



HAL
open science

Aegean mining technologies in Antiquity : a traceological approach : the Laurion mines (Greece)

Denis Morin, Patrick Rosenthal, Adonis Photiades, Serge Delpech, Denis Jacquemot

► **To cite this version:**

Denis Morin, Patrick Rosenthal, Adonis Photiades, Serge Delpech, Denis Jacquemot. Aegean mining technologies in Antiquity : a traceological approach : the Laurion mines (Greece). Kenneth A. Sheedy; Gillian Davis. Mines, Metals, and Money : Ancient World Studies in Science, Archaeology and History, 6, Australian centre for ancient numismatic studies; Macquarie university; The Royal Numismatic Society, London, 2020, Metallurgy in Numismatics, 0-901405-37-X. hal-02943726

HAL Id: hal-02943726

<https://hal.science/hal-02943726v1>

Submitted on 20 Sep 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

METALLURGY IN NUMISMATICS 6

Metallurgy in Numismatics 6

Mines, Metals, and Money Ancient World Studies in Science, Archaeology and History

EDITED BY

KENNETH A. SHEEDY

and GILLAN DAVIS

AUSTRALIAN CENTRE FOR ANCIENT
NUMISMATIC STUDIES

MACQUARIE UNIVERSITY

THE ROYAL NUMISMATIC SOCIETY

SPECIAL PUBLICATION NO. 56

LONDON

2020

ROYAL NUMISMATIC SOCIETY SPECIAL PUBLICATIONS
GENERAL EDITOR: ROGER BLAND

To our daughters:
Lucy Clare Sheedy, Rebecca Allen and Tamara Davis

© The authors 2020

The Royal Numismatic Society Special Publication No. 56

All rights reserved. No part of this publication may be reproduced, stored in any retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise without prior permission of the publisher in writing.

ISBN 0-901405-37-X

British Library Cataloguing in Publication data

A CIP catalogue record is available from the British Library

Set by New Leaf Design, Malton, North Yorkshire

Printed by Gutenberg Press Ltd, Tarxien, Malta

PREFACE

The papers in this volume in part stem from a conference that was conceived and organised by the Australian Centre for Ancient Numismatic Studies (Macquarie University) and the Epigraphical and Numismatic Museum, Athens. The conference, held at the Iliou Melathron in Athens from 20-22 April, 2015, was entitled 'Mines, Metals and Money in Attica and the Ancient World'. One of its goals was to survey the applications and current state of non-destructive metallurgical analyses in Greek numismatic study. In recent years, progress in these areas has been rapid; and as laboratory instrumentation and techniques have continued to multiply and expand, the topic could not be more timely. The other work that the conference and now this volume addresses is the renewed interest of geologists and archaeologists in further exploiting the evidence on the ground for reconstructing the silver mining and processing industries in Southeastern Attica and Northern Greece. Accompanying these studies are papers from the staff of the Numismatic Museum on the museum's program of testing new acquisitions and on the study of two hoards excavated in Athens.

Altogether, the articles trace precious metal in the Greek world from the extraction of ore in antiquity to museum artifacts of today. Expanding on previous volumes of the Royal Numismatic Society's *Metallurgy in Numismatics* series, the present contributions range from numismatic metallurgy in its traditional laboratory context to metallurgy in the broader, historical sense of ancient metal working in general. In what is probably the most significant achievement, a core of the papers present abundant, fresh evidence for the tremendous scale of long-distance trade in silver from a handful of sources in the Aegean to the great number of Greek city-states around the Mediterranean that began to coin in the late archaic period, including even the cities of Southern Italy and Sicily.

While this volume will be welcomed for its many such findings, its value rests also on the editors' foresight that by inviting these contributions and bringing them together in one place, the studies will become more accessible and prominent than if they had been published separately.

J. H. KROLL

FOREWORD

As Director of the Numismatic Museum at Athens, I am proud of our longstanding numismatic and scientific collaboration with the Australian Centre for Ancient Numismatic Studies (ACANS) at Macquarie University, Sydney. Many Australian researchers, including the two editors of this volume, have spent extensive periods researching at the museum over many years to our mutual benefit. Together we organised the major international conference entitled *Mines, Metal and Money in Attica and the Ancient World* hosted at the museum from 20-22 April, 2015 which formed the genesis of this volume.

The themes of the conference focused on archaic Greek coinage, methods of mining precious metals, and on the historical and institutional framework of the Archaic period in which the conventions for the organisation and control of mining were developed, and through which the commercial distribution of precious metals was carried out. The conference themes also embraced studies of coin production, and technological and research methods for the analysis and conservation of metals that reliably help authenticate ancient coins. In these themes the conference successfully brought together scientists from all over the world.

At the end of the Conference, the temporary exhibition, *When Silver was Born. Archaic Coinage of Athens, Mines, Metals and Coins*, was inaugurated. The exhibition was displayed in the Great Gallery of temporary exhibitions of the Iliou Melathron, the Library of Heinrich Schliemann, on 28 May 2015. It took as its subject the coinage of the Archaic period, an era during which profound changes occurred in politics, the arts, and in society more generally. The exhibition, which was the conclusion of the very fruitful co-operation of our Museum with our colleagues from Australia, exhibited 263 artifacts, most of them for the first time. The objects displayed included acquisitions by Museums and Ephorates of Antiquities, and objects from the Collection of the Alpha Bank. We thank and acknowledge the Alpha Bank for sponsoring the exhibition, and the Australian Research Council of the Australian Government for sponsoring the Conference.

GEORGE KAKAVAS

3. AEGEAN MINING TECHNOLOGIES IN ANTIQUITY: A TRACEOLOGICAL APPROACH: THE LAURION MINES (GREECE)

Denis Morin, Patrick Rosenthal, Adonis Photiades,
Serge Delpech, Denis Jacquemot

ABSTRACT

The Laurion district was one of the most important mining centres of ancient Greece during the fifth and fourth centuries BC, and the minerals extracted were a foundation of Athenian power. On the surface, remains associated with the whole mining process including adits, mineral processing and metallurgical workshops extend over tens of kilometers. The Laurion lead-silver mines are the only ones known from the ancient world where vertical shafts reach as far as 100m deep to connect underground networks dug to exploit ore deposits. These mines required sophisticated organisational, engineering and technological capabilities, and an excellent understanding of geology. Recently, field investigation has been carried out into these shafts and mines. Analysis of traces found on the walls of the ancient mining galleries and works is providing new information and insights about the structures and technology of the mining industry during antiquity.

INTRODUCTION

The Laurion district contains exceptionally rich mineral deposits covering a surface area of 17 x 6 kilometres along a NNE-SSW orientation in South East Attica, Greece (Figure 1). These silver mines were amongst the most important mines of ancient Greece in the fifth and fourth centuries BC. During the second half of the nineteenth century, the French Mining Company of Laurion (CFML) exploited three concessions with a total surface area of 3,171 hectares. The ancient works were visited by mining engineers who surveyed them, and reused some of the ancient shafts

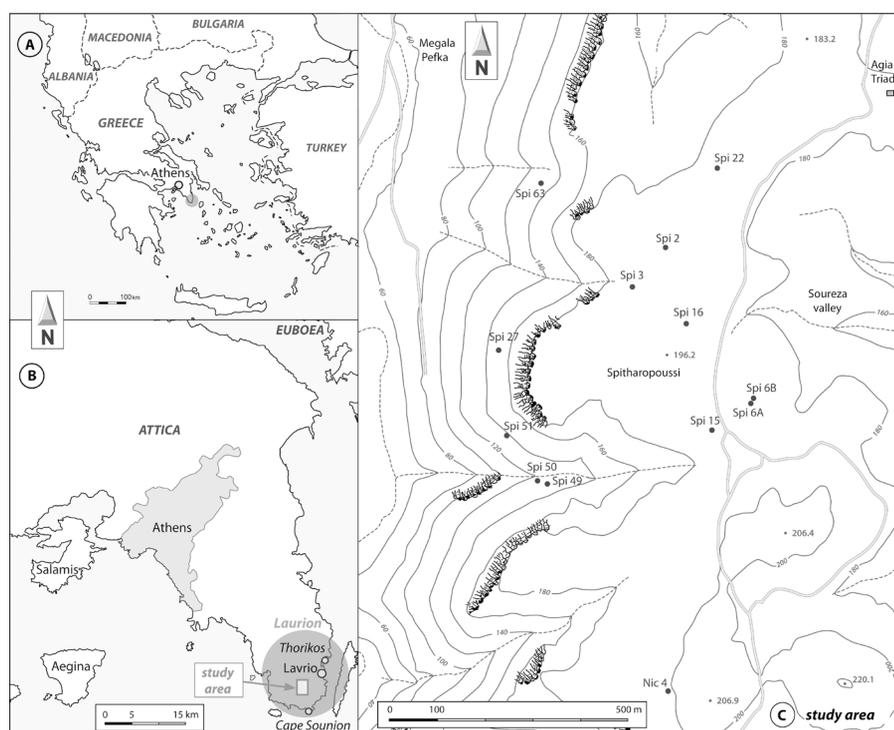


Figure 1. Laurion. Location of the study area



Figure 2. Laurion. Donning breathing apparatus (ARI-Fenzy) before a descent



Figure 3. Laurion. Exploring an ancient shaft (Spitharopoussi area – Shaft n° 15)

for ventilation. This was notably the case with the works in Mégala Pefka and the deepest shafts of the Spitharopoussi area.

In 2002, the first mission concentrated on the deepest shafts of the mining district (Morin *et al.* 2002). Several vertical shafts sounded out previously were explored using techniques developed by Alpine speleologists. Since then, there have been several successive missions under the auspices and permit of the French School at Athens (2002) and the Institute of Geology and Mineral Exploration (in the Department of General Geology and Geological Mapping known as IGME), conducted in order to survey the geology of this metalliferous district (Photiades *et al.* 2004; Photiades, *et al.* 2017), and also to understand how the ancient miners operated. Investigations were carried out into the shafts, with the deepest one discovered so far – the Persephone shaft - descending 109 m. These were exceptional structures for the ancient world (Figures 2 & 3).

This chapter summarises the authors' understandings of how ancient mining was conducted derived from their extensive physical investigations over the past 15 years.

THE COMPLEX NATURE OF THE DEEP DEPOSITS

The Laurion mining area consists mainly of metamorphic schists interposed with marble (Photiades and Carras 2001). The geological unit known as Kamariza comprises from the bottom up: lower marble approximately 100 m thick; Kamariza Schist varying between 15-40 m; and an upper marble layer which can exceed 80 m in places. In contrast to Kamariza, the Spitharopoussi geological area where exploration has been done comprises blue schist and metavolcanic material to the north-east and to the south of the studied area.

Geological surveys indicate that the upper and lower marbles derive from the same formation of marine carbonate from the Triassic/Jurassic periods. The doubling of the marble layers is explained by the tangential deformation into a marble/schist sequence by a bedded and eroded syncline, with the schist occupying the heart of the syncline.

The richest mineralisation is found at the greatest depth making it the most difficult to access. The ancient mine shafts in the area studied were mostly cut through into the upper marble layer, and/or across the schists of Kamariza, or even into the lower marble layer. Exploring them provides hitherto unknown information with each shaft being a veritable mine of information (Figures 4 and 21). The compilation of data from the surface and underground mining has allowed the creation of a geological section through the studied area. Four main layers of mineralisation have been plotted within the Kamariza formation. These are the so-called 'contacts' as described by Ardaillon (1897) and adopted by Conophagos (1980). This theory has been recently fully questioned based on recent geological field investigations and fluid mineral deposit analysis (Scheffer *et al.* 2019, 2017a, 2017b, 2016, 2015; Scheffer, 2016).

TRACES OF MINING ACTIVITY

Mining is a fully destructive and irreversible process; much evidence has been completely erased by later working both under and above ground. It is particularly difficult to date features such as shafts, galleries, stoping areas and toolmarks. Ancient mines usually still contain much evidence; the difficulties lie in interpretation and understanding of the processes used. Fortunately the underground environment preserves traces of mining activity rather well. Toolmarks, footprints in the soil, and tailings are signs of actual work which give indications about how the miners went about their business (Figure 5).

Anyone visiting the ancient mining works for the first time will be struck by the peculiar characteristics of the underground passages, with the regularity of the engineering works, and by the aesthetics of the shafts and galleries. But mostly seeing the mines gives rise to questions - how were the tunnels dug, and how to explain their sheer scale?

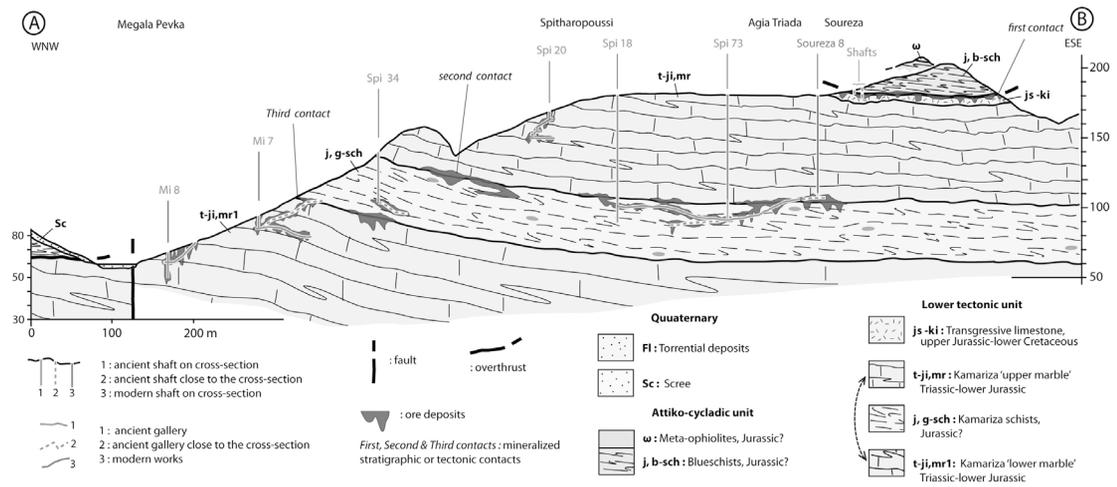


Figure 5. Laurion. Mégala Pefka. Gallery and working face under examination. Point chisel (masonry tool) marks on the walls (Spi. 5)

MEASURING AND ANALYSING TOOLMARKS

Measuring requires discrimination of a range of semiotic traces which are directly observable:

- geological traces which are often tenuous, manifested from fluid circulation in the earth's crust
- traces directly connected to the act of extraction
- traces corresponding to secondary works
- toolmarks and signs of work, witness to the human presence in the galleries.

Macroscopic observation of rock and toolmarks permits a deeper understanding of both the morphology of the ore body and the nature of the mining techniques employed.

PARTICULAR UNDERGROUND ARCHITECTURE

Three types of works are to be found underground at Laurion: galleries, shafts and working areas. Drift galleries criss-cross the underground horizontally. They were the starting point for exploitation of a vein of minerals. They probed the mining area in terms of its potential for current and future exploitation. In the deepest parts, junction galleries connect shafts and mining areas. Influences on the architecture of the galleries include the flow of fracturing and density of marble, carbonisation or not of the rocks, the sloping of the vein, and type of mineralisation. Their morphology is generally very tidy, and form a pattern characteristic of these ancient networks. The size of junction, exploratory, and drift galleries and lanes can vary according to the template. The parameters of the sections are variable. The width at the base rarely exceeds an average of 80 cm, but these measurements are far from consistent. The geometric morphology of the works remains relatively constant, but variations are perceptible



Figure 6. Laurion. Spitharoussi sector. Quadrangular section shafts. Grooves on walls: timber remains of ventilation system seen from the surface. (Spi 6)

on the interior of the same section. They probably correspond with the technique of the miner doing the work, who economised effort in the most difficult areas.

MEANS OF ACCESSING THE DEEP MINING WORKS - THE SHAFTS

To reach the mineralised areas, the ancient miners used vertical shafts. To bore them, and to traverse particularly hard ground, necessitated complex equipment and careful attention. The shafts on the Spitharopoussi plateau had a quadrangular shape, on average 1.35 x 1.65 m. Their depth was variable but could descend to over 100 m absolutely vertically (Figure 6).

Most of the shafts have grooves on their sides. This morphology was used to facilitate clamping the timber of the mine shaft installation onto the walls (Morin and Photiades 2012, 311-312). Studying the tunnels permits an understanding of timber techniques especially in relation to the problem of ventilation (Morin and Photiades 2005), a vital imperative of mining. Traces of many of these processes are in evidence at Laurion and have been the object of recent studies (Herbach *et al.* 2013).

EXTRACTION TECHNIQUES

Tool marks are the best way of identifying human activity, but these marks are often in complex patterns. They come from the nature of the tool used and from the edge, indicating the direction of the blow and the direction of the work. Most of the traces on the walls come from the use of the same type of cutting tool. The mallet and point chisel were the quintessential tools at Laurion. The point chisel, the so-called pointerolle (point chisel), is a small pointed metal chisel with a flattened head that was tapped with a mallet. Extraction in the marble zone was done manually with the point chisel, and probably with wedges inserted in cracks in more friable schists (Figure 7).

TECHNIQUES OF ROCK MINING

In the galleries, traces of mining are everywhere. They are evidenced by a multitude of almost parallel, curvilinear grooves equidistant on the walls. They indicate both the direction of mining and the position of the miner facing the rock. These marks, often very regular, mark the walls of the galleries and are one of the characteristics. Traces are still visible of the final removals intended to complete this task. What significance can be gleaned from this layout?

Repeated blows to the wall might erase all trace of the first part of the operation. The only alternative way of understanding the technique lies in observation and analysis of the 'front



Figure 7. Laurion. Research gallery in progress: miners at work. Reconstructed scene. The miner on the right is drilling through the rock with a hammer and a pointerolle (point chisel). This reconstruction is based on observations made underground. With permission of Bernard Nicolas, illustrator (www.danselombre.com)

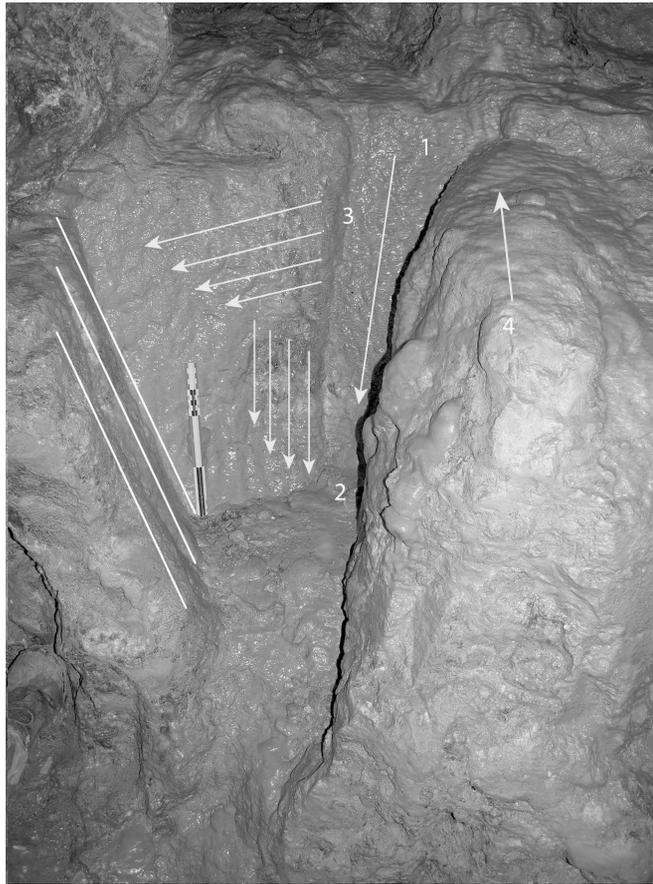


Figure 8. Laurion. Mégala Pefka sector. Spi 49 – a view of a typical working face showing traces of all faces of the process: 1) vertical lateral notch; 2 & 3) vertical lateral mining. Highlighted in white on the left: lateral remains of sections cut out successively

faces'. A front face is a surface at the limit of the working site in the direction of progress. In other words, it corresponds to the terminus of a gallery or work area. It is particularly interesting to observe and study the mining techniques when the work was abandoned for some unknown reason. The observation of front faces and topographical analysis shows that there were many variations to the basic technique which consisted of making a preliminary kerf or notch. The front faces bear the mark of this technique which was generally used in the trial galleries. The notch corresponds to about a third of the width of the face. Removal was carried out all along the operation with successive tiers removed down from the roof (Figure 8).

In larger works, whenever there was a perceptible incline, the miners tended to break up the working face into stopes. Splitting the working area into stopes allowed each to be more effectively exploited. In the networks of the Third Contact, it is not unusual to observe traces of 'underhand stoping' (Mi 7) (Figure 9).

FROM STOPING TO A COMPARTMENT: AN ORIGINAL MINING TECHNIQUE

The general aspect of numerous galleries resembles panels closely butted side by side, but in which their liaison was adjusted depending on the direction of the mining. Such works show a fairly regular succession of stopes. The volumetric standardised dimension of mining is a striking feature of the works. It seems the miners worked to a predetermined volume, defining in advance each compartment or panel to be excavated (Figure 10).



Figure 9. Laurion. Mégala Pefka sector. Mi 7 – Underhand stoping technique



Figure 10. Laurion. Spitharopoussi sector. Spi 15 – Upper marble gallery. Succession of panels

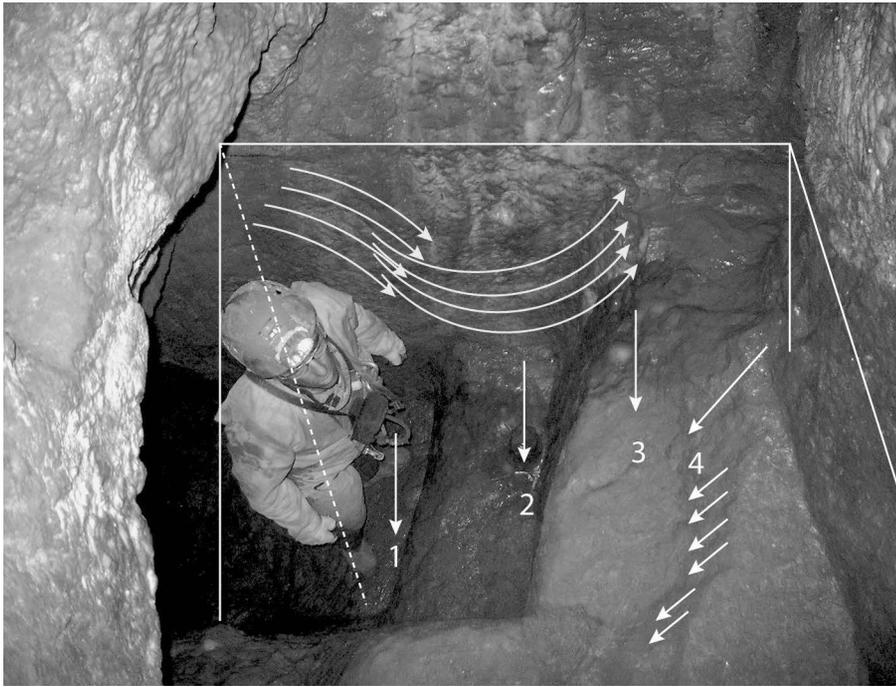


Figure 11. Laurion. Spitharopoussi sector. Spi 5 – Vertical sinking technique. Work in progress with well-preserved remains. The process was: Stages 1,2,3: successive benches; 4: Ongoing breaking of the upper bench. The arrows represent tool marks on the wall: finishing works

TECHNIQUE FOR VERTICAL SINKING: THE STACKING OF PANELS

It is, of course, easier to learn about the techniques of digging in well-preserved areas of the networks, but these examples are rare. The bottom of a shaft (Spi 5) sunk at the end of a network close to the surface permits a partial understanding. It reveals the presence of platform 0.4 m wide in a general section of the shaft measuring 1.02 x 0.96 m. The mining strategy employed here was similar to that in the galleries but progressed in a vertical fashion. Excavation was effected from a deep side notch of 0.56 m which was enlarged horizontally and continued in stopes. Here the progression of underhand stoping went in five successive, unidirectional steps. The final one involved equalising the sidewalls to an oblique position (Figure 11).

Mining carried out in the marble layers reveals a strong dexterity in achieving regularity in the geometry of the galleries. Beyond this aesthetic, the ancient mine indicates a particularly well-developed standard process with a hierarchically-based work flow. Mining at Laurion can be identified with a strong technical tradition in equipment and methods (Vernant 1965; Jockey 2003).

MINING TECHNIQUES AT DEEP LEVELS

The excavation technique differed according to the density or hardness of the rock. Extraction could be starting by scoring the rock, and then making a deep shearing following the horizontal strata (Spi 18) at floor level. This preparatory step, or undercut, was done to undermine the base of the stope, and thus weaken the rock to be extracted and decrease its resistance (Gruner 1921).

Most of the time, the front face progressed perpendicularly in the service gallery, and on each side in an irregular edge, creating a cavity. This could be as long as 15 m. Too great a length risked a roof collapse and was rarely justified, except occasionally by leaving supporting pillars. In the case of an oblique ore deposit, extraction was effected in an upwards

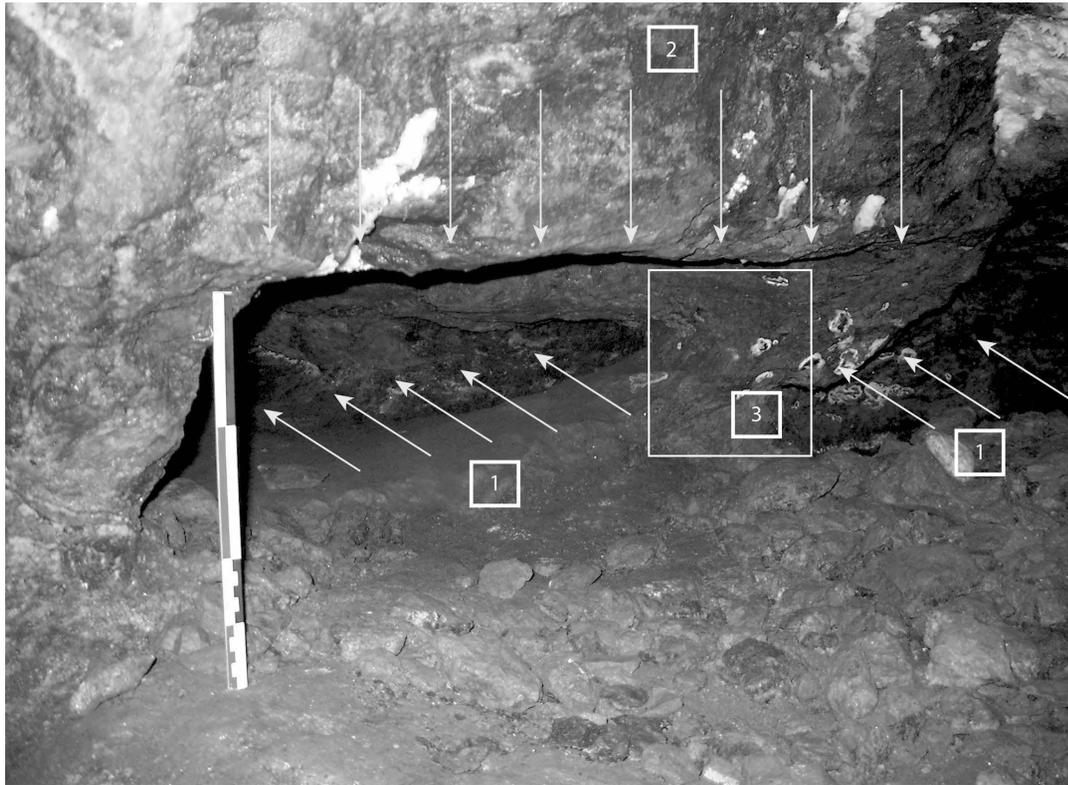


Figure 12. Laurion. Spitharopoussi plateau. Spi 18 – Deep works in the Third Contact. Mining technique process using a horizontal cut to the wall. 1: horizontal mining. 2. Vertical mining. 3. Pillar



Figure 13. Laurion. Spitharopoussi plateau. Spi 18 – Deep works in the Third Contact. Mining technique process using a horizontal cut to the roof. To the right, behind the working face, a cluster of mineralised blocks. 1. Horizontal mining. 2. Vertical mining



Figure 14. Laurion. Spitharopoussi sector – Spi 18. Deep works in the Third Contact. Ancient mining works around – 80m. Access lane and accumulation of waste (backfilling)

direction from a horizontal notch situated on the ceiling directly under a strata join. The disengaged front face was then cleared in a unidirectional fashion from top to bottom and progressed following the inclination (climbing face). (Figures 12 and 13).

The type of deposit in thin veins visible in the networks of Shaft Spi 18 was exploited with a partial or total backfilling of the work areas, and by installing waste deposit areas particularly along traffic lanes. Containing waste in a space avoided having to disperse it and facilitated the transport of materials and movement of workers, but waste deposits were never used to support the roof (Figure 14).

THE LAURION MINES – METHODS OF EXPLOITATION ADAPTED TO THE GEOLOGICAL CONTEXT

Two main scenarios are considered based on the location of the deposits:

1. Mineralisation close to the surface or outcropping was first exploited (Leleu 1966), starting with the outcrop, then underground by cuttings and extension galleries. As they advanced the cutting, the miners dug galleries of lesser size, horizontally and laterally to test the amount of mineralisation. Often the miners had recourse to this to gauge the extent of the deposit, and thus to decide the initial layout of the works.

The downward progress of the works was made by benching (Figure 15). Cuttings following the axis of the gallery were sunk from the floor. Traces of these levels are thus discernible in the roof, and bear witness to this original technique, the first phase of a general lateral exploitation. Certain works are peppered in places by the trial galleries which sometimes overlap, fuse, and can constitute a veritable labyrinth (Figure 16).

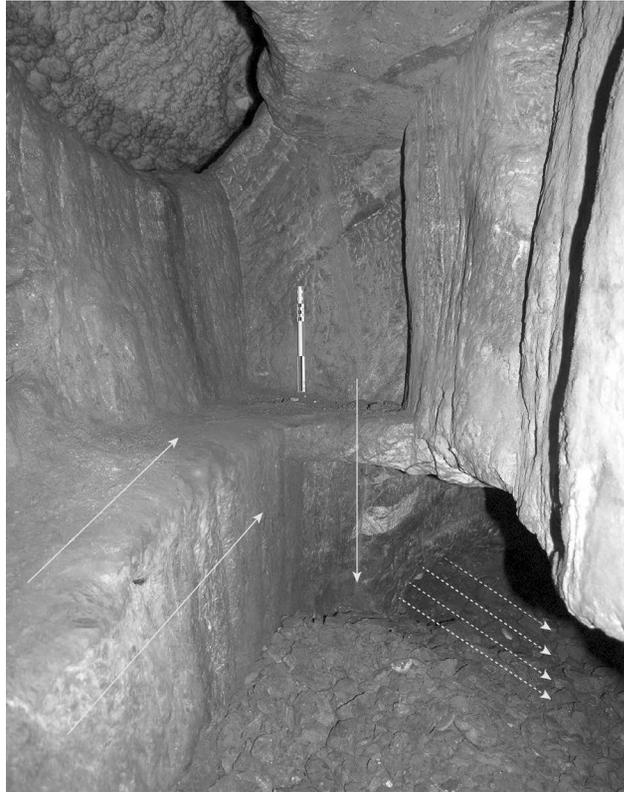


Figure 15. Laurion. Mégala Pefka sector. Mi 7 – Benching works: technique of downward stoping. The gallery is exploited along its length by taking off the material



Figure 16. Spitharopoussi Plateau. Spi 15 – Nyphitsa network. Downward stoping process by benching (rebor-ing) the original gallery. 1. Original 1st research gallery. 2. Remain of 1st gallery floor. 3. 2nd gallery



Figure 17. Laurion. Spitharopoussi sector: Spi 18. Deep works. Junction gallery between 2 work zones in the Third Contact

2. In deep mineralisations, it is possible to distinguish two methods of exploitation directly connected to the morphology and positioning of veins.

a) On top of the plateau, the deep works relied on shafts to the galleries of close to 30 m with quadrangular sections (Figure 17).

The excavations were developed following along thin, rangy axes. The miners then opened the cuttings or cavities, more or less equidistant, following in the direction of the vein. On each side of the leading gallery were openings of works. The layout this produced faithfully followed the morphological characteristics of this type of network served by deep vertical shafts which gave access to the Third Contact from around 80 m (Figure 18). In these cramped spaces, the miners looked for ways to progress efficiently and sought to minimise the quantity of sterile material excavated. They banked up the material they dug in order to obtain precisely what they needed to carry from the mine. In this way, only mineralised rock was extracted each day (Figure 19).

b) On the west side of the plateau, on the slope, the base of the shafts opened in schists often debouching into works. The principal axis of the exploratory galleries was parallel to the hillside. The plan of exploitation was mostly linear. The circulation route, uniquely, was sometimes cut into the block of the quadrangular section or laid out in the partly banked-up excavations.

Larger chambers can be found in the centre of particularly exiguous networks. They often correspond with the junction point of several veins or concentrated mineralisation. Mining was carried out on both sides of the galleries. These works evolved together and sometimes developed in terraces and more frequently in cells. With this scheme, the miners could control the progression from a security point of view. Ore was evacuated on a man's back or by dragging (Figure 20). Traces of the various stages of excavation are still visible.

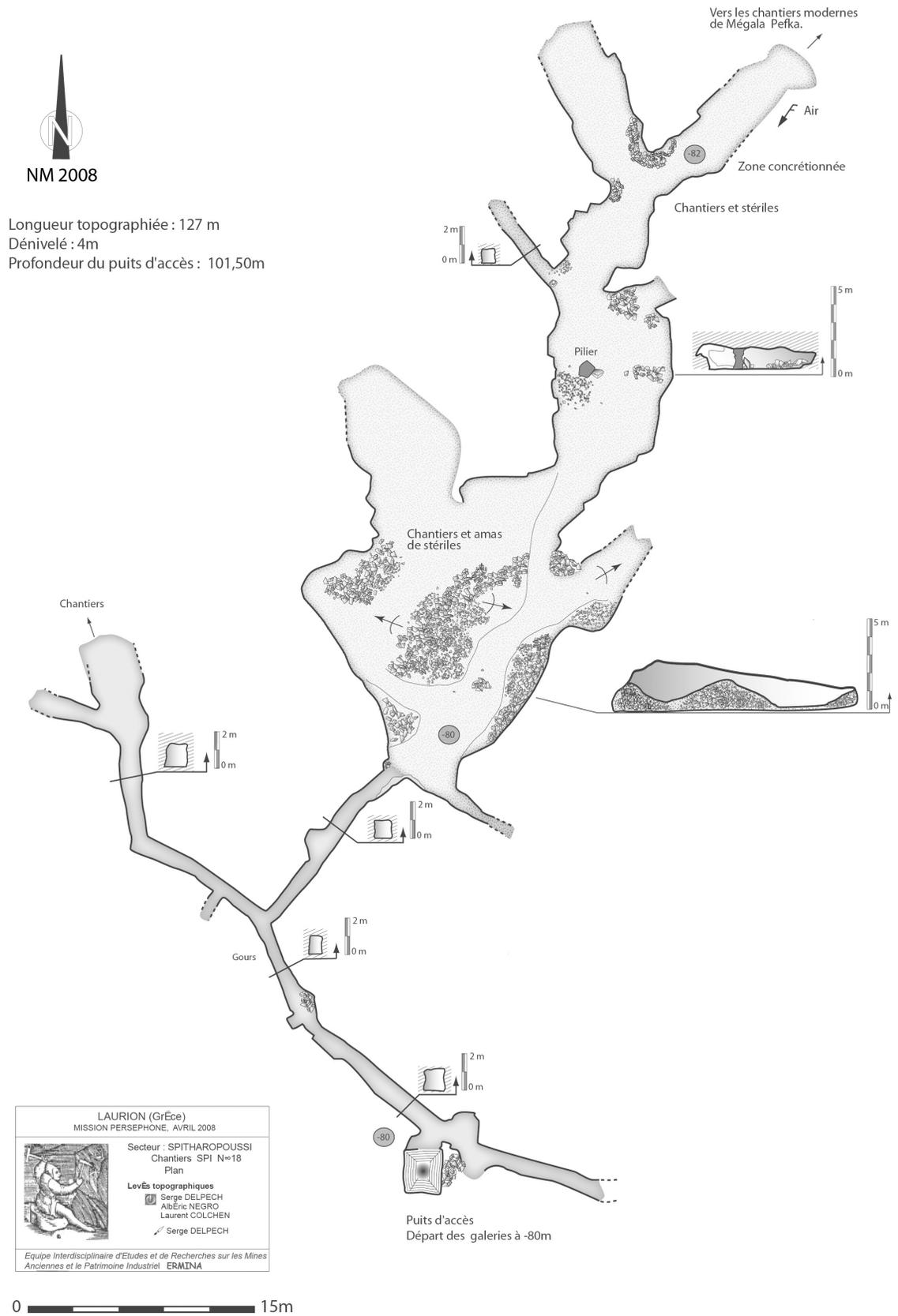


Figure 18. Laurion, Spitharopoussi Plateau : Spi 18. (- 80 m) Topography of the works in the Third Contact. (Drawing: Serge Delpech)



Figure 19. Laurion. Sector Spitharopoussi : Spi 2. Deep works in the Third Contact. Ancient works around –80m. Residual pillar



Figure 20. Laurion. Spitharopoussi Plateau. Spi 49 – Deep works in the Third Contact. Clear traces of dragging on the ground fossilized by the calcite. Junction gallery between two work zones

A RECURRENT PROBLEM: THE CHRONOLOGY OF THE PHASES OF EXCAVATION

The study of such a network of galleries raises the problem of identifying the chronology of mining operations. At first sight, the subterranean networks correspond with a single phase of exploitation. They do not seem to have undergone repeated phases of exploitation, with the exception of certain works in the lower marble layers, and the more easily accessed networks close to the surface. In these, the traces of ancient work are visible especially in the more recent re-workings undertaken for the most part during the fifth century AD. Oil lamp fragments are among the most characteristic markers of these subterranean networks.

CONCLUSION

Understanding the methods utilised by the ancient underground miners is a matter of reading the tiny clues they left. The demonstrated mining techniques are evidence of an art of mining which took on a real importance at Laurion. Regardless of the mode of exploitation, the miners devised processes to suit the mining conditions within the indispensable parameters for maintenance of mining: ventilation, movement of men and materials, extraction. It is also clear that there was a hierarchical structure because to conduct this work, it was necessary to plan the layout of the tunnels depending on the geology. This is attested in Xenophon (*Memorabilia* 2.5.2) who mentions how Nicias paid a small fortune for a slave capable of managing a mine.

In the course of making these investigations, more than 10 kms of underground workings were explored plus some topographic features. The mode of exploitation also frequently raises the central question of the geological and mineralogical knowledge of the miners of these gigantic mining operations. How did the ancient miners know where to locate the ore, and put in place the necessary organisation? The observation of certain mining activity on outcrops allows a partial answer to these questions.

Economic success and choice of method depended on the presence or otherwise of certain key factors: high-value minerals, available land, a workforce with the practical know-how and mastery of the necessary techniques, dynamism of the political elite, existence of a communication network, and availability of funds. These conditions were met at Laurion when mining operations were undertaken by the city-state of Athens (Davis 2014, 257-277). It was a quasi-industrial enterprise in the sense of being a concentration of technical means implemented to extract and process silver by a process unique in the ancient world at this scale.

Photographic credit

Except where otherwise stated, photos are by Denis Morin. Photographic enhancement – DAO: H  l  ne Morin-Hamon.

The research

Underground investigations were the result of a cross-disciplinary research team which combined to handle the important logistics. They have been conducted under the auspices and permit of the *French School at Athens* (2002) and of the *Institute of Geology and Mineral Exploration* (IGME). They were undertaken in a series of short forays under the aegis of the *Institute of Geology and Mineral Exploration of Athens – IGME*, and of the *TRACES* laboratory (UMR CNRS 5608) with the support of the *French School at Athens*. The exploration of the mines was undertaken by members of the *Equipe Interdisciplinaire d'Etudes et de Recherches Arch  ologiques sur les Mines Anciennes et le Patrimoine Industriel (ERMINA)*:

Michel Aubert, Bernard Bohly, Patrice Cocuau, Laurent Colchen, Maryse et Serge Delpéch, Richard Herbach, Yves Imbert, Denis Jacquemot, Denis Morin, Hélène Morin-Hamon, Albéric Negro and Patrick Rosenthal.

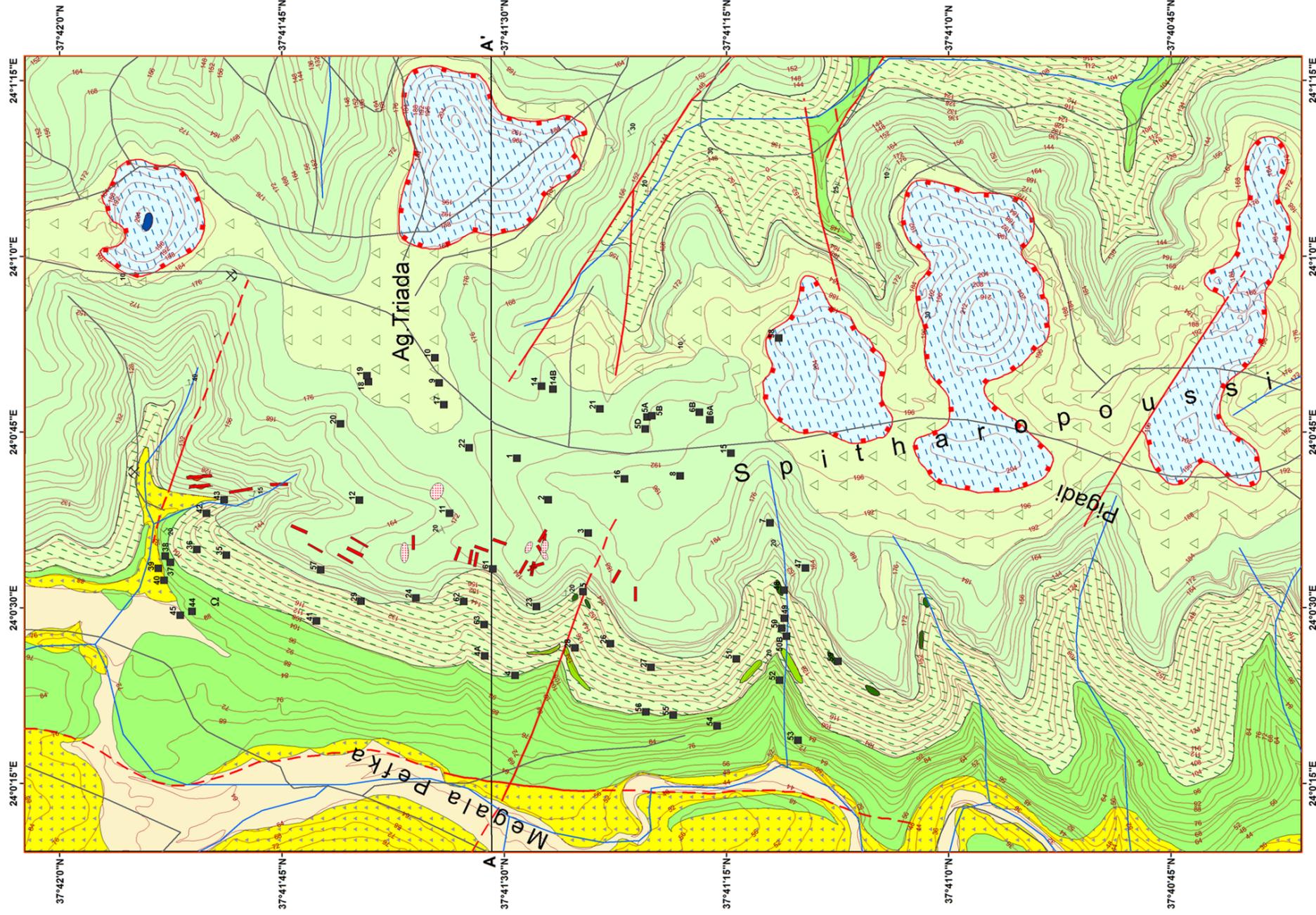
Special thanks go to:

- Dr Gil Davis who translated and edited this paper and also for his corrections and wise advice.
- The *Institute of Geology and Mineral Exploration* in the *Department of General Geology & Geological Mapping of Athens (IGME – Greece)*, in particular to the *Service of Geological Mapping at IGME*, responsible for the geological maps of Laurion (prepared by its Adjunct Director Dr Adonis Photiades and Dr Irene Zananiri).
- The *Ephorate of Attica* and its director, M.G. Steinhauer.
- M. Dimitris Loukas, Mayor of Lavrio.
- M.D. Mulliez, Director of the *French School at Athens*.
- Professor K. Panagopoulos, *National Technical University of Athens (NTUA)*, and director of the *Laurion Technological and Cultural Park (LTCP)*.
- Lionel Fadin, Surveyor at the *French School at Athens*
- The anonymous reviewers.

REFERENCES

- Ardaillon, E. 1897. *Les mines du Laurion dans l'Antiquité*, Bibliothèque des Ecoles Françaises d'Athènes et de Rome, Fasc. 77 (Paris).
- Conophagos, E.C. 1980. *Le Laurium antique et la technique grecque de la production de l'argent* (Athens).
- Davis, G. 2014. 'Mining money in Late Archaic Athens', *Historia* 63/3, 257-277.
- Fadin, L. (2011). Mission IGME - Laurion. Rapports d'activités topographiques. 30 mars et 08 avril 2010. 5 p. 7 plans, 1 tableau (CD Rom). Fadin L. 2011. 21 avril 2011. 4 p. 8 plans, 2 tableaux (CD Rom). *Ecole française d'Athènes*.
- Gruner, L. 1921. *Cours d'exploitation des mines. Méthodes d'exploitation en carrière et souterraine* (Paris).
- Herbach R., Morin D. and Rosenthal, P. 2013. 'La géométrie des puits du Laurion. Traces et indices des technologies minières de l'Antiquité'. *Actes du Colloque Indices et traces : la mémoire des gestes*. Nancy, juin 2011. PUN – Editions universitaires de Lorraine, coll. Archéologie, Espaces, Patrimoines, 171-185.
- Jockey, Ph. 2003. 'L'artisan, l'objet et la société : à propos d'un éventuel blocage des techniques dans l'Antiquité, l'exemple de l'artisanat de la pierre', in Balansard, A. (ed.), *Le travail et la pensée technique dans l'Antiquité classique. Lecture et relectures d'une analyse de psychologie historique de Jean-Pierre Vernant* (Technologie/Idéologies/Pratiques, XV, 1), 57-81.
- Leleu, M. 1966. 'Les gisements plombo-zincifères du Laurium (Grèce)', *Sciences de la Terre, Nancy*, XI/3, 293–343.
- Morin, D. and Photiades, A. 2005. 'Nouvelles recherches sur les mines antiques du Laurion (Grèce). Mines et métallurgies dans l'Antiquité. Etat des recherches', *Pallas, revue d'Etudes Antiques* 67, 327–358.
- Morin, D. and Photiades, A. 2012. 'L'exploitation des gisements métallifères profonds dans l'Antiquité. Les mines du Laurion (Grèce)', in Olshausen, E. and Sauer, V. (eds.), *Die Schätze der Erde – Natürliche Ressourcen in der antiken Welt. Stuttgarter Kolloquium zur Historischen. Geographie des Altertums* 10, 2008. (Stuttgart), 281-335.
- Morin, D., Photiades, A., Jacquemot, D., Rosenthal, P. et al. 2002. 'Mission géologique et archéologique de reconnaissance au Laurion (Grèce). Les puits d'extraction antiques de Spitharopoussi : problématique générale de l'extraction des gîtes de contact. Campagne 2002. Avec une contribution de Domergue, Cl. sur les concessions', DVD - ROM, *Institute of Geology and Mineral Exploration, IGME - CNRS. Avec la participation de l'Ecole Française d'Athènes*.
- Photiades, A. and Carras, N. 2001. 'Stratigraphy and geological structure of the Laurion area (Attica, Greece)', *Bull. Geol. Soc. Greece*, Vol. XXXIV/1, 103-109A.
- Photiades, A., Mavridou, F. and Carras, N. 2004. 'Geological map of Greece in scale 1:50.000', *Laurion-Makronissos-Agios Georgios Islands* sheet. Edited by Institute of Geology and Mineral Exploration - IGME Athens.
- Photiades, A., Rosenthal P., Zananiri, I. 2017. 'Geological map of Spitharopoussi Area (*Lavrión District*) in scale 1: 5000'. Edited by Institute of Geology and Mineral Exploration - IGME Athens.
- Scheffer C., Tarantola A., Vanderhaeghe O., Rigaudier T. and Photiades A., 2017a. 'CO₂ flow during orogenic gravitational collapse: Syntectonic decarbonation and fluid mixing at the ductile-brittle transition (Lavrión, Greece)', *Chem. Geol.* 450, 248–263.

- Scheffer C., Tarantola A., Vanderhaeghe O., Voudouris P., Rigaudier T., Photiades A., Morin D. and Alloucherie A. 2017b. 'The Lavrion Pb-Zn-Fe-Cu-Ag detachment-related district (Attica, Greece): Structural control on hydrothermal flow and element transfer-deposition', *Tectonophysics* 717, 607–627.
- Scheffer C., Tarantola A., Vanderhaeghe O., Voudouris P., Rigaudier T., Spry, P.G. and Photiades A. 2019. 'The Lavrion Pb-Zn-Ag-rich vein and breccia detachment related deposits (Greece): Involvement of evaporated seawater and meteoric fluids during postorogenic exhumation', *Economic Geology*. <https://doi.org/10.5382/econgeo.4670>
- Scheffer C., Vanderhaeghe O., Lanari P., Tarantola A., Ponthus L., Photiades A. and France L., 2016. 'Syn- to post-orogenic exhumation of metamorphic nappes: Structure and thermobarometry of the western Attic-Cycladic metamorphic complex (Lavrion, Greece)', *J. Geodyn.* 96, 174–193.
- Scheffer, C. 2016. 'Réservoirs fluides et transferts en contexte d'exhumation orogénique: Implications sur la position structurale des minéralisations Cu-Pb-Zn-Fe-Ag dans la région Laurion-Eubée (Grèce)' (PhD dissertation, Université de Lorraine, France).
- Scheffer, C., Vanderhaeghe, O., Lanari, P., Tarantola, A., Ponthus, L., Photiades, A. and France, L. 2015. 'Syn-To Post Orogenic Exhumation Of Metamorphic Nappes: Structure and thermobarometry of the western Attic-Cycladic Metamorphic complex (Laurion, Greece)', *J. Geodynamics.*, <http://dx.doi.org/10.1016/j.jog.2015.08.005>
- Vernant, J.-P. 1965. *Mythe et pensée chez les grecs. Etudes de psychologie historique*. Tome II (Paris).
- Xenophon, *Mémorables*. Tome II. 2011. 1^{re} partie. Livres II-III. Texte établi par Michèle Bandini, traduit et annoté par Louis-André Dorion. Collection des Universités de France, Série grecque.



LEGEND

QUATERNARY

- al Alluvial deposits
- lc Talus cones with slope debris

Lavרון Blueschist Unit

Blueschists (sch₂), metabasaltites and metaquartzites followed at top by slices of meta-ophiolite mélanges (o).

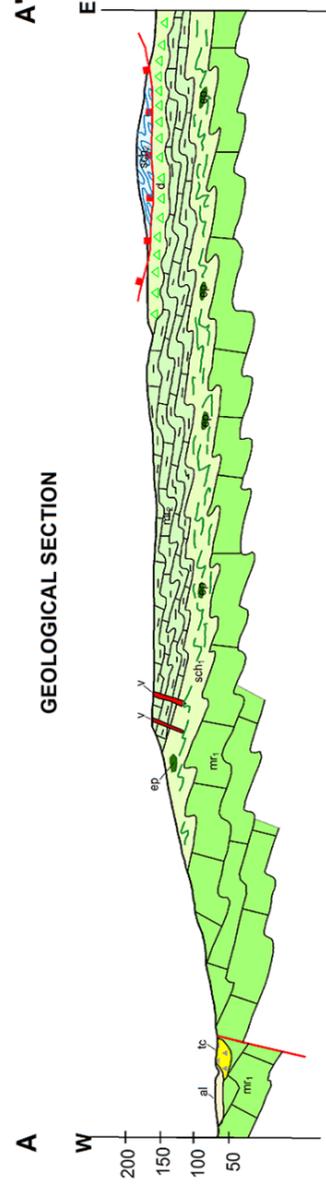
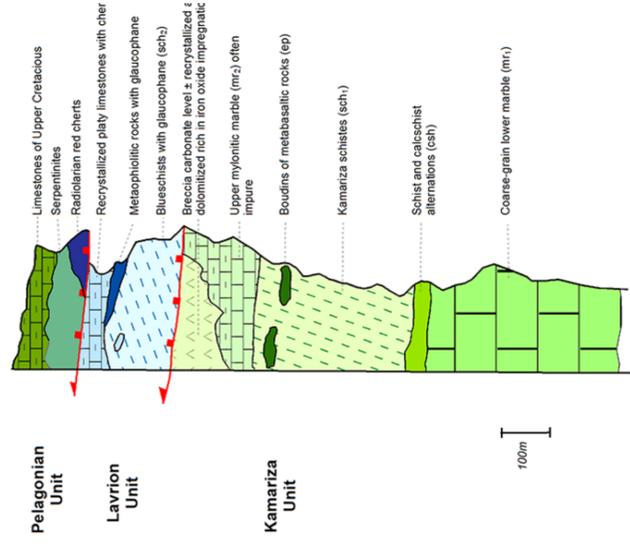
Kamariza Unit

TRIASSIC - JURASSIC (?)

- d Dolomitic breccia level (d) with cataclastic facies and/or impregnated by iron infiltrations; locally becomes breccioconglomerate.
- mr₂ Mylonitic Upper marble (mr₂) very often containing intercalations of impure marble and dolomitic nodules.
- ep Kamariza schists (sch₁), containing at their base levels of calcichists (csh); often bearing within their top levels boudins of metavolcanic basic rocks (ep).
- mr₁ Lower marble (mr₁) massive, coarse-grained, developing a mylonitic facies within its upper part.
- Epithermal veins completely oxidized by iron (in azimuthal orientation).
- Diffuse zone of iron oxides

- Geological boundary
- Topographic contour
- High angle fault
- High angle fault probable or covered
- Low angle detachment fault
- Hydrographic network
- Road network
- Geological section
- Ancient mining shafts
- Gallery entry (Megala Peftka)
- Inactive mine
- Strike and dip of schistosity / foliation

SYNTHETIC COLUMN OF LAVRÓN



The geological and metallogenic mapping was carried out by the geologists Dr. Adonis Photiades (Institute of Geology and Mineral Exploration - IGME, Greece) and Prof. Patrick Rosenthal (Laboratoire Chrono-Environnement, Université de Franche-Comté, Besançon, France).
 Digital cartography - editing: Dr. Irène Zanamiri (Institute of Geology and Mineral Exploration - IGME, Greece)
 Cite as: «Photiades, A., Rosenthal, P. & Zanamiri, I. (2017). Geological map of Spitharopoussi area (Lavרון district), in scale 1:5000. Athens, Greece.»

Contour interval 4 m
 100 50 0 100 200 300 400 m
 GGRS 87 QUADATURE PER 10.000 M.
 WORLD GEODETIC SYSTEM 1984
 The topographic base map originates from the Topographic Map of the HELLENIC MILITARY GEOGRAPHICAL SERVICE (HMGS), Edition 1976.
 Copyright H.M.G.S.



Figure 21. Geological map of Spitharopoussi area (Lavרון district) in scale 1:5,000. (Production by IGME; thanks to Adonis Photiades and Irene Zanamiri)