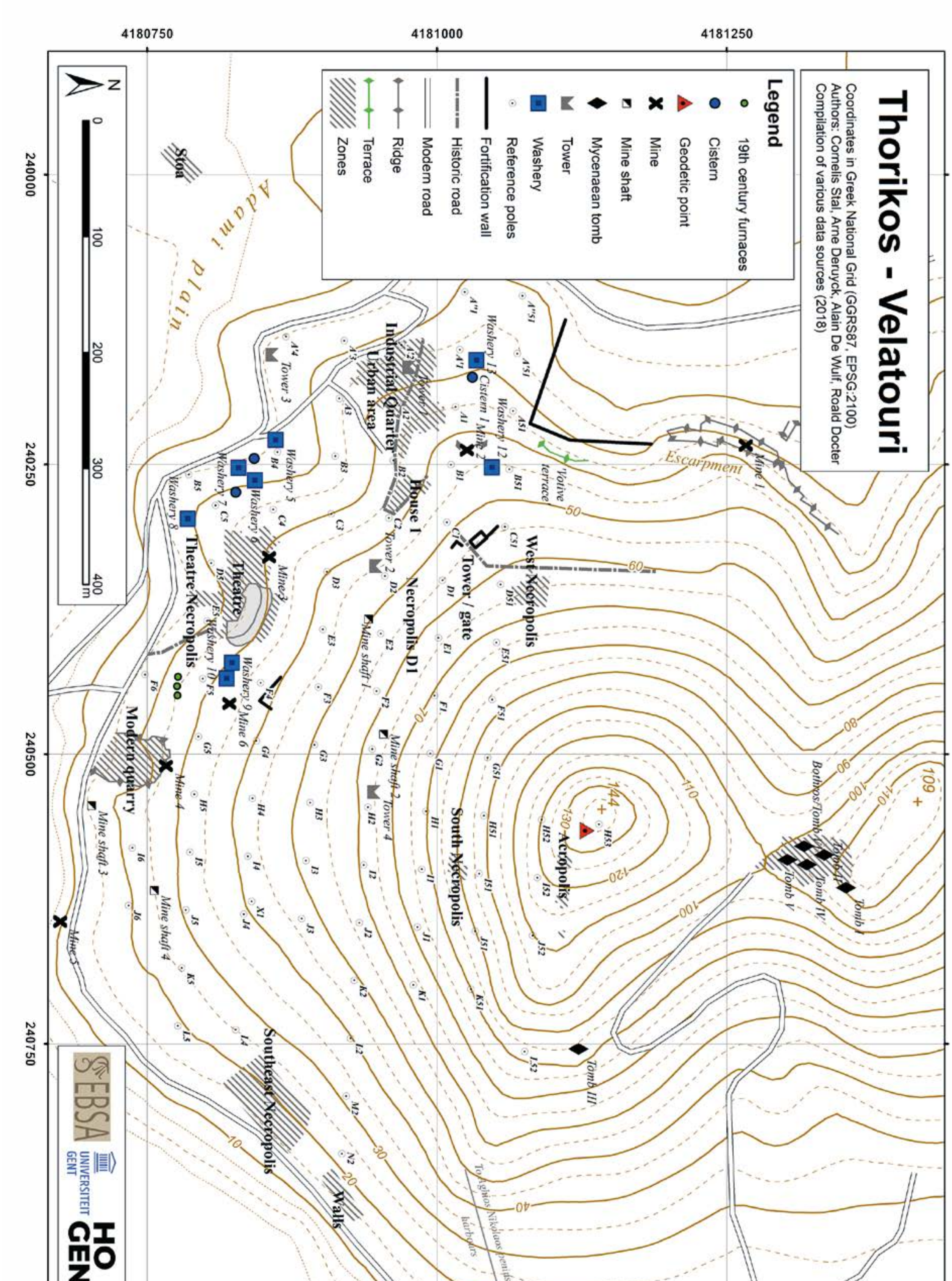

Fig. 1: Map of the Velatouri Hill at Thorikos with indication of the Cistern No. 1 ergasterion (C. Stal – TARP).

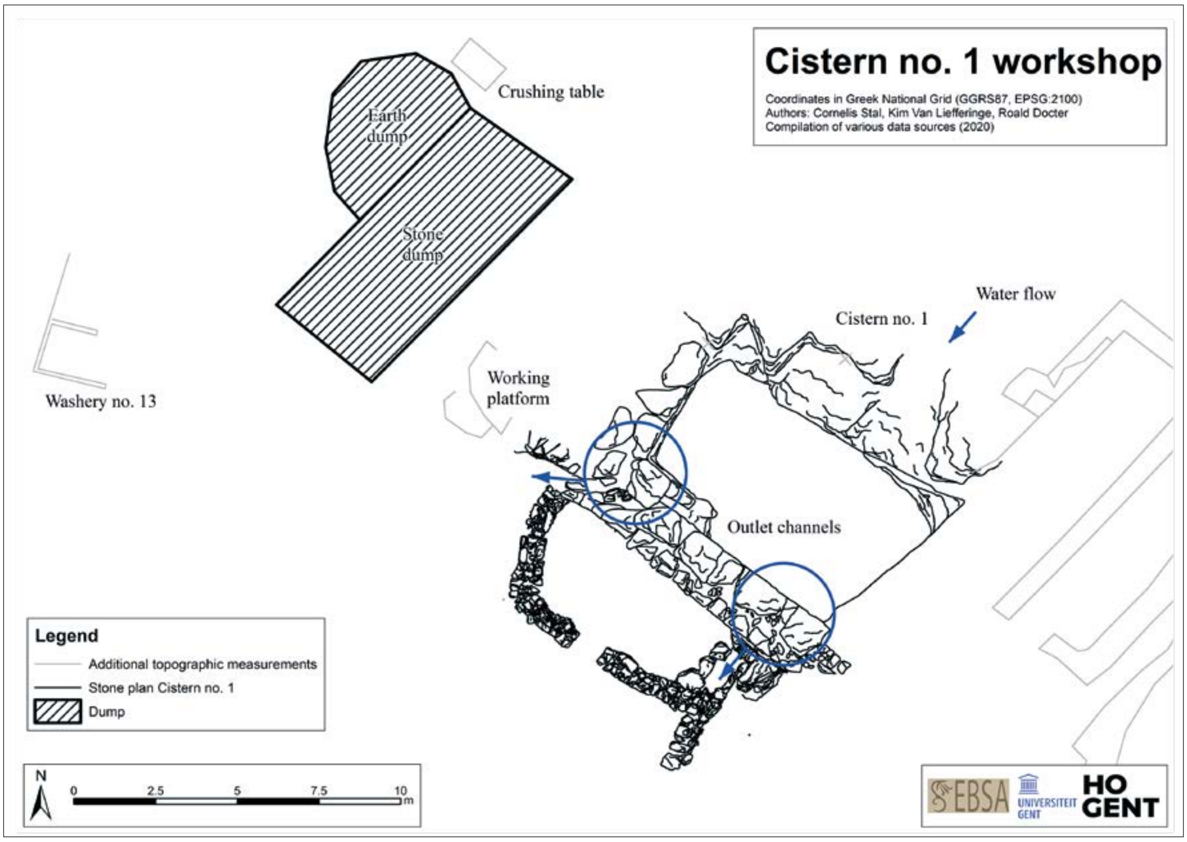

Fig. 2: Plan of Cistern No. 1 and constructions of the ergasterion (K. Van Liefferinge – TARP).

Fig. 3: Cistern No. 1 viewed towards the east with mining waste dump of Mine No. 2 in the background, 2011 (photo: K. Van Liefferinge, TARP).

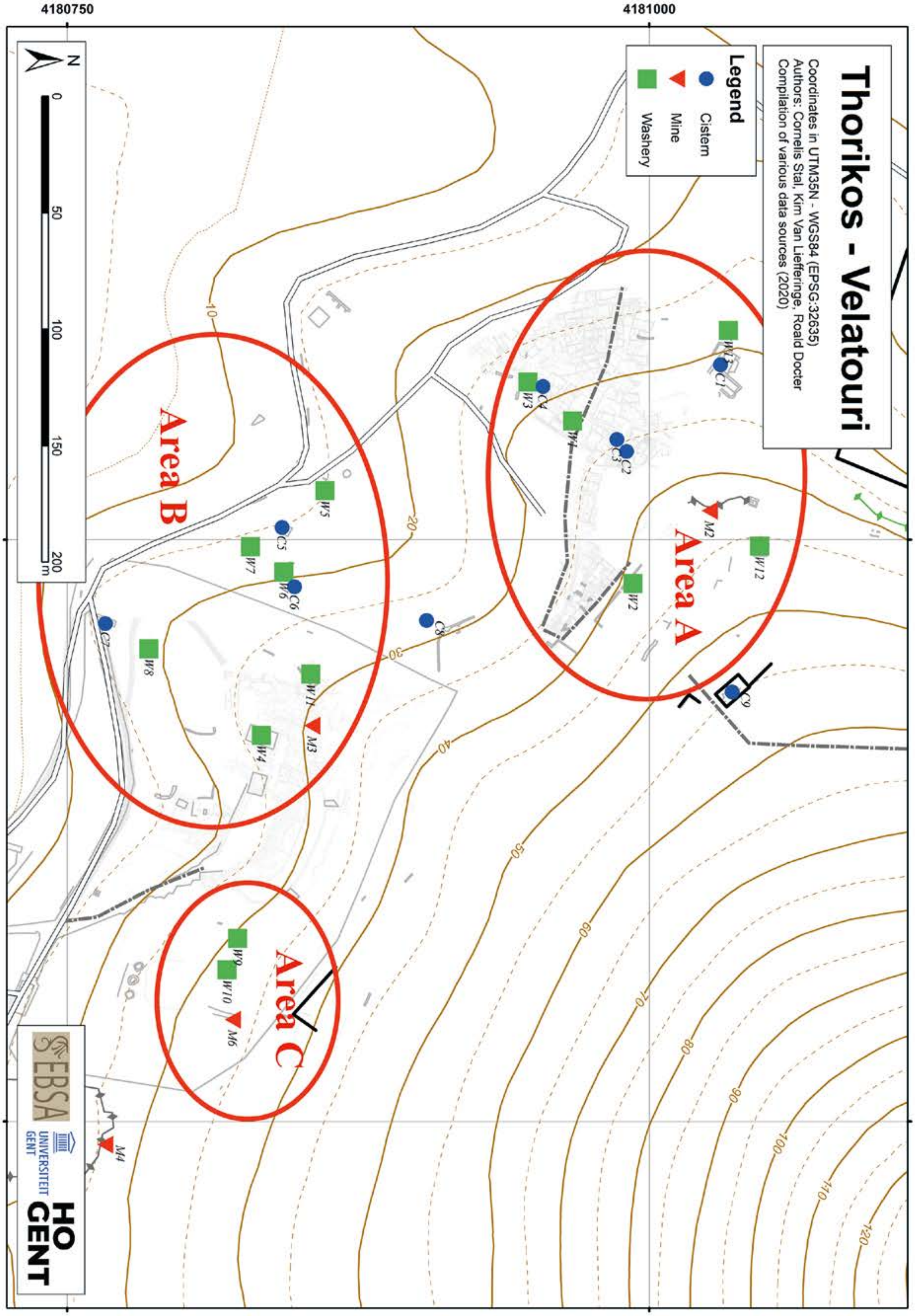

Fig. 4: The three metallurgical complexes (A-B-C) in Thorikos with indication of cisterns, washeries and Mine entrances (map: updated version of Van Liefferinge, et al., 2014, p.277 fig.6: K. Van Liefferinge, C. Stal and R. F. Docter).

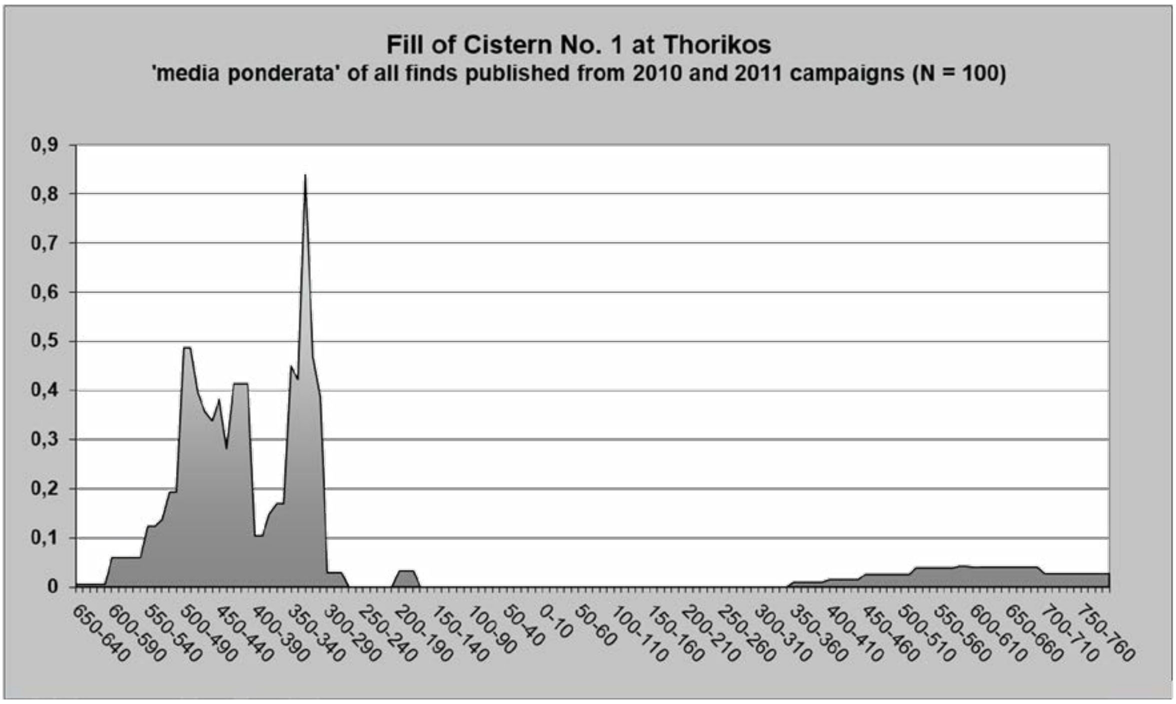

Fig. 5: Thorikos, Cistern No. 1. 'Media ponderata' of fill based upon the published finds from 2010 and 2011 campaigns (Docter, Monsieur and van de Put, 2011, p.119 fig.42).

of careful water management for silver production (Van Liefferinge, et al., 2014).

The cistern, which we discuss here, was first mentioned by H. F. Mussche in his seminal work *Thorikos. A Mining Town in Ancient Attica* of 1998, where it is labelled as Cistern No. 1, but has otherwise escaped scholarly attention (Mussche 1998, 56). It was hewn out of the bedrock – in its northern part from ground level – and constructed with massive ashlars of an average of 1.6 m thickness in its western and southern parts and partially its eastern part (Fig. 3). While Mussche underestimated its capacity at 80 m³, Cistern No. 1 was (and remains) the largest reservoire discovered on the Velatouri hill. The chronology and layout of the *ergasterion* to which the cistern belonged, remained uncertain, however. The surrounding area showed various courses of rubble walls and a marble crushing table was visible to the west (Van Liefferinge, et al., 2011, p.73 fig.17). But the washery, otherwise a conspicuous element in the industrial landscape of Thorikos and the Laurion, remained (yet) invisible. The *ergasterion* clearly depended upon the yield from nearby Mine No. 2, as did four other workshops around it (Fig. 4; Van Liefferinge 2014, p.142 fig.58; Van Liefferinge, et al., 2014, pp.277 – 278, fig.6). Mussche already knew four cisterns in the Industrial Quarter (Area A), of which two are domestic ones (C2 and 3), as well as four washeries (Mussche 1998, p.56). In 2011, the investigation of the area of Cistern No. 1 brought a fifth washery to light (W13; Figs. 2, 4), to the west of the cistern. It clearly belonged to this *ergasterion*. Recently, a new cistern was discovered in Area A, situated in Macrosquare C51 farther to the north-east, which had been constructed in a rectangular structure, interpreted as a gate building, separating the West Necropolis from the Industrial Quarter (Fig. 4, C9; van den Eijnde, et al., 2018a, pp.40 – 41, with fig.). It may have served either Washery W2 or W12, or both. It may equally have served the public water provision, situated at the highest point of entry to the Industrial Quarter and at the lower end of the south-western Velatouri slope, so theoretically with a huge water capturing potential (Van Liefferinge, et al., 2011, pp.60 – 62; 2014, pp.275, 279, figs.3, 8). Another cistern was discovered during the intensive survey on the Velatouri in Area B and may have belonged to Washery W11 (Fig. 4, C8; van den Eijnde, et al., 2018b).

The choice for Cistern No. 1

The investigation of Cistern No. 1 had been high on the list of research priorities in the domain of Thorikos ever since the restart of TARP in 2005. When one of the present authors started a PhD project, funded by the Special Research Fund of Ghent University, on "Technological change in the Laurion silver mining area during the fifth and fourth centuries BC. An archaeological contribution to the study of the Athenian economy" (Van Liefferinge, 2014), we seized the opportunity to use the well-preserved Cistern No. 1 and its *ergasterion* as one of the case studies. Thereby we were guided by three aims: establishing the capacity of the cistern and, hence, its operational potential, establishing the closing date of the cistern and establishing its construction date. Contrary to most of the cisterns in the Laurion, it seemed to have been spared from the fate of partial destruction and industrial emptying in search of re-usable ancient metal waste by the 19th and 20th century Compagnie Française des Mines du Laurion (CFML).

A heavy layer of rubble and large boulders from the superstructure covered the interior of the cistern, thereby allowing us to investigate an untouched fill with the potential of providing a closing date for the use of the cistern and, hence, the *ergasterion*. To the best of our knowledge, no fill of a cistern in the Laurion has ever been carefully excavated or at least been published. Moreover, the fact that it had been partially constructed instead of fully hewn out of the bedrock offered the possibility to investigate the exterior, where we hoped to find untouched foundation layers that would contain datable material. This is clearly linked to the still unsolved question of the beginning of silver mining and metallurgical exploitation in Thorikos within the Classical period: 5th or 4th century BC (Mussche, 1998, pp.13 – 14, 62 – 63). During the 5th century BC Thorikos witnessed a great expansion, especially from ca. 460 BC onwards. There is, however, no reason to believe that Thorikos fulfilled a major role in the actual silver production and exploitation; it may rather have been an important economic, cultural and administrative centre in the Laurion (one is reminded of the impressive theatre), benefitting from good harbour facilities. What is now conventionally called ‘Industrial Quarter’ may not yet have been a metallurgical hotspot during most of the 5th century BC.

Important changes took place only near the end of the 5th century BC, when an ore-washery was installed in Insula 1 (Mussche, 1998, pp.50 – 51, 62 – 63), suggesting an increase or concentration of production in Thorikos itself. It is not unlikely that this was a direct consequence of the Peloponnesian War which started in 431 BC. Athens would have taken measures to secure its finances to cover the expenses of war. Both Thucydides and Xenophon suggest in this connection that the Laurion was of vital importance to the city-state’s economy. Thucydides wrote that the Spartans invaded Attica in 430 BC “where the silver mines are” (2.55 and 57) and that Alcibiades later recommended the tactical siege of Dekeleia in 413 BC, causing a major disruption of the silver exploitation as slaves began to desert. Even though ancient sources may have exaggerated the number of deserted slaves, archaeological research presents irrefutable evidence that it was in fact a critical period. Activity in the Laurion came almost to a complete standstill as a result of the Peloponnesian War (Photos-Jones and Jones, 1994, p.309; Mussche 1998, pp.62 – 63). In comparison to the chronology of other *ergasteria* in Thorikos and the Laurion, we therefore cautiously hypothesized that the Cistern No. 1 *ergasterion* had been constructed somewhere during the last quarter or final years of the 5th or the 4th century BC (Docter and Van Liefferinge, 2010, pp.56 – 57; Duchène, et al., 2018).

The excavation of Cistern No. 1

After cleaning and removal of the heavy overgrowth, the focus of the campaigns of 2010 and 2011 was on the interior of the cistern. Notwithstanding the fact that more than 15 m^3 of stones were removed – manually – and piled up to the west of the cistern, we were unable to reach the bottom during these campaigns. Two preliminary reports were drafted and published in that very same year (Van Liefferinge, et al., 2011; Docter, Monsieur and van de Put, 2011). The main structure of the cistern proved to have been relatively well-preserved, being partly cut into the bedrock and partly built up with ashlar masonry consisting of large, mostly rectangular blocks of (local) stone, averaging in length from 1 to 2 m. In all probability, the irregular shape of the cistern (with sides measuring 9 m, 4.5 m, 7.5 m, and 5.5 m) can be related to the local, pre-existing topographical conditions. Two drainage channels were observed. The first channel, located in the south(-east) corner, was intentionally closed at some unknown moment, the second was probably operational until the cistern’s abandonment and had likely been built at the same time the cistern was created.

Of particular interest was the composition of the ceramic and worked stone assemblage in the cistern’s fill, at least in the upper part reached during these excavations (Figs. 6 – 7, layers 1 – 4; Van Liefferinge, et al., 2011, pp.66 – 67, figs.11 – 12). Based upon a selection of 100 finds we were able to establish a date range for this upper fill of the cistern (Fig. 5; Docter, Monsieur and van de Put, 2011; Mortier, 2011). Two large chronological horizons could be distinguished: the majority of the finds (87%) originated in activities that took place around the cistern, and most likely higher up the Velatouri during the Late Archaic and Classical to Early Hellenistic period. Only 13% of the finds could be attributed to a Late Antique phase, when the cistern was ultimately filled in. Sherd size and the measure to which joins are encountered within the finds played an important role in assigning material to one of the two major chronological horizons, especially in the case of chronologically less distinctive plain, cooking and coarse wares. The Late Archaic to Late Classical/ Early Hellenistic material in the fill proved to be generally much more fragmented, smaller and worn, at least in these upper layers. The Late Antique pottery fragments, which have been studied by A. Konstantinidou, generally seem to be of larger sizes and so to have been subjected less to erosion and redeposition processes. Fragments of a rotary hand mill from these upper layers might even be attributed to the Early Byzantine period (TP11.149 and TP11.545; see Duchène, this vol.). Several contexts with large numbers of animal bones (of relatively large sizes), which have been studied by E. Yanoulli, are thought to belong exactly to this chronological horizon.

Within the Late Archaic to Early Hellenistic finds two marked peaks could be discerned: one comprising the 5th century and one the second half of the 4th century BC, with

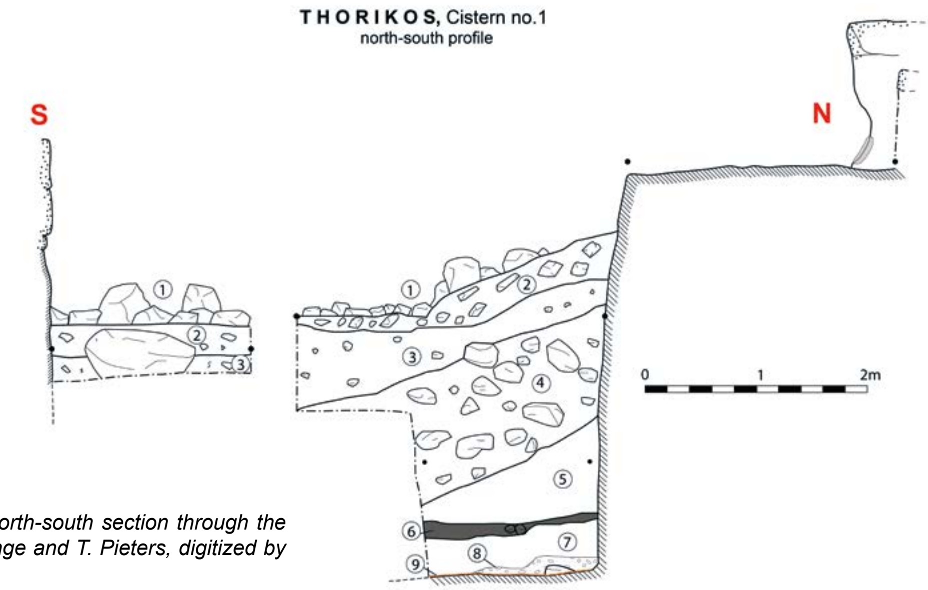

Fig. 6: Thorikos, Cistern No. 1. North-south section through the cistern and its fill (K. Van Liefferinge and T. Pieters, digitized by J. Angenon – TARP).

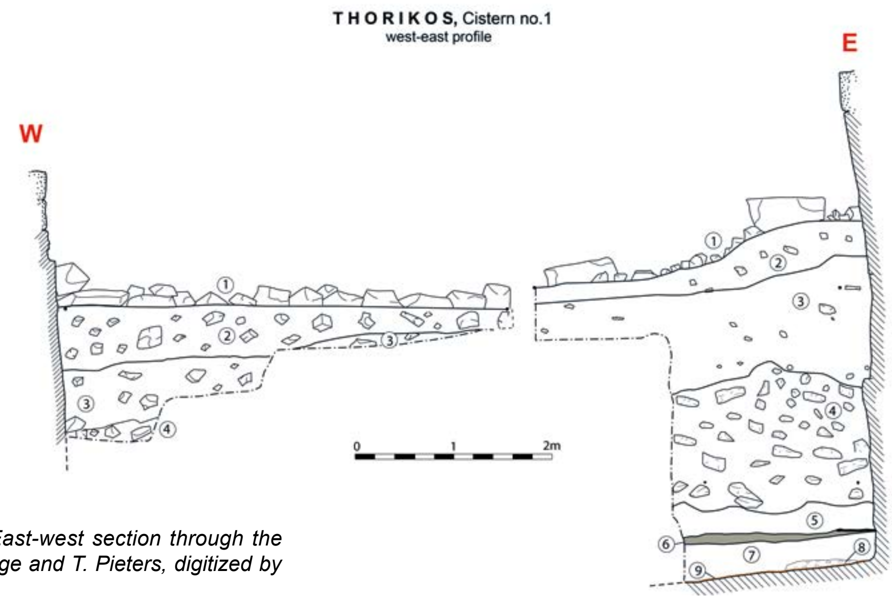

Fig. 7: Thorikos, Cistern No. 1. East-west section through the cistern and its fill (K. Van Liefferinge and T. Pieters, digitized by J. Angenon – TARP).

a significant peak in the period 330 – 320 BC (Fig. 5). The latest part of the pottery in the fill dated coherently to the 6th and 7th centuries CE (viz. between 520 and 700 CE). They even lead us into the Early Byzantine period, with clear indications of finds dating to within the 8th century CE, offering a completely new perspective upon the latest phase of Thorikos' occupation and metallurgical activities in the area of Mine No. 2 (cf. Docter, Monsieur and van de Put, 2011; Konstantinidou, et al., 2018).

Two priorities were set for the concluding excavation campaign of 2012. On the one hand, we focused on the south-western and north-eastern sectors within the cistern (Sector C and A, respectively), where we intended to reach the bottom of the cistern and at least be able to draw up two crossing sections of the fill (Figs. 6 – 7). This would at the same time leave two large sectors untouched for future investigations (Van Liefferinge, et al., 2011, pp.64 – 65, fig.10). On the other hand, we directed our attention to the sector immediately to the south of the cistern with the aim of obtaining dating material from foundation levels against the constructed south wall (Sector G). Moreover, it was hoped to find chronological evidence for the closure of the drainage channel in the south(-east) corner of the cistern that was blocked off at a certain moment of its existence (Sector F; Van Liefferinge, et al., 2011, p.63 – 64, figs.7 – 8). The excavations uncovered a room built against the south wall of the cistern with a stratigraphy that may be suggestive of a late 5th century BC chronology for the cistern's construction (Fig. 9). In the frame of a discussion on the set of geomatical tools

Fig. 8: Thorikos, Cistern No. 1. 3D model of the cistern at the end of the campaign 2012 (C. Stal – TARP).

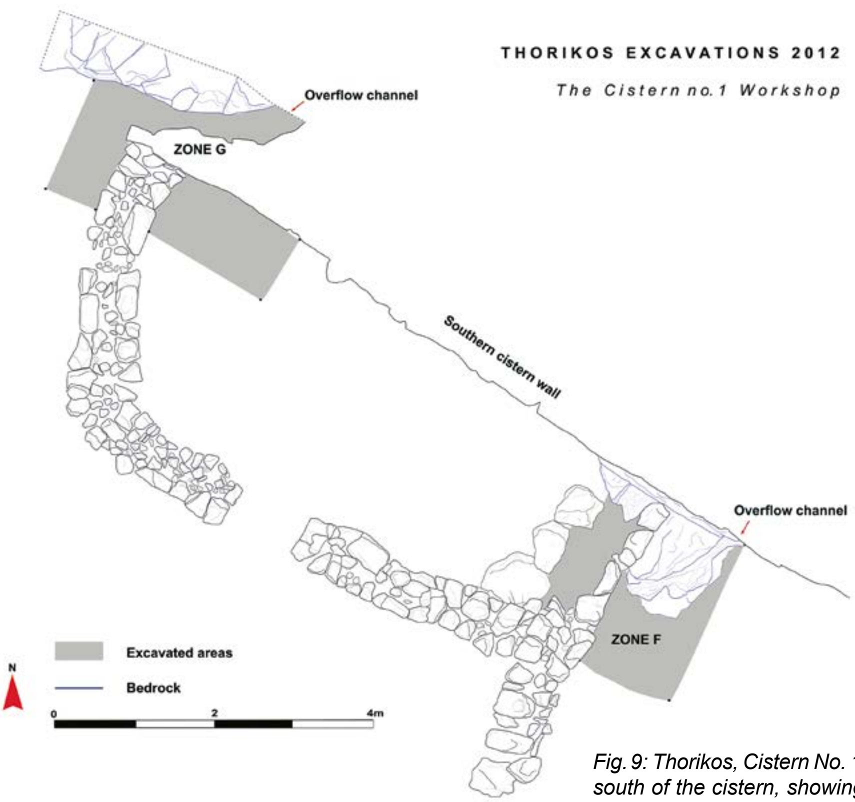

Fig. 9: Thorikos, Cistern No. 1 ergasterion. Ground plan of the area south of the cistern, showing Zones G and F (K. Van Liefferinge – TARP).

that we employed in the 2012 campaign, we already published a preliminary presentation of the architecture and stratigraphy in this part of the site (Stal, et al. 2014). The full discussion of finds, chronology, architecture and stratigraphy, however, is foreseen for the comprehensive publication of the 2010 – 2012 excavations in the Cistern No. 1 ergasterion.

The present contribution focuses on the results of our first 2012 priority, the interior of the cistern. Only in the north-east sector A were we able to reach the bottom (Fig. 8) with a clear stratigraphy that did not yield many finds, but belonged to a sequence of last use and abandonment layers (Figs. 6 – 7). The basin of the cistern turned out to be much deeper than expected and could be accurately calculated to have a capacity of maximum 209.6 m³ (Stal, et al., 2014, pp.119 – 122). Starting from layer 5, of which the upper part had already been documented in 2011 (here, Cat. 1 – 4; Van Liefferinge, et al., 2011, p.67 fig.12), five layers were excavated (layers 5 – 9; Figs. 6 – 7) of which we present the finds below.[2] It will be followed by a discussion of the chronological and functional implications of the cistern's abandonment.

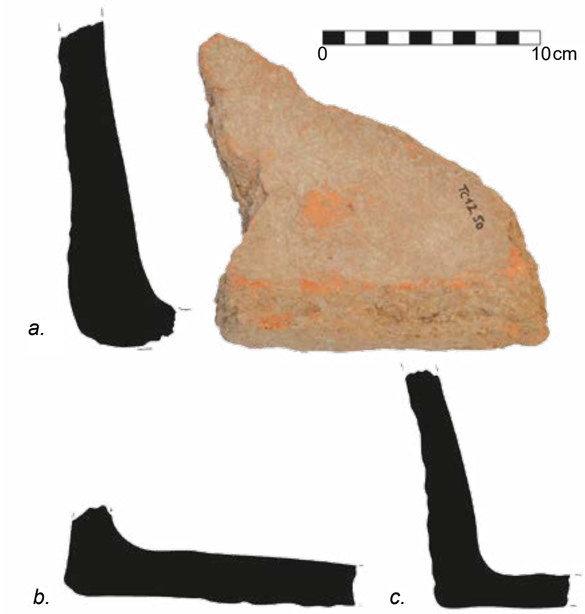

Fig. 10: Thorikos, Cistern No. 1, layer 5: fragment of large oval basin Cat. 5 with some fragments of the same vessel from higher levels in the fill (drawings: R.F. Docter digitized by F. Gignac and Q. Drillat; Photo's TARP). – a. Cat. 5; – b. TC10.52 (context T10-5-2); – c. TC12.122 (context T12-32-2).

Layer 5

Layer 5 can be characterized as a blackish, extremely fine, silty sand layer (T12 – 4-1/2 and T12 – 5-1/2), with few small stones, mixed with fragmented mortar/cistern lining. A limited amount of pottery was found in 2011 and 2012, amongst which are several larger and joining fragments (Cat. 1+5, 2, 11-12; Figs. 10 – 12). A fragmented large water jug or amphora was found lying on top of the layer against the east wall of the cistern (Cat. 6, Fig. 11a).

Context T11-16-1 was found on the very last day of the 2011 campaign and has only been inventoried but, unfortunately, not yet drawn and photographed. It is, hence, not impossible that some of the fragments may join or belong to fragments found in 2012.

T11-16-1

- **Cat. 1**: TC11.500 (context T11-16-1), base fragment of large oval coarse ware basin. Same vessel as Cat. 5 (see below).
  Chronology: Classical?
- **Cat. 2**: TC11.501 (context T11-16-1), ring base fragment of mortar in plain ware.
  Chronology: Classical?
- **Cat. 3**: TC11.502 (context T11-16-1), flat base fragment of jug, red washed on outside.
  Chronology: Classical?
- **Cat. 4**: TC11.503 (context T11-16-1), edge fragment of cover tile in red glazed ware.
  Chronology: Classical?

T12-4-1

- **Cat. 5**: TC12.50 (context T12-4-1), base fragment of large oval basin in Coarse Ware (Fig. 10a).
  PH 15.0, diam base not to be estimated; thickness of wall varies.
  Clay: reddish yellow 5YR6/6 to red 2.5YR5/8. Surface reddish grey 5YR5/2 to reddish brown 5YR5/3. Very coarse fabric with some angular and subangular quartz (0.2 – 1.0 mm), some white particles (0.4 – 0.6 mm), few white lime (?) particles (1.0). Lower interior covered with silver-like white residue (calcium?; litharge?).
  Chronology: Late Classical/Early Hellenistic?
  Layer 5 contained two fragments of this industrial basin, executed in a very distinctive coarse fabric (Cat. 1 and 5, the latter found at the same level as Cat. 6). Apart from that, the higher layers of the cistern fill contained several large fragments of the same fabric that in all probability belong to the same vessel: TC10.52 (Fig. 10b), TC10.207 (context T10-7-4), TC11.156 (context T11-14-1), TC12.48 (context T12.3.1), TC12.122 (Fig. 10c; context T12-32-2), TC12.1559 (context T12-2-3) and TC12.1579 (context T12-2-4). The base fragment TC10.52 (Fig. 10b) had already been published in the preliminary report of 2011, although as a drain or terracotta water channel (Docter, Monsieur and van de Put, 2011, 98 – 99, fig. 24). The alternative interpretation, as a basin, also

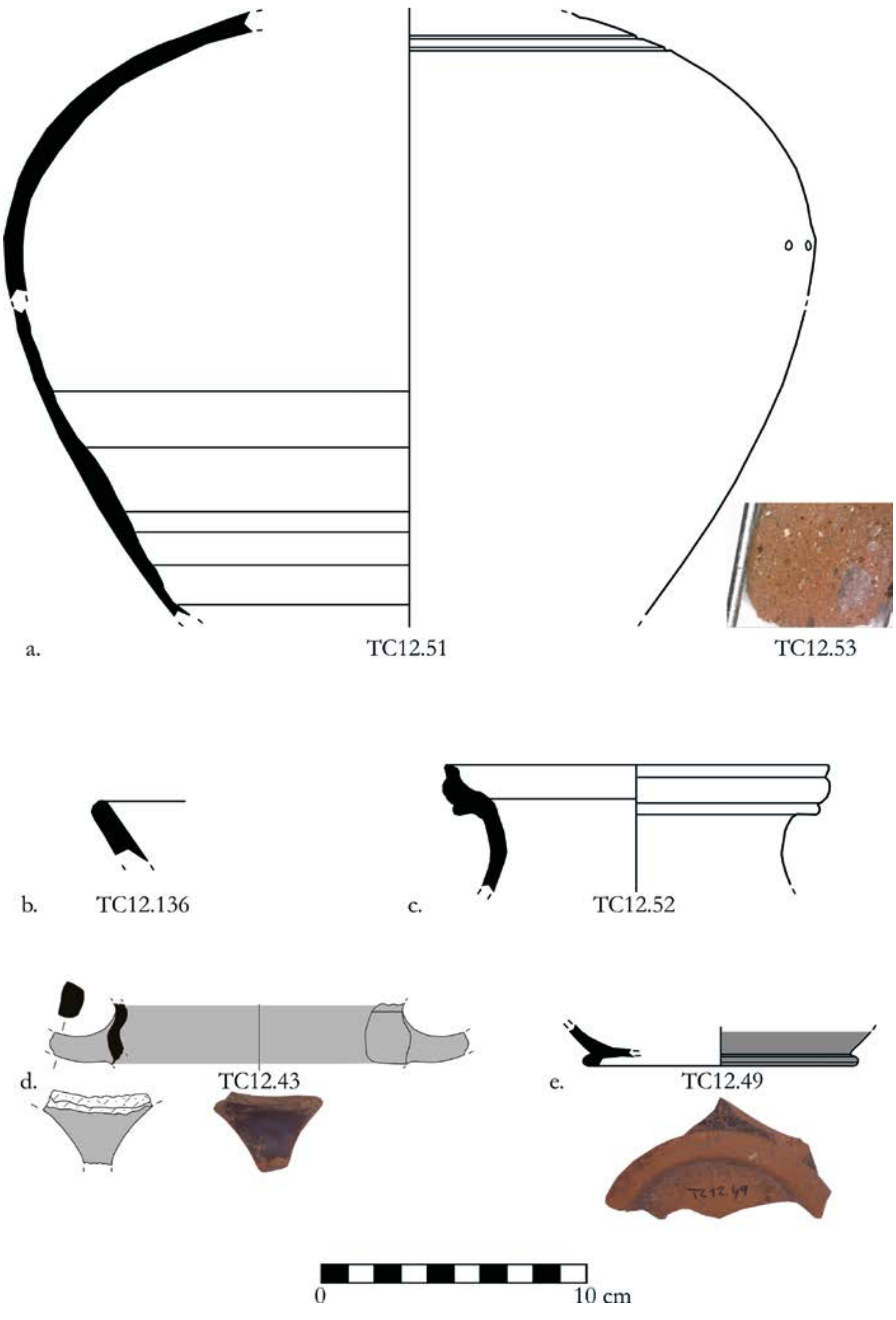

Fig. 11: Thorikos, Cistern No. 1, layer 5: pottery Cat. 6, 8–9 and 13–14 (drawings: R.F. Docter digitized by Q. Drillat; Macro-photo Cat. 6: S. Claeys, not to scale; Photo's TARP). – a. Cat. 6; – b. Cat. 8; – c. – Cat. 9; – d. Cat. 13; – e. Cat. 14.

given in this publication, was based upon the terracotta sarcophagus of a child burial in the West Necropolis of Thorikos (Tomb 70; Bingen 1967, p.55 fig.67), which may well have been a re-used industrial basin rather than a custom-made larnax. The excavator associated the tomb which lacked any grave gifts with the last burials in the necropolis, dating to the years before 300 BC. In 2011, the interpretation as a drain or water channel was still favoured over the alternative of a basin, but now that the other fragments can be taken into account, some of which are clearly curved, one may abandon this hypothesis. All fragments need to be re-studied, if possible re-fitted, and would also deserve to be sampled and analysed in order to corroborate the suggestion that the silver-like white residue on the interior (Fig. 10a) is indeed litharge rather than calcium.

- **Cat. 6:** TC12.51 (context T12-4-1) + TC12.53 (context T12-4-2), 17 fragments of body profile of large

Fig. 12: Thorikos, Cistern No. 1, layer 5: tiles Cat. 7 and 11–12 (Drawings: R.F. Docter digitized by Q. Drillat; Photo's TARP). – a. – Cat. 7; b. – Cat. 11; c. – Cat. 12.

Fig. 13: Thorikos, Cistern No. 1, layer 5: small handstone Cat. 10 (Photo's: S. Duchène – TARP).

water jug or amphora of which 1 × 4, 1 × 2 and 1 × 3 joining (Fig. 11a).
PH ca. 30.0, diam at carination 30.0.
Clay: reddish brown 5YR6/6. Surface light reddish brown 5YR6/4. Imported fabric with some rounded quartz (0.2 mm), some white lime particles (0.1 – 0.3 mm), and few pink particles (0.5 – 1.0 mm).
Carinated at shoulder, grooves around the neck.
Chronology: Early Hellenistic.

At first sight, the shape of the body reminds of that of transport amphoras, which would not be impossible in view of the remarkable fabric that is otherwise not attested in Thorikos and would be suggestive of an import (Fig. 11a). On the other hand, it reminds of S. Rotroff's description of the Pink Temper Fabric (*Agora* XXXIII, 23 – 28), so one is tempted to look for comparisons in the Hellenistic repertoire of household pottery. Indeed, amongst the typical Hellenistic water jugs that started to be produced as from 325 and continued into at least the 1st century BC, one finds several potential comparisons (*Agora* XXXIII, 73–77). Especially in the jug forms 1 and 2 parallels that would match the large size, can be found. The bulging shape of the body finds a perfect parallel in the Agora, contextually dated to ca. 325–290 BC, although of smaller dimensions (*Agora* XXXIII, p.249 fig.7, pl. 7, cat. 39). As S. Rotroff kindly indicated (by e-mail of 2.8.2020), the large size would fit more jug form 2 and the fabric does look quite a lot like the Pink Temper Fabric she distinguished in the Agora material (*Agora* XXXIII, pp.23–28, figs.6–7, tab.7). In Athens, "almost all instances of Pink Temper that I have seen at the Agora date in the 2nd or 1st century – there are only a couple that might date before 200, and none in early Hellenistic deposits."

- **Cat. 7**: TC12.135 (context T12-4-1), edge fragment of cover tile in Plain Ware (Fig. 12a).
  PH 4.2.
  Clay: yellowish red 5YR5/6. Surface reddish yellow 7.5YR6/6, partly covered with calcareous concretions. Fabric with many quartz (0.1–0.2 mm) and few white particles (0.2 mm).
  Chronology: Archaic/Classical?
  The Plain Ware cover tile belongs to a Laconian roof system of which several other ones (in different shapes) have been encountered in the upper fill of the cistern (Docter, Monsieur and van de Put, 2011, pp.114–116, fig.39, cat.96–101, esp. cat. 98).
- **Cat. 8**: TC12.136 (context T12-4-1), rim fragment of mortar in cooking ware (Fig. 11b).
  PH 2.5, diam rim ?
  Clay: red 10R4/6, gray towards both sides. Surface reddish brown 2.5YR4/4, burnished on both sides. Imported fabric with many angular and subangular quartz and stone particles (0.2-0.4 mm).
  Chronology: Archaic-Classical.
  Precise comparisons for the rim fragment could not be found. An Archaic rimless version of a conical flat-based mortarium from the Athenian Agora (P8860) is closest (Villing and Pemberton, 2010, pp.567–568, fig.5). Other parallels in cooking ware show a more rounded rim: one from Thorikos, dated to the second half of the 5th century BC (Vanhove 2014, pp.91, 114, cat./fig.101), and two from Athens, dated to ca. 520–480 and ca. 425–400 BC respectively (*Agora* XII, p.369 fig.16, pl.90, nos.1891, 1893).

T12-4-2

- **Cat. 9**: TC12.52 (context T12-4-2), rim-neck fragment of hydria or table amphora in Cooking Ware (Fig. 11c).
  PH 4.7, diam rim 14.0.
  Clay: reddish yellow 7.5YR6/6 with wide dark grey core. Surface brown 7.5YR5/3. Imported fabric with some dark gey and few shining particles (mica?) (0.1–0.2 mm) and few lime particles (0.5–1.0 mm).
  Chronology: Classical/Early Hellenistic.
  The fragment may have belonged to a hydria or table amphora, even though an exact parallel for the particular rim shape could not be found. Comparable rims of Cooking Ware hydriai have been published from Athens (*Agora* XII, 348, fig. 17, pl. 71, no. 1596; Rotroff and Oakley 1992, 121, fig. 26, pl. 58, cat. 328), dating to the last quarter of the 5th century BC. Also, Late Classical table amphorae of Form 3 from the Athenian Agora, dated to the period 375–300/275 BC, are more or less comparable (*Agora* XXXIII, pp.87, 257 fig.20, pl.18, cat.123). The Vari House yielded a similar rim of a neck amphora, dated by its general context to the period 350–275 BC (Jones, et al., 1973, pp.381–382, pl.74 fig. 8, cat.49). Farther away, a 4th century BC (ca. 375–330) context at Thasos has yielded similar rims belonging to amphoras and large jugs (*cruches*) executed in the local Thasian Cooking Ware (Blondé, 1989, pp.531–532, fig.21, cat.230–231).

T12-5-1

- **Cat. 10**: TP12.39 (context T12-5-1), small handstone (Fig. 13)[3].
  H 6.5, max. preserved length 5.9, max preserved width 4.5.
  Surface dark grey 10YR4/1.
  TP12.39 is a half cobble of fine-grained, greenish grey rock (possibly sandstone) used as a handstone for crushing and perhaps also grinding. The relief of the flatter surface seems to be altered by the use. The edges of the surface are softened. The rounded side features at least three flattened or slightly incurved zones. One of these shows possible impact traces and seems to be covered by a dark polish. Unknown white deposit sticks to the rounded side. The actual and precise function of TP12.39 could only be revealed by a use-wear analysis and by a study of hypothetical residues that might still be trapped in the relief of the stone. This type of tool is not specific to any period and is not incompatible with a Classical or Hellenistic context, as shown by small handstones found in Halieis (Kardulias and Runnels, 1995, p.121, figs104–105).
  Rock: fine-grained, greenish grey rock, possibly sandstone. Unknown provenance.
  Chronology: Classical/Hellenistic?
- **Cat. 11**: TC12.40 (context T12-5-1), 3 joining edge fragments of pan tile in Red Glazed Ware (Fig. 12b).
  PH 10.0.
  Clay: reddish brown 10YR5/4. Surface interior upper side reddish brown 5YR4/3 glaze, partly worn off; roughened on outer, lower side. Fabric with many white foraminiferi (0.1–0.2 mm) and some quartz and dark particles (0.3–0.4 mm).
  Chronology: Archaic/Classical?
  The Red Glazed Ware pan tile belongs to a Laconian roof system of which several other ones (in different shapes) have been encountered in the upper fill of the cistern (Docter, Monsieur and van de Put, 2011,

p.114). The fact that three large fragments (with ancient breaks) join suggests that they ended up as one tile or as a very large fragment in layer 5 of the fill.

- **Cat. 12**: TC12.41 (context T12-5-1), 2 joining edge fragments of cover tile in Black Glaze Ware, recently broken (Fig. 12c).
  H 8.3.
  Clay: red 10YR5/6. Surface red 10YR5/6 on roughened lower side and traces of good black glaze on top, covered with greyish white film. Fabric with much fine mica, some quartz and stone particles (0.5 – 1.0 mm), and isolated reddish particle (2.5 mm).
  Chronology: Archaic/Classical?
  The Black Glaze Ware cover tile belongs to a Laconian roof system of which several other ones (in different shapes) have been encountered in the upper fill of the cistern (Docter, Monsieur and van de Put, 2011, pp.114 – 116, fig.39, cat.94 – 95). The particular edge finishing is more or less comparable with the Plain Ware cover tile Cat. 7 (Fig. 12a).
- **Cat. 13**: TC12.43 (context T12-5-1), wall fragment with lower handle root of kantharos (Fig. 11d).
  PH 2.2, diam wall 11.0, handle section 0.8 × 1.2.
  Clay: pinkish grey 7.5YR6/2. Surface good dark reddish brown 2.5YR3/3 glaze. Fabric with no visible inclusions.
  Chronology: *ca.* 375 – 275 BC.
  The fragment may have belonged to a kantharos with either plain or moulded rim that have been dated from the second quarter of the 4th to the middle of the 3rd century BC, becoming already rare in the third quarter of the 3rd century BC (*Agora* XXIX, pp.83 – 85, figs.4 – 6, pls.1 – 5). Thorikos has yielded quite a few published examples of these kantharoi that may be considered as 'guide fossils' tracing occupation in Late Classical and Early Hellenistic Thorikos. Their presence in the Industrial Quarter of Thorikos is well attested with at least 23 published examples: House no. 1 (Mussche, 1998, pp.70, 160 figs.141 – 142, cat.28); House no. 4 (Mussche, 1990, pp.50 – 51, fig.45, cat.100 – 101); Insula 1 (Vanhove, 2006, pp.10, 159 figs.30 – 31, cat.15); Insula 3, Tower Compound (Spitaels, 1978, pp.92, 94 – 95, 98 – 99, figs.52, 56, cat.98, 114 – 116; cat.98 = Mussche, 1967, p.64 fig.79; Vanhove, 2006, pp.53, 191 figs.203 – 204, cat.98); South of Insula 3 (Vanhove 2006, pp.53, 191 figs.201 – 202, cat.97); Insula 10, Sanctuary (Mussche, 1971, pp.126 – 128, 130 – 131, figs.82, 84); upper layers of Cistern No. 1 (Docter, Monsieur and van de Put, 2011, pp.79 – 80, fig.5; Mortier, 2011, pp.133 – 134, fig.2). The Theatre area and the West Necropolis each yielded one published kantharos of this type (Bingen, 1978, p.181 fig.109 = Vanhove, 2006, pp.102, 226 figs.358 – 359, cat. 167 and Vanhove, 2006, pp.92, 218 – 219, figs.322 – 323, respectively).

T12-5-2

- **Cat. 14**: TC12.49 (context T12-5-2), base fragment of closed vessel (Fig. 11e).
  PH 2.3, diam base 10.
  Clay: yellowish red 5YR5/6. Surface reddish brown 5YR5/4 at base, good black glaze on outside. Fabric with few shining particles (<0.1 mm).
  Chronology: Classical/Early Hellenistic.
  The ring foot is probably to be attributed to an oinochoe or lekythos for which several parallels can be found in the Athenian Agora: Rotroff and Oakley, 1992, 116, fig. 19, pl. 54, no. 285, dated to the period 475 – 425 BC, and *Agora* XII, 313, fig. 19, pl. 38, no. 1108 = *Agora* XXIX, 349, fig. 69, pl. 81, no. 1110, dated to the period 325 – 275 BC.

Fig. 14: Thorikos, Cistern No. 1, layer 9: pottery Cat. 15–16 (photo: TARP); – a. Cat. 15; – b. Cat. 16.

Layer 6

Below Layer 5, a thin layer of ca. 10 cm thickness was encountered containing a large amount of mortar (T12-6-1/2). Consequently, it was much lighter in colour, with an ashy texture. Apart from one very small pottery fragment, no other finds were recorded.

T12-6-1

This context only contained mortar of which one sample was kept.

T12-6-2

This context, dug on the next day, also contained mainly mortar and one tiny fragment in the sieving sample.

Layer 7

Layer 7 (T12-7-1), below layer 6, had the exact same characteristics as layer 5, but contained only one pottery fragment. In the north and west corner, a collection of small rocks and large chunks of plaster were recorded,

No.	Shape + feature	Ware	Remarks	Chronology	Cat./Fig.	Context
1. Transport and Storage						
1	Amphora wall fragments	Plain, White-washed	Import	Classical?		T11-16-1
17	Large jug or amphora profile fragments	Plain	Import	Classical/Hellenistic	Cat. 6; Fig. 11a	T12-4-1
3	Amphora wall fragments	Plain	Lesbian grey, not joining	Archaic/Classical		T12-4-1
2	Amphora wall fragments	Plain	Import, different fabrics	Classical?		T12-4-1
1	Amphora wall fragment	Plain	Import; small fragment	Classical?		T12-5-1
1	Amphora neck fragment	Plain	Imported	Classical?		T12-5-2
1	Closed vessel wall fragment	Black Glaze	Local; thick-walled	Classical		T12-5-2
2. Food preparation (before cooking)						
1	Mortar base fragment	Plain	Local	Classical?	Cat. 2	T11-16-1
1	Mortar rim fragment	Cooking	Import	Classical	Cat. 8; Fig. 11b	T12-4-1
1	Mortar wall fragment	Plain	Import	Classical?		T12-4-2
3. Cooking						
2	Cooking pot wall fragments	Cooking	Local?	Classical?		T11-16-1
2	Cooking pot wall fragments	Cooking	Import	Classical?		T12-4-2
1	Cooking pot wall fragment	Cooking	Import	Classical?		T12-5-1
4. Serving and consumption						
4A. Food serving and consumption						
-	-	-	-	-	-	-
4B. Drinking (serving and consumption)						
1	Jug base fragment	Red Washed	Local	Classical?	Cat. 3	T11-16-1
1	Hydria or table amphora rim fragment	Cooking	Import	Classical/Hellenistic	Cat. 9; Fig. 11c	T12-4-2
1	Kantharos handle fragment	Black Glaze	Local	375-275 BC	Cat. 13; Fig. 11d	T12-5-1
4C. Undistinguishable (eating/drinking)						
2	Undetermined wall fragments	Plain	Small fragments; local	Classical?		T11-16-1
2	Closed vessel wall fragments	Plain	Local	Classical?		T11-16-1
2	Closed vessel wall fragments	Cooking	Import	Classical		T12-4-1
1	Closed vessel wall fragment	Plain	Import	Classical?		T12-4-1
1	Closed vessel wall fragment	Plain	Local	Classical?		T12-4-1
1	Closed vessel wall fragment	Plain	Local; small fragment	Classical?		T12-4-2
1	Open vessel wall fragment	Black Glaze	Small fragment; local	Classical		T12-5-1
1	Oinochoe or lekythos base fragment	Black Glaze	Local	Classical/ Early Hellenistic	Cat. 14; Fig. 11e	T12-5-2
1	Closed vessel wall fragment	Black Glaze	Local; thin-walled	Classical		T12-5-2
5. Lighting						
-	-	-	-	-	-	-
6. Industrial and domestic artisanal activities						
2	Basin base fragments	Coarse	Local	Late Classical/Hellenistic?	Cat. 1+5; Fig. 10a	T11-16-1 T12-4-1
1	Small handstone	Sandstone?	Imported?	Classical?	Cat. 10; Fig. 13	T12-5-1
7. Architectural						
1	Cover tile edge fragment	Red Glaze	Local	Archaic/ Classical?	Cat. 4	T11-16-1
1	Cover tile wall fragment	Red Glaze	Local	Archaic/ Classical?		T11-16-1
1	Cover tile edge fragment	Plain	Local	Archaic/ Classical?	Cat. 7; Fig. 12a	T12-4-1
3	Pan tile edge fragment	Black Glaze	Local	Archaic/ Classical?	Cat. 11; Fig. 12b	T12-5-1
2	Cover tile edge fragment	Black Glaze	Local	Archaic/ Classical?	Cat. 12; Fig. 12c	T12-5-1
1	Cover tile edge fragment	Plain	Local; small fragment	Archaic/ Classical?		T12-5-1

Tab. 1: Functional distribution of the finds from Layer 5 (TARP).

No.	Shape + feature	Ware	Remarks	Chronology	Cat./Fig.	Context
4. Serving and consumption						
4C. Undistinguishable (eating/drinking)						
1	Closed vessel wall fragment	Plain	Local; tiny fragment from sieving sample	Classical?		T12-6-2

Tab. 2: Functional distribution of the finds from Layer 6 (TARP).

No.	Shape + feature	Ware	Remarks	Chronology	Cat./Fig.	Context
1. Transport and storage						
1	Amphora wall fragment	Plain	Imported; small fragment	Classical?		T12-7-1

Tab. 3: Functional distribution of the finds from Layer 7 (TARP).

No.	Shape + feature	Ware	Remarks	Chronology	Cat./Fig.	Context
3. Cooking						
1	Closed vessel wall fragment	Cooking	Imported	Classical	Cat. 16; Fig. 14b	T12-8-1
4. Serving and consumption						
4B. Drinking (serving and consumption)						
1	Cup handle fragment	Black Glaze	Local	Archaic/ Classical	Cat. 15; Fig. 14a	T12-8-1

Tab. 4: Functional distribution of the finds from Layer 9 (TARP).

as indicated on the section drawings (Figs. 7 – 8) as a separate layer 8.

T12-7-1

Layer 9

The last layer encountered in the basin was a very thin compacted stratum, brown reddish in colour with a silty sand texture (T12-8-1). It contained only two small sherds, one of which with heavy calcareous concretions. At a depth of 4.9m, measured from the highest point of the masonry wall, the bottom of the cistern was reached. This cistern floor, which appeared after the removal of layer 9, was meticulously coated with waterproof mortar of a very good quality. As other mortars in the Laurion, it consisted of two layers: a thick white-yellowish lime mortar, measuring approximately 10 cm in width, and a fine coating, black in colour and consolidating the whole (cf. Van Liefferinge, et al., 2011, pp.60, 62 fig. 6).

T12-8-1

- **Cat. 15:** TC12.2 (context T12-8-1), wall fragment with horizontal handle root of Black Glazed Ware cup, with heavy calcareous encrustations all over (Fig. 14a).
  Clay: Attic, good black glaze.
  Chronology: Archaic/Classical.
  The small fragment of a rather sturdy handle may have belonged to several types of Archaic or Classical cups or cup-skyphoi (Agora XII, pp.88 – 112, pls.18 – 27, figs.4 – 6).
- **Cat. 16:** TC12.3 (context T12-8-1), wall fragment of closed vessel in Cooking Ware (Fig. 14b).
  Clay: imported.
  Chronology: Classical.

Last use and abandonment

Cistern No. 1 had been constructed probably during the late 5th century BC and it remained in use (perhaps with a hiatus in the aftermath of the Peloponnesian War) till the end of the 4th or first quarter of the 3rd century BC. The two very small fragments in layer 9 on the bottom of the cistern (Cat. 15 – 16; Tab. 4; Fig. 14) may well belong to the last use phase of the installation, having washed into the basin or remained there after the last cleaning. The calcareous concretions on Cat. 15 (Fig. 14a) would plea in favour of such a reconstruction. Layer 8, consisting of large chunks of plaster and some small rocks, probably originated in a first collapse of the cistern lining higher up and, hence, belong to the phase of abandonment after the cistern fell into disuse (Figs. 6 – 7). The very fine dark brown, perfectly horizontal layer 7 with only one small pottery fragment included (Tab. 3) may originate in the further but gradual deterioration of a mudbrick superstructure, the erosion material of which was able to settle gently in the basin. This layer was covered by the equally horizontal layer 6 consisting of mortar debris, probably resulting from the further collapse of the cistern lining, and only one tiny pottery fragment (Tab. 2). It is very likely that up to that moment the exterior walls of the cistern, at least the northern and eastern uphill ones, still stood to some height, protecting the cistern from filling rapidly with erosion material. It is not even impossible that part of the roof still existed at that time. Layer 5 was formed definitely at the moment, when the uphill walls had (partially) collapsed, allowing water and erosion material to enter the cistern and depositing a thick layer of dark silty sand sloping downwards from north-east to south-west, so coming from uphill (Figs. 6 – 7). As in the case of layer 7, this material is probably to be interpreted as disintegrated mudbrick stemming from these very walls. The chronology of the household pottery included in layer 5 (Tab. 1) that probably originated in the living quarters of the *ergasterion* suggests that this sequence of micro-events may have occurred within the timeframe 325 – 275 BC, exactly the moment when silver extraction also witnessed a sharp decline elsewhere in Thorikos and the Laurion (Docter and Van Liefferinge 2010, pp.57 – 58). The lack of lamps (Tab. 1), otherwise so ubiquitous in mining area deposits, may just be accidental; in the upper layers of the cistern they do occur (Docter, Monsieur and van de Put, 2011, p.81 fig.9, cat.17). The large and joining fragments of tiles (Fig. 12) may suggest that at this moment the remainder of the roof of the cistern or of a nearby construction had collapsed (or had been taken away for reuse elsewhere, leaving only the broken ones). The fragments of the large basin Cat. 1+5 (Fig. 10) may have belonged to the working apparatus of the *ergasterion*, perhaps having stood on the northern platform of the cistern in Sector E (Fig. 6). Once broken, its pieces ended up first in layer 5 and on top of it and – still later – in the upper layers 2 – 4 (Cat. 5; Figs. 6 – 7). Also, the small handstone Cat. 10 (Fig. *13*) in this layer may once have been part of the *ergasterion*'s apparatus. The large profile of a Hellenistic water jug or amphora Cat. 6 (Fig. 11a) that was found in large pieces on top of layer 5 concludes this phase. It may either date to the last phase of use and have fallen, washed or thrown in during this abandonment period, or it may be a testimony of some later Hellenistic visitor or inhabitant of Thorikos trying to scoop water from the abandoned and already partially filled cistern and dropping it in the process. This may well have been as late as the 2nd or 1st century BC, if the attribution of the fabric to the Pink Temper Fabric of Cat. 6 (Fig. 11a) proves to be correct. Such a late chronology for at least some activities around the cistern seems also suggested by the carination fragment of a brown glazed lagynos (?) found higher up in the stratigraphy and dated to ca. 200 – 175 BC (Mortier 2011, p.136, cat.6, fig.5). The upper layers 1 – 4 (Figs. 6 – 7), then, conclude the story of this cistern; they contain mainly rubble and ashlar wall collapse mixed with quite a number of mainly small and worn fragments of Late Archaic and Classical/Early Hellenistic household pottery that had eroded into the basin from higher up the Velatouri (Fig. 5). The fact that also larger fragments of Late Antique domestic pottery and of a rotary hand mill are mixed in these same layers suggests that some activity took place around Cistern No. 1 from the 6th to within the 8th century CE. It is likely that this cistern, even partially filled in, still functioned as a collection basin for water that attracted people to settle nearby, probably the very same people that frequented and exploited (?) the mining galleries of Thorikos in this period (Docter, Monsieur and van de Put, 2011, pp.118 – 120; Morin and Delpech 2018; Konstantinidou, et al., 2018). That the vicinity of the Mine No. 2 entrances, therefore, formed another attraction factor for these people is not unlikely, but remains to be investigated.

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Special Research Fund of Ghent University to prepare the comprehensive publication of the cistern excavations. Unfortunately, the Covid-19 outbreak prevented a scheduled control campaign in the storerooms of the Lavrio Museum (e.g., of Cat. 1 – 5). The Proceedings of the International Conference »Ari and the Laurion from Prehistoric to Modern Times« in October/November 2019 offered the logical venue to present at least part of the results. We thank the organizers, Prof. Hans Lohmann, Dr. Frank Hulek and Dr. Sophia Nomicos, for their warm hospitality at Bochum and their patience in preparing the proceedings and, last but not least, we thank the participants for their comments and stimulating discussions during the conference.

Notes

1 The results presented here mainly stem from the 2012 fieldwork campaign directed by R.F. Docter and F. van den Eijnde. K. Van Liefferinge co-directed the cistern excavations with C. Stal being in charge of the geomatical part. R.F. Docter, W. van de Put and S. Mortier were responsible for the pre-registration of the contexts upon which the conclusions in this article are based. Fabric descriptions and drawings have been made by R.F. Docter. S. Duchène added the comments on the stone tools.

2 Colour descriptions follow *Munsell Color,* 1990. Measurements are in cm unless otherwise stated. All clay descriptions are based upon a macroscopic analysis unless otherwise stated.

3 Although TP12.39 has not been fully studied yet, this description could be given based on the pictures and the preliminary observations made during the pre-registration of the finds. A more comprehensive study of the crushing and grinding stone tools of Thorikos is prepared by S. Duchène, *Crushing and grinding in Thorikos* within the framework of a PhD study funded by the Special Research Fund Ghent University (2017-2021).

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Sophie Duchène

A Byzantine rotary hand mill in Thorikos

ABSTRACT: *The excavation of Cistern No°1 has shown that the latest occupation phase in Thorikos might extend further in time than has been thought initially. Among the finds, two uncommon rotary hand mill's fragments, belonging to the cistern's upper layer, allow expanding upon the knowledge of this latest phase. This contribution presents several aspects of these finds, like their typology and raw material, and discusses their chronology. It also sums up archaeological data relative to Late Antique and Byzantine remains in Thorikos and Lavrio to put the finds into a broader perspective. The paper concludes that the rotary hand mill might date from the 7th – 8th century AD or later and emphasizes the need to publish such kind of data systematically.*

KEYWORDS: LAURION, CISTERN NO°1, MILLSTONES, GRINDING, MILLING EQUIPMENT, VOLCANIC ROCK

Introduction

From 2010 to 2012, a team of archaeologists from Ghent and Utrecht Universities, directed by R.F. Docter and F. van den Eijnde, conducted archaeological investigations in the zone of Cistern No°1 in Thorikos. The excavation of the cistern, co-directed by K. Van Liefferinge, resulted in the publication of three preliminary reports in 2011: one presenting the primary raw data and giving some initial interpretations (Van Liefferinge, et al., 2011), one giving an overview of the Late Archaic to Late Antique finds from the fill and the surroundings of the cistern (Docter, Monsieur and van de Put, 2011), and one focusing on the Late Classical and Early Hellenistic finds (Mortier, 2011). Elsewhere in this volume, another contribution deepens the study of the finds related to the last use and abandonment of Cistern No°1. Within this context, the present publication aims at providing information on an exceptional type of find in Thorikos: a rotary hand mill, of which two non-joining fragments were found during the 2011 excavations. Although somewhat isolated in Thorikos' archaeological record, these two finds are of great importance and provide the opportunity to reflect and expand upon the knowledge of the latest, less well-known phase of the site's occupation.

Description of the finds and contexts

The fragments were registered as TP11.149 and TP11.545. Although they are non-joining, they belong probably to the same grinding implement. Both were found in the same area of the cistern and have the same material characteristics.

TP11.149 is a fragment of the upper stone of a rotary hand mill (Fig. 1). Part of the collar, eye and cutting for the rynd is preserved (see Fig. 2 for the terminology).

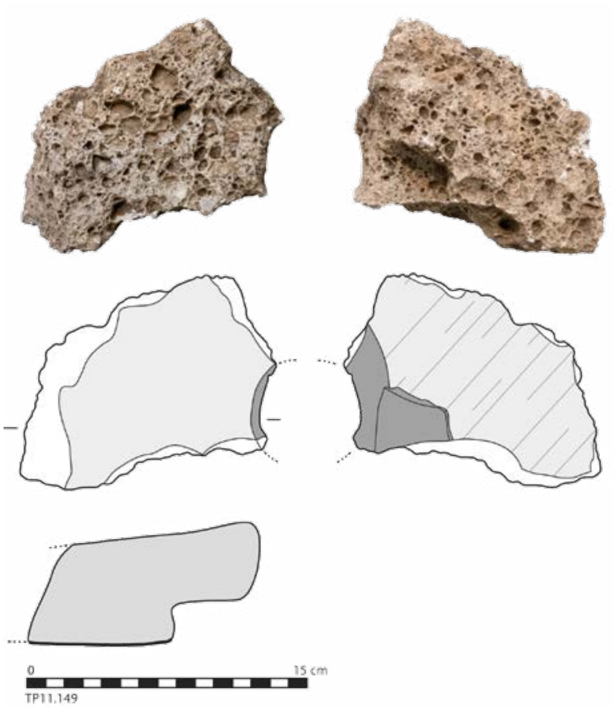

Fig. 1: Thorikos, Cistern No°1, fragment of the upper stone of a rotary handmill, Cat. 1: TP11.149 (source: S. Duchène).

The maximum preserved radius is 13 cm. The preserved height ranges from 6.7 cm at the top of the collar to 6 cm elsewhere. The weight of this fragment is 0.7 kg. It is made of a white vesicular igneous rock.

Likewise, TP11.545 is a fragment of the upper stone (Fig. 3). However, no typological features were conserved. The maximum preserved dimensions of the fragment are 9.5 cm by 7.8 cm, and its maximum preserved height is 5.1 cm. The fragment weighs 0.3 kg. It is made of the same white vesicular igneous rock as TP11.149.

TP11.149 and TP11.545 were found respectively in contexts T11-15-1 and T11-10-3. The latter was excavated in the upper layers of the cistern's zone A (Fig. 4; see also Van Liefferinge, et al., 2011, fig.10). It is the continuation of T11-10-1 and -2 and is followed by T11-10-4, -5, and -6. These contexts are characterized by a layer of fine brownish silty sand and a considerable quantity of stones (layer 2), concealed under a top layer of humus and large stone blocks (layer 1) (Van Liefferinge, et al., 2011, p.66; Docter, et al., this vol., figs.6 – 7). Besides TP11.545, T11-10-3 yielded a series of sherds ranging from Archaic time to Late Antiquity. Like T11-10-3, context T11-15-1 (where TP11.149 was excavated) is located in zone A of the cistern. However, T11-15-1 is completely contaminated as it consists of cleaning operations of a trench dug in 2010.

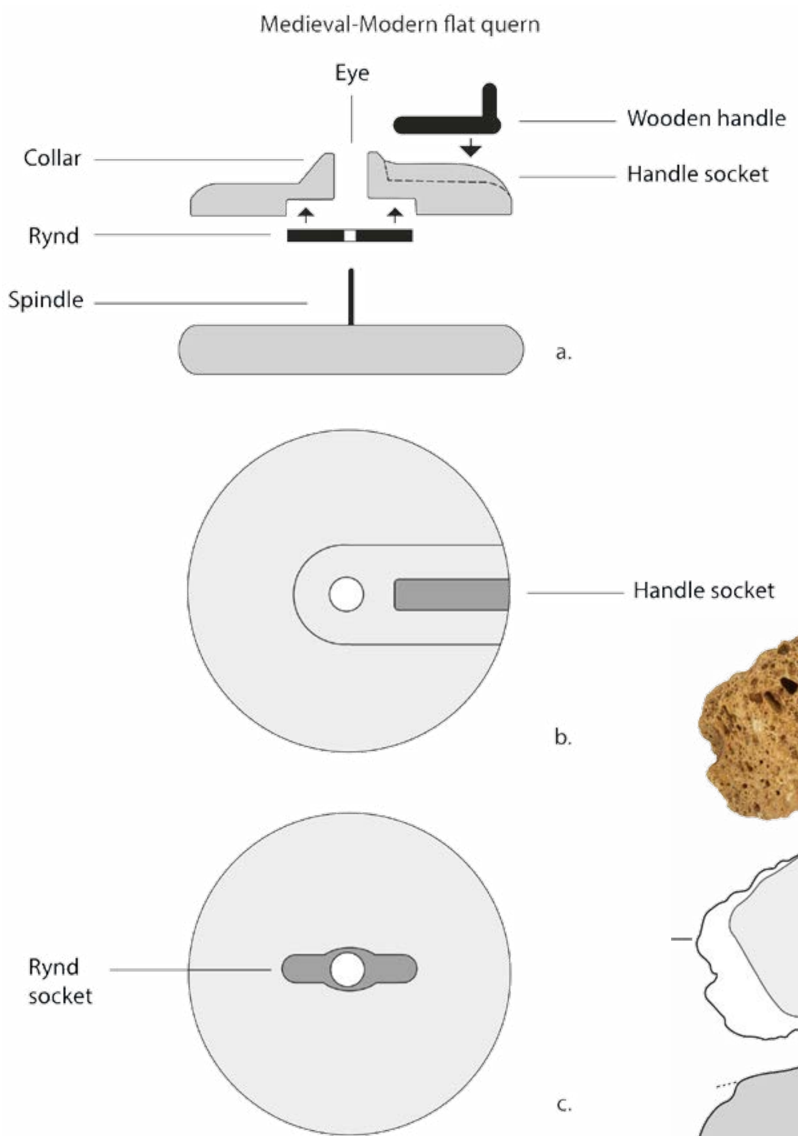

Fig. 2: Simplified drawing of a medieval-modern rotary hand mill, modified by S. Duchène, after Kardulias and Runnels (1995, fig. 96). – a. Section view of the mill; – b. Top view of the upper stone; – c. Bottom view of the upper stone, modified by S. Duchène, after Kardulias and Runnels (1995, fig. 96).

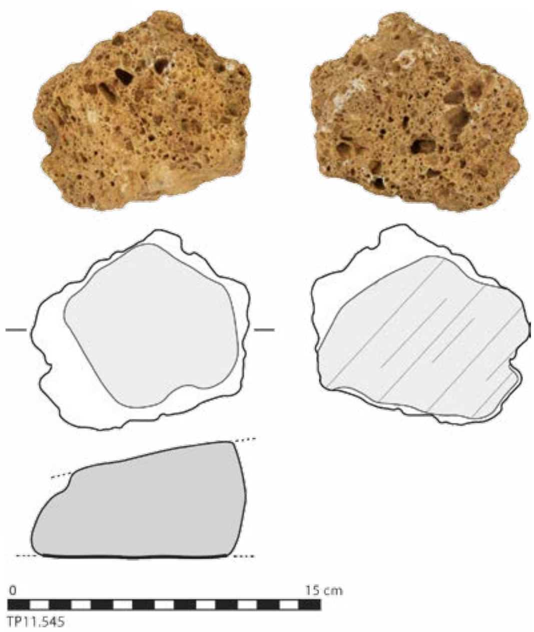

Fig. 3: Thorikos, Cistern No°1, fragment of the upper stone of a rotary handmill, Cat. 2: TP11.545 (source: S. Duchène).

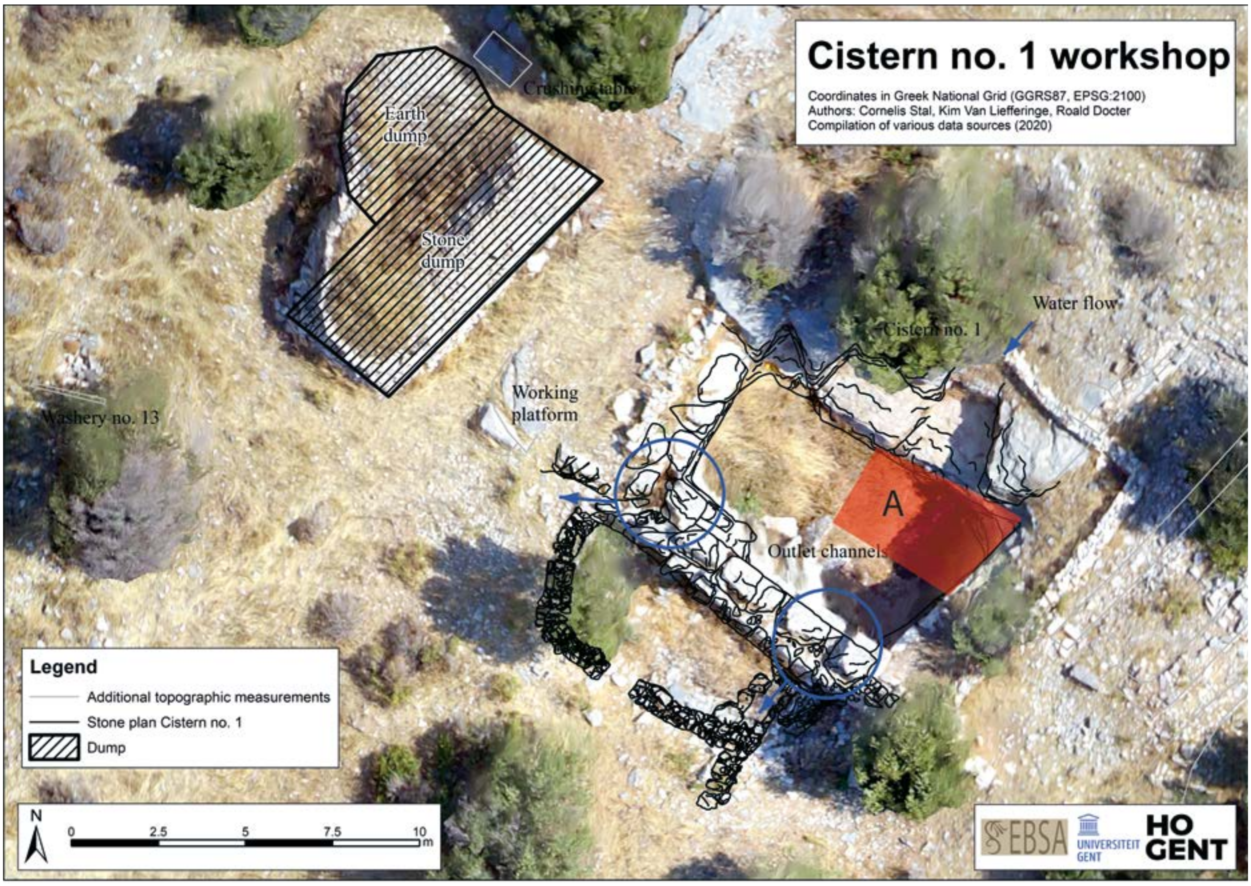

Fig. 4: Thorikos, map of Cistern No°1 with the indication of zone A, modified by S. Duchène, after a map by C. Stal, K. Van Liefferinge and R. Docter, TARP 2020.

The upper layers of the fill belong to the very last episodes of occupation of the cistern's area. These episodes can be situated in the 6th, 7th, and even 8th centuries AD (Docter, Monsieur and van de Put, 2011, pp.95, 108, 119–120, cat.51, 80). The above implies that only limited chronological insight can be obtained from the archaeological contexts to help to date TP11.149 and TP11.545 more precisely. Therefore, the typological aspects of the fragments should be examined in an attempt to identify a more specific period. The next two sections propose, firstly, an overview on rotary hand mills and, secondly, a more specific look at the type of mills in the Aegean.

Rotary hand mills: an overview

Rotary hand mills – or querns – consist of a fixed lower stone (*meta* or μύλη), and of a mobile upper stone (*catillus* or ὄνος) which is operated by hand in a continuous, or in

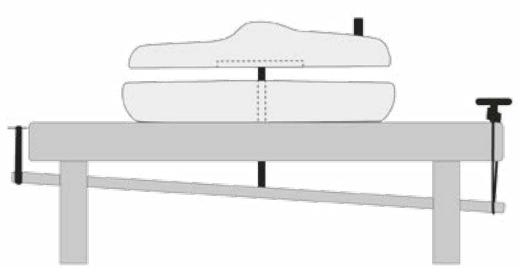

Fig. 5: Simplified drawing of a rotary hand mill with the spindle resting on a bridge tree, modified by S. Duchène, after Runnels (1988, fig. 1) and Longepierre (2010, fig. 7). Not to scale.

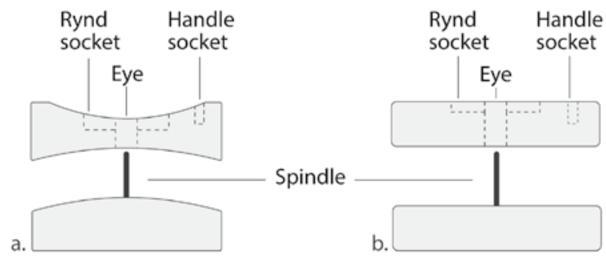

Fig. 6: Simplified drawings of Roman and Late Roman rotary hand mills in Argolid, Isthmia, Corinth and Athens according to C. Runnels, modified by S. Duchène, after Runnels (1990, fig. 1). Not to scale.

some cases semi-continuous, circular motion. Rotary hand mills originate in the Western Mediterranean and seem to be the result of an Iberian innovation taking place at the end of the 6th or the beginning of the 5th century BC (Alonso, 2002; Alonso and Frankel, 2017, p.470). Over the centuries, this new type of implement spread across the Mediterranean to reach Greece in the 1st century BC and Israel in the 1st century AD, under the influence of the Roman expansion (Runnels, 1990, p.147; Alonso and Frankel, 2017, p.470).

Their morphology varies over time and depending on the region, but some general features, not typical to Greek specimens only, can be summed up as follows (Fig. 2).[1] Both stones are generally circular in outline, but their shape can fluctuate in section. The upper stone, for example, can be cylindrical, hemispherical or flat (Peacock and Green, 2013, pp.65 – 71). Besides the shape of the millstones, other elements characterize the rotary hand mill. A hole, or eye, is usually drilled in the centre of the upper stone to allow the material to be ground to flow down between both implements. Another feature is the vertical spindle in metal or wood, which is fastened in the middle of the lower stone and topped the rynd. The latter is a horizontal component usually inserted somewhere above or under the eye. Together, spindle and rynd keep both stones in the same axis and avoid deviations of the circular motion (Alonso and Frankel, 2017, p.470). In more advanced configurations, the spindle goes through the whole thickness of the lower stone and is connected to a mechanism under the latter, which allows adjusting the distance between both millstones (Fig. 5; see also Longepierre, 2010, p.92 fig. 7). Finally, one or more cavities were cut on the top or on the lateral side of the upper stone to fasten the handle.

Rotary hand mills in the Aegean

Turning now specifically to rotary hand mills in the Aegean, a scarcity of finds, publications and recent systematic studies is to be deplored.[2] Medieval hand mills are particularly poorly documented (Arthur, 2011, p.205). However, the seminal article of C. Runnels (1990), based on the examination of 36 specimens from Corinth, Athens, Isthmia and the Southern Argolid, provided a general framework for chronologically distinguishing rotary hand mills. According to Runnels, rotary handmills were introduced in Greece by the Romans after the first century BC onwards (Runnels, 1990, p.147). From then on, rotary handmills underwent a typological transformation which has allowed archaeologists to distinguish between Roman and medieval mills. In his data set, rotary hand mills of Roman and Late Roman sites up until 6th century AD were of two types: hopper querns, which had a large, hopper-shaped upper stone, and flat querns (Fig. 6). The rynd was always inserted above the eye. On the contrary, medieval-modern rotary querns from 12th to 18th-century sites he studied never had a hopper and were always flat. They typically had a raised collar around the eye, and the rynd socket was located underneath the upper stone (Runnels, 1990, p.151) (Fig. 3).

Moreover, according to Runnels (1990, pp.151 – 152), the raw material seems to be another way to distinguish between Roman and medieval querns. Indeed, in his study, the Roman and Late Roman samples were usually made of the same kinds of volcanic rocks[3] that he called andesite and were commonly used for other grinding stones (Runnels, 1990, p.151). By contrast, most medieval and modern querns examined by the scholar appear to be made of a previously not attested, pale orange or nearly white vesicular hydrothermally altered volcanic rock (Runnels, 1990, p.153).

In this framework, the discovery of two pairs of rotary hand mills in the 11th-century shipwreck of Serçe Limani is of great importance since they are well-dated (ca. 1025 AD) and illustrate the typological features of medieval mills: flat querns, rynd cutting at the bottom of the upper stone and a raised collar around the eye (Runnels, 1988; 2004). Moreover, their raw material seemed very similar to medieval querns discovered in the Southern Argolid (Kardulias and Runnels 1995, p.127). O. Williams-Thorpe and R.S. Thorpe (Runnels, 2004, pp.259 – 260) conducted a limited provenance analysis on two samples of the Serçe Limani mills and suggested that they might come from Rema in Milos. In post-Medieval times, this rock was used to produce renowned millstones that made up the majority of the island's exports in the 19th century AD (Runnels, 1981, pp.235 – 236; Renfrew, 1982, p.278). However, Milos may be only one of many possibilities. Indeed, P. Arthur underlines that similar rock crops out elsewhere in the Aegean (Arthur, 2011, pp.205 – 206). Furthermore, according to R. Poupaki, who studied Koan rotary hand mills, a Koan origin for the Serçe Limani mills might also be considered (Poupaki, 2011, p.53; 2017, pp.86, 117).

This section has described characteristics that may help distinguishing medieval and modern rotary hand mills from Roman and Late Roman ones. However, before moving on to the next section, it is necessary to keep in mind that regional variations in typology and raw material undoubtedly existed.

A Byzantine rotary hand mill in Thorikos?

Let us now examine the fragments discussed in this paper in light of the characteristics described above. Even though TP11.149 (Fig. 1) is small and rather poorly conserved, it still preserves two essential features. First, at one end, a circular polished zone can be interpreted as a part of the eye. Secondly, a somewhat regular, although incomplete, cutting underneath the eye can be considered as the socket for the rynd. Noticeably, the section of TP11.149 also reveals a slight elevation around the eye, although the overall shape of the fragment indicates a rather flat quern. The second fragment (TP11.545) is flat in section but, unfortunately, did not keep any other typological feature.

The preserved characteristics of TP11.149 make it possible to attribute the fragment to a late period in the history of Thorikos. The position of the rynd socket underneath the eye suggests that the fragment did not belong to a Roman or Late Roman mill, but to a later one. Published parallels are scarce, but in the ancient Halasarna's data set, which ranges from Roman time to mid 7th century AD, no upper stone seem to have such an underneath rynd socket (Poupaki, 2011; 2017). Therefore, although a later date cannot be ruled out, it seems possible to attribute the fragments to a period ranging from the 7th century to the 8th century AD, following the chronology of the latest sherds identified in the cistern's fill.

Concerning the raw material, both fragments are made of the same white vesicular volcanic rock that seems to match the descriptions given of the Rema stone. As previously stated, caution must be applied since similar rocks possibly crop out elsewhere in the Aegean. The foreseen petrographic and geochemical analyses[4] of one of these fragments will tell whether or not Milos might have been the source of these finds.

Nevertheless, Rema stone remains a possibility, and would not be incompatible with a date in the 8th century AD. Indeed, P. Kardulias and C. Runnels observed a change in the raw material of Southern Argolid's grinding implements from the 7th century AD onwards (Kardulias and Runnels, 1995, p.127). Before that, most of grinding implements around the Saronic Gulf, in Argolid and Attica, were made of volcanic rocks imported from Aegina, Methana or Poros, since the beginning of the Bronze Age up into Classical time (Runnels 1981, p.114). From Classical time onwards new types of grinding implements made of black vesicular lavas were introduced from more distant places like Nisyros, which became the primary sources in Roman times (Runnels, 1981, pp.124 – 126, 130; Kardulias and Runnels, 1995, p.138). These millstones' exchange and trade circuits, which also applied to Thorikos and the Laurion,[5] seem to end somewhere around the 7th or 8th century AD. One explanation given by these scholars is the disruption of these circuits due to Saracen and Slavic raids that took place at that time (Kardulias and Runnels, 1995, p.138).

To conclude this section, although caution must be applied because of the lack of parallels, the fragments presented in this contribution might have belonged to a 7th – 8th-century AD rotary hand mill. This timeframe has been assigned based on the date of the latest sherds identified in the cistern's fill but also on the typological differences between Late Roman and medieval querns. However, this might be a very early date for such a mill, and a later one should not be dismissed. Therefore, it cannot be excluded that future publication of new material disproves this interpretation.

In the next section, some contemporary archaeological evidence in Thorikos and the Laurion will be briefly summed up to put the mill's fragments into a broader context.

Contemporary evidence

Scanty, yet solid evidence for occupation in Thorikos at the end of the Early Byzantine period can be found in Insula 3, more particularly in the Tower Compound AX. This complex, composed of a tower, buildings, and a courtyard, was erected in early 5th century BC. Since then, it has experienced several structural transformations and phases of occupation, the latest going from the 4th/5th to the 7th century AD (Spitaels, 1978, pp.67, 109; Kalaitzoglou, 2004, pp.67 – 94), or even possibly to the 8th century AD (Docter, Monsieur and van de Put, 2011, p.100).[6]

The nature of this latest occupation's phase is not precisely known but was perhaps related to a resumption of the mines' exploitation in the 5th century (Spitaels, 1978, p.109; Docter, Monsieur and van de Put, 2011, pp.119 – 120; Monsieur, 2008; Konstantinidou, forthcoming). According to H.F. Mussche (1998, p.65), the scale of this Late Roman occupation was limited, and it did not last after Slav incursions in 582 – 3 AD. However, as indicated previously, the results of the cistern's excavation and the study of the pottery indicate that this occupation did persist beyond that point and continued into the 8th century AD (Docter, Monsieur and van de Put, 2011, p.119 fig.46).[7]

In her PhD thesis on urban and rural landscape in Early and Middle Byzantine Attica between the 4th and 12th century AD, E. Tzavella reflects on these latest findings. She suggests that, during this last attested occupation phase, Thorikos might have functioned as a guardpost to control the bay (Tzavella, 2012, pp.203 – 204). However, the evidence is too scanty, and Tzavella does not exclude a purely domestic character either.

In Southeast Attica, other places have preserved Late Antique/Early Byzantine, 8th – 9th-century AD, or Middle Byzantine remains. T. Mattern (2010, pl. 53) and E. Tzavella (2012, pp.175 – 190) have listed many of these. Noticeably, at nearby Lavrio and thus not far from Thorikos, excavations have revealed finds or structures of Late Antique to Middle Byzantine date. There is the 5th-century AD basilica, where the well-known mosaic floor was discovered (Gini-Tsophopoulou, 1985, p.82). On the slopes of a little hill near to the scoria mount[8] Cordella (1869, p.32) reports the presence of a necropolis where several hundreds of coins from Constantine (311 – 337 AD) to Honorius (395 – 423 AD) were discovered. M. Salloria-Oikonomakou (2007, p.46) reports recent excavations in that area, which confirmed Cordella's findings, and states that an extensive settlement must have thrived at Lavrion from the 4th to the 7th AD. Besides the coins mentioned above, several later ones were found in Lavrio, some of which from the Middle Byzantine period (Cordella, 1869, p.32). Another unique find is a 9th – 10th century AD decorated bronze buckle that was discovered next to the basilica. Such a buckle could indicate the presence of a local elite in Lavrio at that time (Tzavella, 2012, pp.185, 205).

Although many events might have disturbed Attica's occupation pattern in Late Antiquity and Early Byzantine time (Mattern, 2010, p.202; (Docter, Monsieur and van de Put, 2011, p.120), the above indicates that Thorikos outlived these Late Antique events in a limited but evident way.

Finally, it is not known whether the millstone's fragments discussed in this contribution were used to grind grain or some other type of material. However, they indicate that somewhat regular domestic or artisanal activities may have taken place in the cistern's area. Likewise, millstone fragments discovered in a dark-age settlement in Isthmia's ancient Roman baths were considered as an indication of domestic activities (Gregory, 1994, p.159). If a 7th or 8th-century date is admitted for TP11.149 and TP11.545, they could be concomitant with the latest phase of the Tower Compound AX. If, at a later date, this interpretation turned out to be incorrect, these finds still can bring valuable information about later periods in Thorikos or be brought in relation to Middle Byzantine findings in the surrounding sites.

Conclusion

This contribution has shown that the lack of published parallels can impede a precise dating of finds. This is particularly true for grinding implements, which are often only reported, without any drawings or pictures. Hopefully, the publication of these finds will spark some interest and will encourage more systematic documentation of such artefacts.

Nevertheless, although caution is required, the finds were given a date in the 7th – 8th century AD at the earliest, based on their typological features and the latest sherds identified in the cistern's fill. They might be concomitant with the very last years of occupation in the Tower Compound or be related to a later event. Unlike H.F. Mussche stated (1998, p.65), it has become evident that Thorikos was not abandoned at the end of the 6th century AD.

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Notes

1 For a non-exhaustive overview of different types of rotary hand mills, the reader can consult, among others, the general publications of D. Peacock (2013, pp.54 – 76), and N. Alonso and R. Frankel (2017, pp.469 – 472). Although concerning more specifically specimens in France and Spain, many publications of the Groupe Meule also offer a thorough background on rotary mills (Buchsenschutz, et al., 2011; 2014).

2 Only a few studies were recently devoted wholly or partly to the analysis of this type of mill in the Aegean (e.g. see Poupaki, 2011; 2017).

3 Either grey, brown or reddish volcanic rocks containing crystals of plagioclase and iron-magnesium minerals, coming from the Saronic Gulf, or dark grey or black vesicular volcanic rock occurring in Nisyros or other islands.

4 These analyses will be conducted in collaboration with C. Mavrogonatos (National and Kapodistrian University of Athens, Faculty of Geology and Geoenvironment).

5 This question is part of the author's PhD research on the grinding and crushing implements found in Thorikos. See also Duchène (in prep.).

6 In the Tower Compound AX (Insula 3), one globular amphora initially attributed to the 5th or 6th century AD (Spitaels, 1978, p.103 n.45) might be of a later date given its similarity with 7th and 8th-century amphorae in Gortyn (Docter, Monsieur and van de Put, 2011, p.100; Poulou-Papadimitriou and Nodarou, 2007, p.758 fig. 6, no. 14).

7 The latest ceramic finds in the cistern's fill are 4 joining fragments of a cooking pot with parallels in the 7th and 8th centuries AD, and 2 joining fragments of a globular amphora of the same period (Docter, Monsieur and van de Put, 2011, cat. 51, 80).

8 This is the hill where the Greek Lavrion Mining Company's chimney stands (Salloria-Oikonomakou, 2007, p.45).

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Hélène Morin-Hamon

Flat-bedded washeries at Laurion (Greece): A buddling model.

A comparative study between archival and field evidence

ABSTRACT: *The research carried out on Laurion, and particularly on mining and the importance of the amounts extracted, raises the question of ore dressing and therefore the process involved. This is the presence of flat-washing dressing floors, flanked by tanks and accompanied by grinding workshops, near the extraction areas, the function and the role and skill of the workers in such devices. The washing facilities, used by the miners of the Laurion, have originated numerous interpretations and controversies. The aim of this paper is to update the various hypotheses and to compare the archaeological evidence with the devices implemented by the miners during the 18th and 19th centuries. In their reports, scholars at the Paris School of Mines meticulously described washing installations, particularly the buddles. A buddle is an elementary device used to separate ore from gangue by means of a water stream. The oldest and simplest constructions were an oblong, shallow pit dug into the ground, or a shallow, slightly inclined wooden channel. The process is simple: the mixture of ore and gangue was placed and agitated in a stream of water; the lighter particles were carried away, leaving behind them the much heavier galena. The typical length of a square buddle was around two meters, while the floors at Laurion are shorter. Research carried out on 18th/19th century washing technologies of large-scale washing of secondary iron ores in eastern France have led us to make comparisons with the installations at Laurion. The model proposed here is based on both field observations and iconographic and documentary sources. The washing process is somewhat explicit as soon as the primary product has undergone a first grinding treatment. The precise way to operate the devices becomes obvious once one immerses in such descriptions of the users in old mining journals. The best example is a 18th century mining treatise written by Franz Ludwig von Cancrin, a prominent metallurgist, mineralogist and miner from Hesse, Germany, which proves to be perfectly consistent with the lead-silver ore process in use at Laurion.*

KEYWORDS: LAURION, GREECE, ORE DRESSING, SILVER, WASHERIES, BUDDLE, 18TH/19TH CENTURY, DEVICES

Introduction

The research carried out on lead-silver mining at Laurion and the amount of the volumes extracted naturally raises the question of how to dress so much quantities of ore, and, consequently, of the whole process involved. The presence of dressing floors flanked by tanks and accompanied by grinding workshops close to the mines also raises the question of the system implemented; how did these devices work? What was the workers' role? What was the functionality of the structures themselves?

More generally, the washing devices used by ancient miners on Laurion have promted many controversies. This contribution aims to present different positions and to suggest some interpretation based on archaeological evidence and particularly on structures widely used and described since the 16th century and mainly during the 19th century by mining engineers and mining engineering students of the Paris School of Mines in their *Journaux de voyages travel (reports)*.

Lead-silver ore dressing at Laurion: Archaeological evidence

Lead-silver: A sophisticated process

The whole silver process starts underground where the ore, after being mined, is broken down and sorted. Such working sites are still perfectly visible in the Acropolis mine of Thorikos going back to prehistoric times (Fig. 1). The site is a typical multiphase mining working site with

Fig. 1: Breaking/crushing remains in the Acropolis Mine (Mine n°6) at Thorikos (Laurion). The photo shows a waste dump made up of carefully broken/crushed rocks in a worksite inside a gallery. The work was carried out directly on the floor or on large rocks visible on the photo (photo: D. Morin).

waste deposits and, in some parts, several well preserved breaking and crushing places.

Underground, miners organized small working areas in order to crush the ore. Rocks were crushed right on the floor or using crushing tables, in a distant area, in order to be able to sort them as well as and to estimate the ore concentration.

Some galleries of the Early Helladic (EH II) mining works at Thorikos, in which breaking/crushing places are preserved are full of waste deposits. In some other parts, miners have broken down the rock slabs they have removed first.

A never omitted general step of the ore dressing is to operate as much as possible by hand sorting and to avoid as far as possible the formation of very fine particles

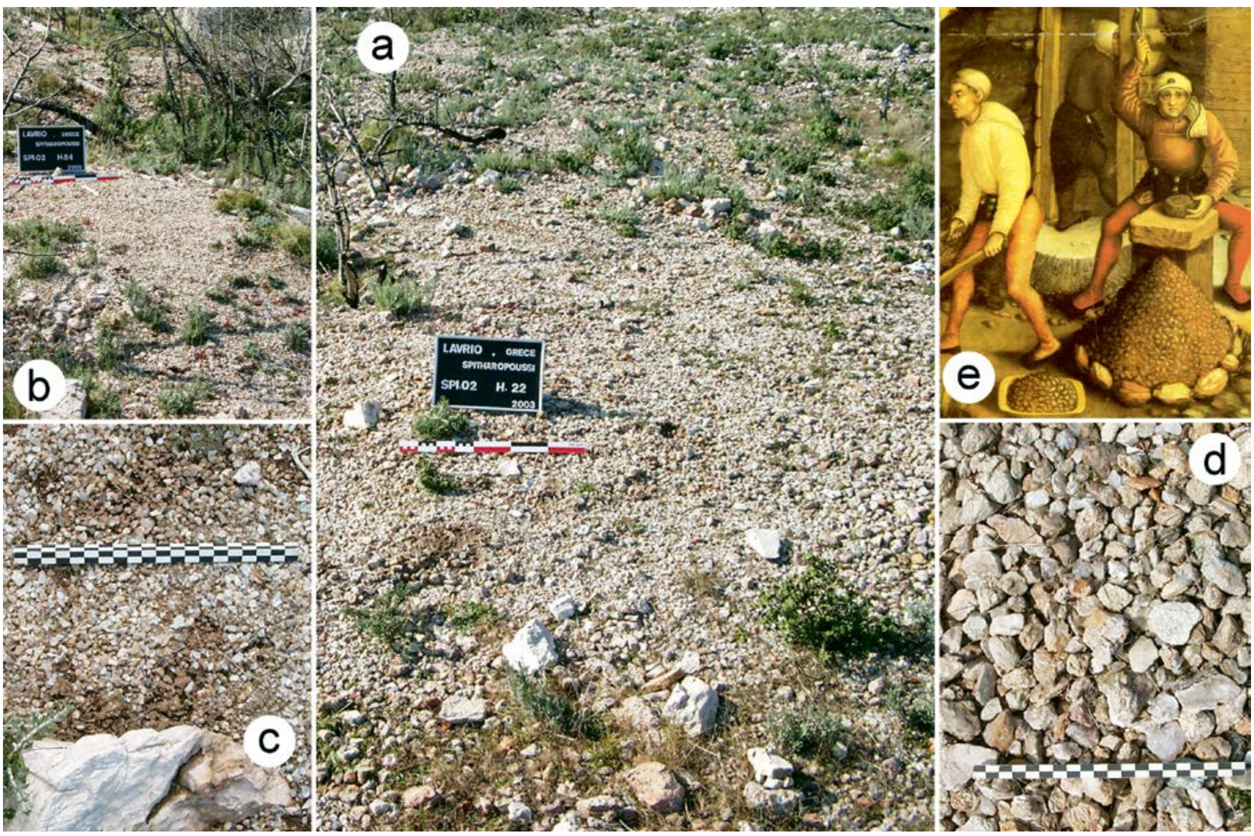

Fig. 2: Laurion mining district. Spitharopoussi plateau. (a) Ore-dressing workshops remains in situ near the collar of a shaft. In this context, different ore processing areas at the mine exit are clearly visible (b, c, d). (Photos: H. Morin-Hamon).

(slime). The treatment of slime is difficult because – even if this is a very fine-grained material – there can be excessive differences of the grain sizes. And such differences may have influence on the density and may affect the separation of ore from gangue.

On surface, one can still observe many remains of sorting, crushing and grinding activities. Like in the Spitharopoussi plateau area (Fig. 2), evidence of small workshops are visible in the entire Laurion area. Around the deepest shafts, crushing activity is often identified along with accumulation of large sedimentary deposits and circular features. Working places like that were probably organized in a similar way as shown on a picture from the Annaberger Bergaltar painted 1521 by Hans Hesse (Fig. 2b).

Small heaps of stratified sediments show an organization of space and the different crushing/chipping and sorting stages. These remains resemble the 16th century painting of the Annaberger Bergaltar (Fig. 2e). Three main panels present a mining landscape showing both the extraction sites and different workshops. Fig. 2e shows a miner crushing the ore on a crushing stone. His activity is materialized on the ground by a stone entourage inside which the sediments are piled up.

When they left the mine, larger pieces of ore were probably sent to the cobbers: these were workers who broke them into smaller pieces, taking care to reject immediately the sterile parts of the gangue that do not contain metal.

Grinding was the last stage before washing. The essential condition for a density classification by this process is that only particles of approximately equal volume are present in a water stream. It therefore requires a prior classification by size, hence the need for meticulous preliminary grinding like on grinding table or using a hopper quern (Olynthus mill). Mechanical grinding on a round table, the so-called *helicoidal washeries* is a part of the process enlighten at Laurion (Nomicos, 2017).

Flat-bedded washeries at Laurion (5th – 4th century BC): Evidence and interpretation

The washing devices used on Laurion by the miners, during the 5th and the 4th century BC have caused a lot of discussion, even recently (Fig. 3). We present below the main hypotheses put forward by various authors who have written on this subject.

Cordella 1869

The mining engineer A. Cordella was one of the first authors who described the flat-bedded washeries, the

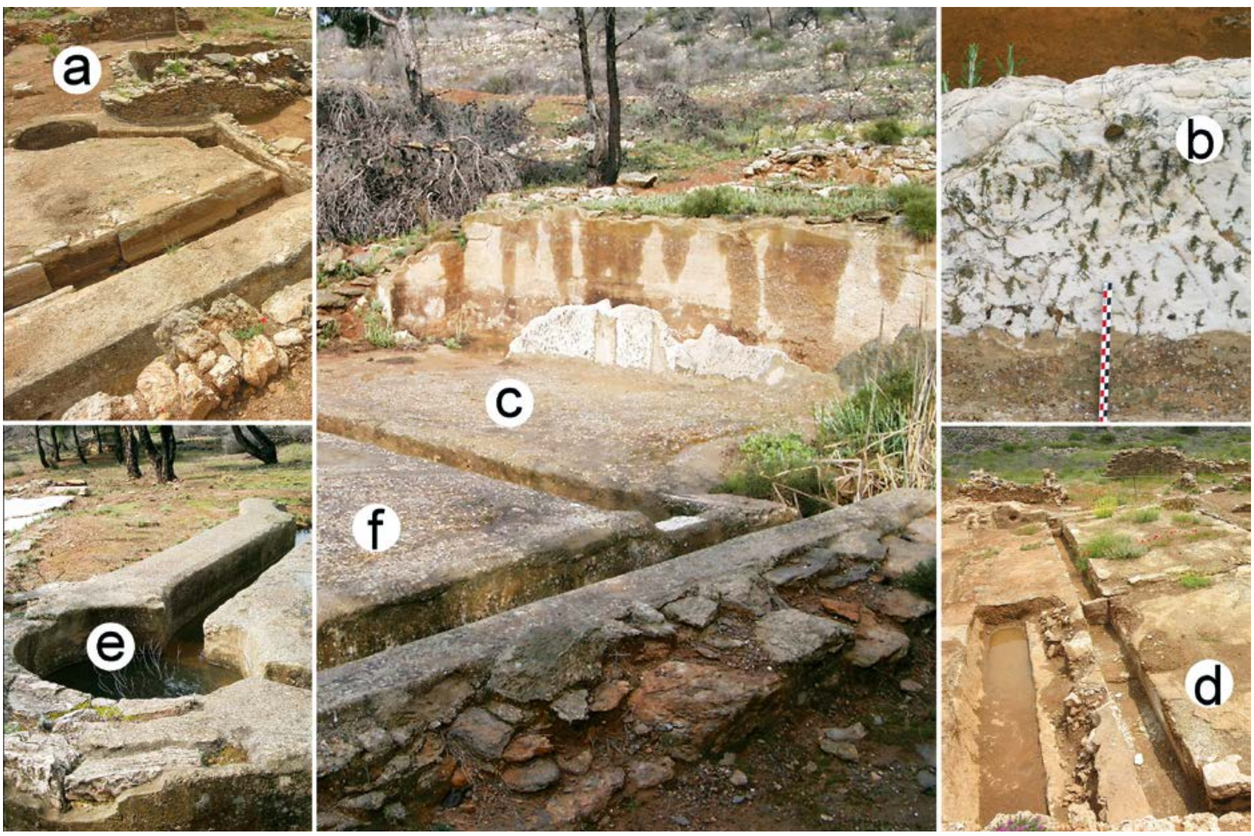

Fig. 3: Laurion mining district, Souresa valley. Flat-bedded washery. Details of the different building elements: – a. water tank; – b. marble wall with outlets; – c. washing floor; – d. overflows; – e. settling basins; – f. drying floor. (Photos: H. Morin-Hamon).

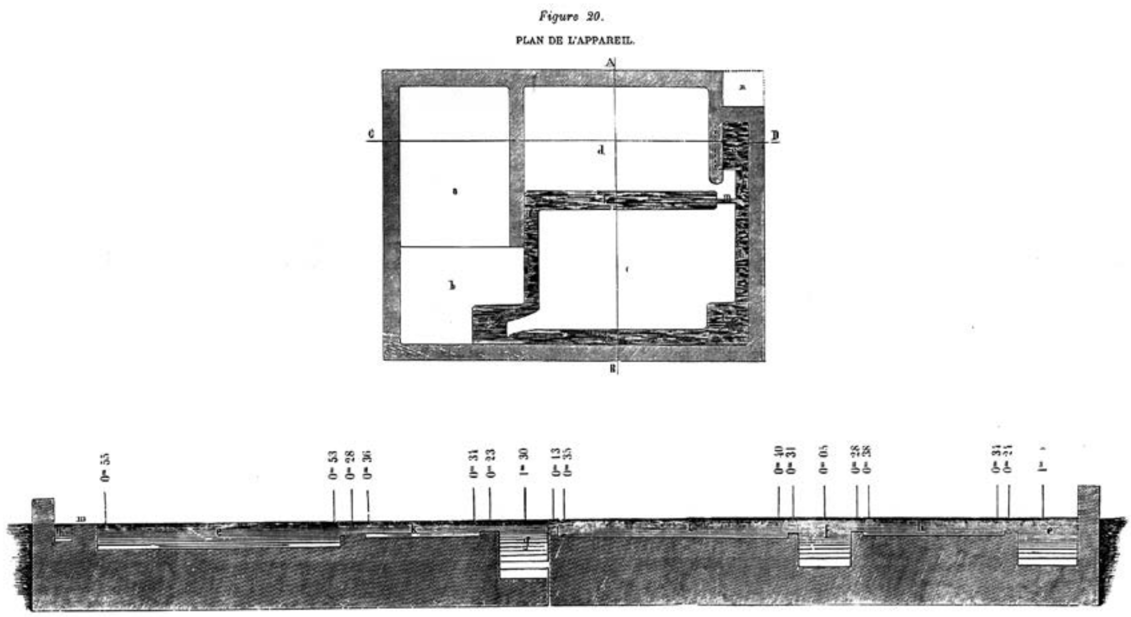

Fig. 4: Laurion. Flat bedded washery according to Cordella (1869, p.95 fig.20 plan, p.97 fig.23 section).

most characteristic ore-processing structure at Laurion. His description was based on the remains of a washery discovered in Camareza when ancient slags were removed (Cordella, 1869). His testimony is particularly accurate. One example of his sketches is drawn in Fig. 4. He wrote:

> *"The heavy and rich materials were deposited there, while the water carried towards the "l" end of the apparatus the lighter and less rich materials which were deposited, according to their order of density, in the various basins and channels serving as a labyrinth. The circulation of the water stopped when its level reached the highest point "m", so that the current was established in the direction of the arrow "X", as a result of the difference in levels between the extreme points; and this difference occurred either by removing the ores deposited in the apparatus, or by drawing the water from the end of the channel "l", to pour it into the initial basin "e". Thus, the same water could be used to wash an indefinite amount of ore, or at least a considerable amount of it. The total square area of the ditches and channels is 11 square metres and the amount of water needed to fill the device to its peak is 7 cubic metres".*

Phillips 1884

J.A. Phillips' description suggested corresponds to the operating hypothesis of a running water hydro-classifier. Phillips (1884) takes over Cordella's data. He compares the system to a vast sluice system with a series of tubs.

> *"The dressing-floors of the mine are always arranged as near as possible to the mouths of the principal shafts or main entrance; the ore being conveyed to them with buckets, and they are always provided with an adequate supply of water. Water was scarce at Laurium, and large reservoirs were built for storing a sufficient supply. The washing apparatus was so planned as to admit of the water being used over again continuously, and consisted of a large sluice, some seventy feet long (21 m long average), provided in its length, at intervals, with small reservoirs or wells. Instead of being straight, this sluice formed several angles in such a way that its head and lower end were in close proximity, so that ore, placed at its head, could be washed by water baled or otherwise raised from the well at its lower extremity. In this way a current was established, and the ore washed by a stream of water constantly returning to the wells to be again used".*

Negris 1897

In 1897, in the *Annales des Mines*, Ph. Negris, completed Cordella's argument and stated that the ancient miners used to spread the ground ore directly over the space where the water fall down from the outlets (b in Fig. 5). These are made at regular intervals through the walls of the catchment basins. The rich ore was directly recovered from this site, while the grains with lower grade mineral content were dragged by water into the channel set up for this purpose.

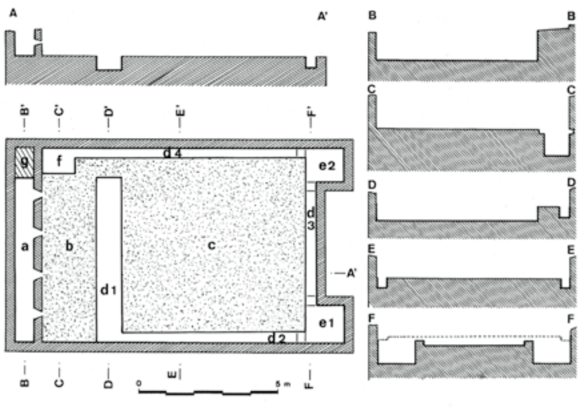

Fig. 5: Laurion. Flat-bedded washery according to Negris (1881, pl. I, fig. 3-9, plan).

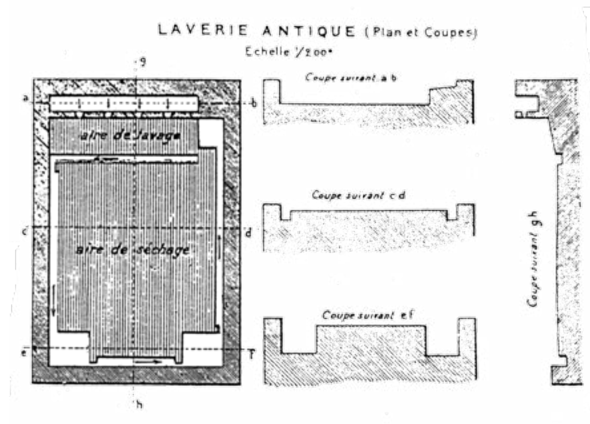

Fig. 6: Laurion. Flat-bedded washery according to Ardaillon (1897, p.63, fig. 20, plan).

This hypothesis was taken up by Ardaillon (1897). In the light of the descriptions made by the mining engineers and that of many mine engineering students quoted in the *Annales des Mines*, it appears that the process thus described corresponds to the classic mechanism of a washing operation using materials that had previously been finely crushed and ground.

Ardaillon 1897

E. Ardaillon goes further in detailing the process. He is even more precise: he meticulously describes the function of each space (Fig. 6). On the first washing operation he wrote:

> *"The sifted ore is spread in thin layers on the sloping area of the washery, which was used as a washing table. The tank openings were unclogged, and the operation started. What was going on? The plots of ore that are too light to withstand the flowing water, are dragged away and will flow into the canal. On the contrary, the heavy plots remain on the table, and it is enough for a worker equipped with a rake to shake them and push them under the water jets, so that they are soon isolated from all those who do not have the same weight. Thus, most of the heaviest fragments, the lead ore, will remain on the washing table. The various parts of the canal, especially if it is equipped with dams and overflow devices that only allow surface water to escape, and the various basins form a series of settling tanks, where lighter and less and less rich materials are deposited, depending on their distance from the starting point".*

If the Laurion washery model remains the same, Ardaillon notes, with discernment, the presence of variables within these systems. According to him, they were used to process minerals of different sizes: large, small and fine. The height of the waterfall above the inclined table, the shape of the exhaust outlets, the slope of the channels, the height of the dams, the depth of the basins, are all elements that can vary according to the case. In a word, washeries were never isolated but operated in series.

Mussche 1963

In his report on the excavation of several flat-bedded washeries in Thorikos, H.F. Mussche (1963) going back on the initial hypotheses first describes clearly the archaeological evidence:

> *"A flat-bedded washery consists of a tank, a sloping area, and a circuit of canals and settling basins. The elevated tank above the entire installation allows water to escape through small conical holes. The water then splashes onto the inclined area, where the ground ore is spread and sieved. The heavy plots remain on the washing table. Rich moor plots that do not contain lead ore are entrained by water because of their lighter weight and fall into channels that extend around a central area as they pass, with overflows that only allow surface water to flow through two settling basins. The slope is designed so that all the water flows into a final basin. The plots, which are increasingly light, settle as they move away from the first canal. Finally, the water completely freed of these impurities is drawn from the last basin and returned to a slope that brings it back into the tank. Then, the ore is dried on the area in the middle of the washery" .*

Conophagos 1970

In 1970, in a communication to the Academy of Athens, the mining engineer Conophagos put forward the hypo-

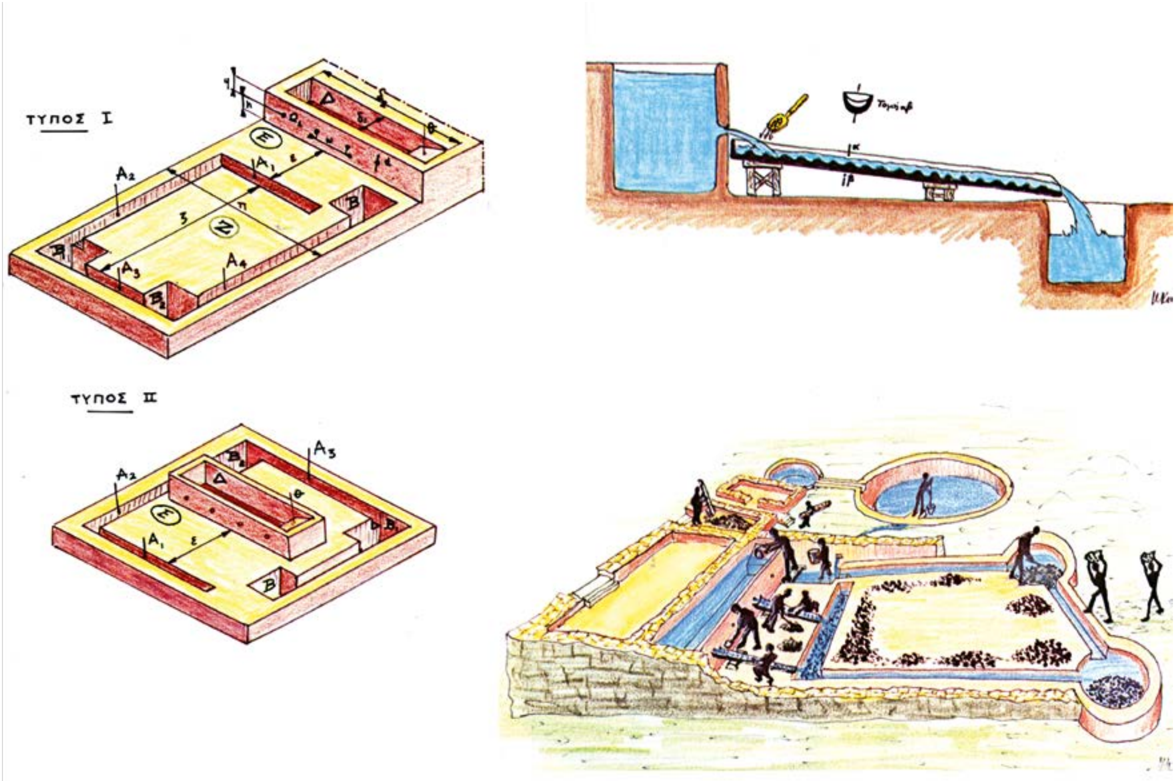

Fig. 7: Laurion. Left: flat-bedded washeries according to Conophagos (1980, p.340 fig.246). Top right: detail of the process with wooden sluices (Conophagos, 1980, p.236, fig.10-19). Bottom right: Reconstruction of a washery in process (Conophagos, 1980, p.237 fig.10-20).

thesis of wooden sluices inclined and arranged under the outlets. The author opposes his theory to that of the previous authors based on three arguments:

- the experiments showed that a direct washing in the first plane where the water falling from the outlets was not satisfactory. He notes
- the absence of wear on the ground on the outlets, and
- the absence of obstacles between the washing area and the recycling basins.

Conophagos considers before all that the quadrangular circuit, was a system for settling and recycling the water (Fig. 7). The washers could recover the richest plynite – waste rock – in the first settling channel.

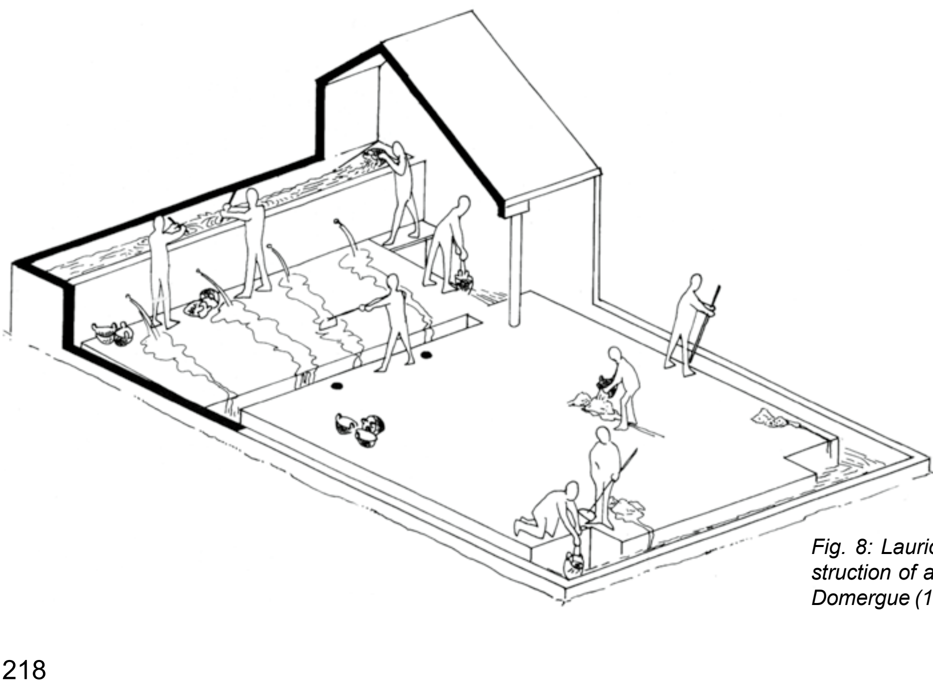

Fig. 8: Laurion. Flat-bedded washery. Reconstruction of a washery in process according to Domergue (1998, p.41 fig. 13, drawing C. Rico).

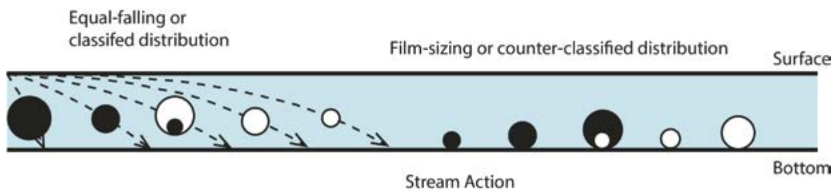

Fig. 9: Stream action diagram of equal-falling or classified distribution. The dark circles represent the ore and the lighter circles, the gangue. From Truscott (1923, p.257, fig. 166)..

Domergue 2008

According to C. Domergue, based on archaeological evidence in the Coto Fortuna silver-lead mine (Mazarrón, Murcia, Spain), most of the concentration would take place in the reservoir itself, i.e. upstream (Domergue,1990, 1998, 2008). With the help of a wooden pole, workers constantly stirred the powdered ore in the elutriation tank, which was always full of water (Fig. 8). The overflow was discharged through the outlets and a concentrate was formed at the bottom of the basin below the level of these outlets. The jets of water loaded with fines escaping through the outlets crashed into the area where the heavier silt was to settle, while the others normally ran through the settling circuit where the classification was completed. In this case study, the tank is considered as the primary elutriation basin.

Sizing and washing: A complex mechanism of redistribution of particles within a fluid

To affect sizing by a rising current, all that is necessary is that the material be brought to a plane across which the water is rising at a velocity capable of lifting the desired fine material to the overflow, while permitting the coarser material to fall. The classifier, in which such a division is made, needs accordingly, no great vertical dimension. There is the further advantage that the separation of materials would be made in a continuously flowing steam. If a separation in still water was applied, deeper constructions would be necessary, and it would be difficult to design a device that could be operated continuously. In some cases, however, particles are transported via a descending current. In such cases, the particles have an increased vertical velocity, and, since differentiation between particles is entirely dependant upon the varying speeds by which the objects sin, the possibility of effective division into to normal equal-falling products is diminished (Truscott,1923). This theory is explained in Fig. 9.

This illustration shows the equal-falling or classified distribution which takes place as mineral particles fall or sink down in a stream, and the redistribution which subsequently supervenes by movement along the bottom. This theory is explained as follows:

> *"[...] Descending currents are accordingly detrimental to classification, and, under some circumstances, to jigging. It also frequently happens that particle fall in a horizontal current as for instance upon entry into some classifiers, settling boxes or pits, and in launders. The vertical element of descent is then the same as though the sinking took place in still water, but, in addition, there is a horizontal displacement in the direction of the stream. All particles are subjected to this stream during the time they take to sink. Movement in response to the stream is governed by just the same factors which govern movement in response to gravity, with the result that the particles take a more-or-less diagonal line downwards, equal-falling particles keeping together. The heavier and more rapidly falling particles being subjected to the stream for a shorter time suffer less displacement, while the lighter and slower-settling particles, being carried forward along a flatter diagonal, are greatly displaced. It must be remarked, however, that if the stream also flows over the bottom onto which the particles settle, the friction of the water against that bottom introduces a new element of such strong effect that the conditions sketched above are largely reversed, and the larger particles, which before the bottom was reached held an upstream position in relation to the smaller particles, now find themselves downstream. Due to their larger size, they protrude into the swifter films of water above. As a result, they are rolled forward, while the smaller particles lie still in the quiet film against the bottom."*

Thus, this effect may be described as film sizing; it is essentially a stream effect, a mechanism of redistribution of particles:

> *"[…] Being almost invariably classified material, the mineral particle is much smaller than the gangue particle. That being so, and the necessity now being a sizing action only possible by water streaming over a surface, practically all the fine separating machines use stream – or film sizing".*

Silver ore-dressing: The evidence of the 18th/19th century archives

To enter their profession, mining engineering students at the *Paris School of Mines* travelled throughout all of

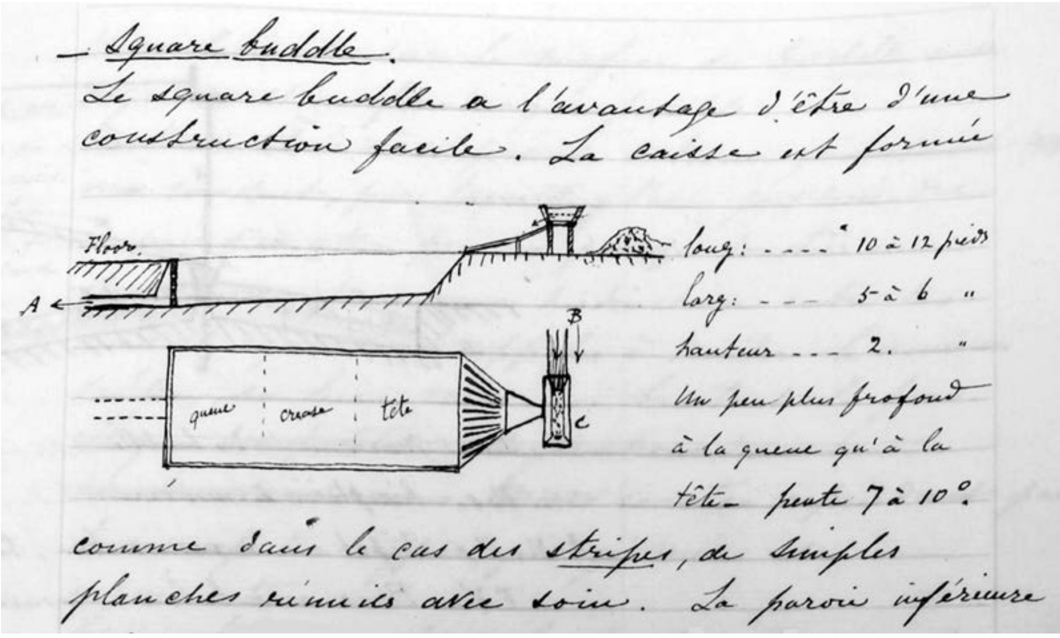

Fig. 10: Plan and section of a buddle (Ellicott and Lacour, 1842, p.113).

Europe and had to visit and study mining and metallurgical companies especially in France but also in Germany, Belgium and in UK (Dufrenoy, 1839). Stays in mining and metallurgical operations were fully integrated into the study cycle when the *Paris School of Mines* was created in 1783. While during the winter term theoretical teaching took place, the summer period served for field work. Following the School's relocation to Paris and its overall reorganisation in 1816 (Aguillon, 1889), the practice of travelling became the essential alternative for field training in the mining and metallurgical establishments run by the *Paris School of Mines.*

As a result of their travels the students wrote, among other topics, detailed reports on washing installations. Usually is that these manuscripts are extensively illustrated by their authors. However, original surveys and drawings occur in diverse forms. The freehand sketches, usually dimensioned and inserted into the text, is one of the most frequent. A lot of examples of these drawings can be found throughout the considered periods. They accompany mine visits reported in travel journals. These figures in the text most often correspond to pencil drawings revised later a second time (Fig. 10).

Illustrations are freehand drawings and varied as the writing itself. They are usually two-dimensional representations, plans, sections or elevation views. These drawings, created by the authors themselves, are valuable evidence of the technologies and machines used in mining in the 19th century. These drawings are accompanied by detailed comments on the dimensions of these devices and their operation. Beyond the diversity of media and modes of representation, the theme of the illustrations reveal the educational positioning of future engineers in the world of mining and metallurgy. The visits in the mines were designed as a form of training in the detailed preparation of inspection reports. These were one of the essential activities of future engineers in the exercise of their administrative function in mining and metallurgical industries (Maisonneuve, 2008). The accuracy of drawings and descriptions is an inestimable source of information to reconstruct the history of mining technologies[1]. It also provides a better understanding of certain transfers of mining technology in Europe during the 19th century (Morin-Hamon, 2003).

In these manuscript reports[2], ore dressing facilities, and especially buddle systems, were described and drawn in detail.

Chipping and grinding

Before any washing operation, the ore must be carefully crushed and ground. E Gatellier, a 19th century mining engineering student at the *Paris School of Mines*, described these first operations as follows (Gatellier, 1857):

> *"This gives us a first coarse classification of size. I will first deal with the portion that did not pass through the stitches. It is shovelled into a small basin in front of the sorting tables and then it is cleaned out. The sorting tables are occupied by women who divide the ore into 4 categories. 1. The one that is sufficiently rich or "best" to which one only makes undergo later a grinding between two cylinders or "crusher" be-*

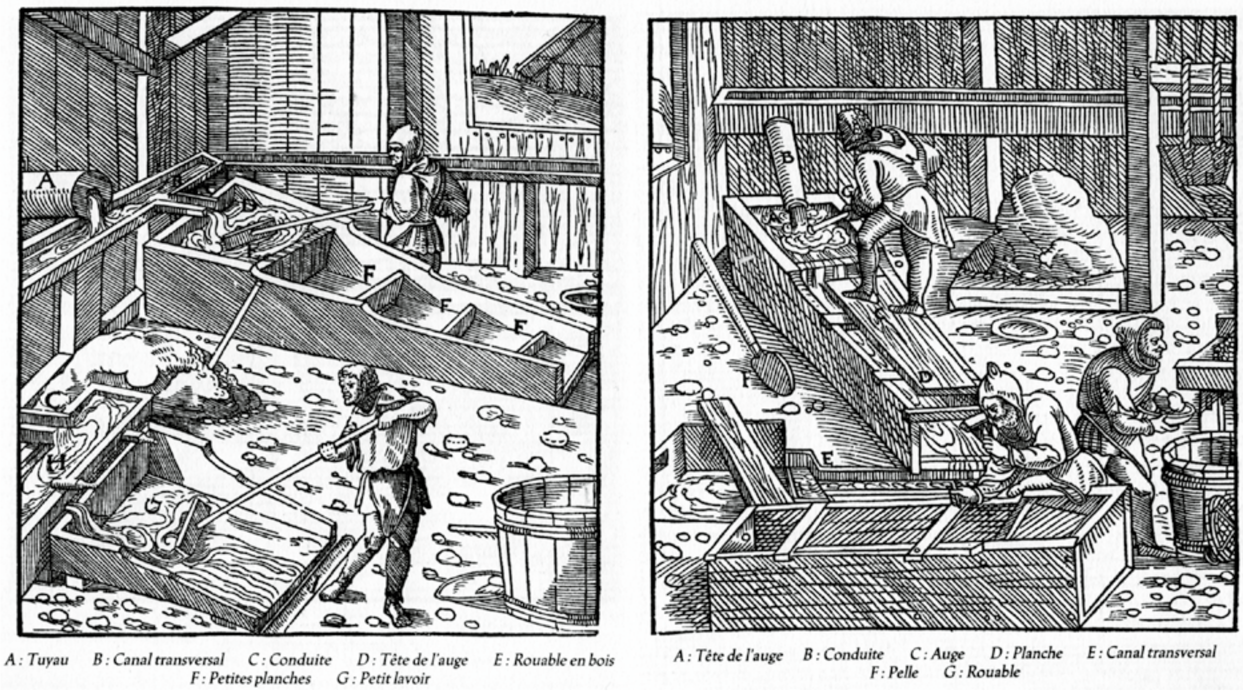

Fig. 12: Buddles and ore dressers in action. (from Agricola, 1556, pp.242–243).

cause one is not used to sell it in large pieces. 2. The "roof best" which includes pieces containing some rich portions with others poorer. It is broken with a hammer to separate the "best"; this ore, which is then worked by hand, also gives sterile or "refused" and "dredge" ore, which falls into the next category. 3. The "dredge" which includes the pieces where the ore is quite intimately mixed with the gangue, and those containing harmful substances. The good metal parts cannot be extracted by hand from these pieces; they must be crushed and then washed to separate the useful portion. 4. The sterile or "refused" rejected immediately.

Thus, finally, from this ore having more than 18 millimetres in diameter, one withdraws, good ore, ore to be crushed and rejected sterile material. Only the ore to be crushed shall undergo further operations.

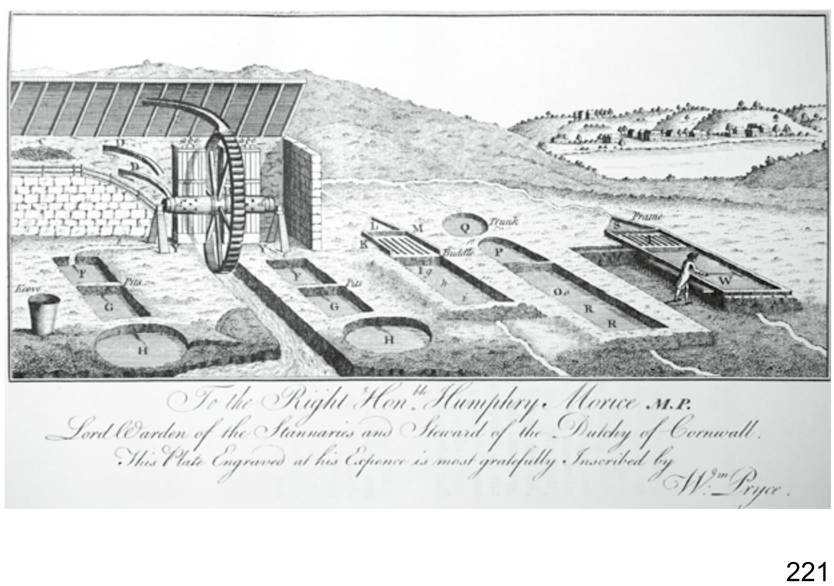

Fig. 11: Different types of concentrators: keeve, pits, buddle, trunk, frame (illustration: Pryce, 1778, p.229, pl. V).

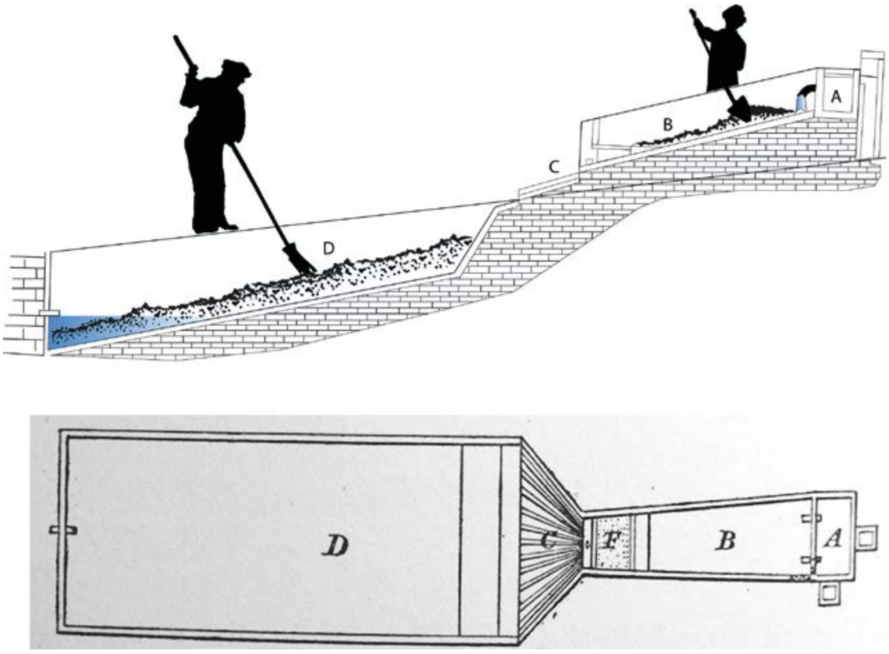

Fig. 13: Buddle described by Hunt (1884). Up: hand or square buddle in action (section). Down: plan (Hunt, 1884, p.764, fig. 217).

Box concentrators

Mechanical concentration is based on the difference in specific gravity of the minerals that are to be separated. The crude application of the process such as the use of hand concentrating tubs and pans, blankets and goat or sheep skins, dates back to ancient times and was used for the recovery of gold, tin and silver.

The buddle

The buddle is an ancient device used to concentrate sands and metalliferous slime by using the difference in specific gravity of both ore and gangue. The action of the miners dressing the ore in such devices was essential as shown in an engraving of Agricola (1556) (Fig. 12).

Buddle was an effective method of concentration throughout the 18th, and 19th century at most tin and lead-silver mines in UK. Buddles came in a variety of shapes and forms, but one of the most common was the square buddle or hand buddle. It was a rectangular box of varying dimensions and capacity sunk below ground

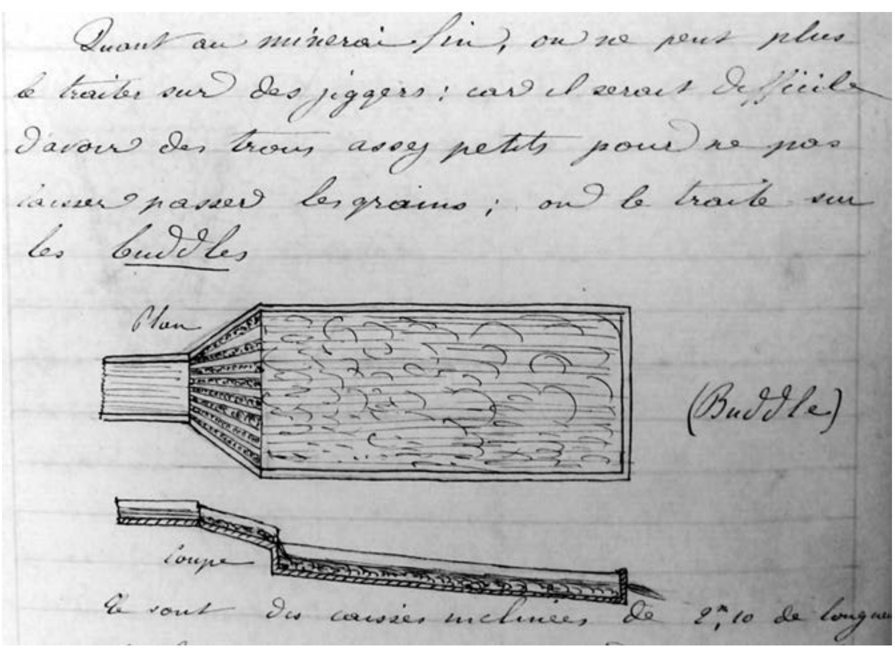

Fig. 14: Plan and section of a buddle from Gatellier (1857). This type of buddle was used for tin, copper and lead ore dressing in Cornwall and Devon.

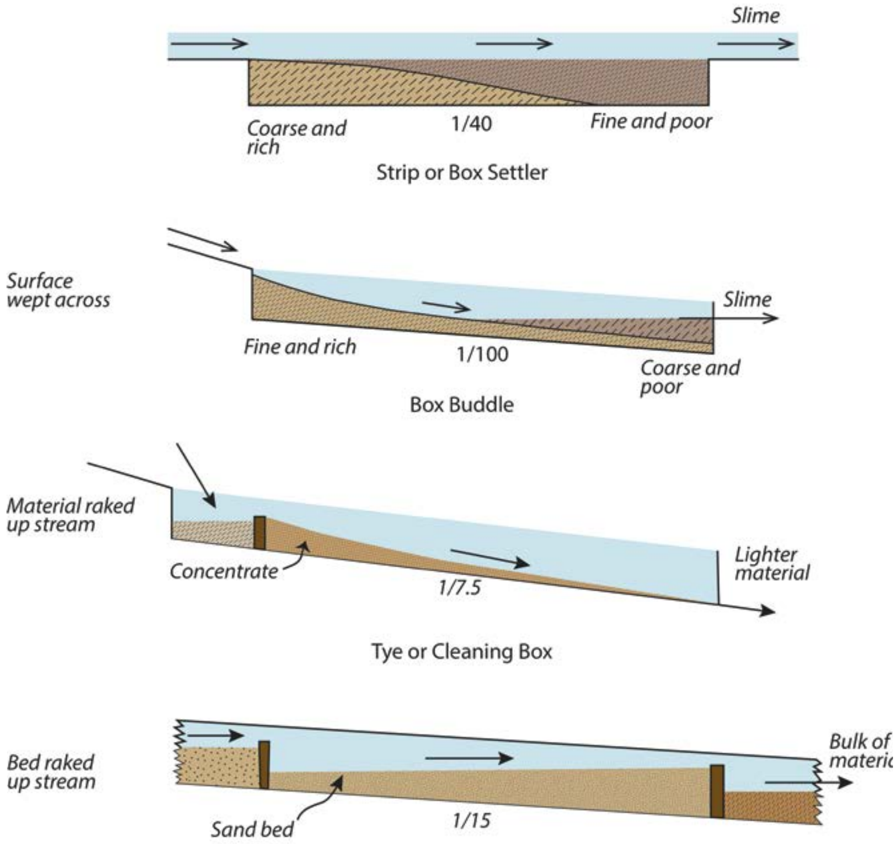

Fig. 15: Box concentrators. Diagrams of strip, buddles and tye. (illustration from Truscott, 1923, p.257, fig. 166).

level, with the lower side being flush with the surface, the floor having a definite slope.

The earliest buddles and simplest forms consisted of either a shallow, oblong pit simply dug into the ground, or a shallow, gently sloping channel made from wood or semi-dressed stone (Pryce, 1778; Muncaster, 1795). Fig. 11 display different types of concentrators: keeve, pits, buddle, trunk, frame. All these devices run on running water and are made up in whole or in part of pits and wooden boxes. Separation is carried out by gravity and organised naturally or by forcing the sediment to mix by means of rakes or brooms. These devices are equipped with overflows to separate the ore particles from their gangue by density.

The ore mixture was placed in the latter at the upper end and agitated in a stream of water; the lighter particles were carried off leaving behind the much heavier galena. The water gradually carries away the particles that settle according to their density.

As described, buddles were inclined boxes average 2.10 m long, 0.75 m wide and 0.60 m deep. At the top end, material was thrown onto a triangular inclined and constantly washed out by a jet of water, which featured fan-shaped stips that distributed the material. This was then evenly distributed by falling on to a small, narrow sloping board of the same width as the buddle. An ore dresser would constantly work the buddle to ensure that the deposits formed a level inclined plane, usually with the aid of a long-handled broom. At the head of the device, the richest and heaviest particles of ore are deposited. Material was divided into the head, fore-middle head, hind middle head and tail (Henderson, 1859). The water carrying fine slime escaped from the lower end of the buddle through holes pierced in the tailboard a wooden partition which formed the bottom of the buddle. Plugs were placed in these holes in the tailboard as the level of deposited material grew. Then, an underground channel carried away the gangue with the wastewater (Moissenet, 1858).

The buddle described by Hunt in 1884 consists of a wooden box (Fig. 13), about 8 feet in length, 3 feet wide, and from 2 to 2.5 feet deep in the ground, and having an inclination of some feets in its whole length. At the head of this box a distributing-board, C, placed, laced, which is in communication with the trough B, and a water launder A. The stuff is thrown into the trough B, when it is stirred by the buddler's assistant. The fine slime then passes through a perforated plate to the distributing-board C, and from thence in a thin and uniform stream into the huddle D, when the buddler carefully and continually sweeps the slime and water across the buddle and somewhat against the direction of the current, with the view of freeing the grains of ore from any viscid matter which may accompany them, and depositing them at the head of the buddle (Fig. 14).

Fig. 15 shows how fine ore is processed on buddles (Gatellier, 1857). Four types of boxes for the same ore dressing process were fully in action during the 19th

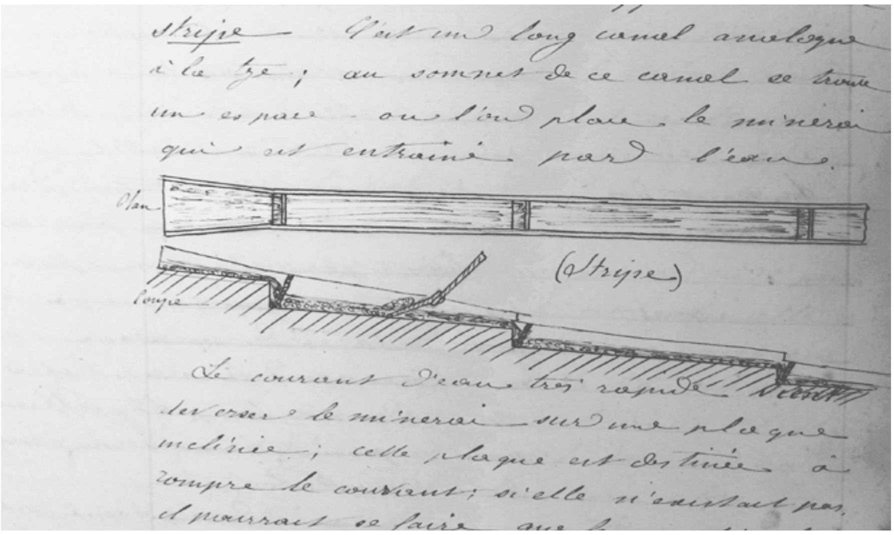

Fig. 16: Plan and section of a stripe employed in Cornwall and Devon by Gatellier (1857). Fine ore is processed on a stripe.

century in most of the mines especially in UK, all of them wooden boxes and with a similar system to concentrate the ore with a water stream.

Evolution and mechanism of these devices have been largely discussed in detail by L. Willies (1975) and R. Burt (1982). The running buddle as described by Muncaster (1795) and Pryce (1778) was a simple trench, lined with wood or stone flags, about 6 x 2 feet, and 8 inches deep. Water entered by a notch in the stone or board at the head. Material to be treated was placed on the floor of the buddle at the head in front of the notch, and by turning the material over, the lighter stuff was washed out and was carried to the bottom of the trench from which it could be removed.

Fine ore was also processed on another type of device called a stripe. Gatellier (1857) describes this device, like that of the buddle (Fig. 16).

"[…] For the richer categories [...] another treatment is used to separate immediately and very quickly a very large portion of the arsenic. A new device called a stripe is used. It is a long channel similar to the tye; at the top of this channel is a space where the ore, which is dragged along by the water, is placed.

The very fast current of water pours the ore onto an inclined plate; this plate is designed to break the current; if it did not exist it could happen that the larger and heavier parts would be dragged beyond the space suitable for their volume and density because of the surface they present to the water current. The material therefore settles in the channel, the heaviest at the beginning,

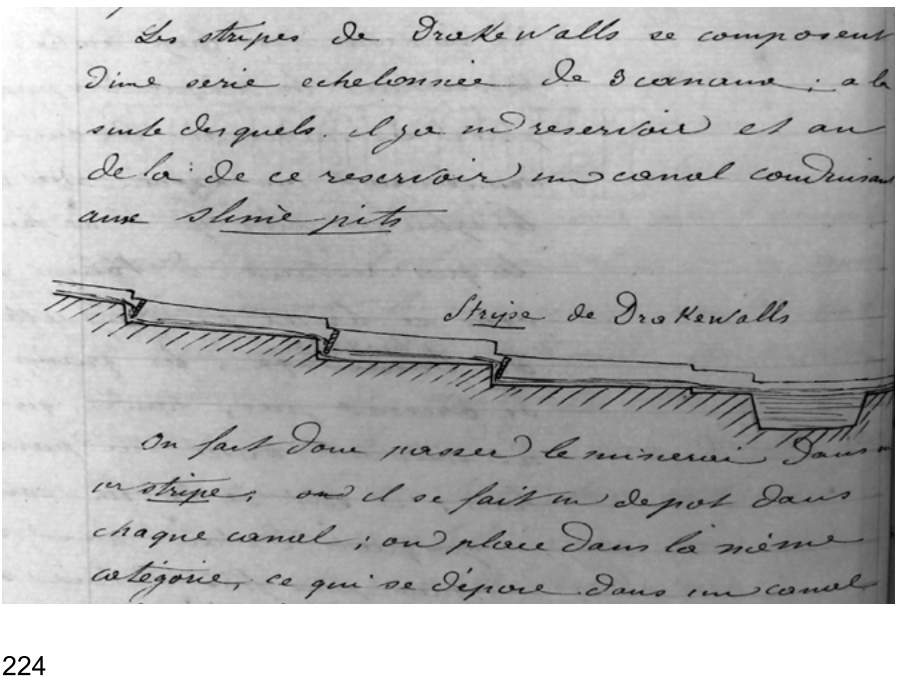

Fig. 17: Drake walls stripe (section) for washing lead-silver ore in Cornwall and Devon. The stripe is another device which uses a washing system that functions similarly to the buddle (from Gatellier, 1857).

the lightest at the end. To prevent the lighter materials from being retained at the beginning by impastoing the heavier materials, a worker is continuously busy lifting the deposit already made in the canal […]" (Fig. 17).

Gatellier (1857) continous:

"[…] It is because of the considerations I have just mentioned that for tin ore after grinding, the stripe is used, a device that works very roughly, but in a very fast way. The crushed ore is processed as follows: The Drakewalls strips consist of a staggered series of 3 channels; after which there is a reservoir and beyond this reservoir a channel leading to the slime pits. (...) in the pits 3 divisions are made; the portion at the head contains the richest ore, the portion in the middle contains a lower grade of ore, and the portion at the end is discarded as sterile […]".

Stream action and buddling process

The buddling process had two principal functions: to separate the very fine clay or sludge from the mineral material, and to separate the heavier lead ore from the gangue. Taggart (1951) is explaining:

"A mineral-separating machine is one in which a process utilizing one or more of the differences

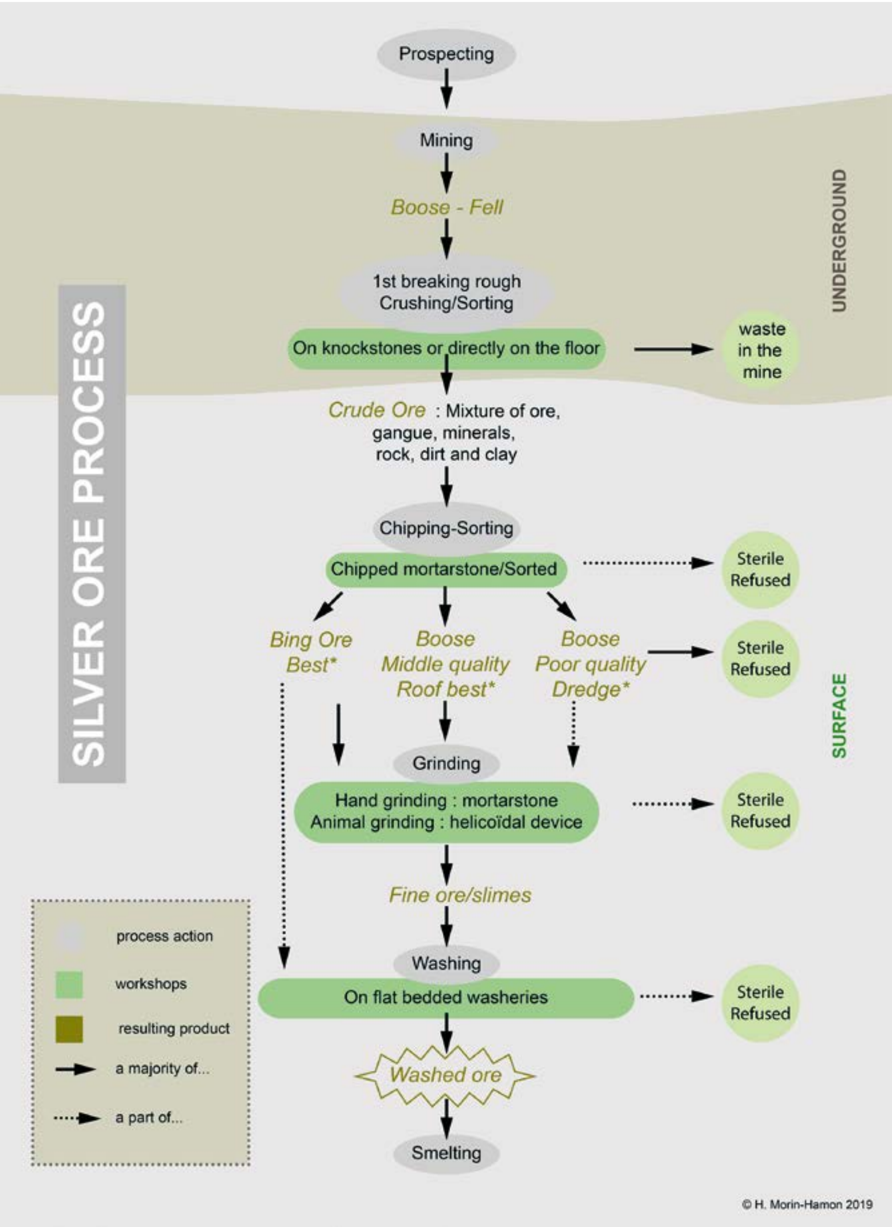

Fig. 18: Archaeological evidence – silver ore dressing process at Laurion, from mine to surface (schema: Hélène Morin-Hamon). The diagram shows the various stages identified from the most recent research on the mechanical preparation of mineralization since its extraction. Each stage of the process corresponds to an enrichment device and a more or less important discharge of sterile sediments. It is a process that starts as early as the mining extraction phase.

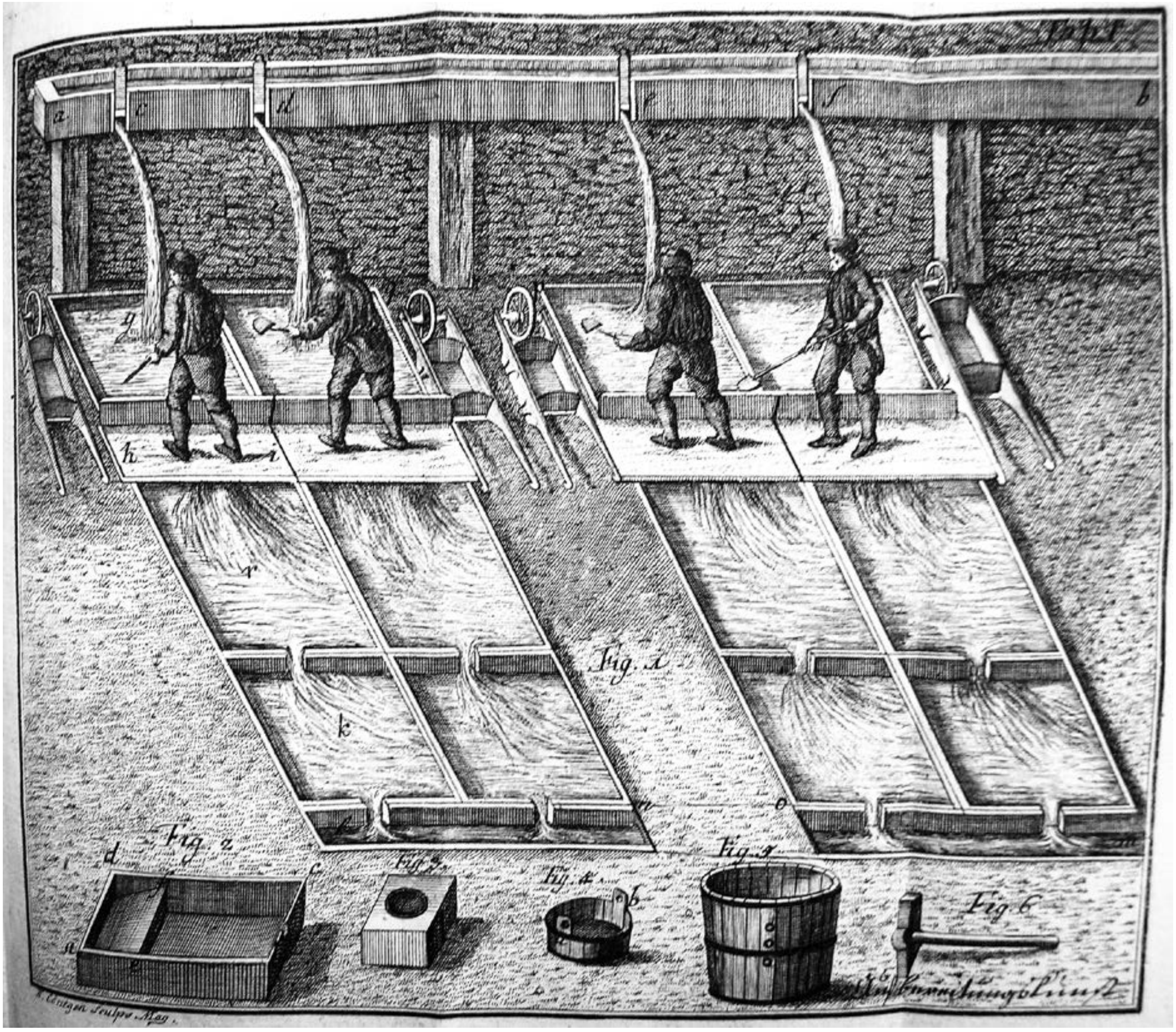

Fig. 19: Washery in process (Cancrin, 1782, plate 1).

among minerals is carried out. Its essential part is, of course, the separating zone, in which individual particles of a mixture should be free to move in the direction of the resultant of the separating forces acting on it. The activating element in the separating zone is a means for exerting a selective force on one species of particles in the mixture. Essential accessories are transport means to carry the feed into the separating zone, and other transport means to carry the products to separate discharge points. These four elements are common to all separating machines. Special additional accessories are found in some".

What happens precisely underwater has been described by Hunt (1884):

"If two spheres of equal volume but of different densities drop together from the same height in a column of water, the heavier of the two will arrive at the bottom first. In this instance the density of each of the spheres is only opposed by the resistance offered to its sectional area, i.e. by the the water through which the sphere is falling. If, however, two spheres of different densities have an equal velocity of fall in water (equivalents), the diameter or sectional area of the lighter will be greater than of the heavier sphere. Now if the two spheres are placed side by side on a perfectly flat table, no movement will occur; but if a slight stream of water will be applied to their surfaces, the one having the larger diameter or greater surface (the lighter sphere) will be impelled more rapidly and separate from the other (the heavier sphere), and if the table be slightly inclined, the rate of movement of these several spheres of different diameters will be accelerated. To these prin-

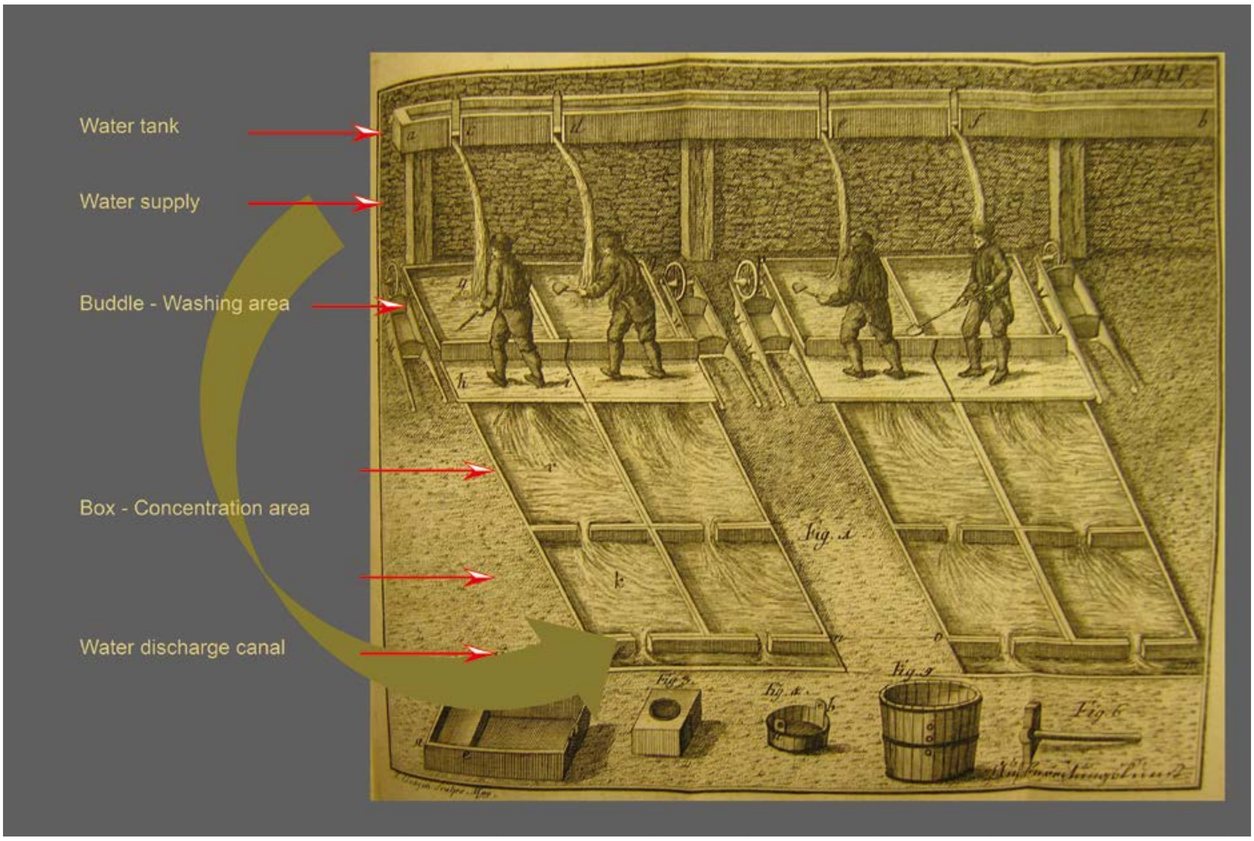

Fig. 20: Washery in process. Interpretation. Top down: the water tank (water supply), the outlets, the buddle (washing floor), the two box concentration areas and the water discharge canal (all connected with small apertures). (Illustration modified after Cancrin, 1782).

ciples, the separation on buddles or tables of metalliferous grains from gangue having an equivalent rate of fall in water must be referred".

Lead-Silver ore dressing process: A beneficiation processing

The diagram in Fig. 18 shows in detail the main stages of the process from mining to the metallurgical stage, identified from the most recent research on the mechanical preparation of mineralizations since their extractions. Each stage of the process corresponds to an enrichment device and a more or less important discharge of sterile sediments. It is a process that starts as early as the mining extraction phase.The first operations of ore dressing are sorting and crushing, were carried out directly underground, and this for all periods from EH II at Laurion. The diagram in Fig. 18 is based on archaeological evidence. It should be noted that these operations were both complex and multiple depending on the quality of the ore. Here, enrichment is at the center of the general system of mining. It required an abundant workforce and operations skilfully orchestrated and controlled.

The Cancrinus Iconography: A reference for technology and operation

Treatises on mining technology of the 18th century, and especially an illustration (Fig. 19) confirms the hypothesis of processing ores like that of a labyrinth, except that at that time the device in question was built in wood or directly implanted in the ground.

In this little-known treatise dated from the 18th century, entitled "*Erste Gründe der Berg und Salzwerkskunde*", Zurich [Ref. *Erste Gründe der Scheide- oder Aufbereitungskunst der Mineralien*] the author, Franz Ludwig von Cancrin (Cancrinus, 1738-1816), mineralogist, metallurgist, engineer and architect from Hesse in Germany, presents an interesting iconography. The originality of this picture lies in its depiction of the workers as well as in the description of their activities and the installations used. Plate XXI of his book is perfectly clear and corresponds to what might have happened during classical times at Laurion. It shows from top to bottom:

- the water tank, here a wooden channel,
- the water streaming directly onto the washing area,
- the buddle or washing area,
- the two-part settling basin of concentration areas with an overflow and finally
- the water drain.

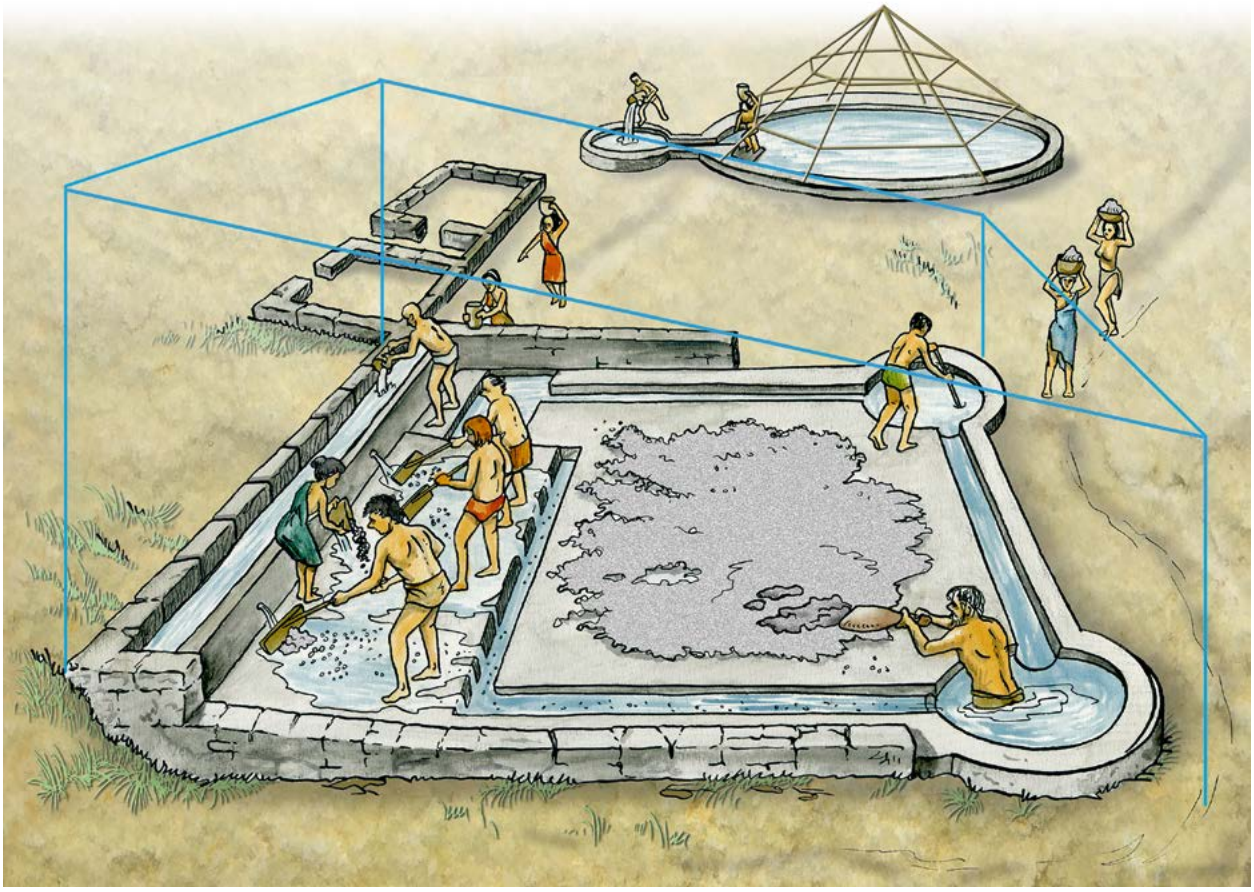

Fig. 21: Laurion. Reconstruction of a flat-bedded washery in progress (Morin and Photiades, 2005, p.21). (Conception: Hélène Morin-Hamon, drawing: Bernard Nicolas, 2005).

Crushed particles are stirred directly under the jet by means of wooden rakes before gradually flowing downstream into wooden settling or grading boxes. The waste water is finally released through a drainIn this case, the water is released into the environment. The concentration of the slime is carried out directly inside the boxes. The image reproduces here shows a dressing floor system and working postures identical to those found in the flat-bedded washeries at Laurion (Fig. 20).

Discussion

Ore-washing at Laurion: A classifying process

In the Laurion, various efficient devices were used to grind to obtain a powdered ore. However, the system described above is incomplete. Because it must admitted that the low-grade particles can hardly stabilize themselves on the flat surface if they are directly exposed to the water jets. Some elementary experiments confirm this. On the other hand, in the case of flat-bedded ore washeries, the water circulation around the square plants allows even the finest particles to settle, even those that slipped through during the first washing. The most plausible hypothesis is therefore here that of a so called labyrinth system. Willies (2007) writes:

> *"The typical length of surviving post-medieval buddles is around two meters, as is the floor at Laurium too. It is a very simple, effective process, capable of easy testing by experiment. Below the buddle-floor is a catch-channel for the water and sediment. This encircles the level drying-floor and seems to have functioned as a clarifying system like the labyrinth on many 19th century sites".*

First, it should be noted that these washing structures have been cleverly dispersed and perfectly adapted to the mining and geomorphological context. Some of them were entirely built, others were cut directly into the rock. This is the case of some ancient washing structures excavated by E. Kakavoyannis (2001) in the Bertseko valley. They all form a system of canals connecting several settling ponds, with an average length of 25 meters. Some of them may have been prototypes in terms of other morphology. Kakavoyannis (2001) writes:

> *"[…] Their channels and settling tanks had no definite number or particular positions in the body of the washery. They were all rather irregular and clearly showed thar their constructors were still at the stage of searching and experimentation, obviously in order to find the best shape and operating method for the construction, elements we see already existing in washereies for the Classical period […]".*

Flat-bedded washeries at Laurion are identical in every way: canal/stand supply tank upstream. The water is then sprayed on a surface or washing table. The supply tank ("a" in Fig. 5) serves exclusively as a water reservoir for the entire downstream system and never as a washing area as suggested by C. Domergue (1998) and J. Kepper (2004).

Thus, the system for washing fine particles used by the miners at Laurion was carried out in two stages in the same structure. Upstream, a regularly supplied water tank made it possible, via outlets or orifices placed at regular intervals, to wash the previously sorted and finely grounded material on a grinding tables: a buddling-floor (the Kepper's working floor) (Cordella, 1869).

In any event, contrary to what Cordella claims, the tank "a" found in all the washeries cannot be the basin where the work began, and thus served as a de-sludging box. This location found in all the washeries consists of a tank intended to supply the water distribution.

Washing was probably carried out using brushes. Here, the solid particles were stirred with the water counter to the current. This water loaded with gangue particles and ore then flowed directly into a first receptacle parallel to the axis of the tank "a" and the washing table, the surface of which was made of a particularly resistant hydraulic mortar.

Furthermore, there is no need for sluices arranged at the level of the orifices as Conophagos claims. Moreover, traces of such a device would obviously still be visible and would have left imprints on the washing floor, which is not the case. As Willies (2007) expresses, "(...) *flushes and jets of water in sluices, would destroy the differential settling required"*. The recovery of fine particles was carried out directly inside the bins and pipes according to a natural gravity classification.

The water loaded with the grinding products then gradually continued its course in the labyrinth system set up for this purpose. This channel is generally composed of two settling tanks preceded and accompanied by overflows designed to block the particles as the liquid progressed. The last basin is the sump where the settled water is completely recycled to be reintegrated into the supply tank. The cycle is thus perfectly closed. As shown by the layout of the channels and platforms, each element is inclined according to its own location. The gradient gradually decreases with the increasing distance from the water inlet.

These different channels and basins preceded by overflows functioned as a perfect classification device. In there, sediments were trapped by gravity. Depending on the concentrations, these sediments were evacuated outside, dried in the centre of the space or washed again to prevent any loss of material. The length of the channels was deliberately exaggerated so that the water, brought in for clarification, would flow clear for as long as possible over the reservoir or tailings pond, as the sludge would gradually fill up the basins from one end to the other.

Hypothesis of using sea water to feed the washeries has been mentioned. A laboratory study carried out at the *Ecole des Mines* at the beginning of the 20th century already evoked this hypothesis: sodium chloride is rarely an effective agent for both flaking and deflocculating and when added to water, in a special proportion, depending on the nature of the ore, it increases viscosity so that the particles settle slowly in some cases (Roux-Brahic, 1922).

Conclusion

The flat-bedded washeries had a main tank in which a large volume of water could be stored. Water flowed out on a slightly inclined surface: a buddling floor. Water was distributed on a small amount of finely ground ore under the outlets, probably assisted by raking or brushing in order to separate the denser ore minerals from the less-dense gangue. Then, the particles were washed in a stream of water by depositing the heavier fine particles first (slime). Below this buddling floor was a catch-channel for water and sediment. This channel surrounds a central square plan, a drying floor, and it functioned as a clarifying system with overflow facilities like the so called labyrinths on many 19th century sites as described. The layout of the channels, with storage tanks at each corner and narrow inclined channels suggest that sedimentation was occurring gradually. Beyond the tank "a", the main process were the channel and the settling basin circuit.

The research carried out on ore-dressing complexes for alteration iron minerals in eastern France (Morin-Hamon, 1997, 2013a, 2013b) led us to make comparative observations with the Laurion washing facilities. The model proposed here is based on both field evidence and iconographic and documentary sources from 19th century mining engineers. Finally, it is based on the archaeological researches we have developed on the primary washing facilities of iron alterite (Morin-Hamon, ibid.).

Such hypothesis could be supported by future researches, particularly in terms of experimentation. We had already proposed a different method of operation from those usually presented, based on structures that have been widely used and described since the 16th century

(Morin-Hamon, 2005). An attempt at reconstitution thus suggests the specific activity in use in this type of washery.

Fig. 21 shows the reconstruction of the work process on a flat-bedded washery according to the results presented here. The water contained in a collector or tank "a" flows through several outlets to the head of a buddling floor. There, some workers spill in finely ground ore while others rake or brush. Below the buddling floor is a catch-channel for water and sediment. This channel, which encircles a square drying floor, functions as a clarification system like the labyrinths in use on many 19th century sites. The layout of the channels, connected through overflows, with basins or cisterns at each corner and narrow inclined bottom in the channels, suggests that sedimentation occurred in the equivalent of long buddling trenches (Willies, 2007).

The flat washers function here as a complete buddling device in order to catch the maximum amount of low-grade fine ore: at the bottom of the buddle and in the labyrinth below, and thus constitute a second element of buddling. The returned water at the end of the channel system is discharged into the stand-tank (Willies, 2007). The entire ingenious system thus allows the water to be completely recycled through an ingenious decanting system. Scrubbing sludge and mineral-rich sediments are collected directly at the bottom of the cisterns to be spread out and dried on a platform in the centre of the device. To prevent any infiltration, the entire system: tank, dressing floor, channels, and drying platform were carefully sealed with a special hydraulic lime coating.

The number of the flat-bedded washeries of Laurion is clearly related to the extent of the underground mining activities and the volume of material extracted there. The efficiency of ore dressing processes depends as much on the water supply as on the washing and settling structures, a perfect buddling device adapted to the technologies of the time and the particularly abundant and rich mineralogical context. The separation of ore particles from sterile particles depends on the architectural parameters of the device: tank "a", washing floor, outlet length, slope and overflows. Thereby the ingenuity of the ancient miners lies in the total control of hydraulics and particularly of the supply of washing systems in an arid context.

The enrichment model presented here corresponds to washing by stirring and settling. Thus, it was a simple, ingenious and effective process that made it possible to recycle water continuously in a closed system while achieving optimal separation of sediments and a progressive classification of low-grade ore to a precious material of galena and cerussite with high added value.

The buddle technique was mastered here in structures designed and built with perfect waterproofing and protected from the sun to avoid evaporation. This resulted in the quadrangular standard construction, which could be adapted in different proportions and to the volume to be treated, constituting a perfect engineering model.

Acknowledgements

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Notes

1 Many travel journals are now available online on the *Paris School of Mines* archives website (https://patrimoine.minesparistech.fr/).
2 Journaux de voyages (in french).

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APPENDIX

Extract from Cancrinus (1782):

4) Man grabe stets zwei solcher Kasten, die man mit Letten umstampft, nebeneinander unter die Rinne a-b in die Erde, Tafel I, Figur 1, aber so, dass der Wasserstrahl c-g in die Mitte des Gefälles des Waschkastens fället, der ganze Kasten aber völlig steht. Über jeden Kasten nun lege man eine 1 ¼ Fuß breite Bohle h-i, die vorn mit einem 8 Zoll hohen gerade aufstehenden Seitenbrett vor das Spritzen des Wassers versehen ist, worauf dann der Wascher stehen und arbeiten kann. Man mache aber auch
5) vor jedem Kasten einen, und wenn dies nötig ist, an diesen noch einen anderen Sumpf, einen aus Bohlen zusammen gesetzten, und in die Erde gegrabenen Kasten k von vier Fuß lang, breit, und tief, damit sich hierinnen der etwa noch noch gehaltige Schlamm setzen, und dann durch den Graben l-m fortgehen möge: so ist die Wasche fertig, und man kann so viele Kasten machen, als nötig sind, der Raum n-o-p-q aber zwischen zwei Kasten, der 4 Fuß breit ist, dient dazu, das Erz mit einem Laufkarren, in die Wasche, und wieder davon führen zu können.

Der zweite Abschnitt der Verfahrungsart bei dem Waschen und Spülen der Erze

§10
Derbe oder blanke Erze von der Erde und dem Schlamm zu reinigen.

Auflösung

1) Man führe in das Gefülle g des Waschkastens, Tabelle1 Fig.1, einen bis zwei Laufkarren voll von dem zu spülenden Erz, und ziehe den Schieber c auf, damit das Wasser auf das Erz fällt.
2) man scheppe das Erz mit einer Schippe beständig um, so löst sich die Erde und der Schlamm in dem Wasser auf, und das Erz fällt, vermöge seiner größeren Schwere, stets zu Boden, die leichtere Erde hingegen wird von dem Wasser getragen, und fortgeführt (§205, 206, 207 und 208 und §214, 215, 216 und 217 der Bergmasch.). Bei alle dem richte man indessen die Stärke des Wasserstrahls c g durch das mehr oder wenigere Aufziehen des Schiebers so ein, dass die Erzstücken durch den starken Stoß des Wassers nicht heraus, und in den Kasten r unter den Schlamm geworfen werden.
3) Mit dem Umscheppen des Erzes halte man nun so lange an, bis dasselbe ganz rein, und das Wasser fast ganz hell wird. Ist

English version:

4) Two such caissons shall always be dug in the earth (see Table I, Fig. 1) side by side under channel a-b, and [sealed] with packed clay around them. They shall be dug in such a way that the water jet c-g falls in the middle of the fall (?) of the washing caisson, but the caisson remains full. On each caisson a 1-foot wide h-i plank ¼, with an 8-inch high side board at the front to protect from splashing water, will be placed on which the washer can stand and work standing. It will also
5) in front of each chamber a new chamber k, and if necessary another sump (?) against the previous one, dug into the ground and made of assembled planks of four feet in length, width and depth, so that the mud still contained can settle and then drain off through the ditch l-m: and the hand washing is then finished, and as many caissons as necessary can be made, however the 4-foot wide n-o-p-q space between two caissons, is used to supply the wash-house with ore, with a wheelbarrow, and to remove it from it.

The second part of the process is how to wash and rinse the ore.

§10
Cleaning coarse or raw minerals from soil and mud

Solution

1) One or two wheelbarrows full of ore to be rinsed are brought in g into the wash chamber, Table 1, Fig. 1, and the drawer c is opened so that the water falls on the ore.
2) The ore is worked continuously with a shovel, so that the earth and the mud dissolve in the water, and the ore always falls to the bottom, because of its higher weight, while the lighter earth is carried away by the water (§ 205, 206, 207, 208 and § 214, 215, 216, 217 of [the machines of the mines?]). During the operation, the force of the water jet c-g is adjusted by opening the drawers more or less so that the ore pieces are not washed away by the force of the water but remain in the box r under the mud.

3) The ore is kept stirring until it is clean and the water is almost completely clear. When

4) dieses geschehen: so scheppe man das gespülte Erz aus dem Gefälle auf einen Laufkarren, und fahre solches an dem Ort, wo es zum Schmelzen aufbehalten werden soll, auf einen Haufen.

4) this is the case, the cleaned ore is taken out under the water jet with a shovel and transported in the wheelbarrow to a heap where it is to be kept for smelting.

5) Man wiederhole die Arbeit so lang, bis der Kasten r mit Schlamm und kleinen Erzstücken angefüllt ist, alsdann aber schlage man diesen Kasten aus, das ist, man scheppe das kleine Erz mit dem Schlamm neben dem Kasten heraus und spüle dieses Zeug nochmals, man gebe aber nur wenig Wasser, man mache nämlich den Wasserstrahl klein: so bekommt man die groben Stücken alle allein, und das Erz ist von der Erde und dem Schlamm geschieden, also zum Rösten und Schmelzen geschickt.

5) The operation is repeated for as long as necessary until the caisson r is filled with mud and small pieces of ore. Then this caisson is emptied, i.e. the small ore with the mud next to the caisson is taken out with a shovel and rinsed again, giving little water, for this purpose the jet of water is reduced: so the coarse pieces are separated from the rest and the ore is separated from the earth and the mud and is ready to be roasted and melted.

6) Man schlage nunmehr den Kasten r, auch den Sumpf k, wenn solcher mit Schlamm angefüllt ist, wieder rein aus, man bringe aber jeden Ausschlag allein, weil der in dem Kasten reicher an Erz ist, als der in dem Sumpf, indem sich das gröbere und schwerere Erz eher zu Boden setzt, und im Wasser nicht so weit fortgeführt wird, als das kleinere und leichtere (§ 207 und 208 der Bergmasch.)

6) The caisson r, and also the sump k, if it is filled with mud, is then emptied and cleaned, but the mud is kept separate, because the mud in the caisson is richer in ore than the mud in the sump, because the coarser and heavier ore falls to the bottom more quickly and is not carried along by the water like the smaller and lighter ore (§ 207 and 208 of the "Mining Machines").

7) Diesen Auschlag nun, den Schlamm aus dem Kasten r und den Afterschlamm aus dem Sumpf k hebe man auf, und wasche ihn auf Graben und Heerden, wovon wir erst § 75, 90 und 91 bei dem Schlämmen und Waschen der Erze handeln können.

7) The recovered sludge is kept in the r caisson and the sludge from the sump, and is washed on (?) ditches and ...(?) which we will only discuss in § 75, 90, and 91 concerning the washing of minerals.

§11

Diese Wasche ist etwas besser, und vorteilhafter eingerichtet als die gewöhnlichen. Man bedient sich derselben gemeiniglich nur zu dem Eisenstein waschen, man kann aber auch alle Arten von anderen Erzen, besonders Graupen, die nur mit Erde und Schlamm vermengt sind, darauf waschen, nur muss man in diesem Fall die Graupen erst rädern, und das Wasser gleich über dem Kasten bei g in die Wasche führen, damit das zarte Erz nicht durch den Fall des Wassers aus dem Gefälle gespült werde.

Meist bedient man sich inzwischen bei dem Setzwerk eines Durchlassgrabens, den wir § 26 beschreiben, worinnen man die Setzgraupen, die wir § 35 zeigen, spült.

Außerdem kann man sich dieser Wasche auch zu dem Krätzwaschen bedienen, wovon wir in der Schmelzkunst

§11

This washhouse is a little better, and better set up than regular laundries. It is usually used only for washing iron ore, but it can also wash all kinds of other ores, especially granular ores, which are mixed with soil and mud. However, first you have to wheel (grind?) the 'Graupen' and bring the water just above the g caisson into the washtub, so that the soft ore is not dragged out of the waterfall.

In the meantime, a drainage ditch, which we describe in § 26, is used to deposit the ore, in which the granular ore is washed, which we show in § 35.

In addition, this washhouse can be used for scraping (?) which we [...] in the art of smelting

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Earthen and hydraulic mortars used at Lavrion during classical antiquity (5th–4th century BC) – A fundamental relationship between earthen building tradition and sophisticated hydraulic binders and concrete

ABSTRACT: *In Lavrion, silver-bearing ores of lead have been processed to produce silver since prehistoric times. During the fifth and the fourth century BC, an intense exploitation of these ores took place, correlated with a certain historical context of a decisive culmination of wealth and political power of the Athenian Polis (city state). As a result, built structures associated with ore-processing are still ubiquitous at a huge scale in the area. This paper focuses on the mortars, both hydraulic and earthen, used in these structures. At first, a commonly shared building pattern is acknowledged and explained. Earthen mortars were used as structural mortars of stone masonry, while hydraulic mortars were used only as renders. The study on earthen mortars revealed properties similar to those suggested in modern earth-building handbooks and standards. In addition, the production of earth mortars with discretely varying characteristics according to their use, is a noteworthy find. The hydraulic mortars were applied on structures in contact with water or where industrial activity took place. The system of plastering comprised of two distinct materials, both hydraulic: 1) The thin waterproofing layer and 2) the substrate mortar, for which our ongoing research, combined with results of past studies, reveals that it is a hydraulic concrete with extraordinary properties such as high compressive strength, high density and low porosity.*

KEYWORDS: EARTH MORTARS, HYDRAULIC BINDERS, ANCIENT CONCRETE, LAVRION, METALLURGY

Introduction

Lavrion region, located in southeast Attica, approximately 50 km from Athens, is well-known since the remote past until our days for its silver-bearing ores. Their exploitation began in prehistoric times (Kakavogianni, et al., 2018) and went on – not without interruptions – until its cessation in 1977 (Conophagos, 1980, p.51). The most intense mining activities occurred during the fifth and the fourth century BC, when, apparently, Lavrion was transformed into a kind of an “industrial zone” – to use an analogy – of the city-state of Athens. K. Konophagos’ (Conophagos, 1980, p.145) estimate of a produce of circa 3,500,000 kg of silver hints to the extraordinary scale of production during this era. It is also worth noting that one of the first and biggest industries of Greece, established in the 19th century at Lavrio, was predominantly based on processing the tailings and the slags left in situ in huge heaps by the ancient Athenians. Besides the socioeconomic reasons, which led to the flourish of mining activity during classical antiquity, there is also an important technological factor, a breakthrough, which made it possible to extract even a few grams of silver content per ton of ore. Regarding the technological aspect of the ore processing, one can include the mortars used in the various structures, which are the main concern of this paper.

As mentioned above, the heydays of Lavrion were during the 5th and the 4th century BC. As a result of these intense mining activities, there is a plethora of visible archaeological remains in an area of more than 45,000 acres (Kapetanios, 2013, p.185). The built parts of these remains belong principally to hundreds of ore processing workshop modules, i.e., installations for the enrichment of the ore and its preparation for the furnaces. Generally, each module consists of an ore crushing-and-grinding compartment, an ore-washery, an associated cistern, dwellings and ancillary structures. Structures are made of rubble or semi-dressed masonry, the stone units of which are from locally quarried schist, marble and limestone. The size of the units varies, depending on the masonry

Fig. 1: Representative examples of the materials and the techniques used. Stone masonry and earth block masonry, both coated with thick hydraulic renders. The floors are made of various layers of hydraulic mortar. Stone masonry and earth block masonry constructed with earth mortars and plastered with hydraulic mortars constitute a building pattern (photo: N. Meimaroglou).

thickness. There are also adobe masonries, some of which have remarkably survived until our days (Fig. 1). Adobe masonry is built on a stone masonry base in order to be protected from rising damp, while direct contact between rainwater and adobe bricks is prevented by a thick plaster. Ashlar masonry may also be used, less frequently though, in certain components of a workshop complex such as strong and high retaining walls and cistern walls. Nevertheless, most of the structures were constructed with the use of mortars of which two main types can be clearly identified: earth mortars and hydraulic mortars.

Discrete use of hydraulic and earthen mortars and the reasons for this “strange” choice

At first, the discrete application of earthen and hydraulic mortars in these ancient structures must be identified and distinguished. On the one hand, earth-based mortars were used as structural mortars, either in filling the joints or as an infill of three-leaf stone masonry. On the other hand, hydraulic mortars were used only as renders in cisterns, on the floors of the washeries or even at some rooms. They were never used as load bearing elements, something readily apparent in the architecture of classical antiquity in general. One can say that this discrete use of these mortars indicates a characteristic building pattern, a building mode that proves to be typical in every structure related with ore processing (Fig. 1). The question that arises is, why ancient Athenians used earth mortars for structural purposes, since they had the knowledge and the technology to produce hydraulic mortars of high efficiency? This is a tricky question with no unambiguous answer. The possible reasons for this preference are discussed below.

The scarcity of fuel

This first answer comes from far away, from Egypt. A similar question was posed there as well: why did the ancient Egyptians use only gypsum mortars, until at least Ptolemaic times when lime mortars were introduced in their architecture, while there was an abundance of limestone and lime technology was known? This question puzzled archaeologists and engineers alike. The confusion became even greater by the presence of calcium carbonate in Egyptian mortars and renders which led researchers to believe that there was an intentional admixture of lime (Mallinson and Davies, 1987).

It was finally shown that calcium carbonate was just an impurity derived from the raw material in which it occurs naturally, not a deliberate addition, and so the binding material was gypsum (Lucas, 1948). The answer given for the preference of gypsum instead of lime, which is relevant to the case of Lavrion, is the scarcity of fuel. Rock gypsum needs only 130 – 170 °C to form hemihydrates and can be burnt on an open hearth. Limestone on the other hand needs 800 – 900 °C degrees of constant temperature for several hours or even days to decarbonate and produce hot lime. Consequently, much more fuel is needed for lime production, as well as kilns and special arrangements to maintain the temperature. It is known that in Lavrion huge quantities of fuel were necessary for the furnaces and the cupellation process.

Therefore, one can assume that scarcity of fuel is a reason that partly explains why the ancient Greeks did not use hydraulic mortars as load bearing element instead of earth mortars.

Ancient Greek building tradition

Monumental buildings of Athens were made with ashlar masonry, in which no mortar at all was used, while in other buildings of less significance, only earth mortars were used as structural mortars. Thus, the use of earthen mortars in Lavrion is also a matter of building history and tradition. In this respect, the second answer is the deep

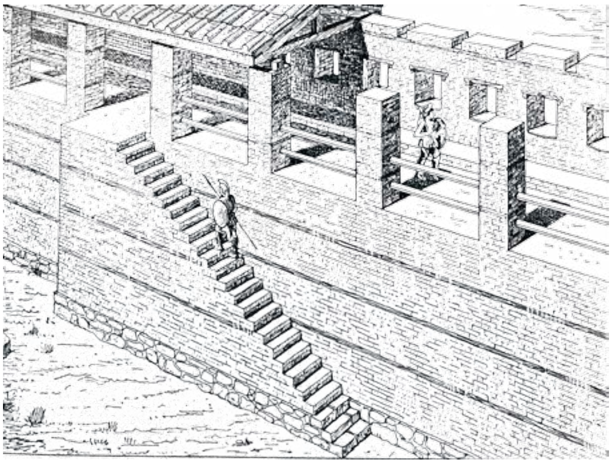

Fig. 2: Representation of the adobe defensive wall of the city-state of Athens by Orlandos (1955, p.79 fig.38).

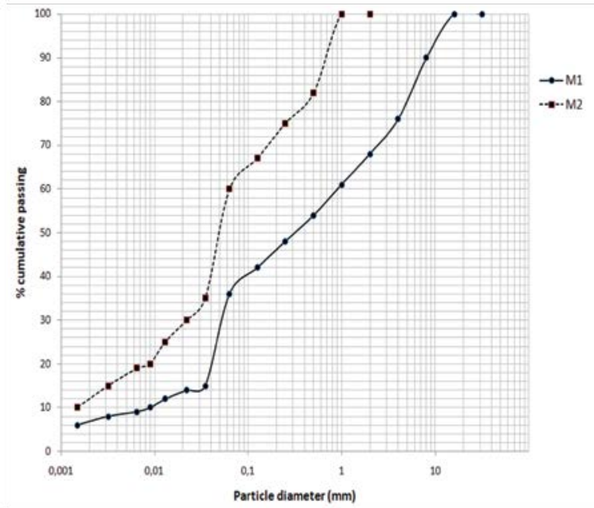

Fig. 3: Granulometric curves of the infill earth mortar (M1) and the joint earth mortar (M2) (chart: N. Meimaroglou).

knowledge of the advantages and limitations of earthen building materials by the ancient Greeks as part of their building culture. As mentioned by A.K. Orlandos in his book on the building materials of ancient Greeks (Orlandos, 1994, p.65 – 83), adobes and earth mortars were used extensively; he cites ancient writers such as Aristophanes, Aristotle, Xenophon and Thucydides who mention earth building techniques in their writings, or Plato who refers to the defensive walls of Athens as "earthen wall" depicting this way the use of adobes in their construction (Fig. 2).

Important buildings like the temple of Hera at Olympia, the first temple of Apollo at Aegina or the mausoleum of Halicarnassus were also constructed with earthen materials. Even in the 'golden age' of Pericles, when ashlar masonry reached probably its highest peak, the city at the foot of the Acropolis was mainly built by adobe bricks (Guillaud and Alva, 2003).

In addition, adobe bricks had a fixed size, depending on their private or public use, revealing some kind of standardization. For instance, the square adobe brick *pentadoron*, with a side of 1.25 feet, was used for public buildings while the adobe brick *tetradoron* with a side of 1 foot was used for private buildings (Orlandos, 1994, p.74).

Furthermore, great care was taken on soil selection for the production of the unbaked bricks. There were specialised workshops (called plinthourgia) and craftsmen specialised in adobe brick production. In order to understand the extent of use of adobe bricks by ancient Greeks, it is worth noting that not only adobe bricks had a commercial value, ranging from three to six drachmas per 100 bricks, but also the surfaces for drying the adobes, made of cane, were considered a commercial good (Orlandos, 1994, pp.72, 82).

Conclusively, earth building was an essential part of ancient Greek building tradition and an elaborated process of earthen building materials production had been developed. Therefore, the use of earth mortars at Lavrion structures, instead of hydraulic mortars, comes as a natural outcome.

Properties of earthen mortar

The property most often employed as a criterion for the characterization of a soil and for assessing its suitability as a building material, is texture (Delgado and Guerrero, 2005, p.241). Texture is the content in particles of different sizes of a soil and in order to assess it, two methods are usually applied: 1) the wet sieving method, to define the granularity of the sand and the gravel and 2) the hydrometer method to define the content of the different soil fractions, i.e., the content of clay, silt and sand. Among these fractions, clay sized fraction is of major importance, since in earth mortars and earthen building materials in general, clay acts as a binder as does the lime in lime mortars or cement in cement mortars and concrete. Therefore, cohesion, adhesion and finally strength are all attributed to clay. But clay is also responsible for the main drawback of earth building materials, which is volume change. In general terms, it can be said that the greater the clay content is in a mortar, the higher its strength but also the higher its volume change and cracking (Meimaroglou and Mouzakis, 2019). In modern earth building standards and handbooks, the clay content or texture is always mentioned and the suggested values range from 5 – 25% depending on the technique and the type of clay (Danso, 2018).

Using the hydrometer method (according to ASTM 422), it was found that ancient earth mortars from Lavrion comply with modern standards in terms of texture. Their clay content ranges from 8 – 18%, as suggested in modern literature. The claim that these values are not coincidental, but the result of a thorough mortar production is further

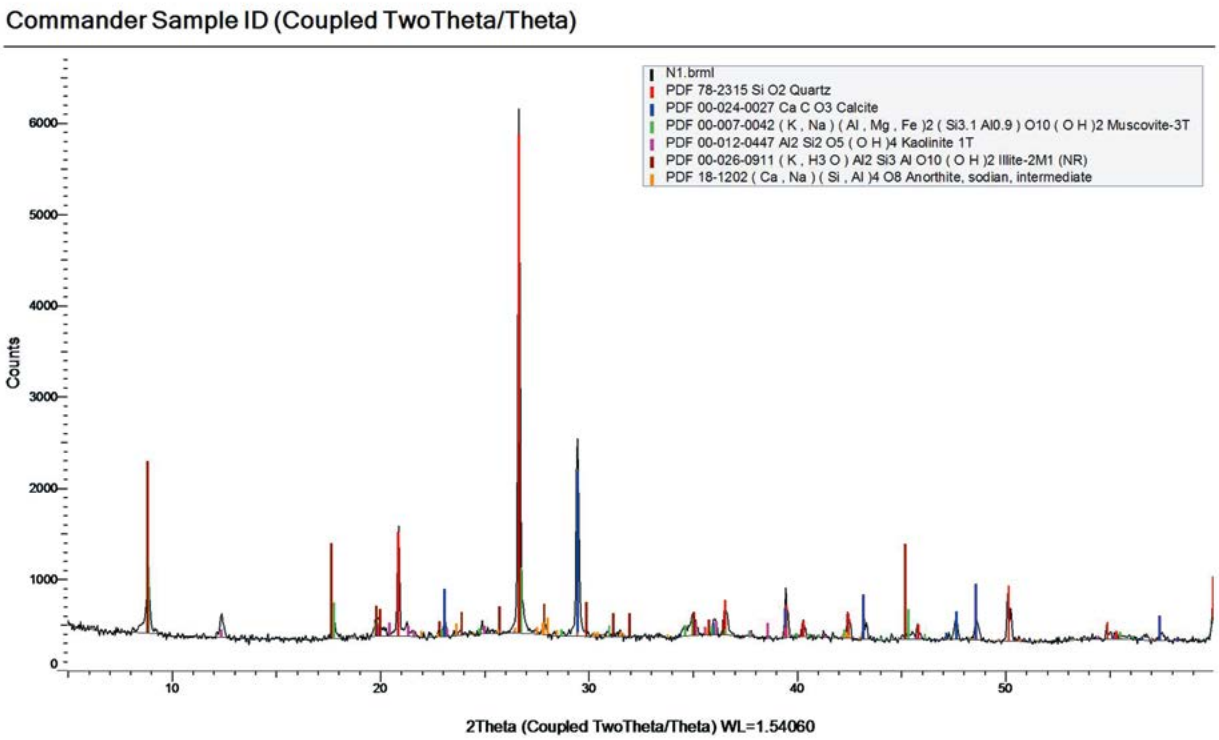

Fig. 4: Typical XRD diagram of an earth mortar from Lavrion (diffractogram: N. Meimaroglou).

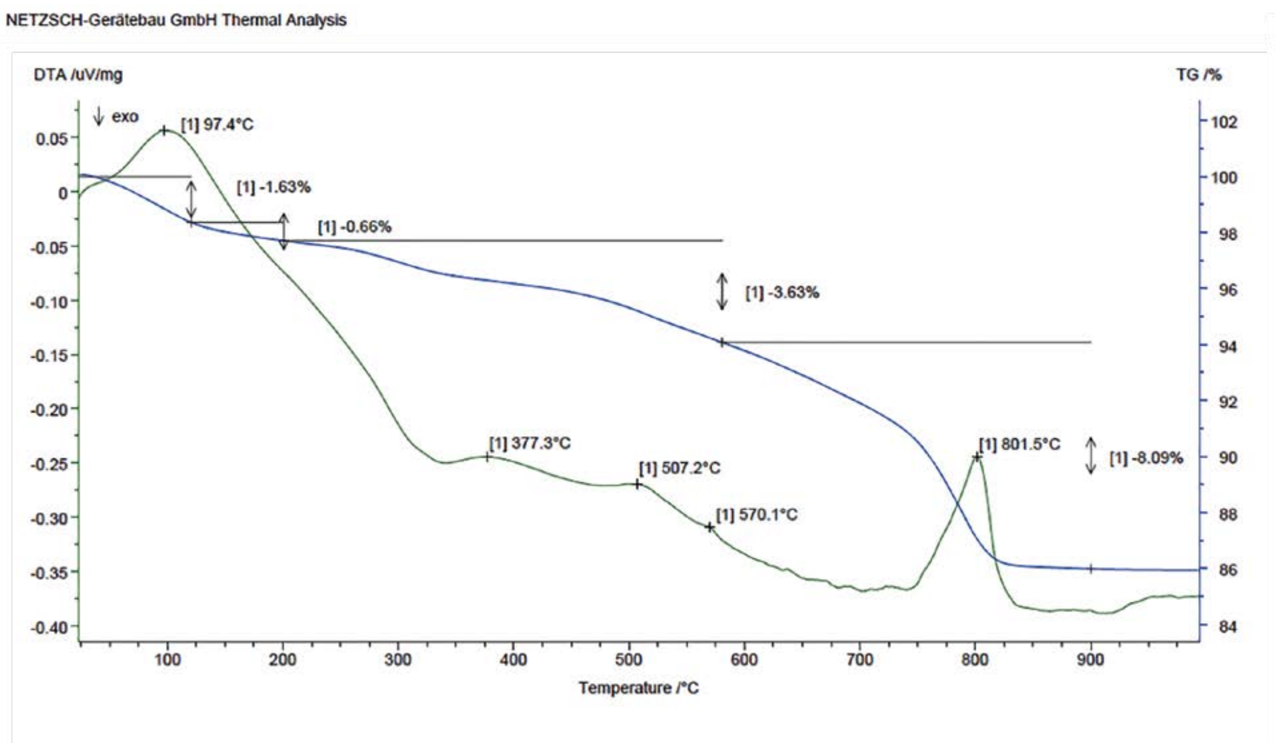

Fig. 5: TG-DTA diagram of an earth mortar from Lavrion (graph: A. Bakolas and N. Meimaroglou).

supported by the results of the wet sieving. The two granulometric curves, presented in Fig. 3, are the outcome of analysis with both hydrometer, to find the clay and silt content and the sieving procedure, to draw the grading curve of the aggregates. They derived from earth mortars of the same masonry. One mortar sample was taken from the infill (M1) and the other from the joints (M2).

The joint mortar (M2), as it can be observed in Fig. 3, has a maximum aggregate diameter of 1 mm and a clay content of 18%. The fact that this mortar is fine-grained permits it to fill the thin joints, while the high clay content ensures a high compressive strength, which is necessary for the load-bearing outer leaves of the masonry. On the other hand, the infill mortar (M1) is completely different. It has a clay content of only 9% and aggregates up to 15 mm. Apart from sand, there is also gravel, in exactly the same proportion: 32% is the sand and 32% is the gravel. These characteristics allow the infill mortar to fulfil its role in the masonry system, which is to provide a bond between the outer leaves. In order to do so, coarse aggregates and a low clay content are necessary, to reduce volume change and shrinkage cracking. As a result, the masonry has strong mortars with fine aggregates in the joints to provide strength to the wall and weaker mortars with coarser aggregate in the infill, to reduce shrinkage and provide bond between the masonry leaves. The exact same principle was observed in recent research on mechanical properties of stone masonry with earth mortars (Meimaroglou and Mouzakis, 2018) and it can't be accidental.

Furthermore, X-ray diffraction (XRD) analysis, to identify the crystalline compounds and thermogravimetric/differential thermal analysis (TG/DTA) to identify physico-chemical transitions were also performed. For some typical diagrams see Figs. 4 and 5. The major phase revealed by XRD analysis (Fig. 4) is quartz while the secondary one consists of calcite, muscovite/illite and kaolinite. The TG/DTA diagram (Fig. 5) is typical of an earth mortar. Mass loss under 120 °C represents physically bound water. Mass loss between 120 – 200 °C represents interlayer water and between 200 – 600 °C the chemically bound water. At temperatures above ca. 800 °C, $CaCO_3$ decomposes. Endothermal peaks at 307.2 °C and 507.2 °C can be attributed to clay minerals. The endothermal peak at 570.1 °C is attributed to the transformation from α-quartz to β-quartz. It is also worth noting the high content of calcium carbonate (18.4% $CaCO_3$) and the absence of swelling clays that could hinder the performance of the earth mortars.

Properties of hydraulic mortars

Mining and metallurgic practices demanded effective and rational management of water resources. In a dry area, with no springs, rain and the subsequently formed ravines were the sole water-sources. This historical, geophysical and climatic context gave rise to an extensive, large scale hydraulic system managing billions of tons of water when operating in full scale during the second half of the 4th century BC. Recent research has elucidated aspects of this system and has pointed out the connection between water management and the productivity of workshops (van Liefferringe, et al., 2014). The technology employed, besides the elaborate built parts (dams and built ravine-bands, on- and under- ground cisterns, aqueducts, distribution and hydrostatic pressure regulating tanks, ore-washeries, etc.), included the use of hydraulic mortars of extraordinary composition, strength and waterproof properties, which are still not fully understood.

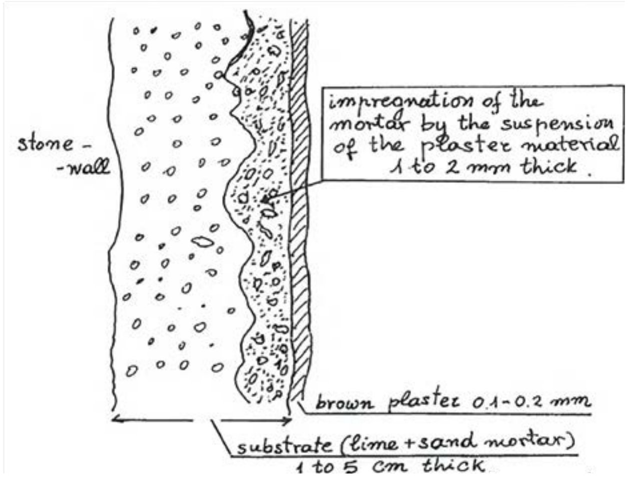

Fig. 6: A typical section of a masonry from Lavrio showing the system of plastering (drawing and comments after Papadimitriou and Kordatos, 1995, p.278 fig.3).

These hydraulic mortars were applied on structures in contact with water or where industrial activity took place (cisterns, floors and walls of the washeries, some ancillary structures etc.). Two hydraulic mortars with different function and composition were used for plastering (Fig. 6): 1) the outermost brown waterproofing thin layer of plaster which has been thoroughly studied (Conophagos and Badecas, 1974; Papadimitriou and Kordatos 1995) and 2) and the concrete substrate, for which only a few studies have been conducted. Our ongoing research, combined with the existing studies, suggest that a binder of hydraulic nature was used for the substrate and elucidate some of its exceptional properties.

The brown plaster

Initially, it was thought that the outermost coat, the thin brown plaster, consists of ground litharge mixed with lime (Conophagos and Badeca, 1974; Badeka, 1974). But it was noticed that the material did not give reflections in XRD analysis, apart from that belonging to calcite, despite that SEM-EDS analysis revealed a high content of lead, manganese, zinc, alumina and silica. So, it was assumed that this brown waterproofing render consists of lime combined with a mixture of ores and litharge which were previously melted together and quenched to obtain a non-crystalline, amorphous material. This material in a fluid suspension was applied on the substrate in layers with a brush (Papadimitriou and Kordatos, 1995).

What is untold until now, but important from a technological aspect, is that this remarkable technology reveals a deep, sophisticated knowledge of hydraulicity. Firstly, the utilization of slags in construction is something relatively modern. Metallurgical slags are used nowadays as supplementary cementitious materials in Portland cement concrete mixtures, in a way pretty much similar to the ancient one. This procedure is described in a few words as melting – quenching –grinding.

The reason behind this procedure is not that simple. One of the main factors affecting the pozzolanic activity of a natural or artificial pozzolan is the $SiO_2 + Al_2O_3 + Fe_2O_3$ content. ASTM C618 standard defines their minimum content at 70%.

But silica, alumina and iron oxides can be found everywhere in nature and in various forms. For example, soil's clays have high content of silica and alumina. Also quartz, the second most abundant mineral on earth's surface, is crystalline silica. But soils, as well as quartz are inert. They do not have pozzolanic activity, which means that they do not react with calcium hydroxide to form hydraulic compounds as calcium silicates or calcium aluminates. But while common soil doesn't react with lime, soil from Santorini Island, Phlegraean fields or Trass from Germany do. The same holds true for soils after sintering to form pottery, ceramics or bricks. If these products are finely ground, they also react with lime.

This different behaviour of SiO_2, Al_2O_3 and Fe_2O_3 is the result of two other factors, apart from the content, which affect the pozzolanic activity: the amorphous or the poorly crystalline fabric (with a few exceptions as the zeolites) and the fineness. Volcanic pozzolans have most times a significant content of fine, amorphous or poorly crystalline components, which explains the pozzolanic activity of the earth from Santorini, Trass and Phlegraean fields. Clay minerals possess a crystalline structure and are therefore unreactive, but after calcining at 700 – 950 °C, this structure is destroyed and a quasi-amorphous structure is obtained. If thermal treatment exceeds this temperature, clays regain a crystalline structure and are again unreactive. Therefore old pottery and bricks are suitable, after grinding, for use as pozzolans while modern bricks calcined at higher temperatures are not.

The same principles are applied for the use of slags as pozzolanic additives. They should be mainly amorphous and with a high specific surface. However, if they are allowed to cool in the air, recrystallization occurs. In modern industry, they must be cooled rapidly most times by pouring them in water to become a granular, amorphous and thus pozzolanic material (Wang, 2016, pp.99 – 100, 315). This knowledge that we possess nowadays and apply in industrial processing of slags was presumably unknown to ancient civilizations. They used pozzolans, either natural or artificial, by accident and by trial and error. The common narrative is that they found by chance that if the specific earth from Santorini or Pozzuoli is mixed with lime, they get a far better product and so they evolved this technique. Consequently, the apparent knowledge by ancient Athenians at Lavrion that some materials as litharge and slags are inactive but if you sinter them, then quench them and ground them, they became active and this is the only way for the material to possess pozzolanic properties, is a knowledge many steps beyond our understanding of ancient building technology.

The substrate: Typical lime mortar or hydraulic concrete?

On the outer layer, the brown waterproofing plaster, systematic research has been undertaken. On the contrary, the substrate mortar has been to a great extent disregarded, because the general idea is that it is a typical aerial lime mortar, an intermediate coat between the masonry and the brown plaster with the exceptional properties mentioned above. Characterization of this material gets even more complicated as each of the few studies undertaken so far had a different purpose and were conducted by different researchers. However, these previous studies combined with our ongoing own one show that the aforementioned general idea, i.e. that the substrate is a common aerial lime mortar playing just the role of an intermediate layer, is erroneous. In the following sections, it is shown that the binder of the substrate is of hydraulic nature combined with a large number of gravel-sized aggregates, with a diameter often greater than 10 mm, leading to a material that simulates the properties of a high-performance concrete.

Previous studies and our ongoing research

E. Badeka, in her pioneering PhD thesis back in 1974 examined, among others, renders from cisterns from Lavrion (Badeka 1974, pp.38 – 94). She assumed that the substrate is concrete made of hydraulic lime and not aerial lime. This is based on XRD analysis, on polarized light microscopy analysis and on the high contents of silica and alumina in the binder matrix determined through XRF analysis.

C.A. Langton and D.M. Roy conducted research on ancient building materials with the aim to optimize modern borehole plugging and shaft sealing materials used to isolate nuclear waste (Langton and Roy, 1984, p.543). Their main concern was the aspects associated with the durability of the ancient concrete. Besides mortars from Italy and Cyprus, they examined some mortar samples of a dam and cisterns from Lavrion. Based on the results of the chemical, mineralogical and petrographic analyses, they assumed that the binder is hydraulic lime, derived from locally quarried impure limestone.

Mishara in 1989 studied renders from Demoliaki, Megala Pefka and Soureza. His aim once again was not to investigate the substrate, but to prove that the brown outer layer was a deliberate fabrication and not the result of a natural process (Mishara, 1989). In his study, a few samples of the substrate were subjected to SEM-EDS analysis in order to be compared with the outer coat. These samples presented a significant content of silica, alumina, lead, manganese and zinc apart from calcium. The author assumed that impure limestone, most likely gangue or plynites, were calcined and so, the lime that was produced had hydraulic properties.

E. Photos-Jones and J. E. Jones studied a wide range of materials from an excavated workshop on the northern side of the Agrileza valley (Photos-Jones and Jones, 1994). They examined tailings, metallurgical waste, soils as well as some plasters, among which some substrate samples. Again, a significant content of silica and alumina in the binder matrix was found.

The aim of a study by A. Galanou, G. Dogani, and K. Lessai was to suggest a recipe and prepare restoration mortars (Galanou, et al., 2008). To do so they studied a few samples of existing mortars, of both the brown plaster and the inner concrete. Their FTIR analysis, thermal analysis, chemical analysis, and microscopy show, for once more, the hydraulic character of these mortars.

Finally, our ongoing study of specimens obtained from floors and renders from washeries, as well as cisterns, confirms the scattered results mentioned above and proves the hydraulic character of the substrate mortar beyond doubt. Mineralogical analysis showed the presence of hydraulic compounds in all samples as it can be seen in a typical XRD diagram at Fig. 7. In addition, after separating the binder from the aggregates and treating it with acid to remove the calcite, a very distinctive hump appeared between 20 – 30° 2ϴ-diffraction angles in XRD analysis (Fig. 8). This hump can be attributed to calcium aluminate silicate hydrates gel (CASH), which is amorphous, not giving any reflection in XRD analysis.

Furthermore, thermogravimetric analysis (TG) revealed that the ratio of carbon dioxide/chemically bound water is in the range between 3.9 and 8. This range is characteristic of lime with hydraulic properties (Moropoulou, et al., 2005). Thermal analysis is a well-established method in mortar characterization (Middendorf, et al., 2005). The weight losses between 200 and 600 °C are attributed to chemically bound or hydraulic water and at temperatures above 600 °C to the decomposition of the carbonates. The ratio between these two values expresses inversely the hydraulicity of a mortar and has been proved useful in the classification of mortars (Bakolas, et al., 1998). The claim that it is a hydraulic mortar is further corroborated by XRF analysis which showed a significant content of silica, alumina as well as of metals and minerals linked

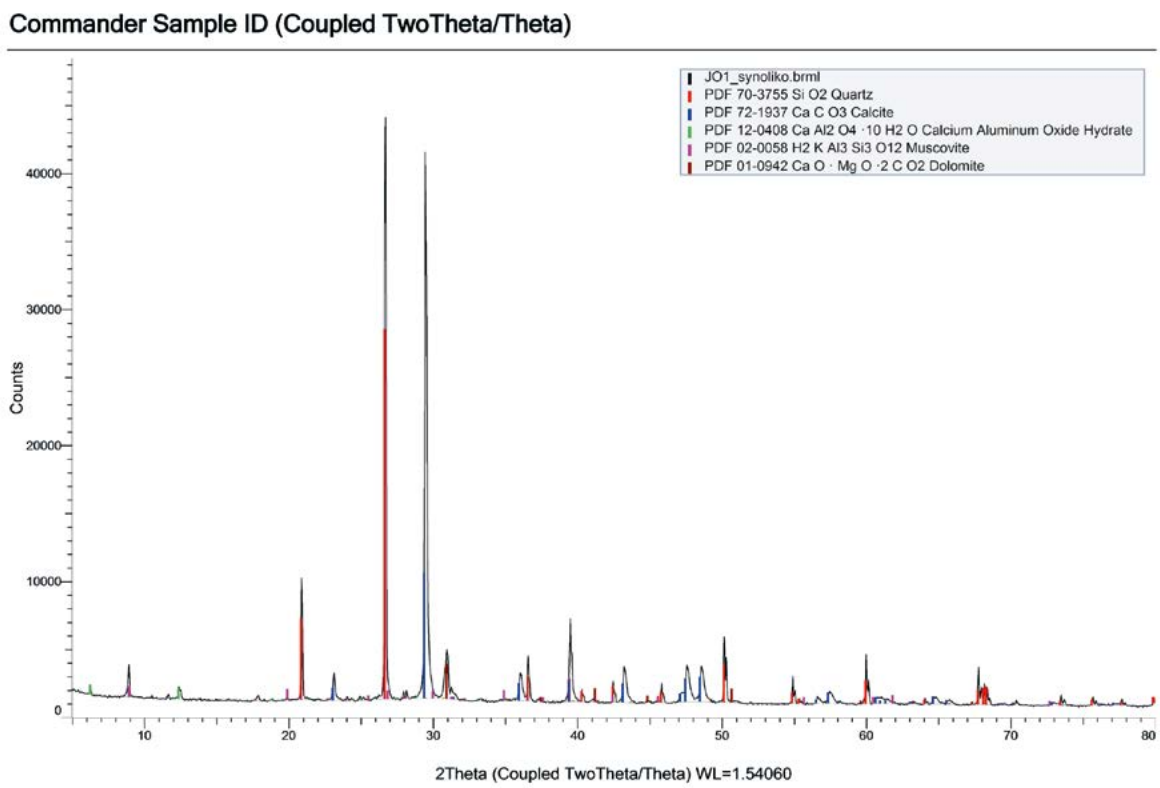

Fig.7: A typical XRD diagram of a Lavrion mortar (diffractogram: N. Meimaroglou).

with the ore processing, both in the bulk specimen and in the binder matrix.

Finally, polarised light microscopy of thin sections was applied. Images captured in parallel and crossed Nicols gave a deeper insight of the nature of the binder. They revealed calcium silicate phases (Fig. 9a) and the presence of amorphous and/or isotropic material (Fig. 9b. c) which, in some instances, has reacted with the binder matrix, as it can be assumed by the formation of rims around amorphous particles (Fig. 9d. e). In addition, metallic minerals (magnetite?) were observed as it can be seen in Fig. 9f.

Intriguing properties of this ancient concrete

Preliminary results of the study on the substrate show not only that it is hydraulic, but that it possesses some properties which could characterize it as unique. These are:

- High compressive strength. Compressive strength is the most fundamental property of building materials. Typical lime mortars used in historic structures have a compressive strength of between 0.5 – 3 N/mm^2 (Válek and Veiga, 2005). Nonetheless, in historic mortars it is most times impossible to measure directly strength because the mortars are in the joints and it is very difficult to form appropriate specimens. So, other methods, the results of which are indirect and unclear as those of the fragments methods, have been developed. The relatively modern breakthrough in the mechanical performance of the binding materials was the introduction of cement, but yet, Portland cement mortars had a compressive strength of 10 – 15 N/mm^2 until the 20th century and exceeded 20 N/mm^2 in the early to mid-20th century when the use of rotary kilns, instead of shaft kilns, became more widespread (Skempton, 1962). For Lavrion mortars, there was in some instances the rare opportunity to create cubic specimens and measure the actual strength (Fig. 10). In both our ongoing research and Badeca's study (Badeca, 1974), there were samples with a compressive strength exceeding 20 N/mm^2, showing that the mechanical characteristics of these mortars exceed our beliefs and knowledge on historic mortars.
- High adhesive strength between binder and aggregates. The bond strength, or adhesion between binder and aggregates, is a property that is very difficult to assess and quantify despite its importance. Under compressive loading of mortars and concrete, the bond between binder and aggregates is lost and cracks deviate mostly through the binder matrix which, even in the case of cement, is much weaker than the rock of the aggregates. By observing the patterns of the specimens' failure under compressive loading, it was noticed something remarkable: cracks did not deviate only through the binder matrix, but as it can be seen in Figure 10b, passed, in some cases,

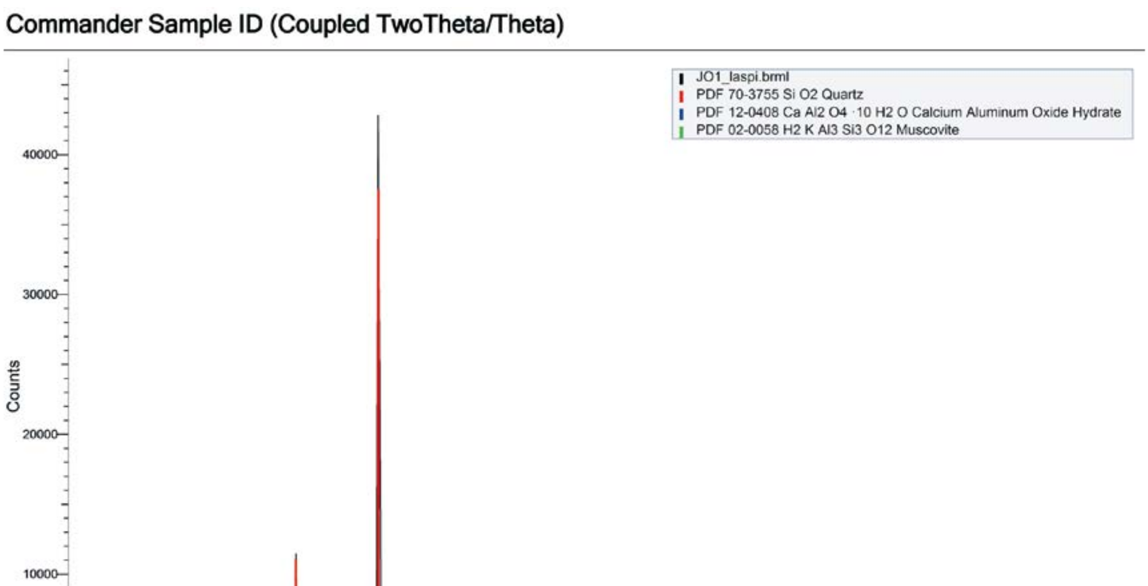

Fig.8: XRD pattern of the acid treated sample. A distinctive hump (between 20–30° 2-theta) reveals the presence of amorphous material (diffractogram: N. Meimaroglou).

though the aggregates. This is something uncommon that shows the high adhesive capacity of the binder, something that can also be seen in Figure 10c, where an aggregate, on which the binder is tightly bonded, is presented.

- Low porosity and high density. Bulk density and porosity are two fundamental properties of building materials. For mortars in particular, porosity greatly affects their strength, their durability and the moisture transport properties (Thomson, et al., 2004). For lime or pozzolanic historic mortars the porosity is usually more than 30% and the density between 1.6 – 1.9 g/cm^3 (Moropoulou, et al., 2005). Modern normal-weight concrete has higher density, which EN 206-1 defines that it should be between 2 – 2.6 g/cm^3. In the case of Lavrion mortars, some of the samples had a porosity of less than 15% and a density higher than 2.1 g/cm^3. Similar results were also reached by Galanou, et al. (2008), who measured a porosity even lower than 10%. Once again, the results obtained are closer to modern concrete than to traditional mortars. A reason behind such extraordinary density and porosity values must be the thorough mixing and ramming with certain tools or devices for this purpose. We also have to envisage a material very different from the slurry or paste like materials that are used nowadays. It must have been

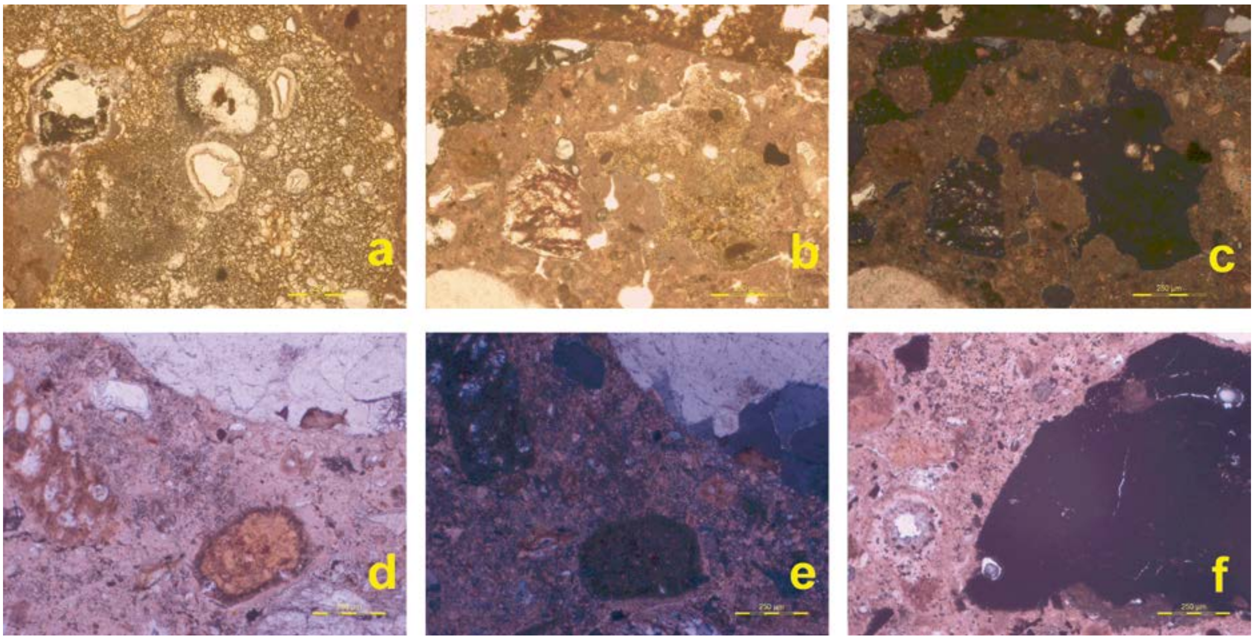

Fig. 9: a. Hydraulic phases of the binder. – b–c. amorphous material can be identified by a comparison between the images in parallel and crossed Nicols, respectively. – d–e. amorphous material (ceramic?) which seems to have react with the binder matrix. – f. Large metallic compounds (microphotographs of the polarized light microscopy: N. Meimaroglou and V. Skliros).

Fig. 10: (a) Assessment of compressive strength (b) Cracks deviating through aggregates during compressive strength testing, (c) High adhesive strength between binder and aggregates (photos: N. Meimaroglou).

a very stiff material, with very low water content at the expense of workability. This is the only way to ram and compact it because if excess water is present and there is no air entrained, it cannot be compacted. This is something that is suggested for Roman concrete and it must be also true for the Lavrion concrete.

Further research questions

As discussed above, the substrate mortar is not a typical lime mortar but a pre-Roman hydraulic concrete, with extreme durability as the longevity of these structures shows. The historical context, as discussed by many researchers (Artioli, et al., 2008; Maravelaki-Kalaitzaki, et al., 2003; Theodoridou, et al., 2013), as well as the technological context in which these hydraulic binders were created and used are of particular importance, but many questions still remain unanswered. Regarding the Lavrion concrete: 1) What kind of lime and pozzolanic materials could they have used for the production of this exceptional material? 2) Is there a standardized formula as suggested for Roman concrete (Brandon, et al., 2014, pp.3, 9, 15)? 3) Is there one type of concrete or more? This material must be the result of a long development through the centuries when these industrial structures were in use. Are different phases of this development recognizable?

Taking into account that the structures at Lavrion, in which concrete was used, are in their hundreds and that concrete served various functions as render on floors, rooms and cisterns, looking for potential answers to these questions is challenging. Apart from the research questions regarding Lavrion concrete, the major question that arises is, did ancient Greeks use concrete elsewhere? In this perspective, the concrete that covered the 5th century BC cistern at ancient Kamiros, Rhodes island (Fig. 11), which also presented high strength and density (Koui and Ftikos, 1998), as well as the work of R. Malinowski (1982), are a good start. It becomes apparent, that to address all these questions, a systematic and consistent interdisciplinary research is required. In this respect, the elaborate study on Roman maritime concrete through the Romacons project can serve as a paradigm (Oleson, et al., 2004; Brandon, et al., 2014).

Conclusions

Within this paper, an overall approach of the mortars used either as structural mortars or renders is presented. Some conclusive remarks are:

1. There is a characteristic building pattern in the structures related with ore processing. Earth mortars were used as structural load bearing mortars and hydraulic mortars as renders. The preferential use of earth mortars, instead of hydraulic mortars, as load-bearing elements, can be attributed to fuel scarcity and to the long-lasting tradition of using earthen building materials by ancient Greeks.
2. Earth mortars were carefully prepared with clay percentage and granularity similar to that which is proposed in modern earth building literature. The hydrometer method showed that the clay content was in the range of 8 – 18%. This range is appropriate to ensure adequate compressive strength with low volume change that could lead to severe cracking in cases, if a higher clay content was used. Furthermore, granulometric curves derived with wet sieving revealed that different earth mortars were used for different purposes. On the one hand, mortars with higher clay content and thus higher strength and binding capacity, with sand-sized aggregates up to 1 mm, were used to fill the stone masonry joints. On the other hand, mortars with low clay content and thus low volume change, with gravel-sized aggregates up to 15 mm, were used as infill mortar to provide bond between the external masonry leaves.

Fig. 11: a. Sample of Lavrion concrete (photo: N. Meimaroglou); – b. Sample of Kamiros concrete (from: Efstathiadis, 2004, p.1 fig.1).

3. The outermost brown waterproofing thin coat has already been thoroughly examined in previous research and has been found to consist of lime mixed with a mixture of ores or/and litharge and slags, which were previously melted together and quenched to obtain a non-crystalline, amorphous material. What is untold so far is that should this procedure – melting quenching and then grinding – not be applied, the material wouldn't possess these remarkable hydraulic properties. Therefore, a knowledge and perception of pozzolanic activity and hydraulicity by the craftsmen of that time should be assumed.
4. Finally, the preliminary results of our ongoing research on the substrate mortar, combined with the few available studies, suggest that it is not a typical lime mortar but a concrete whose binder possesses hydraulic properties. This was confirmed by polarized light microscopy where amorphous-isotropic phases were identified and by TG-DTG and XRD analyses where hydraulic compounds were found. Furthermore, physical and mechanical tests revealed some characteristics uncommon in historic mortars. These are: high compressive strength exceeding 20 N/mm^2 in some samples, high adhesive strength between binder and aggregates, high density which in some instances was higher 2.1 g/cm^3 and low porosity which was measured even lower than 15%. All these characteristics are indicative of an extraordinary material that needs further research to elucidate aspects related to its technology, its evolution and of the history of hydraulic binders in general.

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Effie Photos-Jones

Beyond the silver ‘owls’: Laurion lead and its contribution to synthetic lead-based minerals for the health care/medicines market (4th century BC)

ABSTRACT: *This short paper aims to highlight the use of lead metal from Laurion in the 4th century BC, not merely as a functional metal, but as a raw material in the manufacture of synthetic lead-based minerals, (psimythion, $PbCO_3$) aimed at the health care/pharmaceuticals market of antiquity and as pigments. The paper brings together past and recent work by the author and her colleagues. Past work relates to the analysis of tailings from ore processing recovered from the 1980s excavations of the washeries at Agrileza, Laurion. Recent work concerns the examination of pellets of psimythion ($PbCO_3$) from Athens and Boeotia dating to the 4th century BC, now in the collection of the National Archaeological Museum, Athens (NAM). Comparison of the relative concentrations of Ag and Pb in the three data sets (as grams of Ag to ton of Pb) suggests a preference for an Ag-rich source (whether Pb metal or Pb ore). It is therefore suggested that a) the pellets of psimythion must have been made, if not in Laurion, but of Laurion lead, and b) for the manufacturing of psimythion for the health care/medicines industry, silver-rich lead metal seems to have been preferred over de-silverized lead. Presently, and in view of small data sets, it cannot be said with confidence whether this was a deliberate choice or not.*

After nearly 150 years of continuous research into Laurion’s 5th – 4th century BC activities associated with the production of the Athens silver coinage (owls), it is perhaps now timely to begin looking for evidence for other Pb/Ag-based industrial activities servicing other markets, as well; in that context it is important to keep an open mind as to what we define as ‘waste’. Lithargyros (translated as litharge), thought to have been the ‘waste’ product of silver making was another synthetic mineral in its own right.

KEYWORDS: PSIMYTHION, LEAD CARBONATE, LITHARGYROS, ATHENS SILVER COINAGE(OWLS), AGRILEZA TAILINGS, HEALTH-CARE PRODUCTS

Introduction

Of the Athenian argyreia, and their "ore"

Our view of Classical/Hellenistic Laurion has been largely shaped by its well-documented association with silver extraction and the minting of Athens’ powerful coinage, the silver "owl". There are many contemporary references to Laurion as the locality of the silver mines (*argyreia metalla*) of Athens (or of the Athenians).[1] In the Byzantine sources Laurion is referred to as the gold mines (*chrysseia metalla*) of the Athenians, rather than their silver mines (Suda Lexicon). Nevertheless, we know from the numismatic evidence that gold owls were indeed minted in the 3rd century BC. Interestingly, also in the later periods, Laurion is mentioned in two capacities: first, as having mines (of silver or other metals) (*echon metalla*) and second, as making metal (silver or other) (*poion metallon*).[2] The distinction makes it clear that the word *metallon* (plural *metalla*) could cover, spatially and processually, both the mine (locality of extraction) as well as the activities associated with the manufacture of the finished product, the metal.

But what is the name Athenians gave to the "ore(s)" they extracted in Laurion? There is mention of silver-rich earth (*argyritis ge*) of the Athenians.[3] Lead-rich sand (*molybditis ammos*) is also invoked, in this case as a source of *lithargyros* but not in direct relation to Laurion (Dioscorides *Mat. Med. V.87*). There is an additional reference to *argyritis ammos* again not in direct association

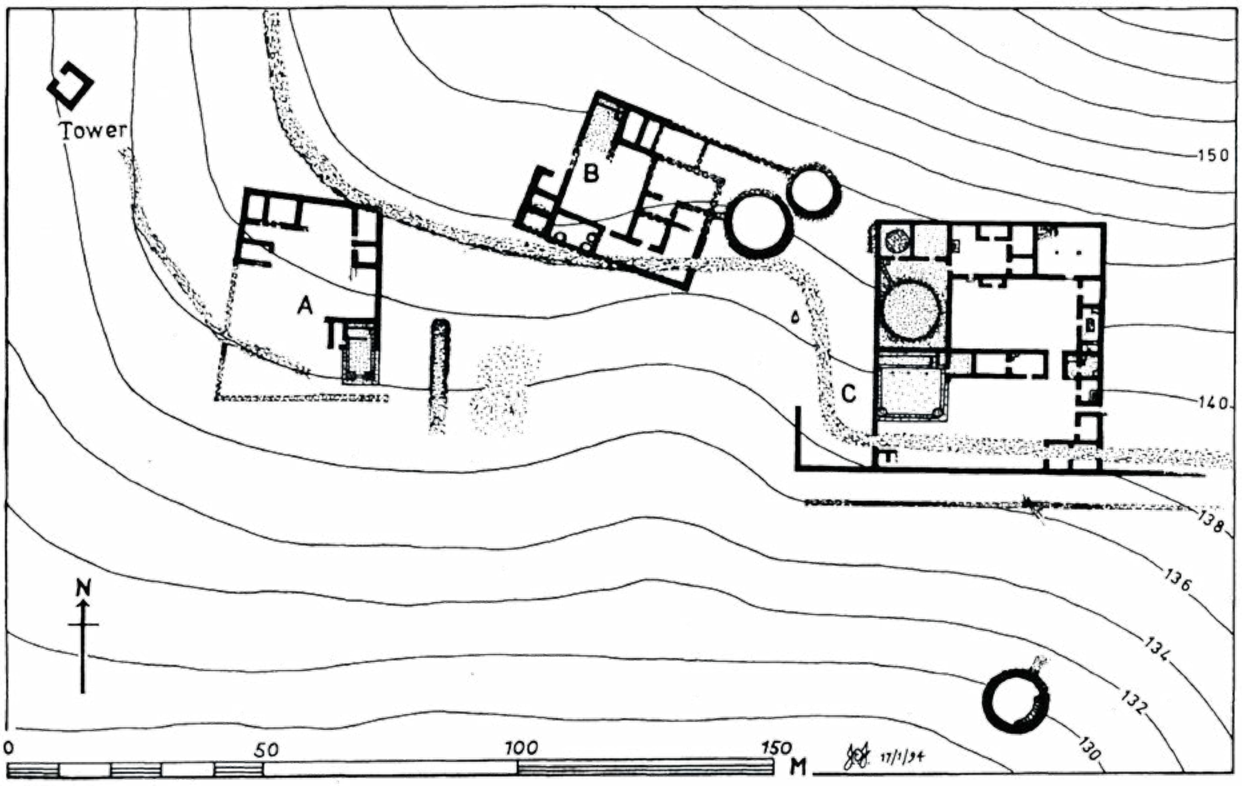

Fig. 1: Plan of Agrileza compounds A, B and C with cistern (bottom right) (after Photos-Jones and Jones, 1994, p. 314, fig. 1).

with Laurion. It is not clear what the difference between *argyritis ammos* and *molybditis ammos* was, apart from the possible assumption that the latter may have not contained silver.

It is curious that Theophrastus, in his treatise *On Stones,* is rather silent about Laurion in reference to silver making, despite the *argyreia* being both active at the time and relevant to his book's title. There is only a mention to the Athenian Callias working the *kinnavaris* (*κιννάβαρις*) in the *argyreia,* for the express purpose of obtaining gold (*On Stones,* 59). This suggests that gold was extracted from *kinnavaris* but silver was extracted from another ore. *Kinnavaris* is thought to refer to cinnabar (mercury sulfide), yet that mineral remains elusive in Laurion.

Since the 19th century, when research interest in ancient Laurion started to take off, it has been acknowledged that Laurion's 5th–4th century BC activities revolved around the extraction and processing of argentiferous galena (PbS). In searching for the "galena" reference in the texts, it has been argued that *molybdaina* (Dioscorides, *Mat. Med*. V. 85) (Beck, 2005) is the mineral that equates with it. But, strictly speaking, that "equation" cannot be correct because the description given for *molybdaina* is that it is yellow (*xanthi*), shiny (*stilvousa*/*ypostilvousa*) and orange-tawny (wax-like). This description does not match the colour of galena which is unmistakably lead grey. On the other hand, Dioscorides (*Mat. Med*. V.85) does not mention Laurion as *molybdaina*'s "site location" but Corycos, the NW promontory of Crete. He mentions that the *molybdaina* of Corycos and of Sevasti (another locality) is *also* mined (*esti de tis kai orykte*)[4], implying that the material described as *molybdaina* may have been extractable from both surface "outcrops" as well as underground veins.

One possible mineral to be equated with *molybdaina* might have been wulfenite ($PbMoO_4$), an orange-red oxide of Pb-Mo with an adamantine and resinous lustre. Wulfenite has been reported in Laurion at Adami mine 2 by Voudouris, et al. (2008, p.93) and in association with the evidence for molybdenite in Plaka. It has been highlighted that the elements Mo, Au, Bi, Sn, Ni exist in elevated concentrations across the Laureotiki but their exact geological origin needs further investigation (P. Voudouris, pers. comm.). Analysed tailings from Agrileza have shown elevated concentrations of Ni and Mo suggesting a tentative but not conclusive association with that deposit (Photos-Jones and Jones, 1994, p.337, tab. 2b).

Over the many years of research in Laurion, there has been little attempt to tie-in particular washeries (and whatever ore remains have been found within) with particular mine galleries, the implication being that mining exploration activities cannot be easily matched to their extractive metallurgical equivalents. Our own analysis of tailings from the processing of the "ore" at the Agrileza washeries (excavations of J.E. Jones in the 1980s) (Fig. 1) showed them to consist not of galena but of cerussite together with fluorite, calcite, quartz and muscovite (Photos-Jones and Jones, 1994, p.357). At the time we assumed that the cerussite detected was the oxidation product of galena and that little of the original "ore" would have been found on site.

I conclude this brief introduction by suggesting that more attention be paid to the name(s) that Athenians (and/or others) used to refer to the lead and/or silver-rich ore extracted from their mines. If *argyritis ge* or *ammos* denotes the raw material extracted, then it is implied that it came with argillaceous materials attached and was of small (sand particle) size. In that scenario, the (pre-smelting) washing cycle would have been particularly targeted to the removal of that argillaceous earth, an activity which may have gone so far under the radar of recent archaeometallurgical investigations. In our paper (Photos-Jones and Jones, 1994) we highlighted the presence of clay minerals like muscovite and kaolinite in the tailings but the samples analysed have been too few to give confidence to the hypothesis.

On minerals *skevasta* and *autophye*

In this paper I shall argue a second point, namely that relatively little attention has been paid so far to antiquity’s synthetic minerals. Nevertheless, Theophrastus is particularly informative about minerals, which are both natural (*autophye,* singular-*autophyes*) and prepared/synthesized (*skevasta,* singular-*skevastos*). He gives the example of *kyanos* (*On Stones,* 55), of which there were three varieties denoting "*both a particular blue precious stone and various blue pigments"* (Caley and Richards 1956,183). The terms "natural" and "prepared" (*skevazomenos* rather than *skevastos*) also occur together in Galen’s *On Simple Drugs*.[5] Apart from *kyanos,* Theophrastus refers to two additional synthetic minerals: *psimythion* (*On Stones,* 56) and *ios xystos* (*On Stones,* 57). Galen also identifies them as prepared together with *hydrargyros*, *lithargyros* and *psorikon*[5].

However, again curiously, Theophrastus (*On Stones*) does not mention *lithargyros* and/or in association with Laurion. Yet modern archaeometallurgical scholarship has for long associated Laurion with *lithargyros* (litharge) (Conophagos, 1980), in the form of either dense tubes or thick slabs of PbO, and in either of its two polymorphs: the tetragonal litharge or the orthorhombic massicot. Both have been considered waste products of cupellation activities.

The *lithargyros* of Dioscorides (*Mat. Med*. V.87), however, is not a waste product at all, but a deliberately prepared material, serving as the raw material for the manufacture of other synthetic minerals. Dioscorides states that the *lithargyros* of Attica was the best*;* it was produced "of silver" and was called *lavritis.* Whether originating from Laurion, Sicily or Campania, *lithargyros* was subsequently placed in a pot, having been "cut up" into bean-sized pieces and processed further. There is little doubt that, whether as a desired product or an intermediate "waste", *lithargyros* would have consisted of PbO (yellow, as litharge, red as massicot). But assuming, *a priori,* that the PbO-rich materials encountered in Laurion were "waste" materials, particularly if de-silvered, is at best short-sighted.

XRD analysis of a relevant (PbO-rich) sample from Agrileza (sample 135) showed lead oxide (massicot rather than litharge) and a small amount of cerussite. ICP-OES/AAS analysis of the same showed it to be devoid of silver (Photos-Jones and Jones, 1994, p.346, tab. 6). We can speculate that Agrileza sample 135 was a *lavritis,* but there is need for more extensive analysis of these materials, starting perhaps with field-based, non-destructive methods, i.e.pXRF, for broader hypotheses to be formulated.

Lithargyros features prominently in the *Hippocratic Opus* often in tandem with *psimythion* and other mineral ingredients in the preparation of medicinals. Thus, in the process of examining the archaeometallurgical evidence from Laurion, or indeed anywhere where lead metal was being manufactured and worked, there is a need to exercise caution as to which materials one delegates *a priori* to the realm of "waste". Certainly, composition alone (as in the case of PbO) cannot be the sole defining criterion.

To conclude this cursory discussion into the Dioscoridean lead-based synthetic minerals, apart from *psimythion* and *lithargyros,* Dioscorides mentions another one, namely *molybdos kekaumenos* (*Mat. Med*. V.81). It was manufactured from lead metal sheets/plates *(molyvdou elasmata*) and placed, in layered form, with sulphur, within a cooking vessel (*lopas*) and heated from below. The cooking vessel implies heating, kitchen-oven style, rather than furnace-style, and Dioscorides warns against smelling the fumes from the pot by covering the nose (*skepasas tous rothonas*), since "whatever comes out" is deleterious to health (*vlavera gar e apophora).*

This brief report focuses on the relative concentrations of Ag and Pb in three data sets, presented in Tab. 1: in samples of pellets of *psimythion* from Athens and Boeotia, in the National Archaeological Museum, Athens and in samples of tailings from the washery at Agrileza in Laurion, all three sets dated to c. 4th c BC. The following two sections introduce each set.

The tailings at Agrileza washery C and their Ag/Pb ratios

Our work at Agrileza, both in the early 1990s (Photos-Jones and Jones 1994) and subsequently, in the mid-1990s (the work over two seasons 1995 and 1997 is still pending full publication) aimed to analyse materials recovered from the site. Agrileza consisted of three washeries, Agrileza A, B and C combining workshop and residential quarters (Fig. 1).

The material recovered primarily from compound C was: a. "tailings" representing fragments of "ore" either *prior* to being washed in the washery or *after* they were recovered from the washery. Tailings derived from different rooms within the compound as well as the washery floor proper (Tab. 1); b. fragments of building materials like plasters, cements; c. a few (iron and lead based) slags and litharge. The latter two types of materials are not included in the present discussion.

XRD analysis of a select few samples revealed that the "ore" recovered from the site was not galena but rather cerussite (Photos-Jones and Jones,1994, p.352). There was sparse evidence for clay minerals, at least in the samples collected. The following represent some analytical results from the original 1994 publication.

Sample 6, tailings from in Room XII: fluorite (CaF_2), calcite ($CaCO_3$), barium muscovite ($BaAl_3Si_30_{10}(OH)_2$, quartz, cerussite ($PbCO_3$).

Descriptor	Sample no	Pb%	Ag (ppm)	Ag (g)/Pb (ton)
Athens psimythion pellet 01	13676b-1	47,8	1702	3561
Athens psimythion pellet 02	13676b-2	47,7	1742	3652
Athens psimythion pellet 03	13676b-3	43,5	1883	4329
Athens psimythion pellet 04	13676b-4	44,2	1602	3624
Athens psimythion pellet 05.1	13676b-5.1	44,3	1562	3526
Athens psimythion pellet 05.2	13676b-5.2	41,0	1479	3607
Athens psimythion pellet 06	13676b-6	47,3	1561	3300
Athens psimythion pellet 07	13676b-7	43,2	1607	3720
Athens psimythion pellet 08	13676b-8	45,0	1625	3611
Athens psimythion pellet 09	13676b-9	48,4	1617	3341
Athens psimythion pellet 10	13676b-10	42,5	1499	3527
Boeotia simythion pellet 03	11332-3	57,8	2156	3733
Boeotia simythion pellet 04	11332-4	53,7	1921	3579
Boeotia simythion pellet 05	11332-5	54,1	1908	3529
Boeotia simythion pellet 06	11332-6	57,5	2348	4082
Boeotia simythion pellet 07	11332-7	57,3	2009	3509
Boeotia simythion pellet 08	11332-8	56,2	2205	3923
Boeotia simythion pellet 09	11332-9	53,6	1973	3681
Boeotia simythion pellet 10	11332-10	53,0	1885	3557
Boeotia simythion pellet 11	11332-11	56,0	2021	3609
Tailings, Room XII, Compound C	6	5,47	183	3346
Tailings, Room XII, Compound C	11	7,49	118	1575
Tailings, Room XII, Compound C	16	5,03	185	3678
Tailings, Room XII, Compound C	29	4,02	69	1716
Tailings, S Court, Compound C	30	5,08	50	984
Tailings, S Court, Compound C	37	4,87	49	1006
Tailings, S Court, Compound C	38	4,40	110	2500
Tailings, Room VI, Compound C	39	3,05	122	4000
Tailings, Room VI, Compound C	40	3032	120	3614
Tailings, Room XXI, Compound C	76	4,91	260	5295
Tailings, Room XXI, Compound C	102	3,67	163	4441
Ore washery tailings, Washery C	111	2,94	73	2483
Ore washery tailings, Washery C	114	7,14	299	4188
Ore washery tailings, Washery A	115	4,01	142	3541
Tailings, Room XV, Compound C	142	3,41	97	2845
Tailings, Room NC, Compound C	149	5,20	77	1464
Tailings, Room II, Compound C	196	4,33	153	3533
Tailings, Room II, Compound C	197	6,11	61	998
Ore washery tailings, Washery C	116,1	5,29	284	5369
Ore washery tailings, Washery C	116,2	5,71	345	6042
Ore washery tailings, Washery A	172,1	3,09	96	3107

Tab. 1: Composite data sets consisting of data presented in Photos-Jones and Jones (1994) and Photos-Jones, et al. (2020) showing silver and lead concentrations and their ratios. Different analytical techniques have been used: AAS for Agrileza, pXRF for psimythia.

Sample 116, tailings on washery C floor: fluorite (CaF_2), calcite ($CaCO_3$), barium muscovite ($BaAl_3Si_30_{10}(OH)_2$, quartz, cerussite ($PbCO_3$), in addition to kaolinite.

Sample 135, a piece of litharge: red massicot and small amounts of cerussite.

Photos-Jones and Jones (1994, various tables) reported the major, minor and trace elements in these and other samples determined by ICP and AAS analysis, the latter for Pb and Ag. Tab. 1 above combines the Pb and Ag concentrations and the Ag/Pb ratio determined as grams of Ag to a ton of Pb of the ICP-determined Agrileza tailings. The mean ratio is 3119 (st. dev. 1528). We return to this table after presenting the NAM pellets of *psimythion.*

4th century BC *psimythion* pellets at NAM and their Ag/Pb ratios

Psimythion is widely reported as face whitening material (Aristophanes *Ecclesiazusae* 1072; *Plutos* 965), but it also made a strong appearance in the *Hippocratic Opus* as a mineral ingredient in medicines, often together with *lithargyros*. The *Thesaurus Linguae Graecae* (TLG) research digital data base of Greek texts from Homer to the end of Byzantium contains no less that 1,200 entries for *psimythion,* a number of them in association with other metallic minerals and as ingredient in remedies.

Psimythion in the form of either standardised white pellets or small lumps have been found within (usually but not exclusively) female burials and within clay pots (*pyxides*). These materials have for long been assumed to be items of beautification that the deceased took to her grave. Despite the commonality of the *psimythion* (used often together with the plant-based rouge, *eghoussa)*, its appearance amongst the burials offerings is surprisingly rare. So far, there are no more than a dozen published such clusters of artefacts found within burials across various localities in Greece (Photos-Jones, et al., 2020, tab. 1). There is currently an attempt to bring together the extant archaeological evidence for such finds from burials across Greece, in an effort to address this question (Oikonomou and Photos-Jones, forthcoming).

Regarding the method of *psimythion* preparation, Theophrastus (*On Stones*, 56) gives a detailed account:

> *"(...) lead about the size of a brick is placed in jars over vinegar (oxos) and when this acquires a thick mass, which it generally does in ten days, then the jars are opened and a kind of mold (evros) is scraped off the lead, and this is done again until it is all used up. The part that is scraped off is ground in a mortar and decanted frequently, and what is finally left at the bottom is white lead (psimythion)" (Caley and Richards 1956, p.188) ([oxos] and [evros] have been inserted by this author).*

Oxos is translated as *"poor wine or vin ordinaire"* or *"vinegar produced from oxos"* (see entry in LIddell-Scott-Jones Dictionary – www.perseus.tufts.edu). In the second meaning, it is made clear that *oxos* is distinct from and not synonymous with *vinegar.* For long it has been assumed that *oxos* "equals" vinegar, however the

Fig. 2: Pyxides NAM13676a and 13676b (photograph courtesy of National Archaeological Museum, Athens).

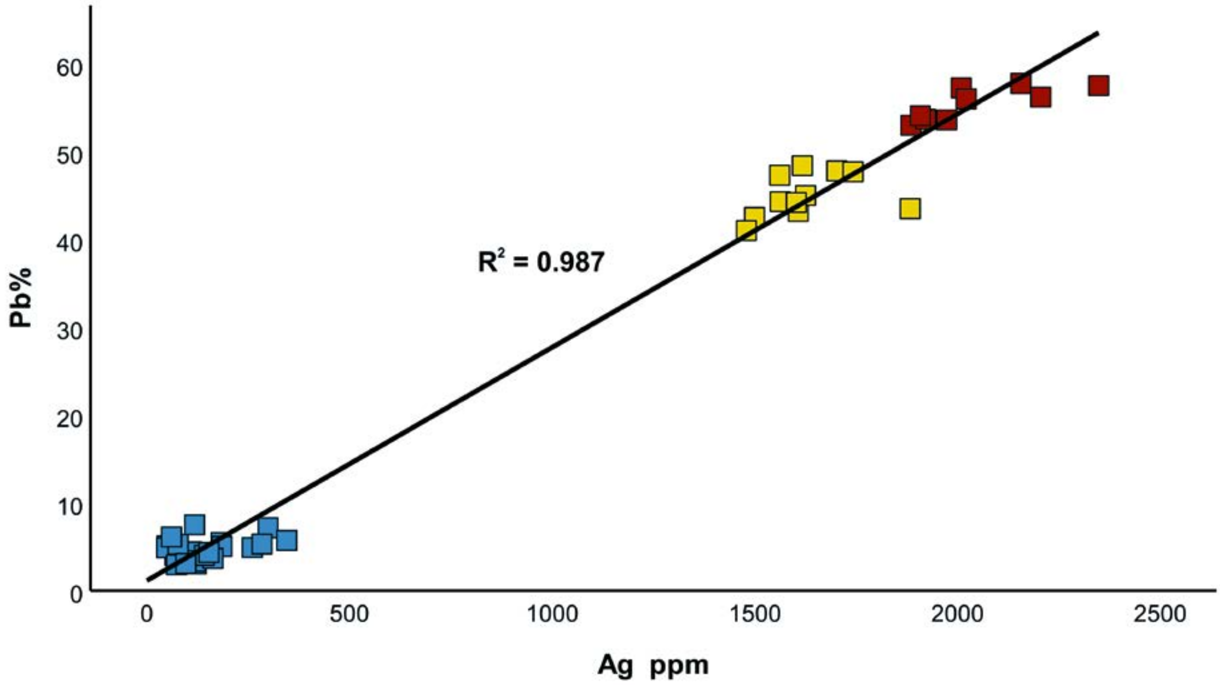

Fig. 3: Plot of Pb vs Ag data shown in Table 1. Coloured in blue are the Agrileza tailings; in yellow, the Athens/Attica psmythia; in red, the Boeotia psimythia.

product of the reaction of lead metal with acetic acid would have led to the formation of lead acetate, a soluble salt and thus unsuitable as a pigment (Stevenson, 1955). In their attempt to find a source of CO_2 which would have driven the reaction to the production of lead carbonate, Caley and Richards (1956, p.188) correctly proposed an alternative source of carbon dioxide like "*spoiled grape juice undergoing both alcoholic and acetous fermentation"*. This, they reasoned, would have provided "*ample carbon dioxide"*.

In our recent study, permission was given by the NAM to sample and analyse destructively three very fragmented pieces, one from each pyxis (13676a, 13676b, 11332) (Photos-Jones, et al., 2020). XRD analysis showed that the samples consisted of near-pure cerussite with only very small amounts of hydrocerussite (usually not exceeding 3% and only in one out of ten cases with amounts c. 11%). More extensive analysis was allowed, non-destructively, by portable XRF on twenty pieces: ten of 13676b from Athens and ten of 11332 from Boeotia. Calibrated pXRF elemental analyses showed only two main elements i.e. Pb and Ca with c. 80% Pb and 2–3% Ca. The uncalibrated pXRF analyses for trace elements showed Ag, Cu, Sn, Sb and Cd (in ppm). Results are shown in Tab. 1. Column 5 in the same table shows the ratio of silver to lead, reported as grams of Ag to a ton of Pb. The mean ratio for *psimythion* pellet is 3635 (st. dev. 238).

Demonstrating that the 4th century BC *psimythia* (Fig. 2) in the National Archaeological Museum, Athens (NAM) consisted of near pure synthetic lead carbonate (cerussite, $PbCO_3$) runs contrary to the long-held assumption, namely that it was basic lead carbonate (lead white or hydro-cerussite ($2PbCO_3 \cdot Pb(OH)_2$)) that would have been made in the Theophrastus pot (Photos-Jones, et al., 2020). Lead white used as pigment has been the predominant compound arising from the industrial-scale Dutch/stack process of the later centuries, but the source of the CO_2 in the two different set-ups (that of Theophrastus vs. that of later periods) is not the same. As early as the middle of the 19th century researchers wondered whether the Theophrastus pot could have sustained the production of any compound beyond lead acetate (from the reaction of acetic acid vapour with lead metal).

In our attempt to understand the presence of Pb carbonate as the main phase, we hypothesized a series of possible reactions which could have taken place between the biotic (both aerobic and anaerobic microorganisms) component in the pot and the abiotic i.e. the lead metal; since lead metal and *oxos* were not in contact, this interaction would have been via the gas phase over the surface of the liquid (Photos-Jones, et al., 2020, figs. 5 and 6). We suggested that the conditions within the pot and in the course of the ten-day cycle would have been dynamic, the oxygen-full environment of the first few days gradually depleting and the CO_2 increasing; at the same time, there would be different minerals forming on the lead metal surface starting with lead hydroxide, followed by lead acetate, and then by hydrocerussite; the simultaneous gradual increase of CO_2 would have pushed the equilibrium from the hydrocerussite to the cerussite.

We turn now to the main topic of this paper, namely the relative concentrations of Ag and Pb within the NAM pellets of *psimythion*; for the Athens pellets the relationship between the two elements is linear but their correlation is poor (R^2=0.11). This suggests that the pellets have originated from different batches of $PbCO_3$ making and by extension of lead metal (different smelts or co-melts). The corresponding plot for the Boeotia *psimythia* again shows a linear relationship but with greater correlation (R^2=0.62), suggesting that most of the pellets have come from the same batch of $PbCO_3$ making. Finally, when the same plot is generated for the Agrileza tailings, again there is poor correlation (R^2=0.14). This means that the samples we chose to analyse from the plethora dispersed across the site originated from "ore" deriving from different mines/sources within the Laureotiki and/or they may have originated from different stages of washing.

When all three data sets are treated in a single plot (Fig. 3) there is nevertheless a good correlation between all three data sets (R^2=0.99). Fig. 3 does not suggest that the source for all three groups is the same, but rather that all three groups have a high Ag content relative to their Pb content. Furthermore, and in the case of *psimythion* pellets, it suggests that there was little attempt to de-silver the Pb metal prior to inserting it within the Theophrastus-type pot and converting it (after 10 days) to the Ag-rich lead carbonate. We do not know at this stage whether the decision to use non-desilvered Pb, namely material in theory destined for cupellation and the minting of the silver owls, was deliberate or not. If it can be demonstrated, through the analysis of many more such pellets which are in themselves rather rare, that it may have been deliberate, then one has to surmise that antiquity may have had some understanding of silver's antibacterial properties.

Conclusions

Classical/Hellenistic Laurion is pre-eminently associated with the extraction of silver from lead derived from the smelting of the local argentiferous galena. The silver was used in the minting of the powerful Athenian coinage, the silver "owl". As a result, relatively little attention has been paid to the "fate" of the lead metal *per se,* its role seen more as that of a supporting "actor" to the production of silver. However, a closer look at contemporary and later texts makes it clear that lead metal had many and varied applications beyond being a functional metal and/or a vehicle for silver acquisition. It was used, *inter alia*, for the manufacture of lead-based synthetic minerals like *psimythion, lithargyros*, or *molybdos kekaumenos,* the carbonate, the oxide, and (likely) the sulphate of lead, to mention only three. Far from being a waste material, *lithargyros* was considered a mineral useful in its own right and as a starting material for other processes.

Comparison between the *psimythia* of NAM and the Agrileza tailings, makes it clear that both sets of archaeological materials have a considerably elevated Ag content with respect to the Pb present. The question then arises whether the choice of high-silver lead metal for *psimythion* making was deliberate or not. Was there an empirical observation that Ag-rich lead and, by extension, Ag-rich *psimythion* may have been the "preferred" raw material in pharmacological preparations?

Silver is known as an antibacterial (Mijnendonckx, et al. 2013) and the antibacterial action of silver nano-particles (AgNPs) has been well researched (Oei, et al. 2012), and it has been claimed that the antimicrobial action of silver metal was already known in antiquity. Clement and Jarrett (1994) mention the reference in Herodotus about Xerxes using silver vessels to store water. The bioactivity testing of the *psimythion* pellets from Athens and Boeotia was never carried out as part of our recent work, the assumption being that no microorganism would live in the vicinity of so much Pb, the latter being toxic to life. Whether the silver concentration (and particle size?) present within the NAM *psimythion* pellets is sufficient to impart (some) antimicrobial properties to the pellets, in the presence of lead carbonate, will remain at present an open question.

In conclusion, I argue that:

a) it is timely to begin looking at Laurion's activities beyond the 'lead-for-silver' owls narrative, which has dominated Laurion studies for a very long time.
b) there is a need to revaluate our own definitions of what may have constituted "ore" and/or archaeo-metallurgical "waste" in the context of 5th/4th century Laurion and how the "owl"-making industry fed into or worked in parallel with ancillary industries which may have also had a need for silver-rich lead.
c) industries involving mineral synthesis using (argen-tiferous) lead as one of the raw materials and their representation in the archaeological record is a relatively little-researched field. This is on account of the sparsity of residues it leaves behind, at least compared to pyrometallurgical waste.

On a final note, the greater Lavreotiki peninsula would have also provided the second major ingredient needed in the manufacture of synthetic minerals like *psimythion and ios xystos* (verdigris*)*. This is the good wine of the modern Mesogheia, turned (on "demand") into *"oxos"* for the purposes of the pharma industry of antiquity!

Notes

1 For the purposes of this short paper, only Greek sources were explored and within the comprehensive digital DB, *Thesaurus Linguae Greacae* (http://stephanus.tlg.uci.edu). Translations of individual words, derive from Liddell-Scott-Jones (LSJ) Greek-English Lexicon (www.philolog.us); also, the Greek name is given in Latin characters to retain the meaning of the original. *τὴν·Πάραλον·γῆν·καλουμένην·μέχρι·Λαυρείου, οὗ·τὰ ἀργύρεια μέταλλά·ἐστιν·Ἀθηναίοις (*Thucydides Hist 2.55); *τὰς τοῦ Λαυρείου τῶν αργυρείων μετάλλων προσόδους* (Thucydides Hist 6.91); *Λαύρειον·τόπος·τῆς·Ἀττικῆς,·ἐν·ᾧ ·τὰ ἀργύρεια ἦν μέταλλα* (Photius Lexicogr); *Θουκυδίδης α΄·χρῆσίν τ' ἔχει τῶν χρυσείων μετάλλων. ὥσπερ καὶ αργύρεια λέγεται δευτέρᾳ. μέχρι Λαυρίου, οὗ τἀργύρεια μέταλλά ἐστιν*

Ἀθηναίοις (Suda Lexicon under Ἀργυροῦν καὶ Χρυσοῦν); *ἐν Λαυρίῳ γὰρ τὰ μέταλλα τὰ αργυρεία (*Hesyschius, Lexicon); *Καὶ πρῶτον μὲν τὴν Λαυρεωτικὴν πρόσοδον ἀπὸ τῶν αργυρείων μετάλλων ἔθος ἐχόντων Ἀθηναίων διανέμεσθαι* (Plutarchus, Biography of Themistocles); *ὡς τῶν περὶ τὴν Ἀττικὴν αργυρείων* (Plutarchus, De defectu oraculorum).

2 *Λαύρειον τόπος ἐν Ἀττικῇ ἔχων μέταλλα* (Aelius Herodianus and Pseudo-Herodianus); *Λαύρειον*: *ἔστι δὲ τόπος τῆς Ἀττικῆς ποιῶν μέταλλον* (Aelius Herodianus and Pseudo-Herodianus); *Λαυρείω; τῆς Ἀττικῆς γίνονται χρύσεια μέταλλα* (Suda Lexicon).

3 *αργυρίτις γή των Αθηναίων* (Scholia in Aelium Aristidem).

4 There is one that is also mined.

5 *Γαληνοῦ, Περὶ κράσεως καὶ δυνάμεως τῶν πλῶν φαρμάκων* (XII. 237,12 – 16 Kühn): [*λβ΄. Περὶ ὑδραργύρου*] *Ὑδράργυρος οὐκ ἔστι τῶν αὐτοφυῶν φαρμάκων, ἀλλὰ τῶν σκευαζομένων, ὥσπερ ψιμμύθιόν τε καὶ οἷος καὶ ψορικὸν λιθάργυρος. ἔχω δ' ἀυτῆς οὐδεμίαν πεῖραν οὔθ' ὡς ἀναιρούσης, εἰ καταποθείη, οὔτ' ἔξωθεν ἐπιτιθεμένης.*

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Christophe Flament

Fiscal and administrative aspects of the Laurion's mining leases during the 4th century BC

ABSTRACT: *This study is devoted to the main fiscal and administrative aspects of the mining leases in Laurion. It begins by considering the operating system of the Athenian mines, including discussions about their legal status, drawing mainly on the text of the Aristotelian Constitution of Athens. The next step is to give an order of magnitude of the state incomes from the mines, turning to the question of the distribution of the metal extracted from the mines between lessees and the city. This means investigating the prices of the leases and estimating the yearly output of the mines by developing a model based on the mining's sector profitability. At this point, the key issue is to determine what lessees did with their metal so that they could be able to pay the costs associated with mining activities. It is advocated in this paper that a lot – if not nearly all – of the silver produced in Laurion was actually converted into coins, the renowned Athenian "owls". Several important consequences for the Athenian monetary history follow from this conclusion, regarding the role of state authorities in the monetary process, the parameters determining the rhythm and scale of the monetary production, as well as the dissemination of the Athenian coinage.*

KEYWORDS: ATHENS, SILVER, COINAGE, FLEET, FINANCES

Introduction

The main aim of this study is to provide appropriate and supported answers to several crucial questions related to the fiscal and administrative aspects of the mining leases of Laurion during the 4th century BC: What happened to the silver after the smelting process? Could the lessees freely dispose of the metal? How did Athens earn revenues from the mines? How significant were they? Were they sufficient to maintain the war fleet?

Operating procedures of the Laurion mines

To answer those questions properly, a main parameter must be taken into account: since at least the seminal work of R.J. Hopper (1953, pp.200 – 209; see also Harrison, 1968, p.316; Healy, 1978, pp.103 – 105; Domergue, 2008, pp.181 – 182), it is admitted that silver veins were publicly owned in Athens. However, the nature of this right remains very difficult to establish. Since É. Ardaillon (1897, pp.173 – 174), the existence of a kind of "*Bergregal"* is assumed; by virtue of this right, the city would have reserved the property of the mineral resources of the underground, while private individuals could own the surface as any ordinary private property.

This assumption is entirely consistent with the indications of the mining leases erected during the 4th century BC by the *Polētai*, the magistrates who carried out public contracts in Athens.[1] Those documents are written on *stelai* registering leases year by year, including the names of the lessee, of the registrant, and of the mine with its location, as well as its category and price. Several aspects of those *stelai* still pose problems of interpretation, notably the meaning of mine categories (ἐργάσιμα, ἀνασάξιμα, παλαιὰ ἀνασάξιμα)[2] and the nature of payments made by lessees. Were these one-off payments (Crosby, 1950), annual fees, or prytany charges (Hopper, 1953)?[3] May this as it be, it should be noted here that in most instances, the lessee was obviously not the owner of the land on which his mining concession was located.[4]

However, as É. Ardaillon (1897, pp.175 – 176) himself granted, such a *Bergregal* would have been almost unique for the Greek world; even Roman laws did not distinguish between soil and underground products (Hopper, 1953, p.205 – 209; Harrison, 1968, p.234; Osborne, 1985, p.116; Faraguna, 2006, p.143, n.8). Furthermore, this *Bergregal* did not seem to have applied to stone quarries: quarries in

Athens were the property of demes, or of gods, and were rented like lands or houses, but not leased (Flament, 2013; 2015). It suffices to say that I am not very convinced that such a *Bergregal* ever existed in Athens during Classical Antiquity, but to take up this question would require extensive discussion and thus go far beyond the scope of this study. Furthermore, the outcome would not change the fact that, in one way or the other, Athens claimed ownership of the silver deposits or of the underground in which they are located.

As the exclusive owner, the city had two options to exploit the silver deposits: direct-labour operations or leasing out to private individuals. Each system actually has both advantages and disadvantages. In case of direct-labour operations, the main advantage consists in keeping nearly all the metal produced, but the city has, in return, to fully support the costs and the organization of all the operating systems. Conversely, by choosing leasing, most – if not all – of the operating costs are then incumbent on lessees but the city has *de facto* to abandon a large part of the metal produced to the same lessees.

Considering the organisation of the Athenian finances during the Classical period (Flament, 2007a), it is all but surprising that Athens opted for leasing: this is actually the way in which the various means supposed to provide revenue to the city were managed, notably taxes affecting many goods and activities,[5] of which Aristophanes drew up a non-exhaustive list (Vesp., vv.656–660). Each year, the *Polētai* sold at public auction the "right" to collect those taxes (Arist., *Ath. pol.* xlvii,2; Langdon, 1994; Migeotte, 2001). The winner of the auction was then required to pay the price he announced, not the amount obtained from the collection of the tax. His profit being precisely the difference between the sum announced and the amount he actually collected. Apart from the fact that such a procedure exempted the city from organizing itself the collection of those taxes, leasing had two other major advantages: firstly, to know in advance the income of each revenue – the sum being fixed at the public auction –; secondly, to collect all the revenues on a fixed date, usually at the end of the 9th prytany (Arist., *Ath. pol.* xlvii,4), that is to say just before the beginning of the next civil year.

Basically, the principles that have just been clarified for the management of the taxes are also valid for the leasing of the mining concessions in Laurion, as it can be deduced from this quotation of the Aristotelian *Constitution of Athens*:

> *"Ἔπειθ' οἱ πωληταὶ ί μέν εἰσι, κληροῦται δ' εἷς ἐκ τῆς φυλῆς. Μισθοῦσι δὲ τὰ μισθώματα πάντα, καὶ τὰ μέταλλα πωλοῦσι καὶ τὰ τέλη μετὰ τοῦ ταμίου τῶν στρατιωτικῶν καὶ τῶν ἐπὶ τὸ θεωρικὸν ᾑρημένων ἐναντίον τῆς [βουλῆς]˙ καὶ κυροῦσιν, ὅτῳ ἂν ἡ βουλὴ χειροτονήσῃ, καὶ τὰ πραθέντα μέταλλα τά τ' ἐργάσιμα τὰ εἰς τρία ἔτη πεπραμένα καὶ τὰ συγκεχωρημένα τὰ εἰς †[6] ἔτη πεπραμένα.*
>
> *Then there are the ten Vendors, elected by lot, one from each tribe. They farm out all public contracts and sell the mines and the taxes, with the co-operation of the Treasurer of Military Funds and those elected to superintend the Spectacle Fund, in the presence of the Council, and ratify the purchase for the person for whom the Council votes, and the mines sold, the* ergasima *that have been sold for three years and the* sunkechorèmena *sold for … years" (Arist., Ath. pol. xlvii,2, trs. H. Rackham, Loeb Classical Library).*

Several elements mentioned in this text are still debated, especially the meaning of the different categories of mines (ἐργάσιμα / συγκεχωρημένα), and the duration of the leases. Fortunately, the outcome of these various questions would have very limited impact on the topics discussed here. Most importantly it was precisely the vendors of the taxes, the *Polētai*, who were also responsible for the leasing of the mines, and the vocabulary used is, exactly as in the case of taxes, that of a sale: it is actually a "right" that the *Polētai* sold, the right to collect a tax, or to exploit a mine (Hopper, 1953, p.235; Domergue, 2008, pp.181 – 182).[7] There are, however, some specificities in the case of mining leases: firstly, unlike the farming of the taxes,[8] no document mentions the obligation for lessees to provide guarantors (Hopper, 1953, p.225; Faraguna, 2006, p.150); secondly, the concession period is obviously longer – at least three years, maybe even up to ten years (see n.6) – than in the case of taxes, which are theoretically sold for one year only.

In Athens, the mines of Laurion were then leased almost like all the other state revenues and, moreover, by the same *Polētai*. In the case of mining concessions, leasing also reduced for the city the risks associated with the hazards of exploitation, since lessees were, like tax farmers, forced to pay the sum fixed at the public auction, no matter what the actual output of the mine was. But this operating system had a huge impact on the field by dividing the Laurion's area into multiple mining concessions whose limits were minutely described in the abovementioned *Polētai* records. Such a concession system leads to multiple shafts for reaching the ore, because each concession had to possess its own.[9]

Order of magnitude of the state incomes from the Laurion mines

At this stage, it is time to ask the crucial question of the division between lessees and the city of the metal extracted from the mines. Several indications scattered throughout the literary tradition suggest that mining revenues made up a large part of Athens' ordinary revenues.[10] But unfortunately these sources do not provide any precise figures at all. However, we have several indications of amounts paid for acquiring a mining concession (see Shipton, 1998, p.58 for a table with the existing prices), but they are at first sight contradictory. On the one hand, Attic forensic speeches mention substantial sums (9,000 drachmas in Dem. 37,22; 2,000 drachmas in Dem. 40,52)[11]; on the other hand, sums inscribed by the *Polētai* in their records are most often of a very inferior amount: 20 (39 times) and 150 drachmas (21 times). In our opinion, the best way to reconcile these two orders of magnitude is to interpret the sums indicated by the *Polētai* as rents due to each prytany, that is to say ten times a year. It should be noted that on the oldest stele of this *corpus* known so far (Langdon, 1991, P5; Hopper, 1953, p.238), the leases are precisely organized by prytanies and, furthermore, that rents of many other public leases were also paid each prytany.[12]

On these grounds, we are able to propose an order of magnitude of the revenues the city was supposed to derive from the leasing of the mines of Laurion, by following this reasoning. Relying on statistics based on the *Polētai* records, G.G. Aperghis (1997/8, p.18) estimated that about 500 mines were in operation simultaneously during the 340s BC.[13] On the other hand, the average price of a mining lease in those same *Polētai* records is a little bit more than 242 drachmas (Flament, 2007a, pp.72–80). If we consider that payments were due by lessees each prytany this would result in an annual income of about 200 talents, or 5.2 tons of silver.[14] This sum may seem considerable, but it fits perfectly in the order of magnitude of the revenues that the Thasians were supposed to draw from their own mining district during the Archaic period (according to Herodotus, 6, 46). At the scale of the Athenian finances, 200 talents represent roughly half of the city's entire ordinary incomes, which various testimonies allow us to fix to ca. 400 talents per year (Flament, 2007a, pp.31–64). Therefore, it is not at all surprising that many testimonies insist on the importance of the mining sector for the Athenian finances.

Collection of mining revenues and estimate of the annual output of the mines

Several fundamental questions remain however unanswered at this point: how did the city collect these mining rents? And, above all: to what proportion of the total production of silver in Laurion corresponded the revenues of Athens?

Regarding the first question, the speech entitled *Against Pantaenetus* from the Demosthenic *corpus* (*or.* xxxvii) proves to be of great interest (Flament, 2016). From the text it becomes clear that Pantaenetus, a mining lessee, had to bring himself his lease payment to the city. He complains indeed that Evergos, his opponent, seized the money his slave was bringing to be paid to the state for his mine, and caused him to be inscribed as public debtor (§22). There was therefore no automatic levy at the smelting furnace, or at the mint as postulated by some scholars (Aperghis, 1997/8, p.19; Bissa, 2009, pp.55–6; Faraguna, 2006, p.151). Nothing in this speech, however, makes it possible to determine if this payment to the state was made in coins or in raw silver.

This question related to the form of payment actually opens up more broadly to the issue linked to the part of the silver produced that remained in lessees' hands. As previously pointed out, by choosing the leasing procedure, Athens automatically abandoned a part of the silver produced to lessees; in any other way a leasing system as described above could simply not work. But what was the proportion? The testimony of lexicographers reporting a levy of a 24th of the production by the state can resolutely be dismissed: this proportion seems far too small (see Lazzarini, 2001, p. 75), and may have been in force only after the Classical Period (Rhodes, 1985, p.554; Momigliano, 1932, p.255), maybe in Roman times only (Crosby, 1950, p. 203):

> *"Ἀγράφου μετάλλου δίκη: οἱ τὰ ἀργύρεια μέταλλα ἐργαζόμενοι ὅπου βούλοιντο καινοῦ ἔργου ἄρξασθαι, φανερὸν ἐποιοῦντο τοῖς ἐπ' ἐκείνοις τεταγμένοις ὑπὸ τοῦ δήμου καὶ ἀπεγράφοντο τοῦ τελεῖν ἕνεκα τῷ δήμῳ εἰκοστὴν τετάρτην τοῦ καινοῦ μετάλλου. Εἴ τις οὖν ἐδόκει λάθρα ἐργάζεσθαι μέταλλον, τὸν μὴ ἀπογραψάμενον ἐξῆν τῷ βουλομένῳ γράφεσθαι καὶ ἐλέγχειν."*
>
> *Suit for unregistered mine: those who work the silver mines, whenever they wanted to begin a new work, make it known to those put in charge of those by the demos and registered a tax of one twenty-fourth of the product of the new mine. If someone was suspected of operating illegally an unregistered mine, anyone who wished can bring a public suit against him (Suid. s.v. «Ἀγράφου μετάλλου δίκη»)".*[15]

Fundamentally, there is a more indispensable condition for the efficient functioning of the leasing system as it was organized in Athens: the mining sector had first and foremost to be regarded as profitable by the private individuals, i.e. that the profits generated had to be greater than the expenses incurred. Fortunately, many of these expenditures can reasonably be estimated for the mid-4th century BC, thus adding key data to a theoretical break-even point of the mining operations in Laurion during that period. Those figures are summarised in Tab. 1.

Given these results and the number of expenditures impossible to estimate, fixing the break-even point of the Laureotic mines during the intensive phase of exploitation of the second half of the 4th century at *ca*. 700 talents is probably still far below the actual value.[16] It is worth noting too that this break-even point is likely to vary widely according to the number of mines in operation, but also – and even especially – to the fluctuations of certain expenditures, as those devoted to feed the slave population, especially when grain prices rose over the last quarter of the 4th century (Descat, 2004, pp.267–280).

Nature of expenditures	Annual costs
Payments made by lessees to the State	ca. 200 talents
Rental and maintenance of the slaves: - rental of 15,000 slaves, at the rate of 1 obol each per day - food supply for 15,000 slaves, at the rate of 2 obols each per day - maintenance of the working force (fixing the life expectancy of a slave at 10 years, and the cost of one slave at 200 drachmas)	 ca. 150 talents ca. 300 talents ca. 50 talents
Rental of working installations - workshop for ore processing (ἐργαστήριον) - mill (κεγχρεών?) - furnace (κάμινος) - lifting machinery?	impossible to evaluate
Miscellaneous charges - equipment such as tools, lighting (oil for lamps), timber for the chambering of mines - fuel for furnaces - possibly: rent of the land on which the mining concession was located	impossible to evaluate
Total	at least 700 talents (ca. 18 tons of silver)

Tab. 1: Estimate of the mining expenditures in Laurion around the middle of the 4th century BC. This table is drawn by Flament (2019), where the reader will also find the details of the calculations on which those estimates are based.

More fundamentally, I argued in another study (Flament, 2007a, pp.79 – 80) that the interruption of the mining activities at the end of the 4th century was less caused by the depletion of the silver veins than by the increase of the break-even point of the mining sector, due in large parts to the enormous metallic stocks the conquests of Alexander the Great put back into circulation.[17]

But time has now come to ask another crucial question: how did the lessees defray those significant operating costs, and even made profits? Of course, Laurion being a polymetallic region (Rihll, 2001, pp.128 – 132), silver was not the only exploited resource in this area.[18] However, if one reads the *Poroi* of Xenophon, he is convinced that the key product of Laurion was silver; the main challenge is therefore to determine what the lessees do with this metal so that they could meet the various expenses listed above.

It is very unlikely that payments made to the city were made in bullion then converted into coins by state authorities themselves. This scenario would involve a special procedure for the payment of the mining rents (contrary to all other rents that would of course have been exclusively paid in coins) of which there is no mention in the description of the leasing procedure detailed in the Aristotelian *Constitution of Athens* quoted above. Furthermore, in such a scheme, only rents paid to the state would have been converted into coins, i.e. *ca*. 200 talents at the most. Given the level of coin production in Athens during the Classical period as well as the number of engravers employed in the mint evidenced by the diversity of “styles” recognizable on coins (Flament, 2007b, pp.61 – 120), this seems highly unlikely. More fundamentally, the other charges (notably for food supply) could not have been paid with bullion, but only with coins. Thus the question: how did they obtain those coins?

Silver was used in various fields related to craftsmanship, in Athens and elsewhere. Lessees may thus have sold some bullion to jewellers or other craftsmen,[19] but of course not all their silver stock: this solution would have implied enormous market opportunities, because almost 500 talents at least (i.e. the equivalent of the annual spending on slaves as estimated in Tab. 1) had to be sold off in this way every year. However, even flourishing craftsmanship certainly did not require as much silver as this.

Some scholars (recently Bissa, 2009, pp.60 – 61) suggested that silver bullion from Laurion could be sold abroad, notably to governments of other cities to strike their own coinage, since elemental analyses attest that many Aegean coinages were made of Laurion’s silver (notably Aegina, Corinth, Samos and even Rome; see on this topic Flament, 2018b). I, however, argued in another study (*ibidem*) that most of the Laurion’s silver was actually exported in the form of coins, then melted down and restruck by other cities. These considerations however highlight that in Athens the “owl” coinage offered the miners the main opportunity for the silver produced in Laurion, as already suggested by Aristophanes who called the coins of his city the “Laureotic owls”.[20] Since more than a century this has also unquestionably been revealed by metal analyses (Flament, 2020). Fundamentally, if we want to explain the gigantic quantity of silver coins issued in Athens during the 5th and 4th centuries, it must be admitted that a considerable quantity of the Laurion’s metal was in fact coined.

Because of these considerations, our main research question has therefore to be re-formulated as follows: how was the raw silver extracted from the Laurion’s mines converted into “owl” coins? In my opinion, the only reasonable assumption is to admit that mine lessees had the opportunity to bring their silver bullion to the Athenian mint for converting it into coins. I am perfectly aware that according to the *communis opinio*, the principle of the so-called “free silver” or “frappe libre” would have been unknown in Greece during Antiquity[21]. There are however undeniable examples of this practice in written sources (Howgego, 1995, pp.33 – 34; Picard, 2000, p.83).

In other studies (Flament, 2018a; 2019), I tried to define the modalities of those operations in Athens by analysing epigraphic documents of the 5th and 4th centuries BC. The main conclusion is that private individuals would have been allowed in Athens to bring silver[22] to the state mint[23] for converting it into coins. The mint staff actually retained a given sum (3 or 5 drachmas) from every 100 drachmas (or mina) of coins produced. This levy was probably intended to cover the manufacturing[24] but also the essaying costs,[25] as well as the maintenance of the mint staff.[26] It seems quite logical indeed that the city controlled the quality of the silver[27] in the mint before striking the coins and not in the smelting places, most of the furnaces being actually privately owned.[28] Like the *dokimastes* mentioned in the Nicophon's decree of 375/4 (Rhodes and Osborne 2003, n.°25; Stroud, 1974; Alessandri, 1984; Martin, 1991; Feyel, 2003; Psoma, 2011), it were probably public slaves who carried out this control. The mint staff actually consisted largely of skilled slaves who were supervised by a board of Athenian magistrates called "*Epistatai* of the *argyrokopeion*". Unfortunately, almost nothing is known about them.[29]

According to the scheme developed in this paper, the manufacturing of coins would thus be considered in Athens as a direct extension of the refining process of ore, minting thus being the ultimate stage of the silver mining. In those conditions, the break-even point here fixed at ca. 700 talents for the mining activities in Athens during the mid-4th century would thus also correspond to the minimal quantity of silver yearly produced in Laurion during that period. More than two thirds of the silver extracted in Laurion (i.e. 500 talents out of 700) remained in the hands of the lessees. Furthermore, in this scheme, those *ca*. 700 talents (the equivalent of 1,200,000 tetradrachms or 4,800,000 drachmas) also correspond to the minimal quantity of metal coined every year during the mid-4th century BC.

But this clarification of the links linking mining in Laurion to monetary production has far more important implications. It implies first that the intensity of the monetary production would have to be principally correlated to the intensity of the mining activity in Laurion. Still more fundamentally, the logical extension of this model is that the initiative to strike coins in Athens would not have come from state authorities, but from private individuals – essentially mine lessees – for the purpose of their financial activities. This is probably why Demosthenes says in his *Against Timocrates* (§ 213) that the laws (νόμοι) were the νόμισμα – that is to say the "norm" – of the City, while the coins were the νόμισμα of the individuals (ἰδιῶται). Athenian authorities let thus coin production regulate itself on the basis of individual needs, guided by the precept that the more silver is coined, the more profit there is for the community, persuaded that silver never loses its value, as Xenophon naively stated in his *Poroi* (4,11). This situation perfectly accounts for the lack of information dealing with the monetary process in ancient sources. The few decisions directly related to coinage actually suggest that the Athenian state took a greater role in the coining process only when the normal situation was deteriorating: the "Coinage decree" (IG I³ 1453), as well as the emergency coinages at the end of the Peloponnesian War[30] and the above-mentioned Nicophon's decree of 375/4 BC all clearly sound like emergency measures rather than elements of a long-term monetary policy strategy. It is thus no coincidence that coinage is totally absent from the knowledges an Athenian politician is supposed to master according to Socrates in the *Memorabilia* of Xenophon (III, 6). If Glaucon wants to preside over Athens' destiny, he has to be aware of the revenues and expenses of the city, of the state of its armed forces, of the production from its mines, of the quantities of wheat produced in Attica, but there is no mention of any decision about coinage, which would naturally have been expected when Socrates was dealing with financial matters.

Athens was however not totally deprived of "monetary policy": this was actually merged with its policy towards the mining sector. An increase in coin production necessarily supposed a rise in the volume of silver produced in Laurion. State authorities could promote this increase in mining activities by modifying the leasing procedure,[31] or by introducing financial incentives such as those to which alludes the litigant of the Demosthenic speech entitled *Against Phaenippos*.[32] In those conditions, coinage would not have been totally beyond the scope of the would-be politician in the *Memorabilia*: if there is no mention of coins as such, Socrates is indeed dealing with Laurion's mines, and thinks that Glaucon ought to find out why their production is then so low:

> *"Εἴς γε μήν, ἔφη, τἀργύρεια οἶδ' ὅτι οὐκ ἀφῖξαι, ὥστ' ἔχειν εἰπεῖν δι' ὅ τι νῦν ἐλάττω ἢ πρόσθεν προσέρχεται αὐτόθεν."*
>
> *"Οὐ γὰρ οὖν ἐλήλυθα, ἔφη."*
>
> *"Καὶ γὰρ νὴ Δί', ἔφη ὁ Σωκράτης, λέγεται βαρὺ τὸ χωρίον εἶναι, ὥστε, ὅταν περὶ τούτου δέῃ συμβουλεύειν, αὕτη σοι ἡ πρόφασις ἀκρέσει."*
>
> *SOCRATES: "Now for the silver mines. I am sure you have not visited them, and so cannot tell why the amount derived from them has fallen."*
>
> *GLAUCON: "No, indeed, I have not been there."*
>
> *SOCRATES: "To be sure: the district is considered unhealthy, and so when you have to offer advice on the problem, this excuse will serve" (Xen., Mem. 3,6,12, trs. Marchant, Loeb Classical Library).*

In the light of the scheme developed in this study, does Socrates not simply implies here that Glaucon has to find a solution to increase the coin production of his

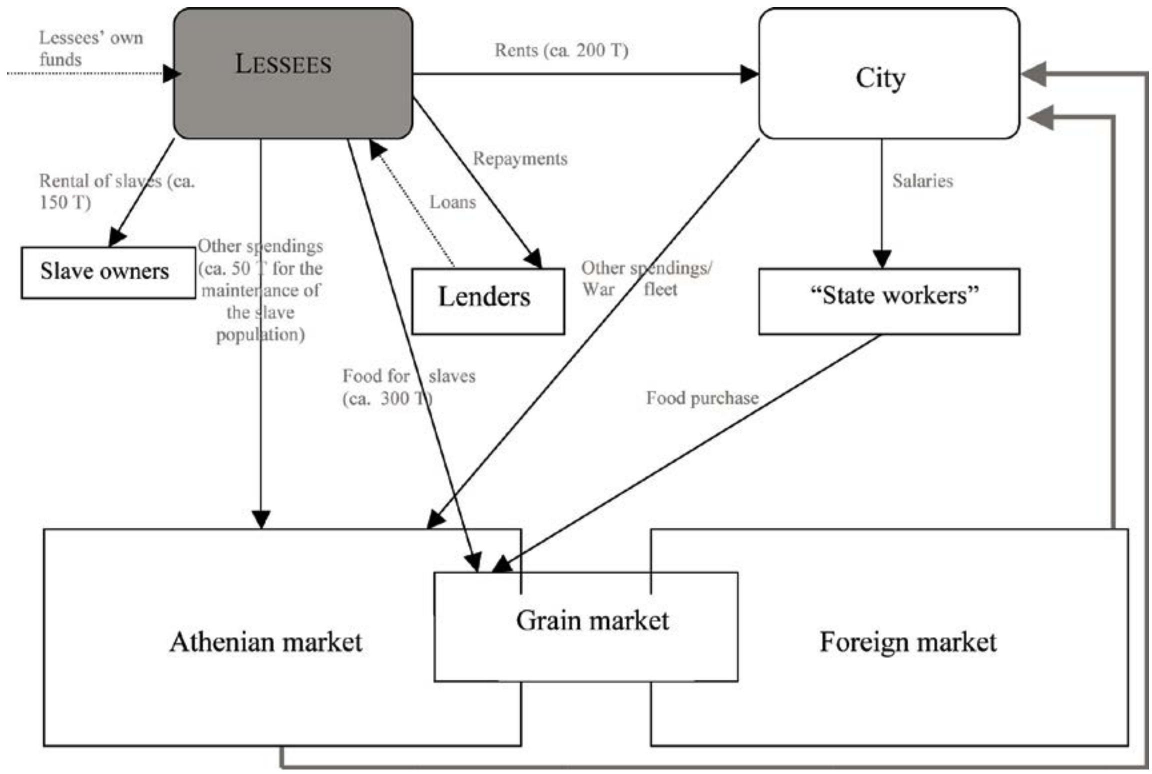

Fig. 1: Channels through which new Athenian coins were disseminated during the 4th century BC.

city, a very salutary measure at a time when the Athenians were running short of cash?

Channels through which new Athenian coins were disseminated during the 4th century BC

Finally, it was not state authorities but the lessees of the silver mines who put most of the newly minted coins into circulation, to a very large extent when paying for the above-detailed expenses related to mining exploitation. As the nature of those expenditures was previously clearly identified and quantified, it is therefore possible to reconstruct the channels through which these new coins were disseminated (see black arrows in Fig. 1).

- *Ca*. 300 talents were devoted to feed the slaves and were thus flowing to the grain trade.
- *Ca*. 150 talents were paid to the owners of the slaves rented by lessees.
- *Ca*. 50 talents fed the slave trade[33] for the maintenance of the slave population.
- An indeterminate amount was used to repay loans to lenders: indications from the Demosthenic *corpus*[34] suggest that it was not uncommon to borrow money for buying mining leases.[35]
- *Ca*. 200 talents were paid as rents to the city. As indicated above, this income corresponds to half of the annual incomes of Athens. These funds were mainly spent by the city on the maintenance of citizens serving as magistrates[36] or as juries (Flament, 2007a, p.45 – 57; Pritchard, 2015, p.52 – 82), on the improvement or renovation of urban infrastructures,[37] on the celebration of religious events,[38] as well as on the maintenance of the war fleet. If Athens intended to maintain a constant strength of 300 vessels, and the lifespan of a trireme was 20 years (O'Halloran, 2019, p.139; but 25 years according to Acton, 2014, p.197), an average of 15 new ships had thus to be built every year, which corresponds to an expense of 15 talents (1 talent being the building cost of a trireme: O'Halloran, 2019, p.140). The budget allocated to the war fleet would thus have corresponded to less than 4% of the total annual incomes of Athens, or less than 8% of its revenues from the mines.
- Finally, lessees also retained as profits an indeterminate amount of raw silver or coins. Mining industry had a reputation of being particularly lucrative in Athens: according to Hyperides (*Eux*. 35 – 6), a mine yielded to its lessees 300 talents in three years during the 330s. In another study (Flament, 2019), I regarded the celebrated Thorikos hoard (*IGCH* 134) as the cash reserve of a lessee directly taken from the mint because of the proportion of coins in mint condition, the number of die-links, and also the homogeneity of style for the majority of coins. But other expenses than those related to the mining industry also fell

on many lessees, because during the 4th century BC about one-fifth of them belonged to the liturgist-class.[39] It is therefore probable that a part of the newly minted coins was used for paying liturgies, and the sums involved could have been large: V. Gabrielsen (1994) thought that the *trierarchy* (the most expensive of the liturgies) costs *ca*. 60 talents per year, while disbursements related to religious celebrations would have been around 16 – 17 talents.[40]

- Determining the proportion of new coins carried in each of these channels is unfortunately out of the question because, whatever the channel taken, those new coins are likely to be mixed with old ones.
- The new coins represent only a part of the funds devoted to pay for the expenditure related to the mining exploitation, the other funds being constituted of sums lent by lenders or taken from the private fortune of the lessees, which of course could derive from many other activities (dotted arrows in Fig. 1).
- Passing through the hands of *apodektes* and *kolakretes*, new coins were mixed with old ones collected from the other state incomes, mainly from taxes paid by Athenians, as well as by foreigners who dwelled in the city and attended its *agorai* (grey arrows in Fig. 1). Anyway, if the total amount of the Athenian revenues was annually *ca*. 400 talents, mining revenues represented only a half. Given the special links uniting the war fleet and the Laurion's mines since the celebrated episode of the "naval law" of Themistocles in 483/2 (Flament, 2013b; 2014), it is possible that a part of the revenues from the mines (about 8%, see above) was directly devoted every year to the maintenance of the Athenian fleet.

Conclusions

To conclude, I propose to come back to the questions raised at the outset of this study.

The Laurion mines were leased by the city to private individuals at public auction for a certain period of time. The lessees paid rents, probably each prytany (so ten times a year), and the total amount of the revenues perceived by the city was *ca*. 200 talents (5.2 tons of silver) during the 350s, which corresponded to half of its yearly incomes. Among the many city´s expenditures, those devoted to the maintenance of the war fleet could easily be met, because they amounted to only a small percentage of the annual income (8%) from the mines.

According to the scheme developed in this study, a lot – if not nearly all – of the silver produced in the Laurion was actually converted into coins every year by the lessees themselves. The majority of those new coins were then probably used to defray the operating costs that were estimated here at *ca*. 700 talents (18 tons of silver) per year. This scheme also implies that the initiative to strike coins in Athens would not have come from state authorities, but essentially from mine lessees who also put most of the newly minted coins into circulation. It can be concluded therefore that in Athens, the intensity of the monetary production would have to be principally correlating with the intensity of the mining activity in Laurion. Under this scenario, the only way for state authorities to increase coin production was therefore to implement positive measures in favour of the Laurion's mining sector.

Notes

1 All these records are now published in Langdon (1991). See on this topic Crosby (1950; 1957), Hopper (1953; 1968), Vanhove (1996), Shipton (1998); Aperghis (1997 – 1998).

2 Opinions of scholars diverge widely (see Crosby, 1950; Hopper, 1953; Aperghis, 1997 – 1998; Vanhove, 1996; Flament, 2007a, pp.69 – 72; Bissa, 2009, p.51). See Domergue (2008, p.183) for a table summarising most of these proposals.

3 See also Shipton (1998) for an alternative explanation: payment indicated on the *stelai* corresponds to the total amount of a 5 drachms-tax to be paid every prytany (but Faraguna, 2006, pp.146 – 147 against this hypothesis).

4 But there were cases where a lessee was also the owner of the surface land (Healy, 1978, p.110). In other cases, several leases are located on the same property (Faraguna, 2006, p.156).

5 A vivid picture of the leasing procedure may be found in Plut., *Alc.* 5.

6 The papyrus is here damaged, the number half-erased may be 10 or 3 (see Vanhove, 1996, p.243).

7 It should be noted that in both types of operations, the vocabulary of sale is used: the winner of the tax auction and the mining lessee are both labelled ὠνητής by the *Polētai*. From this point of view, there is a very clear difference with the public contracts also awarded by the same *Polētai*, where derivatives of the term μισθόω are usually employed. On this terminological issue, see Martini (1997, pp.40 – 43. 45, n. 33).

8 This was indeed commonplace in many public contracts, as in those compiled and commented by Hellmann (1999). State authorities could also turn against the guarantors for a fine imposed on the original contractor: see IG VII 3073, ll. 2 – 6; 29 – 41, with Pitt, 2014.

9 More than 2,000 shafts would have been reported in the Laureotic area (Forbes, 1950, p.182; Acton, 2014, p.18; Kakavogiannis, 2005, p.333 [including air-shafts]). More than one thousand (Conophagos, 1980, p.163; Domergue, 2008, p.102). But see the contribution of M. Vaxevanopoulos in this volume p.49: there would have been at least 284.

10 The above-mentioned Aristot., *vesp.* vv.656 – 660; Thuk. VI, 91; Hyp. *Eux*. iii, 36; see Samons II, 2000, pp.17 – 18.

11 Sums of the same order of magnitude appear also in mining leases, but are very rare: 1 talent and 100 dr.; 2 talents and 5,550 dr. (Crosby, 1957, p.13, S5, l. 15).

12 See, amongst others, D. lix, 27. Aeschin. iii, 25 reports that a receiver had to inform the *demos* of the city's incomes at the beginning of each prytany.

13 Aperghis explains that during the 340s, there have been as many as 140 mines leased annually. With a 10-year period for an *anasaximon* and a 3-year period for an *ergasimon*, he considers that there may have been at least 500 mines in operation simultaneously. In this volume (p.49), Vaxevanopoulos reports the discovery of 284 shafts. I consider this figure as a strict minimum. There are 62 concessions preserved in *Agora XIX, P26 (342/1);* this stele would thus have probably originally recorded at least one hundred leases. If the shortest duration of the lease was three years (cf. Arist. Ath. XVLII, 2), and unless Agora XIX, P26 is an exceptional document, this figure must therefore be multiplied by three, so 300 mines being potentially active simultaneously. But this duration of 3 years was for ergasima only, which represent one fifth of the leases recorded by the Poletai (Aperghis 1997 – 8, pp.4 – 5); the duration of the other leases

(anasaxima, palaia anasaxima) was longer (7, 10 years?). Therefore, the number of mines in operation simultaneously should *a fortiori* have been higher than 300.

14 Bissa (2009, p.53) following a different reasoning, advances the more important figure of 300 talents.

15 See also *Lexica Segueriana* s.v. « φάσις »· μήνυσις πρὸς τοὺς ἄρχοντας κατὰ τῶν ὑπορυττόντων τὸ μέταλλον, ἢ κατὰ τῶν ἀδικούντων χωρίον ἢ οἰκίαν ἢ τι τῶν δημοσίων, ἢ κατὰ τῶν ἐπιτρόπων τῶν μὴ μεμισθωκότων τὰς οἰκίας τῶν ἐρφανῶν. As well as Hyp. *Eux*. iii, 34: Καὶ πρῶτον μέν, Τ(ε)ίσιδος τοῦ Ἀγρυλῆθεν ἀπογράψαντος τὴν Εὐθυκράτους οὐσίαν ὥς δημοσίαν οὖσαν, ἢ πλεόνων ἢ ἑξήκοντα ταλάντων ἦν, καὶ μετ’ ἐκείνην πάλιν ὑπισχνουμένου τὴν Φιλίππου καὶ Ναυσικλέους ἀπογράψειν, καὶ λέγοντος ὡς ἐξ ἀναπογράφων μετάλλων πεπλουτήκασι. “Let me give an instance. When Tisis of Agryle brought in an inventory of the estate of Euthycrates, amounting to more than sixty talents, on the grounds of its being public property, and again later promised to bring in an inventory of the estate of Philip and Nausicles saying that they had made their money from unregistered mines” (trs. J.O. Burtt, Loeb Classical Library).

16 But is of the same order of magnitude as the estimate made by C.E. Conophagos (1980, pp.136–140) which was based on the 1.5 million tons of ancient slags that were still visible in Laurion during the 20th century.

17 The equivalent of *ca*.180,000 talents of gold and silver, according to Callataÿ (1989).

18 Vitruvius (De arch. 7.7.1) records that ochre (iron hydroxide) was extracted, as well as zinc, realgar, orpiment, chalcopyrite, and cyanus (Thphr. Lap. 51). Copper ores were also mined in the Bronze Age (Gale and Stos-Gale, 1989), however there is no evidence for its working during the classical period (but Rihll, 2001, p.132). See also the contribution of E. Photos-Jones in this volume about lead. Lead was exported abroad (Jones-Eiseman and Sismondo-Ridgway, 1987, pp.53–60 [Laurion lead ingots in the Porticello shipwreck]) and employed in construction and shipbuilding. But lead was a very cheap commodity in Athens: we learn from Arist. Oec. II, 37, that a talent of lead costs only 2 silver drachmas.

19 Notably to make phials mentioned in huge quantities in the sacred inventories (Harris, 1995, pp.58–61, 68–74, 99–100, 148, 152, 154–5, 169–78, 212–4).

20 Aristoph., *Av.* 1105–8 (trs. Melville-Jones, 1993, n. 58): “First of all, which every judge longs for most of all, Laureotic owls will never leave you, but will dwell within (your city), and will nest in your purses, and hatch out little (deposit of) small change”.

21 See Callataÿ, 2005. Faraguna (2006, p.150, n. 37) acknowledges its existence, but considers that this practice remained exceptional during Antiquity.

22 Probably not only silver directly extracted from the mines. Many silver objects (like vessels, foreign coins, etc.) could also be converted into Athenian coins. A Demosthenic speech (xxii, 48–9) clearly suggests that during the 4th century the melting down of vessels or offerings always remained an option when public funds were lacking. See Aleshire (1992).

23 In any case, the mint was located in a place easily accessible to the public, because a clause of the so-called “Coinage Decree” (IG I^3 1453, section X) ordered that information that everyone should be able to consult have to be displayed in front of this building.

24 It is worth noting that the manufacturing costs of other metal products were calculated exactly in the same way, that is to say by deducing a given sum from every mina manufactured, as in a excerpt of a 4th century inscription dealing with the manufacture of dowels for the Telesterion in Eleusis (*IG* II^2 1675,31).

25 This situation indisputably evokes another one, far much closer to us: the regulation of the law of 7 germinal 1803, by which the *premier consul* Bonaparte established the *franc germinal* as the currency of the French Republic. The article 11 of this law stipulates that individuals were allowed to bring precious metals to the mint and will only be required to pay for the manufacturing and essaying of the coins, costs that were precisely related to the weight of the metal coined. See Doyen (2013) for more parallels between this law and antic numismatics.

26 The members of the mint staff were not paid from the ordinary revenues of the city, but have their own funds, as it can be deduced from a clause of the Nicophon’s decree. This decree specifies that the *apodektai* had to pay for the salary of the public tester (*dokimastes*) only during the year 375/4 BC; for the future, his salary will be paid from the funds of the mint staff; those funds were thus necessarily distinct from the city’s ordinary incomes: « Τ[ὴν δὲ μ]/ισθοφορίαν εἶναι τῶι δοκιμαστῆι τῶι ἐν τῶι [ἐμπ]/ορίωι ἐπὶ μὲν Ἱπποδάμαντος ἄρχοντος ἀφ’ οὗ [ἂν κα]/τασταθῆι, μεριζόντων οἱ <ἀ>ποδέκται ὅσομπερ ṭ[ῶι]/ ἐν ἄστει δοκιμαστῆι, ἐς δὲ τὸν λοιπὸγ χρόν[ον ἑνα]/ι αὐτῶι τὴμ μισθοφορίαν ὅθεμπερ τοῖς ἀργυ[ροκό]/ποις. » (Rhodes and Osborne, 2003, n.°25, ll. 49–55).

27 The majority of elemental analyses confirm the very high percentage of silver in Athenian coinage (more than 95% usually), which probably explains why the owls were considered as the first international currency in the ancient world, as Aristophanes proudly wrote in his *Frogs* (*Ran.* 718–25).

28 The 6 furnaces mentioned in the *Poletai* records (Crosby, 1950, p.195) are each identified by their owner’s name. One of them was indeed pledged in a 4th *horos* related to a *prasis epi lusei* (IG II² 2750), proof, if any were needed, that they were actually privately owned.

29 They are mentioned in IG I^3 1453, sections X, XIV, and were the dedicants of SEG XXI, 667 a-b (*ca*. 360). In this last inscription, the Leontid tribe counts two representatives; this detail could mean that the *Epistatai* of the mint were not drawn by lot, but selected according to specific criteria or skills. Ferguson (1932, p.77–78) proposed that the *Epistatai* mentioned in the 5th century inscription IG I^3 379 (ll. 28, 40, 72) were also those of the Athenian mint.

30 On golden coinage, see Philochoros (FGrH 328 F141); about the emergency coinages in general, see Flament (2007b, pp.118–120).

31 Several scholars think that the engraving of the διαγραφαί of the *Polētai* from 367/6 BC reflects a change in the management of the mining concessions (Hopper, 1968, p.303; Osborne, 1985, p.116; Lazzarini, 2001, p.64).

32 See § 31 of this speech. In §§ 17 and 23, the speaker says that the capitals invested in the mines were not to be included in the citizen’s declaration of property used as a basis for tax calculation.

33 On the Athenian slave market, see Harp. and Hesych. s.v. « Kuklos »; Poll. iii 78; vii, 1,1. A tax was levied on this trade: Xen., *Vect.* iv,25.

34 Dem., *Epitaphios* 52; xl, 52.

35 Shipton (2000, p.76) thinks that it should have been common practice, because all social classes were represented among the mining lessees.

36 They would have been no less than 20,000 during the 5th century BC according to Arist. Ath. xxiv,3.

37 Xen., *Ath. pol.* ii,10.

38 An expense that could amount to *ca*. 75 talents, according to Pritchard (2015).

39 Shipton, 2000, pp.31–37. According to Bissa (2008, p.266) this proportion could have been higher.

40 But the expenses could have been greater, maybe close to 25 talents (Pritchard, 2015).

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Glossary of special terms of geoscience, mining-archaeology and archaeometallurgy

This glossary is an arbitrarily collected composition of terms mentioned in manuscripts of the Laurion Conference 2018 at Bochum. Please consider this not to be a systematically collected glossary. Not all definitions of certain terms result from one source. They are adapted or enlarged according to the interdisciplinary variety of faculties.

Adit: Drifting an adit from the surface was originally performed to follow a mineralisation exposed at the surface. In a second stage an adit could be constructed for prospecting purposes and transportation of ore.

Batholith: Large, intrusive bodies with steeply dipping walls and lacking any visible floor. Typically composed of granite, granodiorite, and other related acidic rocks.

Blueschist: A metamorphic rock formed under conditions of high pressure and relatively low temperature. Characteristic minerals are glaucophane and kyanite.

Bonanza: Very rich and profitable part of an ore deposit.

Boudinage: Structure found in sedimentary rocks subjected to folding. It consists of strike-elongated “sausages” of more rigid rocks enclosed between relatively plastic rocks.

Buddle: Shallow annular pit for concentrating finely crushed, slimed, base-metal ores.

Buddle-work: Treatment of finely ground, metal-containing materials by gentle sluicing in which a heavier fraction of a fed pulp is built up (buddled) while the lighter fraction flows to discard. This is continued until a satisfactory concentrate is produced.

Cataclasis: Cataclasis is a rock deformation accomplished by fracture and rotation of mineral grains or aggregates without chemical reconstitution.

Cataclasite / Cataclastic rocks: The terms are used for solidified metamorphic rocks formed by low temperature and pressure. Cataclastic rocks are widespread concomitants of fault belts (compression fault, subduction zones, shear zones). They are composed of different sized, angular fragments embedded in changing amounts of fine-grained material (clay minerals, mica). Not solidified cataclastic rocks, so-called fault gouges, are often feeder conduits for hydrothermal solutions. Frequently secondary minerals are formed here by decomposition of primary sulfidic ores such as galenite and chalcopyrite which are malleable by cataclastic input. Well known in old mining activities in Germany is the term "Bleischweif". Other minerals are brittle (pyrite) and will be broken and squeezed out (cataclasic deformation).

Chamber: A large irregular or rounded body of exploited ore, occurring alone or as an extension of a vein.

Chamber and Pillar Mining: It is a mining system in which the crushed material is extracted across a more or less horizontal plane, creating arrays of rooms (chambers) and pillars or blocks. “Rooms» of ore are dug out while «pillars» of untouched material are left to support the roof overburden. Calculating the size, shape, and position of pillars is a complicated procedure, and is an area of active research. The technique is mainly used for overwhelming flat-lying deposits. Room and pillar mining reduces the risk of surface subsidence compared to other underground mining techniques. It was one of the earliest mining methods used.

Chipping: The removing of surface defects from semi-finished metal products by pneumatic chisels.

Cobber: Mining-friend and -colleague, German: Kumpel.

Contact (1st, 2nd, 3rd): Name of mineralised interfaces between marbles, schists and shale sequences. Argentiferous lead sulfides (galena) are abundant at Laurion along the 3rd contact than in higher stratigraphic levels.

Crushing: Size reduction into relatively coarse particles by stamps, crushers or rolls.

Croiseur: A single vertical lens of oxidised mineralisation extends about 15 m below the contact at the S end of the main section in Ross et al. this vol. p.Seite 34 fig.6A. It is an example of fractures with primary mineralisation within the Lower Kamariza marble, termed by the French as croiseurs. Marinos and Petrascheck, 1956, noted that croiseurs contained primary and oxidised sulfide mineralisation, commonly trended 20–50 W of N and generally extended no more than 15 m below the third contact. Croiseurs attain their maximum width at the third contact.

Cupel: A porous ceramic, often made from bone ash or other refractory components. The cupel is used to extract or assay precious metals that have been dissolved in metallic lead by the process of cupellation. See Cupellation.

Cupellation: Process used for extracting silver and/or gold from lead. The principle involves first the dissolution of the material to be tested in molten lead, then the oxidation of this lead to litharge (PbO) in a shallow, dish-shaped crucible often made of bone ash (cupel), leaving the precious metals behind as a molten globule. A temperature of about 1,000 ºC is needed. The litharge volatilizes or is skimmed off, or is combined with the bone ash in the cupel.

Dipp: The angle of a slope, vein, rock stratum or borehole is measured from the horizontal plane downward.

Drainage: Drainage is meant to include all provisions to reduce the water in mines and its planned removal from the underground workings.

Dressing: Rock ore crushing and screening to required sizes.

Edge runner mill, rotary mill driven by animals: Edge runner mill, also known as Chilean mill or Roller stone mill, consists of one or two heavy stone or steel rollers mounted on a horizontal shaft and turned round a central vertical shaft on a bed of steel or granite. The stones may vary from 0.5 – 2.5 m in diameter, the larger size weighing up to about 6 tonnes. The material to be ground is kept in the path of the runner by scrapers. The beneficiation is partly due to crushing: by the weight of the stones, but more to friction between the surfaces of contact between the runners and the bed stone. The Chilean mill was an artisanal machine used for the beneficiation of gold. The machine was composed of two rotating wheels that would revolve over a pan filled with gold-bearing rocks. The idea was that the wheels would break open the rocks with gold, so they could harvest gold from multiple rocks at a time.

Ekvolades: Ekvolades refers to ore relatively low in metal (lead, silver, copper) which was extracted in the ancient mines, but was judged as unprofitable for further metallurgical processing. It was abandoned as waste near exits of galleries. Ekvolades were enriched by beneficiation in workshops (ergasteria).

Elutriation: This is a process for separating very fine-grained particles based on their size, shape and density, using a stream of liquid flowing in a direction usually opposite to the direction of sedimentation. The smaller or lighter particles rise to the top (overflow).

Exploitation: A) The process of winning or producing from the earth oil, gas, minerals or rocks that have been found by exploration. B) The extraction and utilization of ores.

Fabric: The sum of all the textural and structural features of a rock.

Film sizing: Concentration of finely divided heavy minerals by gently sloped surfaces which may be plane, riffeled, or vibrated.

Gallery: A horizontal or nearly horizontal underground passage in a mine. Drifting a gallery can be done within an ore deposit or in the adjacent host rock to open a mine.

Glancing of silver: At the end of the cupellation silver will be segregate when lead is oxidized to litharge and is removed. Silver will remain in the bottom of the cupel and it will appear quite characteristic as the glancing of silver (German Silberblick). In actual metallurgical jargon this separation is called a "dore". This raw silver contains impurities.

Gossan: Term for a rusty-coloured, iron-rich, leached outcrop of a sulfidic ore deposit at surface. The gossan / leached capping formation process commences when ore assemblages and their associated wall rocks encounter the interface between the water table and the overlying surficial zone. This is in essence the transition from a reducing to an oxidising environment. A gossan may be divided in 2 zones. 1: Surficial total leached capping. Minerals: quartz, Fe-(hydr-) oxides (limonite, goethite, jarosite) and carbonates (siderite, ankerite). This part is also called Iron Hat. 2: Decreasing leaching with remnant sulfides (galena, chalcopyrite etc.) become visible at lower depths. Major formation of metalliferous secondary minerals zone (malachite, cerussite).

Granite: Light-coloured, coarse-grained felsic igneous magmatic rock composed of quartz, feldspar and ferromagnesium minerals (muscovite, hornblende). It is the intrusive equivalent of rhyolite.

Granodiorite: It is similar to granite. There are transitions, but granodiorite contains twice the amount of plagioclase over orthoclase, and biotite and/or hornblende.

Gravity separation: is a physical process which consists of the separation of different minerals in ores and rocks due to differences in specific gravities. Force of gravity is present in nature (rivers), but can be influenced extensively by centrifugal force, resistance to motion by a fluid (e.g. air, water) etc. Gravity separation is the oldest known ore beneficiation technique and led probably to the discovery of gold.

Griffon: Term used by French miners at Laurion in the 19th century AD to designate near-vertical, irregular, downward-thinning lenses of zinc oxide calamine, often associated with iron oxides and galena rich ore. Formation by redistribution of zinc and iron from contact mineralisations into underlying marble. Strongly influenced by steeply dipping of pre-existing fractures.

Grinding: Comminution of minerals by dry, or more common wet methods in rod, ball, or pebble mills.

Helicoidal washery: Helicoidal washeries do not exist in Laurion. The objects in question were misinterpreted by K. Konophagos. Instead, they are → edge runner mills or pan grinders.

Hopper quern: Hopper quern is the upper part of a pair of round stone dishes (quern stones) for hand-grinding a wide variety of materials (vegetal food processing, inorganic materials). The lower stationary stoneslab is called a saddle quern. A handle slot contained a handle which enabled the rotary quern to be rotated. This system was used worldwide since prehistoric times.

Hydrothermal deposit: Precipitation of minerals or ores from hot aqueous ascending solutions from a magma in open spaces (tectonic cleavages, tubes, chimneys, karstic cavities) ("open space filling"). Brekzia-style hydrothermal mineralisation occurs in near surface fissures.

Intercalation: The term means the interbed of layered, lenticular or sheeted layers of remarkable rocks or mineral aggregations in a geological sequence.

Karst: Any uneven limestone topography, characterized by joints enlarged into criss-cross fissures (grikes) and pitted with depressions resulting from the collaps of roofs of underground caverns. It is formed by the action of percolating waters and underground streams.

Kollergang: see Edge runner mill

Litharge: Lead oxide ($Pb^{2+}O$) formed by cupellation by oxidation of lead. Red modification: stable < 540 °C. Formed by slow cooling down to the environmental temperature. Yellow modification: stable at high temperature. Will be kept at quick cooling.

Mantos: Network of parallel cavity fillings in lead-zinc-silver mineralisations in karstic deposits. At Laurion, manto-style mineralisations occur within marbles as massive replacements.Thickness of mantos varies from a few centimeters to a few meters.

Marble (Upper/Lower Marble): Marble is a metamorphic rock composed of recrystallized carbonate minerals such as calcite and/or dolomite. Marble occurs at several geological units. Monomineralic marble of pure calcite is suitable for sculpting. It occurs at Laurion.

Marl: General term for very fine-grained rock, either clay or loam, with a variable admixture of calcium carbonate.

Massicot: Yellow lead oxide. In metallurgy it is formed by rapid cooling from high temperature. In nature a rare mineral of secondary origin associated with galena.

Melting: In metallurgy the term melting is used if two or more metals are liquefied to produce alloys or larger units out of small particles.

Metabasite: Basic magmatic rocks (gabbro, diabase, basalt and other), which were exposed to regional metamorphic conditions and changed their compositions to new characteristic mineralogical associations.

Mica schist: Mica schist is a crystalline metamorphic rock. Main components are quartz, muscovite, biotite. Mica shist has a pronounced tendency to split into layers (schistosity).

Migmatite: High-grade metamorphic rock consisting of dark, solid old parts (Palaeosome: biotite, hornblende, cordierite) and light, liquefied parts (Neosome: quartz, feldspar).

Mine: Μέταλλον is used as a general term for a “mine” in ancient Greek. It must be distinguished between opencast mining to exploit mineralisations at or closed to the surface. Shafts and galleries were constructed to exploit ore from veins or irregularly formed ore body in the underground.

Mylonite: Strongly deformed, layered, fine-grained solid rock showing layering caused by shearing.

Olynthos mill: Olynthos mill belongs to hand-driven mills. It consists of rectangular-shaped lower and upper stones. The top stone had a long handle and was moved in reciprocal fashion from side to side. The mill also had a hollow cavity (or hopper) with a narrow slot at its centre through which the miller fed the grain. It can not be ruled out whether this mill in addition was used for crushing ore.

Ophiolite suite: Geological complex of basic and ultrabasic magmatic rocks (peridotite, gabbro, basaltic rocks, Deep Sea sediments). Overview of composition of earth’s crust and mantle. Contains frequently volcanogenic massive sulfide-ore deposits (copper).

Orogenic belt: Extended areas in earth crust which were exposed intensive folding and other tectonic activities (metamorphosis, intrusion of magmatic rocks).

Outcrop: see Gossan

Pattinson process: Obsolescent metallurgical process used for the separation of small quantities of silver from lead by partially solidifying a molten bath of the two metals and separating the remaining liquid. This process is repeated several times and the silver is concentrated in the liquid.

Plain table: An inclined ore-dressing table.

Plynite: Residues of ekvolades waste and/or from fine-grained, desilverized litharge produced on the drying floor of washeries.

Refining: Refining is the separation of a metal from its impurities. As such it is applied to a wide range of different processes for different metals (copper, gold, iron.

Rhyolite: Generally light-coloured volcanic rock, high in quartz content (> 20%) and alkali-feldspar. Rhyolite is the extrusive equivalent of granite.

Shaft: Miners are sinking a vertical or diagonal shaft to follow a mineralisation (vein) exposed to the surface and to open a mine. Further, the construction of shafts served as vertical adits to climb down to an underground mine, for hauling and for ventilation.

Sizing: Sizing is the general term for separation of particles (ores, gangues, rocks) according to their size. There are a number of ways to do this kind of dressing. The simplest sizing process is screening, or passing the particles to be sized through a screen or number of screens.

Skarn: Replacement of limestone or other carbonate-rich rocks (dolomite, marl) close to an intrusive contact caused by high temperatures and magmatic, hydrothermal fluids (metasomatism). Formation of various calc-silicate minerals and metal bearing ores of Cu, Fe, Pb-Ag-Zn. Skarn ore bodies are characterized by irregularly shaped forms caused by lithology and structure of host rocks. Typical are zoning of ores.

Slime: Particle of crushed ore which are of such a size that they settle very slowly in water and through a bed which water does not readily percolate. Such particles are regarded as powder or dust produced by crushing, grinding or rubbing.

Sluice, Sluices: are long, narrow “boxes” used in the exploitation of black sands, gold, and other heavy minerals from placer deposits or form finely crushed ores using water. Traditional sluices have transverse riffles over a carpet or rubber matting, which trap the heavy minerals.

Slurry: Fine carbonaceous discharge of a mine washery. All washeries produce some slurry which must be treated to separate the solid particles from the water (usually by settling) to have a clear effluent for reuse.

Smelting: Smelting is a metallurgical process of extracting a base metal (copper, iron, silver, tin etc.) from its ore by applying heat. This involves a chemical reaction between the ore and the fuel, or between the heated ore and a reducing atmosphere. Most smelting processes are carried out above the melting point of the metal concerned. So that both the metal and waste products (slag) are liquid and can be separated using gravity. The main exception being iron smelting, before the introduction of the blast furnace process, where the iron remained solid or at least in a pasty state, but the waste products formed a molten slag.

Strake: Gently sloped, flat table used for catching grains of heavy water-borned minerals. The German term is “Gerinne”.

Strike: The course or bearing of the outcrop of an inclined bed, vein, or fault plane on a level surface; the direction of a horizontal line perpendicular to the direction of the dip.

Stripe: Stripe is a long channel similar to the tye.

Structure: In context of geology this term in English is above the terms structure and texture. It refers to folds, cleaving/jointing, parting, segregation etc. Basaltic columns represent a structure. Structure is more or less synonymous with the German "Textur".

Subduction: The geological process of one lithospheric (oceanic) plate descending beneath another.

Subduction zone: Long, narrow belt in which subduction of an oceanic plate takes place. It is characterized by high seismic activities, volcanism and orogenesis.

Tailings: Rejected portion of an ore, waste, gangue. Portion washed away in water concentration. Maybe impounded in a tailings dam or pond, or stacked dry on a dump.

Tailings dam: One used to hold mill residues aftertreatment. These arrive as fluent slurries. Dam may include arrangements for run-of for return of water after the slow settling solids have been depoited.

Texture: In context of ceramic refers to the special relationship among the materials it is composed. Broadest textural classes are crystalline (in which the components are intergrown/interlocking crystals; grain size, particle shape, arrangement), fragmental (accumulation of of clastic temper fragments), glassy (particles are too small to be detected and amorphous arranged). Texture is more or less synonymous with the German "Struktur".

Tye: Strake in which a considerable thickness of low grade concentrate is collected. In German language it is a Schlämmgraben/-kasten.

Ultramylonites: Metamorphic rock close in composition to cataclasite. It is a dense, fine-grained rock showing ± layered structure. It looks like chert or fine-grained volcanic rocks.

Vein: Tabular or sheet-like body of rock or ore penetrating a different type of rock.

Ventilation: This is the term for enhancement of the prevailing air content in a mine. The atmosphere, according to its composition and suitability for breathing,can be fresh, good, stagnant or sticky, noxious or poisonous and gassy (firedamp). In many ancient mines air circulation due to different levels of temperature inside and outside of the mines was sufficient. By using fire setting ventilation shafts, ventilation interconnections or galleries were constructed.

Washery: A place at which (crushed) ore is separated from the waste by washing. Also called wet separation plant; washing plant.

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