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Technological change in the Laurion silver mining area during the fifth and fourth centuries BC

An archaeological contribution to the study of the Athenian economy
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Demetrius [of Phaleron], he says, states in reference to the Attic silver mines, that the people dig as strenuously as if they expected to bring up Pluto himself.

Strabo, *Geography* 3.2.9
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Part 1 The Laurion in context
Chapter 1  Introduction

It is a commonplace that the Greeks and Romans together added little to the world’s store of technological knowledge and equipment.

With this statement, Finley began his influential article Technical innovation and economic progress in the ancient world (1965, 29-45), an opinion that would have far-reaching consequences for the debate on ancient technology. Starting from the primitivistic idea that the ancient economy was characterised by stagnation, technological innovations and their diffusion have been systematically minimised and the role of technology as an agent of social change denied. Finley’s views have been nuanced and adjusted, but the study—or perhaps better the appreciation—of technology is only slowly finding its way into the field of ancient history and especially economic history. Despite the fact that technology is now acknowledged as a basic determinant of economic performance¹ and is given considerably more attention as a decisive element in history, the debate remains biased. More than any other topic in ancient history, the study of technology seems to be a victim of our modern-day perceptions of this concept. Living in a world obsessed by technological and economic advance, it is no wonder that apparently simple improvements such as the pulley or the diffusion of technologies as the water mill have long not been valued within their historical context. Admittedly, technological improvements never led to drastic changes in the social structure as during the Industrial Revolution; however, this does not mean that ancient technological improvements, ‘minor’ as these might have been in the light of our modern attitudes, were insignificant. Technology did enable modest economic growth in Antiquity and, not to be forgotten, affected positive changes in the quality and efficiency of the everyday life. Arguing for a different evaluation of technology, these issues have been tackled by several scholars, such as White (1984),

¹ Starting from D. North’s important Structure and change in economic history (1981), The Cambridge Economic History of the Greco-Roman World (2007) recognises technology as a determinant of economic processes and devotes a separate chapter to this topic.

Within the framework of this study, there are two main gaps in the present research that I wish to see filled. The first one concerns the overall focus in the study of ancient economies on Roman history, resulting in the general neglect of the Greek world. Millet (2001, 35) has even considered economic growth in the centuries BC to be elusive or non-existent. Ironically, this attitude demonstrates striking parallels with the one mentioned earlier. While the entire ancient world used to be judged for its ‘weaknesses’, this trend seems to have shifted to a dichotomy between Greece and Rome: the latter is now given more credit but the former disparaged for the seemingly less impressive nature of its technologies. The question whether or not the Greek world reached a similar level of economic dynamics and technological complexity, however, is simply not an appropriate one to ask. The Roman and Greek worlds are two significantly different contexts, triggering substantially different outcomes and therefore, the Roman model cannot be used as a criterion. The former was a unified economic body where the demand for resources and products was large, consequently enhancing technological advances and their diffusion, whereas the latter was characterised by scattered geographical, political and economic entities, in the form of the poleis. Millet (2001, 35-6) is right to point out that this made the Greek economy more fragile and susceptible to externalities, such as war and famine, but he is mistaken to equate this with economic and technological rigidity. The initiatives and applications were there, if only one asks the right questions, takes the appropriate sources into account, and appreciates the Greek city-states within their own context.

The second hiatus ties in with this last remark and is a methodological one. The ancient Greek economy has principally been the playground of historians, but in this study I will argue to move more thoroughly towards an archaeology of its economy. The best illustration of the potential of archaeological research lies hidden behind the opening quote of this chapter. In a brilliant article, Greene (2000) meticulously goes through Finley’s paper, meeting many of his assertions with archaeological counter-arguments. Finley (1965, 41), who has once claimed that we are too often victims of that great curse of archaeology, has ironically been reduced to silence largely by that same field. In this context, Morris (2005, 104) judged fairly when saying that The Ancient Economy (1973) would have looked different if Finley had taken the archaeological sources seriously or at least attempted to analyse these data adequately. Archaeological remains are proxy-data (Morris 2005, 93), in the sense that they act as a substitute for the actual data that are investigated. Ore processing ergasteria, for example, can

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2 K. Greene has already strongly addressed this issue in study of the Roman economy with his publication of The archaeology of the Roman economy (1986).
be employed in the wider debate on the ancient economy because these workshops were the focus of economic activities, in this case silver production. If the sequence of the operations, also referred to as chaîne opératoires (Leroi-Gourhan 1964), can be reconstructed through the investigation of architecture and the spatial distribution of recovered finds, the division of the labour tasks and thus the level of work specialisation –horizontal as opposed to vertical– can be deduced. When doing so, however, one should take into account the formation processes, affecting the conservation of the site (Schiffer 1987; Morris 2005). Archaeological sites do not present a mirror of the studied community, which is a matter that can often lead to much confusion, especially among historians. I will attempt to point out several of these issues in the course of this study.

The involvement of archaeology inevitably implies the broadening of the debate towards other fields of research as well. Archaeology currently embraces an interdisciplinary discourse of which the potential is immense, at least when these data are analysed and interpreted in an appropriate way. When discussing water technology, for example, it is vital to involve hydrological research. The hydrologic cycle and climate are major explanatory factors in the search for technological answers to environmental challenges, such as water scarcity. Since it is very hard to grasp such trends without scientific training, these approaches have been generally judged as a weakness by historians, but this cannot serve as an argument against their inclusion. Economic behaviour cannot be adequately investigated in a solely historiographical or archaeological discourse but should be immersed in the broader context, in which it was carried out and formed a central nexus in society.

There is no better case study to tackle these issues than the Athenian silver mines at Laurion. On the one hand, this area offers a unique opportunity to study an ultimately economic infrastructure within a Greek context. On the other hand, the Laurion enables us to investigate economic initiatives from diverse angles and subsequently amalgamate these approaches. We are not only provided with a wealth of epigraphic and literary data but also with an overwhelming archaeological dataset, consisting of a variety of metallurgical features scattered over the Laurion landscape. This offers an opportunity to challenge the over-reliance on text-based analyses in the study of ancient economy and stimulates the integration of different forms of evidence in order to develop a more contextualized, balanced, and thorough knowledge.

The Athenian silver resources played a pivotal role in the economy and welfare of the city-state. Xenophon demonstrates with his *Poroi* that silver was not only an important determinant throughout Athenian history but also one of its most vital sources of revenue. Silver affected the economy on two levels: first, this happened through the technological issues and costs involved in the silver production process, from the extraction, washing and smelting of ores to the minting of coins. These activities require a significant labour force,
capital investment, and constant technological ingenuity. Second, there is the importance of silver as a commodity, an item of trade and a resource for the manufacturing of coins (Hopkins 1978, 55). The importance of the Laurion area for Attica and the Aegean is, as hinted by Xenophon (Poroi 4.2), further demonstrated by its long metallurgical history. The area was already mined for lead and silver ores since the transition of the Final Neolithic to the Early Bronze Age I (Kakavoyianni et al. 2008), activities that were greatly intensified from the late Archaic period onwards and remained to have a high profile in the available sources until the Athenian city-state crumbled under Macedonian pressure by the end of the fourth century BC (Mussche 1998, Kakavoyiannis 2005). This florescence in mining was sparked by a range of political and economic events, such as the introduction of coinage, the Persian Wars, and the active interference of Athens in the operation of the mines. As a result, the Laurion was transformed into a state-run industry, which had a major impact on population levels, the environment, and the structural organization of the settlements. This last effect is still easily visible in the archaeological record: the Laurion was gradually built up with industrial installations, with the ore processing ergasteria as most noteworthy features.

The production of silver, however, was associated with considerable difficulties. In contrast to other mining areas in the Aegean, the Laurion only yielded low grade ores, which were hardly economically viable to exploit (Rehren 2005, 24-5). The mentioned workshops addressed this issue by clearing the ore from its impurities, leaving only the rich metal particles and consequently converting the mines into a productive lode of mineral resources. A second obstacle was the water scarcity in the Laurion. Ore dressing required vast quantities of water, which the meagre local resources were not able to meet in times of rising silver demand. A well-considered water management and an appropriate set of water technologies were thus vital to both maintain and expand the silver industry. These two aspects make the ore dressing plants the most crucial features of the ancient mining industry, contributing heavily to the economy and by doing so securing the foundations of the Athenian Empire. Until now, these workshops have been studied as static infrastructures, operated throughout the Classical Period by private entrepreneurs and characterised as enclosed compounds in which working and supporting living quarters were tuned to one another. There is, however, a fundamental error in this reasoning: the workshops, as just described, have only been inherent features of the silver industry during the fourth century BC and have not been documented as such before.\(^3\) Moreover, as suggested by Mussche (1990, 38) and Kakavoyiannis (1989, 2001, 2005), there is significant evidence that the introduction of ore preparation did not happen overnight but had been liable to a long process of technological change. Naturally, the accompanying infrastructure will have evolved as well. When one wants to fully understand the contribution of the ergasteria to the Athenian economy and

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\(^3\) Washery no.1, dated to the late fifth century BC, is the sole remarkable exception (see Chapter 5).
society, the workshops should therefore be considered as a both complex and variable entity, rather than a static, unchangeable feature of the silver mining industry.

The following questions are central in this PhD and will be investigated from an archaeological point of view: “How was technological change characterised in these ore processing ergasteria—especially in the context of water management—during the heyday of the Athenian city-state in the fifth and fourth centuries BC? And what was the impact of these dynamics on the Athenian economy?”

Given the potential of the Laurion to learn more about such processes, it is all the more surprising that the region has not been more eagerly exploited in scholarly literature and linked to in-depth research questions embedded within the wider context of the Greek world. The first major works were published in the 19th century by mining engineers Kordellas (1869) and Ardaillon (1897), a line of research that was continued in the next century by Conophagos (1980). Although their work has been of invaluable importance in the development of our knowledge of the silver industry, these scholars were engineers primarily concerned with metallurgical issues, inevitably neglecting the historical background and accuracy in the process. Archaeologists did their best to fill the gap. In the past decennia, research activities in the Laurion boomed, with excavations scattered over the area, from the site of Agrileza by J. Ellis Jones,4 to the Soureza excavations by E. Kakavoyiannis5 and Thorikos under the direction of H. Mussche. The last researcher remains an authority in the study of the Laurion. Until today, Thorikos is the best published site in the area, with ten series of preliminary reports,6 three final reports, six volumes of related articles (Miscellanea Graeca) and numerous articles in international journals. In the past years, however, research on the site was reduced to a lower profile, as excavations at Thorikos came to a halt in 1989 and efforts have been directed towards the finds documentation and organisation of the inventories. Recent fieldwork of the University of Liège focussing on the top of the Velatouri and an ongoing survey on the hill by a team of Ghent University in cooperation with Utrecht University will hopefully be the start of renewed and intensified activities at the site. Despite the great efforts of both Greek and foreign archaeologists, they have left some blanks as well.

The focus of archaeological research is mainly on specific sites, which are rarely immersed in the complex processes characterising the Greek world during the Classical age. An additional issue is the poor state of publication of the bulk of the sites. A crucial part of this PhD entails hydrological analyses (see Chapter 6), but archaeological sites have to be well investigated and published in order to be able to take into account all the parameters required for the

4 The main report is published in Annual of the British school at Athens 89 (1994). An extensive list of interim reports is mentioned this article.
5 The Soureza excavations unfortunately remain unpublished.
6 Thorikos 11 and 12 are forthcoming.
reconstruction of a hydrological context. Thorikos is a welcome exception but, as will become clear in this study, the site differs in some remarkable aspects from what is currently conceived as a metallurgical site. Prudence is thus in order to use Thorikos as a prototype for other sites.

This tendency to generalisation can be linked to a more general remark. The Laurion is an exceptional case study, rooted in the history of an already unique city-state within the Greek world. As Oliver (2010, 283) stressed, Athens offers rich evidence … [but] not all polities in the Greek world displayed the same levels of complexity and sophistication in their behaviour. Although I do not doubt that more case studies illustrating technological ingenuity would be revealed if adequate questions are asked and appropriate evidence employed, one should be careful to generalise the findings of this study to the wider Greek world.

This PhD is composed of two main parts. Part 1 will give a general introduction to the Laurion by sketching its geological, geographical, hydrological, and historical background. This overview serves as a backbone for the economic and technological issues discussed in Part 2. Chapter 4 concentrates on a theoretical discussion of technology by giving an overview of the turbulent history of this field and attempting to formulate a new line of reasoning about this concept. Next, Chapter 5 discusses these issues in relation to the evolution of silver metallurgy and the rise and fall of Athenian supremacy. In Chapter 6, I will go deeper into the incentives of technological advance, specifically in the fourth-century ergasteria. Hydrological analyses on these workshops are an important tool to unravel these processes and will be discussed in detail. Finally, the results of these chapters will be merged into a conclusion.
Figure 1  Overview map of the Laurion (map by author).
Chapter 2  The Laurion landscape

Few ancient landscapes have suffered from human impact as much as the Laurion. Attracted by its mineral resources, people have been exploiting the area for thousands of years, resulting in the exhaustion of nearly all the lead and silver bearing veins. A gigantic network of mining galleries and mine shafts still testifies to the mineral extraction but the surface was also greatly determined by the industrial activities. The contemporary landscape is still scattered with spoilheaps, remains of ore washing plants, furnaces and facilities once housing the workers and workshop owners. The fourth century BC mine leases\(^1\) give a good image of the degree of exploitation and how intensively the area had been built up. The busy industrial activities are also reflected in Xenophon’s remark\(^2\) on the bad living conditions as a result of the poisonous furnace fumes, an observation that seems to be confirmed by modern research. A sharp increase in anthropogenic lead emissions into the atmosphere between 600 BC and 500 AD has been detected in the icecaps of Greenland,\(^3\) peat bogs in Switzerland (Shotyk et al. 1998, 1635–40) and lake sediments in Sweden (Renberg et al. 1994, 323-6). Although the link between these observations and mining in the Laurion has never been confirmed, it is hard to imagine that these two facts were not related at all. It is problematic that the evidence of smelting furnaces, the largest agent of pollution, is scarce. These structures only had a short life, during which they were exposed to extremely caustic conditions, resulting in their continuous demolishing and rebuilding (Rihll 2001, 121). Some Classical furnaces have been recorded as a result of their incorporation into especially designed buildings but these do not give a clear image of the scale of ore smelting. An exception is the large furnace complex in the Bertseko Valley (Kakavoyiannis 1989, 83-85), a discovery that unfortunately has not found its way into scholarly literature and will therefore

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2 Memorabilia 3.6.12: To be sure: the district is considered unhealthy, and so when you have to offer advice on the problem, this excuse will serve.
be further discussed in the following chapters.\(^4\) Whether these furnaces had left their signature in the icecaps or not, the large emission of such a densely packed furnace complex and the subsequent effect on the living conditions in the area is beyond dispute. The degree of exploitation and consequently its impact on the landscape was dependable on the level of technology and innovations carried out in mining and silver metallurgy. Especially water technology played an important role in these advances and was therefore determining for the organisation and success of the industry as a whole. Since these innovations occurred in interaction with the environment, they can only be properly studied and understood against the backdrop of geology and geography. In this context, special attention will also be given to hydrology, a factor too often neglected but given the importance of water technology, indispensable in this overview.

### 2.1 Geology

The great interest in the Laurion was geologically motivated. The geology of the region, which is part of the Attic-Cycladic metamorphic belt, is characterised by two systems of strata, all metamorphic or semi-metamorphic in nature, which contain marbles, dolomites, mica-schists, phylittes and phyllonites. The first system is autochthone (A) and the second one is an overthrust phyllite nappe (B) (Marinos and Petrascheck 1956, 24-25).

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\(^4\) The chronology of this complex is problematic but a dating in the late Archaic or Early Classical period is possible, which would indicate that they had been part of the intensified silver quest in the context of the Persian Wars.
The autochthonous system consists of three alternating layers (Figs. 1-2): (1) the lower marble, which is over 600 m thick, (2) a stratum of mica-schists with a thickness from almost 0 m in the south and southeast of the Laurion to 300 m in the northeast and (3) an upper marble of only a few to approximately 100 m. Above this system, an overthrust nappe is present, considerably differing in structure and consisting of phyllites including marbles, limestone, prasinites, serpentine and sericitic quartzite (Marinos and Petrascheck 1956, 25-35).
In the contact zones of these horizons, more specifically between layers with different permeability, specific minerals were developed, the primary ones being two groups of ores:
(1) iron-manganese, which occurs both in the autochthonous and nappe system, and (2) mixed sulphides of lead (galena, PbS), zinc (sphalerite, ZnS) and iron (pyrite, FeS₂), which are generally restricted to the autochthonous system (Marinos and Petrascheck 1956, 83-5). The richest contacts are the first and the third, since minerals best develop directly under the schist horizon. They appear as irregularly shaped tabular lenses or with veinlike and baggy apophyses (Marinos and Petrascheck 1956, 136-7). It is a widespread phenomenon for these primary ores to weather and form secondary ones, such as cerussite (PbCO₃) and smithsonite (ZnCO₃) (Marinos and Petrascheck 1956, 150-4; Rehren et al. 2002, 30). Galena, rather than cerussite,⁵ is believed to be the most frequently employed ore to extract silver and lead from (Rehren et al. 2002, 27).

An important concept in understanding the evolution of silver metallurgy in the Laurion is the richness of the ore, which can vary substantially from deposit to deposit and therefore directly influence the methods applied in metallurgy. The silver content of galena depends on the amount of lead present in the ore. In the Laurion, the lead content varies from just a few to 65% (Conophagos 1980, 126), consisting of 500 to 5000 g Ag/t Pb depending on the mining area and vein it is exploited from (Marinos and Petrascheck 1956, 147). When the argentiferous lead in the ore exceeds 30%, the silver production process is relatively straightforward, as it will only consist of two phases: firstly, the ores are exploited in the mines and secondly, they are brought to the furnaces to separate the metals. If, however, the amount is less than 30%, the ores should be purified first (Conophagos 1980, 126-7), which will considerably complicate the metallurgical process and the organisation of the industry as a whole. Since the average lead percentage of the Laurion ores is low (about 15-20 %), most of these require purification (Conophagos 1980, 21; 127). This process took place in washeries, in which the heavy metal particles of the ore were concentrated, an activity demanding large quantities of water in a virtually waterless area. As a result, a careful and well-organised water management had to be developed. When the amount of argentiferous lead in the ore is below 7 %, the ores are sterile, also referred to as ekvolades. Large amounts of sterile ores were left behind either in or immediately outside the worked mine and are still visible today in the form of spoil heaps. Given the complexity of ore washing and the scarce water resources, it is reasonable to suggest that experiments were only initiated when the rich ore outcrops were largely exhausted (Krysko 1988, 88-90; Mussche 1998, 11-12; Kakavoyannis 2001, 365), or when people were having increasing difficulties finding rich ores in the vein they were exploiting.

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⁵ Conophagos (1980) believed cerussite to be the main exploited ore, since it is more easily processed than galena and it was present in large quantities in the ekvolades (sterile ores). Nevertheless, it is more likely that the detected cerussite was formed due to weathering of primary galena deposited during ancient times (Rehren, et al. 2002, 30).
Considering the geology of the area, it must not be surprising that other minerals caught the ancient miner’s attention as well. The Laurion is a polymetallic area and although not all minerals, such as thallium, cadmium and bismuth, were recognised in Antiquity, many were known, such as ores containing antimony, arsenic, copper and even gold. The extent of their exploitation is very hard to assess but the metallurgists were likely to have focussed primarily on the byproducts of silver metallurgy (Rihll 2001, 128). Litharge⁶ for example could be used as a pigment or medicament and zinc for brass,⁷ which is an alloy of zinc and copper. Also other minerals could be employed for pigments, such as realgar and ochre. As demonstrated by Vitruvius (*De architectura* 7.7.1), Attic ochre was wanted for pottery glaze (Rihll 2001, 129-32).

Geology is not only important to explain the presence of mineral resources, it also interferes with the geomorphological and hydrological properties of the environment. All of these factors will determine the distribution of human populations in the landscape as well as the activities taking place in them.

### 2.2 Geography

The strategic location of the Laurion within the territory of Athens, added much to the success of the Athenian Empire. The area covers approximately 200 km² in the southeast of Attica, only 50-65 km away from Athens. The geography of the Laurion is characterised by a north-south orientated chain of hills (up to 380 m high at Megalo Ripari) and three plains (see Fig. 1): (1) the Potami plain, through which the connecting road to Athens was and still is running, (2) the 2 km long Adami and (3) the Legraina plain, approximately 7 km in length (Marinos and Petrascheck 1956, 22). Besides the smooth accessibility by road, the Laurion is also easily reached by boat. Largely surrounded by the sea, the area knows several natural harbours, of which most are protected against the strong east winds by the elongated island of Makronisos. Thorikos and Sounion are the best historically documented harbours, but archaeology also demonstrated the existence of minor ports such as at Limani Pasa,⁸ which appears to have been a busy centre in ancient times.

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⁶ See Rehren, et al. (1999, 299-308) more information on the specific use of litharge.

⁷ Conophagos (1980, 160) contra Rihll (2001, 130). Rihll’s arguments for the exploitation of zinc, however, are more convincing.

⁸ Salliora-Oikonomakou 1979, 160-173.
The reconstruction of the Classical landscape is difficult but vegetation patterns should have been very similar to the contemporary ones. The descriptions of the ancient vegetation by authors as Hesiodos and Theophrastos demonstrate this neatly (Grove and Rackham 2001, 169). Also, the limestone geology in combination with similar climatological conditions (see section 2.3), could have only allowed a specific kind of overgrowth. It is suitable for savannah-style vegetation with scattered trees and maquis, rather than substantial forests. This brings us to the much debated topic of deforestation, an issue that in modern research has been automatically linked to metal-working. It used to be a common opinion that Attica and the Laurion suffered from severe deforestation in Classical times and metallurgists had been depending entirely on imports. More recently, however, it has been argued that this view is highly exaggerated and that the Laurion was able to answer to a part or, depending on the period, even the entire demand. The issue of the denuded landscape strongly depends on whether or not the growth of trees could answer the timber demand. Therefore, one should always take the scale of the industrial activities in a certain chronological context into account. In this context, Grove and Rackham (2001, 172) have rightly corrected Wertime (1983, 448-51) in his assumption that the Laurion had been deforested. The latter assumed that for the measured amount of slag in the area one million tons of charcoal would have been needed but he ignored that the slag had been accumulating over a span of a few thousand years, with an intensification during the fifth and fourth centuries BC. Deforestation might not have occurred but how (un)likely were timber shortages? Probably, there never was a pressing lack. Grove and Rackham (2001, 172) calculated that Athens should have devoted one-seventh of their land to the industry to keep the fuel supply going. Furthermore, it should not be forgotten that the degree of exploitation was not equal at all times, giving trees the chance to grow before they were cut for fuel use. The mining industry declined at the end of the Peloponnesian Wars (431-403 BC), only to be resumed towards 370 BC (Mortier 2011, 129-30). This gave the fourth century industry a substantial fuel reserve, at least during the first years of exploitation.

In other words, the arguments of the camp in favour of the “ruined landscape theory” are too black-and-white. This opinion was largely based upon Plato’s Kritias, in which the author describes the Greek landscape as the skeleton of a sick body, stripped from its trees and as a result of the consequent erosion, also of its soil.

So although there have been many devastating floods in the course of the 9,000-year interval between then and now, the soil washed down from the highlands in all these years and during these disasters has not formed any considerable pile of sediment, as it does elsewhere, but is constantly rolled down into the depths, where it vanishes. Just as on the small islands, what remains now is, compared with those days, like the skeleton

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One should be cautious with overgeneralisations, certainly with ones based on Plato’s texts, in which the line between myth and reality is often very thin. Uncritical use of both literary and archaeological sources has been the main reason for misconceptions on this topic. The timber demand was clearly rising in the course of the fifth and fourth century BC, amongst others due to the public building program and the construction of the war fleet (Meiggs 1982) but this, as such, is no proof for the entire deforestation of Attica. Another misunderstanding is that timber imports are necessarily motivated by a shortage, whereas it may simply point to a demand for a specific kind of timber suitable for a specific purpose. For instance, it is known that Athens heavily relied on Macedonian timber for its fleet, which according to Theophrastos (Historia Plantarum 3.3.5) was the best for shipbuilding. In the Laurion, a shortage could have occurred in the Laurion in the course of the fourth century BC but still, there is no single indication that the entire smelting industry was depending on imports. Those assumptions have been merely based on the generalisation of a remark in Demosthenes’ Meidias, and a non-critical evaluation of the distribution of furnaces and slag in the landscape. It is a pity that no pollen analyses have ever been conducted on a Classical

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10 Against Medias 21.167: Meidias says that as part of a more extensive cargo, he imported wood from Euboia for his furnaces in the Laurion.

11 Wertime (1983, 451) and Mussche (1994, 89) saw evidence for timber shortages in the accumulation of slags and furnaces along the coast. However, this is not entirely true. Two complexes have been excavated in the coastal areas: the first at Franco Limani (Conophagos 1974, 262-295) dated in the third century BC, the second at Pontazeeza going back to the fourth and third centuries BC (Conophagos 1980, 287-98). All the other furnaces are situated inland. Furnaces dating to the fourth century have been found at Megala Pevka (Mussche and Conophagos 1973, 61-...
context to add to this discussion. The only performed palaeobotanical and pollen analyses were to a late Neolithic and Early Bronze Age context in the Kitsos Cave. Interestingly, this research has demonstrated that the vegetation and climate during this early phase did not differ much from the modern day situation (Mavrommatis 1981, 677).

2.3 Climate & hydrology

In this section, the effect of regional weather patterns on the management of water resources will be explained. Furthermore, a brief overview will be given of some basic hydrological concepts, which will be further elaborated on in Chapter 6.

2.3.1 Climate

The Mediterranean climate is semi-arid, with mild, wet winters and hot, dry summers. Nowadays Athens has an annual rainfall of only 385 mm, the bulk generally occurring in fall and winter, often in the form of violent showers (Foxhall et al. 2007, 246). This pattern is decisive for the environment and accordingly for the human activities taking place in it, especially for societies based on agriculture as ancient Greece. However, it should not be neglected that other economies, not in the least the mining industry, were also greatly affected by rainfall seasonality.

It is generally accepted that the climate of fifth and fourth century Greece resembles the modern situation, presumably with the same temporal and spatial variability in rainfall. This is strongly indicated by e.g. dendrochronological evidence from the Parthenon and literary sources, such as the accounts of Theophrastos (Historia Plantarum 8.6.6) on the growth of local plants. The variability of rainfall patterns is a typical climatological phenomenon, occurring in both modern and ancient times. Nevertheless, it is extremely difficult to recognise these patterns in the available evidence on Classical Greece. A well-known example is the presumed, probably to Attica restricted, drought between 360 and 330 BC (Sallares 2009, 166). As an indication for this drought, Camp (1977, 22-23, 143-146) has pointed on the use of wells and cisterns on the Athenian agora. Wells were preferred for the provision of water in Athens, a trend which seemingly changed in the beginning of the fourth century with

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73) Recorded yet unexcavated ones have been localised in the area of Stefani/Merkati (Mussche 1994, 93-4) and at Berteuko (Kakavoyianis 1989).

12 Mavrommatis 1981, 674; Sallares 2009, 166.
the introduction of the bottle-shaped cistern. These bottle-shaped reservoirs caught rainwater from the roof of private houses and stored it underground, where it remained cool and clean. Some of these cisterns were abandoned in the third century BC by sinking wells right through their bottom. This implies that the introduction of cisterns was affected by a temporary drop in the water table (Camp 1977, 149). Additional evidence can be seen in the increasing depth of the wells from on average 12.7 m in the fifth century BC to 15.2 m in the fourth, some of them even going deeper than 20 m. It should further be considered that people are generally inclined to use groundwater rather than rainwater since it is more hygienic (Trevor Hodge 2002, 60), especially in an area where people have shown a clear preference for wells in the past. The reason for this possible drop in the water table is less easy deduced. It could just be a local phenomenon caused by the depletion of groundwater due to over-use rather than a prolonged drought. Nevertheless, the hypothesis could stand in combination with the evidence of several food shortages and the coinciding appearance of the large cisterns in the Laurion area. The economic effect of such climatologic patterns is extremely difficult to recognise in the past but we should be aware that their impact had been significant.

2.3.2 The hydrologic cycle, reservoirs and water balance

The hydrologic cycle (Fig. 4) is the continuous movement of water on, above and below the earth surface (Han 2010, 11). Precipitation is an appropriate point to start the discussion of this process: it is water released from the atmosphere as rain, snow, sleet or hail. Some of the moisture will evaporate immediately back into the atmosphere, whereas the precipitation reaching the ground will be intercepted by plants, infiltrate into the soil or flow overland or through gullies into water bodies, such as rivers, lakes and oceans. Part of the water infiltrating into the soil contributes to aquifers, which at a given point will be discharged into these water bodies and again be exposed to evaporation. The cycle recommences. Depending on the climatic region, the process of the hydrologic cycle can differ significantly (Sorooshian and Whitaker 2003, 417). In a semi-arid area such as Attica, evaporation occurs more readily than precipitation does, often with dramatic effects at the catchment scale. A catchment, also called a drainage basin, corresponds to the area for which the surface water drains into a river, lake, sea, ocean, estuary, wetland or also an artificial reservoir (Han 2010, 16).

13 Camp 1977, 152-159; Garnsey 1988, 144-9 (Garnsey gives an overview of food shortages but does not follow Camp’s drought hypothesis); Sallares 1991, 390-5.
To better understand the mechanisms behind the hydrological cycle and human interaction with these processes, two important concepts should be further introduced: a reservoir and water balance.

Although in archaeology a reservoir is only conceived as a physical water tank, it is more generally used in hydrology to refer to a water volume. Critical reservoirs at the catchment scale are fresh water reservoirs, more specifically groundwater or land-based water bodies as lakes and rivers (Sorooshian and Whitaker 2003, 419). People have been interacting with these water sources for thousands of years, resulting in the invention of highly technological constructions and devices, from aqueducts, dams, irrigation canals and cisterns to water pumping devices, such as the shaduf, the Archimedean screw, water wheels and even force pumps.

On a global scale, water can be transferred from one reservoir to another by means of fluxes, such as precipitation, evapotranspiration, sublimation and runoff. At the catchment scale, the last flux is crucial. Runoff, or overland flow, can be described as the movement of excess rainfall over the land surface at the moment when the rate of precipitation exceeds the rate of infiltration. It is convenient to replenish rivers and groundwater or recharge artificial reservoirs quickly. On the other hand, it is also a major cause of erosion (Sorooshian and Whitaker 2003, 423). The architecture in Thorikos demonstrates that the ancients were struggling with such processes. For example, during the short occupation phase of House no.1 (430-400 BC), several repairs had been carried out in the southeastern end of the insula. On this side, the exterior wall was also deliberately built in a curve and connected to a drain,
deriving surface runoff more efficiently (Mussche 1998, 46-50). This also relates to Plato’s remark in his *Kritis* on erosion (see quote above). The total amount of water on this earth remains constant but its distribution does not (Han 2010). *Water balance* (Fig. 5) refers to this distribution and more specifically, to volumes of water flowing through various components of the hydrologic cycle, each evaluated as storage units with several in- and outputs. The most simplistic formula to describe this process implies that changes in storage $\Delta S$ (being positive or negative) is the result of the difference between the input $I$ to the system and the outflow $Q$ from that system:

\[
\Delta S = I - Q
\]

where, for a given system, the total inflow $I$ results from surface runoff and groundwater flow towards the system and precipitation onto the system. The total outflow $Q$ is caused by evapotranspiration from the system, and surface runoff and groundwater flow away from it. As a result, $\Delta S$ represents the change in the stored water volume (Sorooshian and Whitaker 2003, 424).

![Water balance in the basin](image)

**Figure 5** Water balance at the catchment scale (after Sorooshian & Whitaker 2003, Fig. 3).

Water balance models at this scale can also be applied on changes in artificial water storage systems, for example when water was used for specific industrial activities.

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14 Apart from House no.1, similar techniques can be seen in Insula 2, House no.5 and Washery no.11. Furthermore, many minor adjustments are visible in nearly every dwelling at the site.
2.3.3 Reservoirs in the Laurion

The precipitation pattern in combination with the geology of the Laurion makes groundwater an insufficient resource. The marble subsoil does not retain rainwater since it will descend through fractures to lower levels in the underlying rock and subsequently flow in eastern direction to the sea (Fig. 6). Groundwater can be tapped through wells on locations where groundwater –generally of weak potential– is flowing close to the surface. This is the case in some valleys, such as at Bertseko, and alluvial deposits, such as at the Adami and Potami plain (Marinos and Marinos 1981, 40). For example, the Euthydike workshop (K. Mexa plot) relied on wells tapping aquifers for its water supply. It was constructed at the foot of a low hill overlooking the Adami plain, at an elevation of about 12 m from sea level (Oikonomakou 1991, 66-9).

The low water table, however, also brought along an advantage: the Laurion miners did not need to bother with the removal of excessive water in the mine galleries by means of complex pumping installations, as was necessary in the Spanish mines in the Roman period.

Other sources of fresh water are springs. The passage of water through fractures in the marble can be interrupted by impermeable layers, which can lead to the creation of springs or occasionally even to a line of springs at the boundary between these layers (Higgins and Higgins 1996, 11). In the Laurion, springs were few (Marinos and Marinos 1981, 40) but exploited wherever they occurred. Although most springs have dried up today, the archaeological evidence can point out their previous location. In the north branch of the upper Soureza Valley, there could be cisterns relying on spring- rather than rainwater. The Upper Marble is highly fractured here, which can lead to the creation of karstic aquifers. One rectangular cistern seems to have been depending on springwater discharged from a cavern.

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**Figure 6** Schematic representation of rainwater infiltration in the underground at Mikro Ripari, near Aghios Konstantinos (after Marinos and Marinos 1981, Fig. 23).
system. It is walled off from the valley bottom to block surface flows and does also not have a decantation basin at its disposal, which would clean the turbid surface runoff. In contrast, other cisterns surrounding it do make use of such a settling tank. Because of the heavy overgrowth, it is difficult to recognise spring use but the geological conditions in this valley make it likely that more cisterns would have relied on springs along the strike of the Upper Marble unit.\(^{15}\)

Multiple (dried up) springs can also be seen in the Industrial Quarter in Thorikos. The most interesting spring is the one around which Insula 2 has been raised (Fig. 7).\(^{16}\) The spring starts as a deeply eroded fault surface in the marble outcropping enclosed in the rear end of room DR and is running further south through the entire length of the house. This room seemed to have been a small shrine making use of the spring water, as indicated by the gourna and the niche in its northern wall. Passing through the courtyard, the fracture also connected two underground cisterns, cut into the rock and coated with hydraulic mortar. Such subterranean interconnected cisterns, where one collected the overflow of the other, are common features in the Laurion.

Likely, there are two more former springs: one right above the entrance of Mine no. 2 and a second one little east of Cistern no. 1. The archaeological remains seem to indicate that these springs have been exploited in ancient times but without a proper examination of the area, this remains speculative.

Spring and groundwater has surely been the preferred source for drinking purposes. It is fresh and clean, in contrast to the turbid surface runoff harvested in the open reservoirs and used for industrial purposes. The quality of this water must have certainly been questionable, given the heavy metallurgical activities in the area.

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\(^{15}\) This information is based on data retrieved from a fieldwalk in the Soureza Valley during the summer of 2011 and personal communication with J. Kepper, who has published two papers on the Laurion in *Historical Metallurgy* (38, 75-83; 39, 1-11).

\(^{16}\) This spring has been brought to my attention by J. Kepper as well.
Rivulets are scarce. Nowadays, most of them are either seasonal or have dried out completely. It is very difficult to assess the situation 2500 years ago, especially without thorough geomorphological research, but some interesting things can be put forward. It is unlikely for the rivulet pattern to have differed dramatically from the modern one given the similar climatic and geological conditions. Furthermore, the huge number of cisterns relying on rainwater themselves forms clear-cut proof for the poor and seasonal water resources in the Laurion. Not forgetting, the main purpose of cisterns was to bridge the dry periods of the year, indicating that water provision in the dry spring and summer months had been problematic. Nevertheless, some attempts had been made to exploit rivulets for industrial usages, such as in the previously mentioned Bertseko Valley. On the valley side opposite the furnaces, there was an extensive, presumably contemporary washery complex. The washeries should date to a period when the technology of hydraulic mortars was not mastered yet, disallowing the construction of cisterns to supply the washeries. This is a very important observation. The rivulet was undoubtedly seasonal, as suggested by wells dug right in the middle of the riverbed, an action which would have only made sense if the rivulet had dried

up at some point of the year.\textsuperscript{18} As a result, the industrial activities would have been restricted to rainy periods. Apart from the Bertseko workshops, there is–to my knowledge–only one other recorded workshop, which could have been relying on a rivulet: the fourth century BC Zoridis compound built right next to the Potami river near Thorikos (Zoridis 1980, 83; Van Liefferinge 2013, 124), which will be further discussed in the following chapters.

Epigraphic data, especially the mine leases, also give a small glimpse of the Classical landscape. These leases, recorded by the \textit{poletai} during the fourth century BC, contain information about the leased mine, such as its name, the lessee, information about the property on which the mine is situated and its approximate location, indicated by its boundaries (Crosby 1950, 192). These borders can be a workshop, a mine, other private property and sometimes features in the landscape, such as roads, hills and χαράδρα or gullies.\textsuperscript{19} Table 1 on the next page gives an overview of the leases in which these rivulets are mentioned and if available, the location of the leased mine and the direction in which the gully was flowing. It is hard to locate these rivulets in the contemporary landscape, not only because some have undoubtedly dried out, but more importantly, because of the ambiguity of the toponyms.\textsuperscript{20} Two of them, however, can be identified with certainty. The gully mentioned in connection to Thorikos and Laureion\textsuperscript{21} must be the modern Adami (Mussche 1994, 81). Nape can be identified with the Soureza Valley, so the gully \textit{flowing from Nape} is the one little south of the Soureza Valley, with in its east the Michaeli hill, west Spitharopoussi and southwest Mega Viglia (Vanhove 1994, 38-9).

As is clear from this overview, the precipitation regime and climatic conditions strongly controlled water use and management in the Laurion industry. Groundwater, springs and gullies were unreliable, poorly distributed and for extensive industrial activities completely insufficient. Societies dealing with such meagre water resources had few options: either they conveyed water from distant areas through aqueducts, or they tried to employ the local resources through the development of appropriate techniques. Since there were no nearby water sources on which an aqueduct system could rely, the creation of an artificial water storage system was unavoidable, especially when the water demand was rising due to the increasing silver production and growing population. Also clear is that water use and management in the Laurion industry was not a one-sided story. Depending on the context and purposes, all the available water sources had been exploited but for extensive industrial

\textsuperscript{18} These wells have been observed during a fieldwalk in the Bertseko Valley in the summer of 2012.

\textsuperscript{19} For the interpretation of the word χαράδρα, see Crosby 1950; Hopper 1968, 323; Mussche 1994, 79.

\textsuperscript{20} Maroneia, for example, can be connected with the area of modern Aghios Konstantinos but Lohman (1993, 104) also suggests the name may have referred to Noria, Elafos or Lagos. For Thalinos, the evidence is far too ambiguous to allow even a general interpretation (Ibid., 107).

\textsuperscript{21} Laureion has been identified as the modern day Plaka (Ibid., 102).
usage, rainwater was certainly the only feasibly one. The importance of rainwater harvesting can also be seen in the distribution of the workshops, especially in the central Laurion valleys, which were particularly favourable sites for rainwater harvesting.

<table>
<thead>
<tr>
<th>Lease</th>
<th>Location mine</th>
<th>Gully</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crosby 1, 56</td>
<td>Laureion</td>
<td>‘Gully of Thorikos’</td>
<td>Crosby (1941), 14</td>
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<td>Crosby 3, 7-8</td>
<td>/</td>
<td>/</td>
<td>Crosby (1950), 208</td>
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<td>Maroneia</td>
<td>/</td>
<td>Crosby (1950), 56</td>
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<tr>
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<td>/</td>
<td>/</td>
<td>I.G. II², 1583</td>
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<tr>
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<td>/</td>
<td>‘Flowing to Anaphlystos’</td>
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<td>Crosby 8, 16</td>
<td>/</td>
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<td>Thalinos</td>
<td>/</td>
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<tr>
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<td>/</td>
<td>/</td>
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<td>Maroneia</td>
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<td>Crosby (1950), 236</td>
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<tr>
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<td>Crosby (1950), 247</td>
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<td>Crosby (1950), 249</td>
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<tr>
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<td>/</td>
<td>/</td>
<td>Crosby (1950), 261</td>
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</table>

**Table 1** List of the χαράδρια, as mentioned in the mine leases.
Chapter 3  Shaping Athenian history

The history of the Laurion –and as a corollary the evolution of silver metallurgy– is ultimately linked to the history of Athens. Therefore, this study should start with a brief historical background, sketching the political and economic events that affected life as well as work in this region.

Attention will also be given to external factors that seem to have influenced the activities at Laurion, primarily the role of the Thracian mines. The duplicates of toponyms, such as Maroneia and Pangaion, demonstrate that the history of both mining areas is more intertwined than one would presume. Apart from this, inscriptions have revealed a considerable number of Thracian slaves that were set to work in the Laurion mines (Morris 1998, 201-2). These factors prompt to involve northern Greece in this discussion.

3.1  The late Archaic period and the introduction of coinage

It can safely be assumed that the Laurion mines became increasingly important for the Athenian polis from the sixth century BC onwards. Around the middle of that century the first Athenian coinage –traditionally referred to as the Wappenmünzen or Heraldic coins– was struck.¹ Not incidentally, this was also the time when Peisistratos consolidated his tyranny, leaving little doubt that the introduction of coinage happened at his initiative or within his sphere of influence (Van Alfen 2012, 89). It would be wrong to automatically link the

¹ As suggested by Solon’s laws, the Athenians already started to use ‘cut’ silver as a commodity by the early sixth century BC for a variety of payments, which involved public, but likely also private expenses (Van Alfen 2012, 88-89). Although these actions must have already increased the silver demand, this was surely in no comparison to what the introduction of coinage had affected.
introduction of Athenian coinage to the start of the large-scale development of the Laurion. Moreover, research on the mineralogical composition\(^2\) of these early silver coins has demonstrated that the Laurion was only the primary silver source from the introduction of the Archaic owls around 515 BC onwards. The *Wappenmünzen* are manufactured from a less homogeneous group, possibly with a primarily Thracian provenance.\(^3\)

Although its early history is somewhat obscure, Thrace was an area of great interest from the sixth century BC until the Roman occupation, not in the least for the Athenians. During his exile from 556 to 546 BC, Peisistratos was presumably the first prominent Athenian to get actively involved in the exploitation of the Thracian mines. Aristotle (*Athenaion Politeia* 15) and Herodotos (*The Histories* 1.63) described his exile, his role in the development of the mines and the fact that he enriched himself greatly by the revenues drawn from them.\(^4\) In this context, the use of Thracian silver for the *Wappenmünzen* makes sense, but the mineralogical composition of these coins suggests that the Athenians persisted on silver of a non-Attic origin for years after Peisistratos’ return to Athens. Why would Athens continue to put effort in the exploitation of the considerably more remote Thrace, when it was blessed with silver mines within its own territory? Logic dictates that the development of silver mines on its own lands would involve considerably less risks.

A possible explanation could be a purely geological one. As explained in Chapter 2, Laurion ores had a low metal grade of only 15-20 %,\(^5\) necessitating their purification and considerably complicating the silver production process. In contrast, the Thracian ore deposits appear to have been richer.\(^6\) Herodotos (6.46.3) underlined the great potential of the mines, when referring to the Thasians, who benefitted from an annual revenue of 200 to 300 talents from some of their silver mines on the Thracian mainland in Scapta Hyle. The processing of high grade ores does not only require less energy but also less investment and organisation. That being said, it should be borne in mind that the Athenians favoured this region for much more than just its mineral resources. Northern Greece was of strategic importance for the supply of timber and the protection of the corn route to the Black sea area (Hopper 1979, 168).

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\(^3\) See Kraay 1958, 1-2; Kraay and Emeléus 1962, 15; Nicolet-Pierre, et al. 1985, 26; 31; Van Alfen 2012, 91. The drachmes, didrachmes and tetradrachmes of the *Wappenmünzen* were not of Attic origin, but some of the oboles, which show the same characteristics in composition as the Archaic owls, clearly were. Apart from these analyses, there is no convincing literary evidence that the Laurion was being mined on a large scale, only indirect allusions. It has for example been suggested that the tyrant Peisistratos, who was supposed to own property in southeast Attica, had ‘free miners’ among his supporters (Hopper 1961, 140). The analyses also pointed to the use of remelted objects, such as jewelry, ingots, and the reissue of foreign coins or more ancient series.

\(^4\) Shepherd 1993, 101; Hopper 1979, 166.


Under the reign of Hippias and presumably no later than 515 BC, a significantly different coin made its appearance, which would determine Greek coinage for centuries afterwards: the Athenian owls. A drastic change was not only recorded in coin typology but also in the origin of the silver: the primary source was undoubtedly native silver. What could have triggered this switch to chiefly Attic silver? Although we should be cautious about making a too hasty connection, the introduction of the owls coincides suspiciously well with the increasing Persian pressure under Darius, leading to the loss of the Thracian mines in 512 BC. This situation could have stimulated the search for silver deposits closer to home and thus the development of the Laurion as a fully operational mining area (Hopper 1961, 141; Shepherd 1993, 97). In this sense, it is not surprising that ‘the great silver strike of 483/2 BC’ took place during this period of conflict. The discovery of the so-called Third Contact was one of the most decisive moments in Athenian history, ensuring the construction of a new war fleet, the defeat of the Persians and consequently, the birth of the Athenian Empire. This is well illustrated in Aristoteles’ words, when discussing Themistokles’ actions:

Two years later, in the archonship of Nicomedes, in consequence of the discovery of the mines at Maronea, the working of which had given the state a profit of a hundred talents, the advice was given by some persons that the money should be distributed among the people; but Themistokles prevented this, not saying what use he would make of the money, but recommending that it should be lent to the hundred richest Athenians, each receiving a talent, so that if they should spend it in a satisfactory manner, the state would have the advantage, but if they did not, the state should call in the money from the borrowers. On these terms the money was put at his disposal, and he used it to get a fleet of a hundred triremes built, each of the hundred borrowers having one ship built, and with these they fought the naval battle at Salamis against the barbarians.

Aristoteles, Athenaión Politeía 22.7

Under the impulse of Themistokles, the Athenians spend the silver from Laurion on a greater good: the construction of a war fleet to be used in the war against the invading Persians. The exact moment of this often called ‘lucky silver strike’ was in all likelihood not 483/2 BC but several years earlier. Ardaillon (1897, 136) and Conophagos (1980, 94) suggested the discovery of this vein to have occurred five to ten years earlier, a dating that is probably justified. Picard (2001, 1-10) even takes this one step further and states that the Archaic owls...
were already manufactured with silver from the Third Contact, pushing back this date to approximately 515 BC.

This overview shows that not one but rather a wide range of factors added to the development of the Laurion industry, starting with the introduction of coinage and intensifying due to the Persian Wars. Archaeological evidence is hard to involve in this discussion and leaves a somewhat confusing image, since traces of mining and metallurgy are basically non-existent. There is, however, clear proof for an increasingly intensifying occupation pattern, especially from the middle of the sixth century BC onwards.

Actual architectural remains are few but undeniable. Archaic occupation traces are best documented in Thorikos. Besides some wall fragments in the Industrial Quarter, such as at Insula 1 and the shrine for *Hygieia* ([Fig. 8](#)) (Mussche 1971, 103-133), and the hero cults in the Bronze Age graves, the most impressive structure is undoubtedly the well-known and unique theatre with its elongated shape (Mussche 1998, 61-62).\(^\text{10}\)

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\(^\text{10}\) A. Kapetanios has recently raised some doubts about this early chronology of the theatre and expounded his view during the conference *Thorikos 1963-2013. Fifty years of Belgian excavations at Athens* (7-8 October 2013).
Signs of mining and metallurgy are lacking, apart from some small-scale activities. In the primary fillings of the bedrock in the Tower Compound, there is evidence for small-scale iron melting. Based on these finds and their analysis, the excavators considered it plausible that people were mining haematite and limonite on the Velatouri before the construction of this insula (Spitaels et al. 1978, 66). The architectural remains may be scarce, but the substantial quantity of pottery found in the rock fillings reveals a densely occupied Thorikos from the sixth century BC onwards, an image that is maintained until the beginning of the third century BC. This long occupation pattern also clarifies why the earlier remains are so difficult to record: these structures have simply been supplanted by the construction of later dwellings and workshops.

Besides the abundant pottery finds, Archaic occupation is best observable in funerary remains. In the Thorikos cemeteries, from the Theatre Necropolis to the Western, Southern and D1 graveyards,\(^1\) no less than 41 of the 94 datable burials can be dated to the Archaic period, the absolute majority after 650 BC (Mussche 1998, 28). Pathological research could possibly illuminate pathological anomalies caused by the heavy labour involved in mining or

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the working in close contact of the poisonous furnace fumes, but such studies remain unpublished. Other cemeteries in the Laurion indicate Archaic presence as well. At Kalyviou Thorikou, northwest of the tower of Melissourgou, an extensive cemetery was reported dating from the Late Geometric to the Classical period (Tsaravoopoulos 1997, 86). Finally, three urns dating circa 490 BC have been uncovered in a necropolis in the ancient Maroneia area (Salliora-Oikonomakou 1985). The absolute bulk of these graves, however, cluster around 470-440 BC and will therefore be discussed in the next section.

The only archaeological ‘evidence’ for silver mining and metallurgy is the previously mentioned Bertseko washery and furnace complex, situated south of Aghios Konstantinos. As will be discussed in Chapter 5, one should be careful with the dating of this complex, since the excavations did not yield strong chronological indicators. Additional excavations should be done to either confirm or reject this dating. Notwithstanding, the literary and numismatic evidence presented in this overview testifies to the undeniable operation of the Laurion mines during the late Archaic period.

3.2 The fifth century BC and the rise of the Athenian Empire

After the Persian Wars, the Greek world changed enormously. Thanks to the silver resources of the Laurion, Athens consolidated its naval power in the Aegean, supporting the ascension of the Athenian Empire. Nevertheless, this glorious period also leaves us with an ambiguous set of data. As outlined above, we have no supporting evidence for mining or metallurgy in the Laurion until 425 BC, and even afterwards we are ill informed; However, the tremendous coin production, especially around the time of the removal of the Delian treasury (454 BC), and the scale of expenditures—the Acropolis works, the public offices, the military expenses—nearly makes it impossible that the silver mines were not in operation.

There are a few literary references to mining and metallurgy during the pentakontaetia, or the fifty years between the Persian and Peloponnesian Wars. Aischylos referred to the wealth of the Laurion mines (Treasure, a fountain of silver, lies in their soil) in his Persai (238), dating to 472 BC but this may as well be a reminiscent remark to the discovery of the Third Contact some time before. Crosby (1950, 190-191) refers to a second one, in the form of a fragment in the

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12 There is an unpublished master thesis on this topic by Defever (1990). Furthermore, F. Janot has recently investigated the skeletal remains of the Thorikos cemeteries for publication in the forthcoming Thorikos 12.

13 Sector II, Burial 4, 40 and 68.
Parthenon and Propylaia building inscriptions, which could be mine receipts recorded by the treasurers of the Hephaistikon from Laureion. Given that this was a common name for mines during the fourth century BC, this could have been a mine; however, the possibility that it was a sanctuary is perhaps more likely. This image is repeated in archaeology: there was clearly considerable activity in the Laurion but the link with mining cannot securely be made (see further).

The question remains whether or not this hiatus reflects an actual inactivity of the mines. The Athenian Empire profited from a wide range of revenues, from the annual tribute or phoros paid by the members of the Delian League to the appropriation of land and the raising of maritime transit taxes on cargo (Kallet 2000, 177-9). Thukydides mentioned that silver was an integral part of these revenues but the only evidence for Athenian interest in silver mines leads to Thrace and not Laurion. As became clear from the discussion of the late Archaic period, Thrace was not only rich in metals, but was also blessed with a plentiful supply of timber, water and an experienced labour force among the natives (Hopper 1961, 145). Evaluating the continuous attempts to restore her influence in northern Greece, first by the possession of Ennea Hodoi and later by the foundation of Amphipolis in 437 BC, this had clearly not escaped Athens’ attention. Thucydides (4.108.1) is unambiguous when stating that the city was useful to Athens for the ship-timber that it sent and the silver revenue. In addition, the involvement of several prominent Athenians, not in the least Perikles and Thukydides himself, is notable. Both men were owners of Thracian mines and enriched themselves greatly under this situation. Thukydides even married a Thracian woman from Skapte Hyle, inheriting gold mines and by doing so enforcing his position in the region. It is also striking that Perikles in his discussion of the revenues of the Empire at the threshold of the Peloponnesian Wars neither referred to the Laurion mines, nor underlined their importance for Athens.

A coincidence or not but the evidence increases steadily when the Peloponnesian Wars set off and Athenian power in Thrace was jeopardised. The Wars lasted from 431 until 404 BC, with a short break during the peace of Nikias. The fierce attempts of Athens to keep a firm foothold in northern Greece indicate that this area was considered of critical importance. The city-state persisted to be on friendly terms with the Macedonian king Perdikkas and Thracian king Sitalkes (Kallet 2000, 189) but these relations turned out to be less solid than Athens had

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14 Around the same time of the Athenian clash with the Thasians, the Athenians had allies and a part of its own citizenship settle at a place called Ennea Hodoi or “Nine Ways” in the Chalkidiki. The place, however, became a matter of conflict between them and the local tribe of the Edonians, who saw the possession of Ennea Hodoi as act of hostility. Eventually, the Athenians lost this strategic town but continued their attempts to gain foothold in northern Greece, finally succeeding with the establishment of Amphipolis in 437 BC (Hopper 1979, 166-7).

15 Thukydides 1.139-45; 2.13-14.

16 Hopper 1961, 143; Photos-Jones and Ellis Jones 1994, 310.
hoped for: in 424 BC, the Spartan Brasidas persuaded many Athenian allies in Macedonia and Thrace to revolt, not in the least their most strategic colony Amphipolis, cutting off the Athenians from crucial supplies.

Pherekrates, a poet from the Old Comedy, shows with his *Miners*, dated to the early 420’s, that mining was of concern; However, he did not connect it directly to the Laurion. More intriguing is the work of his contemporary colleague-comedian, Aristophanes. His *Knights* suggests the leasing of mines as early as 424 BC (Crosby 1950, 191). In another comedy, the *Birds* (1104), Aristophanes makes this even more obvious when mentioning the *owls from Laurion*. A further reference touching upon the same topic, is a coinage degree from the late twenties, likely 422 BC, from which it is deducible that the *poletai* had been instructed to start regulating the Laurion mines (Meritt 1945, 119-22) but since there is no reference to this ‘law’, it is difficult to assess its true impact. This brings us to the administration of the mines. The fragments of Aristophanes suggest the leasing of mines at least from the last quarter of the fifth century BC onwards. This method of operation contrasts to the image of the preceding period, when mining was clearly a public concern. The information on the administrative procedure, however, is not yet well-defined. During the fourth century BC, the *poletai* were in charge of the administration of the mines, which is well recorded on the *stelai* raised on the agora, listing farmed out mines and their lessees. Aristotle (*Athenaion Politeia* 47.2-3) informs us that the *poletai* were magistrates, working for the Boule and charged with the financial affairs of Athens, such as imposing taxes and the leasing and/or confiscating of land. Pointing out the absence of such earlier inscriptions, some have doubted the involvement of these *poletai* before the fourth century BC, but more decisive arguments have been given in favour of their involvement. In any case, the involvement of entrepreneurs seems to have been a fact from at least the last quarter of the fifth century BC.

A further interesting trend is the increasing amount of references to enterprises closely linked to the mining industry, such as the rental of slaves. Several individuals gained significant wealth from such businesses. Nikias I was known to have owned no less than 1000 slaves, Kallias 600 and Philemonides 300 (Cartledge et al. 2002, 164). Also involved in mining may have been Hipponikos II, known for owning property in the Laurion and a predecessor of the family of Kallias-Hipponikos mentioned in the fourth-century mine leases (Hopper 1961, 147). An example of a lesser known person is Diokleides (Andokides, *On the Mysteries* 1.38).

In spite of the increased level of activity observable at Laurion during the Peloponnesian Wars, these activities were disturbed little time afterwards. After the loss of their assets in northern Greece, the Athenians got a second ‘silver’ blow in 413 BC. Thukydides (7.27.3-5)

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17 Only fragments have been preserved of this play, of which the authorship is contested (Storey 2011, 470-1).
18 Aristophanes, *Knights* 362: “ὠνήσομαι μέταλλα”.
19 For a detailed motivation of this hypothesis, see Langdon 1991, 61.
reports that on the advice of the deserted Athenian Alkibiades, a Spartan garrison was installed at the northern Attic town Dekelea, an action that clearly did not miss its goal: no less than 20,000 slaves revolted, further weakening Athens’ position in the war. Although this number is undoubtedly exaggerated and not all slaves would necessarily have been set to work in the mines, this amount is fascinating, since it further testifies to the considerable economic activity in the region and the strategic importance of the Laurion for the Athenians.

The Peloponnesian Wars ended catastrophically for Athens. In 406/5, the city-state was forced to mint two emergency coinages, consisting of gold staters and fractions on the one hand and silver-plated bronze drachmes and tetradrachmes on the other. This indicated not only the obstructed silver supply but also the economic and political chaos, in which Athens found itself. The empire came to a definite end in 404 BC, when the Spartans surprised the Athenian fleet at Aigos Potamos, subsequently sailed to Athens, blocked the harbour and by doing so forced the city-state to capitulate (Kallet 2000, 194).

Reminiscent to the late Archaic period, the archaeological evidence for the Laurion presents a different image than the literary sources. On the one hand, there is significant fifth-century evidence, even for the period between the Persian and Peloponnesian Wars, but on the other hand, the remains do not clearly point into the direction of mining and metallurgy.

In Thorikos, the middle of the fifth century BC was a period of great expansion, especially in the Industrial Quarter. The first building phase of Insula 3 and Insula 1 goes back to the second quarter of that century. During the following 25 years, building activity continued to increase, with the construction of new buildings (e.g. House no.1) and the adjustment of older ones (e.g. Insula 10, see also Fig. 8). During the Peloponnesian Wars this pattern can be further observed: House no. 5 was constructed and according to Mussche (1967, 48-62, 1968, 97-104, 1998, 50-51), Insula 1 was reorganised into an ore washing workshop, now named Washery no. 1. Outside the Industrial Quarter, the construction of the fortification on the peninsula of Aghios Nikolaos in last quarter of the fifth century BC should be mentioned.21

Burials further support this image. In Thorikos, 19 graves spread over the different necropolises can be convincingly dated to the fifth century BC (Mussche 1998, 62). At the cemetery of Kalyvia Thorikou, several fifth-century graves have been reported (Tsaravopoulos 1997, 86). As already mentioned in the previous section, the Maroneia cemetery was still in use, peaking during the period from 470 to 440 BC (Salliora-Oikonamakou 1985, 91-132). These burials might offer the only evidence for mining during the pentakontaetia. Since this large cemetery is situated in an area known to have been a mining

21 Mussche rightly defends that this fortification is likely the one mentioned by Xenophon and that the date, the 93rd Olympiad, can be narrowed down to 412 BC (Mussche 1961, 176-205; 1998, 16-7).
centre during the late Archaic and the fourth century BC, it is tempting to link these burials to a mining community. Morris (2011, 179-88) mentioned that in comparison to the rest of Attica, a high number of burials had no or poor offerings, tentatively allowing their identification as slaves. It is known that the number of slaves at Laurion was high, and therefore, the involvement of these individuals in mining could be assumed. Salliora-Oikonomakou (1985, 128), the excavator of the Maroneia necropolis, further pointed out burial I.25, which she dated to the mid fifth century BC. This dating would not attract much attention if it was not reusing an inscription recording the sale of mining rights. This would lead to the conclusion that mines had been leased to private entrepreneurs before this grave was sealed. Nevertheless, this is not very plausible. First of all, the inscription mentions the sale of an anasaximon mine, a terminology that is known only to have been commonly in use from the fourth century BC onwards. Furthermore, there is neither epigraphic, nor literary and archaeological evidence for the leasing or selling of mines before 424 BC. Finally, critiques can also be given on the dating: due to absence of grave gifts, Salliora-Oikonomakou established a chronology based on the surrounding burials, yielding grave goods from the mid fifth century BC. Of course, this does not automatically mean that this grave is contemporary. In Thorikos, graves of varying date are scattered over the cemeteries, often without a clear organisation in terms of chronology. All things together, this conjectural evidence is not satisfactory to use as proof in this discussion. Pathological research on the skeletal remains, for example, could help clarify the issue but such research has unfortunately remained unpublished.

The general image, however, is clear. Mining in the Laurion had a low profile after the Persian Wars, possibly under influence of the silver resources of northern Greece, an image that changed from the last quarter of the fifth-century BC. The most notable event is the first evidence of a new organisational structure that allowed private entrepreneurs to be actively involved in the mining industry. The public mining concern, as revealed by Aristoteles, no longer seems to be a mainstream practice.

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22 70 % of the intact adult and 68 % of the child burials did not contain any grave goods at all (Morris 2011, 181).

23 An estimated slave:free ratio in the late fifth century Laurion must have been 1:1 or 2:1 and could have even been 3:1 or higher in the late fourth century BC. As a matter of comparison, this ratio elsewhere in Attica must have been significantly lower, more likely ranging between 1:4 and 1:10 (Morris 2011, 180).

3.3 The fourth century BC and the issue of the regression of mining

Despite the severely weakened position of Athens after the Peloponnesian Wars, the city-state not only managed to restore its democracy, but also initiated a public building program and strengthened its naval power. Instead of drawing revenues from the empire, Athens now sought capital through contributions from mainly the elite, such as liturgies and taxes on property (Millett 2000, 38). Xenophon’s pamphlet *Poroi*, dating to circa 355 BC and listing a series of possible measures to increase revenues, fits in well into this picture. The author pays substantial attention to the Laurion mines, a business where many well-off Athenians got engaged in around the time this pamphlet was published.²⁵ Interestingly, Xenophon did not only pin his faith upon leasing funds to support the expenditures of the State but also on businesses connected to the mining industry, notably the rental of slaves. Referring to the case of Nikias, he pleads for Athens to get involved in this enterprise itself by creating a public body of slaves to be rented out for one obol a day (*Poroi* 4.14-24). The impact of Xenophon’s suggestions, however, is uncertain.

In 393 BC the familiar silver coinage was reintroduced but this does not seem to coincide with an immediate reopening of the Laurion industry. The recovery was slow, with the first signs of activity around the transition of the first to the second quarter of the fourth century BC. The first proof appears in the form of the mentioned stelai raised on the agora. The leases recorded transactions between the State, under surveillance of the *poletai*, and private businessmen. The mineral deposits of the Laurion remained property of the State, but the mining rights were farmed out, a system that would create a substantial cash flow in favour of the city-state. The first preserved lease dates to 367/6 BC but the text allows deducing the establishment of one earlier stele, which—considering that the mines were let out for either seven or three years—leads to a date between 374/3 or 370/9 BC. This coincides well with the economic policy of Kallistratos (373-366 BC), underpinning the revival of the Athenian economy. A similar chronology is suggested by Xenophon’s remark (*Poroi* 4.28) that mining had only recently been resumed. Mussche (1998, 64) sees archaeological indicators for the restarted mining activities in the inkwell lamps²⁶ uncovered in Mine no. 3 but this would, as has rightly been suggested by Mortier (2011, 129-30), lead to a circular reasoning. Mussche (1998, 64) explains that the dating of these lamps, produced between 370 and 260 BC, is a reliable archaeological argument for dating the resumption of mining activity but omits that Blondé has

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²⁵ Shipton (2000, 31) notes that 12 to 19 % of the wealthy elite had been directly involved in mining through leasing contracts.

established the starting date of her chronology based on the leases. There are no strong archaeological arguments allowing a specification of the resumption of mining but the general image is clear. By the middle of the fourth century and under the financial advisor Eubolos (354-340 BC), the mining industry peaked, which is not incidentally also the period to which the bulk of the archaeological remains date. Ergasteria appear everywhere in the landscape. The observable trend is that workshops were either raised from scratch or –more interestingly– installed in older residential buildings, an image that is particularly noticeable at Thorikos (Mussche 1998, 64) and will be further elaborated on in Chapter 6. Apart from this, Mussche also reports the extension of the koilon of the theatre, the erection of the so-called Demeter temple and multiple adjustments to the houses. Furthermore, noteworthy information can be gained from Mine no. 3. The mine, located directly west of the theatre, is the only excavated mine of the Laurion and yields finds dated to four distinctive periods: the Early Bronze Age, the Late Bronze Age, fourth century BC and the late Roman period.

The literary evidence is also unambiguous about the fact that the mining industry had become an integral part of the public life. As revealed by several orators, mining operations were a frequent matter of dispute. In order to steer these operations in the right direction, a Metallikon Dikasterion (mine court) was established and Metallikoi Nomoi (special mining laws) were promulgated (Kakavoyiannis 2005, 153-4). Illegal mining, for example, was considered a severe offense. Lykourgos had one Diphilos convicted to death, charging him for impairing and diminishing the props of the metal mines, and unjustly making himself rich therefrom (Plutarchos, Vitae Decem Oratorum 843d). Furthermore, issues are recorded concerning the sale and (re)leasing of property, such as the case of the ergasterion of Pantainetos. These speeches are valuable: they do not only indicate the high degree of activities but also point out that ergasteria, in contrast to the mines, were private property to be sold, leased and mortgaged as a security together with its slave staff. It is not surprising that such a situation lead to discord. The archaeological remains show how closely these ergasteria were packed together. There were many parties included in this industry, from the State and the local community, to entrepreneurs, who were exploiting and building over the latter’s lands.

The leases decreased afterwards, the last one dating to 307/6 BC (Crosby 1950, 190). This pattern can be linked to the increasing international pressure, especially due to the battle of Chaeronea in 338 BC, the Lamian War and the installation of the oligarchy of Demetrius of Phaleron, events that did not encourage involvement in the risky mining business. It should also not be forgotten that the market was flooded with silver and gold looted during the

29 Against Pantainetos 2-5; 9-13, 22, 25-6, 28-9, 35-8.
conquest of the Persian Empire by Alexander, causing a devaluation of silver. Even though the literary sources suggest a rather abrupt ending, this is harder to deduce from archaeology. Albeit on a smaller scale, silver was still worked and evidence for a continuous occupation can be observed during the first half of the third century BC. Several workshops in the wider Thorikos area, such as the Zoridis (Zoridis 1980, 75-84), Skitzeri (Oikonomakou 1996, 125-133), Kavodokano (Oikonomakou 1996, 133-139) ergasteria, demonstrate silver processing during the first half of the third century BC. The same goes for the Ari workshops located more to the north of the Laurion region (Tsaimou 2005, 19-28; 2008, 435-52).

Thorikos is a more difficult case study to include but a pattern of (more scattered) occupation is represented. Noteworthy is the monetary hoard uncovered in a chytra in Insula 2, containing 282 Attic tetradrachmes and 10 coins of different origin with a closing date of 295 BC (Bingen 1973, 2010). Other evidence for Early Hellenistic activity can be seen in the earlier mentioned inkwells lamps, dated by Blondé between 370 and 260 BC (Mortier 2011, 130-1). The most obvious Hellenistic material, however, was found in House no. 2, directly west of the Theatre. ‘Megarian’ bowl fragments indicate the use of the house in the early third century BC (Mussche 1998, 34-5).

Figure 9
Find locations of Late Classical and Early Hellenistic material in Thorikos with on the left the Industrial Quarter and on the right the Theatre zone (Mortier 2011, Fig. 1).
Evidence disappears after this period, with a short revival in the second century BC. Although there is no proof for actual mining at Thorikos, mining and metallurgy must have reached a certain level again, considering the introduction of the so-called New Style coins in 164-3 BC. Apart from this, the slave uprisings of 134 and 104 BC indicate that the metal industry was operational (Mussche 1998, 65). Actual archaeological evidence is, apart from an iron forge installed on top of a burial monument in the Theatre Necropolis, scarce (Varoufis 2014, 119-24). A more intensified revival occurred in Late Roman times, presumably initiated when the exploitation of the Spanish mines was jeopardised under Theodosius II (408-450 AD) and Marcianus (450-471 AD). The finds of 70 Roman lamps in and around Mine no.3 demonstrates that the mines at Thorikos were reopened (Mussche 1998, 65), while the installation of smelting ovens, such as at Skitzeri (Oikonomakou 1996, 124-33), testifies to the resmelting and processing of argentiferous phynites (the waste of the ore beneficiation) and slags. Scattered finds, from amphorae fragments in Insula 3 to graves in the Theatre Necropolis and a variety of finds spread over the site, indicate that Thorikos was inhabited, albeit on a more modest scale. A recent excavation campaign in Cistern no.1 north of the Industrial even yielded finds of the eighth century, indicating that the site was occupied into the Early Byzantine period (Docter et al. 2011, 118-21).

3.4 Conclusion

The exploitation of the Laurion provided much to the economic security of Athens and therefore determined its position on the world stage. Despite the continuous interest of Athens in silver mining, the profile of the Laurion mines does not seem to have been the same at all times, as suggested by hiatuses in the available sources. The first gap, occurring roughly during the pentakontaetia, is the most controversial one. Apart from a possible ascendancy of the Thracian mines, there is no clear-cut motive for why mining would have decreased, especially not after the discovery of the third contact veins. Ignoring this hiatus altogether would be wrong but accepting that mining in the Laurion came to a complete standstill might be one step too far either. In any case, if the mining industry was operational, the scale must have been considerably more modest than during the preceding or following period. The second hiatus is much easier interpretable and can be securely linked to a complete regression. Mining ceased after the Spartan raid in 413 BC and came to a standstill after the battle of Aigos Potamos in 404 BC. Not only mining but also life in the Laurion

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seems to have been interrupted: in Thorikos, the houses in the Industrial Quarter and beyond were temporarily abandoned (Mussche 1998, 63-4). The policies of Kallikrates marked the beginning of a new and likely more intensive period of exploitation than ever before.

A second observation is the switch in the operational structure of the Laurion. Identifiable as an obviously public mining cooperation at first, the organisation moved to the partial privatisation of the industry from probably the last quarter of the fifth century BC onwards. This can be seen in the light of measures taken by the State to increase its revenues, especially after the dissolution of the Delian League and the loss of the Athenian assets in northern Greece.

A last notable fact is the distribution of the archaeological remains. Why are we left with so little fifth-century traces of mining and metallurgy in the archaeological record, while there are many occupational traces testifying to the intensive habitation of the Laurion? There are neither mines, nor washeries or furnaces that can convincingly be dated to this phase, even when the literary sources demonstrate the operation of the industry. Different factors should be taken into account here. First of all, mining and metallurgy are particularly hard to recognise in the archaeological record, especially in areas with a complex and intensive occupation history. Mines tend to be exploited continuously, consequently destroying most or all traces of earlier activity. Additionally, the production of metals leaves few traces: furnaces are constantly exposed to destructive conditions. Furthermore, most of the ancient slag had been resmelted during later phases. Our knowledge of the earlier remains is also hampered because most research has been directed towards the most visible structures, which are predominantly fifth-century houses and fourth-century workshops. Is it plausible that researchers are focussing on the wrong locations to enhance our knowledge of early mining and metallurgy? If the dating of the Bertseko workshops to the early fifth century BC or even earlier is correct, this would explain much. These workshops are installed in a different geographical context than their fourth-century counterparts and additionally show a completely different organisation and level of technology, seemingly more random and experimental. This neatly illustrates why hiatuses can in fact be meaningful, since these often point to a form of organisation or technique that leaves no or few footprints. This prompts to involve the study of technology in this debate. A better understanding of technology can explain the economic and environmental challenges that people were struggling with, the technological answers they provided and therefore, shed light on the evolution of silver metallurgy and how this progress contributed to the Athenian economy.
Part 2  Technology as an agent of change
Chapter 4 Technological change and the Athenian economy

The study of ancient technology is inextricably tied to the study of the ancient economy. Economic activities depend on the level of technology developed in a society and at the same time create the context demanding for technological progress (Schneider 2007, 147). The economy of Greek city-states was based on agriculture and therefore relied largely on the yields of their *chora* or countryside (Oliver 2010, 285), making advances in agricultural technology of specific importance to stimulate economic growth. Nevertheless, many innovations carried out in sectors beyond agriculture contributed substantially to the economy as well. This is illustrated perfectly in Classical Athens. More than any other city-state, Athens was dependent on grain imports rather than the yields of its own countryside, which was of limited potential (Wilson 2002, 30). Not incidentally, Athens developed a diverse non-agricultural sector, which is clearly reflected in the extensive list of 170 occupations practised on the Agora, but also in the unique role played by the silver mines in Athenian society. As explained in the introduction, the metal industry will influence the economy not only through the technological issues and costs involved in the silver manufacturing process but also through the use of silver as a commodity and resource for the production of coins (Hopkins 1978, 55).

Before moving towards further discussion, some basic economic concepts should be explained, starting with *performance* and *structure*. Performance concerns typical economic matters such as production rates and distribution of costs, whereas structure refers to the determinants of economic performance, more specifically ideology, political and economic institutions, demography, ecology and technology. Because of the more extensive quantitative information on the Roman economy (e.g. wages or production rates), the study

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1 Harris presents an overview and in-depth study of these professions in his article *Workshop, marketplace and household: the nature of technical specialization in Classical Athens and its influence on economy and society* (2001, 67-99).
of performance has been more prominent in Roman than Greek historiography. As a consequence, the impression often arises that the Greek world did not or hardly experience economic growth, an image that is both problematic and false (Morris 2004, 709).

Next are the concepts of *aggregate* and *per capita* growth. The former refers to growth with the level of productivity remaining stable, implying a numerical increase in labour force. In Antiquity, growth remains mainly but not exclusively restricted to this type. It is obtained for example through the extension of agricultural land, the construction of more workshops or the opening of more mines. In contrast, the latter entails an actual increase in work productivity. This requires intervention in the work process itself through raising financial expenditure, changing work organisation or technological innovation, such as through the improvement of existing tools or the introduction of new and increasingly complex mechanical devices (Schneider 2007, 166-8). This type of growth is normally linked to industrialised societies but has also occurred in the ancient world, albeit on a smaller scale. The Laurion is a case in point demonstrating both types of economic growth.

### 4.1 The study of ancient technology and its contribution to economic history

The study of ancient technology has known a turbulent history, which is closely linked to the theoretical debate on the ancient economy. For a large part of the 19th and the beginning of the 20th century, the discussion was polarised. *Primitivists*, such as A. Bücher (1893), saw the ancient economy as primitive, small-scaled and only aiming at self-sufficiency, while *modernists*, such as E. Meyer (1924) and M. Rostovtzeff (1941), defended the entire other end of the spectrum. They stated that ancient economic activities were similar to those in the modern, capitalised world. Apart from the inherent value-judgements such views inevitably entail, *this narrowed the discussion down to the single issue of where to place Greece and Rome along a continuum from self-sufficient household to contemporary industrial nations* (Morris 1999, x). These issues were soon realised and the primitivist-modernist debate came under increasing attack. The most important figure triggering a shift in this debate was Moses Finley. Drawing on the social theorists as Max Weber and Karl Polanyi, the *substantivist* view was put forward: this

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5 Many overviews of this debate can be found in scholarly literature but in this study, I have been supporting on Austin and Vidal-Naquet (1977), Morris et al. (2007) and Oliver (2010).

approach characterised the ancient economy as dependent on social relations—as opposed to formalism, which sees the economy as an external sphere of interactions. Therefore, the economy can only be understood when immersed in the social and cultural context it was developed in. These views culminated in Finley’s most influential work, The Ancient Economy (1973), in which a qualitative model of the ancient economy, covering no less than 1,500 years (from roughly 1000 BC to AD 500), was proposed. The central theme of this study was that economic growth had never really been accomplished as a result of a constant concern for citizen status.

Technology was long not considered as a crucial part of this discussion, as is well illustrated by specialist books as the Oxford History of Technology,5 in which the study of technology as an agent of change was entirely brushed aside. Although Finley attempted to tackle this issue by investigating technology with more socially driven questions in mind, he did more harm than good by systematically underestimating innovations and their diffusion. This view was unambiguously expressed in his article Technical innovation and economic progress in the ancient world (1965, 29-45), which was taken as a common place and continuously and uncritically recited afterwards. Until the eighties, the debate about ancient technology was held in a particularly negative atmosphere, emphasising the sharp division between science and practice. This is an inevitable corollary of substantivistic views: since the ancient economy was characterised by stagnation and people were primarily concerned with status, technology could have never been put to economic use. A central argument in this discussion is an attitude labelled banausis,6 referring to the presumed condescending position of the Greek and Roman elite towards the practical application of technology. The mistake in this reasoning, however, is to generalise the disparaging views of some individuals to the entire ancient society, creating an unrepresentative image of ancient attitudes (Wilson 2002, 4). Adherents of this opinion also seem to forget that, even if some individuals would despise manual labour, improvements would still be carried out by those who were actively using these technologies. This tendency of viewing technology as marginalised from the society is remarkably still present among many scholars and has been described by Cuomo (2007, 4-5) as the mainstream view. Many arguments against the influence of technology on the economy were largely based on a social level: technological innovation involves certain risks, which people with a ‘conservative mentality’ were not willing to take. It demands resources that ancient societies were not supposed to have or spend because the incentives, such as patent rights, were missing (Persson 1988, 5). Since innovators never saw the yields of their inventions, there was no trigger for innovation. This point illustrates a persistent trend in the study of ancient technology, labelled as the blocage question by Cuomo (2007, 3-4): technological progress is seen entirely against the background of the modern industrialised world, in which success is a

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6 Wilson 2002, 4-5.
central notion and technological innovations are introduced with a speed beyond comparison. Starting from the stubborn supposition that improving technology equals economic progress, scholars have been intrigued by the question why the Greco-Roman world had not known its own Industrial Revolution. It is, however, a more valid question to ask why this event emerged in 18th century Western Europe specifically rather than persist on why it did not 2000 years earlier (Schneider 2007, 146). Realising the uniqueness of this event should be sufficient to understand that projecting contemporary conceptions on the past is misplaced, even more so when this position is used to downplay the accomplishments of ancient societies. The pitfall is to see technological change as a necessary linear phenomenon, whereas an approach starting from a more irregular pattern with emerging and disappearing technologies is certainly more appropriate (Wilson 2002, 31). Hydraulic mortars and by extension cisterns form a good example of a non-linear technology: several Bronze Age cisterns7 are known in the Aegean but the technology seems to have been lost during the Dark Ages, only to be picked up again during Classical and especially Hellenistic times.8 From the fourth century BC onwards, cisterns became common features in both private and public infrastructure and were diffused over the entire Mediterranean world.

Critiques on Finley’s single model for the ancient economy were bound to come. Keith Hopkins, the successor of Finley in Cambridge, acknowledged that the ancient economy was more complex and dynamic than his predecessor granted it to be and that there was modest but genuine economic growth in Antiquity. He listed seven clauses,9 in which growth was manifested during the same period discussed by Finley. First of all, agricultural activities were expanding. Second, there was a significant increase in population. Third, an increasing group of the population got engaged in economies beyond agriculture, particularly in the growing city centres, which leads to a fourth point: specialisation of labour and non-agricultural production. Fifth, improving technology contributed to rising per capita productivity in both agricultural and non-agricultural production. Saller (2002, 257-67), who has further developed Hopkins’ clauses, suggested a raise of 0.1 % per annum between 200 BC and AD 100. To modern standards, the effects of such a growth might seem negligible but this would have been significant in pre-industrial times. For periods for which we have less quantitative data available, such as Greek Antiquity, this is much harder to assess; However, a genuine growth could also be deduced from other, less straightforward sources (see further). Sixth, the increasing size of towns and states demanded a surplus to maintain the infrastructure, which stimulated the raising of taxes and rents extracted from primary producers. Seventh, the

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7 E.g. in Myrtos Pyrgos (middle Bronze Age), Archanes, Tylissos and Zakro (late Bronze Age) (Cadogan 2007).
8 Some but very few examples date to the Archaic period, such as the underground cistern next to the temple of Aphaia at Aegina and the rectangular cistern at Kamiros in Rhodos.
expenditure of taxes at some distance from where these were collected, triggered long-
distance trade. This last clause relates especially to first and second century Rome, where a
large part of the taxes was spent along the frontiers of the empire.
Since Hopkins, the occurrence of economic growth in Antiquity is no longer denied but still,
the debate remains biased. Due to an overwhelming body of Roman data that is more easily
applicable to the study of the economy, the focus has merely been on the period post-dating
200 BC. The image is a positive one. Economic growth was enabled by the relative stability
of the Roman Empire and its unified economic body, also enhancing technological
innovations and their diffusion. This picture contrasts with the more shattered geographical,
political and economic nature of the Greek poleis, which have consequently been given much
less credit. It is, however, a wrong starting point to judge the Greek world based on its
weaknesses, rather than its realisations. It is undeniable that these factors formed a
considerable constraint since it made the Greek economy more susceptible to external
factors, such as war, plague or famine (Millett 2001, 35-6), but it is at the same time unfair to
automatically assume that this excluded growth –both aggregate and per capita– or hampered
innovations and their diffusion. As a result of the smaller economic scale of the Greek city-
state, it is just much harder to evaluate such factors. Economic growth does become more
apparent when starting from a long-term approach. In the course of the first millennium BC,
increasingly more land was brought into cultivation in the Aegean world and people
developed new methods of risk-buffering to compensate rainfall variability in agriculture,
such as through the diversification of crops and fragmenting of landholdings.10 Furthermore,
non-agricultural activities and specialisation increased. This is neatly illustrated in the
previously mentioned list of occupations carried out on the Athenian Agora (Harris 2001, 69)
but also in ancient texts, such as Xenophon’s Cyropaedia, in which the author compares life in
small towns and large cities.

For just as all other arts are developed to superior excellence in large cities, in that same
way the food at the king’s palace is also elaborately prepared with superior excellence.
For in small towns the same workman makes chairs and doors and plows and tables,
and often this same artisan builds houses, and even so he is thankful if he can only find
employment enough to support him. And it is, of course, impossible for a man of
many trades to be proficient in all of them. In large cities, on the other hand, inasmuch
as many people have demands to make upon each branch of industry, one trade alone,
and very often even less than a whole trade, is enough to support a man: one man, for
instance, makes shoes for men, and another for women; and there are places even
where a man earns a living by only stitching shoes, another by cutting them out,
another by sewing the uppers together, while there is another who performs none of
these operations but only assembles the parts. It follows, therefore, as a matter of

10 Witcher 2009, 466; Oliver 2010, 289. For Attica in specific, see Lohman 1993.
course, that he who devotes himself to a very highly specialized line of work is bound to do it in the best possible manner.

Xenophon, Cyropaedia 8.2.5

Unfortunately, it is difficult to express these trends in precise numbers due to a lack of sufficient quantitative data, hampering the study of performance in the Greek world. Since the 1990's, however, scholars have started taking on first sight less straightforward (mainly archaeological) data into account that are better applicable to Greek history. In an article in Journal of Institutional and Theoretical Economics (160, 709-742), Morris has given an overview of these data. Through the study of burials it is possible to deduce aspects of stature, nutrition, mortality and morbidity, while the study of architecture and material increases our understanding of housing and living conditions. The quality of the investigated skeletal remains is poor but does point to an increase of the average age of death between 800 and 300 BC (Morris 2004, 719-20). This indicates improving living standards —although the Laurion could be an exceptional case, where externalities were restricting the quality of life through pollution and the consequent impact on health (Millett 2001, 21). This also shows that technological progress should not exclusively be seen in the strict context of economic growth. Notwithstanding the negative impact of metallurgy on health in the Laurion, it adds significantly to better living conditions as well. Improving water technology for example secured water supply in dry areas through the construction of aqueducts or a network of simple supply channels and cisterns. This resulted in the creation of a water surplus, enabling a more comfortable life and even luxury on locations where this would have otherwise been unthinkable. The archaeological remains in the dry Laurion heartland confirm that this was also the case in the mining industry (see Chapter 6 for further discussion of this issue). Furthermore, the sizes and quality of the houses rose substantially during that same period. Even the most modest houses of the fourth century were better built than the average Dark Age dwelling. The same goes for domestic assemblages, which can be well studied on sites that have suffered from sudden destruction (Morris, 2004, 720-3). It is open to debate how much household contents rose in quality and quantity, but a five- to ten-fold has been suggested and may reasonably be assumed. These remarks demonstrate that consumption was increasing as well. For ancient Greece between 800 and 300 BC a per capita raise in consumption of 0.05-0.1 % per year has tentatively been put forward (Morris et al. 2007, 6). Finally, intensive field surveys in different parts the Greek world, such as Kea, the southern Argolid, Sicily (cf. Morris 2004, 726-7) and Bocotia, have suggested a significant increase in population.

12 Persson 1988, 2-3; Schneider 2007, 170.
Thus, the Greek world did experience slow but undeniable economic growth. The degree to which technological innovation was an active agent in this evolution, however, is yet another matter. With his fifth clause, Hopkins acknowledges the influence of technology on economic progress and by doing so dissociates himself to a certain extent from Finley. Since the 1980’s, an increasing group of scholars has taken a more positive attitude towards technology and its role as a determinant of economic performance. In sharp contrast to the proceeding work, the archaeological evidence has been fully involved in the discourse, proving that many technological devices were not only developed earlier than literary sources allowed us to believe but also spread more intensively. Unfortunately, research is heavily skewed in favour of the Roman world, a matter that is to a certain extent understandable given the extensive literary and archaeological evidence of technologies dating to this period. There is also no discussion about the unique technological dynamics in the Roman world and the skills of their engineers. The most noteworthy Roman contribution is undoubtedly the application of devices and methods replacing human power. The use of water power was a breakthrough, with applications in agriculture (i.e. the water mill) as well as mining (i.e. through hushing techniques) —not incidentally the two most crucial sectors influencing the ancient economy. Nevertheless, the unfortunate corollary of the overemphasis on the Roman period is that Greek technology not only seems more ‘primitive’ but also that its impact on the economy had been virtually non-existent. The Greeks did introduce a range of innovations that were, despite their seemingly unimpressive appearance, significant contributions to the store of technological knowledge. Examples are the winch, the compound pulley and the ratchet, which are the basic elements of a crane. Another striking example is the alphabet. Although writing was not a Greek invention, the alphabet was (Rihll, 2009, 488), and this enabled the specification of contracts and the reduction of measurements costs, permitting the growth of impersonal exchange (North 1981, 11). Rather than using the Roman accomplishments as a criterion, the study of Greek technology should in first instance evaluate and appreciate economic and technological change within its own historical context. As already mentioned, the Greek and Roman world were significant different contexts triggering totally different outcomes. The high demand for products and resources in the Roman Empire stimulated technological changes, their diffusion and mechanisation to a much larger extent than in the scattered Greek world. Nevertheless, Greek technologies could very well be pioneering within their own chronological framework. As already

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17 White 1984; Rihll 2009, 488.
suggested by Schneider (2007, 148) and Persson (1988, 12-32), it is appropriate to involve the concepts of technological systems and sequences in this debate. A technological system refers to the mutual dependencies of various branches of technology, from agriculture to mining, which all added to a continuously growing technological heritage. In fact, this principle was already realised in Greek Antiquity (Schneider 2007, 148): Plato pointed out the interdependency of technologies, when referring to craftsmen who were producing materials for other crafts. Technological sequences entail the evolution of technologies over time (Persson 1988, 12-3). The store of technological knowledge is thus steadily increasing by building on previous developments, both within the same as well as other sequences of technology. Such matters should be taken into account when studying ancient technology. Aqueducts are a further case in point. Generally admired as Roman masterpieces, these systems were in fact in use many centuries before and in all parts of the world. In Greece, the earliest archaeological proof is the Mycanean 6.5 km long aqueduct of Lake Copais in Thessaly (White 1984, 158). Furthermore, Peisistratos and his sons constructed a 7.5 km long aqueduct, partly carved out as a tunnel and partly consisting of terracotta pipes, to supply the city of Athens as early as 540-30 BC. Water from the Hymettos mountain was conveyed through this aqueduct to the centre of Athens, where it branched off to provide fountains and reservoirs (Tassios 2007). The tunnel of Eupalinos, which is part of a longer aqueduct once supplying water for the city of Samos in the second half of the sixth century BC, is another example illustrating the skills of Greek engineers: the 1 km long tunnel, measuring approximately 1.8 x 1.8 m in diameter, was cut right through a mountain, starting from two opposite entrance points. The only possible technique to establish such a venture seems to be a survey method explained by Hero in a passage of his Dioptra, dating to the first century AD, in which the author seems to have had the Eupalinus tunnel in mind for his description. If this was indeed the case, the implications are significant, since it would mean that this particular survey technique had already been developed 600 years earlier than Hero’s description. An important difference between Greek and Roman aqueducts is that the former run entirely underground, whereas a (small) part of the latter took the shape of elaborate arcades. Although these arches were an extremely important Roman innovation in the developments of their aqueduct network and monumental architecture in general, this does not alter the fact that the basis of the technique was part a technological sequence going back a long time before the heyday of the Roman Empire.

19 Cratylos 387d-389d; Politeia 370c-e; Nomoi 678c-679b.
20 White 1984, 158-60; Trevor Hodge 2000, 42-3. The tunnel has been described by Herodotos (The Histories 3.60).
21 Note that arcades were already occasionally used by the Greeks but were never incorporated in aqueducts (Trevor Hodge 2000, 42).
Besides the significance of archaeological sources in the discussion, this overview has demonstrated that the largest obstacle in the study of ancient technology and its influence on economic progress is in fact still our current definition of this concept.

4.2 Reconsidering the concept of technology in pre-industrial societies

In contrast to how it is traditionally represented, technological innovation is a multi-faceted phenomenon. In this context, P. Millett (2001, 34-5) has rightly picked up K. Persson’s analysis of Medieval Europe.\(^2\) I do not follow Millett’s stagnationist\(^3\) conclusions about ancient and especially Greek technology and economy, which he has partly drawn from Persson’s theoretical framework; however, this reference is important for the appreciation and study of technological progress in the ancient world and will therefore be summarised and further commented below. As has already been explained above, Persson (1988, 7-13) states that modern scholars are projecting a concept of technology on the past that is to a great extent moulded by its meaning in the modern industrialised world, resulting in an intangible linking of technological innovation with a necessary increase in per capita product or income. Although this did occur in pre-industrial societies, growth should generally be characterised differently. Persson handles the following definition of technological progress:

The general meaning that will be given to the concept of technological progress here is that a unit of a good or service is produced by a new technique using fewer resources than the previous one. A technique can be represented by a production function relating output to inputs. Technological change then represents a change in the parameters of the inputs in that production function. As a contrast, the concept of technical change is reserved for changes in the methods of production involving only substitution of inputs but with unchanged parameters … The introduction of new goods and services is considered as a specific type of technological progress.

Persson 1988, 1-2

Persson opposes the idea that technological improvements are necessarily triggered by exogenous shocks, such as population pressure, climate change or the introduction of new institutions (1988, 4), but motivates that these are primarily endogenous in nature. There are

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\(^3\) See also Wilson 2002, 3.
systematic forces operating in favour of technological progress (Persson 1988, 7), and these are coming from within the society. He distinguishes five types of endogenous technological change (Persson 1988, 7-13):

1) Random changes over time.

Over a long time span small and unintentional changes can be made to productive operations, which are adopted because they seem to positively influence the production process and output. This process is clarified in the figure below.

![Figure 10](image_url)

**Figure 10** Random changes over time (after Persson 1988, Fig. 1.2).

This figure represents an economy with a certain input of labour/land for a unit of output. The dots show possible output combinations. It can be surmised that people rationally attempt to minimise the input (resources, labour) for a certain unit of output. The best possibly outcome of their choices is represented by the best-practice curve $B_1 P_1$. People will select a specific combination of inputs on this curve, such as point $a$, which refers to the standard method they are using at a specific moment. This method will also be susceptible to random changes, represented by the dots around point $a$, allowing the best-practice curve to move until a new and better standard method is found: for example, point $b$ on curve $B_2 P_2$. 

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The inward movement of the curve implies a new method, which will allow a lower input of resources and is a perfect example of what can be achieved through technological change.

2) *Economies of practice* (Arrow 1962)

Products can also be improved through the experience of the producers, who are making as well as using the product. This ‘learning by doing’ also allows considerable specialisation. It can enable the same inward movement of a given point on the $B_1P_1$ curve to $B_2P_2$. This knowledge can for a long time remain within the same working environment but is also transferable outside the family or workshop. The same type of change can occur independently in different parts of the world as well.

3) *Trial and error*

In contrast to 1 and 2, the process of trial and error occurs more intentionally and can therefore involve extra costs. Given the economic and political context of ancient societies, these costs are generally limited, since most performed variations are only small. Therefore, the eventual result is similar to these made by random changes.

4) *Division of labour and regional specialisation*

Both division of labour and regional specialisation are enhanced by population growth or—in Adam Smith’s words (2008)—the ‘extent of markets’ and can significantly increase productivity. The division of labour will affect a more efficient work process, since the producer only has to concentrate on a specific task, which subsequently will be performed more efficiently. The division of labour is linked with the issue of indivisibilities in learning, which implies that production methods have minimum requirements of training to enable efficient production. This issue is shown in the following figure:
On this diagram, a specific technology performed with (DL) and without division of labour (NDL) is represented, with L as input (labour), Q as the produced good and T as labour time. NDL proves to be more efficient as long as the demand is lower than $Q_1$. Once the demand is higher, people are better off with DL, since the labour input per output unit will be lower than with NDL.

As is pointed out by Plato in his *Republic* (369-71), the Greeks were aware that specialisation of labour was leading to both an improvement in the quality of goods, as to a greater efficiency and increase in wealth (Schofield 1993, 190). In spite of this, it was not often practised because of an insufficient demand.

5) Increase in population

The technological progress exhibited in point 4 also explains how an increase in population affects the scale of the markets and the aggregate demand.

By involving this theoretical framework, small technological changes in ancient times can be better recognised, understood and appreciated. It respects technological change in ancient times within its limits but simultaneously does not devalue its contribution to economic growth. After all, the accumulation of small improvements will eventually lead to significant technological progress and even per capita growth. Independently from Persson, Schneider (2007, 168) has also pointed out that *the importance of improvements in the details of technical equipment is often underrated*. These arguments count for Classical Greece as well. Slow
technological change, generally in the form of refinement of techniques, was the most prominent form of progress. The evolution of agriculture but also metallurgy forms a good example of how the accumulation of technological improvements can contribute to the development of a technological heritage (Persson 1988, 21-24). Exploitation and smelting techniques were gradually developed, through random changes, ‘learning by doing’ but also conscious experimentation. There is increasing evidence (e.g. radiocarbon dating) that there were several centres of origin for metallurgical techniques in Europe, rather than that metalworking would have spread from the ‘more advanced’ Near East (Renfrew and Bahn 2004, 347). It is likely that metallurgy gradually developed from sequences of pyrotechnical knowledge (needed for ceramic production) on the one hand and of stone tool technology on the other. Stone has limited possibilities as a raw material for tool use, mainly in the manufacturing of sharp edges, whereas metal does not have this limitation (Persson 1988, 22). The first metallurgical practices must have been relatively simple, consisting of the shaping (hammering, cutting and polishing) and annealing of copper. The latter process implies that the metal is heated in order to be able to shape it more easily. Later, pyrotechnical techniques are introduced: it is plausible that the brightly coloured oxides and carbonate ores of copper were the first ores to attract attention for the manufacturing of tools. This was followed by the melting and casting of copper in a single and then a two-piece mould. The alloying of copper marks an important moment in the technological sequence: by adding arsenic and tin to copper, the metal becomes less brittle and the working is facilitated. It avoids the formation of bubbles during the casting process and allows repeated hammering. Sulphide ores, which are more complex to be smelted, were involved in a later stage (Renfrew and Bahn 2004, 347-8). It is likely that the extraction of silver from argentiferous lead ores (such as galena or cerussite) was accidentally discovered during the cupellation of lead and the techniques were then further developed. In the Near East, the considerable time lapse between the first appearance of manufactured lead in Turkey in the seventh millennium BC and the more widespread use of silver in the fourth millennium seems to indicate this (Moorey 1994, 233). Nevertheless, this proof is lacking in the Aegean and people seemed to have been practicing a combined silver/lead metallurgy (Gale 1979, 32). The earliest evidence for silver metallurgy was found in the form of litharge in the eastern Anatolian site Fatmalı-Kalecik dating to the beginning of the late Chalcolithic period, to be precisely the end of the fifth to the early fourth millennium BC (Hess et al. 1998, 58). As far as the Aegean is concerned, recent excavations in the Mesogaia plain indicate that this activity was taking place from the transition of the Final Neolithic to the Early Bronze Age in the Laurion (Kakavoyianni et al. 2008). It is unclear if metallurgical knowhow was diffused to the Aegean from the east. Given the time lapse, this could be a possibility. There are some striking parallels between bowl-shapes cupels at Laurion (used in the cupellation process, see below) and Habuba Kabira, an Uruk settlement in Syria dating to c. 3300 BC. Closer research, however, is required to say anything with more certainty.

One should be careful, however, not to incline too much towards a solely deterministic debate. True, endogenous changes were the most prominent form of technological progress
and a deterministic trajectory can clearly be recognised, but this does not exclude simultaneous, more far-reaching developments and even rational behaviour. Although Persson’s framework is partly used by Millet to back up his thesis about technological and economic rigidity, Persson does not deny that to ancient standards drastic changes have taken place. Through his study, he just wishes to address stagnationist tendencies that see technological change exclusively within the context of exogenous shocks and then use the general lack of such changes as an argument to completely neutralise the debate on technological change in Antiquity (1988, 3-6). In Classical Athens, I see clear indicators for both forms of innovation, endogenous as well as exogenous in nature. As Schlebeker (1977) has proposed, accumulating knowledge is not the only premise for technological innovation. Important triggers are also an evident need, the economic possibility to introduce it and cultural and social acceptability in the community and these matters. Such dynamics were present in fifth- and fourth-century Greece. The introduction of coinage, the Persian Wars, the rise of the Athenian Empire and the consequent demand for silver to finance its extreme expenditures were disruptive events that affected the silver demand to a large extent. The simultaneous appearance of washeries in the silver mining area evokes serious questions about the role of these events in the introduction of technological innovations. In the next chapter, these issues will be further investigated supporting on the findings of this theoretical framework. Reminiscent to what the involvement of Roman technologies affected in the discussion on ancient technology, the focus will now be primarily on the archaeological record.
Chapter 5 Technology and organisation in silver production

The silver production process was labour-intensive and put heavy demands on the environment and society: 16 kg of ore had to be extracted and processed to produce one silver drachme of approximately 4 g (Rihill 2001, 115). In a very general sense, silver production consists of two phases: 1) the exploitation of ores in the mines and 2) smelting in the furnaces. If the extracted ore does not contain enough metal to be smelted efficiently, a second phase is introduced during which the ore is mechanically prepared. Referred to as ore dressing or also ore beneficiation, the metal is liberated from the gangue (waste material) by subsequently crushing, grinding and washing the extracted ore. In theory, this process can be limited to hand-picking, if it is macroscopically possible to distinguish the different ore particles. In the Laurion, however, this was generally not the case: the Laurion ores had a particularly low argentiferous content, necessitating crushing and grinding to a size less than a millimetre (Conophagos 1980, 216, Rehren 2005, 30) and subsequently the involvement of water to be able to sort this floury powder based on density. This process can be repeated several times until the satisfactory amount of metal is collected. The flow-chart below (Fig. 12) gives a good illustration of this process. Once crushed and grinded, the ore body is separated into three parts: 1) the concentrate, 2) the middlings, which still have metal caught in the gangue, and 3) the tailings or phynites, which are discarded since they are considered to contain no more valuable material. The middlings need further processing to free the remaining metal, but it is not entirely clear to what degree the ancient metallurgists were involving these products in the process (Photos-Jones and Ellis Jones 1994, 332-4).
Just by looking at the archaeological remains of the *ergasteria*, it becomes clear that ore preparation has taken up a special position in the mining industry. Water was crucial to perform this phase efficiently but in a semi-arid area as the Laurion, the availability of this resource was far from self-evident. Unsurprisingly, water technology was given considerable attention by miners and metallurgists. Focus in the following overview will therefore be on processes in which water technology played a vital role and resulted in drastic changes in work and organisational structure of the silver mining industry.¹

### 5.1 Ore extraction

Mining started on a small and dispersed scale as early as the transition of the Final Neolithic (4200-3100 BC) to the Early Bronze Age I (3100-2650 BC). As indicated by small mining galleries spread over the Laurion, these were opencast mines, digging in the easily visible ore

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¹ It is not the intention of this study to explain every phase of the silver production process in great detail, since this has been done before. For more information on ore extraction and smelting, see Conophagos 1980. Also useful are Rihll 2001 and Kakavoyiannis 2005.
outcrops of the First Contact and following the vein some distance through small drifts (Kakavoyianni et al. 2008, 46). Such configuration has been revealed during archaeological excavation of Mine no.3 (Thorikos), dating to the Early Bronze Age (Spitaels 1984). The silver production process in this early phase was certainly less complex than in Classical times: the mining of outcrops did not require sophisticated techniques, such as the digging of deep shafts. In addition, most First Contact ores were rich and therefore suitable for smelting without any purification.2

As time passed, exploitation became more systematic. Galleries were extended and greater risks were taken to discover yet unexploited veins. This necessitated the digging of shafts, either as a demarcation of metalliferous veins, to ventilate mine galleries or to transport the extracted ores to the surface (Morin et al. 2012). The Third Contact was hit in the years before the battle of Salamis, suggesting that the deepest shafts date from this period or not long before. The efforts for digging these shafts were significant: Conophagos (1980, 200) has estimated that it would have taken three workmen nearly a year for a 100 m shaft with a surface area of 2 m². The significant energy put into these shafts without the assurance of actually finding ores says much about the pressing silver need during the Persian Wars.

In the Laurion, ores were extracted solely by human power with a modest selection of equipment, such as an iron chisel, a hammer, lever, pick, sledge and bucket. Lighting was provided by oil lamps.3 A more complex way of extracting ores was performed through fire setting, the fracturing and splitting of rock by heating. During this process, water (or vinegar) would have been used (Rihll 2001, 116), but it is impossible to assess the scale on which this technique was implemented. Galleries are narrow, no more than 0.6 to 1 m in section (Conophagos 1980, 195). A first selection of suitable ore for smelting must have been done in the mine itself by weighing it by hand. The rest was brought to the surface to be assessed further: the sterile ores or ekvolades were dumped near the entrance of the mine and, depending on their lead content, the remaining ores were transported to dressing plants or straight to the furnaces. As opposed to high grade minerals, the smelting of poor ores was not rewarding and a costly affair, demanding significantly more timber.4 Clearance of the gangue was thus a viable thing to do.

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3 For a detailed discussion of the lamps found at Thorikos see Blondé 1983.
4 Rihll 2001, 117; Christesen 2003, 40.
5.2 Ore dressing

Ore dressing is the key to our understanding of the development and exploitation of the Laurion. Nevertheless, the history of the mines has never been taken into consideration from this point of view. In contrast to what Aischylos would make us believe, the mines were not an easily available fountain of silver (Persai, 238) and the large-scale operation of the Laurion had been far from self-evident. The Laurion ores had a lead-silver content of hardly 15-20 %, which is barely economically viable to exploit. If the Athenian city-state wanted to make full use of the minerals buried under its lands, it was forced to develop sustainable methods to involve these lodes into the silver production process. Ore dressing addresses exactly this issue by clearing the ore from its impurities, consequently raising the argentiferous lead content up to 45-50 % (Conophagos 1980, 146) and making the smelting of these ores profitable.

The relative poverty of the Attic mines is elucidated in some ancient texts but these references have generally not been interpreted as such. A valuable fragment comes from Strabo’s Geography:

Demetrius [of Phaleron], he [Poseidonios] says, states in reference to the Attic silver mines, that the people dig as strenuously as if they expected to bring up Pluto himself. So Poseidonios implies that the energy and industry of the Turdetanian miners is similar, since they cut their shafts aslant and deep, and, as regards the streams that meet them in the shafts, oftentimes draw them off with the Egyptian screw. However, the whole affair, he says, is never the same for these miners as for the Attic miners; indeed, for the latter, mining is like a riddle: "What they took up," he says, "they did not take, yet what they had, they lost"; but, for the Turdetanians, mining is profitable beyond measure, since one-fourth of the ore brought out by their copper-workers is pure copper, while some of their private adventurers who search for silver pick up within three days a Euboean talent of silver.

Strabo, Geography 3.2.9

Demetrius of Phaleron (350-283 BC) lived when the activities in the Laurion peaked and the absolute majority of the ergasteria date. This fragment demonstrates that people were not only well aware of the ‘poverty’ of the Laurion mines, but also of the challenges involved in the economising of such deposits in general. The truthfulness of this fragment could be questioned since Strabo is referring to an indirect quote of Demetrius of Phaleron through

5 I owe this point to Thilo Rehren (2005, 24-5).
Poseidonios, of which the original texts are both lost. Nevertheless, this fragment is backed up by archaeology: the Laurion washeries number in the hundreds, testifying to the necessity of ore enrichment. This also aids to better understand the intriguing riddle mentioned in the fragment. As explained at the very beginning of this chapter, 16 kg of ore had to be extracted to produce a 4 g drachme, corresponding to hardly 0.025 % of its original volume. Thus, the absolute bulk of the ore body had to be discarded, clarifying why Poseidonios stated that *what they took up, they did not take, yet what they had, they lost* (Geography 3.2.9).

Strabo (Geography 3.2.10) also made more general remarks about this issue and the awareness about economic viability of low-grade silver ores, for example when referring to the poor silver ores at Castalo of which the refining was not considered profitable.

The purification of silver ores was thus a vital task for the Athenian miners. When did this awareness filter through and how did this process develop? The Laurion and its metallurgical infrastructure can possibly be understood without starting from a broader approach. In contrast to the impression given by the remains in the Laurion, ore dressing mostly stays unnoticed in the archaeological record. It is only due to the industry’s dependence on large-scale rainwater harvesting during Classical times that we are getting a glimpse of its metallurgical legacy. In regions with sufficient water resources the construction of large cisterns was mostly superfluous, explaining why there are no parallels with the Laurion elsewhere in the world. Investigating this paradox more closely can enhance our knowledge on this region significantly.

The principle of ore dressing is straightforward: regardless the execution, it requires a movement of water, allowing the separation of the light impurities from the heavier metal particles. A critical study of literary and archaeological sources shows that the variety of techniques to perform this process is great. Most of the methods are simple and low-cost, but some are more complex and suggest the injection of significant capital into metal production.

### 5.2.1 Textual evidence on ore dressing

Textual evidence on the processing of silver ores is virtually missing until the Roman period, but there are two exceptions. The first is a dubious Old Babylonian fragment (first half second millennium BC) from Mari. The text in question mentions that ‘mountain copper’ was washed and lead was used with silver to produce ‘washed silver’. The text is ambiguous, but it is quite possibly a reference to the purification of copper and silver rather than to liqutation as
It has rightly been suggested by Moorey (1994, 233). It is not possible to deduce when experiments with ore washing were initiated but this Old Babylonian text could indicate a less recent origin than generally assumed.

Greek Antiquity leaves us with only one fragment in the context of the Laurion and ore washing. In his On Stones, dated around the end of the fourth century BC, Theophrastos wrote:

They say that Kallias, an Athenian from the silver mines, discovered and demonstrated the method of preparation; for thinking that the sand contained gold because it shone brightly, he collected it and worked on it. But when he saw that it did not contain any gold, he admired the beauty of the sand because of its color and so discovered this method of preparation. This did not happen long ago, but about ninety years before Praxiboulos was archon at Athens.

Theophrastos, On Stones 59

In all likeliness, Kallias is the son of Hipponikos, a man who is known to have had mining interests in the period that coincides with Theophrastos’ dating of the event. Praxiboulos was archon in 315-4 BC, placing this ‘invention’ somewhere around 405 BC (Caley and Richards 1956, 199-200). There are some issues with this date, since it falls within a period of ceasing mining activities during the aftermath of the Peloponnesian Wars. Mining declined after the occupation of Dekelea in 413 BC and came to a halt after the battle of Aigos Potamos in 405 BC, only to be resumed in the course of the first half of the fourth century BC (Mussche 1998, 64). Some questions should also be raised about the fact that Kallias is mentioned as the one discovering and demonstrating the method of preparation. Considering the time frame and the archaeological finds that will be discussed later, Kallias could not have established ore washing as a technique; it would be more plausible that he introduced a more mechanised form of this process.

Roman authors have contributed much to our understanding of metallurgical processes in ancient times. Strabo, Diodoros of Sicily and Plinius the Elder are of special importance.

With his Naturalis Historia Plinius wrote down one of the most extensive encyclopaedia of ancient times. Book 33 and 34 are dealing with minerals and mining. What is most remarkable from Plinius’s work is his consciousness about the difficulties involved in the production of metals and the environmental impact of these activities. The author stresses the contrast between ‘natural’ metals, as gold (gold is gold straight away, 33.19.62), and ‘artificial’ ones, which require smelting. Silver is categorised in the latter group and its exploitation and processing is acknowledged by the author as a madness of mankind (33.31.95). The washing of

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6. Liquation is the process during which lead is used to extract silver from copper.
minerals is mainly mentioned in the context of surface gold deposits in connection to water courses. Possibly, the techniques are similar to what is nowadays called ground sluicing or placer mining: in its most simple form, gold nuggets in the soil can be collected by means of a handheld sieve attached to a basket or by a single pan. The latter procedure is also called panning: the soil is added to a pan filled with water, which is then stirred, an act that will wash the impurities over the side of the pan and leaving the nuggets on the bottom. Although not described as such by Plinius, other authors do prove that these manual techniques were used in ancient times (see Strabo). Another method implies diverting a water stream over the deposits and subsequently over a sluice or riffle, in which the gold is concentrated. Executed in a more extensive way, gold mining can take the form of hushing (nowadays called hydraulic mining or hydraulicking). This environmentally challenging method is described in detail by Plinius (Naturalis Historia 33.21.74-75) and was developed in the Spanish mines of Las Medulas during the first century AD, allowing the extraction of ores on a much larger scale than through underground mining. The erosive power of water is exploited to break up the overburden and expose ore deposits in the landscape. In case of Las Medulas, water was stored in gigantic reservoirs constructed above the opencast mines and then released. For this purpose, water was transported by an extensive aqueduct system over large distances to provide the hushing tanks, in case of Las Medulas 50 km along the mountain contours (Wilson 2002, 17-9). Las Medulas is an interesting case study because it illustrates the measures employed to facilitate extensive mining activities in a water scarce area.

In his Bibliotheca Historica, Diodoros of Sicily not only gives interesting details about metallurgical processes, such as the use of wooden washing boards, but also insights into the organisation of work. Especially in the context of ore dressing, his information is valuable:

In the last steps the skilled workmen receive the stone which has been ground to powder and take it off for its complete and final working; for they rub the marble which has been worked down upon a broad board which is slightly inclined, pouring water over it all the while; whereupon the earthy matter in it, melted away by the action of the water, runs down the inclined board, while that which contains the gold remains on the wood because of its weight. And repeating this a number of times, they first of all rub it gently with their hands, and then lightly pressing it with sponges of loose texture they remove in this way whatever is porous and earthy, until there remains only the pure gold-dust.


Just as Plinius, Diodoros (5.27) further mentions the washing of surface gold deposits in connection to the river banks.

Strabo is another important source, especially for his frequent references to the lost works of older authors, particularly Polybios. Book 2 concentrates on mining and metallurgy in Iberia.
Although he mostly refers to gold mining, Strabo’s accounts are nonetheless instructive in the context of silver metallurgy. He mentions the mining of surface gold deposits in river banks, the washing of gold in troughs and containers dug into the ground and the invention of the so-called gold washeries, now more numerous than the gold mines (Geography 3.2.8). Unfortunately, he does not specify the chronological context of this last event. In reference to silver mining at Cartagena, he refers to the work of Polybios who mentioned a process nowadays called *jigging*: a sieve with grinded ores is immersed in a container filled with water and then stirred, leaving the particles with a greater density on the sieve. This process is repeated several times until all the gangue is discharged:

But as for the processes of the work, I omit all he [Polybios] says about it (for it is a long story) except what he says of the silver-bearing ore that is carried along in the streams, namely, that it is crushed and by means of sieves disengaged in water; then the sediment is again crushed, and again strained through (the waters meantime being poured off), and crushed; then the fifth sediment is smelted, and, after the lead has been poured off, yields the pure silver.

Strabo, *Geography* 3.2.10

Strabo (3.2.10) stresses the significance of water and describes how water courses were adjusted and channels constructed to support ore dressing, for example when mentioning the works in connection to the Durias river in Cisalpine Gaul. Finally, he gives an interesting remark about the usage of perishable materials for the mining of placer gold. Referring to the myth of the golden fleece (9.2.19), he explains that gold carried down by mountain torrents in Boeotia was collected by means of perforated troughs or fleecy skin.

Belonging to a wholly different chronological context but useful in this study are Renaissance scholars. Their accounts show many similarities with those of their Roman counterparts: the great variety of ore washing methods, the vicinity of natural water sources and the widespread use of perishable materials. Nonetheless, they go beyond the ancient authors because of their greater eye for detail, the rich use of iconography to clarify their descriptions and the information given about the spatial organisation of work. Of particular significance is *De Re Metallica* of Agricola, dated to 1556. This book became an authoritarian work, translated in three languages and published in ten editions, serving as a miners’ and metallurgists’ guide for nearly two centuries. Between 1530 and 1533, Agricola travelled all over Europe to visit and study mines, so almost everything in his book must have written down on the basis of his own experience and observations (Hoover and Hoover 1950, iv, viii). On his illustrations Agricola mentioned in the preface that he hired illustrators to delineate their forms, lest descriptions which are conveyed by words should either not be understood by men of our own times, or should cause difficulty by posterity (Agricola 1556, xxx).
In Book 8 Agricola mentions a detailed list of both general and specific methods for the mechanical preparation and washing of minerals:

> Seven methods of washing are in common use for the ores of many metals; for they are washed either in a simple huddle, or in a divided huddle, or in an ordinary strake, or in a large tank, or in a short strake, or in a canvas strake, or in a jigging sieve. Other methods of washing are either peculiar to some particular metal, or are combined with the method of crushing wet ore by stamps.

Agricola, *De Re Metallica* 8, 300

It is often hard to evaluate which techniques have been known in ancient times. There is no doubt that *jigging* had been practised for a very long time, since it is described by Polybios (Strabo, *Geography* 3.2.10) (Domergue 2008, 154-5), illustrating perfectly the non-linearity of technological change (*Fig. 13*). Since the technique was discussed by Polybios, the method was known from (at least) Hellenistic times but a remark of Agricola, saying that *the jigging sieve has recently come into use by miners* (8, 310), suggests this technology to have been lost at some point afterwards, only to be picked up again not long before Agricola.

Perishable materials are omnipresent in Agricola’s text and illustration. Wood was used for most of the infrastructure, from washing boards and channels to equipment; textile was mainly favoured for the purification of surface gold deposits but is mentioned in the context of the concentration of silver and gems as well (8, 330). On *Fig. 14*, two metallurgists are shown concentrating placer gold next to a small water course: gold particles cling to the cloth, attached to a frame. Afterwards, the cloth is removed and washed in a special tub in which the gold nuggets can be collected. Agricola mentions the many variations of this technique: some people (such as the Colchians) prefer the *skin of animals*, whereas others employ a *green cloth*, a *cloth of tightly woven horsehair* or even *turf*. Agricola describes that Plinius knew of the use of turf for the concentration of gold pallets.\(^7\)

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\(^7\) *De Re Metallica* 8. 330-33; Plinius, *Natural Historia* 33.21.77-8.
Figure 13  Jigging (De Re Metallica 8, 331).
Figure 14  Use of cloths during the concentration of surface gold deposits (De Re Metallica 8, 331).

Figure 15  Washing of ores by means of a buddle (De Re Metallica 8, 301).
Apart from the use of containers, the majority of the methods seemed to have relied on either buddles or strakes, in which the metals are washed (Fig. 15). These devices are supplied with water through a launder that is often connected to a stand tank. After the ores are washed, the water flows into one or a series of settling tanks. Another ubiquitous feature is a scrubber, used by the washer to stir the grinded minerals and enhance the separation of the concentrate from the dross. The huge variety in techniques is not only revealed in the execution of the devices but also in metallurgical practices themselves, such as the intensity of the washing process. Some people washed their ores twice in a row, while others appear to have done this up to seven times (8, 304).

Although differing in many aspects, the Laurion washeries fit into this pattern of techniques--the stand tank, the supply of water through a pipe, the washing area and the settling tanks. Dissimilarities seem merely the result of the geographical context in which the techniques were executed. In most of Agricola’s descriptions water was abundantly available, not necessitating the sustainable use of this resource. This is in sharp contrast to the Laurion, where the washeries were not only constructed of durable, waterproofed material but also provided with sedimentation tanks organised in a closed circuit, allowing to recycle rather than discharge waste water.

Besides Agricola, there is also a painter deserving special reference, more specifically Heinrich Gross with his La rouge myne de Sainct Nicolas de la Croix (circa 1530) (Morin-Hamon 2013, 17). With a great eye for detail, Gross illustrates work at the silver mines of Croix aux Mines in 25 pages of aquarelle paintings (Fig. 16). These give information on processes that are nearly impossible to recognise in the archaeological record, for example the treatment and sorting of ores immediately after their extraction from the mine. In this phase, ores are broken into smaller pieces and useless rock already removed on the spot. During a next step, the remaining ores are washed in perforated containers in order to get rid of most of the gangue. The richest components of the ore are kept aside and then crushed and grinded. Afterwards, the powder is washed on special tables with the help of long wooden scrubbers, reminding of Agricola’s descriptions. This process is continued until all the dross is removed. Wooden channels and containers were the main installations used during the harvesting of water and the ore dressing process.
The universality of many of these methods also becomes clear when looking at even more recent techniques, such as the picture on the painting shown on Fig. 17. Here as well, the proximity to water sources attracts attention.
Several things are noticeable from this overview. A first noticeable fact is the significance of water resources in the vicinity of the ore washing site. In environmentally more challenging areas, such as the Spanish mines, the absence of such sources was faced by means of a vast network of aqueducts. Then, there is the preponderant use of perishable materials, particularly wood and cloth. Finally, the huge variety visible in ore washing methods and devices is obvious. People were clearly tuning mining and metallurgical techniques to the environmental context in which they were operating. Archaeologists should take these comments into account in the reconstruction of metallurgical processes.

5.2.2 Archaeological evidence of ore dressing

It must not come as a surprise that remains of ore dressing installations are scarce. Nevertheless, recent and more targeted research is providing accumulating evidence for such sites. Several have been brought together in the PhD study of Hélène Morin-Hamon (2013, 23-9) and will be briefly repeated below. The uncovered washing plants are mainly rudimentary installations, consisting of rock-hewn basins and a series of water supply channels.

Some sites demonstrate that ore washing has been practised from very early times onwards. In Monte Loreta (NW Italy), excavations have revealed a copper mining site, dated by C\textsuperscript{14} to
the fourth millennium BC (Maggi and Pearce 2005, 281-6). Located in the proximity of a rivulet, the site consisted of a crushing area and rectangular reservoirs carved into the rock, suggesting the washing of minerals at this spot. A contemporary discovery has been made at Roque-Fenestre (France) (Ambert et al. 1984, 83-8). Several ditches cut out into the schist were supplying small reservoirs, indicating the presence of a washing installation. Similar installations were furthermore recognised at Gros-Callet (France), likely dating to La Tène ancienne and moyenne (Cauuet 1994). A rare, however contested, find of a wooden washing table has been uncovered at Modlesovice (Czech Republic) and linked to the Helvetian gold mines. Nevertheless, the dating of this device has not been confirmed (Müller and Furger 1991).

Domergue (1990, 502-3) has found a series of basins and channels at Barbantes (Portugal) in connection to a mining and crushing site of gold containing quartz and has interpreted these as an ore washing plant. A last example is found at the well-investigated mining site of Limousin, dating to the third and second century BC (Fig. 18). Water was stored in small cisterns carved out into the rock. The process has been reconstructed as follows: grinded minerals were added to water, which was diverted through inclined channels towards a final stand tank and could be subsequently reused. The gold pellets were collected upstream, perhaps by means of sheep’s wool or skin in which the gold could get stuck (Cauuet 1999, 57).
Apart from installations consisting of a rock-cut channels and basins, there is some evidence for more advanced devices constructed of durable material. These all date to Roman times. The washery of Cabezo Rajado, which was processing silver ores from the Cartagena mines, is such a rare example. It was composed of five lead basins (measuring 1 m in diameter and 0.75 m in depth) set into a masonry construction. The containers were located at approximately 0.5 m from one another and connected by lead pipes (Domergue 1990, 501-2).

Another fascinating ore washing installation was uncovered at Coto Fortuna in Spain (Domergue 2008, 152-3). The washery (Fig. 19) consists of a 15 m long series of closely packed but independently working settling tanks, each consisting of two parts: the first is circular with a concave bottom and is connected to a water supply channel; the second is smaller and rectangular in shape. Both parts seem to have been separated by a moveable sluice. Domergue suggests a *vanning* process to have taken place in the circular tank. The heavy metal particles settle on the bottom of this reservoir, whereas the lighter ones remain...
suspended in the water. The wooden sluice likely consisted of separate boards, which could be removed one by one until all the floating impurities were discharged into the rectangular reservoir. The process could be repeated until the required result was obtained.

The given overview explains why ore dressing leaves so few traces in the archaeological record. Such sites are hard to recognise because of the widespread use of perishable material and rock-cut basins and channels, which are easily filled up and if encountered during excavations, problematic to interpret without a trained eye.

Both the historical and archaeological evidence indicates that ore dressing has been an integral part of metal production for a very long time. The sites seem to have been confined to a specific geographical context: the prerequisites are the proximity of a mine and sufficient water resources. The Roman washeries—notably those of Chezo Rajado and Coto Fortuna—differ from this pattern. First, water was not abundantly available and was therefore transported to the plant from considerable distances. Second, these washeries are well-

![Figure 19](image)

Figure 19 The washery of Coto Fortuna (Domergue 2008, Fig. 97).
structured, built up with durable materials and lined with hydraulic mortar. It is clear that the high level of water technology was vital for the successful operation of these mines, since it made the industry less constrained by inhospitable environmental conditions. By constructing cisterns and aqueducts, the production output of the workshops was no longer restricted by the scarce water resources. Hydraulic mortars had a particularly important role to play: their application enabled a sustainable water management and brought along considerable organisational advantages. Washerries could be raised as independent entities, not confined to a water source or convenient underground. As has been explained before, a better work organisation is equally important to raise the efficiency of an industry and therefore contributes as much to the production output as technological improvements. Hydraulic mortars are thus a crucial technological step forward for mining industries in water scarce areas.

5.2.3 The development of ore dressing in the Laurion

Nevertheless, these crucial technological measures were not exclusively Roman innovations. The archaeological heritage in the Laurion indicates that this leap had already been taken at least 500 years earlier. Although there are significant differences, the Laurion washeries resemble the examples from Roman Iberia and this gives us some clues on the development of the Laurion mines. However, many questions remain unresolved, especially about the role of ore dressing in this evolution. The current evidence is inadequate to allow a comprehensive reconstruction and therefore, it will not be possible to offer clear-cut answers in the following section. Nevertheless, by building on the theoretical framework and the comparative research presented earlier, it is feasible to open the debate and formulate some suggestions.

It is not possible to pinpoint when ore dressing was initiated but the first experiments likely go back a long time in the Laurion’s history. The archaeological and historical evidence shows how mining and metallurgical techniques could have easily been developed by chance or, as the metallurgical knowledge of a society increases, by learning and doing or trial and error. Ore dressing can be performed simply by hand-picking, whether or not with the help of crushers and grinders to better separate the metal from the gangue (Photos-Jones and Ellis Jones 1994, 332). There must have been a growing awareness about the concept of ore density, necessary to perform this process, during exploitation of the ores in the mines. The weight of the minerals is commensurate with their metal grade. Ores were first weighed by hand in the mine itself and once brought to the surface, further assessed by colour as well. The useless rock was discarded, as indicated by the large quantity of ekvolades dumped near mine entrances (Rihll 2001, 116-7). This procedure is neatly described in the De Re Metallica. Agricola mentions that experienced miners … :
…, when they dig the ore, sort the metalliferous material from earth, stones, and solidified juices before it is taken from the shafts and tunnels, and they put the valuable metal in trays and the waste into buckets. But if some miner who is inexperienced in mining matters has omitted to do this, or even if some experienced miner, compelled by some unavoidable necessity, has been unable to do so, as soon as the material which has been dug out has been removed from the mine, all of it should be examined, and that part of the ore which is rich in metal sorted from that part of it which is devoid of metal, whether such part be earth, or solidified juices, or stones.

Agricola, De Re Metallica 8, 268

Metals with more than 1/3 lead could immediately be brought to the furnaces, whereas the remaining ore was further sorted and transported to washeries (Rihll 2001, 117). This last remark is an important one: experiments with ore dressing must have started at a time when rich ores became increasingly difficult to find and people therefore tried to include low grade ores in the process. Charcoal was expensive and is needed in large quantities for smelting: the costs for smelting galena (low- as well as high grade) are more or less the same, about 20% of its weight in charcoal; However, low-grade ores yield much less argentiferous lead, making the fuel-input and thus the costs to produce silver considerably higher. Smelting ores with a 25 % metal content will thus be double as expensive in comparison to minerals with a metal-grade of 50 %. The metallurgists must have noticed these difficulties quite rapidly, urging them to include methods to reduce these costs. The Laurion ores were processed to a very small grain-size (Rehren 2005, 30), in order to be able to remove as much of the gangue as possible; however, this disabled the metallurgists to sort the ores with the naked eye only. The addition of water to get rid of useless rock is a tricky, yet logical next step since water can perform this process for the metallurgists. The parallels in other mining areas suggest that experiments started in connection to a water source, such as rivulets or springs, allowing the clearance of mud and other impurities. The process was facilitated by the use of simple basins and channels to supply and carry off water, either made of wood or simply carved out next to the riverbed.

An intriguing site already discovered in the late eighties but only slowly finding its way into scholarly literature could give a glimpse of this evolution. A series of ore washeries differing significantly in typology from the familiar Laurion ones, were carved out into the riverbed of the Bertseko Valley, located in the heart of the Laurion little south of Aghios Konstantinos (Figs. 20-22). The channels and settling tanks of the washeries are rather unorganised in

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9 See Christesen (2003) for a strong motivation of this fuel issue.
layout and not waterproofed by means of a special coating. Additionally, the washeries did not depend on cisterns for their water supply but on a small rivulet and wells carved next to the riverbed. Kakavoyiannis, who discovered the washeries, has rightly suggested that this could present an experimental phase of ore washing.

The poor stratigraphic conditions, however, did not allow establishing a firm chronology but Kakavoyiannis suggested the beginning of the fifth century BC based on scattered and poor pottery finds. Furthermore, he linked Bertseko to the battle of Salamis and ancient Maroneia, where the great silver strike took place (Kakavoyiannis 1989, 85-7). Perhaps one should be a little cautious with this conclusion. The Bertseko Valley is believed to have been located in the ancient Maroneia area but this is not sufficient to securely date an archaeological site, let alone to connect it to such a major historical event. There are unsatisfactory indicators for a precise absolute dating but Kakavoyiannis (2001, 369) does suggest three strong arguments for relative chronology. First of all, the washeries seem to be a rudimentary version of the rectangular washeries. The settling tanks, channels and main reservoirs can all be identified but their shape and organisation is disorderly, indicating that people were still looking for the most convenient layout. Second, hydraulic mortars—which are overwhelmingly present in the fourth century workshops—were completely absent at the entire site, suggesting that the technology of hydraulic mortars was not yet mastered. This also explains why none of these

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11 The most accepted theory is for ancient Maroneia to have been located at Kamariza.
washeries relied on cisterns; without the application of mortars to its walls, cisterns cannot be secured against water loss and their construction was therefore not feasible. Finally, a chronological indication can be seen in the structural organisation of the complex.

Figure 21  A washery in the Berseko Valley (photo taken by author in August 2012).
Figure 22  The riverbed of the Bertseko Valley with several washeries on the background (photo taken by author in August 2012 from the east valley flank).

As nicely put by Domergue (2008, 179), l’archéologie excelle à révéler l’organisation spatiale d’une mine ou d’un établissement métallurgique. The archaeological record in the Laurion reveals two completely different organised groups of metallurgical sites. The first group is represented by the Bertseko workshops. As Kakavoyiannis has proposed (1989, 82), it is doubtful for these workshops to have been privately run. The washeries were closely packed together and carved in parallel rows next to a rivulet that acted as a communal water source, forcing the workers to cross other washeries in order to reach the rivulet. The furnaces situated on the opposite hill flank show a similar pattern, indicating that these were all integrated into the same industry. As can be seen on Fig. 23, the second group of workshops present the other end of the spectrum: they are generally organised as independent workshops, shut off from the surrounding infrastructure, and with a private water source in the form of a cistern. The workshops generally consist of rooms to crush and grind silver ores, an ore washery to purify these, an accompanying water reservoir and living quarters for the workers and workshop owners. These compounds were not strict workspaces, in the sense that they were generally linked to a domestic context, supporting the industrial activities. Kitchens as well as bathrooms are common features of these workshops. A well-documented example is Compound C in Agrileza, which will be further discussed in detail in the next chapter (Fig. 23).
Figure 23  Compound C, Agrileza (After Photos-Jones and Ellis Jones 1994, Fig. 3).

But how can this enhance our knowledge about their chronology? Literary and epigraphic data help to further tackle this issue. The pattern observed in the archaeological record repeats itself here: 99% of the available evidence comes from the fourth centuries BC and points to a system that could nowadays be characterised as public-private partnership (Wilson 2002, 25). The mineral resources are without exception owned by the city-state of Athens, but the rights to exploit these ores are farmed out to private entrepreneurs. The most decisive proof for this system is presented by the previously mentioned mine leases, kept by the poletai during the fourth century BC. The first lease recorded on stone stelae dates back to shortly
before 367/6 BC, but it is likely that this system already came into use at least from the beginning of the Peloponnesian Wars. This is revealed by the comedian Aristophanes in his *Knights* (362), dating to 424 BC (Crosby 1950, 191). Another reference touching upon the same topic is a coinage degree from the late twenties of the fifth century, likely 422 BC, of which it can be deduced that the *poletai* had been instructed to start regulating the Laurion mines (Meritt 1945, 119-22). However, this inscription is the only fragment referring to this ‘law’, making it difficult to assess its true impact. The fragment of Aristophanes does suggest the leasing of mines to private entrepreneurs at least from the last quarter of the fifth century BC onwards. During this entire phase there is no proof for a publicly exploited mining cooperation. To this end, we have to go back to the early fifth century BC. The scarce evidence for this period hampers an elaborate reconstruction but it seems undeniable that public operation was mainstream. Herodotos leaves no doubt that the silver bonanza was the result of a public mining program and that the *poletai* were not involved in the administration of industry.

The advice of Themistocles had prevailed on a previous occasion. The revenues from the mines at Laurium had brought great wealth into the Athenians’ treasury, and when each man was to receive ten drachmae for his share, Themistocles persuaded the Athenians to make no such division but to use the money to build two hundred ships for the war, that is, for the war with Aegina.

Herodotos, *The Histories* 7.144.1

This does not necessarily exclude the private exploitation of mines in this period, but apart from a rather dubious remark about the tyrant Peisistratos owning private property (perhaps even furnaces) in southeast Attica and having ‘free miners’ among his supporters (Hopper 1961, 140), there is no convincing evidence at all. Langdon (1991, 68) points out that although Herodotos (*The Histories* 7.144.1) and Aristotle (*Athenaion Politeia* 22.7) discuss the great silver strike, they do not give the slightest indication that this silver reached the Athenian treasury through the leasing of mines, suggesting that the state was more closely involved in mining. This tentatively contributes to the conclusion that a group of workshops organised as the Bertseko ones probably date before the Peloponnesian Wars but again, one should be prudent to link them directly to a specific historical event. There is simply no sufficient evidence for this.

A similar pattern of exploitation can be seen in the Roman Empire. There is considerable proof for a system of public-private operation, where the mines are owned by the state but farmed out to *publicani*. This was the case at the gold and copper mines of Vipasca in Spain, as indicated by uncovered administrative tablets. Additionally, Plinius (*Naturalis Historia*

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12 There was likely one lease before the 367/6 BC one (Crosby 1980, 190).

33.21.78) mentioned the work of contractors at the Victimulae gold mines, who were ‘limited’ by a ruling not to employ more than 5000 men. The transition of state to public exploitation is also represented. Strabo (Geography 3.2.10) writes that the silver mines at Cartagena are no longer the property of the state, neither these nor those elsewhere, but are possessed by private individuals. Similarly, it seems that works in the Dolaucothi mines (Wales) were initiated under military supervision but taken over by private entrepreneurs in the second century AD (Wilson 2002, 25). This switch is important, especially because it seems to coincide frequently with a technological uplift. Many technologies were initiated under state exploitation but expanded in the private sphere, often resulting in real breakthroughs (Wilson 2002, 32). The current evidence indicates that a similar development may have occurred at Laurion. The basic layout of the washery complex at Bertseko can be linked to public mining but a real take-off with hydraulic mortars, more standardised washeries and cisterns, was apparently only enabled under private entrepreneurship. The fragment of Theophrastos (On Stones, 59) comes to mind. Although the historical accuracy can surely be questioned, it is no coincidence that a businessman as Kallias was mentioned to have discovered and demonstrated the method of preparation.

There is no solid archaeological proof for intermediate forms linking the Bertseko washeries to the fourth century BC ones. Some washeries seem a little more random in shape but this cannot be safely linked to an earlier chronological setting. Notwithstanding, two finds cannot be fitted into the current metallurgical picture and therefore deserve some further explanation. Both are incorporated in a private dwelling, show the same —although more primitive— configuration of a typical washery, but are not waterproofed. It should be mentioned, however, that the excavation of these installations has not revealed sufficient chronological and metallurgical data to involve them fully in this discussion.

First, washery Π’3 in the Asklepiakon should be presented (Figs. 24-25). The device is small, measuring only 6 x 4.30 m, and entirely carved out into the schist rock. It is not coated with hydraulic mortar and not provided with a clearly identifiable water supply. Apart from this, it has all the typical features of a Laurion washery: a stand tank, channels and sedimentation tanks basins. The excavation did not yield datable finds but Tsaimou (1988, 152-4) believes the fifth century BC to be a likely option. One should be careful though. Workshop 3 with its large rectangular washery and accompanying cisterns had been installed into a probably fifth-century dwelling in the course of the fourth century BC, by doing so turning it into a full-operational ore washing compound but there is no real confirmation to which building phase Π’3 belongs. One can only tentatively suggest that this installation was a forerunner.
Figure 24  Washery Π’3 in Workshop 3, Asklepiakon, Soureza Valley (after Tsaimou 1988, Figure A95).

Figure 25  Washery Π’3 (photo taken by author in July 2013).
Another rudimentary installation has been encountered during the excavations of Insula 3 in Thorikos. In the west part of that insula, several rooms (CB, CC, CD, CE, CH, CI, CG, CW) are organised to form what seems to be an open air workshop, with some roofed rooms on its east side (CC, CD and CE). Several slightly inclined channels were carved out into the (marble) rock but were lacking an impermeable coating and water supply. There are no traces of combustion indicating the smelting of minerals. Additionally, a number of circular holes for stakes and mortises for iron bars have been encountered and—very meaningful—fine gravel, which is typically found in the Laurion as the result of the grinding and processing of minerals. The workshop was incorporated into a building erected in the course of the first half of the fifth century BC but the area and this installation was already overbuilt around the middle of that same century (Mussche et al. 1990, 17-20, 37-9). Mussche suggests this installation to have been a primitive ore washery but in absence of analyses of the gravel, this is difficult to confirm. One should also take into consideration that this is an isolated example; no parallels have been found in the other Thorikos workshops.

This overview brings a noteworthy difference between the two discussed groups of workshops to the foreground: the level of water technology, with hydraulic mortars as most important innovation. These mortars were the enablers of significant progress. First of all, the acute water shortage in the Laurion could be addressed through the waterproofing of installations and surfaces. This is of particular importance for the creation of a permanent and dependable water stock in the form of a cistern. The rivulets in the Laurion are not only few but also of weak potential, generally just flowing during the rainy seasons. This limitation must have been the most important motive for the use of cisterns: these structures enable to bridge the dry period of the year and thus the full-year operation of the industry (Kakavoyiannis 2001, 375). Second, there are the organisational benefits. The use of mortars allows constructing washeries (and thus entire workshops) independently, making them less susceptible to their geographical and geological context. The same goes for cisterns: mortars enable to raise these reservoirs next to favourable water catchments, which is crucial to guarantee continuous industrial operations. The ostensible trivial innovation of hydraulic mortars thus made a complete reorganisation of the industrial activities possible.

The Laurion mortars are of a very high quality and did not lose their waterproofing abilities to this day: several cisterns still manage to hold water throughout the summer. The mortar was applied in two layers. First, the inner basin of the cistern was lined with a 2-5 cm thick layer of lime plaster, filling the fractures in the rocky surface and covering the cistern’s walls. Subsequently, this layer was provided with scratches in order for the next coating to stay firmly attached (Fig. 26). This mostly brownish or blackish layer of only 1 to 2 mm thick is the actual hydraulic plaster (Fig. 27).
Figure 26  Inner wall of a cistern in the Soureza Valley, showing the first lime coating provided with scratches (photo taken by author in July 2011).

Figure 27  Black hydraulic mortar applied on a cistern (photo taken by author in July 2011).
Nothing is known about the actual development of this mortar but scientific analyses, such as XRD and XRF, do shed light on its composition and preparation. The metallurgists seem to have been following a specific recipe that not incidentally contained the most important byproduct of cupellation, namely litharge or lead oxide (PbO). Analyses done by the late Prof. Conophagos revealed a composition consisting of SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, CaO, MgO, ZnO, PbO and MnO. Recent analyses performed on the mortar of Cistern no.1 in Thorikos lead to similar results. Further chemical analyses on the same sample confirmed that the heavy metals in the mortar were not merely impurities but rather the result of intentional addition.

Based on the current analyses performed on Laurion cisterns, there seems to be a universal recipe for hydraulic mortars with litharge as the most important waterproofing component. This opens up an interesting discussion: How were these mortars prepared exactly? Were these mortars made wherever they were required or were there rather, as the universality of the recipe suggests, separate workshops responsible for this duty? How did this sector fit into the wider pattern of activities in the Laurion? This shows yet again that the Laurion was much more than just the producer of silver and that the level of vertical specialisation was much higher than previously imagined. The supporting businesses of the metallurgical workshops must have been immensely varying and did clearly not only consist of life provisions. The mining industry was also in need of a variety of industrial products to assure its operation.

All the investigated ore dressing workshops have so far been dated to the fourth century BC, with the exception of Washery no.1 in Thorikos, which according to Mussche (1967, 62; 1998, 50-1) goes back to the last quarter of the fifth century BC. These remains show that ore dressing was a specialised and well-organised activity, with different facilities to crush, grind and wash ores incorporated into the same compound. Before the enriched ores were carried to the furnaces, however, there was still a last crucial thing to do: the consolidation into pellets to avoid the grinded ore to smother the fire when smelted. There is much obscurity about this last phase, resulting in the general neglect of this issue in scholarly literature. However, recent finds at Ari located in the very north of the Laurion bring more clarity (Fig. 28). Three remarkable circular installations have been encountered in

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14 Conophagos and Badécas 1974, 254-60; Conophagos 1980, 255-256, 273; See also Mishara 1989, 191-205; Protopapas, et al. 2000, 71-6 for a more recent analysis. All scholars came to the same results.

15 The results of the XRD, XRF, thermogravimetric and chemical analyses will be published in Thorikos 12, which will appear in 2014 Van Liefferinge, et al. 2014b.

16 The chronology of this washery is remarkable, since it is the only washery dated to the fifth century BC and even more since its typology does not differ in any aspects of its fourth century counterparts. Based on these facts, some doubts could be raised about the validity of this dating; However, because the excavation diary (1963) is lost, it is no longer possible to verify this chronology.
the ore washing compounds Ari II, III and IV, all three dated to the late fourth and early third century BC (Tsaimou 2005). The device is made of marble blocks aligned in a closed circular circuit of approximately 20 to 25 m. It is unlikely that water formed an integral part of the procedure: the channel shows no inclination, is not waterproofed, nor is there a stand tank to provide a water supply. All but one of these installations consist of a series of bowls, carved out over the entire length of the circuit. In the neighbourhood of these devices, a significant amount of worked ores have been uncovered: crushed ores, plynites as well as brick-shaped pallets, which analyses indicate to consist enriched ore. Tsaimou believes these pallets to form the key in unravelling the function of the peculiar devices: they would have been involved in the preparation of the concentrate for use in the furnaces. The ‘palletisation’ process would be mechanised by a movable wooden beam, as indicated by the cavity in the middle of these installations (Fig. 29). Supporting this hypothesis, a low column was discovered right in the middle of the Ari IV installation. It was provided with a hole, which could have supported a beam that was turned around by workers in order to mix the enriched ores smoothly with clay. A next step was to shape the mixture into bricks, which were laid to dry and subsequently brought to the kilns. Installations like the ones uncovered at Ari undoubtedly made the work process more efficient, not only by reducing time and efforts, but also by the more practical use of manpower.

It is remarkable how much these installations are reminiscent of the so-called helicoidal washeries, of which six have so far been identified (Tsaimou 2004). This link has recently been picked up and critically investigated by S. Nomicos and will now be further looked into.17

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17 Nomicos has presented her findings in the paper *Conophagos reconsidered: the case of the circular installations* at the conference ‘Thorikos 1963-2013: 50 years of Belgian excavations’, Athens/Lavrio 7-8 October 2013, organised by the Belgian School at Athens (EBSA). This contribution will also be published in the proceedings of the conference (Nomicos 2014). A brief note on this issue has recently been published in *Metaallia* 20.2, 25-7.2013
Figure 28 The silver processing workshop Ari III, with on the right a circular sluice (after Tsaimou 2008, Fig. 8).

Figure 29 The circular installation at Ari II. Reconstruction of the work process according to Tsaimou (after Tsaimou 2005, Fig. 5).
The typology of the Laurion washeries currently consists of two main groups: the helicoidal washeries on the one hand, and the rectangular ones on the other. The latter class is further subdivided in Type I, which is the most common model, and Type II, which is rare and likely somewhat later in date.

The so-called ‘helicoidal washery’ is undoubtedly the most debated type (Fig. 30). Following Conophagos’ theory, the device has been interpreted as a washery, an opinion that – partly because of the authority of Conophagos’ work – has not really been questioned since. Nomicos (see above), however, states that there is no ground for such a claim and that these installations, just as the Ari ones, should rather be characterised as grinding devices. Let us first go into the first theory, postulated by Conophagos (Mussche and Conophagos 1973, Conophagos 1980).

Conophagos and afterwards Tsaimou have performed extensive experimental research (Fig. 31) on the system of the ‘helicoidal washery’ and concluded that it worked well, leaving a pure concentrate. Nevertheless, they did point on several disadvantages. First of all, its construction and maintenance were costly: the washery consisted of large marble blocks, which had to be shaped perfectly and with the correct inclination. 25 tons of marble were required for a 20 m long circuit with approximately 180 meticulously carved out bowls, having a denivellation of only 6 cm over its entire length. It is estimated that this painstaking work would have taken 40 days (or 120 working days), as opposed to 20 days in case of the rectangular washery. In addition, once damaged or worn out, the washery was nearly
impossible to repair. Second, the operation was labour-intensive: experimental research revealed that only the first 40 bowls would have been involved in the separation of the material, whereas the 140 remaining ones purely functioned to clear the water. Still, the long circuit had to be cleaned after each operation. The work in a rectangular washery is certainly more user-friendly. Third, the yields were not satisfying: a ‘helicoidal washery’ brought in 2 tons during a 12 hours working day, whereas a rectangular washery yielded no less than 4.5. Fourth, the fact that there are only six conserved washeries, as opposed to the hundreds rectangular ones, demonstrates that the latter must have been preferred. This is further supported by the fact that the helicoidal washery at Megala Pevka was apparently never finished, the one at Demoliaki was abandoned when a new, rectangular washery was raised and the Bertseko one is so badly preserved that any conclusions are ruled out. I would like to add a fifth point: none of the six preserved washeries, nor their direct environment show traces of waterproof coating, even though a considerable amount of water would have been used during the work process. Consequently, the water loss must have been significant. According to this theory and argumentation, the helicoidal washery was a failed experiment. The rectangular one managed better at all the points raised above. It was cost-effective, less labour-demanding, had higher yields and allowed a more economic water management. There is some discussion about the dating as well, as a result of the lack of convincing stratigraphy: the majority of scholars prefer to place them before the development of the rectangular washery, as opposed to Kakavoyiannis (2005, 253-5), who believes that they were introduced in the late fourth or early third century BC; However, a precise dating remains unattainable, a matter that will be further dealt with below.
Figure 31  Reconstruction of the circular installations according to Conophagos (Conophagos 1980, Fig. 10-34).

The second hypothesis rejects this reconstruction, pointing to the similarities with the previously discussed installations at Ari. Nomicos' critique is mainly based on the lack of convincing archaeological proof for the identification of this device as a washery. The main issue is that Conophagos started from a certain assumption and has subsequently adjusted and reconstructed the device to this idea. The first and most important argument points to the water supply. Conophagos included a stand tank in his reconstruction, while such a reservoir has never been encountered in reality. This ties in closely with a remark given above: if the installations would have been used for ore washing, one would expect them to be securely waterproofed. Grinders, on the other hand, logically never are. Second, the archaeological remains do not support the presumed helicoidal shape. It is as likely for these devices to have had a circular form, as observed at Ari. Third, the ancient surface has disappeared in all cases, making the determination of the inclination particularly questionable (Nomicos 2013, 25-7).

This brings us to the typology of the rectangular washery, the typical feature of the Laurion area (Fig. 32). It is a rectangular structure built up with masonry, often partially carved out into the rock, and entirely coated with hydraulic mortar. Two kinds of washeries have been described: Type I has its stand tank (Δ) on the short end of the washery. This reservoir has a number of funnels at a height of approximately 50 cm, through which water was fed into a series of slightly inclined channels (A1, A2, A3, A4) and rectangular or round settling tanks (B1,
These channels enclose a flat area that acted as a drying table (Z) for the washed ores (Conophagos 1980, 224-44). Type II knows a similar configuration but has its stand tank built on top of the drying table. Due to this, the water runs in the opposite direction.\textsuperscript{18}

\textbf{Figure 32} Type I and II washery (Conophagos 1980, Fig. 10-16).

There is no agreement on how the beneficiation process had been performed but it is generally accepted that the washery served a double purpose. First, the washery was employed for ore enrichment. Second, it was a water recycling device: water was redirected

\textsuperscript{18} Conophagos 1980, 244-5; Kakavoyiannis 1989-91.
through the channels and settling tanks to the rebailing basin (B3), from where it could be lifted back into the stand tank (Δ) for reuse. How and where the actual ore beneficiation took place is contested. A division should be made between two groups of theories: the first group holds the view that ore was enriched on E, which is a 2% inclined space in front of the stand tank, whereas the second group rather believes that this main reservoir played an important part in the purification process. Although it is hard to reach any solid conclusions and all scholars have provided valuable insights to the discussion, the reasoning of the first group is generally considered as more convincing. Nevertheless, some critical remarks should here be made as well.

The first group found its origin in the work of Phocion Negris (1881, 160-4). This 19th century Greek engineer was the first to give a proper identification of the washing procedure in the rectangular washery. In accordance with this reconstruction, the grinded ores were deposited on the surface of zone E, which acted as a washing table (Fig. 33). While water was flowing through the nozzles of the stand tank, the ores were stirred, presumably with the help of a wooden scrubber. The ore particles are sorted based on their gravity: the heavier minerals remain on this surface, while the lighter ones are drained off to the channels and sedimentation tanks. This technique reminds of what Agricola recorded in many areas in Europe: washing tables and scrubbers were omnipresent in the mining landscape. Nevertheless, Conophagos brushed away Negris’ suggestion based on the following arguments (1980, 242): experimental research would rule out the use of zone E as a washing table; the results were apparently not satisfactory, even when the procedure was performed with a scrubber. Additionally, Conophagos saw two _argumenta ex silentio_ for Negris’ false interpretation: there were neither traces of wear on space E, nor was there an obstacle prohibiting the water flowing from E directly into the rebailing tank (B3).
Conophagos did agree with Negris for E to be the actual place for ore enrichment, but he opted for another method: water was fed from the stand tank, through a fixed number of nozzles connected to wooden sluices shaped as their helicoidal counterparts, in which the beneficiation process took place (Fig. 34). According to Conophagos the system worked flawlessly, leaving the water clean by the time it had reached this final reservoir B3. At the end of the beneficiation process, the concentrate was collected and laid on the drying table (Z).
Figure 34  Type I ore washery and the beneficiation process according to Conophagos (1980) (After Salliora-Oikonomakou 2007, Fig. 5 and Conophagos 1980, Fig. 10-18).

Although Conophagos’ theory (1980, 242-4) has been generally accepted, there are some inherent difficulties with this reconstruction. Conophagos was undeniably a brilliant scholar, who has given invaluable insights into the history of the Laurion, but it should also be admitted that he was in first instance a metallurgist, who was not very familiar with archaeological research and this is clearly reflected in his work. His reconstructions were often based on assumptions, for which there is little or often no clear-cut archaeological proof. Mussche (1998, 10), who closely cooperated with him during his life-long career, wrote that Conophagos emphasised that he was an engineer, a practical man, and not a historian, and that the historical development did not really fascinated him; that was a problem for the archaeologists. Probably due to Conophagos’ authoritative work, few (especially non-Greek) archaeologists have actually attempted to nuance his theories.

The largest issue with this theory is its unstable basis. Conophagos saw the main evidence for the wooden sluices in stone counterparts as presented by the helicoidal washeries. It has already been shown that the identification of the circular installations is doubtful but even if their authenticity is given the benefit of the doubt, this reconstruction remains questionable. First, there are neither archaeological remains of these sluices, nor negative traces that would support their use. Furthermore, Conophagos based his reconstruction on a problematic chronology, by assuming that the helicoidal washeries were the technological predecessors of
the rectangular ones. Mussche’s argument (2006, 229) that it is absolutely certain that the sluice was
known in the Laurion and there are indications pointing to its existence already in the fifth century BC: the
helicoidally shaped washeries, does not really stand. As I have explained earlier and Rehren (2001,
42) has rightly pointed out as well, there is no solid archaeological proof for an archaeological dating of
them at all. The antique surface has either disappeared or is disturbed at all sites. I do not agree
with Mussche’s argument (1973, 62) for the device to be Archaic based on the ‘Lesbian’
building style of the cistern located next to it. The cistern was built up with rubble masonry,
which does not offer a solid enough dating argument at any archaeological site. Moreover,
there is no single evidence that this cistern had actually been connected to this installation.
Arguments for a more relative dating have been put forward as well: the ‘helicoidal’ washery
of Megala Pevka was demolished by the construction of a rectangular one (Rehren 2002, 42)
but the only thing that this demonstrates, is an earlier use and not necessarily its fifth century
BC construction. The other ‘helicoidal’ washeries are also not able to guide the debate in the
right direction, since these are badly preserved.
The problem is that all the remaining arguments have been further built on this rather shaky
basis. Conophagos (1980, 244) mentions that the nozzles of the rectangular washery are
exactement comme dans les laveries helicoïdales où il n’y avait qu’une seule tuyère. In none of the cases,
however, the nozzles of the ‘helicoidal washeries’ have been preserved. In a next point,
successful experimental research on the helicoidal washery and the sluices are put forward as
evidence for their use but satisfactory yields do not automatically confirm their application,
even less when the reconstruction is made to produce successful results. As already explained,
Conophagos added a water reservoir to this device, whereas such a basin has never been
discovered. This can also serve as an argument against Conophagos (1980, 242) rejection of
Negris theory. He was very brief on the experimental research that was performed on Negris’
hypothesis: La répétition expérimentale de ce traitement dans les mêmes conditions donne des résultats
négatifs. Ceci est vrai même si l’on veille à reconstituer constamment la couche de minerai à l’aide d’un racloir
lors de la chute de l’eau. Under what conditions was this experimental research performed and
how negative were these results really? This is not clear from the very brief footnote
Conophagos devotes on this topic but when bringing the parallels provided by Agricola back
to mind, this hypothesis should at least be given a fair chance. Conophagos started from the
idea that only one cycle was required to purify ores and that the water should have been pure
when it reached the rebailing basin. Agricola, however, mentioned that the ore washing
process was generally repeated, sometimes even up to seven times, until the satisfactory result
was obtained. I find no reason to suppose why this could not have been done in the Laurion.

This leads to a crucial, yet undeservedly neglected argument in the general discussion about
ore washing, namely the mineralogical composition and distribution of the tailings (the waste
of the washing process) within the washery. A huge amount of washeries have been
uncovered over the past century but only very few have been properly sampled, subjected to
the correct analyses and finally published. If this would have happened more systematically,
the current image on ore washing method would undoubtedly have been different. Rehren
(2002) and Ellis Jones (1994) are among the few who have provided an interesting discussion of this topic but they have reached somewhat different results, making the debate not particularly easier. Rehren (2002, 39) mentions that tailings were generally found on space E (Fig. 34), the first channel and the drying table in connection to this channel, which corresponds with the Negris-Conophagos reconstruction. In contrast, Ellis Jones (1994, 335-7) found tailings spread over the entire washery, even in the rebailing and stand tank (although these were few), putting Rehren’s but also Conophagos’ observations in another light. Ellis Jones is careful in his conclusions and rightly stresses the issue that the exact mineralogical composition of the original Laurion ores is unknown, consequently hampering a correct identification of tailings. Nevertheless, the ore remnants encountered in the settling tanks of the Compound C washery (see Fig. 22) have been analysed and still proofed to yield argentiferous lead. This could imply that either the workers were unaware of the fact that they were discarding lead-rich material or they collected and processed the ores a second time. Ellis Jones’ discussion is well-founded but extensive and will therefore not be repeated in detail here. Nevertheless, he does believe the possibility of the multiple processing phases to be more a realistic interpretation.19

Let us now move to the second group of theories, identifying the stand tank as the location of ore purification. The very first hypothesis ever postulated on the working of the Laurion washery can be assigned to this class. Kordellas (1869) was influenced by Strabo’s mentioning of the jigging sieves for his hypothesis. If Strabo’s quotation of Polybius is indeed correct, this technique must have been known since at least the second century BC but it cannot be traced back further in time. Not much attention has been given to this suggestion, especially not since Conophagos’ influential work, but Kakavoyiannis (2005) has recently put forward a similar theory based on findings made in the Aghia Triada excavations at Soureza. Inside the ore washeries and in their direct neighbourhood, he has recorded large quantities of lekanai, leading him to assume that these had some part in the purification process. He suggests a panning process to have been taking place in the stand tanks: the ores were dropped in lekanai, which were subsequently immersed in the water. Another possibility would be for the concentrate to have been obtained through vanning in mortars. It is very difficult to assess his theory, since his excavations remain, apart from some brief reports (Kakavoyiannis 1992, 70-93; 2005, 240-2), unpublished. Mussche (2006, 227-8) did not welcome this theory enthusiastically, arguing that the large amount of lekanai in and immediately around the washeries (and thus also his hypothesis) cannot be generalised. According to Mussche, the total amount of then 9000 inventoried finds in Thorikos yielded 360 lekanai, of which hardly

19 An additional study on this issue has been published by E. Photos 1992, 55-66.
0.06 % was found in the washeries. Terracotta mortars are even scarcer; out of the 0.2 % mortars none were find in the washeries. Admittedly, lekanai do not seem a particularly suitable instruments; one would certainly be better off with the light, thin metal pans, which are nowadays still used in the mining of placer gold, or with a kind of jigging sieve, as suggested by Kordellas (1896). Such devices, however, are made of perishable material and have never been encountered in the archaeological record. Until this happens or mineralogical research can give more clarity, there is no firm ground to accept this theory. Another method has been suggested by Domergue (2008). He opts for a vanning, rather than a panning process. Ores were stirred together with the water, an action that discharged the lighter particles through the nozzles whereas the heavier ones settled down on the bottom of the tank. This view is likely influenced by his own reconstruction of the work process in the washery of Coto Fortuna in Spain but does probably not apply to the Laurion washeries since these know a significantly different configuration (Domergue 2008, 152-3). Mussche raises some interesting questions in this context as well (2006, 228-9): if the ores would have been washed inside the stand tank, why then was the washing table in front of it so wide? And why are there no traces of wear visible on the inner walls of the tank, which this process would have undoubtedly caused?

Taking a position in this discussion is difficult but, especially when taking the mineralogical research into account, the first one remains best working model. There is, however, no ground for Conophagos’ specific reconstruction. The presumed link between the ‘helicoidal’ and the rectangular washery is a problematic starting point; there is not only no certainty about the identification and chronology of this installation, but the theory can also not be confirmed archaeologically. Additionally, their function as forerunners of the rectangular washeries is peculiar from a technological point of view. Taken the theoretical framework into account, the switch of a helicoidal to a rectangular washery strikes me as odd, even more so when a steady technological development of the rectangular washery is likely represented in the archaeological record (see Bertseko). Based on the current evidence, the use of washings board cannot be ruled out entirely, but shaping this equipment to the circular installations is untenable. Perhaps it is advisable not to desperately look for one single correct method. Since private entrepreneurs were the ones running the plants, considerable experimenting must have been done in an attempt to tune the techniques to their needs, opening up the possibility of the use of differing ore washing methods from workshop to workshop.

20 The total amount of inventoried finds is now considerably larger but since no more washeries have been studied, the number of finds encountered in these devices is still representative. On lekanai in Thorikos see also Docter 2011, 83-9 and Lüdorf 2000 (for reviews of Lüdorf’s study see Fless 2003, Rotroff 2004).

21 As mentioned in the overview of the textual sources on ore washing, Diodoros and Agricola also mentioned the use of washing boards.
Many variations of the washery plan exist and this could possibly correspond to such patterns. The current washery typology is definitely far from comprehensive, giving a somewhat distorted image of reality. In this context, it is not unreasonable for Kakavoyiannis to have looked for other options, especially since the Agia Triada washeries are difficult to fit into the current picture. His discussion rests on two interconnected washeries, of which the second seems to be subsidiary to the first. The latter works independently but receives waste water in its own water circuit from the former installation, which does not have its own channels, a situation that is highly unorthodox for a Laurion washery (Kakavoyiannis 1992, 79-93). The Agia Triada washeries are not isolated case-studies; When looking closer at the archaeological remains, variation in washery shape appears to have been more rule than exception.

As mentioned above, the most noteworthy variation is the so-called Type II configuration. Although such washeries hold a minority position, several of them have been discovered spread over the Laurion. A first group is situated in the area of Thorikos: 1) the Belplast workshop (Liangouras and Kakavoyiannis 1972, 148-50), 2) Roma plot at a place called Ergastirakia, 3) the Violari estate (Oikonomakou 1979, 88), 4) the Zoridis workshop in the Potami valley. The last mentioned workshop is better published and will therefore be discussed in more detail. The ergasterion is located little northwest of Thorikos. Washery A (Fig. 35) in the north part of the estate has two of its sedimentation basins installed in a narrow space immediately north of the washery’s stand tank. This stand tank was divided two basins: the first is small and has only one nozzle (1.32 x 0.89 m), while the second is longer and provided with three funnels (3.75 x 0.90 m). In contrast to the Type I washery, the water circuit of the washery is organised in such a way that water flows in the opposite direction. Furthermore, the circuit consists of a chain of five reservoirs (nos.5-9, Fig. 35), installed immediately next to one another and eventually leading to two elongated settling tanks (nos. 1-2) in the space immediately north the main tank. Finally, an underground channel is leading to a small, separate reservoir (0.94 x 0.7 m; depth: 1.04 m; no.4) used to refill the stand tank. The paved floor A has been interpreted as the drying table. The second washery (E) of the workshop shows the same configuration but is smaller, with one three-nozzle stand tank and a shorter water circuit.

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22 No report has been published but Kakavoyiannis (1989-91, 5) suggests that it is probably one of the oldest washeries surviving from the Classical period.

23 No precise coordinates were mentioned in this report, so this workshop could not be plotted on the overview map included in this PhD.
As can be seen on Fig. 35, Zoridis incorporated Conophagos’ theory to clarify the washery’s operation, which—taken into account the remarks above—seems inaccurate. Even more, this washery could provide extra counter-arguments to Conophagos’ sluice theory. If such washing boards would have used, one would expect them to be well in line with the settling tanks in this specific configuration. In Washery A, however, the central and right sluice would have both ended up in the same tank, very close to the border of the plate dividing these basins. Furthermore, there are only three nozzles in the main reservoir for four tanks. The same comments apply to the second washery. Here, there would be three sluices for two tanks, with the middle washing board running right onto the dividing plate.
Figure 35  The work process in washery A at the Zoridis workshop according to Zoridis (1980) (After Zoridis (1980), Figure 3-4).
A survey at Spitharopouisi and in the Botsari and Soureza Valleys executed between 1983 and 1987 has revealed several more examples, of which the plans can be seen on the figure below.

Figure 36 Type II washeries in the heartland of the Laurion (After Kakavoyianni 1989-91, Fig. 4-8).
Further south on the opposite side of the Adami plain, the Skitzeri workshop (Fig. 37) offers another interesting case-study: the large washery A, installed in the centre of the complex (13.9 x 8.10 m). The first noticeable feature is the ramp, a small sloping surface that is part of all washeries. In normal circumstances, this ramp is incorporated on the right side of the stand tank just above the rebailing tank, allowing to smoothly fill the stand tank with the recycled water. In this case, however, this feature is installed in the opposite corner. This can probably be related with the fact that the washery was lacking the channel linking the second to the third sedimentation basin. Instead of a closed water circuit, this washery thus has two separate and considerably shorter series of tanks and channels at its disposal. Adding to this, there seems to be a secondary system to the west of the washery, consisting of the rectangular space (B) and a smaller reservoir directly to its south, which is sloping towards the most western channel of the washery and subsequently feeding it. A last interesting feature is a plate positioned in this channel, dividing it in two parts (Oikonomakou 1976-7, 129). Such plates, probably acting as a kind of barrage to enhance the sedimentation process, are not that uncommon in the Laurion but have not been frequently reported. These features can for example be viewed in the Kordellas workshop as well. ‘Room’ Γ (5.7 x 5.7 m) located to the washery’s west was entirely covered in hydraulic plaster and is suggested to be the supplying cistern.

Figure 37  The Skitzeri workshop (Oikonomakou 1976-1977, Fig. 2).
Although these major variations are important arguments in the debate, it should be stressed that most washeries show only minor differences, such as variations in the length, size, depth and shape of the channels and settling tanks. Nonetheless, small interventions – how little these might be – can modify and enhance the operation as well and should thus be involved in this overview. The figure below gives a nice overview of such adaptations.

![Figure 38](image)

**Figure 38** Small variations in the rectangular washery plan (Ellis Jones 1982, Fig.2).

In the Soureza area, e.g. the Asklepiakon and the Agia Triada excavations, several washeries have round settling tanks, some even provided with holes in its inner wall, allowing the smooth cleaning of the reservoirs. Other observed features are oblong settling tanks. At
Demoliaki, two such washeries (C and D) have been uncovered (Fig. 38). Destroyed by the construction of Washery D, only the lower part of Washery C consisting of two oblong tanks (2.40 x 0.95 m) has been preserved. D is of the exact same type as C but much larger (10.80 x 8.80 m) and with apsidal shaped basins (3.80 x 1 m) (Mussche and Conophagos 1973, 63-4). Because these tanks are not that omnipresent, it can tentatively be suggested that this intervention happened under the impulse of the same owner, who wanted to increase the yields of his workshop.

**Figure 39** Washery C and D at Demoliaki (After Mussche and Conophagos 1973, Plan 2).
At Agrileza, Washery A (6 x 12 m, **Fig. 40**) shows all the typical features of a Laurion washery but has nevertheless a peculiar series of shallow grooves in connection to the first channel, interpreted by the excavator as a kind of overflow runnel (Ellis Jones 1985, 110).
Some washery plans serve as good examples of how these were often adjusted to the pre-existing infrastructure. This indicates that we should be careful not to assign every variation to intentional experimentation with ore washing methods. Such a pattern can be seen at Belplast, an *ergasterion* situated not far from the Skitzeri workshop (Fig. 41). The washery in question had a remarkable elongated shape and was missing a third settling tank in the lower right corner. Furthermore, its left settling tanks were set outside the line of the first channel. Especially the last intervention seems the result of improvisation and adaptation to the available space. Besides some short reports, this workshop has regrettably not been published, so no more information can further be given.

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The best example of such an improvisation pattern is undoubtedly Washery no. 11 in Thorikos (Mussche 1998, 40). This small washery (Fig. 41) was literally squeezed into an older residential building in the course of the fourth century BC. It measures 10.20 m on its longest side, with a varying width of 3.75 m on its upper end and 6 m on its lower end. There was not much room to manoeuvre, which is quite clear from the position of the last settling tank (B4). Although this reservoir is supposed to act as rebailing tank, it is installed no less than 4.50 m away from the stand tank. The workers clearly had to be creative with the available space.

The mentioned overview, although brief, is noteworthy because it forces us to look at the current theories and typologies more critically. All these changes—from small interventions to significant technological adaptions—illustrate the constant search for new and better
techniques, the willingness to invest capital to serve this purpose and likely also the drive to increase yields.

These last remarks do not only apply to the washeries, but are even more noticeable in the water management strategies. Despite the differing views on ore purification, there is general agreement on the fact that the ore washery is a water recycling system. Its closed circuit of channels and sedimentation tanks are especially designed to purify the waste water of the beneficiation process and redirect it to the stand tank for reuse. Apart from the washeries, there are many more features testifying to a careful water management, such as cisterns, water channels, waterproofed surfaces and more generally, the distribution of the workshops. All efforts were aimed towards the harvesting of rainwater, which was basically the only reliable water source, especially in the heartland of the Laurion. Barrages blocked the surface runoff, diverting it to channels that were subsequently linked to large cisterns, lined with hydraulic mortar. Central in this discussion are the cisterns, of which two types are encountered in the Laurion: (1) domestic and (2) ‘industrial’ cisterns.

The former cisterns are underground bottle-shaped reservoirs with a narrow neck of approximately 1-1.5 m that broadens towards the bottom. A widespread practice was to connect several domestic cisterns by means of an overflow channel, increasing the feasible amount of harvested water substantially. Examples can be seen in the previously mentioned Insula 2 in Thorikos (Fig. 7), in the Kakavoyiannis excavations and Compound B in Agrileza, which will be more elaborately discussed in the next chapter. There is a difference, however, between the ones in Thorikos and the other mentioned cisterns: in Insula 2, a natural overflow channel is used to connect the reservoirs in the form of a large eroded fracture running through the entire length of the dwelling.

The latter reservoirs come in various shapes and sizes, a situation that seems merely the result of topographical conditions; some are round or oval, other rectangular or square. They are set into the ground, partly built with massive ashlar masonry and partly carved out into the rock to retain the water pressure. In a fair number of cases, the cistern is provided with a stair in order to clean the basin when empty. Just as the reservoir itself, the surface of this staircase is firmly waterproofed (Fig. 43).

As industrial cisterns were meant to provide water for ore processing, they were always built in the proximity of the washeries that they served. In well-organised workshops, a conduit was often constructed, leading from the cistern towards the washeries. When a similar channel was not attested, water was likely to have been raised from the cistern with a container and subsequently brought to the washeries, where it was siphoned over into the stand tank. A block projected from the rim of many cisterns (Fig. 44), testifies to such a practice and simultaneously would have allowed drawing water from the cistern without the risk of breaking the vessel.
Figure 43  Staircase in cistern Δ3, Asklepiakon workshops (photo taken by author in July 2012).

Figure 44  Stepping stone in a cistern in the lower Soureza Valley (photo: author).
The presence of a decantation basin, with an average content of 2 to 5 m³ (Trikkalinos 1978, 15) is recorded in the majority of the cases, although I have not been able to record such tanks in the area of Thorikos. This small cistern was meant to clarify the water before it flowed through a channel into the principal basin. Plinius (Naturalis Historia 33.21.10) mentions that these basins were a vital feature because contaminated water hampers the purifying process.

To prevent both evaporation and contamination, cisterns must generally have been roofed, as suggested by the presence of a column base on the bottom of many cisterns (Fig. 45).

Special measures were taken to secure the water provision of the cisterns. Barrages and supply channels blocked and directed surface runoff during rains to the cisterns (Figs. 46-47). Very often supply channels were no more than the consolidation of the gully that was running through the valley during rains, which can be clearly seen in the Agrileza Valley. In other cases, these channels were carefully constructed as two parallel walls and provided with the same type of waterproof plaster as mentioned above. Secondary branches were used to join the cisterns with the main channel. In normal conditions, water was first led to a decantation cistern in order to be clarified and thereupon flowed to the actual cistern. Furthermore, to guarantee a maximum of water recuperation, the surface around the inlet of
the cistern and the area above, was mostly waterproofed. In Agrileza, a plaster floor was recorded directly west of Compound C. It was likely to have been serving as a catchment for the main reservoir and the cistern in room XIII (Photos-Jones and Ellis Jones 1994, 327). Smooth surfaces disallowing seepages were likely considered as favourable water catchments, a situation that seems to have been the case in Thorikos. The surface immediately above the largest cistern of the site, Cistern no. 1, was remarkably smooth and without fractures (Van Liefferinge et al. 2011, 60).

In case of domestic cisterns, water was mainly collected through the roofs of houses, since this is more hygienic than gathering surface runoff. Nonetheless, several exceptions have been recorded. In the Soureza Valley for instance, domestic cisterns are observed making use of the same supply channel as the industrial ones. Therefore, these examples were often accompanied by a small decantation cistern.

Figure 46 The Botsari Valley with a central supply channel providing the workshops (Ardaillon 1897).
Communal channels are not only important in the context of sustainable water usage, they also indicate the identification of often complex organisational structures. Their use and maintenance influences the distribution of workshops and settlements, with the upstream ones having significant advantages over the downstream ones (Scarborough 1991, 113). It is no coincidence that the upper branch of the Soureza valley has many more workshops constructed along the gullies than the lower valley. In the former area, the workshops were so closely packed together that it was absolutely paramount for them to cooperate, since water allocation often forms a principle source of conflict (Scarborough 1991, 115-124). One channel dug in the wrong place could easily cut off a neighbouring workshop from its water supply. These issue is also reflected in Strabo’s *Geography*, when mentioning the mining of placer gold in connection to the Durias river in the land of the Salassi (located in Cisalpine Gaul):

The Durias River was of the greatest aid to them in their mining — I mean in washing the gold; and therefore, in making the water branch off to numerous places, they used to empty the common bed completely. But although this was helpful to the Salassi in their hunt for the gold, it distressed the people who farmed the plains below them, because their country was deprived of irrigation; for, since its bed was on favourable ground higher up, the river could give the country water. And for this reason both tribes were continually at war with each other.

Strabo, *Geography* 4.6.7

This indicated that the Laurion workshops were part of a larger social sphere, in which workers were continuously communicating with one another. In this context, it is interesting to point at the sharp contrast between the heartland of the Laurion, such as the Soureza and
Botsari Valley, and the Thorikos area, where such channels have not been observed. This implies a different, possibly more private work sphere, requiring a less intense communication between the different parties.

This mutual divergence between several areas in the Laurion is not only expressed in the channelling of surface runoff, it also seems to apply on cistern sizes. It is a common place that the Laurion cisterns are gigantic reservoirs. True, the central valleys testify to the construction of particularly large cisterns (Fig. 47) but this image cannot be generalised. A topographical survey conducted in 1971 by Petropoulakou and Pedazou allows making a rough calculation of the average volume of the 60 preserved cisterns, which appears to be approximately 265 m³ (Figs. 48-9). These results are in sharp contrast to the image one gets in the Thorikos area, where hardly any (large) cisterns are observable, inevitably raising some questions about the scale of ore processing. It can be surmised that the cistern volume correlates with the production output of a workshop. The higher the water availability, the larger the workshop output and consequently the feasible silver production. Could this mean that the workshop owners in the Thorikos area were less focussed on silver production due to water scarcity? Or were other factors involved in their decision-making? How far did they go to create the ultimate conditions for water harvesting? These are essential issues to raise when investigating the motives behind the starting up of an ore-processing business, questions that will be further dealt with in the next chapter.

Figure 48      Example of a large cistern in the upper branch of the Soureza Valley (photo taken by author in July 2011).
Figure 49  Map of a topographical survey executed in 1971 in the upper Soureza Valley (Conophagos 1980, Fig. 10-25).
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**Average volume** 264.8

**Figure 50** List of the 60 cisterns in the Soureza Valley based upon the 1971 survey (Petropoulakou and Pedazou 1973) with measurements and volumes (table author).
5.3 Ore smelting

The last phase in the silver production process took place outside the ore dressing *ergasteria*, more specifically at furnace workshops. We are ill informed about smelting and cupellation, so the reconstruction of these activities merely rests upon our understanding of the metallurgical processes. Nevertheless, the few recorded finds have significant value. The earliest evidence for the smelting of lead and silver ores in the Aegean was recorded in the Laurion: fragments of litharge (lead oxide, PbO), which is a waste product of cupellation, were observed at sites dated as early as the transition of the Final Neolithic (4200-3100 BC) to the Early Bronze Age I (3100-2650 BC) (Kakavoyianni et al. 2008, 50). More litharge has been found in Thorikos, more specifically in the Early Geometric Room XI in a house next to the West Nekropolis and in a late 16th century BC house on top of the Velatouri Hill. Finally, several Classical, Early Hellenistic and late Roman furnaces have been recorded but no single cupellation hearth.

The smelting of ores was a highly specialised procedure, the details of which differed from ore to ore. Cerussite could be smelted immediately and brought to the cupellation hearth afterwards. For galena ores, however, the procedure was more complex since these had to be roasted to liberate the sulphur in the ore. This can be done in the same furnace where smelting is performed but only if the correct conditions are created. Roasting occurs at 600° when the ore is exposed to oxygen; smelting takes place beyond 750° under reducing circumstances, transforming lead oxide into metallic lead, still holding the silver. In a next phase, the lead flowed through a tap-hole into a pit in front of the furnace. Due to the greater gravity of the lead, the slag floats on top and can be skimmed off and disposed in a separate slag pit. The use of (rich) galena did have a significant advantage to cerussite: it required considerably less charcoal: only 20% of its weight as opposed to 50% (Rihll 2001, 118-21). In the next phase, the silver is separated from the lead through cupellation. As mentioned, no cupellation hearths have ever been recorded but the waste material of the process, litharge (PbO), and litharge-soaked cupels (Conophagos 1980, Fig. 12.4-7) have. When temperature in the hearth exceeds 800°, the lead cakes are added and oxygen is blown through the hearth. Under these oxidising conditions, the lead will react and form lead oxide, which is subsequently absorbed by the cupel or skimmed off, whereas less reactive silver sinks to the bottom of the cupel. Finally, the silver cake can then be removed.

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25 Besides the site of Koropi, see also Lambrika, Merenda Markopoulou, Velatouri Kerateas and Thorikos (Mine no.3 and excavation on top of the Velatouri hill) (Kakavoyianni 2008, 45-51).
There is no information about the organisation of the smelting business or how the state claimed silver for money-making, perhaps through a tax. Nevertheless, some data can be deduced from the archaeological remains of the furnaces. Rihll (2001, 118, cf.14) rightly defends the existence of larger enterprises, which is indicated by the low quantity of furnace sites, the incorporation of several furnaces into especially designed buildings (Fig. 51) and the highly complex working procedures. Another thing to be kept in mind is that smelting was a very unhealthy job, affecting all life in the nearby environment. Centralising these activities to a certain extent would surely have been appropriate. Nevertheless, this does not exclude that some furnaces were privately owned, as demonstrated by epigraphic and literary sources, for example by Demostratus of Cytherus (Crosby 1950, 240, no.1, 54) or Meidias (Demosthenes, Against Meidias, 21.167).
5.4 Towards an understanding of technological change in the Laurion

In the previous section, I have discussed the development of ore dressing from a technological point of view and already hinted possible triggers of this evolution and their implications. These incentives and their effects will now be further elaborated on.

As shown in the theoretical framework, there used to be a persistent trend in the study of ancient technology to view technological change solely within the framework of far-reaching development, stimulated by exogenous dynamics. This overview has shown that the story is often less one-sided than this. Technological progress occurs against a certain geographical, climatological and chronological background and these conditions should not be brushed aside in the debate, even less when the discussion focuses on a primordial resource as water. In a strict physical sense, people need a minimum of two to three litres of water a day to survive but this amount increases significantly to maintain a household and even more, to develop and sustain industries. Environmental conditions dictate how water can and will be used but the distribution of water resources on the earth’s surface is not equal and this affects different responses to environmental challenges. Differing geomorphological and climatological conditions will determine the amount of work necessary to manipulate water sources, particularly when the population reaches a threshold and the demand for resources of any kind inevitably rises. In this sense, technological change is responsive to resource availability. Arid climates and complex geomorphology (determining soil permeability and thus the rate of seepage) have often stimulated experiments and significant innovations in water technology because such environmental conditions offer the most pressing challenges (Scarborough 1991, 102-3). Cisterns are typically built in areas without a reliable riverine system. Simultaneously, a rugged topography can be used as an advantage to tap surface runoff and direct it towards these reservoirs. In combination with a hostile geomorphology, this will often trigger the development of hydraulic technologies. Nevertheless, real technological breakthroughs will only occur if there was a receptive atmosphere and sufficient knowhow to enable such innovations. The Laurion fits well into all aspects of this picture.

Looking at it on a long-term scale, technological change in the Laurion was a steady process, consisting of random changes over time, learning by doing and deliberate experimentation, all contributing to a continuously growing metallurgical knowhow. The search for appropriate technological answers should not be seen as a long series of successes, inevitably leading to technological and economic take-off. Some technologies were successfully implemented, others rejected and abandoned. The interdependence of technological sequences was
particularly important in this evolution. Since the beginning of mining people were looking for the best suitable ways to economise silver ores but their solutions never occurred isolated from other fields of knowhow. A rough, undoubtedly too simplified sketch of such sequences can be seen in Fig. 52. It only takes into account sequences within metallurgy, whereas one should realise that these were influenced on their turn by external lines of events, such as the pyrotechnical knowledge obtained from ceramic production.

This image shows that many sequences were complementary, without necessarily being synchronised to one another. As previously explained, advanced ore dressing methods could only be developed once the link between the density of minerals and their metal grade was realised. In that sense, mining as well as pyrotechnology added much to the development of ore beneficiation and the washery as a device. Ore extraction acquainted people with the composition and density of minerals, while failed attempts of smelting low-grade ores contributed to the awareness that such ores could not be processed efficiently. People must have realised quite rapidly that the fuel input decreased significantly when high-grade minerals were smelted instead. The relationship between the hydraulic mortar and ore washery sequence is more straightforward. The introduction of the ore washery in a context

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of water scarcity brought along the need to waterproof this device but this was only attainable by involving the accumulated pyrotechnical knowledge developed in the Laurion. The most important ingredient of this mortar is litharge, a byproduct of cupellation. It is remarkable that the time lapse between the techniques to produce litharge and the development of mortars is at least 2500 years. Technologies can thus know a delayed complementarity as well. The development of hydraulic mortars was a superior solution to an issue inherent in the Laurion, i.e. the need to involve low grade ores in silver production in combination with the high water demand and an inhospitable geomorphology. The connection with cisterns is easily made: the need for a permanent water stock for ore washing was met by waterproofing technologies. A less straightforward link is the one between the mining and cistern sequences: the Laurion miners were well educated in the digging of deep mine shafts, a knowhow that could also be used for cisterns, whose basins were carved out into the bedrock in order to retain the water pressure. Many of these issues, however, only became increasingly pressing in the socio-economic context of fifth- and fourth-century Greece, when the silver demand rose to an unseen level in history and an atmosphere was created to enable real technological take-off.

It could be stated that the political, economic and institutional context of Athens since the late Archaic period provided the framework for a more rapid economic and technological development. This evolution, however, occurred with intervals that seem to have been dictated by the organisational structure of the Laurion: the first incentives were given under state exploitation and these were further built on under private entrepreneurship. From the introduction of coinage onwards the economic atmosphere in Athens changed drastically. The demand for silver raised significantly, a matter that was further enforced by the Persian Wars and subsequently the rise of the Athenian Empire. A crucial moment was surely 512 BC, when the Athenians lost their rich Thracian mines to the Persians, forcing them to focus solely on the Laurion for their silver production and develop it as fully operational mining industry. The silver quest triggered by this event resulted in the discovery of the Third Contact at Maroneia, probably in the early fifth century BC. After the Persian Wars, the demand remained high due to the extreme expenditures of the Athenian empire, which were financed by revenues squeezed out of the Delian League and –if the Laurion was indeed exploited during the pentakontaëtia– the silver mines. As discussed, the direct involvement of the state during this period cannot be questioned. Still, the archaeological and historical evidence hardly provides evidence of this sixth- and fifth-century page of the Laurion’s history. This is in sharp contrast to the footprints left by the private businessmen during the fourth century BC. The dichotomy in the current evidence seems to have been principally caused by the radically different organisational structure of the mining industry. As far as the archaeological record goes, there are two issues involved in the documentation of these early phases: first, much of the earlier traces, especially in the mines, have simply been destroyed during the busy fourth-century exploitation, the Late Roman mining revival and then even more drastically by the French and Greek mining companies during the 19th and 20th century.
Secondly, this issue is aggravated by the dominant focus of archaeological research on the most visible structures in the landscape. Scholars have often pointed to the lack of clarity on the earlier phases of Laurion’s metallurgical history, but as the chaîne opératoire is likely to have differed, it is not surprising that this information will not be found within this fourth-century management framework of private compounds. The available hints on state exploitation might be few but they are nonetheless valuable. The administration of the mines was definitely much less complicated compared to the leasing system required to organise public-private ownership. The finds in Bertseko could also explain why archaeology is a difficult partner in this research. Ore dressing was organised in a way leaving hardly any traces: washeries were rudimentary installations, consisting of rock-cut basins and channels that easily fill up after abandonment. Such an organisation more easily lends itself to public than private exploitation because of several environmental constraints: workshops were geographically restricted to rivulets that were not only few but also particularly poor. Organising the work of numerous entrepreneurs around so few water sources is hardly manageable. Nevertheless, the main limitation must have definitely been the long spring and summer drought, forcing silver production to remain only a seasonal activity. Wells dug in the middle of the Bertseko riverbed clearly indicate that the stream clearly ran dry during a certain period of the year.

The answer to these issues were the high-quality hydraulic mortars, a measure with far-reaching consequences. First, this apparent simple technology helped to address the water scarcity, by doing so enabling a full year operation. Water could be caught during the rainy months, stored in cisterns and subsequently used to bridge the dry periods of the years. Mortars were also employed to turn washeries into true water recycling devices and waterproofed surfaces where water-using processes took place. Secondly, hydraulic mortars allowed an entire reorganisation of the silver industry, adjusted to the needs of the Athenian city-state and its citizen body, since the ore washing plants could now be constructed with masonry and therefore even be incorporated into separate compounds. There was also a significant reduction in physical exertion, since transportation costs of the exploited ores decreased (Kakavoyiannis 2001, 376). Washeries could be built closer to the mines and still be located in areas favourable for rainwater harvesting.

The impact of this ‘public-private’ partnership was substantial. The Laurion was scattered with ore processing workshop, an evolution that must have been particularly disruptive for the local population. The trend of ‘industrialisation,’ already observed by Mussche (1998, 64) in Thorikos, can thus certainly expanded to the wider Laurion region. At this site, the washeries were often installed into older residential buildings, turning them into full-operational workshops. From the overwhelming proof of technological ingenuity visible in the workshops (the water supply measures, the waterproofed surfaces, variations in washery layout, etc.), it can be deduced that these businessmen were acting both as innovators and investors. This comes as no surprise: the involvement of entrepreneurs brought along considerable capital and created an environment in which pursuit for profit likely came to the fore.
### 5.5 Conclusion

As a result of the innovations described in this chapter increasing steps were taken towards the mechanisation of work processes, as is well illustrated by the introduction and continuous amelioration of the washeries. Although these changes cannot be compared to what occurred in the Roman mines in Spain, where human power was fully replaced by alternative power sources, this does not mean that these changes were insignificant in terms of economic progress. The scale on which these improvements were applied was, as far as is observable, unique within the Greek world and this had important implications for the Athenian society and economy. The economic uplift during the fifth and –after a period of regression during the Peloponnesian Wars and its aftermath– again in the fourth century BC is for a large part attributable to silver revenues, and therefore to the use of increasingly complex metallurgical techniques combined with an efficient organisation of labour. It is fair to say that the Athenian economy was raised to a level that would not have been feasible just by relying on its (rather poor) chorai (Wilson 2002, 30). According to Xenophon (Poroi 1.5), silver was one of Athens’ most important resources, feeding the Athenian treasury and paying for crucial imports of corn and timber. This becomes clear when involving figures of the scale of production. In the second half of the 19th century, the French and Greek mining companies started resmelting the ancient slag, ἕξωλαδες and ἀκιλλίτες scattered over the Laurion, by doing so destroying valuable data for the evaluation of the industrial activities. Nevertheless, they did keep calculations of the size of the spoilheaps: a minimum amount of 1,500,000 tons of ancient slag were recorded and 10,000,000 of ἕξωλαδες and ἀκιλλίτες. By doing so, it is possible to compare ancient and modern rates of metal production: the Greek and French mining companies –the former operating from 1865 to 1917 and the latter from 1877 to 1977– produced 860,000 ton of lead in total, whereas ancient production is estimated at 1,400,000 ton, the bulk quite surely during the fifth and fourth centuries BC. Besides lead, the ancients were estimated to have produced 3,500,000 kg of silver, which translates into an amount of no less than 773,000,000 drachmes. The efficiency of silver production was also high, especially considering the period it had been performed. The ancient metallurgists were able to extract 87.5 % silver out of the ore (Conophagos 1980, 138-52).

Technological change effected both aggregate and per capita growth. The former is well illustrated in the current Laurion landscape: the output of the industry was raised by the opening of more mines and ergasteria. Given the hundreds of workshops scattered over the hills, aggregate growth must have been significant, especially during the fourth century BC. The exact amount of workshops has never been quantified but the estimated amount of 250 (Rehren 2002, 27) is undoubtedly underrated. This number has been based on a survey by Conophagos, producing a distribution map of the mine entrances, cisterns and washeries encountered in the Laurion; Nevertheless, this survey has not been performed in a systematic way, focussing primarily on the Sourza area and neglecting for example large parts of the
northern region (Fig. 53). The valleys surrounding Thorikos are left almost entirely blank, a situation that simply does not match reality. A simple fieldwalk proofs the contrary. Per capita growth is less readily retrievable but still added much to the economic uplift. When subjecting the archaeological remains to a close and critical investigation, a series of technological innovations becomes apparent: first, the introduction of the basic layout of the ore washery enabled a significant increase of the silver output; second, the development of hydraulic mortars made the refinement of this device as well as the construction of cisterns possible. The ore washeries attained a larger output, the work process became more efficient and a full year production feasible, since ore washing was no longer restricted to the badly diffused water sources in the Laurion. It should also be stressed that there were other technologies beyond water technology that have not been involved in the discussion but yet contributed to the efficiency of the workshops. One may mention the solid evidence for experimentation with mills, as the Ari workshops show. There were, however, also clear limitations: the size of an ore washing workshop remained small to modest. The largest recorded metallurgical workshop owned by Pantainetos, deployed 30 slaves (Demosthenes, Against Pantainetos 2-5; 9-13, 22, 25-6, 28-9, 35-8) but most were smaller. Nevertheless, the change enabled by these innovations and the speed with which they were incorporated in the chaîne opératoire, especially in the fourth century BC, was of great significance to the development of the Laurion and consequently, the Athenian economy.
Figure 53  Distribution map of the mine-shafts, washeries and cisterns in the Laurion area by Conophagos (Conophagos 1980, Fig. 1-2).
Chapter 6  Risk and return: assessing economic strategies in the silver processing *ergastería*

The great diversity of technological innovations, which are especially well-documented during the fourth-century BC, offers a unique opportunity to increase our understanding of the incentives of technological change in the Athenian city-state. Christesen (2003, 43-4) has already pointed out that the Athenians displayed a high degree of economic rationalism\(^1\) in the mining business by introducing ore preparation as a means of reducing smelting costs. Although this is undeniably so, the previous chapter strongly suggests that the pursuit to maximise profits seems to be observable in many more aspects of the silver industry. Nevertheless, the implementation of technological improvements can only be defined as true rational economic behaviour, if the investments pumped into these systems are proven to have paid off:

The instrumentally rational investor seeking income maximization demands a rate of return that is commensurate with risk. When, for example, given the choice between two investments with the same yield but differing risks, the economically rational individual selects the safer of the two. The result is that, in an environment dominated by rational investors, there will be a correlation between risk and return. The presence of such a correlation is, therefore, a strong test for the presence of income-maximising instrumental rationality.

Christesen 2003, 46

This chapter will investigate the correlation between risk and return in the silver processing *ergastería* by supporting on primarily archaeological evidence and making a relative comparison between the capital injected into the construction and maintenance of a

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\(^1\) For a more detailed theoretical discussion of the terminology concerning economic rationalism, see Heap (1989, 1-11) and, applied to Antiquity, Christesen (2003, 31-9).
workshop on the one hand and the potential production output of the workshop on the other hand. The lack of data renders a thorough quantitative analysis impossible when discussing the Laurion, but there are other ways to measure productivity without having numerical data in our toolbox.

6.1 Assessing the risks

In order to assess the risks, an overview of the efforts put into the construction and maintenance of a workshop should first be made. In his article *Workshop, marketplace and household*, Harris has argued that:

> Given the low level of technology and vertical specialization, very little investment was required to set up a workshop and take advantage of market opportunities.
> 
> Harris 2001, 81.

In the context of this study, this statement is problematic in several respects and therefore, I will defend a different, more nuanced case. In Harris’ argumentation, three facts are inherently related to one another: 1) low technological development, 2) limited vertical specialisation and 3) low capital investment for the setup of the workshop. Let us first look into the issue of low technological progress in relation to vertical specialisation. Harris has used two case-studies – charcoal production and metallurgy – to make his point, but in his very brief description completely underestimated their level of complexity. As far as metallurgy is concerned, I hope that the previous chapter was sufficient to persuade the reader of the opposite. Coin production might seem a straightforward activity but behind the minting of silver lies a long, labour and capital intensive process hidden, demanding considerable organisation to gear the crucially different work stages to one another: mining, ore washing, smelting and cupellation are the most straightforward work processes but there are other, less visible activities, only revealed through a close study of the archaeological remains: the manufacture of mortars, the grinding and crushing of ores, the construction of cisterns, the preparation of purified ores into pellets, and – ironically – charcoal production, which is a vertically specialised work process as well.³ Besides these two examples, vertical specialisation was applied to a considerable degree in other fields as well, not in the least in temple and navy construction (Oliver 2010, 290). Furthermore, it is a fallacy to link the generally low level of vertical specialisation solely to the assumed basic level of Greek

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technology: a more decisive motive in this context is the lack of sufficient demand. A high level of vertical specialisation did thus not incidentally occur in the silver industry. As already explained extensively, the demand for this resource became tremendous from the introduction of coinage onwards.

A second fact that should be nuanced is the very little investment required to set up a workshop. It should be taken into account that the term ‘workshop’ covers a very heterogeneous range of establishments. As also expounded by Schneider (2007, 169), most ergasteria would not have been insurmountable investments, but this does not count for all workshops. Ore processing ergasteria were certainly no small undertakings, since they were provided with an expensive set of equipment. The available documents offer a various range of transactions concerning workshops, from sales to security for loans. The interpretation, however, is often difficult. It is for example hard to deduce the value of an estate based on a loan or a security for a loan because we do not know to what extent of their value workshops were mortgaged (Ellis Jones and Lambert 1999, 135). In this context, Nevett (2000, 336) refers to the exclusion of parts of the property in sales or loans, such as a store, storey or even minor architectural fitting such as doors. Slaves were often seen as part of the ‘furniture’, significantly altering the price of the estate as well. The market price in Athens for regular slaves, the type which was probably used in mining, was approximately 150-200 drachmas, but the price for a specialised craftsman could go up to 1000. Nikias even invested 6000 drachmas in the Thracian Sosias, the well-known foreman who organised his slave business (Lauffer 1979, 65-7). Despite these pitfalls, some trends are clear. Millett (1982, 222) has calculated the mean for a general security on a loan for a workshop to be 1,100 drachmas. There are Laurion workshops of the same value, e.g. an ergasterion with slaves mentioned on a boro from Soreza worth 1,110 drachmas (SEG 32.236). Other securities, however, exceed this amount significantly. On the same boro from Soreza, another security of 6,000 drachmas is mentioned. Furthermore, a (presumably in situ) boro found at Compound C in Agrileza records a 3,000 one. IG II² 2747 further mentions a 6,000 drachmas security on an ergasterion with slaves (Ellis Jones and Lambert 1999, 135 cf.12). Besides these bori, Demosthenes (Against Pantainetos, 37.31) refers to a workshop with 30 slaves sold by Pantainetos for three talents and 2600 drachmas, which is the most expensive price for a workshop that is preserved. These prices were undoubtedly high sums for a modest Athenian citizen. In this context, it is certainly not surprising to see that 12 to 19 % of the entrepreneurs involved in mining belonged to the elite performing the most expensive liturgies (Shipton 2000, 30-7). Table and chart A on Fig. 54 give an overview of the buyers and registrants of the mines. Especially when one compares these figures with the prices and the index rating of the entrepreneurs who paid for them (see table and chart B), these figure become interesting. The wealthy groups A and B paid for no less than 35.38 % of the total amount invested in mining and thus contributed significantly more to the public economy through mining in comparison to the other groups engaged in this business. Their involvement in mining also becomes clear when comparing it to their share in the public land
leases, which is hardly 4.6% (Shipton 2000, 39). Mining was thus an enterprise that the elite was eagerly willing to invest in.

Schneider (2007, 169) gives an interesting remark relating to this topic in the context of Roman case studies. He suggests that men of substance would only have invested their money in enterprises, which guaranteed favourable returns, clarifying why their involvement in commercial businesses was generally low. Simultaneously, this could serve as an explanation why they did voluntarily pump money into the silver business.

One cannot create a coherent cost-assessment by relying exclusively on epigraphic and literary data and ruling out archaeological evidence in the process. By doing so, a crucial factor is neglected: the actual space that was sold or leased. Archaeology might not be able to offer precise cost-assessments but numbers are not necessarily required to offer an idea of value. The archaeological sites testify to the scale of the ore processing industry, with hundreds of workshops scattered over the Laurion landscape, and also to the huge diversity in the nature of infrastructural organisation and sophistication. From a purely archaeological
point of view, it is definitely not surprising to find such a broad range of security or sales prices. Even within the same category of workshops, there is a striking variation in layout and elaborateness. The following factors are suggested to influence the workshop’s price: the property’s size, the material used for its construction, the number and size of fixed industrial features (such as mine shafts, washeries and cisterns), the labour force (whether or not sold or leased together with the estate), and its location.

The last factor is a highly neglected factor that has been put on the agenda by archaeological research in Olynthos (Nevett 2000, 329-43; Cahill 2001, 276-81). It is clear from ancient sources that the Greeks conceptualised the value of a house, in the sense that they made a clear difference between what a house was worth and what it actually cost. The orator Isaicos (ii.35) mentions a little house which is not worth three minae. The most expensive Olynthian houses clustered near the agora and did change hands more often than houses in other districts, all suggesting that these properties were favoured. House A v 10 near the agora was the most expensively recorded house of Olynthos, sold for 5,300 drachmas. For the exact same type of property (of an equal size and quality) two houses further away were sold for 1,200 (D v 6) and 900 drachmas (the house next door). A house at South Hill was even sold for the extremely low price of 230 drachmas. It would not be unreasonable that the same principle applied to the Laurion as well but unfortunately, there is not enough evidence to make a coherent assessment of this issue. Apart from the location, the size of the property is also an important indication of its value. Even at Olynthos, a site with a very regular grid plan, the variation of prices according to their size is a general tendency (Nevett 2000, 337). The property size of an ore washing workshop is generally large because of the required metallurgical infrastructure, a matter that can also explain their apparent high value. Workshop 2 and 3 of the Asklepiakon were of a ‘modest’ size of respectively 610 and 870 m², but other workshops as the Kavodokano workshop measure 1,209 m², the Skitzeri workshop 1,689 m² and Compound C in Agrileza no less than 2,160 m².4

It is unfortunate that so few secure links can be made between horoi recording prices and the actual workshops in the Laurion. Even at Thorikos, a site of which a large part is extensively excavated, planned and published, very little can be said. The inscription found at Compound C at Agrileza is a valuable exception. As mentioned, the workshop is a particularly large one. Ellis Jones (1999, 131-6) encountered two horoi, one inside one of the settling tanks of washery C and a second in the rubble alongside the wall next to the washery, recording the security of a loan. The second mentions a price of 3,000 drachmas, which is higher than average Attic security loans but not an unusual amount for an ore processing workshop. It should, however, be taken into account that andrapoda or slaves were not included in the transaction and given the size of the workshop, a considerable amount of them should have

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4 These numbers refer to the approximate surface area of the workshops and not the surrounding property.
been required to keep this ergasterion running. The issue, however, is that we do not know what extent of the workshop was leased.

The actual construction costs are hard to assess but again, an idea can be given of the efforts required for such a venture. Entrepreneurs always seem to have exploited local stone for construction material, which is not surprising given the suited geology of the area. This is also demonstrated by the numerous quarries in the region. In the Stephani area and in Thorikos, several marble quarries are grouped together. Another even better known quarry area is Agrileza. Scattered over this valley, numerous extraction traces of blocks and column drums can be observed.\(^5\) It should not be forgotten that the rock cut out during the digging of cisterns and shafts could be used as construction material as well, albeit not in the form of slabs and ashlars, and by doing so reducing the costs of building material and efforts otherwise lost on transportation.

The costs brought along by industrial features can be tentatively expressed in man-days of labour. Conophagos (1980, 200) calculated the amount of time needed to dig a 100 m deep mine shaft. Assuming an average speed of 5.76 m\(^3\) per month and a surface area of 2 m\(^3\), three slaves should have been able to descend 8.46 m each month. A 100 m deep mine shaft, which is quite common, should have therefore taken nearly a year of continuous work. If the work was performed by two slaves, this amounts to even 1.5 year. These efforts perfectly illustrate how risky the mining industry was, since there was never an assurance to actually hit a productive lode. This is in accordance with the restraints towards the opening of kainotomia or new cuttings. The mine leases record only five of them (Crosby 1950, 198-9).\(^6\)

Furthermore, Xenophon (Poroi 4.27-8) clearly hinted that such ventures were avoided in the 350’s, a matter that is also echoed in Hypereides’ fourth oration (4.36). Based on Conophagos’ calculations, it is also possible to make a rough assessment of the construction time for a cistern. I will use two well-known reservoirs of the Asklepiakon workshops as an example. Cistern 2 has an estimated depth of 4.5 m (see section 5.2.2.1, Fig. 60), of which averagely 3 m has been carved out of the rock, leaving a masonry superstructure of 1.5 m. Conophagos starts from the idea of one slave/m\(^2\), a number that seems too crowded for the cutting of such a basin. Cistern 2 has a surface area of approximately 45 m\(^2\). As suggested before, the ‘waste’ could be used for other building purposes, such as the upper structure. With its 5.2 m depth and 494 m\(^3\) volume, Cistern 3 is significantly larger. For a ground surface of 95 m\(^3\), it would take the same amount of slaves about 8.5 months. Since these calculations only apply to the actual basin, the cistern will take up considerably more time to finish. The reservoir still had to be completed with an upper structure – consisting of ashlars that had to transported from the quarries – a decantation tank, supply channels and the whole finally had to be waterproofed.

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\(^6\) Crosby no. 28, line 6; no. 32, lines 5-6; no. 33, line 2; no. 35, line 3, and no. 38, lines 1 and 8.
The construction and the value of a workshop is one thing but this says virtually nothing about the maintenance costs and the investment made during the actual operation of the workshop. One can assume that these costs were generally low but archaeology still demonstrates that workshops were constantly reorganised and expanded with new rooms, washeries and cisterns. The washeries of Demoliaki, presented in Chapter 5, are a case in point. A modest sized washery (C) was destroyed to make place for a more extensive device producing higher yields (D). Maintenance efforts are also revealed by the cisterns: repairs to the hydraulic mortars were clearly continuously made. Adding to this, ore processing workshops also required resources, such as water, timber, litharge for mortars, and food. Rihll (2001, 115) calculated that 4000 kg of food per day was required to support the labour force. Water was the most crucial resource for the operation of the workshop, directly affecting the amount of processed ores. No less than 19.5 m³/month was required to maintain the operation of a four-nozzle washery, an amount of water that demands considerable rational decision-making and organisation to harvest. This leads us to the next section.

6.2 Assessing the returns

As shown above, ore processing workshops were pricy undertakings in comparison to other ergasteria, an issue that could only be compensated by high returns. To what degree were businessmen aware of the factors influencing successful returns and in anticipation, succeeded to create and maintain a high production output? As was clear from the previous chapters, Laurion workshops were constrained by their unfavourable hydrological setting, issues that were to a large extent overcome by technological innovations, such as the introduction of hydraulic mortars; however, it takes more than these technologies to guarantee the smooth operation of an ergasterion. Even though these mortars enabled the creation of a water stock by means of a reservoir within the workshop, the workers still needed to ensure the harvesting of sufficient water into these cisterns. Water was the most vital resource for ore processing workshops. Without water, ores could not be processed and hence, silver not produced. It might seem straightforward that cisterns were able to supply a reliable amount of water but this becomes less so when looking at the variations in the size of these reservoirs. As already briefly mentioned in the preceding chapter, cisterns are not only fewer but also conspicuously smaller in the Thorikos area than in the central valleys. Smaller cistern volumes suggest a lower water availability and therefore a potentially lower production output. This could have significant implications for our knowledge of the production of the silver industry and especially of the motivations of entrepreneurship. In order to clarify these problems, a comparative estimation of the scale of production should be made but it is particularly hard to quantify such trends, especially when working with an archaeological
dataset. Nevertheless, one does not necessarily require numbers to shed light on these issues. It may not be possible to analyse how much a workshop was actually producing, but it is feasible to deduce if a workshop was constructed in such a way that it was able to attain a continuous production throughout the year. Archaeology proves to be specifically suited to assess such trends. Although the number of published sites is few, it is possible to create a representative dataset consisting of workshops in both the heartland and coastal zones of the Laurion and investigate how investors dealt with local hydrological challenges. Modelling efforts can help to understand the potential impact of the hydrologic cycle, the climate and local topography on human activities and will thus be particularly helpful in this discussion.

6.2.1 Methods and theory

In the Laurion, water was collected in cisterns from surface runoff, i.e. rainwater that did not infiltrate into the soil, but ran off the hillslopes. This allows performing a hydrological analysis of runoff water accumulation and routing. The applied methodology is executed in three phases. First, a Digital Elevation Model (DEM) is derived from topographical maps of southeastern Attica. Second, this DEM is subjected to a hydrological analysis of the Laurion. Specifically, the flow accumulation along the hillslopes is determined and a water balance model of the cisterns is used to assess the effective availability of water for ore processing in washeries. In a third and final phase, the results will be interpreted from an archaeological perspective.

Several case-studies have been selected from different areas in the Laurion: on the one hand, workshops in a coastal area –more specifically Thorikos and its surroundings– and on the other hand, workshops in the heartland of the Laurion. The hydrological analyses of the Velatouri and the centre of the Laurion have been carried out in a similar fashion, using the ArcGIS software suite.\(^7\) The primary data source for this analysis is the 1:5000 topographical map of the region,\(^8\) of which the contour lines have been digitised. These lines have then been imported into ArcGis 9.3, and transformed into a DEM using a contour line interpolator, allowing only positive values, and setting a grid resolution of 11.6 m. This allows both DEMs, for the Soureza and Thorikos regions, to be of equal resolution without compromising accuracy too much. For both DEM’s, small local sinkholes, which may be the result of data imperfections, were identified and removed from the original DEM through raising its elevation to the lowest value on the rim of the depression (Jenson and Domingue 1988). Using this depressionless DEM, the flow directions of the runoff water were determined, which equal the direction of the downward steepest slope.

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\(^7\) License Ghent University.
\(^8\) Purchased from the Hellenic Military Geographical Service, Athens.
To be able to calculate the volume of water running off the hill to a certain point (see further), the area draining to that specific point, referred to as the contributing area, is calculated based on the flow directions. For each pixel of the DEM, the contributing area is derived based on counting the number of cells that flow to it (Jenson and Domingue 1988). Through multiplying the number of draining pixels with the area of a pixel, the contributing area is obtained, as shown on Figure 55 and 56. To obtain this result, the flow accumulation algorithm of ArcGIS was used. The workshops themselves (see next section for a more detailed description) have local inlets for their cisterns. For the case studies, these inlets have been situated as indicated by local archaeological investigation. Using this flow accumulation, together with a rainfall time series and a water balance (or reservoir) model of the cistern, it is possible to estimate the effectively available water for ore washing (see below).
The water use of an ore washery has been defined in a study by Prof. C. Conophagos (1980, 246-250), in which he concluded that a standard Type I washery with four functioning nozzles in its reservoir used approximately 19.5 m³ water/month, based on a 12h working day. To make a reliable comparison, all the discussed washeries in this paper are of this type. The water balance model of the reservoir can easily be expressed through stating that the change of volume during a time step should equal the net inflow in the reservoir, i.e. the difference between the harvested runoff water and the water removed from the cistern (for operation purposes and/or through evaporation). This can mathematically be expressed as:

\[
\frac{\Delta V}{\Delta t} = I(t) - Q(t) - E(t)
\]
This formula describes the change of water volume in the cistern $\Delta V$ (m³) during time interval $\Delta t$ (in our case, $\Delta t = 1$ day). $I(t)$ (m³/day) is the inflow rate at day $t$, $Q(t)$ (m³/day) is the water use of the ore washery taken from the cistern at day $t$. We assume $Q(t)$ to be constant in time and equal to the average daily water use which is calculated from a water use of 4.875 m³ per nozzle per month. $E(t)$ (m³/day) is the volume of water evaporated from the cistern during that same day. The inflow rate $I(t)$ can be calculated from the runoff produced during day $t$. This equals:

$$I(t) = C \cdot R(t) \cdot A$$

$R(t)$ (m/day) is the rainfall intensity during day $t$, $A$ (m²) is the total area draining to the cistern, i.e. the contributing area (as derived from the DEM analysis) and $C$ is a runoff coefficient, which determines the fraction of precipitation data that forms runoff. Since the surface of the catchment was nearly impermeable, a high value of $C = 0.95$ could be chosen, i.e. 95% of the precipitation runs off the surface whereas only 5% infiltrates. The temporally variable water volume in the cistern $V(t)$ can be calculated for any time instant $t$ as:

$$V(t) = \begin{cases} 
0 & \text{if } V(t - 1) + \Delta V \leq 0 \\
V_{max} & \text{if } V(t - 1) + \Delta V \geq V_{max} \\
V(t - 1) + \Delta V & \text{otherwise} 
\end{cases}$$

This framework is used to simulate the water availability to ore washeries, after which the percentage of dry time during the year is calculated, i.e. the period during which the washeries failed to operate because of a lack of water. This is done with the aid of a recent 5-year rainfall time series, taken from a rain gauge near Athens, which shows a typical pattern but does contain two drier years (Fig. 57).
Figure 57  Recent five-year rainfall time series taken from the rain gauge of the Athens.

Given the short distance to the Laurion and the type of analyses, this rainfall series is assumed to be a representative dataset. Accordingly, potential small differences between both areas will not affect the conclusions of this study. As previously mentioned, nowadays Athens has an annual rainfall of only 385 mm, the bulk generally occurring in fall and winter (between mid-September and April) and it is generally accepted that the climate of fifth- and fourth-century Greece resembles this modern situation, presumably with the same inter-annual and seasonal variability. Based on this, we may safely assume that modern rainfall data can be used for hydrological analysis with good accuracy. The analyses are performed with the assumption that the Laurion cisterns were roofed to prevent evaporation (i.e. $E(t) = 0$ in the model) and to prohibit contamination of the water. Almost all of the cleared cisterns in the Laurion show evidence for this, either in the form of column bases on the bottom of the basins or by the presence of a roof supporting ridge on top of the cistern walls. Furthermore, an average depth of 5 m will be employed to determine the capacity, when dealing with unexcavated cisterns. Almost all Laurion cisterns have a depth ranging between 4.5 and 5.5 m, making this assumption tenable.
6.2.2 The coastal area

The focus in the coastal area is on the site of Thorikos but the discussion will be expanded to the wider area of the Adami and Potami plains. Bordering these plains, the Kavodokano, Skitzeri, Zoridis and Euthydike workshops will be assessed.

6.2.2.1 Thorikos

The site of Thorikos is strategically located on the two-peaked Velatouri Hill, next to the natural harbours of Porto Mandri and Franko Limani. On the lower slopes of the hill a clear nucleus of Archaic to Early Hellenistic habitation can be recognised, nowadays distinguished in two zones: the Theatre Zone, located closest to the sea, and the so-called Industrial Quarter, a little further to the west.9 Spread over these zones, three metallurgical complexes can be identified (Fig. 58). The first area (A) is situated in and immediately above the Industrial Quarter, with Mine no.2 as its focal point. The second area (B), located more downhill, between the theatre and the Industrial Quarter, is likely to have been processing ores from Mine no.3. The available information on the third area (C) –focussing on Mine no.6– is limited, since the area was badly disrupted by the mining activities of La Compagnie Française des Mines du Laurion in the 19th and 20th century (Mussche 1998, 56). Given that the Industrial Quarter is one of the best studied areas in Thorikos, Area A will be our main focus.

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9 The recent survey campaign by Ghent University in cooperation with Utrecht University (2012-2014) has also localised a strong concentration of finds dating to that same period on the southeastern slopes, suggesting that the habitation pattern stretched much further along the lower slopes than previously considered.
AREA A

In Area A, five washeries (W1, 2, 3, 12, 13) and four cisterns (C1, 2, 3, 4) have been recorded (Fig. 59).

Two of the cisterns were domestic reservoirs (C2 and 3), recorded in Insula 2. As discussed in Chapter 2, their location is not accidental, since this insula seems to have been raised on the location of a former spring. The spring starts as a deeply eroded fault surface in the marble outcropping enclosed in the rear end of room DR and runs further south through the entire length of the house. This room was probably a small shrine making use of the spring water, as indicated by the gourna and the niche in its northern wall. Passing through the courtyard, the fracture further connects two underground cisterns, cut into the rock and coated with hydraulic mortar. It is no coincidence that specifically this kind of cistern was
connected to the spring: because the water is stored underground, it stays fresh at all times, making it convenient for domestic usage. Adding to this, spring water is a pure water source, in sharp contrast to the often contaminated surface runoff, harvested by the open industrial reservoirs. The cisterns have been partly cleared during the excavation of the insula but their volume is unknown. Another interesting feature is a drain, constructed along the full length of the corridor of the house (Room C) and leading excessive water under the threshold to the street, called the Industrial road.

![Map of Thorikos](image)

**Figure 59** The metallurgy complex A (map by author).

The rest of the cisterns in this complex can be characterised as industrial reservoirs.

In total, four workshops can be recognised. Two of these are badly known, unfortunately disallowing their involvement in the analyses. The first is Washery no. 2 located above House no. 1, in a building of which only a small section has been excavated. Just as the other

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10 It would definitely be interesting to further clear these cisterns, as well as other domestic reservoirs encountered in Thorikos, to get a better view on domestic water use at the site. An establishment of the precise volume would also be of value to derive the number of workers that were dependent on these water sources.

11 For further information on the typology of cisterns see Trevor Hodge (2000; 2002).
washeries in Thorikos, it can be classified as a Type I washery. Based on pottery finds, Mussche has concluded that the workshop was installed in a fifth-century building in the course of the fourth century BC. Because of the limited excavation, the cistern of this workshop has not been localised yet. Even less is known about the second washery no. 12, located approximately 20 m to the north of Mine no. 2. Undoubtedly, their cisterns are not extensive. Large cisterns are unlikely to be missed, given their monumental walls, the overall presence of waterproof mortars and the intensity of the research during the last decennia.

The remaining two workshops can be investigated in greater detail: the Washery no. 1 workshop (to which washery no. 3 is also linked) and the Cistern no. 1 workshop.

![Thorikos Cistern no.1 Workshop](image)

**Figure 60** The Cistern no.1 workshop in Thorikos (map by author).

The workshop of washery no. 13 is referred to as the *Cistern no. 1 workshop*, because of its eye-catching water reservoir (**Fig. 60**). Cistern no.1 is with a capacity of 209 m³ Thorikos’ largest water reservoir (Van Liefferinge et al. 2011). The cistern is situated northwest of the Industrial Quarter, is partially hewn into the rock and partially built up with massive walls, measuring on average 1.6 m in width. The cistern’s basin has an irregular shape (**Fig. 60A**): a quadrilateral with sides 9 m, 4.5 m, 7.5 m and 5.5 m), adjoining a small, higher zone, of which the rocky underground was left unadjusted (B). In all likelihood, this area fulfilled several purposes: water could be raised more easily out of the cistern when it was not entirely
full, but it could also slightly enlarge the cistern’s capacity in case of a higher water level. A sounding in the basin of the cistern during an excavation campaign by Ghent University, partly in collaboration with Utrecht University, established an average depth of 4.9 m, measured from the highest point on the masonry wall, resulting in the calculated maximum volume of 209 m³. West of the cistern, a flattened working platform (C), a crushing area (D) and washery no. 13 (E) are situated. The present state of knowledge on the workshop does not permit characterising the scene as a typical Laurion workshop, which is carefully compartmentalised in different rooms. The almost total lack of walls on its west side rather suggests that it was a more open workspace. On the east side of the cistern several notably organised walls (F) were observed, which will be discussed further on in this chapter.

The second workshop Washery no. 1 (Fig. 61) presents a significantly different configuration than the workshop described above.

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**Figure 61**  The Washery no.1 workshop in Thorikos (map by author).

Here, a metallurgical workshop was installed into an older residential building during the last quarter of the fifth century BC. Besides a large courtyard, the insula contained living quarters, such as a bathroom, dormitories and a kitchen, as well as working areas (Mussche 1967, 47-62; Mussche 1968; Mussche 1998, 50-1). The washery (no. 1) can be characterized as a typical Type I ore washery, with modest dimensions (5.3 x 10.3 m) and, according to Conophagos (1980, 247), four nozzles in its reservoir. The workshop has a remarkably small cistern (no. 4)
of 17.7 m³ at its disposal, which was built immediately south of the workshop, in the corner of rooms AM and the extension of AN. The basin has a semi-rectangular shape (2.50 - 2.75 m x 3.00 m; depth 2.24 m) and was obviously collecting water from the roof of the workshop, a practice which was rather uncommon for industrial cisterns. Washery no. 3, built immediately below the insula, was also supplied by Cistern no. 4, but it was raised when washery no.1 was no longer in use.

![Diagram](image)

**Figure 62** Zoom of the contributing area map, showing the lower slopes of the Velatouri Hill and the runoff values, expressed in pixels (map by author and C. Stal).

The contributing area map (Fig. 62) indicates two interesting facts.

1) The rainwater harvesting in the Industrial Quarter was not particularly efficient because the site, as opposed to the case studies in the centre of the Laurion (see further), depended on non-concentrated surface runoff, i.e. runoff that flows overland as sheet flow and not through little streams.
2) Cisterns were also not necessarily erected near the most favourable water catchment areas on the Velatouri. Apparently, other factors were involved as well. To minimize transportation efforts, cisterns were generally constructed in the close vicinity of their washeries. Moreover, as ore processing entirely relied on water, workshops had to be raised where water availability was guaranteed. This is particularly clear in the Laurion valleys. The situation in Thorikos, however, is different as the site knew a long occupation history. Archaeological research has shown that Thorikos, and especially the Industrial Quarter, was a residential area primarily in the fifth century BC. After the Peloponnesian Wars, the site was temporarily abandoned and subsequently reoccupied towards the middle of the fourth century BC (Mortier 2011, 129-30), when it went through a real ‘industrialisation’ and ore processing workshops emerged all over the Archaic and Classical sites (Mussche 1998, 62-4). As far as can be observed from the present archaeological evidence, two trends can be described: either workshops were incorporated in older houses, which functioned simultaneously as working and living areas, or they were constructed along the borders of the former residential nucleus. In case of the latter, washeries, cisterns and crushing areas appear to have been erected as more independent entities, rather than as part of a larger complex where labourers were living simultaneously. This suggests that the deciding factor in determining workshop location was primarily the presence of former living quarters and only thereafter water availability was taken into account. Evidently, this considerably jeopardised water harvesting.

This image certainly applies to Cistern no. 1. The workshop did not show any proof of the presence of living areas contemporary to the use period of the cistern so far, and was located directly above the Industrial Quarter and close to Mine no. 2. Its water catchment area was determined by the hydrological analysis to be roughly 864 m² (i.e. 6 pixels of the DEM). The surface of this zone was rocky, smooth and free of fractures, enabling maximum water recuperation. The contributing area map clarifies that the function of the unfamiliarly organised walls east of the cistern could have had a part in this process (see also Fig. 60). Runoff water was redirected by the upper curved wall. Both the prolonged east and south wall of the cistern acted as a barrier to prohibit water from flowing further downhill and eventually conveyed the water to the cistern. Furthermore, the model also enhances our understanding of the workshop’s washery, of which only one settling tank is nowadays visible. Using the parameters of the model (as explained in section 6.2.1), the full red curve in Fig. 65 was calculated where the percentage of dry time is shown in relation to the number of nozzles. From this analysis, one can assess that this cistern was able to serve one washery with four nozzles throughout the year without any issues. A large six-nozzle washery was feasible with only 10 % of dry time. However, the environmental conditions did not allow creating a water surplus to support other water consuming activities or enable more comfort. As discussed in section 5.2.1, the rainfall time series contains two drier years. If these years
are left out of this analysis to negate the effect of drought (dotted lines on Fig. 65A), the situation improves but not sufficiently to speak of favourable water availability.

**Figure 63** Graphs representing the percentage of dry time in relation to the number of nozzles/washery. A) The full red curve shows the washery’s use during the full time series, the dotted lines only the last two (much wetter) years; B) Seasonal washery use from September until March (dotted curve) is represented in contrast to continuous use throughout the year (full curve) (graph by author and M. van den Berg).

It should be stressed, however, that within the context of Complex A, the location and size of Cistern no 1 is by no means random. The reservoir is located directly above the Industrial
Quarter, which was the only rational option to catch a decent amount of water in this zone. Furthermore, the water catchment area was rocky, smooth and free of fractures, thus enabling maximum water recuperation.

The Washery no. 1 workshop has a significantly smaller cistern (17.7 m³) with only the roof as its catchment. As a result, even at the bare minimum of operation, this cistern would not have been able to operate a single nozzle of the washery continuously (see Fig. 63A, blue curve). When the drier years are left out, the situation stays more or less the same.

One should also consider the possibility of seasonal use. The same figure (Fig. 63B) shows the washeries’ use from September until March, which are the wettest period in the used rainfall series (dotted lines). From this diagram, it can be deduced that seasonal use has a positive effect on the washeries’ operation but in case of Cistern no. 4, the difference is not large enough to be really beneficial to the washery’s production. Additionally, the results do not help us clarify the remarkably small capacity of the cistern. In all likeliness, this was purely due to local conditions: at the time when the water reservoir was built, there was simply insufficient space in this densely built up area to raise a more extensive one. The cistern was constructed when the Therippides Street (see Fig. 61) was still in use, allowing only a small reservoir in order not to cause an obstruction. Rooms AQ, AP, BA and Washery no. 3 were constructed in a later phase, through this shutting off the street completely (Mussche 1998, 53-4).

AREA B (Fig. 66)

This complex, with Mine no. 3 as its focus, is located in and directly west of the Theatre Zone and counts five washeries (W4, 5, 6, 7, 8 and 11) and three cisterns (C5, 6, 7). Several of the washeries and cisterns were grouped west of this complex. Cistern no. 6 is an underground, bottle-shaped, domestic water reservoir, similar to one found in Insula 2. Cistern no. 5 and 7 are industrial water reservoirs of modest rectangular size, both on average 4 x 6 m. They remain unexcavated, but when applying the average depth of Laurion cisterns, their volume should have been approximately 120 m³. Given their location, it can be surmised that no. 7 was providing washery no. 8 and cistern no. 6 was possibly responsible for the water supply of both washery no. 6 and 7. As deducible from the contributing map (Fig. 62), this is a more favourable catchment area, since water is accumulating in a small stream. Overgrowth hampers a precise reconstruction of the water management strategies but Cistern no. 5 seems to have been tapping its water directly from this gully (with a catchment area of 116 px on the contributing area map).
Figure 64 Complex B (left) and C (right) (map by author).

The water balance model (Fig. 65) further confirms the more favourable conditions in comparison to the rest of Thorikos, making it no coincidence for this group of washeries to be raised within this small zone. It would, however, be difficult for this single cistern to supply two common four-nozzle washeries the entire year through, which could mean that washeries nos. 6 and 7 were either devices with a lower capacity (for example three nozzles) or that Cistern no. 5 was backed up by an additional reservoir. Clearance of the overgrowth in this area could help to clarify this issue. This graph also shows the effect of seasonal use (dotted lines), which would make the provision of two four-nozzle washeries attainable.
Figure 65  Graph representing the percentage of dry time in relation to the number of nozzles/washery. The full red curve shows the washery’s use during the full time series, the dotted one presents seasonal washery use from September until March (graph by author and M. van den Berg).

The remaining two washeries, no. 4 and 11, do not give us any indications on their water supply. The zone in which the fourth century washery no. 4 (11 x 6.5 m) is located, has unfortunately been disrupted by agricultural activities. As far as no. 11 is concerned, the workshop has only been partly excavated. As discussed in Chapter 5, the washery is small and irregular due to the fact that it had been squeezed into an older building, which clearly lacked sufficient space for the incorporation of this device. Its cistern—surely a small structure—must be situated in the still unexcavated part of the workshop.

6.2.2.2  The wider Thorikos area

Despite their abundance, little is known about the sites surrounding the Velatouri Hill. 15 sites are recorded on a topographical map by Oikonomakou (1996, figure 1), 13 of which workshops, but in reality there are significantly more in this neighbourhood (Fig. 66). The few sites that have been published properly will be included in this section, more specifically the Kavodokano, Skitzeri, Euthydiike and Zoridis workshops. All these ergasteria show the typical features of ore processing workshops, in which living and working quarters are geared
to one another. Because of the nature of their water supply, none of these sites allow running a water balance model but despite this, interesting things about their water management strategies can be said.

**Figure 66** Overview map of the archaeological sites on the Adami and Potami plain (map by author. Location of the sites after Oikonomakou 1996, Fig. 1).

**KAVODOKANO WORKSHOP**¹²

The Kavodokano workshop (Fig. 67) is an extensive complex, consisting of two different wings. The first is an apparent residential area, occupying the northern, southern and western part of the complex and containing a large courtyard, a hall and ten surrounding rooms. Also, an underground cistern with a round shaft was carved out into the rock for domestic use. In the east wing, two washeries (A and B) are situated and one rectangular cistern (Δ1, 6.5 x 5 m). As is common for Laurion cisterns, it was carved out into the rock and lined with hydraulic mortar. The report mentions that this cistern was relying on a nearby well, which could be possible since the cistern is located within the workshop, hindering the harvesting of surface runoff. Another option would be that the cistern was collecting its water through the workshop’s roof. This indicates that, just as in case of cistern no.4 in Thorikos, industrial

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¹² Oikonomakou 1996a, 133-9; 1996b, 65.
cisterns did not always collect their water from surface runoff. Furthermore, there were rooms for crushing, grinding and storage (G, D, E). In room E, which had been an open space covered by a roof, fragments of mills were found.

Figure 67  The Kavodokano workshop (Oikonomakou 1996a, Fig. 5).
Because of the lack of sufficient stratigraphy and finds, only a few things can be said about the workshop’s chronology. The workshop was likely to have operated in the fourth and third century BC, with small scale activities during the late Roman period. Thanks to the *horos*,\(^{13}\) the workshop can be attributed to Philokrates, an entrepreneur also known from the *poletai* inscriptions (Oikonomakou 1996a, 137). The workshop was able to accommodate a considerable number of people and it has been suggested that the courtyard and hall were also used for other transactions, such as the sale of workshop products and other goods. Kapetanios (2013, 190) mentions another interesting inscription recording that the compound had been serving a double, both mining and agricultural, purpose. *Ergasteria* have generally not been conceived as multi-purpose infrastructure but these discoveries force us to challenge this image. Given the fact that more farms had been recorded in this fertile, alluvial area, this should perhaps not come as a surprise.

SKITZERI WORKSHOP\(^{14}\) (See Fig. 37)

The Skitzeri workshop was built with great care, at a short distance of the road leading from Plaka to Palaiokamariza. Three large rectangular washeries (T, A and Y), storage and crushing rooms with accompanying living quarters were recorded. Washery T (12.8 x 7.5 m) is located in the northwest of the Skitzeri estate and was largely disturbed on the north part during late Roman times when a metallurgical furnace, employed to resmelt the Classical slag, was installed. It seems that a cistern had been installed on this spot but the Roman alterations limit further observations. Room D was used as a crushing and storage area for the ore. On the east side, four more rooms (H, Θ, I, M) can be observed. H, L and M all had a plastered floor but their function is unknown. Θ can with good accuracy be identified as a kitchen, as indicated by a large amount of cooking ware, a hearth and a small partition, most likely for the storage of small kitchen utensils.

Washery A, a large device in the centre of the complex, shows several special features. ‘Room’ G was entirely covered in hydraulic plaster and is suggested to be the supplying cistern (5.7 x 5.7 m). Directly north of the washery, a narrow conduit was installed, which crossed room N and ended in I. Both of these rooms were characterised by the excavators as bathrooms, because they were fully covered with hydraulic plaster and contained typical features, such as a quadrangular bathtub (1 x 1.58 m). It is clear that, as in the Asklepiakon in the Soureza Valley (Tsaimou 1988, 81-176), waste water of the bathroom was recycled to be used in the ore washery. Further covered in hydraulic plaster are room K and D. The latter room contained a rectangular shallow basin, pieces of grinding stones, iron tools, black-glazed ceramics and lamps, clearly suggesting metallurgical practices. The former room does not allow being more specific about its function. Space Ξ was an outdoor courtyard, probably partly roofed. A small rectangular cistern (1.45 x 1.1 m, depth 1.1 m) was carved out into the rock and connected to three other small cisterns located more to the south, assuming that the central cistern was catching runoff water from the roof, which was subsequently distributed to these other reservoirs.

Washery Y (13.10 x 6.25 m), 4 m away from A, had a different orientation, indicating that it belonged to another, yet unknown complex. It was nicely preserved and had one adjacent room (Ψ), covered in plaster and in all likeliness used for storage. More to the south, another probably Roman, smelting furnace was found.

The Skitzeri workshop has been suggested to be the residence of the workshop owner and its workers. The material and several additional features found in the compound deliver clear-cut proof for its additional function as living quarters. This is not only indicated by the presence of a kitchen and a bathroom but also by the discovery of a rich mix of pottery, from cooking

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\(^{14}\) Oikonomakou 1996a, 125-32.
ware to *kantharoi*, plates, bowls, *skyphoi* and *lekanes*. The first building phase of the workshop goes back to the second half of the fourth century BC, possibly even closer towards the early third century BC, and was in use until the middle of that century. Subsequently, this *ergasterion* was deserted, only to be reoccupied in the Roman period on a smaller scale.

**EUTHYDIKE WORKSHOP**

The Euthydike workshop (Fig. 69) is a northeast-southwest oriented, luxurious *ergasterion*. The workshop is well-organised and consists of living quarters, located in the northeast part of the estate, and a workshop, situated in the southwest. The former consists of a paved courtyard around which several rooms are organised. Noteworthy is the *andron*, a feature not often recognised in the Laurion workshops (3A on Fig. 69). This space is not immediately accessible from this court but could only be reached through a small, paved lobby (3B). In this area a *stele* was found with an inscription ascribing the workshop to Euthydike, daughter and heiress of Epicharinos of Eleusis. There was also a paved bathroom with a bathtub (O) and on the opposite side of its southern wall, a kitchen (Ξ).

The workshop contained several typical facilities: there were grinders for minerals as well as grain (Z) and three small, simple washeries (Α, Γ, ΣΤ), carved out into the rock and supplied by wells.

A second inscription uncovered in this workshop reveals the name Philokrates, not incidentally the same name as the owner of the nearby Kavodokano workshop, suggesting that Euthydike was related to this man.

The first building phase of this complex goes back to the second half of the fifth century BC but the building was thoroughly reorganised and expanded in the course of the fourth century BC.

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16 *Androna* are not often observed in ore dressing workshops. Another example has been identified in Workshop 3 of the Asklepiakon in the Soura Valley (Tsaimou 1979, 15-23).
Figure 69  The Euthydike workshop (K. Mexa plot) (Oikonomakou 1991, Fig. 4).

ZORIDIS WORKSHOP\textsuperscript{17}(Fig. 70, see also Fig. 35)

About 1.5 km north of the Athens-Lavrio road and northwest of the Velatouri hill, the Zoridis workshop is located, containing two Type II washeries. Since the washeries have

\textsuperscript{17} Zoridis 1980, 75-84.
already been discussed in the previous chapter, some more attention will only be given to the remaining rooms and its water supply.

![Figure 70](image)

Washery A, in the north part of the estate, was provided by two small cisterns (2.5 x 1 m; 2.05 x 1 m; depth: 1.4 m), installed in a narrow space immediately north of the washery’s main reservoir. Since the space immediately to the north of these rooms (Γ) was coated in waterproof plaster, this area could have served for water catchment but since it has not been further documented, this cannot be confirmed. In all likeliness, the Potami –the nearby stream that runs through the eponymous valley– had an important role in the water supply of the compound. Although the rivulet is nowadays poor and runs completely dry during summer, it cannot entirely be ruled out that the situation was different in ancient times. South of the washery, a paved drying table (A) was located with to the east of it, a well-preserved, waterproofed storage room (B) with a triangular shape. The washery used to be covered by a roof, as indicated by the presence of a monolite against the wall of room B.

A door with threshold gives access to a large court, where a smaller washery (E) with the same configuration is included. To its northwest, outside the washery room, a small, rectangular cistern was raised (2.93 x 1.42 m; depth: 1.3 m). In the western extension of Room Z was the crushing and grinding area. In room Λ, an amount of plynites has been discovered. The paved room Θ was one of the largest rooms of the complex with in the north, an oblong cistern (4 x 0.75 m). The similarities with E and A lead to believe this could
have also been a drying area. Room N, situated in the south end of the complex, is suggested to be a bathroom. Several rooms (such as H, I and K) were coated in hydraulic mortar; however, their exact function is difficult to deduce. The west side of the complex has been identified as living quarters.

The chronology of the Skitzeri and Kavodokano workshops is applicable to this complex as well: the workshop was in use in the fourth and early third century BC and knew a small-scale reoccupation in late Roman times.

6.2.2.3 Discussion of the results

The workshops in Thorikos and those on the hills facing the Velatouri are similar in many aspects; however, there are some striking differences deserving some attention.

Starting with the similarities, the most remarkable trend is undoubtedly the lack of large cisterns in the Adami and Potami area. Oikonomakou (1996, 140) sees an explanation in the presence of πλούσια, μεγάλα ρέματα or copious streams flowing through the plains, on which the washeries could have relied. The 19th century maps of J.A. Kaupert and E. Curtius (Fig. 71), offering an interesting image of the landscape and the visible archaeological sites in those days, are mentioned as an argument in favour of this hypothesis.

![Figure 71](image_url)  
*Figure 71*  
Detail of map XVI showing the Adami-Potami surroundings (after Curtius and Kaupert 1889, map XVI).

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However, caution is in order since a 19th century map is not necessarily proof for more favourable hydrological conditions in Classical times. Curtius and Kaupert (1889, 22; 26) mention two streams: the Potami, flowing through the eponymous valley, around the Velatouri Hill and subsequently to the sea, and the Adami, running from Plaka towards the sea. They did not characterise the Adami and Potami as abundant streams but rather as Bäche—just as one would today. If these streams would have been abundant in ancient times, one would perhaps expect for the distribution pattern of the sites to be different and to find more workshops along their course. In fact, the Zoridis workshop is to my knowledge the only workshop that was raised in very close proximity to the Potami, making its reliance on this stream a valid suggestion (Zoridos 1980, 83). As can be seen on the overview map (Fig. 66), all workshops are either built on the hill slopes or border the plains. On the other hand, the thick alluvium in this plain could hamper such observations. It is furthermore remarkable that these washeries did not rely on the characteristic large cisterns for their water supply as is the case in central Laurion. In this context, the motives behind the construction of these reservoirs should be taken into account. Cisterns are generally only constructed when other water resources were either not available or unable to answer the water demand. As explained in the previous chapter, one should also not underestimate the complexity of the construction techniques. Cistern water is also less fresh and clean than well or spring water is, making it less suitable for domestic usage. In other words, if there were more qualitative and less labour and capital intensive opportunities, people would have definitely exploited these. People could tap the water table through wells or depend on springs. As explained in Chapter 2, ancient springs are difficult to recognise but examples such as Insula 2 in Thorikos do indicate that these sources were exploited where these occurred. Furthermore, the Euthydike workshop seemed to have relied completely and the Kavodokano at least partly on wells. Because wells are not easily visible in the archaeological record without excavating the site, this can give a rather confusing image of the employed water management strategies, especially in contrast to the workshops in the central valleys. For Thorikos, however, the explanation is not always this straightforward, since wells have not been recognised in the well-investigated Industrial Quarter and Theatre Zone. Rainwater harvesting was clearly the main water source in this site (see further).

A second resemblance between the two groups of workshops is that workshops took care of their water supply independently, i.e. they did not cooperate to optimise their water supply by constructing barrages, supply channels and/or consolidating the gullies. Instead, cisterns relied on their own micro-catchments.

Apart from these similarities, the workshops differ in some aspects as well. First, there is a striking difference between the sites in terms of water availability. As a place to harvest rainwater, Thorikos is utterly unsuited but this is not the case for the adjoining hills, where water did accumulate into ephemeral streams. Nevertheless, the workshops did not choose to cooperate to optimise their water supply, what indicates that the competition for water
resources was not pressing in this region. Second, there is a remarkable contrast in the quality of the workshops and their water management. At Thorikos, strikingly less attention was given to the layout and technology of the *ergasteria*. The poorer quality and carelessness observed in the architecture and pottery assemblages during the fourth century BC (Mussche 1998, 64) thus seems to be a much more general trend at the site. Several washeries were squeezed into older dwellings and their cisterns were installed where space was available. Washery no. 1 and 11 illustrate this well. The construction techniques employed for Cistern no.1 also catch the attention. Generally, Laurion cisterns are meticulously carved out into the rock on all sides; however, the rocky surface on the north side of this reservoir was left entirely unworked. Even though this zone probably functioned as a place for drawing the water out of the cistern when the water level was low, this testifies to a rather haphazard construction. A final remark concerns the hydraulic mortars. In the workshops as well as the residential houses little care was further given to the waterproofing of surfaces. A clear example is the Washery no. 1 workshop, of which only AM was coated. In sharp contrast, hydraulic mortars are almost overwhelmingly present in the compounds examined in the surrounding sites of Thorikos. Although there are indications for more favourable hydrological conditions, the reduction of water loss was obviously still contemplated as highly important. In general, more thought had also been given to the structure of the workshops in the wider Thorikos area. The organisation of working and living areas, which are located in different parts of the same walled complex are still perfectly tuned to one another. Amongst others, this is illustrated by the presence of a drain linking the bathroom area to the washeries in order to recycle wastewater. In all likeliness, the issues encountered at Thorikos can for a large part be ascribed to the long occupation history of the site. Houses were built closely together, leaving little space for adaptation and even less for efficient water management.

It is imperative to make a brief note on the ore washeries in this discussion. Washeries in the Thorikos region seem to have a capacity that generally does not exceed the amount of three or four nozzles per washery. In contrast, the devices in the central valleys are often larger, sometimes counting no less than seven nozzles. This suggests that the workers were not producing similar outputs as in the centre of the Laurion. In Thorikos, unfavourable water availability and unhappy decision making towards water supply seem to have been important factors; however, this cannot be generalised to the wider area. These workshops had sufficient water resources but notwithstanding, entrepreneurs choose not to exploit these sources fully for metallurgical purposes. The geographical context may clarify some things: the workshops border the alluvial Adami and Potami plains, which were one of the few places in the Laurion where agriculture could be performed. Furthermore, the harbours were also within reach, creating a wider range of business possibilities. An argument in favour of this hypothesis could be seen in the person of Philokrates, who was the owner of the Kavodokano workshop and who was known to have been involved in other affairs than silver processing, such as beekeeping (Oikonomakou 1991, 68). One may mention Kapetanios’ suggestion that the workshop served a double purpose, embracing both mining
and agricultural activities. Grain mills were furthermore encountered in the Euthydike workshop, suggesting that agriculture was part of the business of this entrepreneur as well. This image is further backed up by observations of Salliora-Oikonomakou (2004, 123-6) and Lohman (1993), who present evidence for farms in this area. The Thorikos area should thus not be considered as a solely metallurgical region and the possibility of seasonal mining-agricultural activities would therefore not be unreasonable to put forward in this area.

6.2.3 The central Laurion valleys

The central Laurion valleys present an entirely different image. The hydrological analyses discussed above are applied to different valleys and workshops (Fig. 56). First of all, the Soureza Valley and more specifically the Asklepiakon workshops are analysed. Furthermore, ergasteria in adjacent valleys are involved, particularly the excavations of Ellis Jones in Ano-Agrileza (or the upper Agrileza Valley) and the Negris workshop in Spitharopoussi. Unfortunately, the lack of detailed published plans does not allow including more workshops but this modest selection of case-studies already testifies to a clear trend.

6.2.3.1 The Soureza Valley

The Soureza Valley is situated in the heartland of the Laurion, near the Agia Triada church and approximately 3 km from the sea.
Figure 72  The Asklepiakon workshops in the Soureza Valley (after Conophagos 1980, Fig.17-1; map by author and C. Stal).
In 1976, Conophagos started excavations in the lower Soureza Valley (Tsaïmou 1979, 15-23; Conophagos 1980, 375-89; Tsaiom 1988). He uncovered a total of four workshops and named the site Asklepiakon after an inscription encountered in Workshop 3, mentioning that Simos (of Paiania) had occupied the Askalipiakon mine (Σιμος κατέλαβε Ἀσκαληπιακόν). This workshop along with its companion Workshop 2, date to the second half of the 4th century BC (Fig. 72).

Workshop 2 is a complex organised around washery Π2 and its cistern Δ2. The washery (5.4 x 9.19 m) was of the common Type I and had four nozzle openings in its reservoir. Its water supply was provided by a round cistern of 204 m³ (Δ2, diameter: 7.6 m; depth: 4.5 m), southeast of the washery. A covered channel (0.40 m x 0.42 m) leads water from the gully, under the threshold of a door entrance in the most eastern room, over the central courtyard Σ2 to the cistern’s decantation basin (diameter: 2.25 m; depth: 1.3 m). A stone plaque projecting from the rim, used to draw water out of the cistern, and a conduit connecting the cistern to the washery’s reservoir, have been preserved. Around the central courtyard 15 other rooms were organised. A2, B2 and Γ2 were probably storage rooms. Two of these (B2 and Γ2) were coated with watertight plaster. The bathroom area of the house (H2-Z2-E2), situated immediately east of the cistern, was connected to Π2 by a covered channel, which recycled wastewater by leading it back to the washery’s reservoir. Except Z2, the rooms’ walls and floors were fully covered with the same plaster to reduce water loss to the absolute minimum.

Workshop 3, the largest of the two, shows a similar organisation, but the washery (Type I) was more extensive (12.22 x 7.33 m; 5 nozzles). The washery’s water was supplied by at least one large round cistern, located directly to its south (Δ3, diameter: 11 m, depth: 5.2 m, capacity: 494 m³). Two column bases were encountered on the bottom of the cistern, indicating that it was covered by a roof to reduce evaporation. Water catchment was also effected through a conduit, covered by stone plaques and leading right through the complex to the decantation tank, located to its northwest. Immediately southeast of this cistern, a second round cistern (diameter: 6 m; depth: approximate capacity of 141 m³) with a decantation cistern on its northeast, was constructed. The complex contained several rooms organised around three courtyards (O3, T3 and Ψ3), of which T3 and rooms A3, B3 and Y3, all lined with waterproof cement, were the washery’s actual working and storage spaces. Both workshops drew drinking water from two underground, interconnected cisterns (Δ6 and 7), located southeast of Workshop 2.
Figure 73  Detail of the contribution area map, showing the Soureza Valley. The values of the key points refer to the number of pixels draining to it, instead of to the value expressed in km² (map by author, M. van den Berg and C. Stal).

Rather than depending on the harvesting of direct runoff, the Asklepiakon workshops relied on ephemeral streams running through the valley during rains (Fig. 73). Both workshops were supplied by small covered channels feeding directly from these streams, which provide enough water for the cisterns to be used throughout the entire year. As such, the cisterns were filled during rainy periods and subsequently formed a buffer against drought during the rest of the year. This becomes clear through studying the result of the water balance model (Fig. 74), suggesting a virtually inexhaustible water supply.
It is interesting to compare Δ2 with Cistern no.1 in Thorikos. Even though both cisterns have approximately the same capacity, their location effects a totally different water provision. Cistern no. 1 offers a sufficient but far from plentiful supply, whereas Δ2 is capable of providing an almost unlimited water surplus, which allows supporting other water consuming activities and simultaneously enables a more comfortable life at the workshop.

The abundant water stock of Workshop 2 is further illustrated by the presence of baths in the complex, which are luxurious and water consuming installations. **Fig. 73** shows that the Asklepiakon workshops were indeed built to be perfectly orientated in the direction of the gullies. Workshop 3 tapped water directly from the main channel, whereas Workshop 2 relied on a smaller, yet substantial tributary. This simple comparison illustrates the importance of selecting an appropriate water catchment area to maintain metallurgical practices and the awareness of the entrepreneurs to anticipate this issue.

As mentioned above, Workshops 2 and Workshop 3 have a total of three cisterns, with one large cistern (Δ3) and two smaller ones (Δ2, Δ4). It is evident that Δ3 belongs to workshop 3, and Δ2 to Workshop 2. However, the role of Δ4 is not so easily deduced, especially since it does not appear to have a channel, from which water could be diverted. Given the location of the Δ4's decantation tank, it can be surmised that this channel collected the overflow from
Cistern Δ3, which would have been ample given the available water, and fed it into the decantation tank of Δ4. On first sight, this cistern seems to have belonged to Workshop 3; however, it may be well possible that it acted as a ‘back-up cistern’ for both workshops, considering their presence within the same walled compound and the similar distance to both the workshops’ washeries. The contributing area map also enhances our understanding of the location of the domestic cisterns (Δ6 and 7), which on first sight are located a little out of range of Workshop 3. Here, the cisterns were not only able to collect water directly from a tributary but there was also enough free space to construct them.

6.2.3.2 The Agrileza valley

Agrileza is a large valley situated about 2 km away from the sea, which can be divided in Kato- (/lower) and Ano(/Upper)-Agrileza. The former area lends itself more to agriculture but the steep slopes in the upper part are exquisite places to harvest water. Not incidentally, most metallurgy workshops are situated in this area. Between 1977 and 1983 J. Ellis Jones executed five excavation campaigns at a complex of ore washing installations on the south slope of Mount Michaeli in a northern branch of the Agrileza Valley, which until today are the best studied and published workshops in the entire Laurion (Fig. 75).

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19 The main report is published in ABSA 89 (1994), 307-358. In this article, an extensive overview of all the interim reports has also been given.
Figure 75  Overview of the archaeological remains at the site of Agrileza (Ellis Jones 1984-5, Fig. 2).

As can be seen on the image above, several other features can be observed in the direct vicinity of the compounds but these were only prospected and not subjected to further research. In order to give a good image of the nature and density of the remains in this area, these structures will be shortly discussed. The most impressive feature is undoubtedly the square tower (Fig. 76), measuring 6 m externally, situated a few meters northwest of Compound A and known as the Golden Pig Tower (Young 1956, 126-7). It has a centrally set doorway in its northwest wall with an inscription ΔΙΟΔΔ carved into the southern doorpost. More to the northwest, the foundations of a rectangular enclosure (18 x 13.50 m), probably linked to this structure, are visible.
There are two mine shafts in its neighbourhood and a little further to its southeast, a rock cut inscription (ΟΡΟΣ) is visible. Other interesting structures are present on the other side of the site in the area of Compound C. South of this workshop, a round freestanding cistern with internal staircase and measuring 10 m diameter, was constructed. Like all industrial water reservoirs in the Laurion, it was partly carved out into the rock and partly built up with massive polygonal masonry. 100 m further to the east, there is an ancient mine entrance, which seems to have remained untouched in modern times (Photos Jones and Jones 1994, 315). Right of the road, another compound is visible (D) but since no metallurgical features are observable, it was probably not an ore washing ergasterion. Finally, four—unfortunately looted—cist graves were found.

Compounds A and B were only briefly investigated with focus on their washeries and adjacent rooms. Measuring 28 x 36 m, Compound A contains at least four different rooms and a Type I ore washery (6 x 12 m) with three nozzles in its reservoir (Fig. 77, left). A narrow doorway connected this washery to a small room (2.80 x 4.80 m), which had a second entrance in its southern wall. Hydraulic mortar at the doorway from the washery to this room indicates that the entire space would have been waterproofed. Ellis Jones has suggested the

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washery to have been partly roofed, as can be seen on the reconstruction (see Fig. 40). Unfortunately, the restricted excavation and later disturbances hamper the reconstruction of its water supply.

Figure 77 The washery of compound A and C (Photos-Jones and Ellis Jones 1994, Fig. 2).

Compound B is slightly better known (Fig. 75, middle). Its washery (7.3 x 14 m) is badly preserved but a column base does suggest that the installation was protected against the strong sunlight by a roof. There are several rooms east of the washery, suggesting that the ergasterion had a rectangular plan of approximately 30 m². Two large cisterns, the first with a 10.20 m and the second a 7.5 m diameter, located directly east of the workshop likely secured its water supply but neither of these structures have been investigated. Because the reservoirs are situated so close to one another, Ellis Jones has assumed the ‘smaller’ one to have served as a decantation tank; however, this would be unlikely given its large size. In comparison to the main reservoirs, clarification basins are usually considerably smaller in size, often with a volume of about 5 m³ (Trikkalinos 1978, 15).

Compound C has been entirely excavated and is with no doubt the most meticulously investigated workshop of the mining region. It is a well-organised, nearly square compound, measuring 45 x 48 m, with no less than 21 rooms organised around two separate courtyards, probably focusing on different activities: as will be discussed further below, domestic
activities would have been taking place in the northern courtyard, whereas the southern one was likely exclusively used for ore washing and related activities.

In the northwest corner of the south court, a huge ore washery (13.5 x 14 m) with no less than 7 funnels in its stand tank was revealed. The composition of the channels and settling tanks make it a perfect example of a Type I washery. There are three column bases on the northern end of the drying table, indicating that this washery was partly covered by a roof as well. At least 12 rooms were installed around the courtyard, many of which containing features that point to industrial activities, such as crushing tables, fragments of grinding stones, a limestone trough and a network of channels discharging waste water. There was also evidence for iron-working in the form of small hearths in room III.

![Figure 78](image)

**Figure 78** The south court of Compound C, Agrileza (Photos-Jones and Ellis Jones 1994, Fig. 4).

Directly above this washery, two cisterns were incorporated into two separate rooms. The first and largest one, measuring 11.20 m in diameter, was supplying the washery. The massive limestone wall of the cistern has collapsed but a narrow staircase is still visible and has been partly cleared during the excavation. If we assume a depth of 5 m, the volume of this cistern can be calculated to be around 492 m³. Because the structure has been heavily disturbed, it is not entirely clear how this cistern collected its water, especially because there is no remaining supply channel. Nevertheless, it can be surmised that its water catchment area was located west of this cistern, directly outside of the workshop (see Fig. 79). A strip of waterproof mortar has been partly preserved on the surface but unfortunately, most of it has been destroyed by the erosive power of the surface runoff, passing through this point during rains.
In all likelihood, both Compound B and C had been relying on this small gully, since their cisterns were all raised alongside of it.

**Figure 79** The north court of Compound C, Agrileza (Photos-Jones and Ellis Jones 1994, Fig. 5).

Besides this large cistern supporting the metallurgical activities on the south court, a network of channels and underground reservoirs guaranteed the domestic water supply of the workshop. The main cistern harvesting the runoff is a round reservoir (4.60 m in diameter, 5.30 m deep; volume 88 m³) sunk into room XIII. This cistern was clearly linked to the mentioned water catchment area through an inclined conduit running through the northwest wall of the room. This cistern was part of a larger network of water relating structures securing the domestic water supply of the workshop. From this reservoir, an 8 m long underground conduit (0.65 – 1.10 m wide x 1.62 m high) leads to a 6 m deep, narrow drawshaft in room XV, provided with hand and foot holes for maintenance. This shaft communicates through an overflow channel with a subterranean, bottle-shaped reservoir situated on the north court. The cistern has collapsed and was not entirely cleared during Ellis Jones’s campaigns, so its volume remains unknown.

Although metallurgical operations are mainly linked to the south court, some evidence can also be seen on the north court, such as in Room XXII, where iron-working hearths have been discovered.

When involving the contributing area, it becomes clear that the location of the workshop was not accidental. As can be seen on Fig. 80, the workshop was constructed between two small
gullies, in which water accumulated during rains. This is further indicated by the heavily eroded surface between Compound B and C, around which the cisterns are clustering. In comparison to the Asklepiakon, the water volume passing through this point was not substantial but still, it was sufficient to provide the workshop’s huge seven-nozzle washery.

The contribution area demonstrates a catchment area of 3312 m² (23 pixels on the DEM) for the large cistern (green curve on the graph below). This amount of water was more than enough to provide the washery throughout the entire year and additionally to create a backup for the domestic activities (Fig. 81).
It is clear that workers at this site were painfully aware of the importance of a proper water management. Even more than at the Asklepiakon, water supply was meticulously taken care of and guaranteed by a range of measures, from the well-considered location of the workshops to the large capacity of the cistern, the waterproofed catchment area and the carefully laid out network of channels and reservoirs for the domestic water supply. It is interesting to see that, although Compound C can certainly be described as a well-organised and successful workshop, there is no decisive proof for real luxury, such as a bath complex; However, given the water availability at the site, this is perhaps not surprising. The water demand seemed to have been met by the cistern, but still, the surplus is not extensive.

In the discussion of this workshop’s water supply, an additional factor should be taken into account. Approximately 40 m south of Compound C, a large freestanding cistern with an estimated volume of 392.5 m³ is situated. As can be seen on Fig. 80, this cistern is perfectly orientated on a larger gully and has a catchment of no less than 13,824 m² (96 pixels on the DEM). Unsurprisingly, the water balance model demonstrates that this reservoir was ample during the entire year. Would it be possible that the workers of Compound C and/or the other surrounding workshops relied on this cistern in case of water scarcity? Considering the

**Figure 81**  Graph representing the percentage of dry time in relation to the number of nozzles/washery. A) for the Agrileza cisterns (graph by author and M. van den Berg).
fact that this cisterns does not seem to be part of a larger workshop, this could be a valid suggestion.

6.2.3.3 Spitharopoussi

The Negris workshop,\textsuperscript{21} named after its excavator, is an impressive workshop, which unfortunately remains unpublished to this day. Nevertheless, because the workshop is rather well preserved, a basic and brief description of its layout can be given.

The most impressive feature of this workshop is undoubtedly its gigantic, nearly square cistern measuring approximately $11 \times 12$ m (Fig. 82). With a presumed depth of 5 m, the cistern should have an approximate volume of 660 m$^3$. It is provided with a carefully built staircase for maintenance. The upper part of the cistern was built up with walls consisting of large polygonal blocks of marble measuring no less than 1.60 m in width; the bottom part is carved out into the rock. Its location is particularly strategic: the cistern was raised to block the surface runoff right in the middle of the valley bed, by doing so also protecting the rest of the workshop against the erosive power of the accumulating rainwater. Northeast of the cistern, a large washery and several adjacent rooms with crushing tables and special limestone troughs, which have also been found at Agrileza, can still be recognised. Finally, a mine shaft was incorporated into the workshop, directly north of the cistern.

\textsuperscript{21} In Thorikos 10 (65), Fig.9 has inaccurately been linked to the Negris workshop. In reality, this workshop lies more the northwest of the cistern shown on Fig.9.
Figure 82  The cistern of the Negris workshop. View from the south (photo by author).

Figure 83  The washery of the Negris workshop. View from the southeast (photo by author).
A striking feature is the triangular structure/basin installed in front of the cistern. It is perfectly orientated towards the gully and coated with the hydraulic mortar, suggesting that this space could have acted as a decantation tank, clearing the turbid surface runoff. The location of this workshop is most convenient: the contribution area points to a water catchment of no less than 75,744 m² (526 pixels on the DEM), an amount that provides not only an inexhaustible water supply for the metallurgical activities (Figs. 84-5).

Figure 84  Detail of the contribution area map, showing the Negris workshop at Spitharopoussi (map by author, M. van de Berg and C. Stal).
6.2.3.4 Discussion of the results

In comparison to the Thorikos region, the strategies in the central valleys are significantly different. Forming one of the busiest mining and processing areas of the Laurion, washeries and large cisterns are packed together and testify to a well-organised water management laid out by cooperating workshops. Two strategies can be recognised. The first is a central water catching and distribution system, created by a group of workshops raised alongside consolidated gullies, which were tapped by cisterns through artificial supply channels. The Asklepiakon workshops seem to have been part of such a system. Ardaillon (1897) shows with his hand-drawn map that this strategy was utilised in the Botsari valley as well (see Fig. 46) but this can no longer be checked on the field because the valley is now incorporated within a military domain. Furthermore, the sites of the Kakavoyiannis excavations relied on such a system. This workshop complex is fascinating because the washeries and cisterns were constructed along the length of a tributary, without showing a clear-cut division between the different ergasteria. Since the privately owned workshops cannot be recognised, could it be possible that multiple entrepreneurs have joined forces here to process silver ores? Sadly, this valuable site has not been published yet, so these remarks remain tentative. A second strategy
is the reliance on micro-catchments, a technique that is exclusively used by individual workshops. Both systems seem to have worked perfectly. All of the analysed workshops displayed an almost inexhaustible water supply, which enabled them to process silver ores the entire year round and thus to pay off their investments.
Chapter 7  Conclusion

This PhD has been set out to explore technological change in the Laurion silver mining industry within the wider debate on the Athenian economy. The study of ancient technology has known a turbulent history, which was heavily determined by primitivistic and substantivistic views. Under this influence, the debate on economy and technology was immersed in a particularly negative atmosphere: the ancient economy was believed to have been characterised by stagnation and hence, technological growth would have never been accomplished. In spite of the fact that several of these ingrained prejudices have been put aside and technology is generally considered as an important agent in history, the present research is still inconclusive in two distinct respects. A first problem is the overemphasis on Roman technologies in the study of the ancient economy, with the underestimation of Greek realisations as unfortunate corollary. A second issue is the general neglect of the archaeological evidence in the scientific discourse on the Greek economy. Given this current state of affairs, a targeted study of Greek technology from an archaeological point of view was thus imperative.

In order to tackle these issues, this study has chosen to concentrate on one of the most remarkable technological infrastructures of the ancient Greek world: the Laurion silver mining area. On the one hand, this PhD has sought to know how technological change was manifested in this region, especially in terms of water management, during the heyday of the Athenian city-state in the fifth and fourth centuries BC. On the other hand, this research has focussed on the impact of these dynamics on the Athenian economy. The main findings of this PhD are chapter specific and will now be synthesised with respect to these research questions.

Part 1, consisting of the introduction and two specialised chapters, has outlined the context in which the silver industry was developed, respectively focussing on the geological, geographical, hydrological and historical background. Chapter 2 has revealed both the environmental advantages and restrictions that miners and metallurgist were confronted with. As Xenophon articulated, there is silver in the soil, the gift, beyond doubt, of divine providence (Poroi 1.5), which was of strategic importance for the Athenian economy and hegemony within the wider Greek world. The production of this silver, however, was much less of a divine gift. Strabo (Geography 3.2.9) indicated that work at the Attic mines was considerably more labour intensive than in other mining areas, not only because the minerals could only be exploited through underground mining, but also because these ores required substantial processing due
to their low argentiferous content. This last remark is linked to a second obstacle: the preparation of these minerals necessitated a significant water stock, which the meagre water resources at Laurion were not able to provide in times of rising silver demand. If the Athenians wanted to maintain and expand their silver production, solutions to these environmental challenges were thus expedient.

These conditions heavily influenced the history of the Laurion and Athens, a matter that has been further elaborated on in Chapter 3. The first evidence for lead and silver mining and metallurgy dates back to the transition of the Final Neolithic to the Early Bronze Age I (Kakavoyianni et al. 2008) with an uplift from the late Archaic period onwards. The literary evidence is unambiguous: the Laurion silver was of strategic importance for the Athenian society and economy during the next two centuries; however, our sources display an irregular pattern of exploitation. A first gap appears during the pentakontaetia. Given the importance of the mines immediately before and after the ‘golden century’ of Athens, this would improbably reflect a total inactivity of the mines. More plausible would be that the operation reduced to a somewhat lower profile, whether or not under influence of the renewed Athenian activities in Thrace. The second hiatus is straightforwardly the result of the aftermath of the Peloponnesian Wars, with a slow resumption of mining in the course of the second half of the fourth century BC (Mortier 2011, 129). Another important observation from this historical overview is the shift from the public to private exploitation of the mines. Although a clear transition phase is not determinable, the mines were almost certainly leased by the State to private entrepreneurs from the 420’s onwards. It is probably not incidental to see the sources increasing specifically in the context of private entrepreneurship. After all, the administration and infrastructure required to maintain such an operation is considerably more complex.

Supporting on this background, Part 2 has fully focussed on the research questions. Imperative for a good understanding of ancient technology is a sound theoretical basis. Chapter 4 has therefore given an overview of the history of this field within the framework of the debate of the ancient economy, followed by suggestions that could enable to move towards a less biased theoretical framework, appropriate to its chronological and geographical setting. In this context, the overview presented by Persson (1988) in his analysis of technological progress in Medieval Europe has been particularly valuable. Rather than defining technological innovation solely within the context of externalities –e.g. institutional or climatological changes– Persson (1988, 7-12) has stressed that pre-industrial technological change and economic growth rather occurs within the community through small yet continuous improvements, from random changes and learning by doing to conscious trial-and-error, improvements under the influence of work specialisation and demographic changes. In the end, such changes will enable considerable, even per capita, growth. The merit of such an approach is the appreciation of technological change within its own chronological context, without it being judged for the seemingly less impressive nature of its realisations. Additionally, the concept of technological systems and sequences have been introduced,
implying the mutual dependencies of various branches of technology, of which the knowhow was steadily increasing in the course of time by building on previous developments.¹ This framework has been the basis of the evaluation of technological changes within Laurion, but remarks on this theory have also been taken along in my analysis. To leave no doubt, refinements of technologies are the most prominent form of technological change in ancient societies, and Greece is no exception. Nevertheless, the possibility of changes triggered by more exogenous dynamics cannot be neglected. The line between both types of change often proves to be very thin, especially in the complex international context in which Athens found itself during the fifth and fourth centuries BC. Due to the introduction of coinage and the Persian interference on the world scene, the silver demand rose to an unseen level, starting off a chain of events that deeply affected the Athenian society. Given the importance of silver for Athens, the effects would have certainly been felt within silver mining area as well.

In the light of these findings, the history of the Laurion silver mining area has been re-examined in Chapter 5. This chapter is based on the chaîne opératoire of silver production, more specifically (1) the exploitation, (2) dressing and (3) smelting of minerals, which each testify to a further work specialisation. Focus of this study has been on the second stage of the process. In order to deal summarily with the current preconceptions, this phase is best perceived as ore sorting, during which the metal particles of the ore were selected by handpicking and/or washing. Although the literary and archaeological sources on first sight suggest otherwise, this phase did not develop out of nothing but was liable to a steady and empirical evolution. In contrast to high grade ores, the smelting of low grade minerals demanded a much higher amount of charcoal. This specification must have triggered handpicking activities, during which the gangue was macroscopically removed. If the metallurgists wanted to reach a higher efficiency, the minerals had to be crushed and ground in order to liberate more metal from the gangue. The impossibility of sorting this finely ground ore by the naked-eye prompted the inclusion of water in the process. This was an extremely important step, not only allowing a higher productivity but also a partial mechanisation of the work process. A correct reconstruction of ore dressing, however, is hampered because the evidence is heavily skewed in favour of the fourth century BC, leaving the unfortunate impression that ore dressing was exclusively employed in the Classical Age. A critical analysis of the literary and archaeological evidence, however, suggests that this phase was already introduced long before the fourth-century installations and even independently in different parts of the world. From the comparative overview of ore dressing activities in Europe, it became clear that the nature of the sites depended heavily on their geographical context. A prerequisite is the proximity of a water source, preferably running water. Furthermore, washeries are characterised as simple installations, consisting of a series of wooden or rock-cut basins and channels, making these devices extremely difficult to

¹ Gille 1978; Persson 1988, 12-32; Schneider 2007, 148.
recognise in the archaeological record. Strengthened with this information, the Laurion has been further investigated. The Bertseko workshops, discovered by Kakavoyiannis (1989, 2001, 2005), seem to fit into all aspects into this picture: a complex of closely packed washeries consisting of a series of rock-cut basins and channels were installed in a long strip next to an ephemeral rivulet. Although one should be cautious with the proposed dating in the early fifth century BC (Kakavoyiannis 1989, 85-7; 2001, 369), the suggestion that this was an earlier ore dressing site is very likely to be valid. Apart from this find, almost the entire body of archaeological evidence of these activities dates to fourth century BC, showing a completely different configuration: workshops were now raised independently from rivulets and chiefly as separate compounds, consisting of a workspace (with one or more washeries, cistern(s), storage rooms and an area for crushing and grinding) and often also living quarters, supporting these activities. The sequence of the operations is especially clear in these workshops: as demonstrated by the numerous crushing stones and grinders, the ores were first crushed and ground, already removing the most obvious gangue. Then, the floury powder was purified in washeries, a process that was perhaps repeated, as indicated by the results of Ellis Jones' analyses of Compound C in Agrileza (1994, 335-7). Finally, the enriched ore was consolidated into pellets, which were then ready to be transported to the furnaces. These two presented groups of sites are reminiscent of observations made in Chapter 3, pointing out a shift in the operation of the mines from a public concern to partly privatised enterprises. The archaeological record, which is an ideal tool to unravel the spatial organisation of industrial sites (Domergue 2008, 179), seems to suggest a pattern that equals this transition. Most strikingly, this switch seems to have coincided with the appearance of technologies that could not be recognised in the archaeological record before. Vital are the high-quality hydraulic mortars, which were an indispensable technology to construct workshops independently from the meagre rivulets. These mortars also made way for the improvement and introduction of a whole series of further technologies, from the refinement of the washeries to the construction of cisterns, providing the workshop with a private water stock. These innovations fit in with the general concern in the Laurion for a sustainable water management, which was of invaluable importance for the smooth operation of the silver industry. Without water, ores could not be processed and, hence, silver not produced. It is also important to note that this innovative process never came to a standstill. Improvements were continuously carried out, as is well illustrated by the many variations in washery layout. Although some interventions were dictated by local conditions, others were undoubtedly the result of conscious experimentation in the search for more optimal techniques. It is important to note that innovations were not restricted to the process of ore washing. As illustrated by the Ari workshops (Tsaimou 2004), the crushing and grinding of ores was also susceptible to a process of change.

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Within the discussion of technological innovations, this fourth-century infrastructure offers a unique opportunity to investigate the underlying motives of these improvements more closely. Chapter 6 has focussed specifically on this topic. The innovations made in these ergasteria suggest that the entrepreneurs were driven by profit maximisation but this can only be proven when a correlation between risk and return is demonstrated (Christesen 2003, 46). This chapter is divided into two parts, each making a qualitative assessment of these two factors. In the evaluation of risk, a rough idea has been given of the value of an ergasterion through the investigation of epigraphic sources, such as prices listed on borni, and literary evidence, such as speeches. These sources generally bear witness to high prices paid for ore processing workshops or securities for their loans, including the highest price ever recorded for an ergasterion (Demosthenes, Against Pantainetos 37.31). Additionally, there are indications for a general constraint towards the involvement in the mining business because it was perceived as a risky undertaking. Further contributing to this picture is the remarkably high representation (12-20 %) of elite members in mining and even more, the proportion of money paid by this group in the total amount of capital (no less than 35.38 %) invested in the industry (Shipton 2000, 30-7). A coherent estimation of an ore processing workshop’s value, however, cannot be made without involving the actual place in which the work was conducted. Archaeology cannot offer numbers, but does enable a tentative estimation of the efforts involved in the construction of an ore processing workshop, whether or not expressed in man-days of labour. The ergasteria are generally large properties, provided with particularly labour intensive features, such as mine shafts, washeries and cisterns. Workshops also had to be maintained. Archaeology indicates that the infrastructure was constantly adjusted and improved, e.g. by the inclusion of larger washeries, as can be seen at Demoliaki (Mussche and Conophagos 1973), and cisterns, such as at Workshop 3 in Soureza. Although the evidence is sketchy, the general trend is clear: the establishment of an ore processing enterprise was an expensive venture, of which the investment could only be compensated by high returns. The second part of this chapter further concentrates on this factor. Since there are no epigraphic or literary data on the production output of these workshops, this section has focussed on archaeological evidence. In order to make a reliable assessment of the workshop output and possible rational decision-making during the operation, the resources determining these yields have to be considered. As explained, the most crucial resource in the ore dressing process was water. The awareness of the entrepreneurs about the significance of this resource is revealed by the investments made to secure the workshop’s water supply: 1) the hydraulic mortars, used to waterproof the infrastructure, 2) the washeries, which were basically water recycling devices, 3) the cisterns, allowing the harvesting of surface runoff and providing a

3 See Hypereides’ fourth oration (4.36), Xenophon, Poroi (4.27-8) and the low number of new cuttings or kainotomia recorded in the mine leases (Crosby 1950).

4 Tsaïmou 1979, 15-23; Conophagos 1980, 375-89; Tsaïmou 1988. Cistern Δ4 was likely added in a later phase.
reliable water stock. Nevertheless, these efforts as such are not sufficient to proof profit-maximising economic rationality. Therefore, these interventions should translate in successful production outputs. Although such a link might seem straightforward on first sight, this becomes less so when looking at the variations in cistern size. In the area of Thorikos, the cisterns are not only few but also conspicuously smaller than in the Laurion heartland, suggesting a potentially lower production output in the former area. This could have significant implications for our knowledge on the silver industry and also on the incentives of entrepreneurship. In order to clarify these problems, a comparative estimation of the scale of production has been performed through hydrological analyses, consisting of a water routing and accumulation model of the Laurion landscape on the one hand, and a water balance model of the effective water use of the washeries on the other. The two already mentioned zones have been used as key areas.

The archaeological investigation of water related structures within their hydrological context indicates that workshops relied mainly but not exclusively on rainwater harvesting. Where the hydrological conditions allowed the inclusion of other water resources, such as streams or springs, these opportunities were exploited. This makes sense, since the construction of cisterns is an investment that a rational entrepreneur will only make when it is compelling. Judging from the archaeological remains, the central valleys were one of the Laurion’s busiest mining and processing zones. Two water management strategies were observed: either workshops were relying on central water channels, which were mostly a consolidation of the gully flowing through the valley bed during rains, or they relied on micro-catchments to which they are perfectly orientated. It is interesting to see that the distribution of water in the landscape also seems to have determined the organisation of workshops: at the Kakavoyannis excavations in Soureza, clearly separated workshops cannot be recognised, suggesting a cooperation of several ergasteria, harvesting surface runoff that was accumulating in the valley bed during rains. Altogether, the competition for the scarce water sources was large, necessitating this well-regulated water management. The hydrological analyses show that both strategies were successful. All the discussed sites were able to maintain a full-year production and additionally to create a surplus, providing a buffer against drought as well as a higher life comfort. The results further suggest that investors were indeed aware of the factors influencing returns, since they consciously selected appropriate water catchments and successfully anticipated on water issues.

The situation is much less straightforward in the Thorikos area. First of all, a division should be made between the workshops in Thorikos on the one hand and the ergasteria on the opposite hills on the other. The latter workshops were notably luxurious and testify to a heterogeneous water supply. Mostly, the workshops were provided by small cisterns and wells. The possibility of reliance on the Adami and Potami rivulets cannot be excluded but the thick alluvium accumulated in these valleys hampers a confirmation. It is notable that the workshops did not cooperate in this area to optimise their water supply through central channels, even though there was a substantial amount of surface runoff accumulating in these hills during rains. This suggests that the competition for water sources was significantly lower.
than in the central valleys. Another interesting observation is that these workshops owners did not seem to have invested all their capital into the silver business. Entrepreneurs as Philokrates were for example also involved in apiculture. Perhaps this image is not surprising altogether. The close proximity of the harbour and a fertile alluvial area must have created opportunities that are much wider than the silver business. In sharp contrast, Thorikos had a distinctively more ad hoc character, tentatively illustrating that not all businessmen were capable of the same rational decision-making. By persisting on the use of former living structures and taking water supply only into consideration afterwards, the production output of these workshops was jeopardised. Although most cisterns did provide a sufficient amount of water for a full-year operation, these hardly created a surplus. This contrast becomes especially clear when Cistern no. 1 in Thorikos is compared with Cistern Δ2 in Soureza.

This study has encountered some limitations that could not be tackled within the framework of the current study but could be a starting point for further research. In case of the Laurion, the limitations are expressed on two levels: the early stages of ore processing on the one hand, and the fourth-century phase on the other. The debate about the former is hindered because it remains mainly a theoretical one. If more clarity wants to be obtained, targeted archaeological research should be performed to discover similar sites. Early ore dressing sites were confined to a specific geographical context, more specifically natural water sources as rivulets. In this context, Kakavoyiannis (2001, 373) already drew attention to the gullies close to Thorikos and in the area of Megala Pevka. A field survey along the course of these streams, in combination with excavations could possibly reveal similar sites as encountered at Bertseko. The problem with the latter is of a completely different nature. Our evidence of the fourth-century infrastructure is abundant but the general research strategies do often not allow a deep understanding of the complex work processes at these sites. This situation for example applies to the past research at Thorikos. Although 13 ore washeries have been localised, only one actual workshop (Washery no. 1) has been completely excavated. Four further washeries (no. 2-3-4-11) have been entirely or partly cleared but never within the context of its wider workspace. This is a missed opportunity. The chaîne opératoire cannot be properly understood without taking this into account. In this context, the Agrileza excavations of Ellis Jones can certainly be taken as an example. On a larger level, it is necessary to further contextualise the findings of this study, especially given the fact that the Laurion is (or seems to be) a unique case study within the Greek world. As illustrated throughout this PhD, there is no better partner to increase our understanding of this underestimated aspect of the Greek economy than archaeology. The involvement of contexts revealing vertically specialised work processes would be especially interesting.

This PhD holds implications for both the study of the Laurion and the ancient Greek economy.
As far as the Laurion is concerned, this study has challenged the current trend to view the mining and metallurgical activities solely within the context of the fourth-century infrastructure. This is principally the merit of the decision to define “the ore dressing ergasterion” as a dynamic rather than a static feature. This point of departure helped to contextualise and nuance the current, still widely accepted theory of Conophagos on ore washing and further elucidates that the fourth-century workshops were in fact just one link in a long chain of a technological change. Furthermore, this research has pointed out that the study of the Laurion is heavily directed towards a limited selection of sites, of which Thorikos is undoubtedly the most prominent one. The comparative research of different groups of workshops based on the hydrological research, however, suggests that Thorikos was far from the prototype of a metallurgical site. This does not diminish the overall importance of this site for our knowledge of the silver industry throughout history; however, it does put its role—and in extension, the position of the other mining and ore processing zones—into a wider perspective.

Furthermore, the Laurion silver mining region has been proven a perfect case study to trigger the debate about ancient Greek economy and technology. It has been shown that technological change should be defined as a heterogeneous phenomenon, stimulated by both endo- and exogenous developments that could occur simultaneously. Especially two findings hold implications. First, technological change can generally be conceived as a steady process, of which the pace could be increased in an atmosphere receptive to such change. This seems to have occurred under the influence of more external events, in this context institutional changes in combination with environmental constraints. To modern standards, the carried out innovations might seem trivial, but they were the enablers of significant progress: more ores could be processed, more silver produced and hence, more capital injected into the Athenian economy. Although such developments have already been observed in Roman contexts (Wilson 2002, 32), the occurrence in a Greek one has not been taken as a possibility so far. Secondly, there is evidence for a remarkably high level of vertical specialisation observable in the silver production process and, specifically within the context of fourth-century Athens, for profit-maximising behaviour displayed by private businessmen. These results not only make primitivistic/stagnationist views, suggesting the elusiveness of economic and technological growth in ancient Greece (Millet 2001, 35), untenable, but will hopefully also form a stimulus for a different, less negative and biased debate on the ancient Greek economy, in which archaeology fulfils a more prominent role. In the end, the ultimate challenge is to make the study of the ancient economy a less scattered field and develop a discourse in which both archaeology and historiography reinforce one another. The contextualization of these different forms of evidence is absolutely paramount for moving research towards a more thorough yet nuanced understanding of the role of technology in the development of ancient economies.
Nederlandstalige samenvatting

Dit doctoraat heeft tot doel technologische verandering in de Laurion zilverindustrie te onderzoeken binnen het bredere debat over de Athenese economie. Binnen de klassieke geschiedenis is de studie van technologie een relatief jong vakgebied, dat te maken kreeg met een heel aantal vastgeroeste vooroordelen, veroorzaakt door de projectie van moderne opvattingen van dit begrip op de geschiedenis. Ondanks het feit dat veel van deze misconcepties opzij geschoven zijn en technologie nu wordt aanzien als een belangrijke agent in de antieke geschiedenis, is het huidige onderzoek nog steeds ontevreden in verschillende aspecten: een eerste probleem is de te sterke beklemtoning op de Romeinse wereld, met de onderwaardering van de Griekse technologische realisaties als onvermijdelijk gevolg. Een tweede probleem is de verwaarlozing van de archeologische bronnen in het discours over Griekse technologie. Gezien deze stand van zaken is een nauwgezette studie van Griekse technologie vanuit een archeologisch standpunt een absolute noodzaak.

Om deze problemen aan te kaarten, viel de keuze op een van de meest opmerkelijke technologische infrastructuren van de antieke Griekse wereld: de Athenese zilvermijnen in de Laurion, gelegen ten zuidoosten van Attica. Enerzijds bestudeert dit doctoraat hoe technologische veranderingen zich in deze streek manifesterden tijdens de bloei van de Athenese stadstaat in de vijfde en vierde eeuw VC. Anderzijds focust dit onderzoek op de impact van deze dynamieken op de Athenese economie.

Deel 1 van dit doctoraat, bestaande uit de inleiding en twee gespecialiseerde hoofdstukken, schetst de bredere context waarbinnen de zilverindustrie is ontwikkeld, meer bepaald de geologische, geografische, hydrologische en historische achtergrond. Hier vallen vooral de environmentele voor- en nadelen op. Zoals Xenophon (Poroi, 1.5) reeds benadrukte, was de Laurion rijk aan zilver maar de productie van dit metaal was geen eenvoudig proces. In scherp contrast tot andere mijnstreken hadden de Laurion-ertsen een bijzonder laag metaalgehalte, wat hun verwerking in sterke mate bemoeilijkte. Dit gaf de aanzet tot de ontwikkeling van gesofisticerde verwerkingstechnologieën, zoals ertspruimen, om deze mineralen te zuiveren. Dit maakte de zilververwerkingsworkshops een van de meest cruciale onderdelen van de antieke mijnindustrie.
Steunend op deze achtergrond, concentreert Deel 2 zich volledig op de onderzoeksvragen. Noodzakelijk voor een goed begrip van antieke technologie is een solide theoretische basis. Hoofdstuk 4 geeft daarom een overzicht van de geschiedenis van dit gebied, gevolgd door suggesties die een minder bevooroordeeld theoretisch debat in de hand kunnen werken. Centraal in deze discussie is het theoretisch kader uitgezet door Persson (1988) in zijn analyse van middeleeuws Europa. In plaats van technologische innovatie louter te zien binnen de context van externe gebeurtenissen, zoals institutionele of klimatologische veranderingen, benadrukt Persson (1988, 7-12) dat pre-industriële technologische groei zich eerder voordeed in de vorm van kleine maar continue verbeteringen, van willekeurige veranderingen, learning by doing en bewuste trial-and-error tot ingrepen onder invloed van werkspecialisatie en demografische veranderingen. Uiteindelijk zullen dergelijke veranderingen een significante, zelfs per capita, groei bewerkstelligen. De meerwaarde van dergelijk uitgangspunt is dat technologische groei wordt geapprecieerd binnen de eigen chronologische context, zonder afgeëerd te worden voor de ogenschijnlijk minder impressionante aard van de technologieën. Hoewel, de mogelijkheid van verandering gestimuleerd door meer exogene dynamieken mag niet zomaar aan de kant geschoven worden. Door de introductie van de muntslag en de Perzische bemoeizucht binnen de Griekse wereld, steeg de vraag naar zilver naar een ongezien niveau en dit zette een kettingreactie van gebeurtenissen op gang, die de Atheneanse maatschappij diep beïnvloedde. Gezien het belang van zilver voor de stadstaat waren deze effecten ongetwijfeld eveneens voelbaar binnen de Laurion.

Tegen deze achtergrond werd de geschiedenis van de Laurion heronderzocht in Hoofdstuk 5, waarvan de opbouw steunt op de chaîne opératoire van het zilverproductieproces, meer bepaald 1) de exploitatie, 2) de verwerking en 3) het smelten van de mineralen. Deze studie focust, zoals hierboven aangestipt, op het tweede deel van het proces. Ondanks het feit dat de literaire en archeologische bronnen op het eerste zicht het tegendeel bewijzen, is de introductie van deze fase onderhevig aan een lang en empirisch proces. De Bertseko workshops, opgegraven door Kakavoyiannis (1989, 2001, 2005), geven een idee van hoe de vroege fasen van deze evolutie zich karakteriseerden: erstwasserijen bestonden uit in de rots uitgehouwen bassins en kanalen en waren dicht opeengepakt in een lange strook langs een seizoensgebonden riviertje. Ook al dient men voorzichtig te zijn met de datering van Kakavoyiannis in de vroege vijfde eeuw VC (1989, 185-7), is zijn suggestie dat dit een vroege fase van ertsverwerking voorstelt, gegrond. Los van deze belangrijke vondst, dateren bijna alle andere archeologische bewijzen voor ertsverwerking uit de vierde eeuw VC en tonen ze een compleet andere organisatie: workshops werden opgericht als een onafhankelijke infrastructuur, bestaande uit een werkplaats (met een of meerdere wasserijen, cisterne(s), opslagruimtes en kamers voor het malen van erts) en vaak ook leefruimtes, die deze ruimtes ondersteunden. Deze twee groepen van workshops lijk een overgang in de organisatiestructuur van de mijnindustrie te suggereren, van publieke naar private uitbating, een situatie die eveneens in de literaire bronnen kan worden gelezen. Deze switch lijkt gegaan te zijn met de introductie van een hele reeks technologieën, die niet eerder in het archeologisch erfgoed kunnen herkend worden. Cruciaal zijn de hydraulische mortels, die
een noodzakelijke technologie zijn om workshops onafhankelijk van rivieren op te richten. Deze mortels lieten de verbetering en introductie van een verdere serie technologieën toe, van de constructie van wasserijen als aparte entiteiten tot cisternes, die het mogelijk maken om een private en betrouwbare waterstock te creëren. Deze innovaties passen ook binnen het algemene belang van een duurzaam waterbeheer in de Laurion. Zonder water kunnen ertsen niet verwerkt en zilver niet geproduceerd worden. Het moet ook benadrukt worden dat het innovatieproces niet tot stilstand kwam na de introductie van deze technologieën maar voortdurend werd uitgevoerd, zoals goed te zien is in de vele variaties in de configuratie van erts- wasserijen.

Binnen deze discussie biedt de vierde-eeuwse infrastructuur een unieke gelegenheid om de onderliggende motieven van deze innovaties nader te bestuderen. **Hoofdstuk 5** focus specifiek op deze stimulansen. De besproken innovaties suggereren dat ondernemers gedreven werden door winstbejag, maar dit kan enkel bewezen worden als een correlatie tussen risico en opbrengst kan worden aangetoond (Christesen 2003, 46). Dit hoofdstuk is onderverdeeld op basis van deze twee factoren.

In de evaluatie van de risico-factor wordt een ruw idee gegeven van de waarde van een *ergasterion* door middel van onderzoek naar epigrafische bronnen, zoals *borei*, literaire bronnen, zoals redevoeringen, en archeologische sites. Ondanks het feit dat de bewijzen beperkt zijn, is het algemene beeld duidelijk: de oprichting van een workshop is een bijzonder prijzige onderneming, waarvan de investering enkel kan gecompenseerd worden door hoge opbrengsten. Deze laatste factor is moeilijker te onderzoeken, aangezien er geen literaire of epigrafische bronnen bestaan die ons exacte cijfers kunnen voorschotelen. We hangen dus volledig af van de archeologie in onze beoordeling. Om de output van een workshop en de mogelijke economisch rationale besluitvorming in de operatie te bepalen, dienen de determinanten van deze productie te worden betrokken. Zoals reeds uitgelegd, is water de meest essentiële determinant. Het bewustzijn van de ondernemers over het belang van water kan worden aangetoond door de aandacht besteed aan watervoorziening (zoals de hydraulische mortel, de wasserijen, de cisternes, ...), maar deze ingrepen an zich zijn niet voldoende om winstmaximalisering te bewijzen. Hiervoor moeten de interventies zich rechtstreeks vertalen in productieoutput. Deze link lijkt misschien vanzelfsprekend, maar dit wordt veel minder het geval wanneer men de variaties in cisterneomvang nader onder de loep neemt. In het Thorikosgebied zijn cisternes niet enkel veel kleiner dan in de centrale Laurionvalleien, maar ook opvallend minder talrijk, wat suggereert dat de productieoutput van workshops in het eerstgenoemde gebied een stuk lager ligt. Indien dit het geval is, kan dit significante gevolgen hebben voor onze kennis over de interacties binnen de zilverindustrie en de motivaties van ondernemerschap. Om deze problemen op te helderen, wordt een vergelijkende schatting gemaakt van de productieschaal van de industrie door middel van hydrologische analyses, bestaande uit enerzijds een wateraccumulatiemodel van het Laurion landschap en anderzijds een waterbalansmodel van het effectieve watergebruik van wasserijen. De twee hierboven vermelde gebieden worden gebruikt als casestudies.
Afgaand op de archeologisch resten zijn de centrale valleien een van de drukste mijn- en ertsverwerkingsgebieden in de Laurion. Er kunnen twee strategieën in het waterbeheer worden onderscheiden: ofwel deden de workshops beroep op centrale waterkanalen, ofwel op micro-opvangbekkens, waarnaar ze perfect georiënteerd zijn. Over het algemeen was de competitie voor water groot, wat een goed gereguleerd water management absoluut essentieel maakte. De hydrologische analyses tonen aan dat beide strategieën succesvol waren, aangezien alle bestudeerde workshops niet enkel in staat waren om hun productie het volledige jaar door te onderhouden, maar ook om een surplus te creëren, die als een buffer tegen droogte fungeerde en eveneens een hoger comfort met zich meebracht. De resultaten wijzen er verder op dat investeerders zich wel degelijk bewust waren van de factoren die een goede opbrengst beïnvloedden, zoals door het selecteren van een geschikt opvangbekken en het succesvol anticiperen op waterproblemen.

De situatie is een stuk minder voor de hand liggend in het Thorikos gebied. Eerst en vooral moet er een onderscheid gemaakt worden tussen de workshops in Thorikos aan de ene kant en de ergasteria in heuvels tegenover deze site aan de andere kant. Deze laatste workshops zijn opvallend luxueus en getuigen van een heterogene watervoorziening. Over het algemeen hangen deze workshops af van kleine cisternes en waterputten. De mogelijkheid dat ook beroep werd gedaan op de Adami en Potami rivier kan niet worden uitgesloten maar het dikke alluviale pakket in de valleien laat het niet toe om dit te bevestigen. Het valt op dat de workshops in dit gebied niet samenwerkten om hun watervoorziening te optimaliseren via centrale waterkanalen, wat suggereert dat de competitie voor water er een stuk lager ligt dan in het kernland van de Laurion. Een verdere interessante observatie is dat de workshop eigenaars niet al hun geld lijken ingezet te hebben op de zilverindustrie, wat alles in beschouwing genomen niet geheel verassend is. De nabijheid van de haven en het vruchtbare alluvium moeten bredere zakenmogelijkheden gecreëerd hebben. In scherp contrast heeft Thorikos een opvallend groter ad hoc karakter. Door gebruik te maken van oudere woonstructuren en watervoorziening maar achteraf in overweging te nemen, werd de operatie van deze workshops op het spel gezet. Ook al voorzagen de meeste cisternes voldoende water voor een bescheiden waterrij, creëerden ze zelfs amper een surplus. Dit doet vermoeden dat niet alle zakenlui dezelfde hoeveelheid kapitaal in huis hadden om een workshop te bekostigen of in staat waren om dezelfde rationele beslissingen te nemen.

Deze studie heeft implicaties voor onze kennis van de Laurion, zowel als van de antieke technologie en economie. Eerst en vooral heeft dit doctoraat de trend om deze streek enkel binnen de vierde-eeuwse infrastructuur te bekijken, getracht te doorbreken. Hierbij werd aangetoond dat de "ertsverwerkingsworkshop" geen statisch gegeven was maar een aanzienlijke transformatie heeft ondergaan, die lang voor de vierde-eeuwse ergasteria en zelfs de Bertseko workshops teruggaat. Verder is aangetoond dat de Laurion een uitstekende casestudy is om het debat over Griekse technologie open te trekken. Technologische veranderingen werden gedefinieerd als een heterogene en continu fenomeen, dat zowel endo- als exogene ontwikkelingen omvatte. Dit heeft als gevolg dat primitivistische/
stagnationistische visies, die technologische en economische groei in de Griekse wereld ontkennen (Millet 2001, 35), niet langer houdbaar zijn.
English summary

This PhD has been set out to explore technological change in the Laurion silver mining industry within the wider debate on the Athenian economy. The study of ancient technology has known a turbulent history, which was heavily determined by primitivist and substantivistic views. Under this influence, the debate on economy and technology was immersed in a particularly negative atmosphere: the ancient economy was believed to have been characterised by stagnation and hence, technological growth would have never been accomplished. In spite of the fact that several of these ingrained prejudices have been put aside and technology is generally considered as an important agent in history, the present research is still inconclusive in two distinct respects. A first problem is the overemphasis on Roman technologies, with the underestimation of Greek realisations as unfortunate corollary. A second issue is the neglect of the archaeological evidence in the scientific discourse on Greek technology. Given this current state of affairs, a targeted study of Greek technology from an archaeological point of view was thus imperative.

In order to tackle these issues, this study has chosen to concentrate on one of the most remarkable technological infrastructures of the ancient Greek world: the Laurion silver mining area. On the one hand, this PhD has sought to know how technological change was manifested in this region during the heyday of the Athenian city-state in the fifth and fourth centuries BC. On the other hand, this research has focussed on the impact of these dynamics on the Athenian economy. The main findings of this PhD are chapter specific and will now be synthesised with respect to these research questions.

Part 1 has outlined the context in which the silver industry was developed, respectively focussing on the geological, geographical, hydrological and historical background. Focus was mainly on the environmental advantages and restrictions that the miners and metallurgist were confronted with. The Laurion was rich in silver ores but the production of silver was far from self-evident. In contrast to other mining areas in the Aegean, the Laurion only yielded low grade ores, which were close to the margin of economic viability (Rehren 2005, 24-5). This prompted the development of sophisticated ore processing techniques that could clear the ore from its impurities, leaving only the rich metal particles and consequently converting the Laurion mines into a productive lode of mineral resources. This made the ore dressing plant the most crucial feature of the ancient mining industry, contributing heavily to the economy and by doing so securing the foundations of the Athenian empire.
Supporting on this background, *Part 2* has focussed fully on the research questions. Imperative for a good understanding of ancient technology is a sound theoretical basis. **Chapter 4** has therefore given an overview of the history of this field, followed by suggestions that could enable to move towards a less biased theoretical framework, appropriate to its chronological setting. In this context, the overview presented by Persson (1988) in his analysis of technological progress in Medieval Europe has been particularly valuable. Rather than defining technological innovation solely within the context of externalities—e.g. institutional or climatological changes—Persson (1988, 7-12) has stressed that pre-industrial technological change and economic growth rather occurs within the community in the form of small yet continuous improvements, from random changes and learning by doing to conscious trial-and-error, improvements under the influence of specialisation of the work process and demographic changes. In the end, such changes will enable considerable, even per capita, growth. The merit of such an approach is the appreciation of technological change within its own chronological context. Nevertheless, the possibility of changes triggered by more exogenous dynamics cannot be neglected either. Due to the introduction of coinage and the Persian inference on the world scene, the silver demand rose to an unseen level, starting off a chain of dynamics that deeply affected the Athenian society. Given the importance of silver for Athens, the effects would have certainly been felt within silver mining area as well.

In the light of these findings, the history of the Laurion silver mining area has been re-examined in **Chapter 5**. This chapter is composed based on the *chaîne opératoire* of silver production, more specifically (1) the exploitation, (2) dressing and (3) smelting of minerals, which each testify to a further work specialisation. Focus of this study has been on the second stage of the process. Although the literary and archaeological sources on first sight suggest otherwise, this phase did not developed out of nothing but was rather liable to a long and empirical evolution. The Bertseko workshops, discovered and excavated by Kakavoyiannis (1989, 2001, 2005), give a hint of this evolution: a complex of closely packed washeries consisting of rock-cut basins and channels were installed in a long strip next to an ephemeral rivulet. Although one should be cautious with the dating proposed by Kakavoyiannis (1989, 185-7) in the early fifth century BC based on surface pottery finds, his suggestion that this was an earlier phase of ore washing is very likely to be valid. Apart from this find, the almost entire body of archaeological evidence on ore dressing dates to fourth century BC and shows a completely different configuration: workshops were now raised as independent compounds, consisting of a workspace (with one or more washeries, cistern(s), an area for crushing and grinding, and storage rooms) and often living quarters, supporting these activities. These two groups of sites are reminiscent of observations made in Chapter 3, pointing out a shift in the operation of the mines from a public concern to partly privatised enterprises. The archaeological record, which is an ideal tool to unravel the spatial organisation of industrial sites (Domergue 2008, 179), seems to suggest a pattern that equals this transition. Most strikingly, this switch seems to have coincided with the appearance of technologies that could not be recognised in the archaeological record before. Vital are the
high-quality hydraulic mortars, which were an absolutely necessary technology to be able to construct workshops independently from the meagre rivulets. These mortars also made the improvement and introduction of a whole series of further technologies possible, from independently constructed washeries to cisterns, providing the workshop with a private water stock. These innovations fit in with the general concern in the Laurion for a sustainable water management, which was of invaluable importance for the smooth operation of the silver industry. Without water, ores could not be processed and, hence, silver not produced. It is also important to note that this innovative process did not come to a standstill after the introduction of these significant technologies. Technological improvements were continuously carried out, as is well illustrated by the many variations in washery layout.

Within the discussion, this fourth-century infrastructure offers a unique opportunity to investigate the underlying motives of these improvements more closely. Chapter 6 has focussed specifically on this topic. The innovations made in these ergasteria suggest that the entrepreneurs were driven by profit maximisation but this can only be proven when a correlation between risk and return is demonstrated (Christesen 2003, 46). The chapter is divided into two parts, each making a qualitative assessment of these two factors. In the evaluation of the risk factor, a rough idea has been given of the value of an ergasterion through the investigation of epigraphic sources, such as prices listed on horoi, literary evidence, such as speeches, and archaeology. Although the evidence is sketchy, the general trend is clear: the establishment of an ore processing enterprise was an expensive venture, of which the investment could only be compensated by high returns. The second part of this chapter further concentrates on this factor. In order to make a reliable assessment of the operation and output of a workshop and possible rational decision making in this process, the resources determining these yields have to be considered. As explained, the most crucial resource in the ore dressing process was water. The awareness of the entrepreneurs about the significance of this resource is revealed by the investments made to secure the workshop’s water supply: 1) the hydraulic mortars, used to waterproof the infrastructure, 2) the washeries, which were basically water recycling devices, 3) the cisterns, allowing the harvesting of surface runoff and providing a reliable water stock. Nevertheless, these efforts as such are not sufficient to proof profit-maximising economic rationality. Therefore, these interventions should translate in successful production outputs. Although such a link might seem straightforward on first sight, this becomes less so when looking at the variations in cistern size. In the area of Thorikos, the cisterns are not only few but also conspicuously smaller than in the Laurion heartland, suggesting a potentially lower production output in the former area. This could have significant implications for our knowledge on the silver industry and also on the motivations of entrepreneurship. In order to clarify these problems, a comparative estimation of the scale of production has been performed through hydrological analyses, consisting of a water routing and accumulation model of the Laurion landscape on the one hand, and a water balance model of the effective water use of the washeries on the other hand. The two already mentioned zones have been used as key areas.
Judging from the archaeological remains, the central valleys were one of the Laurion’s busiest mining and processing zones. Two water management strategies were observed: either workshops were relying on central water channels, which were mostly a consolidation of the gully flowing through the valley bed during rains, or they relied on micro-catchments to which these were perfectly orientated. Altogether, the competition for the scarce water sources was large, necessitating this well-regulated water management. The hydrological analyses show that both strategies were successful, since all case-studies were able not only to maintain a full-year production, but also to create a surplus, providing a buffer against drought as well as a higher life comfort. The results further suggest that investors were indeed aware of the factors influencing returns, since they consciously selected appropriate water catchments and successfully anticipated on water issues.

The situation is much less straightforward in the Thorikos area. First of all, a division should be made between the workshops on the Velatouri on the one hand and the ergasteria facing this hill on the other. The latter workshops were notably luxurious, and testify to a heterogeneous water supply. Mostly, the workshops were provided by small cisterns and wells. The possibility of reliance on the Adami and Potami rivulets cannot be excluded but the thick alluvium accumulated in these valleys hampers a confirmation. It is notable that the workshops did not cooperate in this area to optimise their water supply through central supply channels. This suggests that the competition for water sources was significantly lower than in the central valleys. Another interesting observation is that the workshops owners did not invest all their money into the silver business. Perhaps this image is altogether not surprising. The close proximity of the harbour and a fertile alluvial area must have created opportunities that are much wider than the silver business. In sharp contrast, Thorikos had a distinctively more ad hoc character, tentatively illustrating that not all businessmen were capable of the same rational decision making. By persisting on the use of former living structures and taking water supply only into consideration afterwards, the production output of these workshops was jeopardised. Although most cisterns did provide a sufficient amount of water for a full-year operation, they hardly created a surplus.

This study holds implications for both the study of the Laurion and ancient Greek technology and economy. As far as the Laurion is concerned, this study has challenged the current trend to view this region solely within the context of the fourth-century infrastructure, particularly the ore processing ergasteria. It has been shown that “the ore dressing workshop” was not a static feature but underwent considerable transformation in the course of time, going back a long time before the fourth-century ergasteria and even the Bertseko workshops. Furthermore, the Laurion silver mining region has been proven a perfect case-study to open the debate about ancient Greek technology by defining technological change as a heterogeneous phenomenon, triggered by both endo- and exogenous developments. These results make primitivistic/stagnationist views, suggesting the elusiveness of economic and technological growth in ancient Greece (Millet 2001, 35), untenable.
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