

Ores from the ore washeries in the Lavriotiki

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Abstract

The Lavriotiki, the south-eastern part of Attika in Greece, is one of humankind's most famous silver mining regions. The most impressive evidence for this activity today are remains of c. 250 ore washeries, installations used to concentrate the ore. These ore washeries comprise by far the best evidence for the beneficiation of ores in Antiquity, most of them dating to the Classical period. The separation of the primary ore into metal-rich concentrate and waste minerals or tailings exploited the density difference between the various mineral constituents of the ore, and was most certainly achieved through a washing activity using running water. The industrial scale of the operation and the vast quantities of water necessary in its conduct required a careful management of water supplies in a semi-arid environment. It is primarily the installations for water management which survived until today, allowing to reconstruct the actual ore washing activities.

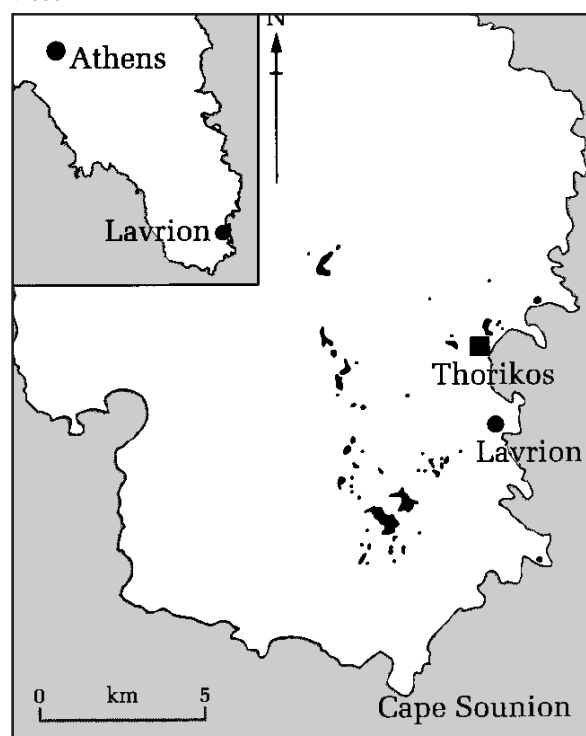
This paper focuses on the physical remains of the ore as found within the washeries in an attempt to elucidate the mineralogical nature of the primary ore, some operational details of the beneficiation process, and the quality of the concentrate. To this end, published data from a number of excavations in the Lavriotiki is combined with information accumulated over the last few decades during regional field surveys, two dedicated study seasons in 1996 and '97, and analyses of selected samples from several ore washeries. It is demonstrated that the ore was mined in Antiquity as galena, which since then has weathered almost completely to cerussite. The characterisation of the ore samples made it possible to identify two different ore types, with about 1000 and 2000 grams silver per ton of lead, respectively. In addition, the processing of cupellation residue in several of the washeries could be demonstrated. The system of channels, platforms and basins which make up most of the ore washeries is shown to serve exclusively the water management, with the beneficiation activity proper being restricted to a device, probably made of wood and now lost, situated in front of the water tanks.

Zusammenfassung

Die Lavriotiki, d.h. die Region um Laurion im Südosten von Attika ist eines der berühmtesten archaischen Silberreviere. Die Ausbeutung der Lagerstätte erstreckte sich von der Frühbronzezeit bis in die Proto-Byzantinische Epoche und erlebte eine Renaissance vom mittleren 19. Jahrhundert AD bis in das ausgehende 20. Jahrhundert. Der Höhepunkt der Aktivität lag im 5. und 4. vorchristlichen Jahrhundert. Noch heute zeugen eindrucksvolle Reste von ca. 250 Erzwäschen aus dieser Periode von dem einstigen Umfang der Erzgewinnung. Diese Erzwäschen sind

Fig. 1: The situation of Laurion and Thorikos in the south-eastern part of Attika, Greece. Black are the major ore outcrops.

Abb. 1: Die Lage von Laurion und Thorikos im Südosten von Attika, Griechenland. Schwarz sind die wesentlichen Erzausbisse.



die bei weitem besterhaltenen Beispiele antiker Erzaufbereitung. Die Erzaufbereitung in der Antike erfolgte durch eine Dichtentrennung des fein gemahlten Erzes unter Ausnutzung fließenden Wassers. Das industrielle Ausmass der Aufbereitung und die dazu nötigen Wassermengen erforderten ein sorgfältiges Management der Wasservorräte in dieser semiariden Region. Die zahlreichen Zisternen und die besondere Bauweise der Waschanlagen legen hiervon noch heute ein eindrucksvolles Zeugnis ab.

Dieser Beitrag konzentriert sich auf die Untersuchung der tatsächlich in der Antike aufbereiteten Erze, deren Identität Gegenstand widersprüchlicher Aussagen in der wissenschaftlichen Literatur ist. Hierzu verbinden wir publizierte Informationen von einer Anzahl von Ausgrabungen in der Lavriotiki mit Daten unserer eigenen Geländearbeit und Laboruntersuchungen aus den Jahren 1996 und 1997. Das Erz wurde in der Antike als Bleiglanz gewonnen und aufbereitet, hat sich aber seither durch die Verwitterung des feinkörnigen Materials weitgehend zu Cerussit umgewandelt. Dabei konnten zwei unterschiedliche Erztypen identifiziert werden, die sich durch ihre Silbergehalte von rund 1000 bzw. 2000 ppm, bezogen auf den Bleigehalt, und die Art der Begleitminerale unterscheiden. Zusätzlich konnte nachgewiesen werden, dass auch Kupellationsrückstände in einigen der Wäschereien aufbereitet wurden. Das System von Kanälen, Plattformen und Basins, das gemeinsam die einzelnen Wäschereien ausmacht, diente ausschliesslich dem Wassermanagement, während die eigentlichen Aufbereitungsanlagen, die vermutlich aus Holz bestanden und vor dem Haupt-Wassertank standen, nicht erhalten sind.

Introduction

The Lavriotiki consists of the mountainous south-eastern part of Attika (Fig. 1), from ancient Thorikos and the modern town of Laurion in the east to Sounion in the south. Its western border is defined by a distinct north-south running valley between the granitic intrusion at Plaka in the north and Legrana in the south. Rich mineralised contact zones between various stratigraphic units are exposed in the slopes and valleys cut into the highland. Periods of metallurgical activity span the Early Bronze Age to the Proto-Byzantine period, and again the last third of the 19th and most of the 20th centuries AD. Its heydays, however, were during the Classical period, during the 5th and 4th centuries BC, although there is also evidence for activity in the Hellenistic and Roman period. Indirect evidence, such as lead isotope studies of metal artefacts, indicates the extraction of significant

quantities of metal, both silver and possibly copper, from the Early Bronze Age onwards.

The particular fame of the Lavriotiki as a mining district rests on the role which the rich revenues obtained by Athens from the mining activity played in building the city's naval fleet, and the subsequent defeat of the Persian naval force at the battle of Salamis in 480 BC. The decision to spend the revenues on such a far-sighted investment rather than immediate consumption is credited by ancient authors such as Herodotus, Xenophon, Aristoteles and Plutarchus to the then leader of the Athenians, Themistokles. Other written sources give some details, of mostly legal content, of the organisation of the mining industry during the 4th century BC (Crosby 1950; Vanhove 1994), as preserved in a number of leases and several comments in political and private speeches, e.g. by Demosthenes. However, no significant ancient texts have survived about technological details of the mining industry.

The post-Classical activity is indicated by the new issue of Attic coinage in the 2nd century BC, the finds of Megarian vessels in Thorikos and the Lavriotiki as well as amphorae from Knidos, Kos and elsewhere, and type Lamboglia 2 amphorae, all dating to the 3rd to 1st centuries BC, and finally the forge in Thorikos, built up on the classical graves in the Metropolis.

In Roman times, according to Strabo in the 1st century BC, the Lavriotiki was a scarred, waste land, with only limited reworking of remains from earlier activities, and little of its former glory preserved.

But there was a revival, not only by mining, but also by re-furbishing and re-use of installations such as dwellings and ore washeries. In the Proto-Byzantine period (4th to 6th centuries AD) miners went again in the galleries in search for ore, as demonstrated by archaeological finds. Eighty lamps were found in Mine No 3 in Thorikos (Butcher 1982), and many others in dumps near extraction pits throughout the Lavriotiki (Vanhove 1994). This can be ascertained on an architectural basis and the material used, i.e. the masonry of the constructions and the stones used. For repairing the walls they used not any longer the freshly-cut white-veined local marble as used in the Classical period (Vanhove 1994), but the steril waste material from the mines, without dressing them, so that the joints of the walls are not any longer lined out neatly, but leave a rather careless impression. On many places, polychrome lead-glazed ceramic is scattered around the dwellings. After these workers stopped their activity in the Lavriotiki its glory was waning.

Such it remained for more than a millennium until the 1860s, when first Italian and later French mining entrepreneurs revived the local mining industry. Much of this mining aimed at the ancient remains, both tailings and slag heaps, which covered the landscape in vast quantities. Even after exhaustion of the

economically viable ore reserves in the Lavriotiki in the 1970s, smelting for lead, zinc and silver in Laurion continued for some more years, using the existing smelters to process imported ore concentrate. At present, the works of the former Compagnie Française des Mines du Laurion (CFML) are part of an industrial archaeological park, developed with much local support and a grant from the European Commission.

The identification in the mid 19th century AD of huge deposits of obviously artificial materials (e.g. Cordella 1864, 1869; Binder 1895; Ardaillon 1897; most of it summarised in Conophagos 1980) and the excavation of it during modern mining stimulated an early interest in the origins of these deposits. As so often (Weisgerber pers. com.), it was educated mining engineers who first recorded what they found, preserving at least some documentation before destruction. Academic interest in social, economic and legal aspects, primarily based on written sources, set in only about a century later (Crosby 1950; Lauffer 1979; Kalcyk 1982; Vanhove 1996). It was soon followed by archaeological surveys and excavations, first based on Ardaillon's earlier work (Cunningham 1967) and later on dedicated excavations (Mussche & Conophagos 1973; Jones 1988; Photos-Jones & Jones 1994). To the present day the definitive volume on the ancient mining industry of the Lavriotiki is written by a metallurgist, the late Professor Constantinos Conophagos (1980; Fig. 2).

In the absence of written sources on ancient metallurgical practice in the Lavriotiki, we have to rely in most parts on archaeological evidence to study, and hopefully understand, this past mining and smelting. What is this archaeological evidence? Remains of washeries and cisterns, dwellings and workshops, furnaces, sanctuaries and cemeteries, roads and tower complexes and so on. Despite the inherent flexi-

bility of archaeology to deal with practically all aspects of human's environment, live and death, a highly specialised and systematic approach based on team work is necessary to cover adequately technological as well as archaeological issues - the wish of the late C. Conophagos. Despite the recent developments in archaeology with all their technical and scientific underpinnings, and an abundance of published work on the Laurion, too much is still based on 19th century observations, and much more primary, i.e. field, research has to be done in the Lavriotiki (Weisgerber & Heinrich 1983).

This paper aims to contribute at least some fresh observations relating to long-standing issues, such as the nature of the ore mined in Antiquity, and the function of the washeries. The former is addressed by mineralogical and chemical analyses of tailings and other waste products excavated from a number of ore washeries and their surroundings. For this, we were able to sample materials from a number of collections in Germany and Belgium, and past and present excavations under permit by the second Ephorate of Prehistoric and Classical Antiquities and the archaeologist, Maria Oikonomakou, responsible for the whole area. The discussion of the function of the washeries is based on observations during two extended field surveys in the vicinity of Thorikos and the northern part of the Lavriotiki, and on published data from C. Conophagos' excavations in the 1970s (Conophagos 1980) and the recent British excavations in Agrileza (Jones 1984, 1988; Photos-Jones & Jones 1994). A further aspect of the project, carried out in collaboration between the Deutsches Bergbau-Museum in Bochum and the Belgian School in Greece: University Ghent with a grant from the Volkswagen-Foundation in Hanover / Germany, covered the landscape archaeology of the Lavriotiki and the setting of the various installations within the local environment. This will be dealt with in a separate publication elsewhere.

Fig. 2: Tomb of the late Professor Constantinos Conophagos and his wife, Evgenia, in Thorikos. The monument is built from lumps of slag from the modern metallurgical plant.

Abb. 2: Das Grab von Professor Konstantinos Konophagos und seiner Frau, Evgenia, in Thorikos. Das Denkmal ist aus Schlackenklötzen der modernen Htte errichtet.



The nature of the ore mined in Antiquity

The geology of southern Attika is well known, not least due to the economic importance of the ore deposits in the Lavriotiki (Marinos & Petraschek 1956) and continuing interest in the ore-forming processes involved in their formation. The primary ore, precipitated probably from a number of hydrothermal solutions and particularly enriched at the interfaces between different lithologies (primarily three 'contacts' between various marbles and schist and shale sequences), consists of galena and sphalerite with varying amounts of pyrite, chalcopyrite, and several minor sulphides in a matrix of gangue minerals such as fluorspar, quartz, calcite, siderite and others. The silver was found to be bound primarily to galena, partly as solid solution within the galena lattice, partly as discreet particles of rich minerals intergrown with the galena (Pernicka 1981). Inevitably, this primary ore weathered to some degree near the surface, to form a number of secondary minerals, notably cerussite, smithonite and malachite. The deposit is known to have produced during the modern mining period an ore of 20 to 60 wt% lead with between 800 and 3000 grams silver per ton of lead. It is generally assumed (e.g. Conophagos 1980; Bachmann 1982) that the mining during the Classical period was for the argentiferous lead mineral, containing about 0.1 percent silver, which was smelted to rich lead metal. From this, the silver was then extracted by cupellation.

Based on his experience as a metallurgist with the CFML and various analyses of tailings from the ancient beneficiation, locally known as *ekvolades*, Conophagos (1980) concluded that it was mainly cerussite which was mined and processed in Antiquity. Cerussite, or lead carbonate, is indeed easier to smelt than galena, lead sulphide, and would thus have been a suitable ore. H.G. Bachmann (1982) argues, however, that the chemical and mineralogical composition of ancient slags from the Lavriotiki strongly indicates the smelting of sulphidic ore, and that the prevalence of lead oxide over lead sulfide in the ancient *ekvolades*, cited by Conophagos (1980) as evidence for the use of cerussite, could well be due to weathering of the primary mineral subsequent to its deposition in Antiquity. A further issue in this context is the richness of the ore, *i.e.* the silver content relative to lead. Conophagos (1980) gives here a figure of about 1000 ppm, or 0.1 percent, again based on his experience with the modern workings. More detailed geochemical investigations of the Laurion deposit (Pernicka 1981), however, and experience with ore deposits in general, urge us to be cautious with such general statements. The silver content of the ore can vary to a great extent between different parts of a deposit, depending on the exact nature of

the mineralisation and possible alterations over geological times. Cordella (1869: 68) gives between 1200 and 3500 grams of silver per ton of lead for the Camariza ore, and 800 to 3000 grams per ton for 'irregular masses' of ore. Pernicka (1981) found silver concentrations relative to lead of between 500 ppm in the north of the deposit near Plaka, and 5000 ppm, *i.e.* about half a percent, in vein mineralisations just west of Thorikos. In a recent paper, Krysko (2001) discusses the possibility of very rich silver ore having been found in the earliest phase of the workings at Laurion; however, no direct evidence for such ore has been unearthed yet. But even within an individual working huge differences in the silver content of the ore are possible, as recently demonstrated for a medieval silver mine in Germany (Rehren *et al.* 1999a).

Theoretical considerations, as used by both Conophagos (1980) and Bachmann (1982) to support their mutually exclusive interpretations, allow us to explain most of the observations within the framework of either basic assumption; hence it appeared necessary to tackle the central, though 'almost laughable' (Weisgerber & Heinrich 1983: 196) issue of the ore type mined in Antiquity head-on, through a detailed microscopical investigation of the archaeological material preserved in the tailings. The analyses of ancient tailings, taken from secure contexts, guaranteed that we were studying material which was actually processed in Antiquity, rather than freshly mined ore either left behind by the ancients for economic reasons in the ancient galleries, or from parts of the deposit mined in the modern period only, and hence inaccessible to them altogether. We had, however, to take into account the weathering of the material over the last two and a half millennia, greatly facilitated by the small grain size of the crushed and ground material and hence its large reactive surface area. Therefore, microscopical studies were given preference over other phase-identifying approaches such as X-ray diffraction (XRD). This allowed us not only to identify the phases present, but also to interpret the microstructure of the material for effects of weathering, and possible remains of the primary structure.

The sample material

There were two major occurrences of remains of the ancient beneficiation processes, one being the massive *ekvolades* accumulated in Antiquity, the other much more small-scale scatters of tailings within the ore washeries themselves. The ancient tailing heaps, estimated in the 19th century to total several million tons, were thoroughly reworked in later periods for their residual lead and silver content. In particular the mining activity of the 4th to 6th and the 19th and 20th



Fig. 3a: Thick blanket of processing remains (dark brown) within the ore washery at the Property Mecha. Length of the nail (in the centre of the image) c. 6 cm.

Abb. 3a: Dicke Schicht dunkler Verarbeitungs- r ckstände innerhalb der Erzwäsche in der Property Mecha. Länge des Nagels (Bildmitte) ca. 6 cm.



Fig. 3b: Close-up of the layer of processing remains overlying the artificial floor of the ore washery. Length of nail c. 6 cm.

Abb. 3b: Nahaufnahme der Schicht von Verarbeitungs- r ckständen, aufliegend auf dem künstlichen Boden der Erzwäsche. Länge des Nagels ca. 6 cm.

centuries concentrated on these 'deposits' and eventually removed them almost completely, using then modern beneficiation and smelting techniques. Hence, they are now almost totally gone, and what is left behind may well have been re-worked and re-deposited once or twice. Weisgerber and Heinrich (1983) report one surviving occurrence in the Legrana Valley, and several others are said to exist in the Lavriotiki. However, due to the general scarcity of this type of material, and the seemingly insurmountable problems in their proper dating and allocation to a specific washery or mining district, they were thought to be less suitable for the intended study. In contrast, the material preserved within the ore washeries appeared to be much more promising, suggesting a close chronological and regional link between the period of use of the installation, and the material preserved within it. Initially, tailings were known only from a few - and unfortunately not yet completely identified - washeries, where they were found in the progress of excavations in such quantities that they attracted the attention of scholars interested in mining history. As such, they were added over several decades to various collections in Europe, including the Deutsches Bergbau-Museum, and provided the initial material for our investigation; subsequently, similar occurrences were uncovered in controlled excavations, e.g. by Maria Oikonomakou at the Property Mecha (Rehren *et al.* 1999b), where it covers one corner of the installation up to ten centimetres thick, equalling an estimated quantity of some 360 kg (sample LTH2; Fig. 3a, b), and within the ancient town of Thorikos where a small mound of this material was uncovered, comprising several hundred kilograms (Mussche 1968; samples LTO and LTU). Following

initial characterisation and the development of identification parameters, it became possible to visually identify this type of material in almost every ore washery excavated so far, typically as thin layers of rather limited extension at the working platform (Fig. 4), and occasionally on the drying floors as well. We were able to identify several of these among the samples taken in the 1960s from within the boundaries of the Thorikos excavation of the Belgian School. In addition, it was possible under the licence of the present project to sample a number of ore washeries excavated previously within the northern part of the Lavriotiki, and from current excavations of the second Ephorate under the direction of M. Oikonomakou. It

Fig. 4: Typical flimsy layer of processing remains preserved in an ore washery. Tip of shoe for scale.

Abb. 4: Typische Form d inner Verarbeitungs- r ckstände in einer Erzwäsche. Schuhspitze als Maßstab.



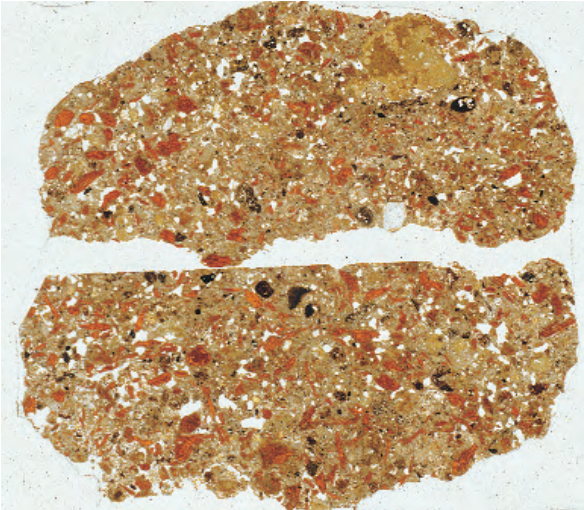


Fig. 5: Thin section through a sample of the third ore type. Note the frequent red specks of litharge. Width of image 3 cm.

Abb. 5: Dünnschliff durch eine Probe des dritten Erztyps. Die zahlreichen roten Partikel sind Bleiglätte. Bildbreite ca. 3 cm.

is this body of material from within the actual ore washeries which forms the core of the current scientific investigation of the ancient tailings. A detailed geographical discussion of the samples will be given within the forthcoming publication on the geomorphological aspect of the project.

The ancient tailings were macroscopically identified by their distinct sugar-like grain size and angular shape, a brownish reddish colour, and the prevalence of ore minerals such as fluor spar, lead minerals etc. when studied in the field with a hand lens or binocular microscope. Typically, the originally loose material had solidified over the millennia, adhering directly to the original surface of the floors of the washeries, cemented by a matrix of clay minerals, iron hydroxides and various carbonates. Differences in thermal expansion and weathering effects following the excavation of these washeries lead to the palling of the edges of these layers, often separating them from the underlying floor surfaces while retaining the initial texture of the anthropogenic sediment. In effect, the material is distinctly different from the surrounding geological soil, which has a much lighter yellow or *terra rossa* colour, a clearly different grain size distribution and well rounded grain shapes, and a very different mineralogical composition. Already during the fieldwork it became apparent that there are three different types of tailings, two relatively coarse ones and one rather fine-grained. The two coarse ones are separated by different gangue mineral associations, one being characterised by a high percentage of fluor spar crystals (see below). The fine-

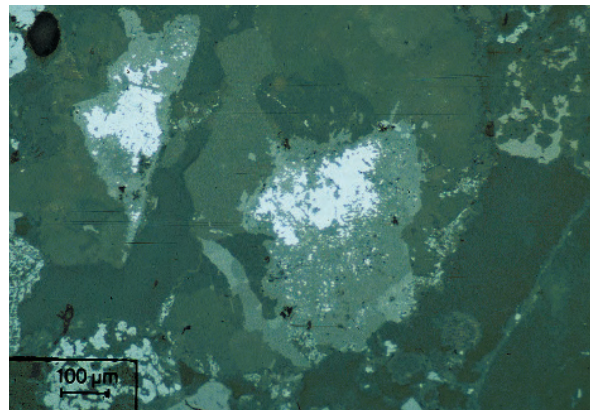
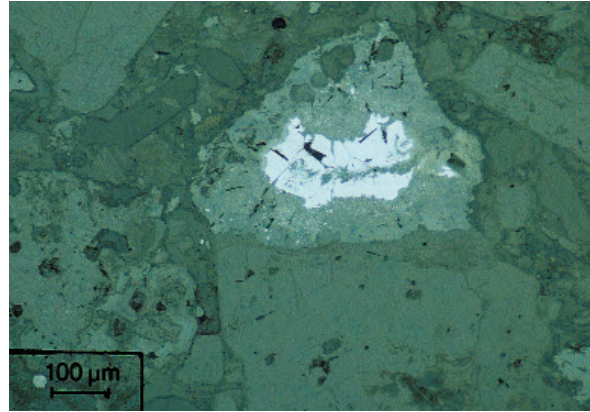
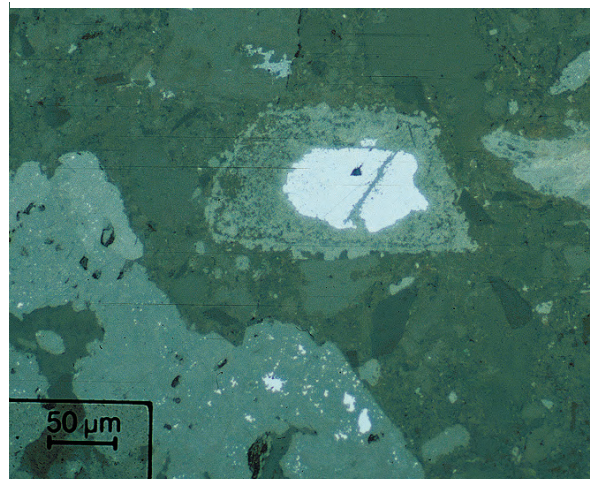


Fig. 6a, b: Galena as remnants in the core of a cerussite grain (centre), showing the progressive weathering of the sulfide mineral preserved in the microscopic texture of the crushed ore.

Abb. 6a, b: Bleiglanz als Relikt im Kern eines Cerussit-Korns (Mitte). Die Form zeigt die fortschreitende Verwitterung des Sulfidminerals im gebrochenen Erz.

Fig. 6c: Very clear example of galena (centre) surrounded by a homogenous layer of cerussite, clearly demonstrating that this transformation occurred only after the crushing of the ore.

Abb. 6c: Sehr deutliches Beispiel von Bleiglanz (Mitte) umgeben von einem gleichmässigen Saum von Cerussit. Das Gefüge ist offenkundig erst nach dem Brechen des Erzes entstanden.



grained type is characterised by the frequent occurrence of tiny bright red flakes within the matrix (Fig. 5). When present in large enough quantities, e.g. such as the massive infill of one of the washeries excavated by M. Oikonomakou at the Property Mecha or indeed the material from the Thorikos excavation, this third type is recognisably denser than the previous two.

Mineralogical results

The mineralogical work aimed to identify the nature of the ore processed in Antiquity; was it galena or cerussite? It was known from previous work, summarised by Conophagos (1980), that the ancient tailings contained on average still seven weight percent lead, and 140 ppm of silver. This clearly indicated that the beneficiation process as carried out during the Classical period was not quantitatively successful; indeed, even modern technology can not easily achieve a complete separation of ore into tailings and concentrate based on density differences alone. Inevitably, some of the rich mineral will remain with the tailings, while the concentrate will always contain some gangue minerals as well. In contrast to slags, where the smelting products are mineralogically and chemically very different from the initial ore, both the tailings and the concentrate will have qualitatively the same range of mineral phases present in the initial ore, though at quantitatively different proportions. This is the underlying rationale which allows us to mineralogically characterise the initial ore - and thus the concentrate - based on the study of the tailings.

The microscopical work hence concentrated on the identification of the rich mineral within the tail-

ings; based on an average lead content of seven percent by weight and a density of lead minerals of two to three times the density of gangue minerals, it was expected to find about two to three percent by volume (or area in the thin sections) of lead minerals. The investigation of the two coarse grained types of tailings confirmed this expectation; within a matrix of carbonatised clayey material we found an abundance of gangue minerals such as siderite, goethite, calcite, fluor spar, sphalerite, and the occasional grain of cerussite or galena. Very often, these lead mineral grains were of roughly isometric or euhedral shape, consisting of a core of galena surrounded by a layer

Fig. 8a-c: Litharge cake from Thorikos (top, scale in cm) and thin section from a similar fragment with silver-rich lead metal prill (Centre and bottom).

Abb. 8a-c: Bleiglätte-Kuchen von Thorikos (oben, Maßstab in cm) und D nnschliff eines ähnlichen Fragmentes mit silberreichem Blei-Tropfen (Mitte und unten).

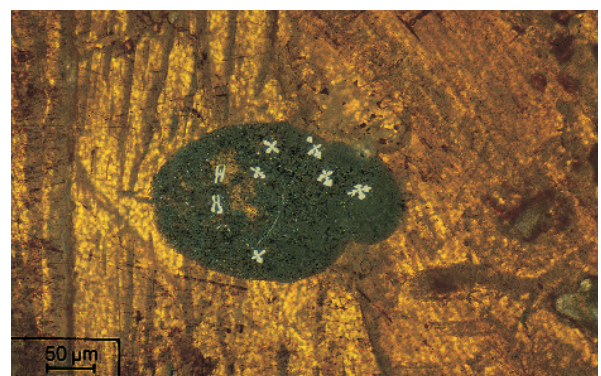
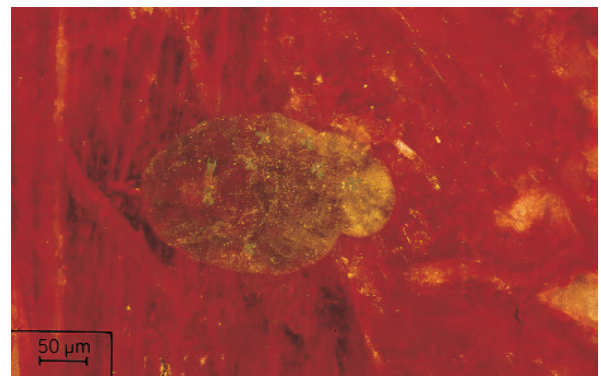
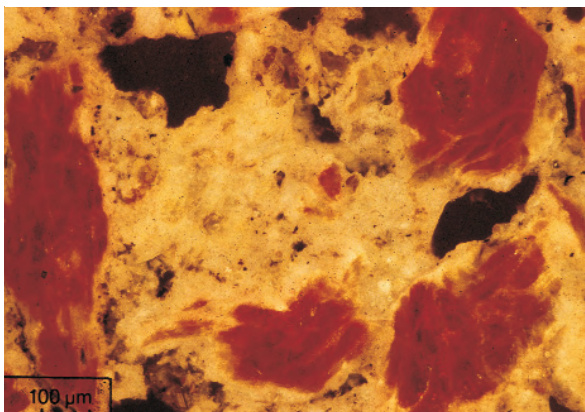


Fig. 7: Litharge crystals in a clay-rich matrix. Sample from an ore washery in the Thorikos region.

Abb. 7: Kristalle von Bleiglätte in einer tonigen Grundmasse. Probe aus einer Erzwäsche bei Thorikos.



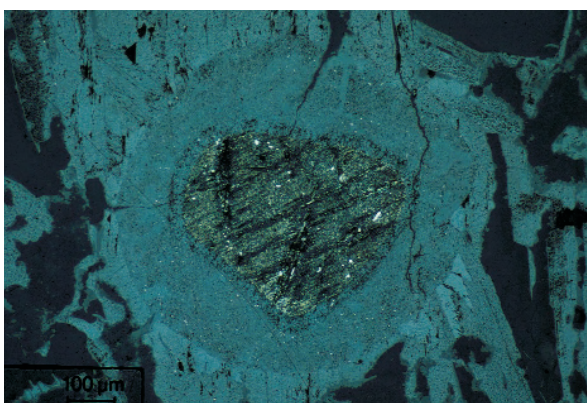
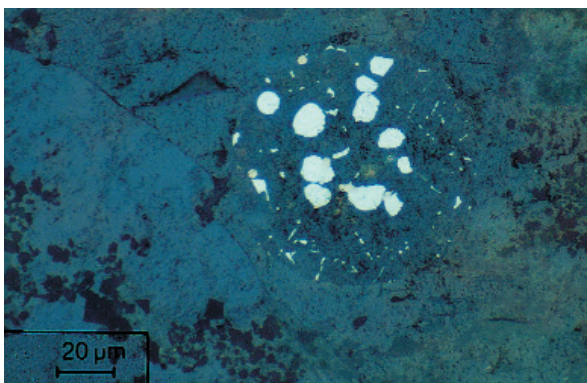
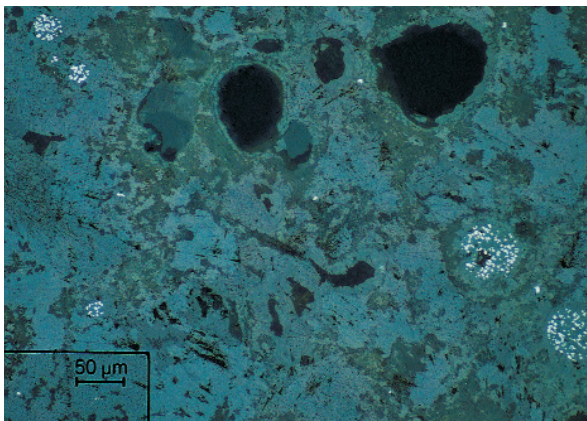


Fig. 9a-c: Scatter of mostly weathered droplets of lead, leaving behind a stippled network of silver metal in cerussite matrix. The original outline of the lead metal prill is still visible in the texture of the cerussite.

Abb. 9a-c: Gruppe von weitgehend verwitterten Bleitropfchen, erkennbar an dem punktförmigen Netzwerk von Silbermetall in einer Cerussit-reichen Grundmasse. Die ursprüngliche Form der Bleimetall-Tropfen ist in der Textur des Cerussits erhalten.

of varying thickness of cerussite. The interface between galena and cerussite is typically irregular, often with tiny islands of sulphide preserved in the inner parts of the cerussite layer (Fig. 6a, b), but not near the surface. This texture is interpreted as a clear indication that the ore mineral was mined, ground and beneficiated as galena. Massive aggregates of cerussite, a rhomboedric pseudo-hexagonal mineral,

would have fractured differently from cubic galena; furthermore, it would be highly unlikely that mixed aggregates of cerussite and galena would always fracture in such a way that a core of galena is surrounded by cerussite. Instead, it is assumed that the ore was crushed as galena, resulting in grains which subsequently weathered to cerussite during burial. This weathering was greatly facilitated by the crushing of the ore, providing a large surface area relative to the grain volume. Obviously, weathering would start at the surface and penetrate then towards the core of the grain, roughly preserving the initial shape of the grain, and a residual core in the centre (Fig. 6c). This weathering explains the apparent discrepancy between the early analyses of the tailings, cited by Conophagos (1980), to contain much more lead oxide than lead sulphide, or the more recent identification by XRD of cerussite in the tailings by Photos-Jones & Jones (1994) on the one hand, and on the other hand Bachmann's (1982) observation that the slags clearly indicate the processing of sulphidic rather than oxidic ore. The chemical and XRD analyses described the status quo, and can not take into account any weathering effect, which becomes visible only in the microscopic study. In this instance, even a firm identification of cerussite by means of X-ray diffraction as the dominant lead mineral would not allow an adequate interpretation. In effect, both are right: The tailings do contain now predominantly cerussite, and the slag was derived from the smelting of a sulphidic ore. As far as the situation in Antiquity is concerned, we can safely assume that the mining and smelting was for argentiferous galena, and only to a very limited extent possibly also for cerussite. So far, a straight forward answer to a straight forward question, proving correct an earlier theoretical suggestion put forward by H.G. Bachmann (1982: 250).

The investigation of the third type of macroscopically identified tailings, however, gave a surprising result. The main 'primary' lead phase present here is litharge, not galena (Fig. 7a, b), often weathered to cerussite, and embedded in a fine matrix of clay minerals, calcite and iron hydroxides. It has to be stressed that such litharge does not occur in any quantity as a natural mineral. Not only is in this type of material the lead present in a different, artificial, phase, but also at much larger quantities than in the previous two types, resulting in the recognisably higher density of this type. The texture of the litharge clearly indicates that it has formed during cupellation, *i.e.* the oxidising treatment of argentiferous lead metal. For comparison, we analysed also a number of solid litharge cakes from the Thorikos excavation (Fig. 8a, b).

Occasionally, there are small crystals of silver and/or copper metal preserved in the litharge (Fig. 9a, b), representing prills of lead metal (Fig. 9c). The

grain size, and its narrow scatter, of the litharge from the ore washeries indicates that the material was initially similar to the massive cakes, but subsequently crushed and ground in preparation for a washing operation. This beneficiation of litharge obviously took place within the ore washeries and on a regular scale, as is evident from the massive and frequent occurrence of it at several such installations. At present, however, it is unclear whether this litharge is the waste product of this washing, or its concentrate. If it constitutes the waste, what then was the concentrate? A higher quality or better enriched litharge, or a metal phase such as lead metal prills or silver crystals? However, if it in itself was the concentrate, as indicated by its richness, why then do we find such large quantities still present in some of the washeries, obviously discarded like a worthless material? Some initial discussion of this is given elsewhere, suggesting the production in Roman times of litharge for medical purposes such as ointments, as indeed reported for litharge from the Lavriotiki by Pliny and Dioscurides (Rehren *et al.* 1999b).

Chemical results

The chemical analysis of the tailings was initially undertaken with the aim to gain a better impression about the silver content - relative to lead - of the ancient ore concentrate and hence the lead smelted. A reliable figure could only be obtained through the analysis of undoubtedly ancient mineral. Even the analysis of ancient lead metal is necessarily ambiguous; the metal could either be primary, rich, bullion, or desilvered metal, or primary lead of intermediate or low silver content, not worthwhile desilvering (Rehren & Prange 1998: 189, Fig. 4).

As mentioned above, various analyses of ore samples from the Laurion ore field indicated a considerable variability of the silver content relative to lead across the deposit (Cordella 1869; Pernicka 1981). This latter study also confirmed through microprobe analyses that the silver is almost entirely present within galena, either as solid solution within the mineral lattice or as microscopic inclusions of silver-rich minerals such as miargyrite or matildite. No lead-free silver minerals of low density such as jarosite were ever reported from the Lavriotiki. One may hence safely assume that the beneficiation of the ore into tailings and concentrate, based on the different densities of the lead mineral and the gangue, did not influence the ratio of silver to lead, but only the absolute lead/silver content of the various products. It is thus reasonable to normalise the silver content found in the tailings relative to the lead content, and to take this figure as a reliable indicator of the richness of the charge processed at the ore washery.

The chemical analysis of the tailings focussed further on the identification of other minor elements related to the lead mineralisation, such as nickel, copper, arsenic and antimony, and the major gangue components, primarily calcium carbonate and fluoride, silica, zinc compounds, iron and manganese (hydr)oxide, *etc.* Dissolution was in some cases incomplete with an insoluble residue of up to 20 wt%; this chemically refractory material was analysed by SEM-EDS and XRD, and found to be fluorspar, resistant against the solvents used. Based on previous experience with ICP analysis of weathered lead-rich material and the difficulties in bringing pre-existing silver halides into solution, a multi-step dissolution procedure was used including a final cyanide leach of any residual material, regardless of whether a residue was visible or not (Rehren & Prange 1998). The amount of silver recovered from the cyanide leach was typically higher than the one found in the main solution, indicating a thorough weathering of the primary silver-bearing mineral; however, no regular pattern or ratio of the silver content between main solution and cyanide leach was found which would have allowed the loss of silver to be estimated when using the main solution only. The silver data given here is the combined data from both solutions.

Based on the chemical analyses, we were able to distinguish two different ore types, in direct agreement with the visual identification based on the fluorspar content mentioned above. Most samples, taken from the excavations at and around Thorikos, have between 15 and 20 wt% each of silica, iron oxide, and lime, plus about 12 wt% lead oxide and 10 wt% zinc oxide (Tab. 1). This ore type is labelled Thorikos Ore, in contrast to the second ore type, tentatively labelled Fluorspar Ore, which has 15 to 20 wt% each of fluorspar and soluble lime, probably calcite, plus ten weight percent each silica and lead oxide, but less than five weight percent each zinc oxide and iron oxide (Tab. 2). The two ore types differ not only in their major elemental and mineralogical composition. At the trace element level, the second type has concentrations of antimony similar to the first one, but only one third of the arsenic concentrations relative to lead oxide (0.8 wt% instead of 2.7 wt%). In contrast, its silver concentration relative to lead oxide is significantly higher, between 1500 and 1700 ppm, instead of an average of 950 ppm in the former. (For ease of calculation, the trace element data were normalised to lead oxide, not lead metal; the resulting rich lead would thus have a silver contents about eight percent higher than indicated here, plus a further premium due to the preferential loss of lead over silver into the slag. Bachmann (1982: 248) found on average 15 wt% lead (calculated as metal), but typically only about 30 to 50 ppm silver in slags from Laurion.) We hope to be able to characterise the second

ore type more fully through additional sampling in the future. This second ore type should have been of better quality for the ancient smelter, not only due to its higher relative silver content, but also through the fluxing properties of the fluorspar.

The third ore type, already characterised microscopically by its preponderant litharge content, is chemically very distinct from the previous two types (Tab. 3). Beside the dominant lead oxide, averaging 65 wt%, the two most important oxides are silica and lime with about five to seven weight percent each. Iron and zinc oxide, prominent in the two other ore types,

occur at less than two weight percent each. A marked reduction as compared to the other ores is also visible at the trace element level, again normalised in the table to 100 % lead oxide. Copper, arsenic and antimony, all present at between about one and three percent (normalised to lead oxide) in the other ores, contribute here only about half a percent each. The most dramatic reduction, however, occurs with the normalised silver content, down to an average 150 ppm.

All this is easily explained by the nature of this material as cupellation residue, originating from the oxidising of argentiferous lead in order to retrieve the

Tab. 1: Chemical composition of the Thorikos Ore, predominant at the ore washeries around Thorikos and the northern part of the mining district. The upper part gives total oxide concentrations as found by ICP analyses. Low totals are likely due to carbonate and hydrous content (many of the metals analysed are likely to be present as carbonate or hydroxo compounds). CaF₂ gives the weight percent of insoluble residue. Trace element concentrations indicated by * in the lower table are normalised to 100 wt% PbO. All data in weight percent. Analyses by W. Steger, Deutsches Bergbau-Museum, Bochum.

Tab. 1: Chemische Zusammensetzung des Thorikos-Erzes, vorherrschend in den Erzwäschen um Thorikos und im nördlichen Teil des Bergbaubezirks. Die obere Hälfte gibt Oxid-Konzentrationen gemäss ICP-Analyse; niedrige Analysensummen sind eine Folge von Karbonat- und Hydroxid-Mineralen. CaF₂ gibt den prozentualen Gewichtsanteil an unlöslichem Rückstand. Die mit einem * gekennzeichneten Spurenelement-Konzentrationen in der unteren Hälfte sind normiert auf 100 Gew.% Bleioxid als Bezugsgrösse. Alle Angaben in Gewichtsprozent. Analysen W. Steger, Deutsches Bergbau-Museum.

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	CaO	ZnO	PbO	Total	CaF ₂
LTP-1	18.6	3.24	17.9	1.27	13.9	6.6	5.8	69.76	0.4
LTP-1a	18.9	2.35	21.6	1.59	5.12	15.3	13.2	80.45	1.40
LTP-ex	19.6	5.01	7.9	0.46	20.0	5.3	14.3	75.04	0.57
LTP-b2	20.3	3.49	18.9	1.25	14.6	7.3	6.5	74.80	0.8
LTP	18.1	2.25	22.6	12.2	6.30	15.0	10.5	89.70	1.9
LAT-W	19.8	3.00	15.4	1.53	15.5	6.5	5.1	69.07	2.3
LTH-2e	18.8	2.55	16.3	1.29	19.5	8.5	8.8	79.45	1.59
LTH-2f	15.6	3.19	9.9	0.69	24.8	6.2	7.6	70.51	2.18
LTH-4	19.1	2.55	13.1	0.89	11.8	19.0	11.9	80.67	0.69
LDK-F1	17.0	0.70	10.2	0.70	9.71	15.3	13.5	70.43	4.11
LDK-F2	19.1	1.40	5.4	0.59	19.4	5.2	25.2	79.37	0.70
LDK-H	17.1	1.90	8.2	0.97	11.7	7.1	22.3	73.55	0.79
Average	18.5	2.64	13.95	1.95	14.36	9.8	12.1	76.07	1.45

Sample	PbO	S	Ni*	Cu*	ZnO*	Ba	As*	Sb*	Ag*
LTP-1	5.82	0.15	0.069	2.06	113		5.15	1.65	0.0860
LTP-1a	13.2	0.18	0.008	1.74	116	0.005	4.02	0.325	0.0850
LTP-ex	14.3	0.09	0.007	0.42	37	0.019	0.15	1.19	0.0830
LTP-b2	6.46	0.15	0.140	1.86	113		3.87	1.50	0.0990
LTP	10.5	0.22	0.067	1.52	143		4.38	1.33	0.1110
LAT-W	5.07	0.19	0.079	1.72	129		2.96	2.56	0.1560
LTH-2e	8.76	0.25	0.137	2.40	98	0.520	4.11	0.73	0.0750
LTH-2f	7.57	0.12	0.489	1.72	82	2.910	1.59	1.32	0.0950
LTH-4	11.9	0.17	0.008	1.26	160	0.084	2.69	0.57	0.0610
LDK-F1	13.5	0.22	0.044	0.74	113	0.390	2.89	1.19	0.0870
LDK-F2	25.2	0.12	0.004	0.32	21	0.035	0.20	0.52	0.0530
LDK-H	22.3	0.15	0.009	0.49	32	0.550	1.26	0.85	0.1490
Average	12.05	0.17	0.088	1.35	96.3	0.564	2.77	1.15	0.0950

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	CaO	ZnO	PbO	Total	CaF ₂
UKN-1	11.82	3.14	3.80	0.39	16.50	4.93	10.53	53.62	15.42
UKN-2	9.50	1.54	2.93	0.26	18.28	3.27	8.64	46.11	20.50

Sample	PbO	S	Ni*	Cu*	ZnO*	Ba	As*	Sb*	Ag*
UKN-1	10.53	0.11	0.044	0.94	52.62	0.14	0.747	1.82	0.170
UKN-2	8.64	0.10	0.018	1.14	43.11	0.02	0.764	0.71	0.150

Tab. 2: Fluorspar Ore, tentatively named after the significant fluorspar content and thought to originate from the central part of the Lauriotike (Ardaillon 1897: 65). See Table 1 for details of the data presentation in this table. All data in weight percent. Analyses by W. Steger, Deutsches Bergbau-Museum, Bochum.

Tab. 2: Chemische Zusammensetzung des Fluorit-Erzes, versuchsweise so genannt nach dem deutlichen Fluorit-Gehalt. Dieser Erztyp stammt vermutlich aus dem Zentralteil der Lauriotike (Ardaillon 1897: 65). Siehe Tabelle 1 für Details zur Präsentation der Daten in dieser Tabelle. Alle Angaben in Gewichtsprozent. Analysen W. Steger, Deutsches Bergbau-Museum.

metallic silver after oxidation of all of the less noble metals. During smelting of the primary ore, only lead, silver, copper, arsenic and antimony will have formed a metallic phase, while zinc and iron went into the slag. The almost complete absence of these two lat-

ter elements is thus no surprise. During the oxidation of the argentiferous lead, as already during the smelting, a fair amount of the arsenic will have volatilised, explaining the significantly lower level of this impurity in the litharge as compared to the ore. Antimo-

Tab. 3: Litharge Ore, predominant at some ore washeries around Thorikos and the northern part of the mining district. See Table 1 for details of the data presentation in this table. All data in weight percent. Analyses by W. Steger, Deutsches Bergbau-Museum, Bochum.

Tab. 3: Chemische Zusammensetzung des Bleiglätte-Erzes, vorherrschend in den Erzwäschen um Thorikos und im nördlichen Teil des Bergbaubezirks. Siehe Tabelle 1 für Details zur Präsentation der Daten in dieser Tabelle. Alle Angaben in Gewichtsprozent. Analysen W. Steger, Deutsches Bergbau-Museum.

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	CaO	ZnO	PbO	Total	CaF ₂
LTU-a	5.8	1.10	1.51	0.09	3.39	0.76	76.2	91.34	0.30
LTU-b1	8.6	1.52	2.76	0.18	5.30	1.25	70.9	92.95	0.10
LTH-2d	4.9	0.94	0.90	0.12	4.12	0.48	69.5	83.21	0.50
LMP-2b	4.9	0.91	1.06	0.06	4.86	0.62	69.2	84.03	0.10
LTH-2	3.3	0.78	0.62	0.14	3.21	0.24	68.4	78.87	0.09
LMP-Be	3.5	0.89	2.59	0.08	2.00	1.78	65.5	78.57	4.63
LTO-b	10.8	2.87	3.20	0.16	6.28	4.20	57.5	87.55	0.39
LTH-1a	10.9	1.51	0.96	0.04	9.56	0.33	56.8	82.05	0.20
LTO-a	8.5	2.28	2.93	0.19	6.86	3.19	52.0	78.95	1.20
Average	6.8	1.42	1.84	0.12	5.06	1.43	65.1	84.17	0.83

Sample	PbO	S	Ni*	Cu*	ZnO*	Ba	As*	Sb*	Ag*
LTU-a	76.2	0.09	0.001	0.29	1.00	0.037	0.39	0.93	0.0120
LTU-b1	70.9	0.11	0.001	0.30	1.76	0.047	0.38	0.68	0.0140
LTH-2d	69.5	0.10	0.013	1.12	0.69		0.07	0.39	0.0090
LMP-2b	69.2	0.12	0.001	0.33	0.90	0.038	1.13	0.40	0.0190
LTH-2	68.4	0.07	0.009	1.11	0.35		0.08	0.39	0.0090
LMP-Be	65.5	0.17	0.006	0.17	2.72	0.017	1.33	0.32	0.0100
LTO-b	57.5	0.10	0.005	0.16	7.30	0.022	0.44	1.01	0.0120
LTH-1a	56.8	0.07	0.002	0.12	0.58	0.009	0.23	1.06	0.0190
LTO-a	52.0	0.13	0.006	1.23	6.13		0.46	1.17	0.0330
Average	65.1	0.11	0.005	0.54	2.38	0.028	0.50	0.71	0.0150

ny, on the other hand, and copper are less likely to volatilise. The reduction in antimony is hence less pronounced, with more than half of the initial concentration preserved in the litharge, the remainder has probably gone into the slag. The lower copper concentrations in the litharge as compared to the primary ore are more difficult to explain; only a very minor proportion of it may have gone with the silver (Pernicka & Bachmann 1983: 594-5). For the time being, it is assumed that in the litharge, copper is present predominantly as copper oxide, while in the ore, it is present as copper sulphide. The former is more likely to weather and migrate under burial conditions than the latter, suggesting that the difference may be due to differential corrosion behaviour rather than different initial concentrations. In addition, some of it may have gone into a - hypothetical - matte phase during smelting. The regular presence of sulphides in the slags, as reported by Bachmann (1982), supports this interpretation, although no detailed investigation of this possibility has yet been done.

The silver content, of about 150 ppm (omitting the unusually rich sample LTO-a, and normalising to lead metal, not oxide), is in reasonably good agreement with the generally accepted level of about 100 ppm for desilvered lead of the Roman period (Rehren & Prange 1998: 189). It is roughly one order of magnitude lower than the initial silver content of the ore mineral, indicating that about ninety percent of the total silver content of the concentrate was successfully extracted during the Classical period. Whether the difference is significant between the 150 ppm found here and the 100 ppm generally assumed for desilvered Roman lead, and possibly indicating a procedural improvement within the same principal technology of smelting and cupellation, remains to be discussed.

Ores and ore washeries

The ore washeries form the core of the preserved archaeological evidence for the processing of ore minerals in the Lavriotiki. Already Cordella (1869) and Ardaillon (1897) know them in their hundreds, and remark upon both their basic similarity in the general layout, and the plethora of technical variability in the detail of their individual design. For the purpose of this study, and following the seminal work of Conophagos (1980), it may suffice to repeat here only a very general summary of the individual units which together make up a typical washery. Detailed description of individual examples are given, e.g., by Conophagos (1980), Jones (1984; 1988) and Photos-Jones & Jones (1994: 313-331). In a recent important paper, Kakavoyannis (2001) summarises the development of these washeries and gives an interesting discussion of their function.

A typical washery has a rectangular water tank, a few metres wide, less than a metre deep from front to back, and standing originally more than one metre high. The front wall of this tank consists of a thin stone slab with several funnel-shaped water outlets at certain intervals at half the full height. These outlets are thought to have had plugs to close or open them individually. In front of this water tank, of the same width and about 1.5 to 2 metres deep, is a smooth work floor, slightly inclined away from the tank and leading to the first of four connected channels. These four channels are a few decimetres wide and deep, and are typically arranged around a central rectangular area, identified as a drying floor. This drying floor, of the same width as the working floor and up to several metres long, forms an extension of the latter, separated from it by the first channel. At the two far corners of the drying floor, and at the near-



Fig. 10: Photograph of an ore washery north west of Thorikos. The view is from the water tank, with the work floor in the foreground and the drying floor in the centre.

Abb. 10: Aufnahme einer Erzwäsche nord-westlich von Thorikos. Der Blick ist vom Wassertank über die Arbeitsfläche (Vordergrund) zur Trockenfläche (Mitte).

by left-hand corner when looking from the working floor, are settling basins. These basins are either round or rectangular, and considerably deeper, easily more than a metre, than the channels which they link with each other. The channels have a very slight slope from the first one counter-clockwise up to the final, near-by, settling basin. Although the final basin is very close to the first channel, often only a few centimetres away, there is hardly ever a connection between the two other than via the long way around the drying floor. Clearly, the water is intended to flow from the tank through the outlets into the first channel, and then counter clockwise through the sequence of basins and channels to the final basin, from where it was bailed back into the tank. This circular flow of water, however, can not have occurred at any significant velocity; the inclination along the channels is almost negligible, the water supply through the small number of outlets from the tank limited, and the flow often further hampered by barriers within the channels, some initially built together with the installation, some obviously added later. All surfaces are worked to an extremely high standard of masonry, either hewn into the country rock or finished with the Lavriotiki's famous watertight plaster (Conophagos 1975; Mishara 1989), allowing to this day the growth of swamp grass in the settling basins even during periods of draught.

Remains of tailings were typically found on the work floor, and often on the drying floor immediately opposite the first channel as well.

Occasionally, heaps of lead-rich material were found stacked away in various buildings adjacent to the washeries, or as thick covers within the installations; typically, these latter occurrences turned out to be of the third type of material, re-processed

litharge rather than ore tailings. The distribution of ore tailings within the washeries is in good accord with their mode of operation as reconstructed by Conophagos (1980); the actual beneficiation took place on some sort of probably wooden installation on the work floor, resulting in some scatter of material around these installations. Though most of this was likely fed back into the process, some will inevitably have escaped the attention and remained on the work floor surface. The bulk of the tailings of the (tentative) sluice box operating on the work floor will have collected in the first channel, from where they were ladled onto the drying floor to allow their water content to seep back into circulation. From here, the tailings were then either re-worked to extract more of the rich mineral, or considered lean enough to be discarded for good (or rather re-working in later centuries). Little if any material will have been ladled onto the drying floor from the other channels; hence, far less frequent are traces of tailings next to those. But how was the decision taken to either re-work, or discard, the material? Published general statements on the lead content of ancient tailing heaps as well as our own data indicate a fair, and fairly consistent, control over the lead content of the tailings, of around five to ten weight percent lead. This indicates that a reliable and reproducible means to assess the quality of beneficiation did exist in Antiquity.

The primary ore mineral processed and concentrated in Antiquity was galena, not cerussite. This is of considerable importance for the argument. While cerussite is whitish and has a density of 6.5 g/cm^3 , galena is black and has a density of 7.5 . This has to be seen - literally - in contrast to the main gangue minerals processed along with the ore mineral, calcite (white to pale yellow, density 2.7), fluor spar (white

Fig. 11: Detail of an ore washery, with remains of the tank (left) and the work-floor (front centre). The canal to the right separates the drying floor, extending to the right beyond the frame. The final settling basin in the centre holds swamp grass even in the summer. The canal is carefully separated from the settling basin, forcing the water to flow around the entire installation.



Abb. 11: Detail einer Erzwäsche mit Wassertank (links) und der Arbeitsfläche (Mitte im Vordergrund). Der vordere Kanal trennt die Trockenfläche ab, die sich nach rechts erstreckt. Das im Wasserlauf letzte Sammelbecken ist in der Bildmitte zu sehen; in ihm wachsen auch im Sommer Sumpfgäser. Der vordere Kanal ist sorgfältig vom Sammelbecken abgegrenzt, so dass das Wasser die gesamte Anlage umfließen muss.

to various pastel colours, density 3.2), and siderite (pale to dark brown, density of 3.8). The separation is generally accepted to have occurred by means of water; this immediately moves the argument from real densities to effective densities, *i.e.* those effective under water, taking into account the buoyancy of the minerals. For the sake of convenience, one may take the density of water as 1 and reduce all mineral values by this; while the absolute differences between the light and the heavy minerals remain the same, the relative differences increase considerably. In air, galena is just over two times as heavy than fluorspar, while in water, it is three times as heavy. Cerussite, in contrast, is only two and a half times as heavy in water than fluorspar. Quite obviously, galena not only responds much better to a density-controlled separation than cerussite, but the quality control of the operation will also be much easier, based on the colour contrast between the various minerals involved. Both excess gangue mineral levels in the concentrate, and intolerable loss of rich mineral to the tailings, become immediately obvious without any need for chemical analysis or elaborate testing. Thus, the question (Photos-Jones & Jones 1994: 334) of how the distinction was made between worthless tailings, those worth further processing, and concentrate of sufficient quality for the smelter, is easily answered.

So far, we have concentrated on the rectangular model of ore washeries. In addition, there are four circular installations, known as helicoidal washeries (Mussche & Conophagos 1973). The chronological relationship of these to the dominant type is still not firmly established; the fact that one remained unfinished could indicate that this model was superseded by the later, rectangular type which allowed a much higher throughput of ore. On the other hand, the helicoidal type may have served a more specialised purpose, requiring a much more precise and lasting installation than the supposed wooden sluice box operated at the rectangular washeries. Recently, Klemm and Klemm (1994) reported the discovery of fragments of another helicoidal installation in an Egyptian gold-mining region; again, however, no precise date is given for it.

The Helicoidal Washeries

An outstanding problem is the chronology and function of the helicoidal washeries. So far, four of them are known: Demoliaki, Megala Pevka 1, Megala Pevka 2, and Berzeko (Mussche & Conophagos 1973: 67). None of these washeries is well-dated by finds from the foundation layers. In 1973, it was stated that (Mussche & Conophagos 1973: 65) "there is practically no evidence for dating the entire plant at De-

moliaki. Cistern A seems to be Archaic, but nothing can be said for certain about its relation to the rest of the construction." Meanwhile the impression developed that the so-called Lesbian style of the masonry of Cistern A seems to occur in the Lavriotiki even into the second quarter of the fifth century BC. Regardless, this is not a satisfactory or decisive argument.

Theoretical and archaeological considerations

Reconsidering the problem, there are three factors to be examined:

1. the technical aspect: the building of the plant and the operating system,
2. the economical aspect: the relation of investment and yield, and
3. the archaeological aspect.

First, there is the question of the construction of a helicoidal plant. This was, of course, a very complicated and precise task. About 10 cubic meters, or about 25 tons, of stone were needed for around 30 stone blocks (approximately 0.80 meters wide by 0.70 meters high) of the 20 meter-long circuit (Fig 12). These had to be transported to the plant location. Following transportation, they had to be cut and assembled with two well-joining faces (Fig 13), and last but not least, levelled. Considering the weight of the blocks, this must have been done with a lifting device which required moving for each block - about 30 times. Once this preparation was finished, there was the painstaking cutting of 180 bowls by skilled stonemasons, with a smooth, very precise denivellation of about 0.06 m over the total length of 20 m. After the cutting, the bowls required rubbing down to the present smooth finish.

In comparison, in Thorikos, the building of a normal-sized rectangular washery with three workmen (one of whom was very skilled) was realized in about 20 days, translating into 60 working days total. Here the only levelling problem was the five overflows within the course of the surrounding channels. The inclination of the wooden sluices was easily adaptable to the quality of the ores. It is a very conservative calculation if we suppose that the building of a helicoidal washery took only twice as much time.

Next comes the operating of the helicoidal washery. The ores were placed little by little in the very beginning of the circuit. As we experienced during Conophagos's tests in the reconstructed washery, two men were needed to turn over the concentrate continuously with their hands. After a short time, there was a perfect material classification: in the first four meters of the circuit was concentrated ore, followed by gravel, sand, and finally silt and clay. This means a classification of waste material over about 16 meters, something completely useless. Moreover,



Fig. 12: Photograph of joint between two blocks of a helicoidal washery near Megala Pevka.

Abb. 12: Aufnahme einer Fuge zwischen zwei Blöcken einer kreisförmigen Erzwäsche bei Megala Pevka.

at the end of the operation, all 180 bowls would have had to be emptied and cleaned by hand. The conclusion is that only the bowls in the very beginning of the circuit were productive, with the existence of the remaining about 140 bowls solely for the purification of the water. In this case, the investment was, of course, extremely disproportionate to the target. It seems more than reasonable that the builders of the helicoidal washeries would have realized this quickly and stopped their trials. An objection to this argument is that the operational length of the helicoidal washery (approximately 4 meters) is more than double that of a washing table in a rectangular washery (1.80 to 2.00 meters). On the other hand, the operation in a helicoidal washery occurred once only, requiring complete cleaning after each operation. Conversely, in a rectangular washery, operating with wooden sluices, the work is easily repeatable and hence more continuous. Furthermore, it is of course true that we don't know exactly how the wooden sluices were made - whether, perhaps, there were different methods or variations adapted to various qualities of ore.

Two other technical aspects are water consumption and solidity of the construction. In terms of water con-

sumption, both types allowed for a perfect recycling of the water, although it was more difficult to protect the helicoidal type against evaporation by the sun. The construction of the helicoidal washery was certainly more chip-proof, but once damaged difficult, ore even impossible, to restore - and even useless, once worn out by the constant friction by the turning concentrate. Repairs in the rectangular type, however, were easy to carry out.

Secondly, there is the economical aspect. Unfortunately here are many unknowns, such the exact prices and the wages, with very little monetary data existing. The average price of a slave was about 200 Drachmes (Lauffer 1979: 65), with skilled workmen or a foreman with experience in metallurgy being substantially more expensive, more than 1000 Dr. Sosias, for example, was 6000 Dr (Lauffer 1979: 67). It is evident that every *ergastirion* needed one man with the necessary know-how.

We have seen that the construction of a helicoidal washery must have been substantially more expensive than that of a rectangular one. Therefore their construction and operating only made sense if it resulted in greater yield or higher quality. The yield of a helicoidal washery can be estimated at about two tons in 12 hours. That of a rectangular with three water outlets was about 4.5 tons in the same time, *i.e.* more than twice as much (Conophagos 1980: 244).

The only remaining solution is the higher quality in operation, but in the absence of experiments we are limited to hypothesis. Here the argumentation of Conophagos (1980: 252) is not convincing. It is absolutely uncertain that the helicoidal washeries are an imitation of the wooden sluices; not one fragment of a wooden sluice was ever found. We do not know how they were made, what kind of wood was used, what the quality of output was at different inclinations and different watering methods. There remains one element: the greater operational length of the helicoidal sluice, permitting a very precise treatment of difficult ores or litharge. It cannot be denied, however, that in the helicoidal sluice, at the point where the concentrate ends and the waste material or tailings begins, there is also a certain loss. This problem cannot be solved without thoroughly conducted trials.

According to Conophagos (1980: 251), litharge contained on average 66 grams of silver per ton; thus a helicoidal sluice could produce a maximum of 132 grams of silver in 12 hours. This equals, assuming a 10 per cent loss, 27 Dr per day (with the Athenian Drachme equal to 4.37 grams), or 9855 Dr per year.

Conophagos (1980: 251) also compares the metallurgical results of conventional and helicoidal washeries: with ores containing 16 per cent lead, a rectangular plant produced a concentrate of 50 per cent

lead, and a helicoidal one of 45 per cent. This is an almost equal result, despite the increased operational length of the helicoidal washeries. Tests, however, with ores containing less than 16 per cent were not made, and the issue of the quality of the concentrate has to remain open until further experiments are done.

If we calculate for each *ergastirion* one free foreman and five slaves (two crushing the material, one transporting water, two turning over material in bowls), the total capital cost for the six should be - if we estimate a depreciation over six years survival of the slaves - about 570 Dr per year. We must also add in the costs of building the plant, food, clothing, water supply, transport (assuming 1 Dr per ton per mile, easily 730 Dr per year), melting down, cupellation, and minting (Van Looy 1987).

It is evident that according to these calculations a helicoidal washery produced not even half of its investment, or less than 4927 Dr (14,700 Dr for the three known plants), a ridiculous amount, whereas Aristoteles speaks of an annual yield of 600,000 Dr for the mines in total (Mussche 1998: 16). Even if this figure is perhaps to a certain extent too high, the reality lies certainly in the hundreds of thousands.

Our third aspect is the archaeological one. Although their construction is even more sturdy than those of the rectangular washeries, so far only four plants were found against more than 200 rectangular *ergastiria*. Of these four, one in Megala Pevka remained unfinished, the second one in Megala Pevka was destroyed

by the building of a rectangular one, and the Berzeko plant was so badly destroyed that it is very hazardous to conclude something at all. In my opinion there is no solid archaeological proof for an archaeological dating of them at all. Few sherds were found in the surroundings, with none Roman or Palaeo-Christian. Moreover, it is well established that in an *ergastiria* in activity in the fifth or fourth century BC, there are always many typical sherds. It is also obvious that many rectangular washeries were brought into use again in the fourth through the sixth centuries AD, with (or without) alterations or adaptations. A characteristic feature of those Palaeo-Christian miners is that they were not investors, but poor squatters, installing themselves in ruined and abandoned dwellings and trying to extract immediate profits. They were not inventing expensive, sophisticated workshops, demanding a considerable capital to invest. The extreme skill of perfect and precise stone-cutting required to build a helicoidal washery is, on the contrary, typical for the fifth century BC.

What conclusion can we reach? There are two possibilities: either the helicoidal washeries date from the fifth century BC or the fourth to the sixth centuries AD. Up to the present time, although there are no decisive arguments yet known, there are rather strong indications in favour of the earlier date.

As early as 1987 R.F. Tylecote (Tylecote 1987: 63-4) was sceptical about the efficiency of both the rectangular and the helicoidal washeries, noting that

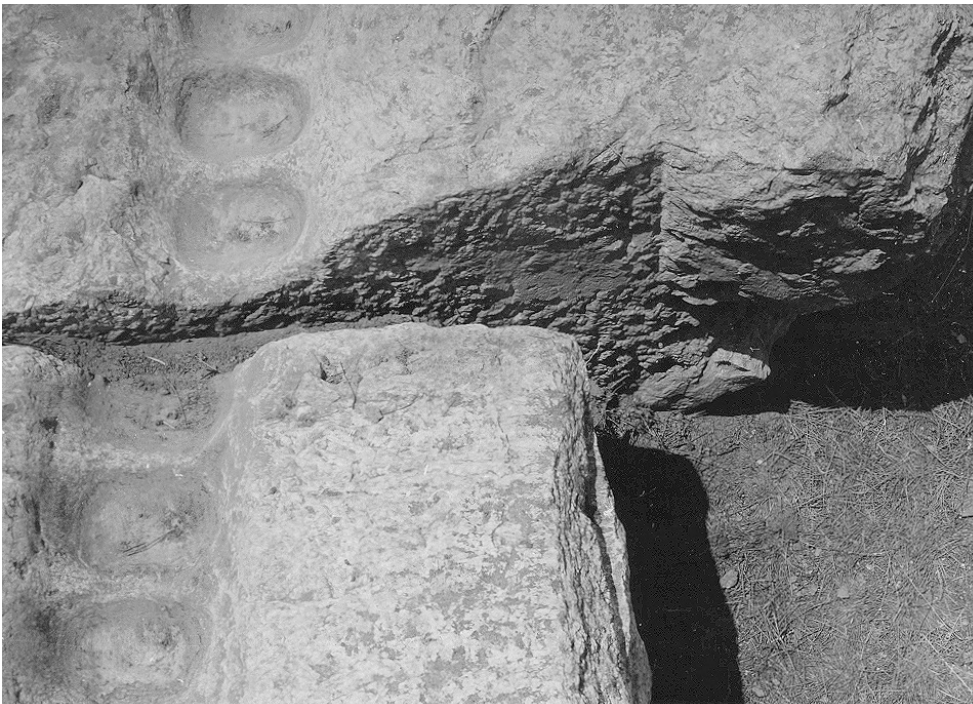


Fig. 13: Photograph of a sequence of blocks forming a helicoidal washery near Megala Pevka.

Abb. 13: Aufnahme einer Reihe von Blöcken einer kreisförmigen Erzwäsche bei Megala Pevka.

"how efficient it was as a integral concentrating process is difficult to estimate", and, specifically concerning the helicoidal washeries, that it "is possible that they were not nearly as efficient" as the almost certainly riffled sloping launders.

In the industrial process (and with approximately 1,500,000 tons of ancient scories recorded in the 19th century, it was obvious that it was in Antiquity a real industrial exploitation), efficiency is essential. As we have seen, there are quite a number of arguments in favour of an early date. As mentioned in Preliminary Report IX (Mussche 1990: 38), "the change-over in ore winning from high grades to lower grades certainly did not come about instantaneously, but was a gradual process. If the yield proved unsatisfactory, there will have been a search for new methods and concentration by running water will have been invented. (They knew e.g. that in the Strymon the gold particles were concentrated by the centrifugal force of the water in the sharp curves of the river.) This will not have happened overnight. Improvements in the later traditional type of washery will likewise have been a matter of time. In the Lavrion it has been established that the conventional type of washery ... was operational towards the end of the fifth century BC. This will undoubtedly have been preceded by a great many experiments."

In 2001, Kakavoyannis published his important find of the rock-cut washery in Berzeko (Kakavoyannis 2001: 365) as a forerunner of the classical washery. The helicoidal type, also cut in stone, might have been one of the trials, but soon recognized as an error, as too expensive and not sufficiently productive. May this be the reason why Megala Pevka remained unfinished?

The material processed in the helicoidal washeries

We were able to study in the field using a binocular microscope remains adhering to the inside of the bowls in the helicoidal washeries preserved. Apparently, they were all extremely fine-grained and rich in litharge. Two samples from the installation at Megala Pevka were available for chemical and microscopical analysis in Bochum (Tab. 3, LMP-2b and LMP-Be), confirming the visual identification. In contrast to most of the other samples of this type, however, the material from the helicoidal washeries seems to be much finer. This, together with the careful and labour-intensive design of these installations, one could tentatively interpret as indicating the use of these installations in the separation of mechanically trapped lead-silver droplets from the litharge and cupellation hearth material. The latter is known to contain sometimes considerable quantities of such sil-

ver (see above, Fig. 9a-c); even textbooks of modern metallurgy point out the need to build the cupellation hearth most carefully to reduce such losses (e.g., Tafel & Wagenmann 1951). Some loss, however, was inevitable and may have stimulated some effort to retrieve this silver. The difference in density between metal (11.3 for lead, 10.5 for silver) and litharge (9.5) is much smaller than between the various ore minerals discussed above in the context of the rectangular washeries; hence, a more careful treatment is necessary, requiring a much longer operational length of the installation than the average sluice box would offer. Also, any loss of the concentrate would be far more serious than in the ore washeries proper: here, the concentrate would be almost pure silver metal, there, it would be ore minerals with only a fraction of a percent of silver in it, requiring considerable effort to extract the silver. Therefore, an installation cut into stone rather than built from wood, and from its very design easily to supervise, would make particular sense in reducing accidental (and 'deliberate') loss of concentrate.

At present, we can only speculate whether such a supposed mechanical separation of metallic silver from the cupellation hearth material was done contemporaneously to the main smelting activity, as an integral part of the total metallurgical procedure, or as part of any later re-working. This was not necessarily a re-working in one of the periods of resumed activity mentioned earlier, but could well have taken place during the (early) Classical Period, when remains of an earlier, Bronze Age, cupellation were already available. Two of the four helicoidal washeries are close to the furnaces of Megala Pevka, a situation where one would expect the processing of litharge to take place, close to any cupellation activity to have taken place, rather than near to the mines, where the rectangular washeries are typically situated.

Discussion and Conclusion

Based on our work in the northern Lavriotiki, we have been able to identify two geologically different ore types which were processed at some time during the Classical period. The two ore types, although both mined for their argentiferous galena, have distinct mineralogical and chemical properties, and appear to follow a certain regional pattern. The Thorikos Ore was found primarily to the north and north-west of the region, while the ore labelled tentatively Fluorspar Ore appears to occur mostly in the central part of the Lavriotiki (Ardaillon 1897: 65 mentions particularly ore from Soureza and Agrileza as rich in fluorspar). More detailed fieldwork and analytical studies are necessary, however, before a reliable interpretation of this phenomenon will become possible. Are these

regional differences, or stratigraphic differences among the various contacts? The recent publication by Photos-Jones & Jones (1994), considering material from Agrileza, corroborates this division. Of particular interest are the data for their third type of tailings, which in appearance and location within the washeries resembles most closely the material studied here. Mineralogical and chemical data provided for four samples of this type (Photos-Jones & Jones 1994: 340-1, 343 Table 5) indicate that they belong to our Fluorspar Ore, with fluorite as the main gangue mineral and silver to lead ratio of between 700 and 1900 ppm (the value of 6866 ppm given in their Table 5 has a decimal error in the calculation, and should read 686.6 ppm). Further XRD data, however, indicate the regular presence of cerussite in their samples. E. Photos-Jones explicitly interprets this as cerussite being the primary ore mined in Antiquity (Photos-Jones & Jones 1994: 340, 352 and 357), an interpretation contradicting our own results presented above. However, the validity of our identification of a distinct ore type rich in fluorspar is confirmed by their data.

The Fluorspar Ore was probably of much better quality for the ancient miners, not only because of its higher silver content relative to lead. One may assume that it was also more easily processed, with more lighter and whiter gangue minerals, such as fluorspar and calcite, than the Thorikos Ore, which is richer in sphalerite and iron compounds, both of darker colour and higher density and hence more difficult to separate from galena. The significance of this effect is underlined by the considerably lower average lead content of the Fluorspar tailings as reported by Photos-Jones and Jones (1994: Tables 2 and 5) and in this paper, as compared to the Thorikos material. While the latter has an average of 12 wt% lead oxide, and at least five weight percent in the best sample, Photos-Jones & Jones (1994) report values of typically below six or seven weight percent lead, and an average between four and five percent. The average of our own two analyses of this ore is below ten weight percent, *i.e.* also lower than the average of the Thorikos Ore. Thus, the yield of argentiferous lead mineral is higher in the washeries, as is the silver content of the lead metal smelted from the concentrate. The strong fluxing ability of fluorspar has been mentioned already.

This leads on to another important discussion, namely the quality of the slag and the efficiency of the smelting operation. Bachmann (1982) reports lead contents of about 15 wt% in the slag, but rather low silver levels. This indicates that most of the lead was present as a lead compound chemically bound in the slags, and not mechanically trapped as lead metal droplets. Only the latter is deleterious for smelting

which aims at the extraction of silver, since only then argentiferous lead is lost in the slag. Lead bound chemically, typically as a silicate glass or phase, is virtually free of silver, and hence a loss tolerable for the smelter. Thus, a low density and low viscosity slag, allowing the bulk of the lead metal to settle out of the melt, are more important for than a low lead silicate content.

At present, we may assume that most Roman reworking was either re-smelting of argentiferous slag, aiming to isolate any metallic lead trapped in it mechanically, or a second washing of relatively rich tailings to extract some more concentrate for fresh smelting activity. This may have included the processing of litharge to be smelted together with galena. However, only the systematic chemical and mineralogical study of well-dated slags from known contexts will allow us to address properly the issue of slag chemistry and possible improvements in smelting technology from the Classical to the Roman period.

A further, artificial, material rich in litharge was identified as occurring frequently in the ore washeries. Some of it was found in minor amounts in immediate context with the helicoidal washeries, while the bulk of it originates from rectangular washeries. The significance of this material has been discussed elsewhere (Rehren *et al.* 1999b); the range of possibilities mentioned there, and those added in this publication, only illuminate further the need to view the ore washeries not only individually, but also in their wider technological, chronological and spatial setting within the mining landscape of the Lavriotiki. We hope to have contributed to this; but much more work remains to be done.

Acknowledgements

We are most grateful to the Greek archaeological authorities, in particular the second Ephorate and Maria Oikonomakou, for giving permission to sample several of the ore washeries in the northern Lavriotiki. Further samples were taken from the collections of the Deutsches Bergbau-Museum Bochum, among them several which were presented to the museum by the then major of Laurion on the occasion of mutual visits in Laurion and Bochum, and the earlier excavations at Thorikos. Andreas Ludwig and Wolfgang Steger of the Deutsches Bergbau-Museum are thanked for their work, meticulous as usual, in sample preparation and analysis. Last not least we acknowledge the financial support of this project by the Volkswagen-Foundation, Hanover / Germany, and the continuous encouragement of our work by G. Dege and G. Weisgerber.

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