

Mining Activities in Ancient Greece from the 7th to the 1st Centuries BC

John N. Economopoulos*

Greece, considering its relatively small size, contains an extraordinary variety of mineral wealth with exceptional commercial value. The tectonic structure of Greece is rather complex characterized by six main geotectonic zones which contain a wide variety of igneous, sedimentary, and metamorphic rocks. The country possesses world class deposits of several industrial minerals, notably magnesite, bentonite, perlite, pumice, asbestos and marbles as well as globally important metallic ores, especially bauxite.

Significant deposits of Ni, Pb-Zn-Cu-Fe (mixed sulfides) Cr and Mn also exist and have been exploited. Quartz, feldspars, kaolin, emery, and other minerals have also been mined on a secondary scale. On the other hand, due to the unlimited deposits of limestone, the clays, the schists and the slates, the cement industry is currently flourishing along with the construction industry which depends on these minerals. Finally, coal mining is very extensive and Greece ranks seventh in world production of lignite-brown coal.

Nevertheless, mining and metallurgical activity in Greece is nothing new. Exploitation of the mineral wealth of the country started during the ancient period. If we consider the archaic period from 2500 BC to 1125 BC, we must admit that our findings and information are very limited, if not poor. By the end of the period, it was known that gold existed mainly in northern Greece (Macedonia, Thrace, Island of Thassos) in the native state as well as in placer deposits. Some gold objects were found in the central Peloponnese not far from a small placer deposit. The precise source of the Minoan and the Mycenaean gold are not known. Probably some local sources had been used but soon they were exhausted.

During the period 1125 BC to 800 BC, metallotechnical activity expanded considerably but

the sources of the metals still remain vague. It is interesting to note that gold is in fact a very commonly mentioned metal in the *Iliad* and the *Odyssey*. At the beginning of the 8th century BC, several mining centers emerged and developed (Rodopi, Paggaion, Thassos, Lavrion, Kythnos, Serifos, Sifnos, etc.) and some of them became famous. In Cyprus, copper and silver was also produced.

There is no doubt that among the famous mining and metallurgical centers of Greek antiquity, Lavrion remains at the top not only because of the importance and duration of its activities, but also because of the value and significance of the spectacular archeological findings. Many ancient authors, poets, historians, and geographers mentioned the Lavrion area in their works. That is why the focus and central concentration of this paper is on the mining and metallurgical activities of the Lavrion area during ancient times. Before going into detail on the subject, it must be stated that the main metals known to the Greeks, with the exception of gold, were rarely found in a free, native state, but as compounds (ores). Early on, miners exploited placers and veins which outcropped on the surface. When these sources became exhausted, the Greeks turned to underground mining. Generally speaking, mining involved prospecting for and collection of the minerals, followed by a specific processing technique designed to enrich the precious material. The subsequent refining was achieved in the metallurgical process. Plato, Aristotle, Theophrastus, Diodorus, Siculus, Strabo, Herodotus, Plutarch, Xenophon, and Pliny are among the sources and all described these processes. Specifically, these authors recorded the principal locations of the minerals and processing techniques of their times, while also occasionally including the commentaries of earlier authorities.

Unfortunately, their chronological evidence is often vague and confusing and different mining and processing techniques are elaborated on in their descriptions. The first attempts to exploit mineral deposits were limited to easily won ores (outcrops) which could readily be collected and treated in primitive furnaces. When vein mining began, however, in each succeeding

* John N. Economopoulos is a Professor of Mining at National Technical University of Athens, Greece.

period, with the development of improved techniques, miners penetrated progressively deeper underground.

As all mining engineers know, it is in the nature of mining that each phase of exploitation tends to destroy evidence of previous workings so that ancient mines are fundamentally poor sites for archeological stratification. An attempt to establish a precise chronological sequence is at best a complicated matter and often virtually impossible to re-create. Nevertheless, in spite of this difficulty, mines can provide a wealth of enlightening archeological material to discern the various techniques employed. As we will see, in our case at Lavrion, pits, open-cast workings, adits, shafts, galleries, washers, furnaces, and cisterns are still intact and may be examined. Likewise, some tools and mine working devices, even in a fragmentary condition, can be found and contribute to the overall picture. Piles of rejected material can yield valuable information not only about the scale of the operations, but, following analysis of their contents, show evidence of the degree of the success and recovery achieved in processing and refining. Coins, statues, and other metal objects can give us important information on the metallurgical side when subjected to chemical and X-ray fluorescence analysis, electron probe microanalysis, spectrometry, and other examination techniques.

The composition of metals and alloys and their physical characteristics in turn reveal their method of manufacture and the mechanical work to which they have been subjected. Now, let us go back to our Lavrion case. Lavrion lies at the southern edge of Attica Peninsula, about seventy-five kilometers south-east of Athens. When mining and metallurgical activities actually started in this area during the ancient period is not clear. By the middle of the 4th century BC, the great Athenian historian Xenophon, referring to the period when mining in Lavrion started, wrote: "Everybody knows that the Lavrion mines are very old, but nobody even dares to say about the time they have started." Therefore, the question is still pending: How old are they?

There are some indicators. The lead that occurs in Minoan artifacts found on the island of Thera, when examined by isotopic analytical methods, proved to be identical to the Lavrion lead ore. Near Thorikos, very close to Lavrion, a tunnel was discovered containing ceramic which could be dated to the early Bronze Age. Consequently, work probably started circa 3000 BC, and blossomed later. It is today accepted that ore was actually won in Mycenaean times, that is, between 2000 and 1200 BC. It seems that organized mining probably began during the middle of the 8th century

BC and there are indications that production of silver took place during the 7th century BC. In the 6th century BC, the production of silver was gradually increased and reached its peak during the 5th century BC when Athens was under the leadership of an amazing statesman, Pericles, who initiated the well known Golden Age of the glorious classical period of Ancient Greece. During the year 483 BC, a rich new deposit was discovered--the Maronia deposit. Its exploitation tremendously advanced the mining activities in Greece which has continued ever since and taken the form of an industry.

The production of silver was considerable during the 4th century BC, only to decline in the 3rd century BC. There was a revival during the middle of the 2nd century BC that eventually went bust. The time of the Roman domination was close at hand. Indeed, during the first part of the 1st century BC (probably 87 BC) mining and metallurgical activities, which resulted in a total production of about 3500 tons of silver, probably came to an end. For the next 2000 years, Lavrion was erased from the annals of mining history, passing into oblivion beneath centuries of pine-tree debris.

GEOLOGY

In order to cover the subject in a spherical way let us first give some general information concerning the geological and mineralogical picture of the Lavrion area. There are five main geological strata composed of alternate layers of calciferous rock (limestone and marble) and of micaschists. These layers have different degrees of porosity and offer different resistance to the upward thrust of hot, mineral-rich liquids from the earth's depths.

In a typical cross section we notice--from the top down--the upper schist (Cretaceous), the upper marble and the lower schist (Jurassic), and the lower marble (Precambrian). In this way, three contacts are formed where the ore exists. The first and third contacts proved to be the richest ore-bearing levels. As already suggested, the metalogenesis is of hydrothermal nature. Hot liquids with the dissolved metals came from veins appear generally where the ore is.

Ancient miners, although they had a very limited knowledge of geology, knew this rule very well. They were looking for guides--e.g., the granitic veinlets--so they followed the contact in order to meet the mineral, and even when the veinlets disappeared they still followed the contact. The ores were mixed sulfides called BPG (from Blende, Pyrite, Galena) as well as oxidized minerals, mainly smithsonite (ZnCO_3) and

cerussite (PbCO_3). The ancient miners were only searching for galena and cerussite because these minerals were argentiferous. Rich galena of the third contact could contain 1.2 to 1.4 kilograms of silver per ton of ore. They naturally exploited the first contact and, when the mineral was gradually exhausted, they were obliged to dig deeper to meet the second and third contacts. Their effort to reach and to exploit the rich third contact is obvious, but the shafts never exceeded a depth of 120 meters and no exploitation took place whenever there was water, i.e., below sea level.

MINING

The earliest mining technique was to cut horizontally from the surface at the contact level, forming in such a way open-cast pits and workings of considerable volume. Penetrating deeper they started driving galleries of very small cross sections, usually 0.6 m^2 ($0.7 \text{ m} \times 0.85 \text{ m}$). Only young boys could walk along these openings. When the galleries intersected the metalliferous area, they were enlarged in order to win the ore, forming considerable chambers or rooms (see Fig. 1). Where these rooms were quite large a column or pillar of natural rock or ore was left to support the roof. Obviously they applied the "room and pillar" mining method so widely used today in coal and metal mining. Sometimes they tried to recover the rich mineral pillar by replacing it with a pile consisting of waste rock. In thicker veins they utilized the "breast

stopping" technique. As the length of the galleries increased ventilation problems inevitably appeared, forcing them to sink vertical shafts. Later, the shafts were sunk not only for ventilation purposes, but they served for exploration (reaching the contact), development, and transportation (hoisting) of the extracted material. The ore was loaded into baskets and carried by workers (on their shoulders) who climbed the ladders installed in the shaft. The rate of advance of the galleries and the shafts was, of course, very low, probably a few centimeters per day. The miners used a limited range of hand tools: hammers with iron heads, chisels or needles of iron for use with hammers, and shovels, mostly wooden. To carry the ore, they used leather sacks or baskets of woven grass. For lighting they had torches and oil lamps especially designed to last a whole work shift. Elementary mine maps were drawn on clay plates and stones to depict topography.

PROCESSING THE ORE

After a preliminary sorting of the lumps of ore underground, a secondary sorting was done outside near the shaft head or the gallery mouth to remove sterile, rock pieces. If the mineral collected in such a way was already rich enough, it went directly to smelting. As the exploitation became more intensive, especially during the 5th century BC, they were obliged to extract ore having a lower silver content which required certain processing.

The first stage was to break the large lumps of ore into small pieces by hammering it with iron mallets, fairly flat-topped boulders, or blocks of limestone or marble. The second stage was to grind the already broken ore pieces into a fine, sandy, granulated form. This was done in hard stone mills of various kinds. The flat type (hopper quern) mills were mostly used which consisted of trachyte. They measured 40 centimeters by 60 centimeters and were 15 centimeters high.

Some conical mills were also found but they were probably used only for grinding wheat. Nevertheless, this type of mill was "invented"

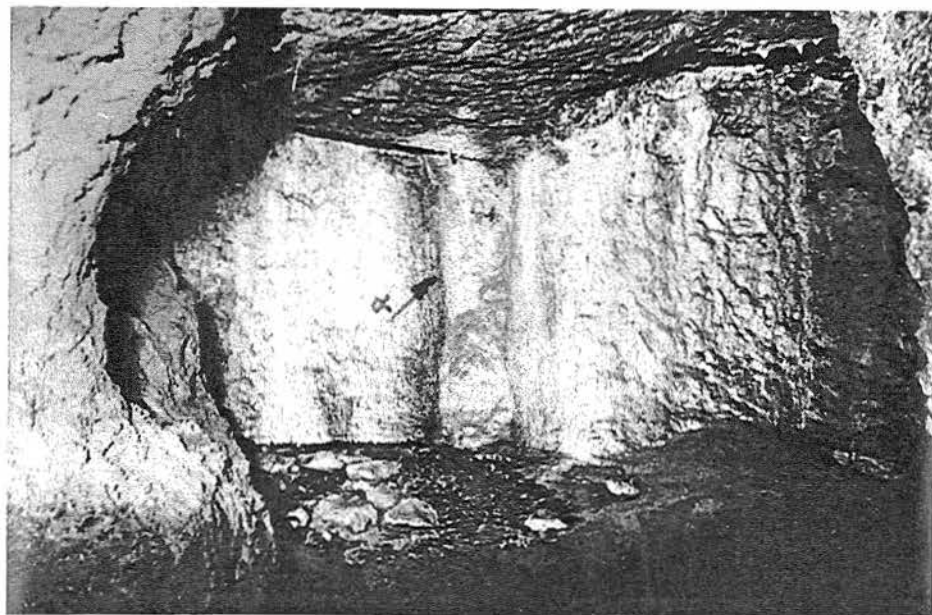


Fig. 1 Enlarged gallery in the ancient Lavrion mines.

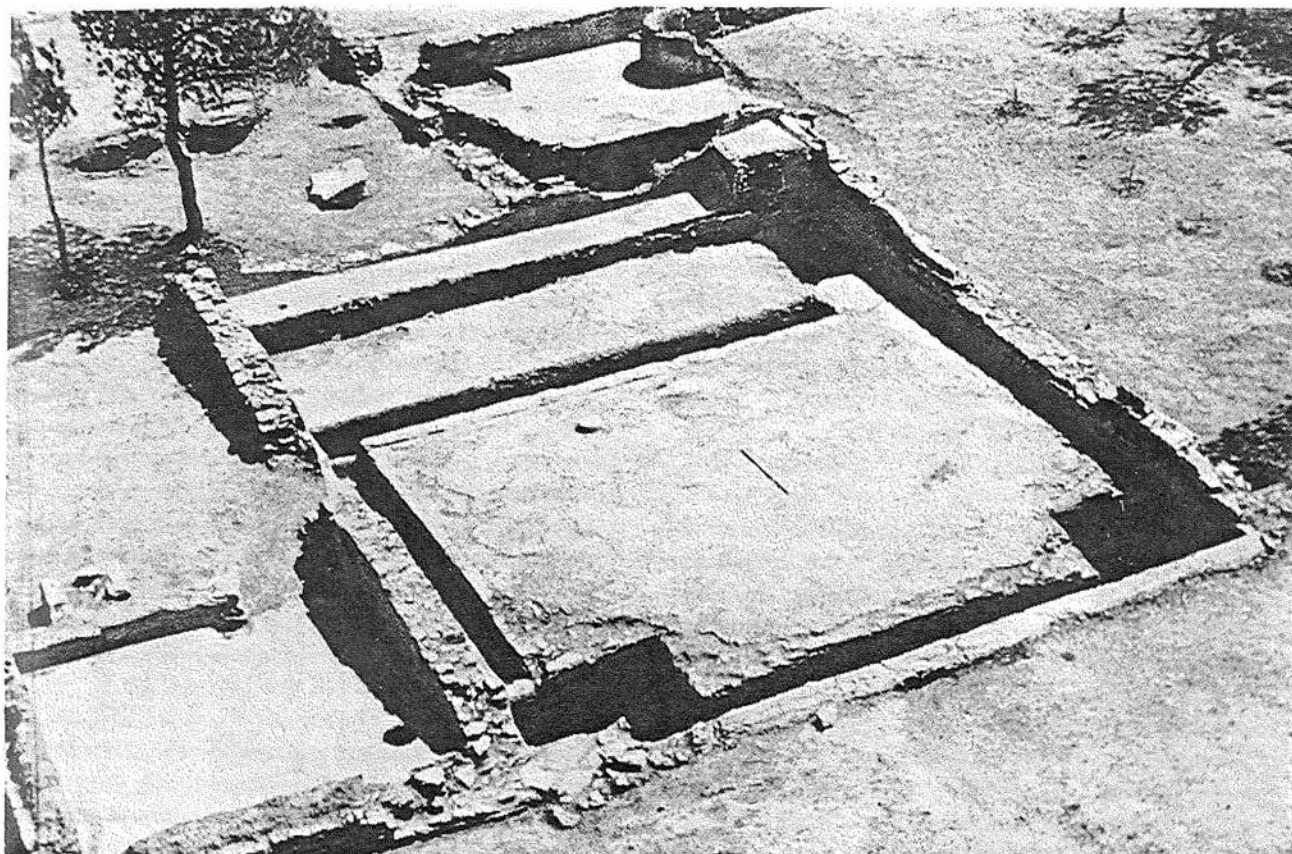


Fig. 2 Rectangular washery

some 2500 years later in the U.S. by Simon, who developed the well-known Simon's cone. In the meantime, it was widely used to grind corn in Pompeii up to 79 AD.

The next stage of ore processing was to wash the fine-milled ore in a flow of water in order to separate the heavier grains of ore from the lighter grains of sterile rock. This way, a classification by gravity occurred and the ore was cleaned and concentrated, making it ready for smelting. For this purpose two main types of washeries were used: The level, rectangular one (see Fig. 2) which was the most common and the helicoidal (spiral) one which was developed later, probably by the end of the 4th century BC (see Fig. 3). There are many rectangular washeries scattered around the Lavrion area, but only a few have been uncovered, cleaned, and maintained. The method of operation was as follows: Water was allowed to flow through the funnel holes out of the main water tank and into wooden troughs (sluices) set in front of the tank on the washery's floor which was slightly inclined. The trough's bottom contained cup-like depressions (traps) where the heavier grains of the ore (finely ground ones were shoveled in the upper end of the trough) was concentrated. The water, still

containing some ore and the lighter sterile grains, first went into a transverse channel and then to consecutive channels and sedimentation basins. Lastly, the water was freed from all the ore and sterile rocks and, once clarified, was redirected into the water tank to refill it. The contents of the troughs were emptied and allowed to dry, whereas the contents of the channels and basins were emptied and disposed of, forming various piles.

Repetition of the process might be necessary to obtain maximum recovery of the argentiferous ore. There was a big problem with the water supply because the Lavrion region was and is one of the driest areas of the country. That is why the sparse seasonal rainwater had to be collected and conserved in large round or rectangular cisterns to be used all year. In the helicoidal washeries water and ground ore was introduced at one end and, due to the form and inclination of the helix, the water carried the material from trap to trap depositing first rich ore, then poorer ore and finally sterile rock, reaching a lower tank in a clarified state to be used again. The trough was cut into the upper surface of a series of large stone blocks set side by side.

It was an ingenious and amazing achievement. Its



Fig. 3 Helicoidal (spiral) washery

principle was "invented" again 2300 years later by Humphrey with his well-known "spiral concentrator." It is worth writing a few words concerning another remarkable achievement: the various mortars were used for the lining of surfaces coming in contact with water to make them impermeable to avoid leakage. As was proven, these mortars contained considerable amounts of PbO , Fe_2O_3 , ZnO , and MnO and were applied in three consecutive layers. Even today they are remarkably well preserved and present a complete example of impermeability.

Recently, two additional helicoidal washeries, which do not contain traps (riffles), were discovered in Lavrion. They were probably used for the treatment of poorer ores. It must be noted that every helicoidal washery was located very close to a rectangular one. Furthermore, there was another startling discovery. Pieces of stones and sluices were found in Macedonia that probably date from the 4th century BC. If in the final analysis they are remnants of helicoidal washeries then a transfer of technology took place from Lavrion to other Greek mines in the ancient world.

SMELTING, CUPELLATION, AND RESMELTING OF THE LITHARGE

The enriched, concentrated ore was next taken to the furnace for smelting in order to recover the argentiferous lead in a metallic state. The ore was subjected to smelting under reducing conditions in vertical furnaces using charcoal as the reducing agent. The furnace had an inside diameter of about one meter and its height probably did not exceed four meters. Its structure consisted of micaschist, and the internal walls were lined with fire clay. The operation was continuous. The furnace was fed from the top with a mixture of ore (mainly oxidized ores and eventually small amounts not exceeding 15% galena) and charcoal.

The necessary air was pumped in with the aid of hand blowers and a temperature of from 1000° to 1200°C was reached. The produced metal as well as the slag emerged from a taphole near the floor. The molten metal produced in these furnaces was a mixture of lead and silver. In order to separate these two metals, they used cupellation furnaces. Air was pumped in vigorously with the aid of blowers and, in the heat produced by burning wood, the lead was oxidized to lead-oxide (PbO) or litharge, leaving the silver in a molten state of its own. The process required special cupels consisting of suitable refractory materials.

Cupellation was done at a temperature of from 900° to 930°C and when the silver appeared the temperature was then increased to at least 960°C . The whole process was very delicate. The quantities of the metal to undergo cupellation were very large and the silver content relatively low. This process was absolutely necessary to attain excellent recovery of silver since litharge was later resmelted to produce metallic lead and, therefore, any amount of silver contained in it was a definite loss. Further heating of the litharge in a furnace similar to one used for smelting the ore could reduce—with the aid of charcoal—the lead oxide and produce lead metal again for commercial use.

MINING RIGHTS AND THE LABOR FORCE

The mines of ancient Lavrion belonged to the state. Any free man could obtain a concession by paying the proper fees to lease a certain mine, or even a certain gallery, for three, seven, or ten years, depending on the conditions that prevailed in the works. It seems that there were many operators as suggested by the

plates found on the site. These operators could also have been owners of washeries and smelting furnaces.

According to estimates, there were about 11,000 workers employed during the 5th century BC in the major Lavrion area, producing 20 tons of silver per year. Some of the workers, especially the supervisors, lived near the mines in rooms having baths and showers and other facilities. There were also slaves working at the mines. Their standard of living was tolerable. If they proved very capable they could be promoted to higher positions.

INFLUENCE OF MINING AND METALLURGICAL ACTIVITIES ON ANCIENT GREEK CULTURE AND CIVILIZATION

Much of the silver of the Lavrion mines was taken to Athens to be minted into coins by the state, while a good portion was exported. The lead--1.4 million tons was produced--was also used for domestic and commercial purposes. Copper was also a valuable product of the district, whereas iron was used for making necessary tools. During the archaic and classical periods of Greek history, operations related to mining and metallurgy undoubtedly played an important role in the creation of ancient civilization, and at the same time helped Greece to confront its various enemies successfully. It is well known that a sudden peak in the production of silver in Lavrion helped Themistocles, for example, to build a naval fleet that won the Battle of Salamis in 480 BC. This great sea victory eventually contributed to the creation of the Athenian Empire.

It must also be noted that by the middle of the 4th century BC, Philip, king of Macedonia, initiated the intensive exploitation of the gold and silver deposits of Paggaion Mountain. This great wealth allowed him to create his own empire that he handed down to his more famous son, Alexander the Great, who conquered expansive kingdoms in the Near East from 334 to 323 BC. The influence of mining on the development of Classical Greece was overwhelming. The wealth allowed for the creation of the Golden Age of Pericles' Athens, the construction of the tem-

ples and mosaics of Pella in Macedonia, and the erection of glorious monuments such as the Athenian Acropolis, all of which made a lasting imprint on Greek society and culture as well as the rest of the Hellenized world.

Apart from its other claims to fame, Classical Greece can attribute much of its glory to individual achievement, assuring the nation a place among the Great Ages of humankind. The miners of Lavrion during the ancient period had almost nothing. They had no doctors to cure them, and no drugs to fight their illnesses. They had no power to help reform their work, and they had no recreation aside from a drama play in an open air theater. They had only their brawn and their brains.

In the eternal darkness of the underground workings they had a flickering light to help them extract the valuable minerals. To overcome these unfavorable odds, they had a power and a will that shadowed them and led them to their destiny: the light of progress.

REFERENCES

- Ardaillon, E. "Les mines de Laurium dans l'antiquite," Paris: Fondeoing Ed., 1897.
- Campesy, A. "Le Laurium," Paris: Rev. Univ. des Mines, No. 6, 1889.
- Conophagos, C. "Le Laurium antique et la technique Crecque de la production de l'argent," Athenes, 1980.
- Cordellas, A. "Le Laurium," Marseilles, 1869.
- Crosby, M. "The leases of the Laurium Mines," *Hesperia* v. 19 (1950).
- Healy, J. "Mining and Metallurgy in the Greek and Roman World," London: Thames and Huston, 1978.
- Ledoux, C. "Le Laurium et les mines d'argent en Grece," *Revu des deux Mondes* v. 13 (1872).
- Mussche, H. "Thorikos: A guide of the excavations," Bruxelles, 1974.
- Negris, P. H. "Laveries anciennes du Laurium," *Annales des Mines* Paris (1881).
- Rangabe, M. "Du Laurium," Paris: Imprimerie Nationale, 1870.