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Roads to riches: making good the silver ore at Lavrion in Greece

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It is well known that the strategic power of ancient Athens rested on its formidable navy, but the value to the Athenians – and later to the Romans – of the silver mines of Attica is less well understood. The Institute's newly appointed Professor of Archaeological Materials and Technologies describes his investigation of the impressive ancient mining installations that survive near Lavrion in southern Attica.

The defeat of the Persians by the Greek fleet at Salamis in September 480 BC was a turning point in Greek, and indeed in European, history. Ancient historians, particularly Herodotus and Plutarch,[1] attributed the Greek triumph to the decision taken three years earlier by the then leader of the Athenians, Themistocles, to spend the city's revenue from its silver mines on building the fleet. The silver mines were situated west and south of the ancient site of Thorikos and the modern town of Lavrion on the Attica peninsula south of Athens (Fig. 1). Mining continued there from the Bronze Age to the late Roman period and was resumed for more than a hundred years from the early nineteenth century AD, first with large-scale reworking of the surface remains of former mining, followed later by extraction of the deep ore left behind by the ancient miners.

The surface remains of the ancient mining aroused considerable interest among modern miners, and subsequently historians and archaeologists, particularly because of the spectacularly well preserved installations that were used in the fourth century BC to separate the ore from the waste rock that was inevitably mined with it. These ore washeries (Figs 2, 3, 4) used the difference in the specific gravity of (heavy) ore and (lighter) rock to separate the two, once they had been crushed and ground to sand. This separation was achieved by the action of water flowing down a gentle slope, pushing the lighter rock farther down than the heavier ore particles, which stayed behind, thus concentrating the metal-rich mineral. Water resources were limited in the dry climate of Attica and careful management of the water supply was required to keep these installations running. The ore washeries comprised a sophisticated system of huge primary water cisterns that collected rain from the surrounding areas (Fig. 5), and secondary tanks that provided a constant supply of water for the actual washing operation. Once used in the process, the water was recovered for re-use by means of small channels surrounding the working and drying platforms, with settling tanks to clean it from any mud and other residues (slurry) (Fig. 4).

Figure 1 *Southern Attica, showing the location of the remains of ancient mines and other metallurgical installations.*

Identifying the ore

Because of the heavy disturbance of the ancient mining landscape by modern activity, both on the surface and underground, it is difficult to identify the actual ore that was mined and smelted by the ancient Greeks. The problem can be approached theoretically and by analyzing the remains left by mining. Both C. Conophagos and H-G. Bachmann, with extensive knowledge of the technology of ancient and modern lead and silver smelting, have done this – and have come to contradictory conclusions about the ore that was used.[2] They agree that the ore deposit consisted initially of galena (lead sulphide), which contained small quantities of silver, but they disagree over whether the ancient Greeks actually smelted this primary mineral.

The question is whether, instead, the ancient miners may have exploited cerussite (lead carbonate), a secondary mineral that forms during weathering and is much easier to smelt. Also, little is known about the percentage of silver in the ore that was exploited. The ore deposit that is known and accessible today has a wide range of silver concentrations in the ore, and on this basis Conophagos estimated that the average silver content of the lead metal was about 0.1–0.2 per cent.[3] However, a general problem when studying ancient mining is the fact that no ore deposit is homogeneous throughout, and it is difficult to assess the composition of the ore that was actually mined. Any material left behind by the ancient miners is likely to have been of no interest to them, and therefore different from what they actually exploited.

To gain the silver from the lead ore, a two-step process is necessary. First the ore

Figure 2 *An excavated ore washery (approximately 4 m wide), viewed from where the water tank would have been, overlooking the working floor (front) and the drying floor (centre). The surrounding channel that collected the water from the drying floor for re-use is clearly visible.*

Figure 3 *A corner of an ore washery excavated by C. Conophagos, showing (left) the remains of the tank that supplied water for the washing operation that was carried out on the working floor (front centre). The settling basin (centre) still holds enough water to allow swamp grass to grow in it permanently. The channel (front right, approximately 20cm wide) separates the working floor from the drying floor (to the right, out of view).*

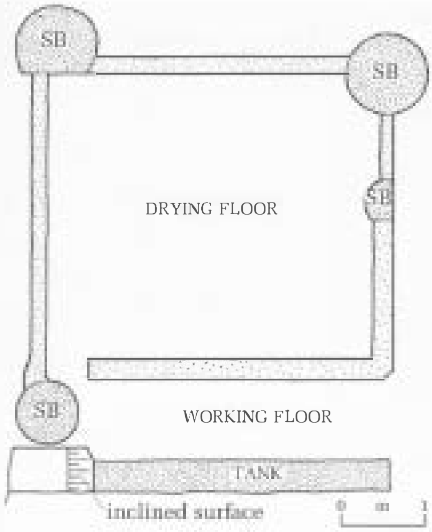

Figure 4 *Plan view of an ore washery. The water flowed from the tank onto a (inferred, probably inclined) wooden structure where the ore was washed by workmen standing on the working floor, which had a watertight plaster surface (often still preserved). After the concentrate containing the lead had been separated from the debris, the water was collected in the surrounding shallow channels for recycling, flowing slowly counterclockwise around the installation. Several settling basins (SB) over a metre deep allowed the mud and fine slurry to settle out. The final basin (front left) provided clean water, which was lifted by bucket and transferred to the tank via an inclined surface in order not to unsettle the water in the tank.*

is smelted to produce a silver-rich lead and a slag (which is discarded). In the second process, called cupellation, the lead metal is burned at high temperature with a strong blast of air in the furnace, leaving behind, untouched, the precious silver metal. Cupellation produces 99 per cent pure silver and vast amounts of lead oxide or litharge.

The first aim of our research, which is conducted in close cooperation with the Belgian School of Archaeology in Greece and the local Greek archaeologists,[4] was to determine whether the ancient Greeks obtained their silver from galena or cerussite. My approach was to sample remains of the ore-dressing activity from the ore washeries for detailed microscopic analysis. These remains are known to contain up to 10 per cent of lead, left behind by the necessarily incomplete separation of ore and rock minerals. They represent the actual material that was processed, although in varying proportions of rich mineral and waste rock. The microscopic investigation demonstrated that it was indeed galena that was mined in antiquity, although it had weathered since then to cerussite (Fig. 6). The microscopic analysis also explained the contradiction between the conclusions of Conophagos and Bachmann. The original grain structures, and the remains of galena in the centre of these grains, prove that the cerussite formed only after the crushing and washing of the ore, that is, while the material was buried in the soil over archaeological, rather than geological, periods of time. Thus, although today the ore mineral consists mainly of cerussite, it was clearly galena when it was mined, crushed and smelted.

A surprising discovery

Thus far, the research had produced a straightforward answer to a straightforward question. Furthermore, a detailed geochemical and mineralogical investigation of the ore remains enabled two types of ore, with different silver levels and different types of impurities, to be distinguished. Then examination of some of the samples led to a surprising discovery. Several of the installations had apparently been used not only to work the local ore

Figure 5 *Part of a system of cisterns used to collect water from the surrounding area for use in the washeries. Water flowing from the hill behind was channelled into a first cistern (front centre), from where it overflowed into the main cistern (left). The main cisterns were typically about 10 m deep and even larger in diameter, and they appear to have been roofed (often with a central column supporting the roof) to reduce evaporation in the hot climate and contamination from windblown dirt.*

but also to process finely crushed litharge. Previously, litharge was considered to be just the final waste product of silver recovery from argentiferous (silver-bearing) lead, although it was sometimes re-smelted to lead for a variety of mundane purposes.

However, the evidence is there. Although it is a waste product, litharge was processed with considerable effort and sophistication, in a manner previously known in antiquity only for the treatment (beneficiation) of ore. There are three possible explanations for this. Either it was processed to gain the last traces of silver still mechanically trapped in it, or it was concentrated prior to being smelted for lead, or it was washed to produce pure litharge for medical purposes.[5] These three possibilities are discussed below.

The recovery of silver from litharge

In theory, silver can be chemically separated from lead almost completely, by selectively oxidizing the latter, but in practice a little lead (of the order of one per cent) always remains in the silver, and also some silver is lost in the litharge. This is mostly because tiny crystals of silver are mechanically trapped in larger lumps of litharge or in droplets of silver-rich lead that happened to penetrate into cracks and voids in the lining of the cupellation furnace. As late as the nineteenth century AD, metallurgical textbooks warned about this latter possibility and emphasized the need to prepare the furnace lining carefully.

Even if such loss cannot be completely prevented in the first place, there is another method by which it can be reduced. The density of metallic silver, and of argentiferous lead, is in the order of 11 grams per cubic centimetre (g/ccm), as compared to that of litharge of just over 9 g/ccm (for comparison, the density of water, which is the standard by which other densities are defined, is 1 g/ccm). This difference is enough to allow a mechanical separation of the metallic silver from the litharge, using the same methods that were used by the ancient Greeks to separate the ore, which has a density of about 7.5 g/ccm, from the worthless mineral, which on average is only half as dense. The separation may have been further augmented by the different forms of the two materials, with the metal inclusions being likely to consist of droplets or small lumps and the litharge of platy flakes and crystals. Flowing water would thus have a greater impact on the relatively larger surfaces (per volume) offered by the litharge as compared to the relatively smaller surfaces of the metallic droplets. However, the absolute amount of silver that could be gained from this extra step in refining is small. It is generally assumed that cupellation left behind not more than about 100–150g of silver per tonne of lead oxide. This equals about 10 per cent of the initial silver content of the ore, and it is unlikely that much of this could have been recovered by mechanical separation.

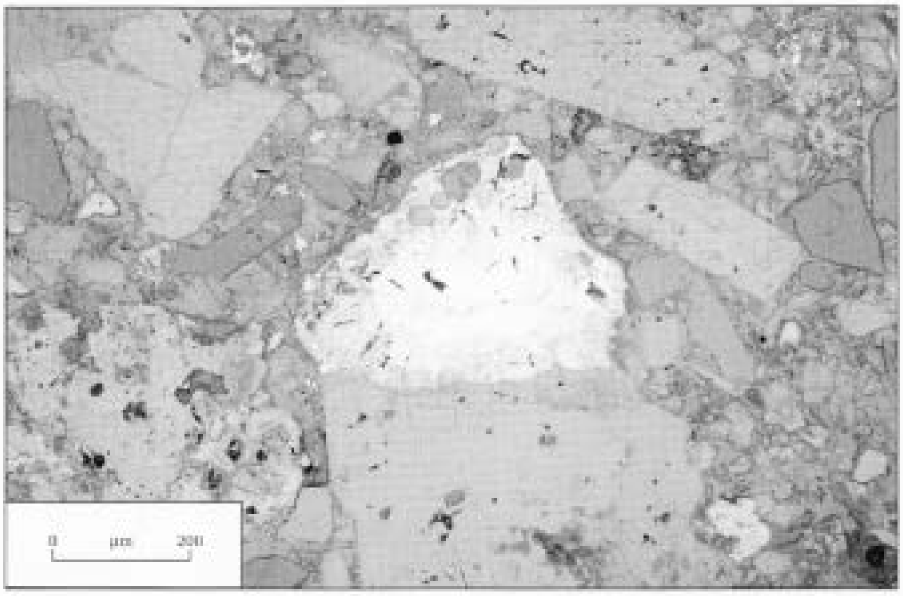

Figure 6 *Micrograph of a thin section of the remains of the ore washings. The mineral grains were crushed to less than 1 mm in diameter and are now cemented together by a fine matrix of soil and dust. The grain in the centre consists of galena that has weathered to cerussite around its periphery. This frequently found phenomenon – a core of galena surrounded by cerussite – is interpreted as evidence for the processing in antiquity of pure galena (lead sulphide) in these installations. The cerussite, which dominates the mineralogical composition of these lead minerals today, was formed by weathering over the past 2500 years since the ore was crushed, resulting in the constant core–periphery relationship of galena and cerussite in these grains.*

Smelting litharge to lead metal

Of the three possibilities mentioned above, re-smelting it to obtain lead is usually regarded as the reason for processing litharge, and it is generally accepted that this was done in antiquity. The use of lead metal in the classical period is well attested. It was used mostly for architectural purposes such as casting lead around iron clamps when joining building stones, for hinge sockets, or in plumbing of all kinds. However, it is difficult to understand why such an effort should have been made to gain finely crushed powdery litharge of high purity, as was the case in the washeries. The cupellation process initially produces solid lumps of lead oxide that are much more suitable for feeding back into a smelting furnace than any dust-size powder. Furthermore, most of this material would have been at least technically pure, with less than 10 per cent by weight of silica, lime and other impurities. Thus, if one wished to produce lead, it would have been best to smelt these lumps straight away and avoid laborious crushing and washing of the litharge. Although the large-scale re-smelting of litharge may account for the general scarcity of this material in the archaeological record of the Lavrion region, it appears an unlikely explanation for the occurrence of it in the ore washeries.

Litharge for medical purposes

The third, and possibly the most likely, explanation for the processing of litharge is to be found in texts of the first century AD by Dioscorides of Anazarbos and Pliny the Elder, who discuss the preparation of litharge for medical and cosmetic purposes.[6] They both state that the litharge of Attica is excellent and the most favoured, followed by that from Spain (another famous silver-producing region of classical antiquity). From the recipes given, it is clear that the litharge had to be used as a fine powder, which was washed and boiled extensively in water and mixed with a variety of organic materials, including wheat and barley grains. The boiling in water was probably done to produce a fine slurry, as well as to help transform some of the lead oxide into hydrous compounds, which are more effective as antiseptic substances in that form; the wheat and barley, cooked with the litharge and afterwards ground "in mortars for six days",[7] would have produced a porridge-like substance, which acted as a carrier for the litharge (like today's vaseline-based ointments).

Conclusion

Only two of the three possibilities mentioned appear to be realistic. The recovery of silver metal from litharge is one possibility, given the expertise in mechanical methods of beneficiation that was available. The small grain size to which the litharge was crushed certainly would have allowed the release and recovery of much of the silver trapped in it.

The other possibility is the preparation of medical litharge of high quality. This may well have involved, and benefited from, a thorough washing of the primary ingredient in order to remove any sand or coarse contamination by soil and mineral particles prior to the preparation of the medicinal materials. The textual evidence for the supreme reputation of medical litharge from Attica favours such an interpretation. However, a problem arises from the chronology of events. The ore washeries are mostly attributed to the classical period, essentially to the fourth century BC. The texts come from the first century AD, almost half a millennium later, when the Romans were re-working the mining remains on a large scale, including the re-smelting of slags from previous periods. There is even evidence for the refurbishment of some of the washeries in Roman times, complete with Roman mosaics.

Future research will have to address this question of the chronological relationship between the processing of litharge and that of primary ore. Were both done at the same time, over a period of almost 500 years? Or did the exploitation of litharge for medical purposes, or its re-working to recover the last remains of silver metal, take place mainly in the Roman period, when easily accessible sources of ore had been exhausted and only a pale shadow of the earlier mining and metallurgical activities survived, based on the scavenging of the waste left by the ancient Greeks?

The investigation of some seemingly uninteresting sediment samples from the ore washeries in southern Attica has enabled a longstanding question in the study of ancient metallurgy to be conclusively answered. The primary ore mined and smelted in classical antiquity was indeed galena, and the cerussite we find today in these remains is a result of subsequent weathering. Most interesting, however, is the identification of two different types of ore, one of which contains almost twice as much silver relative to lead mineral as the other, and the surprising discovery that litharge was regularly processed. The full interpretation of these new findings will be possible only when and if a closer chronological resolution of the sequence of activities in the Lavrion region becomes available, and after a detailed match is made of the geochemical peculiarities of the ore types with the local economic geology. But already a new and more complex picture of the economic history of the region has emerged. The search continues for the various roads to riches pursued in antiquity in southern Attica.

Notes

1. See book VII, pp. 457–8, in *Herodotus*, H. Cary (London: George Bell, 1875) and pp. 11–15 on Themistocles in *Plutarch lives*, translated by B. Perrin (Cambridge, Massachusetts: Harvard University Press, 1914).
2. See C. Conophagos, *Le Laurium antique* (Athens: Ekdotike Hellados, 1980) and H-G. Bachmann, "Archäometallurgische Untersuchungen zur antiken Silbergewinnung in Laurion", *Erzmetall* **35**, 246–51, 1982.
3. See p. 280 in C. Conophagos (cited in *n.* 2).
4. I wish to acknowledge the unfailing cooperation during the fieldwork of my colleagues Professor H. Mussche and Dr D. Vanhove of the Belgian School and of Dr Oikonomakou of the local Ephorate.
5. Th. Rehren, D. Vanhove, H. Mussche, M. Oikonomakou, "Litharge from Laurion – a medical and metallurgical commodity from South Attica", *L'Antiquité Classique* **68**, 299–308, 1999.
6. J. M. Riddle, *Dioscorides on pharmacy and medicine* (Austin: University of Texas Press, 1985) and pp. 81–5 of book 33 in Pliny the Elder, *Natural history* IX, *Libri xxxiii–xxxv*, translated by H. Rackham (London: Heinemann, 1952).
7. See p. 83 in Pliny the Elder (cited in *n.* 6).