Der Anschnitt, Beih. 50, pp.47 – 56, 2023, https://doi.org/10.46586/DBM.264.390

Markos Vaxevanopoulos, James Ross, Konstantinos Soukis, Panagiotis Voudouris, Vasilios Melfos

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 multi-purpose 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

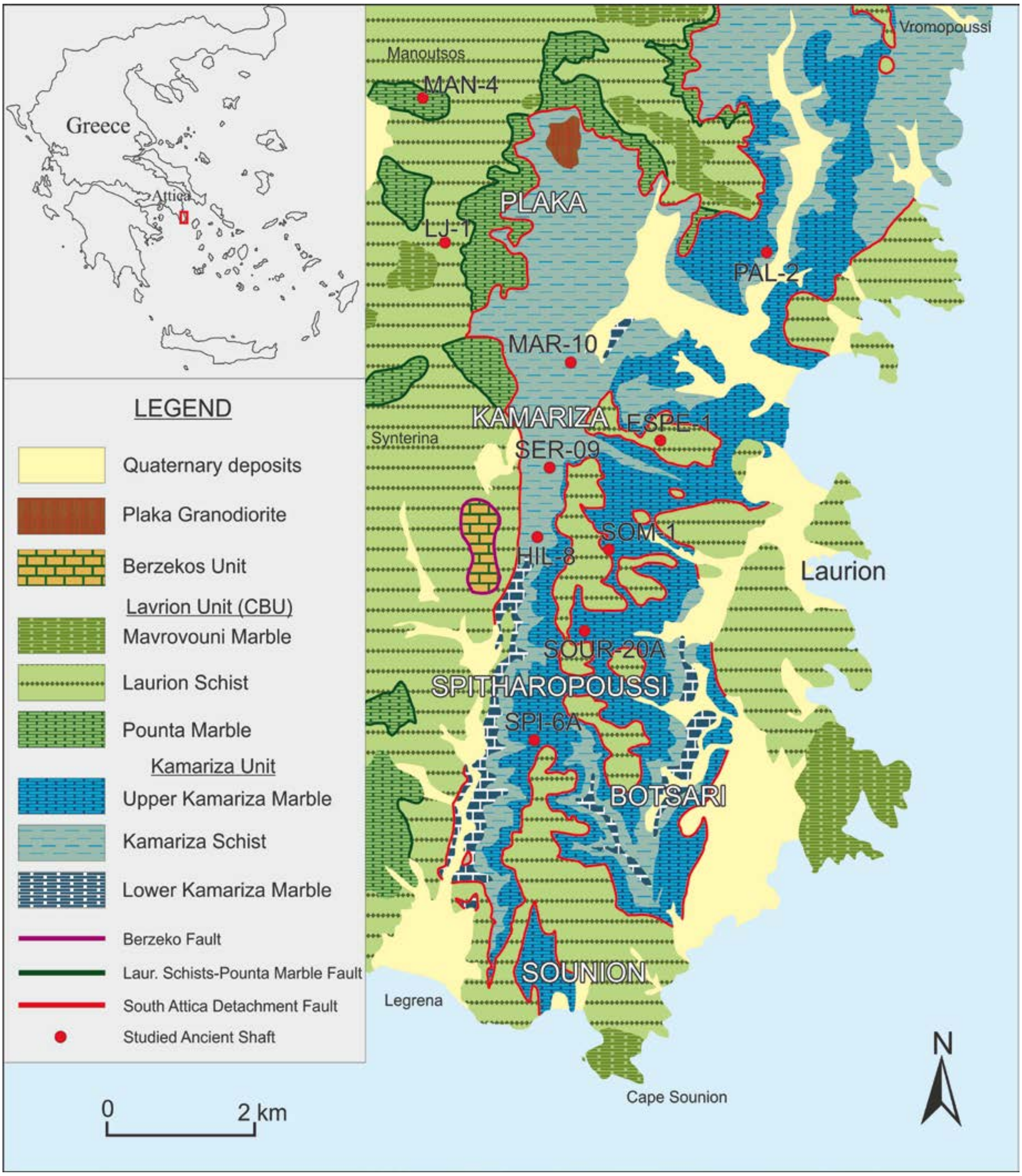

Fig. 1: Geologic map of the Lavreotiki area in Greece (illustration modified from Lekkas, et al., 2011).

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 km² 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 km². 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

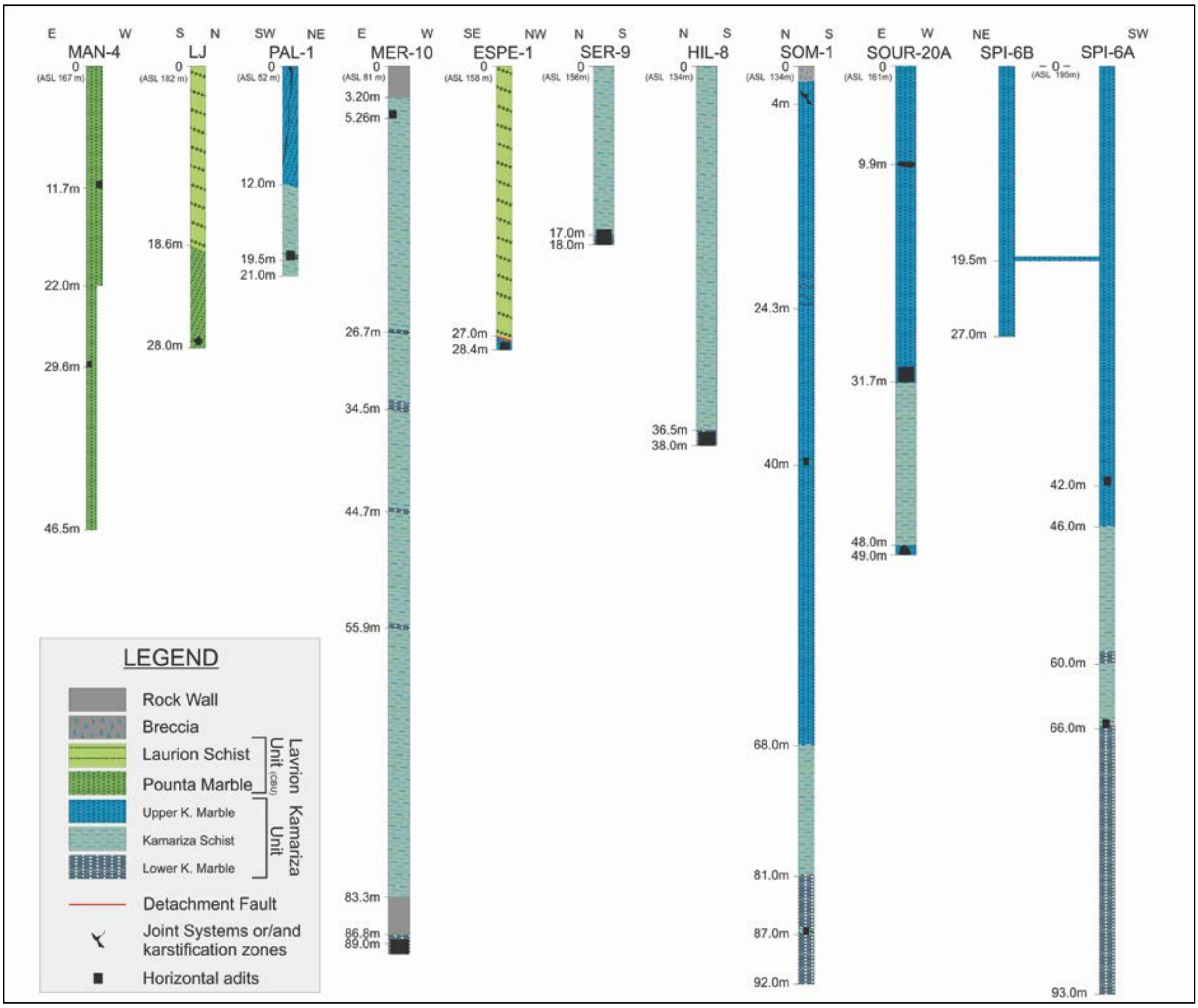

Fig. 2: Stratigraphic columns of the ancient shafts mapped during the "Laurion Shafts Project". From left to right depicted the shafts Manoutsos-4 (MAN-4), Louis Joseph (LJ), Palaeokamariza-1 (PAL-1), Mercati-10 (MER-10), Esperanza-1 (ESPE-1), Serpieri-9 (SER-9), Hilarion-8 (HIL-8), Sommet-1 (SOM-1),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

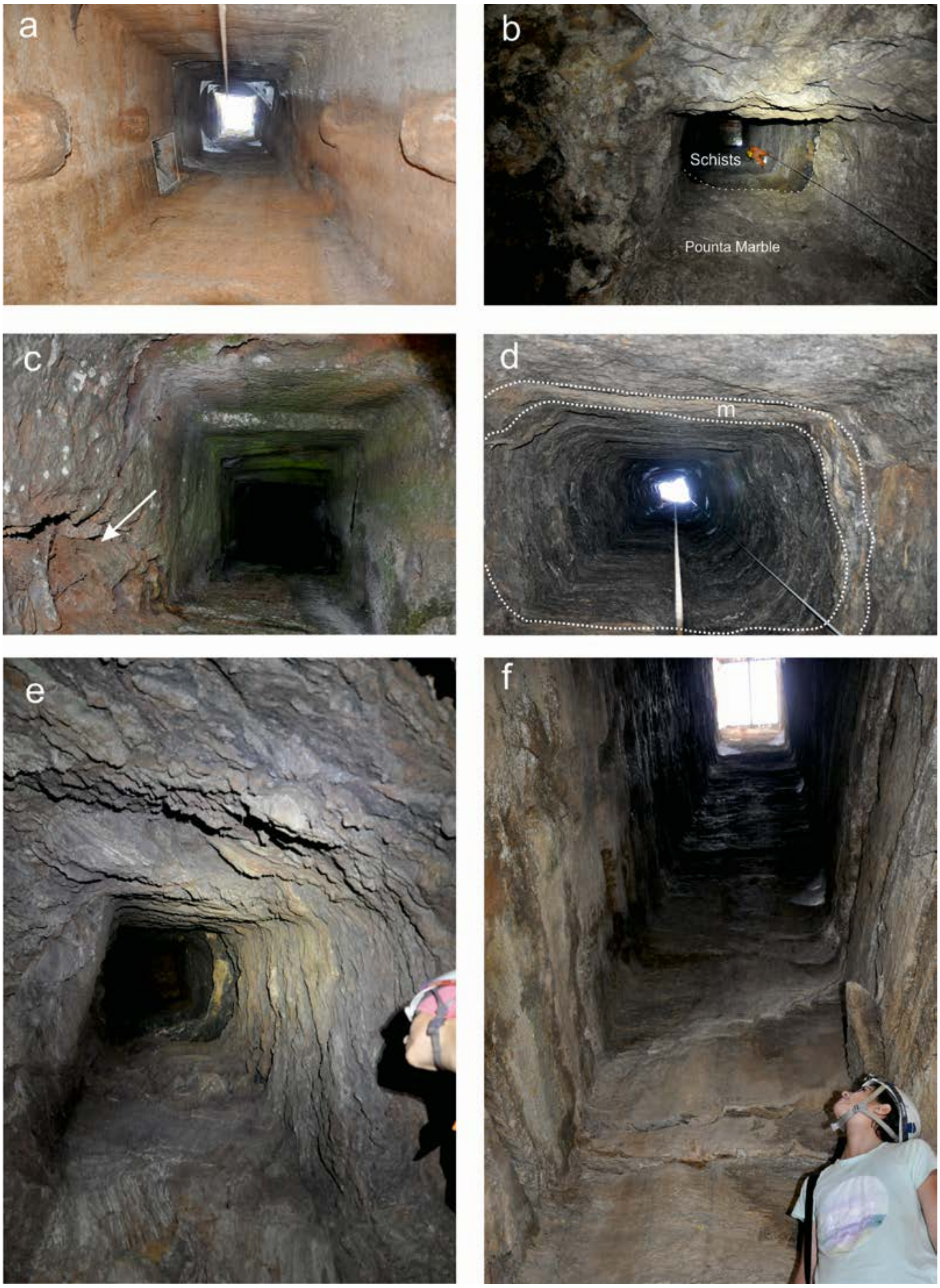

Fig. 3: a. View from the internal part of the MAN-4 shaft. Notches at both sides of the shaft's walls and the position of the horizontal openings imply an internal partitioning. – b. The contact between the Laurion Schist and the Pounta Marble at the depth of 18.6 m. – c. The NNE-SSW joint system was 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).

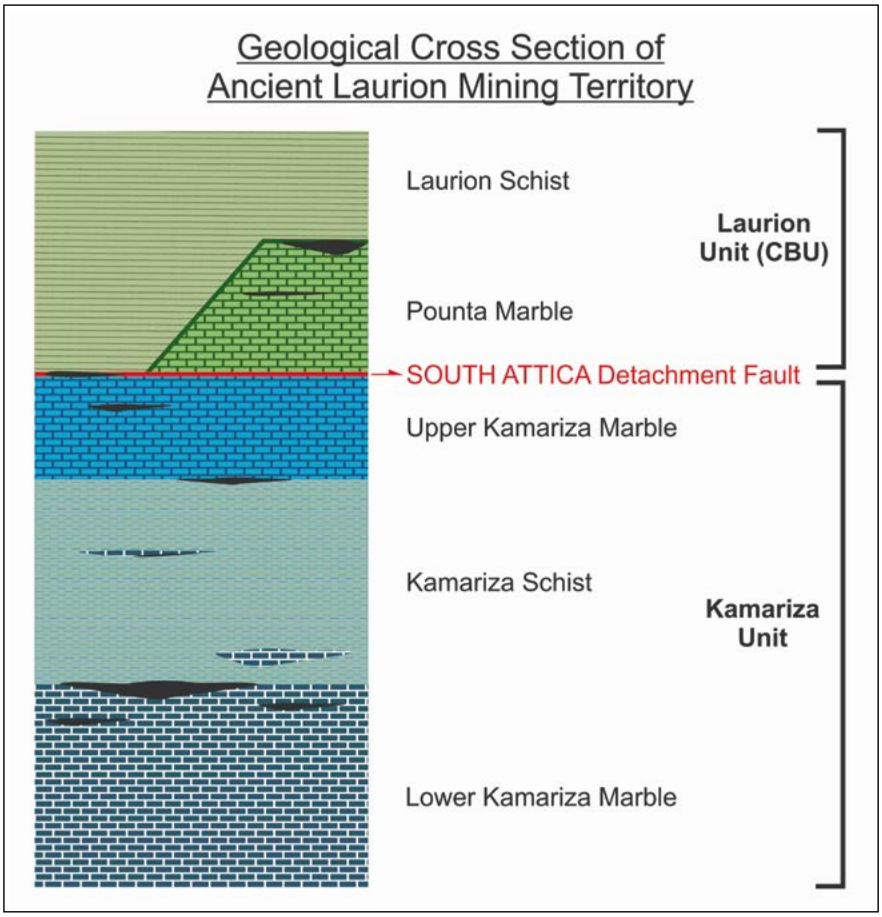

Fig. 5. Generalized stratigraphic column of the ancient Laurion mining territory. Mineralization zones are noted with black color (illustration modified from Lekkas, et al., 2011).

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.

Acknowledgments

This study was financially supported by Dr. James Ross. Shaft exploration and mapping was made possible with the help of the cavers Zaharoula Papadopoulou, Angeliki Reizopoulou, Vassiliki Chantzisava, Evagelia Kolofotia and Panagiotis Karoutsos. The Archaeological Ephorate of East Attica (Greek Ministry of Culture) kindly offered permission for our research. We would also like to thank the Laurion municipality for offering accommodation to the cavers and providing meals through the "Laurion Shafts Project". We are grateful to Hercules Katsaros and Vasilis Stergiou for their contribution in locating numerous shafts openings. We also thank Zaharoula Papadopoulou for the English language editing in the present paper. The first author of this paper benefited from the fruitful discussions with Karl Heinz Fabritz. Dr. Adonis Photiades offered the recently published map of Spitharopoussi and Olga Seni provided our team with a number of maps from the Laurion Technological Park library.

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Authors

Markos Vaxevanopoulos – École Normale Supérieure de Lyon, Lyon, France
James Ross – University of Western Australia and Curtin University, Perth, Australia
Konstantinos Soukas – National and Kapodistrian University of Athens, Faculty of Geology and Geoenvironment, University Campus-Zografou 15784, Athens, Greece
Panagiotis Voudouris – National and Kapodistrian University of Athens, Faculty of Geology and Geoenvironment, University Campus-Zografou 15784, Athens, Greece
Vasilios Melfos – Aristotle University of Thessaloniki, Faculty of Geology, Thessaloniki, Greece

Correspondence and material requests should be addressed to: vaxevanopoulos@gmail.com