

# The Laurion shafts, Greece: ventilation systems and mining technology in antiquity

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*ABSTRACT: Geological exploration of the shafts at Laurion (Attica, Greece) have been carried out yearly since 2002, research being concentrated on the Spitharopoussi area. Among these shafts, remarkable for their regularity, are some which are vertical and deeper than 80m. Observations raised the problem of identifying the technology used to achieve sufficient circulation of air for respiration when sinking these shafts. This question is far from being answered in detail, and even the special case of a single vertical shaft has not previously received due attention. Our initial purpose is to establish what means were required to permit respiration below a certain depth in both winter and summer seasons. We then describe the two most common shaft types already explored, partitioned and twisted, and then some other oddly-shaped shafts. Finally, as work in progress, we report the measurements which are currently being recorded on site in order to develop further theoretical and numerical approaches.*

## The Laurion mines of antiquity

The Laurion mines (Attica, Greece) are among the most important in antiquity. The ancient authors Herodotus, Thucydides, Aristotle and Xenophon in particular recorded the mines' influence on the politics and economies of Athens, and their documents are complemented by epigraphy (Hopper 1968; Domergue 2008). On the surface, mining, ore dressing and metallurgical remains extend over several tens of square kilometers. Several of these have been excavated, but underground explorations have been rare, except of some drifts which could easily be entered by the slopes close to the ancient city of Thorikos ; in addition there is a shortage of accurate land surveys. Previously, major deep workings have been ignored, particularly those reached by vertical shafts deeper than 100m. It is believed that most of the shafts were sunk between the 5th and 4th centuries BC (Cordella 1869; Ardaillon 1897; Conophagos 1980). They were presumably sunk to reach, as directly as possible, underground mineral deposits which the miners were seeking.

To date, apart from on the Laurion, ancient mine

workings reaching 100m in depth are rare. Ancient timbers were found in the Indian mines of Rajasthan and Karnataka at depths exceeding 200m (Willies *et al* 1984; Willies 1987 and 1992; Allchin 1962). However, none of these mines exhibit long vertical shafts as in the Laurion, where a lot of well-preserved square-shaped absolutely vertical shafts close to or deeper than 100m have been explored.

The mines are related to the geological conditions of important lead-silver mineral deposits, *ie* the so-called 3rd contact (Ardaillon 1897). These impressive vertical shafts provide a model of remarkable engineering and, in the ancient world, are the only systems which reached underground networks excavated deep down to several levels. Their study is of great importance for geological analysis and mapping (Photiades *et al* 2004).

In addition to geological study, the aim is to highlight the strategy of mineral exploitation during antiquity. Field investigations were located on a particularly well defined geomorphological area which covers the site of Spitharopoussi on the western side of the laureotic cuesta upstream of the Soureza Valley, well known for

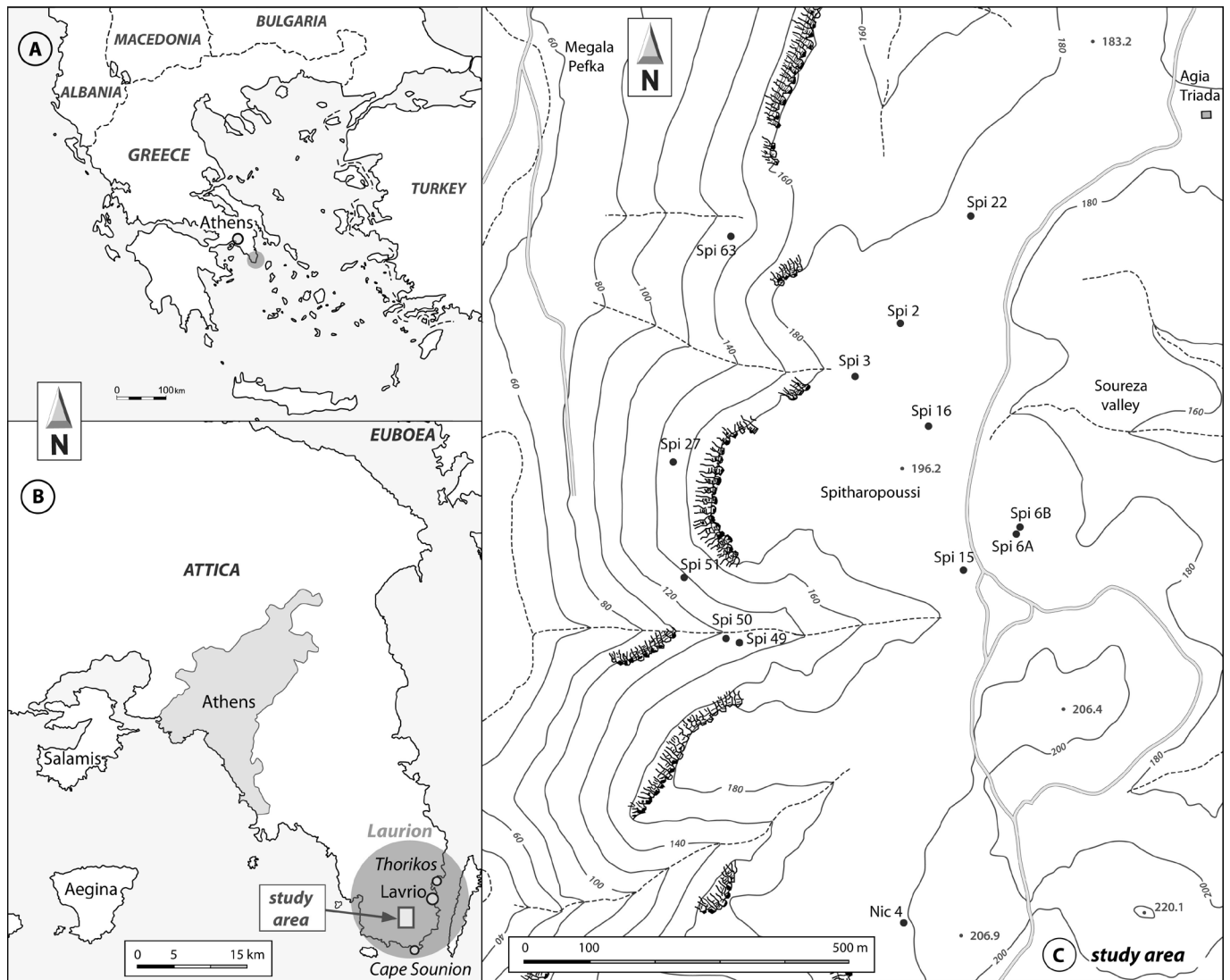


Figure 1: Contour map of the area explored showing the named shafts involved in this study. Spi is the abbreviation for Spitharopoussi.

its ancient hydraulic complex including cisterns and ore washeries (Fig 1). Mining remains, shafts, drifts and stopes are located at many levels within the limestone and calcschist strata: on the plateau, on the slope, and at the bottom of the cuesta, which makes it possible to appreciate different aspects of these works. The area is delimited to the west by the Legrena valley, and to the north and the south by two dry valleys which notch the plateau. The deepest shafts are perfectly vertical and located on the top of the plateau; their depths varying between 25m and 105m, and all of them have now been systematically explored and studied.

Considerable progress has been made over several years in the exploration and study of these ancient mines. This has been made possible by the adaptation of sophisticated alpine caving techniques to the study of underground mines. Thus, caving methods used are those employed for large vertical shafts, such as abseiling with static

and technical ropes, and asymmetrical climbing systems (Fig 2).



Figure 2: Exploration of Shaft Spi 15 at Spitharopoussi, Laurion.



Figure 3: The self-contained breathing apparatus (SCBA) used when exploring the Laurion mines (Fenzy ARI).

An oxygen ( $O_2$ ) detector was used in order to register possible hazards. Exploration of deep vertical shafts sometimes required use of self-contained breathing apparatus (SCBA). This apparatus was successfully tested in 2003, making it possible to reach the first major networks, and involved co-operation between CNRS and Fenzy establishments (Fig 3). Several shafts and galleries have been explored, confirming the importance of these mines and providing precise details about geology and deep ore mineral deposits.

### Shaft ventilation systems

Investigation of the deep vertical shafts of Laurion has been carried out during two-week exploration campaigns annually since 2002. As shown so far, the most common mine working unit in the Spitharopoussi area consists of a network of horizontal galleries emanating from a single vertical shaft. Since they were abandoned the bottom of some of these shafts has been in-filled by waste and it is therefore not possible to know at present if there were connections with other shafts. The situation is far from being fully understood and the special case of a single vertical shaft has not yet received careful attention. This case is dramatically different from more classical mine workings where mechanical means such as fans were in use during the sinking phase; afterwards ventilation was generated by connections at depth between at least two shafts (Gruner 1922; Castelain and Stalinsky 1934).

The atmosphere of a mine is different from that above ground because of its physical state (temperature, pressure, relative humidity acting on air density and viscosity), its gas composition and the dust in suspension. If it is not constantly renewed by a flow of fresh air, the miners' survival cannot be ensured. Thus, ventilation

must provide an underground atmosphere which contains oxygen at levels essential for life. Below 14%  $O_2$  by volume, the air becomes unsuitable for human life because lack of oxygen results in asphyxiation. Oxygen is also necessary for the combustion of oil in lamps which become weak and die down gradually as soon as the air contains less than 16-17% of  $O_2$  (against 21% for the normal case). The reduction of oxygen level is affected by several factors: emission of carbon dioxide due to miners' breathing and combustion of oil lamps, also oxidation of timber structures and decomposition of pyritic minerals. Fresh air injection, at least in equivalent proportion, is thus essential to compensate for losses. The mining engineer Haton de la Goupillière calculated the following effect of combustion: according to him a lamp burns 15-20 grams of oil in one hour, consuming 25-30 litres of oxygen and producing 17-20 grams of carbon dioxide (Haton de la Goupillière and Bès de Berc 1941). Such consumption is similar to that of a man at rest. Reduction of oxygen levels in the mine air is generally accompanied by the appearance of unfamiliar and poisonous gases produced by reactions using oxygen, particularly carbon dioxide ( $CO_2$ ) and carbon monoxide, and possibly also sulphur dioxide and hydrogen sulphide. Thus to allow respiration, poisonous gases have to be diluted and a minimum amount of 12 cubic metres per hour of fresh air is required per miner; the consumption of an oil lamp is included (Fabre 1862). Note that if one considers shafts of roughly  $2m^2$  cross section, a very low air speed such as 5 millimetres per second corresponds to 36 cubic metres per hour, just enough for the breathing of three miners.

In the case of natural convection, the movement of air is driven by small differences in density. These differences can be caused by variations in temperature, pressure, humidity or some changes in air composition like the amount of  $CO_2$ . In what follows, we took as a base for comparison the relative change of air density  $\rho$  caused by an isobaric decrease of  $1^\circ C$  in temperature around  $20^\circ C$ . So  $\Delta\rho/\rho = A = 3.4112 \times 10^{-3}$  (0.341%) if  $T$  varies from  $20.5^\circ C$  to  $19.5^\circ C$  (conversely  $\Delta\rho/\rho = -A$  if  $T$  rises from  $19.5^\circ C$  to  $20.5^\circ C$ ). Table 1, inspired by Jones (1925), summarises the effect of various possible causes of density variation, with respect to standard dry air composition taken at  $20^\circ C$  and at the standard atmospheric pressure. In addition, the mixing of two quantities of air at two different temperatures would be delayed by differences in viscosity. Air diffusion factor involves the ratio of dynamic viscosity to density which gives an increase of 0.61% for an increase of  $1^\circ C$  in air temperature difference (under the previous conditions).

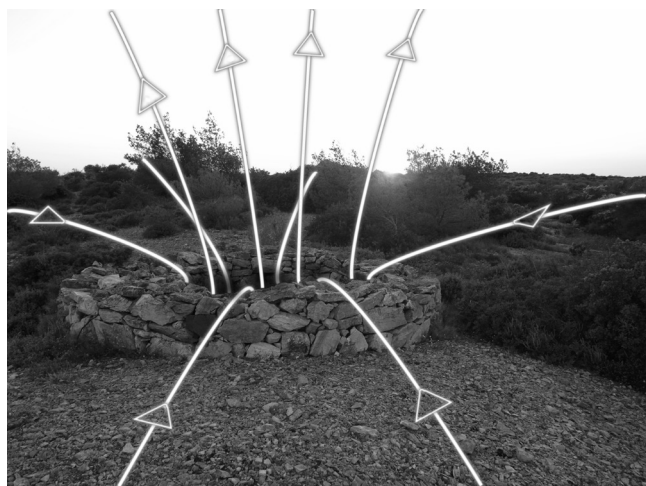


Figure 4: Natural air convection pattern for the winter case. Superimposed lines and arrows indicate air flow directions.



Figure 5: Shaft partitioned into two ducts with a wooden wall. The wooden wall has been schematically superimposed on the picture and arrows indicate air flow.

Deep vertical shafts highlight the question of how to find technical solutions for circulation of sufficient air during both the sinking of the shaft and the mining of ore. Our study is consequently structured as follows: We first examined the case of a single vertical shaft without any special means to circulate the air, as it would be at the beginning of its sinking, our purpose being to establish whether or not technical means were required to provide the necessary volume of air for breathing below a certain depth, whatever the season. Secondly, we studied what appear to have been the two most common solutions used by the ancient miners at Laurion – a shaft partitioned into two ducts by means of a wooden wall, and also a twisted shaft. It should then be possible to interpret many of the variations between the cases already explored, such as shafts with parallel air ducts. Finally, as work in progress, we report what sorts of measurements are currently being recorded on site in order to perform further studies using physical models.

### Single vertical shafts without any ventilation system

During the initial phase of sinking it is reasonable to assume that shafts were devoid of any artefacts for the circulation of air, so we first examined this hypothesis. Air renewal was driven by free convection, *ie* differences in air density which relate to differences in temperature, humidity and altitude (Table 1). Temperature differences between atmospheric air and shaft walls exist because of the thermal inertia of the ground, the poor thermal conductivity of the air and the heat flux coming from depth. In the case studied air speed is assumed to be very low, some millimetres per second, thus the first factor is dominant and below a certain depth it is currently agreed that ground temperature reaches a roughly constant value, the mean temperature of the place, whatever the season (Choppy 1984; Lismonde 2002). Two situations can generally be distinguished: when atmospheric air is colder than the ground (the ‘winter case’) and conversely

Table 1: Relative importance of possible causes of difference in air density, relative to the effect of a 1°C temperature decrease.

Various causes of air density variation	$\Delta\rho/\rho$
Isobaric temperature increase: + 1°C	- A
Isobaric temperature decrease: - 1°C	+ A
Isothermal pressure increase: + 346Pa (34.6mm of water)	+ A
Addition of 5.66g of water-vapour per kg of dry air (0.566 wt%) Note that relative humidity increases from 0 to 39%	- A
Replacement of 13.8g of oxygen by 13.8g of carbon dioxide per kg of dry air (1.38% by weight)	+ A
Replacement of 8.19l of oxygen by 8.19l of carbon dioxide per m <sup>3</sup> of dry air (0.819% by volume)	+ A

Reference: dry air at  $T_0 = 20^\circ\text{C}$ ;  $p_0 = 101325\text{Pa}$ ;  $A = 3.4112 \times 10^{-3}$  (0.341%)

when it is warmer than the ground (the ‘summer case’).

In winter the atmospheric air is colder than the shaft walls and flows downwards in the manner of – but much slower than – a waterfall. The air already in the shaft is warmer, due to its longer thermal exchange with the walls. Warmer air concentrates towards the centre of the shaft cross section and moves upwards. As a result an irregular convective flow drags fresh air down from the surface to the base of the shaft (Fig 4). This description is given in accordance with measurements of air temperature and humidity which were made in the shaft *Spi 16* on 4 April 2010. Air filling the shaft was much colder and dryer in the evening than in the afternoon. One concludes that it was not the same air, because if the hot and wet air of the afternoon were cooled down in the evening it could not become dryer. Thus the afternoon air had really been replaced by evening. Viscosity difference with respect to temperature difference tends also to delay the mixing of the cold fresh air with the air already filling the shaft. However, the downward flow rate of fresh air decreases with depth owing to a decrease in temperature difference due to mixing. During our explorations we directly experienced that respiration generally remained possible to depths of 70m and beyond (March–April 2002 to 2011, *ie* in the winter case), but exceptions do exist. For instance, on 19 April 2005 it was possible to breathe at the bottom of shaft *Spi 22* at a depth of 73m, whilst the next day in the same shaft it was impossible to descend below 35m without a self-contained breathing apparatus (SCBA) as the oxygen percentage having fallen to less than 16% (a possible explanation could be an in-depth release of carbon dioxide which had taken the place of oxygen after a fall in atmospheric pressure).

In the summer case, air filling the shaft reaches the wall temperature and thus remains colder and heavier than atmospheric air above – it reaches a state of equilibrium with the air at rest. The shaft acts as a cold air trap as known from many examples in karst caves (Choppy 1984; Lismonde 2002). However, natural air convection could still occur but would remain extremely weak. It would only be driven by small differences compared with the previous conditions, such as a decrease of atmospheric air temperature during the night or even an increase of wall temperature with depth, although this is not generally the case in summer for the first tens of metres depth. Heat released by miners at work and by oil lamps can also generate air convection. By comparison with the winter case, conditions are clearly worse for respiration in the shafts during summer days. Despite a lack of precise data, such a qualitative argument suggests that summer work was not possible without the help

of additional means specifically dedicated to deliver a sufficient amount of fresh air.

Some authors have calculated that between 12 and 18 months was the time needed by ancient miners to sink a shaft of 100m depth (Ardaillon 1897; Conophagos 1980). This period was calculated for conditions of sustained work by teams of two or three miners, taking turns and working night and day from spring to winter. The hypothesis of a stoppage during the summer case, *ie* for about half of the time, was never considered by the authors and this omission does not seem realistic; it would also apply during the period of ore production. It is therefore probable that ventilation systems had to be used during antiquity in the Laurion area, in order to ensure a sufficient inflow of fresh air all year round.

### Shafts with an internal partition

Investigations in Laurion close to the Soureza valley revealed the presence on the shaft walls of regularly dug notches. This leads to the hypothesis of an internal casing, partitioning the shaft into two ducts of unequal cross-section by a wooden wall as shown in Figure 5. The narrower compartment, approximately 0.4m by 1.3m, was used by the miners to climb up and down, and the broader, square-shaped compartment, approximately 1.3m by 1.3m, to raise spoil and ore (Fig 6; Morin and Photiades 2005). This return airway system can be used to cause a forced draught. Actually a draught is established as soon as any asymmetry develops between the two ducts. Several kinds of asymmetry could have been used in order to circulate the air, such as differences in pressure, temperature or humidity, or even generation of heat or movements, as will be detailed below. The generation of a draught may also have been achieved by means of a wind deflector, as in the case where the wooden shaft lining was used as a forced drain (Gruner 1922). The existence of dominant winds on the Laurion plateau could support such a ventilation system, and it should be noted that in the 16th century Agricola called such systems *pneumatica* or *spiritalis* by reference to a Greek or Latin origin (France-Lanord 1992, 163; Figs 7 and 8). These wooden deflectors have been depicted in some 16th-century paintings such as the well-known Hans Hesse altarpiece (1521) in Annaberg church (Erzgebirge) and at Kutna-Hora (Fig 9), which are close to mining shafts.

The procedure was the same as in the case of two separate shafts connected at depth as described in classical treatises (Castelain and Stalinsky 1934). As soon as an asymmetrical temperature develops between the two air columns, air pressure becomes higher at the bottom of

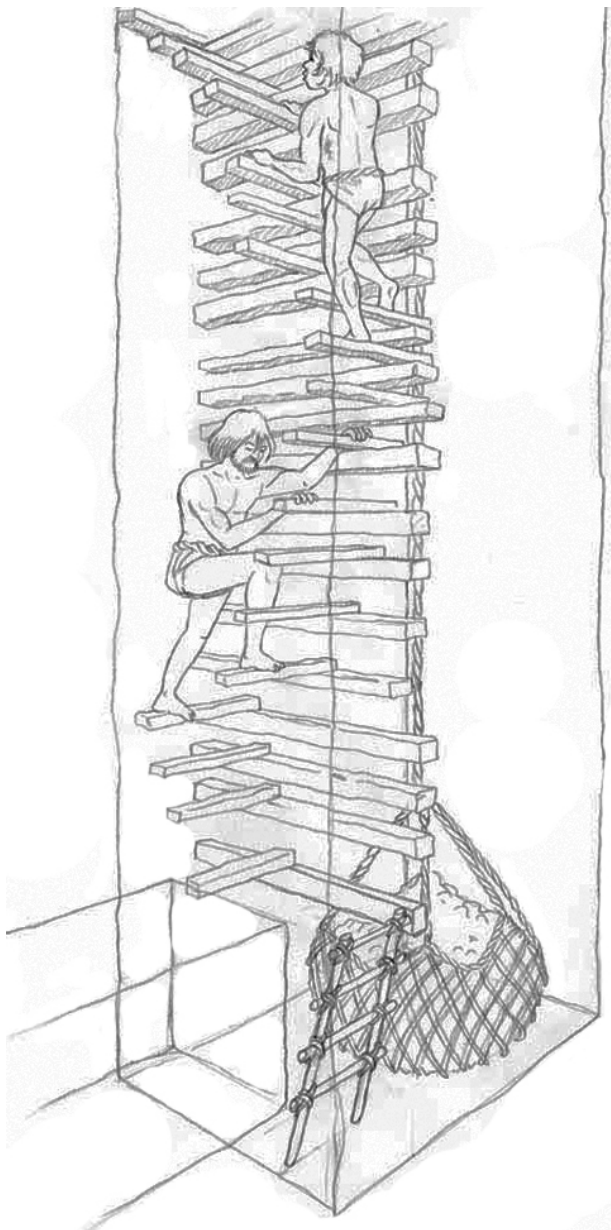


Figure 6: Reconstruction of a partitioned shaft from observation.

the cold duct than at the bottom of the warm duct and this difference generates a draught. In the case of a wind deflector, conversion of kinetic wind energy increases pressure at the top of the downcast duct, with the same effect. Note that extremely weak air speed was able to sustain miners' breathing. For instance, two miners sinking a shaft needed 24 cubic metres per hour of fresh air for respiration which corresponds to an air speed of only 13 millimetres per second for the draught in the narrower compartment (0.4m by 1.3m).

**Twisted shafts and other shapes**

Another common shape found in the Spitharopoussi area is a vertical shaft with a rectangular cross section which is more or less regularly twisted from top to bottom (Fig 10). For instance for the shaft *Spi 16* clockwise



Figure 7: Wind deflector and chimney (after Agricola; France-Lanord 1992, 165).



Figure 8: Other forms of wind deflectors; note that these do not allow extraction (after Agricola; France-Lanord 1992, 164).

rotation of the cross section reaches 40° after 45m depth which is then followed by a counter-clockwise rotation of 15° down to the 65m depth. Ardaillon (1897) and Conophagos (1980) suggested that the twist occurs, with gaps at 10m intervals, to facilitate fixing of a spiral staircase down the walls, clearing the way to bring out spoil and ore through the centre of the section. To date, investigations do not support their hypothesis and further studies are needed to find clues to the design of the ventilation system and to understand how twisted shafts functioned.

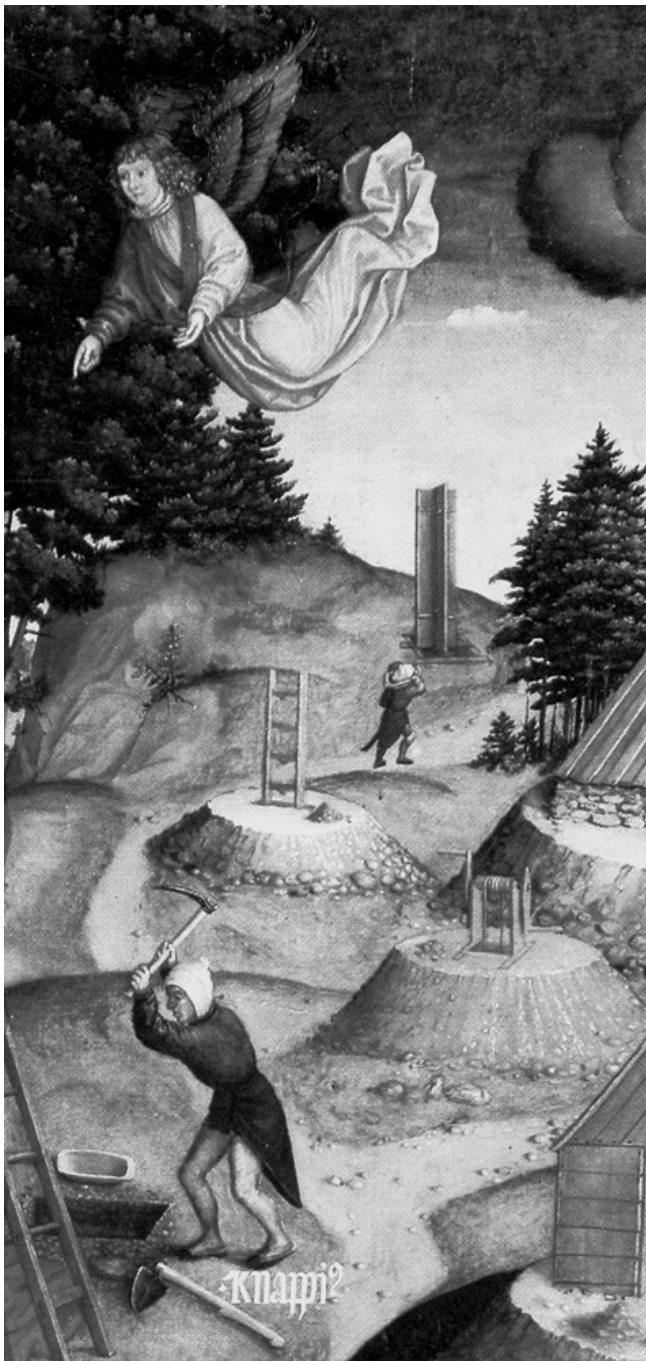


Figure 9: Wooden wind deflector towers close to mining shafts. Kutna-Hora frescos, 15th-16th century.

Taking into account the long period of time during which the Laurion mines were active, from at least the 6th to the 2nd centuries BC, it is not surprising that different solutions would have been implemented successively or simultaneously in order to sink deep vertical shafts. These variations of shape were noted long ago by previous on-site investigations; Conophagos (1980), for instance, distinguished no less than seven different shaft shapes.



Figure 10. Typical twisted shaft Nic 4, called Persephone, in the Spitharopoussi area. Note that the twist occurs either regularly or in sections from top to bottom.

### Shafts with parallel air ducts

The most original and sophisticated shaft type is that with parallel air ducts, which may or may not reach the surface. An example with parallel air ducts rising to the surface is shaft *Spi* 6 (Fig 11). Parallel air ducts not reaching the surface also exist, as in shaft *Spi* 2 (Figs 12 and 13). Further measurements of air and wall temperatures are needed to establish what conditions were able to generate air circulation when these shafts were in use in antiquity.

### Mechanically generated convection

Circulating the air without fans suggests the use of natural or mixed convection. Because inflow has to be balanced by an equal outflow, the question arises as to how to generate such convective air flow. Some possible solutions that could have been used by the miners in antiquity are:

- The use of heat sources and temperature differences: Certain shafts probably used compartmented ducts with a return airway system to cause a forced draught by means of a brazier at depth – the so called ‘toque-feu’ system (Haton de la Goupillière and Bès de Berc 1941). The heat produced at the bottom of the shaft caused the hot and rarefied air in this duct to rise, drawing air down the other duct to replace it. Such a system needs continual careful operation. The installation of a ventilating fire on the surface makes it possible to obtain much more regular results. Its use was widespread in England in the middle of the 19th century (*ibid*). Recent investigations have proved the use of such an installation at the top of some of the Laurion shafts (*Spi* 27). In this particular structure an oblique gallery was worked which joined the shaft a few metres down. This structure is

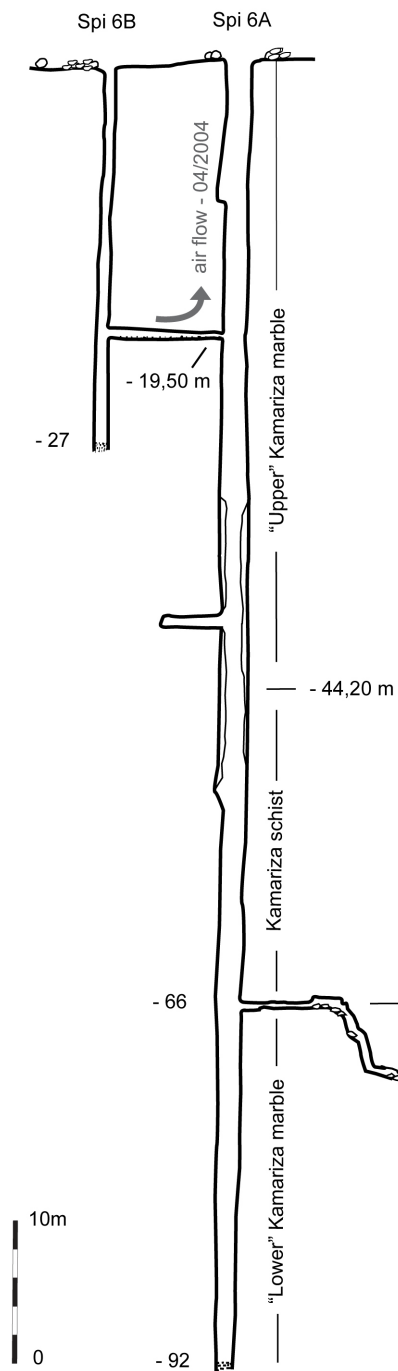


Figure 11: Shaft Spi 6, an example with a parallel air duct rising to the surface. The arrow indicates air flow in the winter case, April 2004.

quite similar to some 16th-17th century features. A brazier lowered a short distance down the shaft was probably set up at this entrance. Such a brazier with a connexion to draw air from the shaft is a plausible hypothesis. In addition, it is worth noting that the heat produced by oil lamps and miners at work can contribute to ventilation, for example two miners at work would generate a heat flux roughly equivalent to a 1000 watt heater.

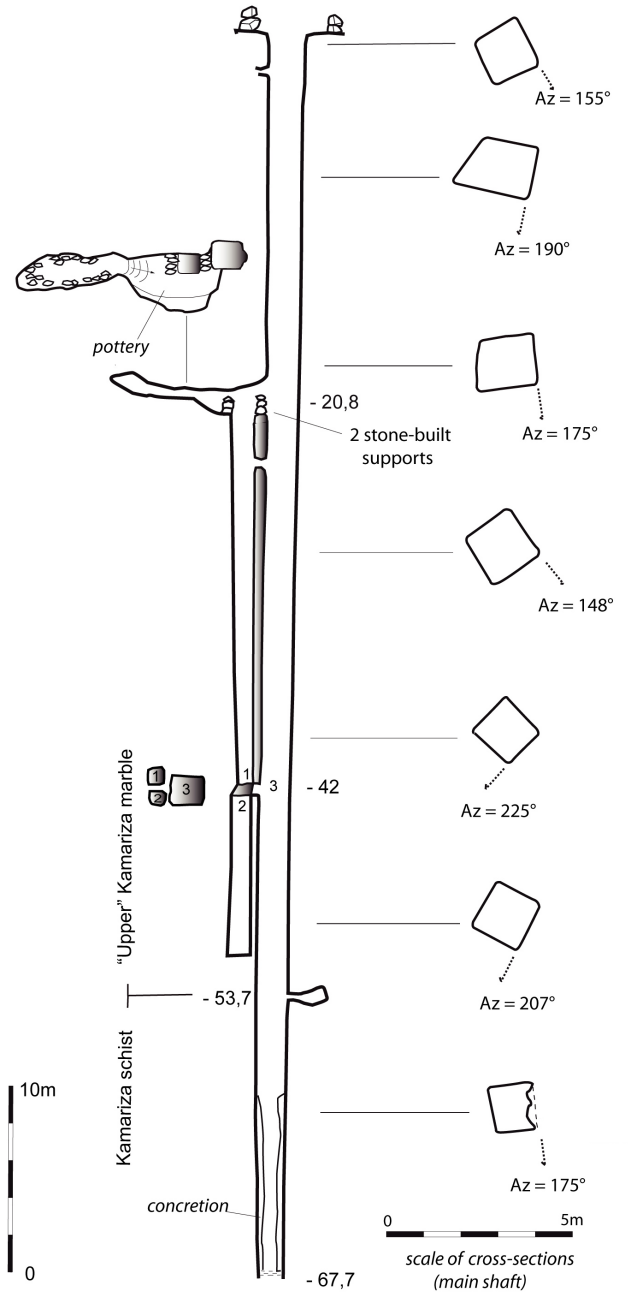


Figure 12: Shaft Spi 2, an example with parallel air ducts not rising to the surface.

- The use of artificial rain falling down a shaft to generate a backward air flow constitutes an effective means of circulating the air, and injection of water down shafts into the mine was common. Artificial rainfall was in use during the 19th century as a safety mechanism against ventilators shutting down (Gruner 1922). Observations carried out on three Laurion shafts (*Spi 2, 3 and 51*) have given indications of the presence of a chute constructed close to the surface. However, there is no indication of the presence of a drainage system at depth, although it seems that the water could drain naturally through the rocks below.



Figure 13: Shaft Spi 2, exploration of the air duct.

- The use of mechanical movements to circulate the air, for example by waving linen, was reported by Pliny the Elder in his *Natural History* (quoted by Ardaillon 1897). Lifting of ore by means of a basket and rope could also have generated air movements in vertical winding shafts.
- The use of connected shafts: In the schist layers, two shafts (*Spi 63* and *49/50*) are well connected by ventilation passages that create continuous air flow.

### A work in progress: measurements now being recorded

In order to characterise the dynamics of the ground temperature, and the other sources of energy, a one-year campaign has been started to measure parameters which control air circulation in the shafts. In particular these include the temperature of shaft walls, air temperature in a cross section, and air relative humidity. These measurements are all taken in shaft *Spi 16* at nine different depths between 2m and 65m, and recorded each 32 minutes over a whole year, to take into account summer/winter and day/night cycles, with an estimated temperature accuracy of  $\pm 0.25^{\circ}\text{C}$ . These measurements at depth are complemented by the recording of the ground temperature over the same period. Air velocity, which appears to be the cornerstone of this study, cannot so easily be directly measured as it requires sensitive instrumentation such as hot-wire gauges able to measure very low velocities, *ie* some millimetres per second (Florsch 1998). A more practical choice is to predict velocities by physical models based on the knowledge of the temperatures and humidity recorded.

After collection of this data, it will become possible to develop analytical and numerical models in a logical order: first for a single shaft without any means of

ventilation, then for a shaft which was partitioned by a wooden wall (and also a twisted shaft) and finally for other odd-shaped cases like shafts with parallel air ducts. Thus it is hoped to reach more precise and detailed conclusions in future.

### Conclusion

Recent geological investigations and explorations of ancient silver mines in the Laurion area prove that sinking deep vertical shafts in the marble, which is a very strong stone, was remarkably well executed by the miners in antiquity. These shafts are not only extraction features but brought real technological assistance as ventilation ducts. Therefore, the miners must have controlled air circulation and perfected mechanisms well adapted to the geological and geomorphological conditions. If ventilation was too weak while working in vertical shafts or horizontal roadways, there is no doubt that as soon as difficulties were encountered the miners refreshed the air at considerable depths. There is a lack of knowledge nowadays about air circulation in twisted shafts and shafts with parallel air ducts, especially during the summer season. Fieldwork and laboratory investigations should help throw new light on these ancient mining technologies.

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