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# Flat-bedded washeries at Laurion (Greece): A buddling model.

## A comparative study between archival and field evidence

***ABSTRACT:*** *The research carried out on Laurion, and particularly on mining and the importance of the amounts extracted, raises the question of ore dressing and therefore the process involved. This is the presence of flat-washing dressing floors, flanked by tanks and accompanied by grinding workshops, near the extraction areas, the function and the role and skill of the workers in such devices. The washing facilities, used by the miners of the Laurion, have originated numerous interpretations and controversies. The aim of this paper is to update the various hypotheses and to compare the archaeological evidence with the devices implemented by the miners during the 18th and 19th centuries. In their reports, scholars at the Paris School of Mines meticulously described washing installations, particularly the buddles. A buddle is an elementary device used to separate ore from gangue by means of a water stream. The oldest and simplest constructions were an oblong, shallow pit dug into the ground, or a shallow, slightly inclined wooden channel. The process is simple: the mixture of ore and gangue was placed and agitated in a stream of water; the lighter particles were carried away, leaving behind them the much heavier galena. The typical length of a square buddle was around two meters, while the floors at Laurion are shorter. Research carried out on 18th/19th century washing technologies of large-scale washing of secondary iron ores in eastern France have led us to make comparisons with the installations at Laurion. The model proposed here is based on both field observations and iconographic and documentary sources. The washing process is somewhat explicit as soon as the primary product has undergone a first grinding treatment. The precise way to operate the devices becomes obvious once one immerses in such descriptions of the users in old mining journals. The best example is a 18th century mining treatise written by Franz Ludwig von Cancrin, a prominent metallurgist, mineralogist and miner from Hesse, Germany, which proves to be perfectly consistent with the lead-silver ore process in use at Laurion.*

**KEYWORDS**: LAURION, GREECE, ORE DRESSING, SILVER, WASHERIES, BUDDLE, 18TH/19TH CENTURY, DEVICES

## Introduction

The research carried out on lead-silver mining at Laurion and the amount of the volumes extracted naturally raises the question of how to dress so much quantities of ore, and, consequently, of the whole process involved. The presence of dressing floors flanked by tanks and accompanied by grinding workshops close to the mines also raises the question of the system implemented; how did these devices work? What was the workers' role? What was the functionality of the structures themselves?

More generally, the washing devices used by ancient miners on Laurion have promted many controversies. This contribution aims to present different positions and to suggest some interpretation based on archaeological evidence and particularly on structures widely used and described since the 16th century and mainly during the 19th century by mining engineers and mining engineering students of the Paris School of Mines in their *Journaux de voyages travel (reports)*.

## Lead-silver ore dressing at Laurion: Archaeological evidence

### Lead-silver: A sophisticated process

The whole silver process starts underground where the ore, after being mined, is broken down and sorted. Such working sites are still perfectly visible in the Acropolis mine of Thorikos going back to prehistoric times (Fig. 1). The site is a typical multiphase mining working site with

*Fig. 1: Breaking/crushing remains in the Acropolis Mine (Mine n°6) at Thorikos (Laurion). The photo shows a waste dump made up of carefully broken/crushed rocks in a worksite inside a gallery. The work was carried out directly on the floor or on large rocks visible on the photo (photo: D. Morin).*

waste deposits and, in some parts, several well preserved breaking and crushing places.

Underground, miners organized small working areas in order to crush the ore. Rocks were crushed right on the floor or using crushing tables, in a distant area, in order to be able to sort them as well as and to estimate the ore concentration.

Some galleries of the Early Helladic (EH II) mining works at Thorikos, in which breaking/crushing places are preserved are full of waste deposits. In some other parts, miners have broken down the rock slabs they have removed first.

A never omitted general step of the ore dressing is to operate as much as possible by hand sorting and to avoid as far as possible the formation of very fine particles

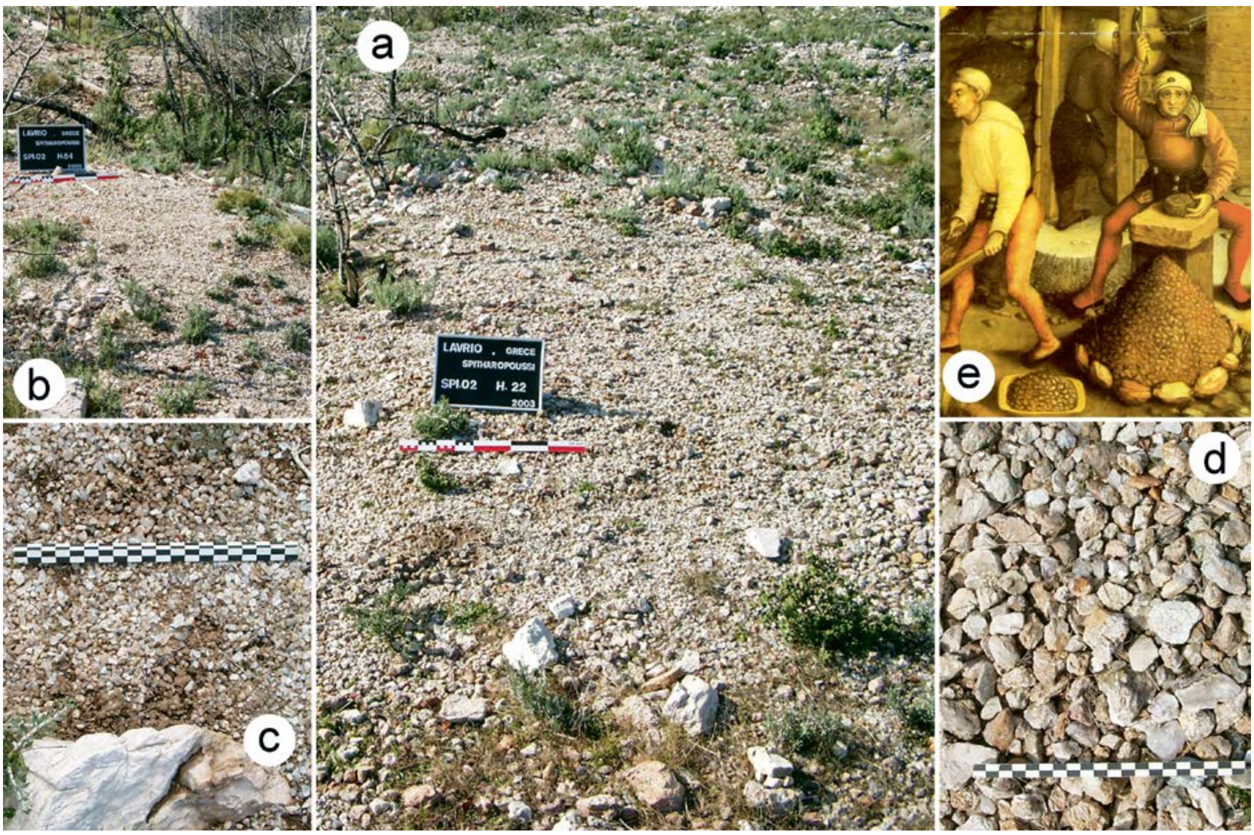



*Fig. 2: Laurion mining district. Spitharopoussi plateau. (a) Ore-dressing workshops remains in situ near the collar of a shaft. In this context, different ore processing areas at the mine exit are clearly visible (b, c, d). (Photos: H. Morin-Hamon).*

(slime). The treatment of slime is difficult because – even if this is a very fine-grained material – there can be excessive differences of the grain sizes. And such differences may have influence on the density and may affect the separation of ore from gangue.

On surface, one can still observe many remains of sorting, crushing and grinding activities. Like in the Spitharopoussi plateau area (Fig. 2), evidence of small workshops are visible in the entire Laurion area. Around the deepest shafts, crushing activity is often identified along with accumulation of large sedimentary deposits and circular features. Working places like that were probably organized in a similar way as shown on a picture from the Annaberger Bergaltar painted 1521 by Hans Hesse (Fig. 2b).

Small heaps of stratified sediments show an organization of space and the different crushing/chipping and sorting stages. These remains resemble the 16th century painting of the Annaberger Bergaltar (Fig. 2e). Three main panels present a mining landscape showing both the extraction sites and different workshops. Fig. 2e shows a miner crushing the ore on a crushing stone. His activity is materialized on the ground by a stone entourage inside which the sediments are piled up.

When they left the mine, larger pieces of ore were probably sent to the cobbers: these were workers who broke them into smaller pieces, taking care to reject immediately the sterile parts of the gangue that do not contain metal.

Grinding was the last stage before washing. The essential condition for a density classification by this process is that only particles of approximately equal volume are present in a water stream. It therefore requires a prior classification by size, hence the need for meticulous preliminary grinding like on grinding table or using a hopper quern (Olynthus mill). Mechanical grinding on a round table, the so-called *helicoidal washeries* is a part of the process enlighten at Laurion (Nomicos, 2017).

## Flat-bedded washeries at Laurion (5th – 4th century BC): Evidence and interpretation

The washing devices used on Laurion by the miners, during the 5th and the 4th century BC have caused a lot of discussion, even recently (Fig. 3). We present below the main hypotheses put forward by various authors who have written on this subject.

### Cordella 1869

The mining engineer A. Cordella was one of the first authors who described the flat-bedded washeries, the

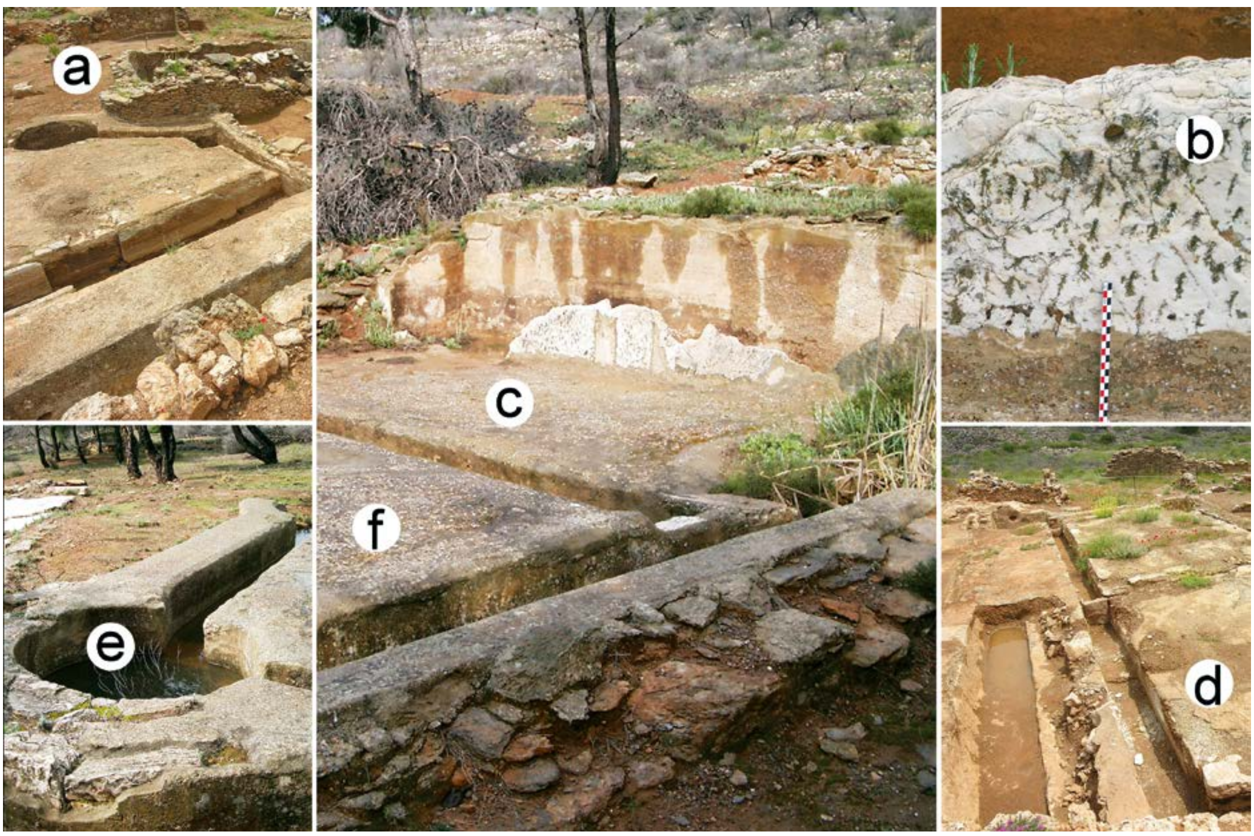



*Fig. 3: Laurion mining district, Souresa valley. Flat-bedded washery. Details of the different building elements: – a. water tank; – b. marble wall with outlets; – c. washing floor; – d. overflows; – e. settling basins; – f. drying floor. (Photos: H. Morin-Hamon).*

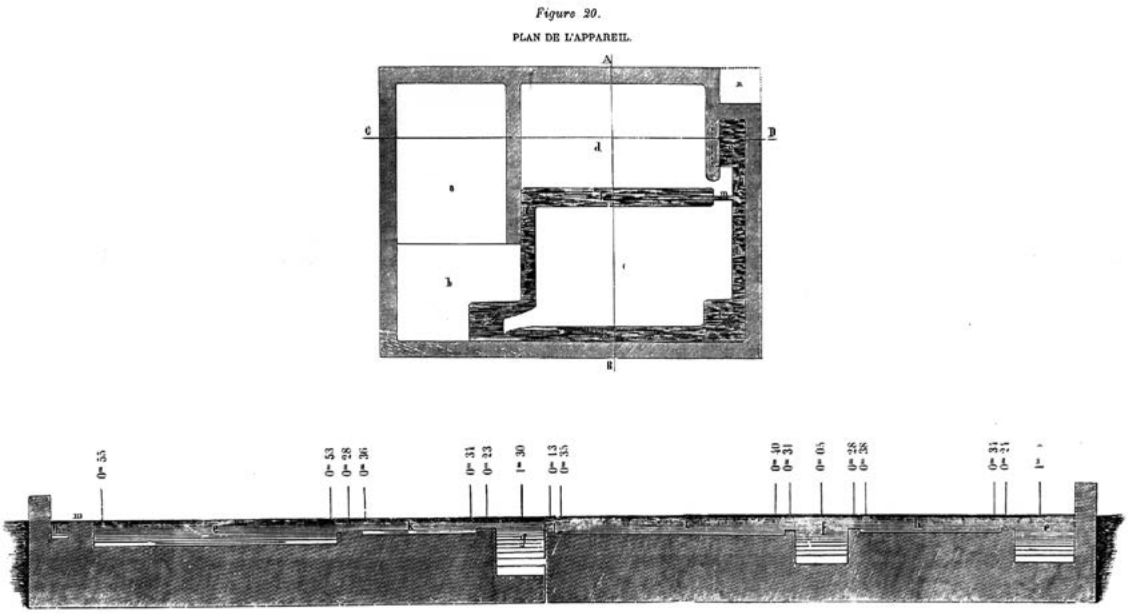



*Fig. 4: Laurion. Flat bedded washery according to Cordella (1869, p.95 fig.20 plan, p.97 fig.23 section).*

most characteristic ore-processing structure at Laurion. His description was based on the remains of a washery discovered in Camareza when ancient slags were removed (Cordella, 1869). His testimony is particularly accurate. One example of his sketches is drawn in Fig. 4. He wrote:

> *"The heavy and rich materials were deposited there, while the water carried towards the "l" end of the apparatus the lighter and less rich materials which were deposited, according to their order of density, in the various basins and channels serving as a labyrinth. The circulation of the water stopped when its level reached the highest point "m", so that the current was established in the direction of the arrow "X", as a result of the difference in levels between the extreme points; and this difference occurred either by removing the ores deposited in the apparatus, or by drawing the water from the end of the channel "l", to pour it into the initial basin "e". Thus, the same water could be used to wash an indefinite amount of ore, or at least a considerable amount of it. The total square area of the ditches and channels is 11 square metres and the amount of water needed to fill the device to its peak is 7 cubic metres".*

## Phillips 1884

J.A. Phillips' description suggested corresponds to the operating hypothesis of a running water hydro-classifier. Phillips (1884) takes over Cordella's data. He compares the system to a vast sluice system with a series of tubs.

> *"The dressing-floors of the mine are always arranged as near as possible to the mouths of the principal shafts or main entrance; the ore being conveyed to them with buckets, and they are always provided with an adequate supply of water. Water was scarce at Laurium, and large reservoirs were built for storing a sufficient supply. The washing apparatus was so planned as to admit of the water being used over again continuously, and consisted of a large sluice, some seventy feet long (21 m long average), provided in its length, at intervals, with small reservoirs or wells. Instead of being straight, this sluice formed several angles in such a way that its head and lower end were in close proximity, so that ore, placed at its head, could be washed by water baled or otherwise raised from the well at its lower extremity. In this way a current was established, and the ore washed by a stream of water constantly returning to the wells to be again used".*

## Negris 1897

In 1897, in the *Annales des Mines*, Ph. Negris, completed Cordella's argument and stated that the ancient miners used to spread the ground ore directly over the space where the water fall down from the outlets (b in Fig. 5). These are made at regular intervals through the walls of the catchment basins. The rich ore was directly recovered from this site, while the grains with lower grade mineral content were dragged by water into the channel set up for this purpose.

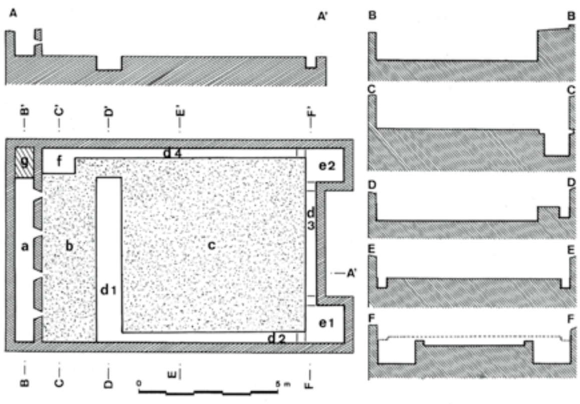



Fig. 5: Laurion. Flat-bedded washery according to Negris (1881, pl. I, fig. 3-9, plan).

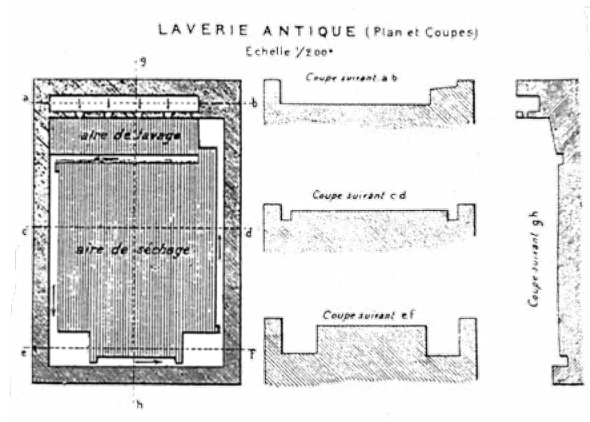



Fig. 6: Laurion. Flat-bedded washery according to Ardaillon (1897, p.63, fig. 20, plan).

This hypothesis was taken up by Ardaillon (1897). In the light of the descriptions made by the mining engineers and that of many mine engineering students quoted in the *Annales des Mines*, it appears that the process thus described corresponds to the classic mechanism of a washing operation using materials that had previously been finely crushed and ground.

## Ardaillon 1897

E. Ardaillon goes further in detailing the process. He is even more precise: he meticulously describes the function of each space (Fig. 6). On the first washing operation he wrote:

> *"The sifted ore is spread in thin layers on the sloping area of the washery, which was used as a washing table. The tank openings were unclogged, and the operation started. What was going on? The plots of ore that are too light to withstand the flowing water, are dragged away and will flow into the canal. On the contrary, the heavy plots remain on the table, and it is enough for a worker equipped with a rake to shake them and push them under the water jets, so that they are soon isolated from all those who do not have the same weight. Thus, most of the heaviest fragments, the lead ore, will remain on the washing table. The various parts of the canal, especially if it is equipped with dams and overflow devices that only allow surface water to escape, and the various basins form a series of settling tanks, where lighter and less and less rich materials are deposited, depending on their distance from the starting point".*

If the Laurion washery model remains the same, Ardaillon notes, with discernment, the presence of variables within these systems. According to him, they were used to process minerals of different sizes: large, small and fine. The height of the waterfall above the inclined table, the shape of the exhaust outlets, the slope of the channels, the height of the dams, the depth of the basins, are all elements that can vary according to the case. In a word, washeries were never isolated but operated in series.

## Mussche 1963

In his report on the excavation of several flat-bedded washeries in Thorikos, H.F. Mussche (1963) going back on the initial hypotheses first describes clearly the archaeological evidence:

> *"A flat-bedded washery consists of a tank, a sloping area, and a circuit of canals and settling basins. The elevated tank above the entire installation allows water to escape through small conical holes. The water then splashes onto the inclined area, where the ground ore is spread and sieved. The heavy plots remain on the washing table. Rich moor plots that do not contain lead ore are entrained by water because of their lighter weight and fall into channels that extend around a central area as they pass, with overflows that only allow surface water to flow through two settling basins. The slope is designed so that all the water flows into a final basin. The plots, which are increasingly light, settle as they move away from the first canal. Finally, the water completely freed of these impurities is drawn from the last basin and returned to a slope that brings it back into the tank. Then, the ore is dried on the area in the middle of the washery" .*

## Conophagos 1970

In 1970, in a communication to the Academy of Athens, the mining engineer Conophagos put forward the hypo-

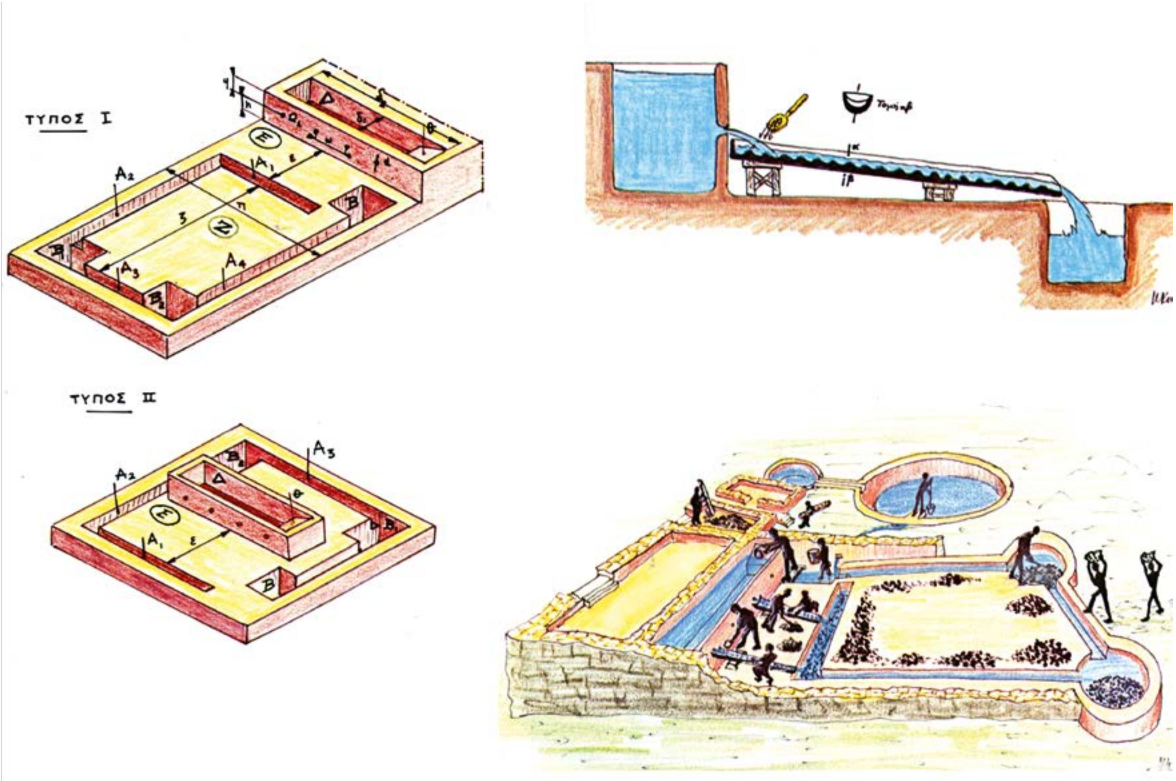



*Fig. 7: Laurion. Left: flat-bedded washeries according to Conophagos (1980, p.340 fig.246). Top right: detail of the process with wooden sluices (Conophagos, 1980, p.236, fig.10-19). Bottom right: Reconstruction of a washery in process (Conophagos, 1980, p.237 fig.10-20).*

thesis of wooden sluices inclined and arranged under the outlets. The author opposes his theory to that of the previous authors based on three arguments:

- the experiments showed that a direct washing in the first plane where the water falling from the outlets was not satisfactory. He notes
- the absence of wear on the ground on the outlets, and
- the absence of obstacles between the washing area and the recycling basins.

Conophagos considers before all that the quadrangular circuit, was a system for settling and recycling the water (Fig. 7). The washers could recover the richest plynite – waste rock – in the first settling channel.

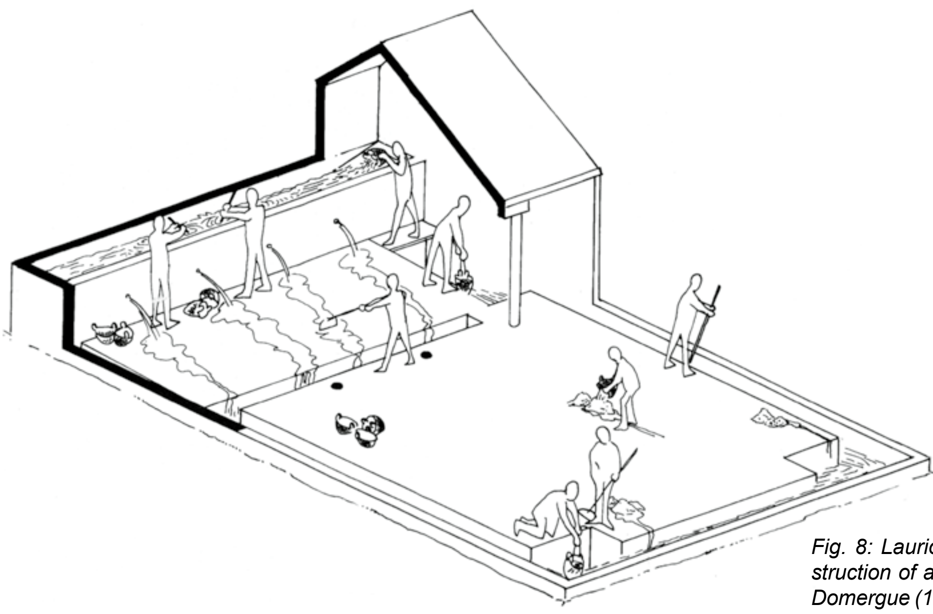


*Fig. 8: Laurion. Flat-bedded washery. Reconstruction of a washery in process according to Domergue (1998, p.41 fig. 13, drawing C. Rico).*

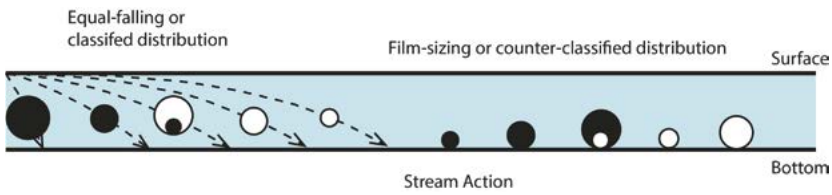



*Fig. 9: Stream action diagram of equal-falling or classified distribution. The dark circles represent the ore and the lighter circles, the gangue. From Truscott (1923, p.257, fig. 166)..*

**Domergue 2008**

According to C. Domergue, based on archaeological evidence in the Coto Fortuna silver-lead mine (Mazarrón, Murcia, Spain), most of the concentration would take place in the reservoir itself, i.e. upstream (Domergue,1990, 1998, 2008). With the help of a wooden pole, workers constantly stirred the powdered ore in the elutriation tank, which was always full of water (Fig. 8). The overflow was discharged through the outlets and a concentrate was formed at the bottom of the basin below the level of these outlets. The jets of water loaded with fines escaping through the outlets crashed into the area where the heavier silt was to settle, while the others normally ran through the settling circuit where the classification was completed. In this case study, the tank is considered as the primary elutriation basin.

## Sizing and washing: A complex mechanism of redistribution of particles within a fluid

To affect sizing by a rising current, all that is necessary is that the material be brought to a plane across which the water is rising at a velocity capable of lifting the desired fine material to the overflow, while permitting the coarser material to fall. The classifier, in which such a division is made, needs accordingly, no great vertical dimension. There is the further advantage that the separation of materials would be made in a continuously flowing steam. If a separation in still water was applied, deeper constructions would be necessary, and it would be difficult to design a device that could be operated continuously. In some cases, however, particles are transported via a descending current. In such cases, the particles have an increased vertical velocity, and, since differentiation between particles is entirely dependant upon the varying speeds by which the objects sin, the possibility of effective division into to normal equal-falling products is diminished (Truscott,1923). This theory is explained in Fig. 9.

This illustration shows the equal-falling or classified distribution which takes place as mineral particles fall or sink down in a stream, and the redistribution which subsequently supervenes by movement along the bottom. This theory is explained as follows:

> *"[...] Descending currents are accordingly detrimental to classification, and, under some circumstances, to jigging. It also frequently happens that particle fall in a horizontal current as for instance upon entry into some classifiers, settling boxes or pits, and in launders. The vertical element of descent is then the same as though the sinking took place in still water, but, in addition, there is a horizontal displacement in the direction of the stream. All particles are subjected to this stream during the time they take to sink. Movement in response to the stream is governed by just the same factors which govern movement in response to gravity, with the result that the particles take a more-or-less diagonal line downwards, equal-falling particles keeping together. The heavier and more rapidly falling particles being subjected to the stream for a shorter time suffer less displacement, while the lighter and slower-settling particles, being carried forward along a flatter diagonal, are greatly displaced. It must be remarked, however, that if the stream also flows over the bottom onto which the particles settle, the friction of the water against that bottom introduces a new element of such strong effect that the conditions sketched above are largely reversed, and the larger particles, which before the bottom was reached held an upstream position in relation to the smaller particles, now find themselves downstream. Due to their larger size, they protrude into the swifter films of water above. As a result, they are rolled forward, while the smaller particles lie still in the quiet film against the bottom."*

Thus, this effect may be described as film sizing; it is essentially a stream effect, a mechanism of redistribution of particles:

> *"[…] Being almost invariably classified material, the mineral particle is much smaller than the gangue particle. That being so, and the necessity now being a sizing action only possible by water streaming over a surface, practically all the fine separating machines use stream – or film sizing".*

## Silver ore-dressing: The evidence of the 18th/19th century archives

To enter their profession, mining engineering students at the *Paris School of Mines* travelled throughout all of

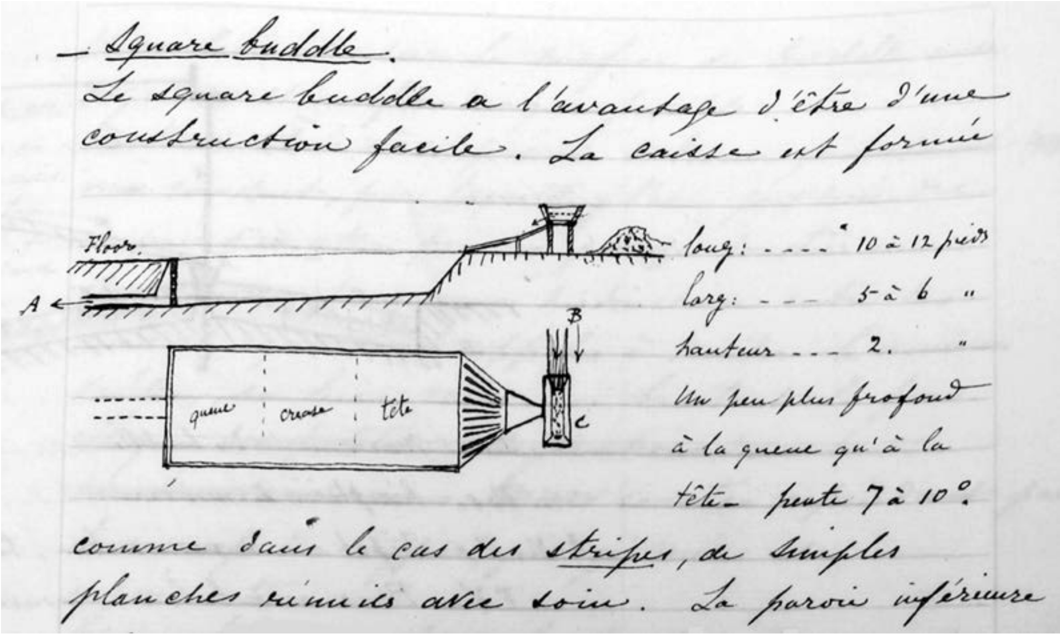



*Fig. 10: Plan and section of a buddle (Ellicott and Lacour, 1842, p.113).*

Europe and had to visit and study mining and metallurgical companies especially in France but also in Germany, Belgium and in UK (Dufrenoy, 1839). Stays in mining and metallurgical operations were fully integrated into the study cycle when the *Paris School of Mines* was created in 1783. While during the winter term theoretical teaching took place, the summer period served for field work. Following the School's relocation to Paris and its overall reorganisation in 1816 (Aguillon, 1889), the practice of travelling became the essential alternative for field training in the mining and metallurgical establishments run by the *Paris School of Mines.*

As a result of their travels the students wrote, among other topics, detailed reports on washing installations. Usually is that these manuscripts are extensively illustrated by their authors. However, original surveys and drawings occur in diverse forms. The freehand sketches, usually dimensioned and inserted into the text, is one of the most frequent. A lot of examples of these drawings can be found throughout the considered periods. They accompany mine visits reported in travel journals. These figures in the text most often correspond to pencil drawings revised later a second time (Fig. 10).

Illustrations are freehand drawings and varied as the writing itself. They are usually two-dimensional representations, plans, sections or elevation views. These drawings, created by the authors themselves, are valuable evidence of the technologies and machines used in mining in the 19th century. These drawings are accompanied by detailed comments on the dimensions of these devices and their operation. Beyond the diversity of media and modes of representation, the theme of the illustrations reveal the educational positioning of future engineers in the world of mining and metallurgy. The visits in the mines were designed as a form of training in the detailed preparation of inspection reports. These were one of the essential activities of future engineers in the exercise of their administrative function in mining and metallurgical industries (Maisonneuve, 2008). The accuracy of drawings and descriptions is an inestimable source of information to reconstruct the history of mining technologies[1]. It also provides a better understanding of certain transfers of mining technology in Europe during the 19th century (Morin-Hamon, 2003).

In these manuscript reports[2], ore dressing facilities, and especially buddle systems, were described and drawn in detail.

## Chipping and grinding

Before any washing operation, the ore must be carefully crushed and ground. E Gatellier, a 19th century mining engineering student at the *Paris School of Mines*, described these first operations as follows (Gatellier, 1857):

> *"This gives us a first coarse classification of size. I will first deal with the portion that did not pass through the stitches. It is shovelled into a small basin in front of the sorting tables and then it is cleaned out. The sorting tables are occupied by women who divide the ore into 4 categories. 1. The one that is sufficiently rich or "best" to which one only makes undergo later a grinding between two cylinders or "crusher" be-*

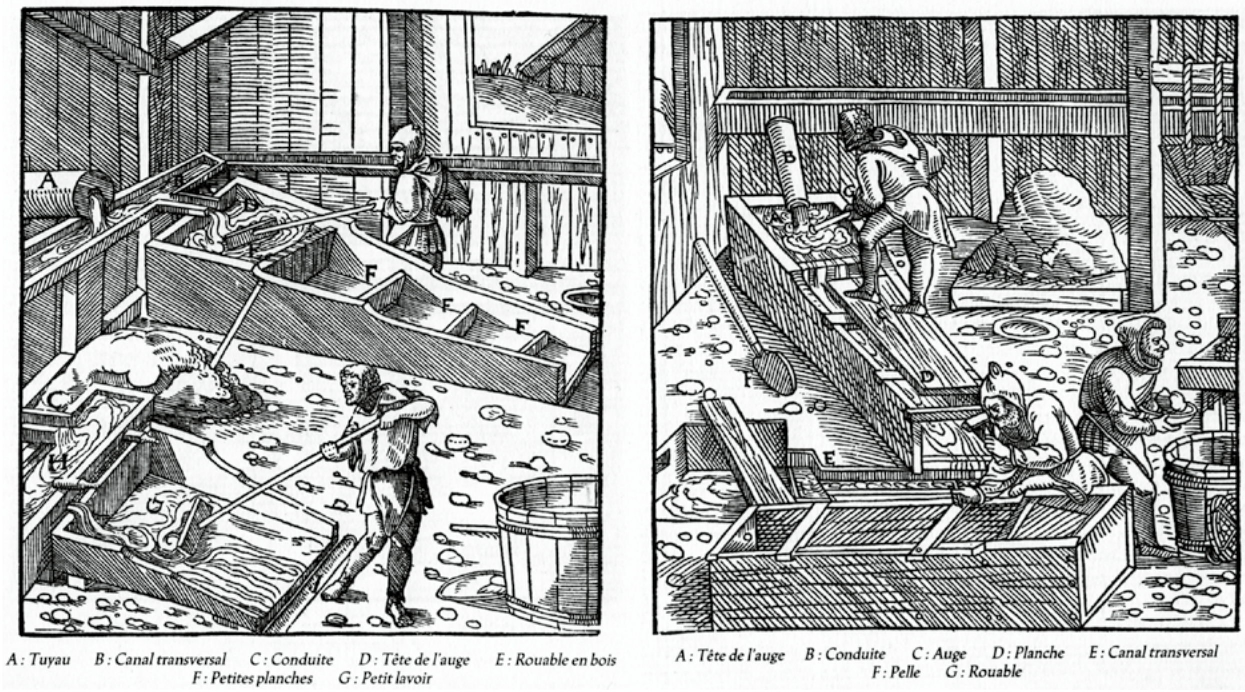



*Fig. 12: Buddles and ore dressers in action. (from Agricola, 1556, pp.242–243).*

*cause one is not used to sell it in large pieces.*
*2. The "roof best" which includes pieces containing some rich portions with others poorer. It is broken with a hammer to separate the "best"; this ore, which is then worked by hand, also gives sterile or "refused" and "dredge" ore, which falls into the next category.*
*3. The "dredge" which includes the pieces where the ore is quite intimately mixed with the gangue, and those containing harmful substances. The good metal parts cannot be extracted by hand from these pieces; they must be crushed and then washed to separate the useful portion.*
*4. The sterile or "refused" rejected immediately.*

Thus, finally, from this ore having more than 18 millimetres in diameter, one withdraws, good ore, ore to be crushed and rejected sterile material. Only the ore to be crushed shall undergo further operations.

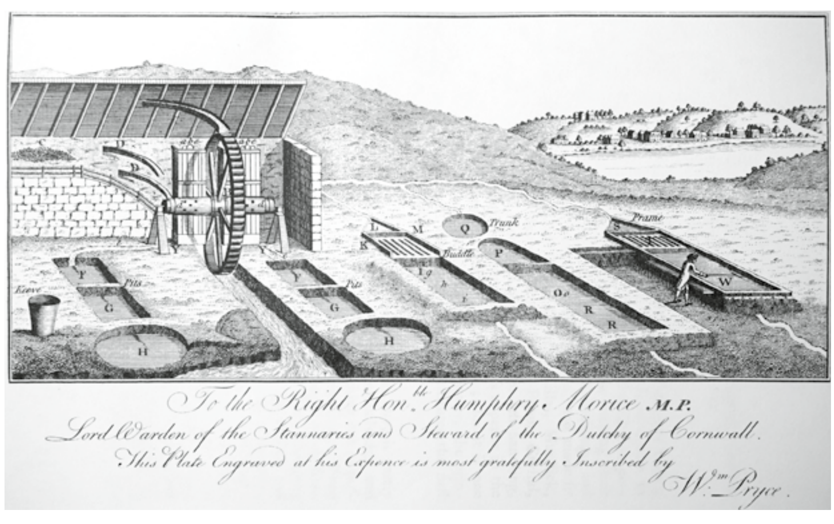



*Fig. 11: Different types of concentrators: keeve, pits, buddle, trunk, frame (illustration: Pryce, 1778, p.229, pl. V).*

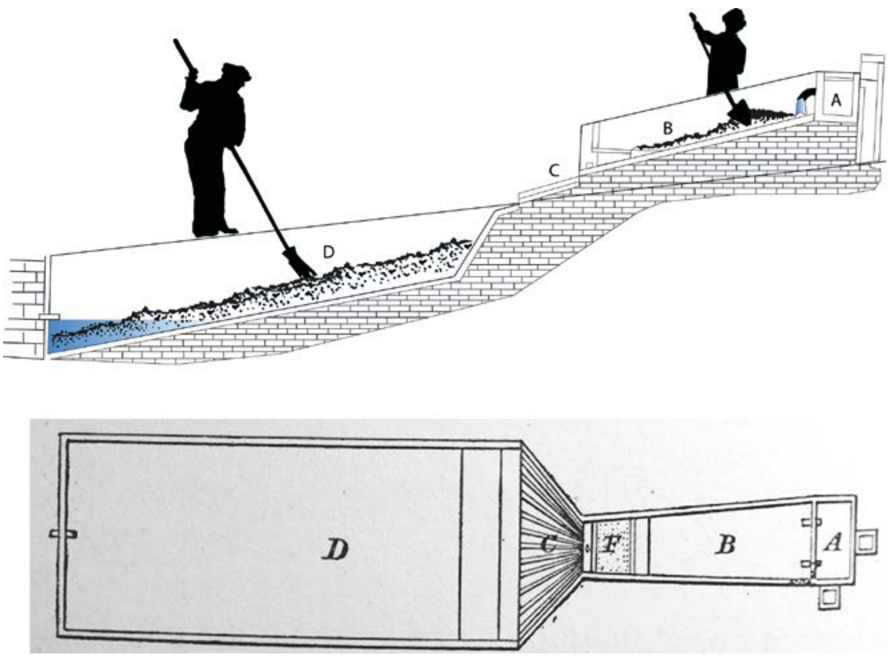



Fig. 13: Buddle described by Hunt (1884). Up: hand or square buddle in action (section). Down: plan (Hunt, 1884, p.764, fig. 217).

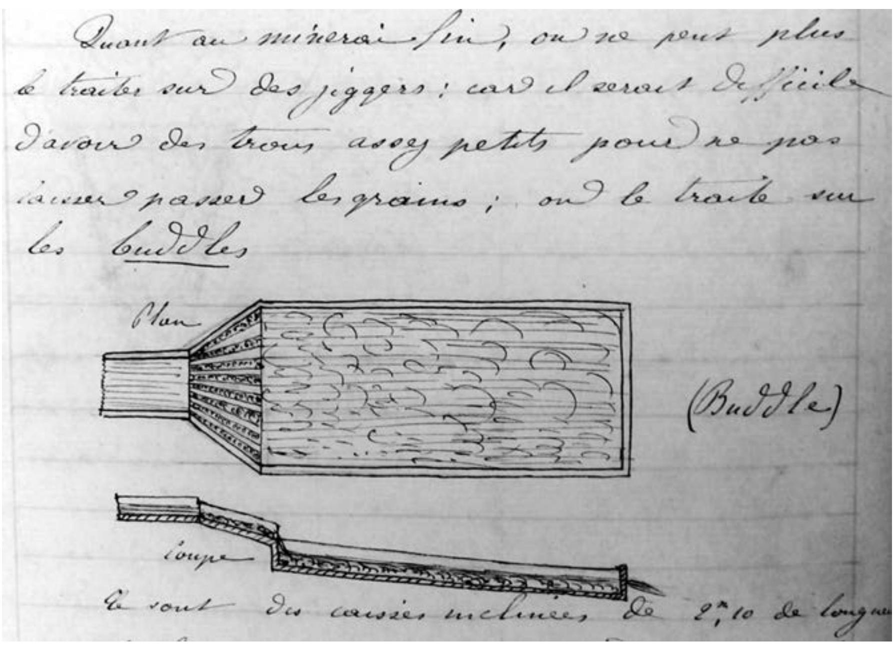
## Box concentrators

Mechanical concentration is based on the difference in specific gravity of the minerals that are to be separated. The crude application of the process such as the use of hand concentrating tubs and pans, blankets and goat or sheep skins, dates back to ancient times and was used for the recovery of gold, tin and silver.

### The buddle

The buddle is an ancient device used to concentrate sands and metalliferous slime by using the difference in specific gravity of both ore and gangue. The action of the miners dressing the ore in such devices was essential as shown in an engraving of Agricola (1556) (Fig. 12).

Buddle was an effective method of concentration throughout the 18th, and 19th century at most tin and lead-silver mines in UK. Buddles came in a variety of shapes and forms, but one of the most common was the square buddle or hand buddle. It was a rectangular box of varying dimensions and capacity sunk below ground


Quant au minerai fin, on ne peut plus le traiter sur des jiggers ; car il serait difficile d'avoir des trous assez petits pour ne pas laisser passer les grains ; on le traite sur les buddles

Plan

(Buddle)

Coupe

Ce sont des caisses inclinées de 2m,10 de longu

Fig. 14: Plan and section of a buddle from Gatellier (1857). This type of buddle was used for tin, copper and lead ore dressing in Cornwall and Devon.

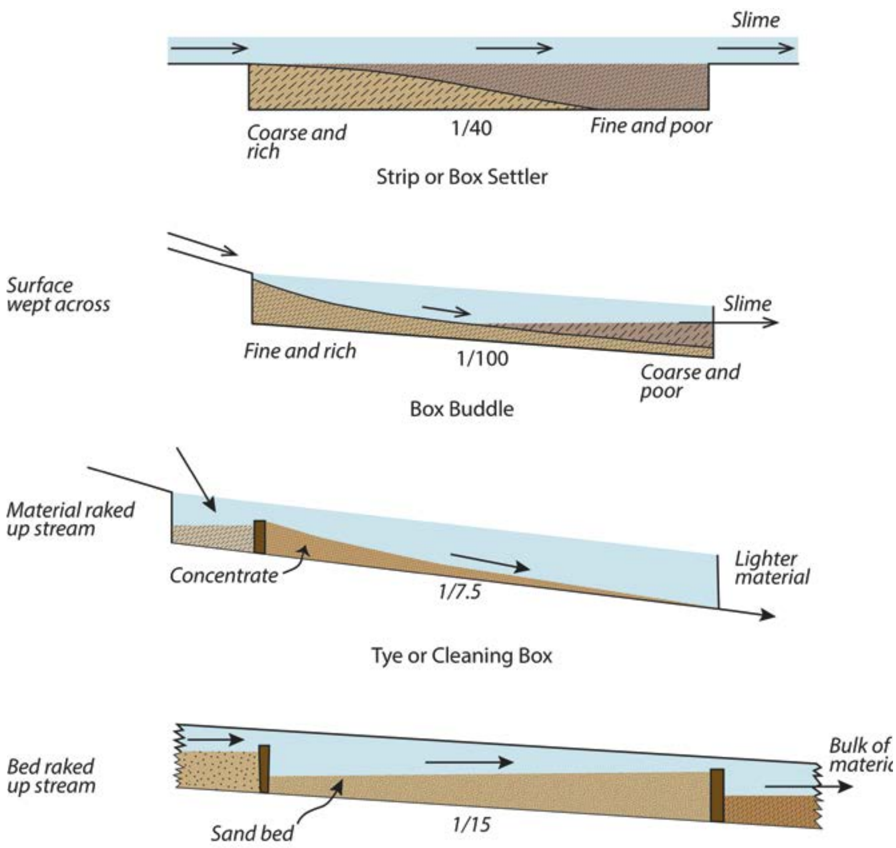



*Fig. 15: Box concentrators. Diagrams of strip, buddles and tye. (illustration from Truscott, 1923, p.257, fig. 166).*

level, with the lower side being flush with the surface, the floor having a definite slope.

The earliest buddles and simplest forms consisted of either a shallow, oblong pit simply dug into the ground, or a shallow, gently sloping channel made from wood or semi-dressed stone (Pryce, 1778; Muncaster, 1795). Fig. 11 display different types of concentrators: keeve, pits, buddle, trunk, frame. All these devices run on running water and are made up in whole or in part of pits and wooden boxes. Separation is carried out by gravity and organised naturally or by forcing the sediment to mix by means of rakes or brooms. These devices are equipped with overflows to separate the ore particles from their gangue by density.

The ore mixture was placed in the latter at the upper end and agitated in a stream of water; the lighter particles were carried off leaving behind the much heavier galena. The water gradually carries away the particles that settle according to their density.

As described, buddles were inclined boxes average 2.10 m long, 0.75 m wide and 0.60 m deep. At the top end, material was thrown onto a triangular inclined and constantly washed out by a jet of water, which featured fan-shaped stips that distributed the material. This was then evenly distributed by falling on to a small, narrow sloping board of the same width as the buddle. An ore dresser would constantly work the buddle to ensure that the deposits formed a level inclined plane, usually with the aid of a long-handled broom. At the head of the device, the richest and heaviest particles of ore are deposited. Material was divided into the head, fore-middle head, hind middle head and tail (Henderson, 1859). The water carrying fine slime escaped from the lower end of the buddle through holes pierced in the tailboard a wooden partition which formed the bottom of the buddle. Plugs were placed in these holes in the tailboard as the level of deposited material grew. Then, an underground channel carried away the gangue with the wastewater (Moissenet, 1858).

The buddle described by Hunt in 1884 consists of a wooden box (Fig. 13), about 8 feet in length, 3 feet wide, and from 2 to 2.5 feet deep in the ground, and having an inclination of some feets in its whole length. At the head of this box a distributing-board, C, placed, laced, which is in communication with the trough B, and a water launder A. The stuff is thrown into the trough B, when it is stirred by the buddler's assistant. The fine slime then passes through a perforated plate to the distributing-board C, and from thence in a thin and uniform stream into the huddle D, when the buddler carefully and continually sweeps the slime and water across the buddle and somewhat against the direction of the current, with the view of freeing the grains of ore from any viscid matter which may accompany them, and depositing them at the head of the buddle (Fig. 14).

Fig. 15 shows how fine ore is processed on buddles (Gatellier, 1857). Four types of boxes for the same ore dressing process were fully in action during the 19th

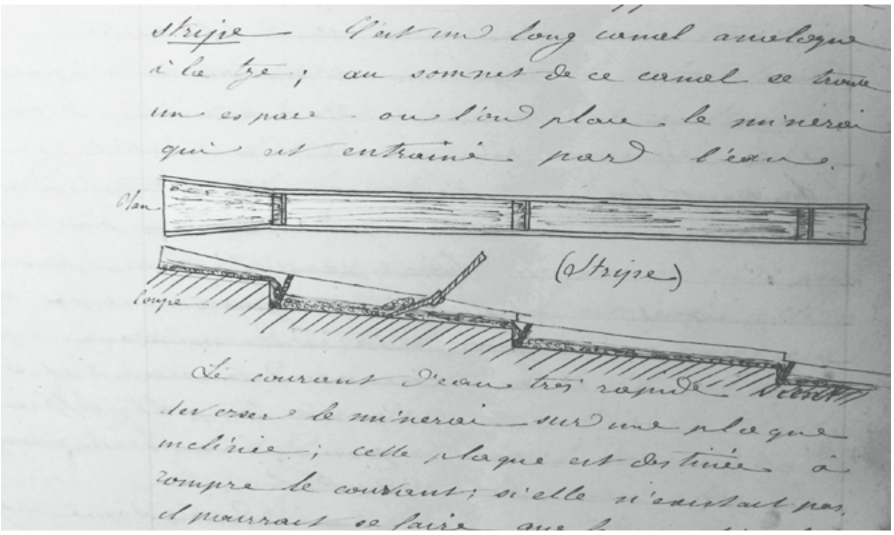



*Fig. 16: Plan and section of a stripe employed in Cornwall and Devon by Gatellier (1857). Fine ore is processed on a stripe.*

century in most of the mines especially in UK, all of them wooden boxes and with a similar system to concentrate the ore with a water stream.

Evolution and mechanism of these devices have been largely discussed in detail by L. Willies (1975) and R. Burt (1982). The running buddle as described by Muncaster (1795) and Pryce (1778) was a simple trench, lined with wood or stone flags, about 6 x 2 feet, and 8 inches deep. Water entered by a notch in the stone or board at the head. Material to be treated was placed on the floor of the buddle at the head in front of the notch, and by turning the material over, the lighter stuff was washed out and was carried to the bottom of the trench from which it could be removed.

Fine ore was also processed on another type of device called a stripe. Gatellier (1857) describes this device, like that of the buddle (Fig. 16).

*"[…] For the richer categories [...] another treatment is used to separate immediately and very quickly a very large portion of the arsenic. A new device called a stripe is used. It is a long channel similar to the tye; at the top of this channel is a space where the ore, which is dragged along by the water, is placed.*

*The very fast current of water pours the ore onto an inclined plate; this plate is designed to break the current; if it did not exist it could happen that the larger and heavier parts would be dragged beyond the space suitable for their volume and density because of the surface they present to the water current. The material therefore settles in the channel, the heaviest at the beginning,*

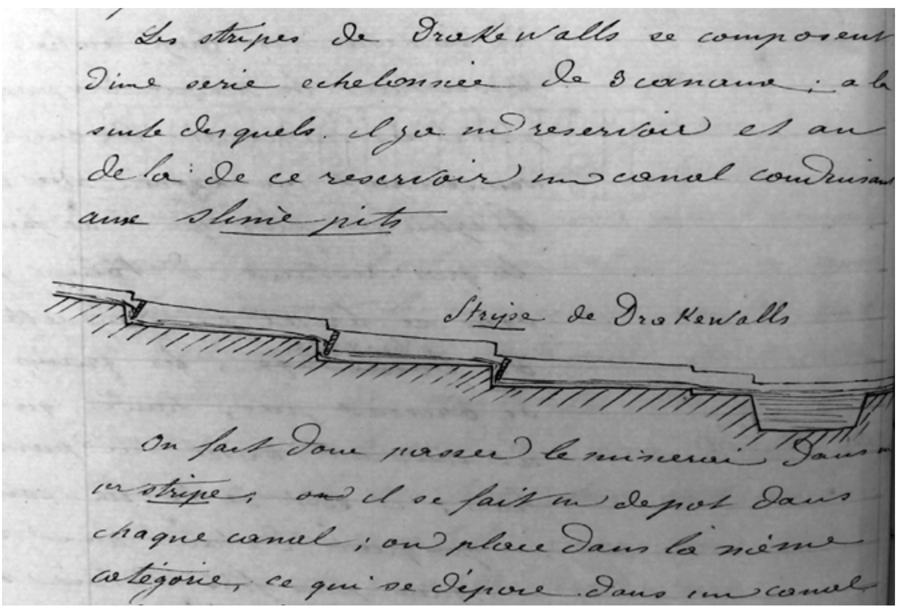



*Fig. 17: Drake walls stripe (section) for washing lead-silver ore in Cornwall and Devon. The stripe is another device which uses a washing system that functions similarly to the buddle (from Gatellier, 1857).*

*the lightest at the end. To prevent the lighter materials from being retained at the beginning by impastoing the heavier materials, a worker is continuously busy lifting the deposit already made in the canal […]"* (Fig. 17).

Gatellier (1857) continous:

*"[…] It is because of the considerations I have just mentioned that for tin ore after grinding, the stripe is used, a device that works very roughly, but in a very fast way. The crushed ore is processed as follows: The Drakewalls strips consist of a staggered series of 3 channels; after which there is a reservoir and beyond this reservoir a channel leading to the slime pits. (...) in the pits 3 divisions are made; the portion at the head contains the richest ore, the portion in the middle contains a lower grade of ore, and the portion at the end is discarded as sterile […]".*

## Stream action and buddling process

The buddling process had two principal functions: to separate the very fine clay or sludge from the mineral material, and to separate the heavier lead ore from the gangue. Taggart (1951) is explaining:

*"A mineral-separating machine is one in which a process utilizing one or more of the differences*

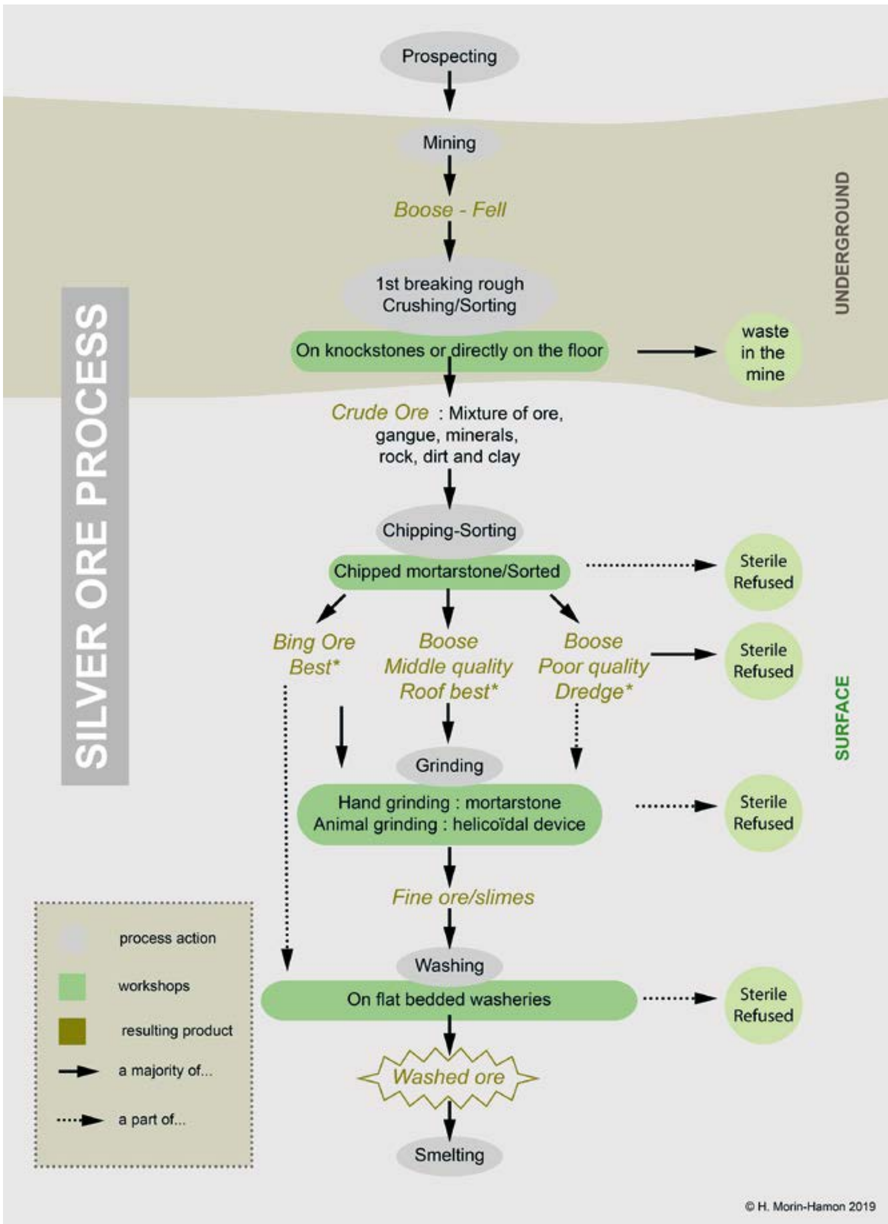



*Fig. 18: Archaeological evidence – silver ore dressing process at Laurion, from mine to surface (schema: Hélène Morin-Hamon). The diagram shows the various stages identified from the most recent research on the mechanical preparation of mineralization since its extraction. Each stage of the process corresponds to an enrichment device and a more or less important discharge of sterile sediments. It is a process that starts as early as the mining extraction phase.*

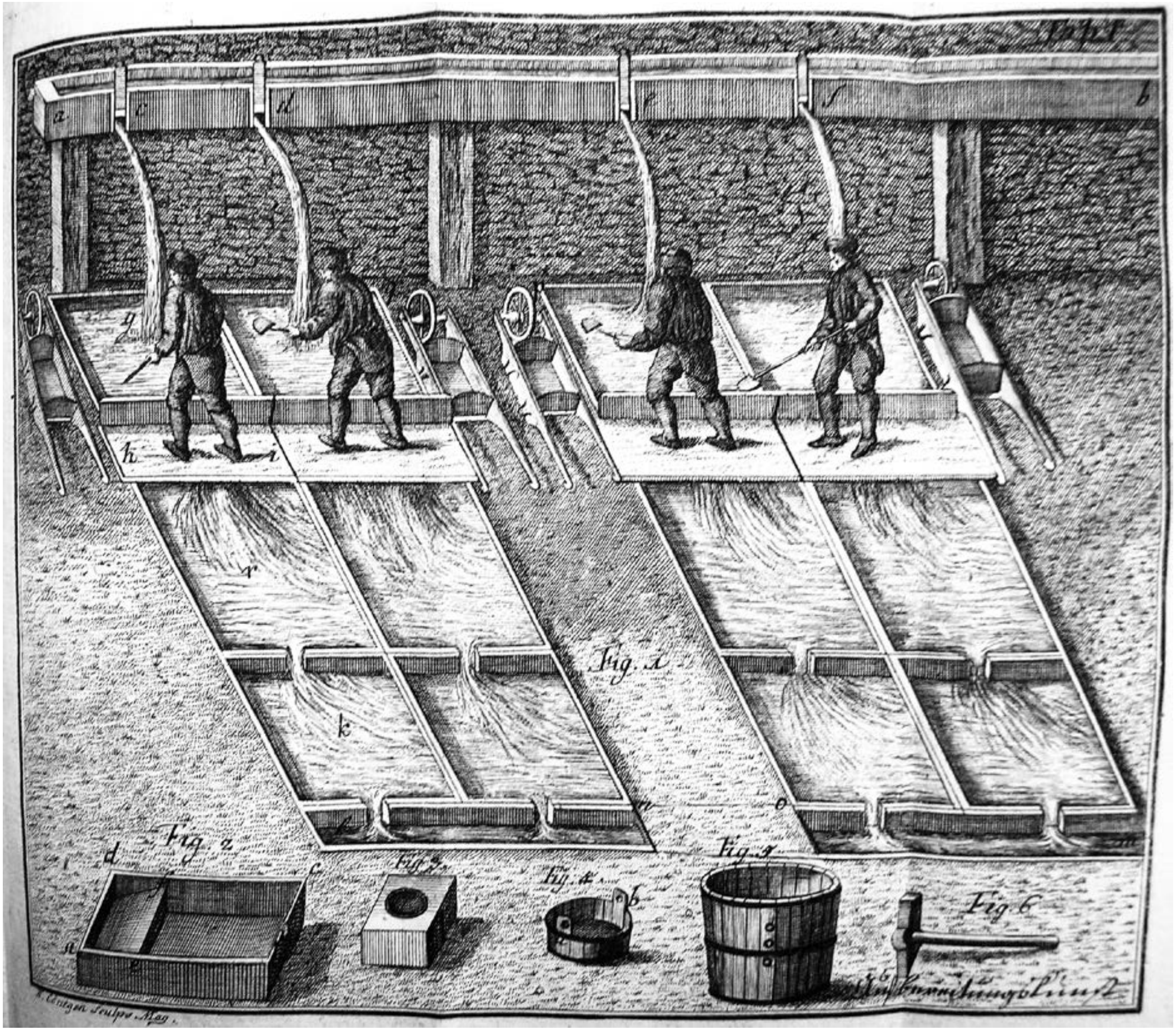



*Fig. 19: Washery in process (Cancrin, 1782, plate 1).*

*among minerals is carried out. Its essential part is, of course, the separating zone, in which individual particles of a mixture should be free to move in the direction of the resultant of the separating forces acting on it. The activating element in the separating zone is a means for exerting a selective force on one species of particles in the mixture. Essential accessories are transport means to carry the feed into the separating zone, and other transport means to carry the products to separate discharge points. These four elements are common to all separating machines. Special additional accessories are found in some".*

What happens precisely underwater has been described by Hunt (1884):

*"If two spheres of equal volume but of different densities drop together from the same height in a column of water, the heavier of the two will arrive at the bottom first. In this instance the density of each of the spheres is only opposed by the resistance offered to its sectional area, i.e. by the the water through which the sphere is falling. If, however, two spheres of different densities have an equal velocity of fall in water (equivalents), the diameter or sectional area of the lighter will be greater than of the heavier sphere. Now if the two spheres are placed side by side on a perfectly flat table, no movement will occur; but if a slight stream of water will be applied to their surfaces, the one having the larger diameter or greater surface (the lighter sphere) will be impelled more rapidly and separate from the other (the heavier sphere), and if the table be slightly inclined, the rate of movement of these several spheres of different diameters will be accelerated. To these prin-*

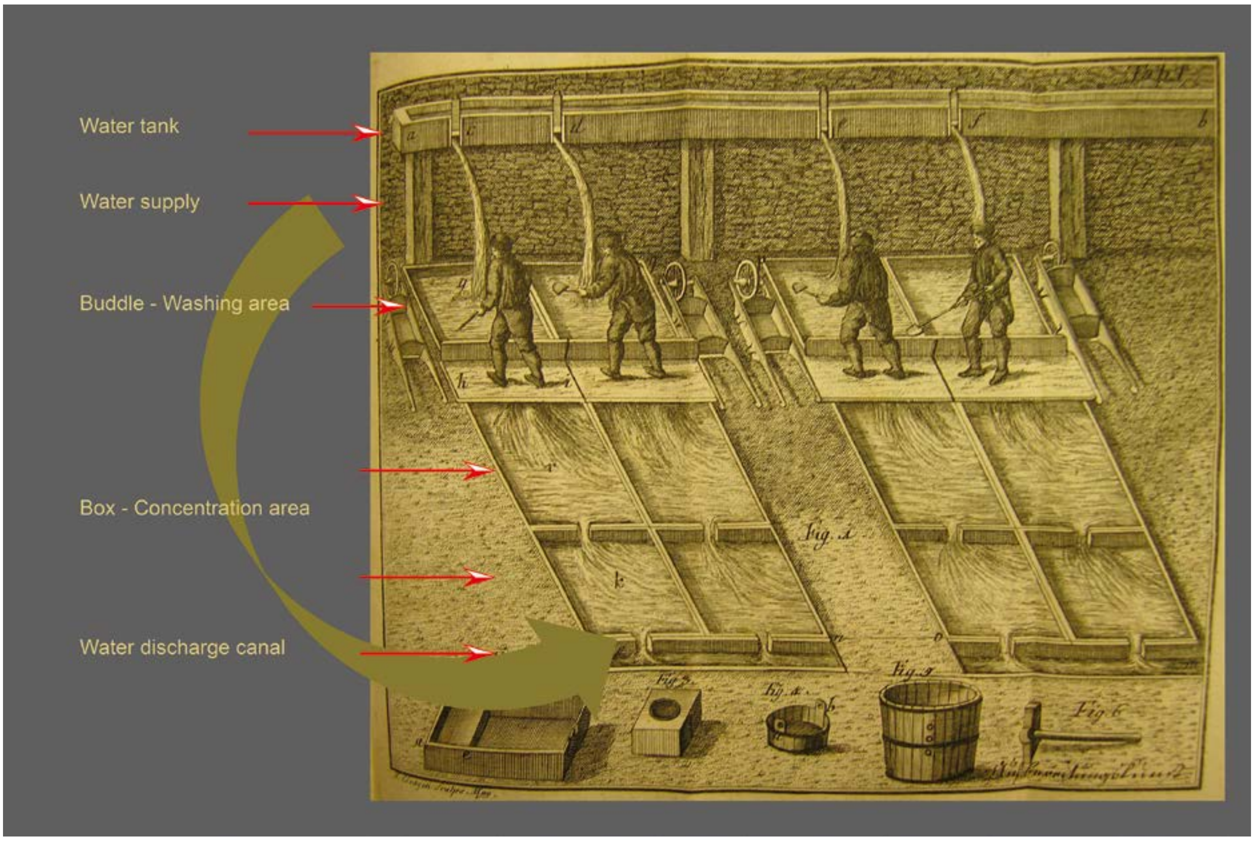



*Fig. 20: Washery in process. Interpretation. Top down: the water tank (water supply), the outlets, the buddle (washing floor), the two box concentration areas and the water discharge canal (all connected with small apertures). (Illustration modified after Cancrin, 1782).*

*ciples, the separation on buddles or tables of metalliferous grains from gangue having an equivalent rate of fall in water must be referred".*

## Lead-Silver ore dressing process: A beneficiation processing

The diagram in Fig. 18 shows in detail the main stages of the process from mining to the metallurgical stage, identified from the most recent research on the mechanical preparation of mineralizations since their extractions. Each stage of the process corresponds to an enrichment device and a more or less important discharge of sterile sediments. It is a process that starts as early as the mining extraction phase.The first operations of ore dressing are sorting and crushing, were carried out directly underground, and this for all periods from EH II at Laurion. The diagram in Fig. 18 is based on archaeological evidence. It should be noted that these operations were both complex and multiple depending on the quality of the ore. Here, enrichment is at the center of the general system of mining. It required an abundant workforce and operations skilfully orchestrated and controlled.

## The Cancrinus Iconography: A reference for technology and operation

Treatises on mining technology of the 18th century, and especially an illustration (Fig. 19) confirms the hypothesis of processing ores like that of a labyrinth, except that at that time the device in question was built in wood or directly implanted in the ground.

In this little-known treatise dated from the 18th century, entitled "*Erste Gründe der Berg und Salzwerkskunde*", Zurich [Ref. *Erste Gründe der Scheide- oder Aufbereitungskunst der Mineralien*] the author, Franz Ludwig von Cancrin (Cancrinus, 1738-1816), mineralogist, metallurgist, engineer and architect from Hesse in Germany, presents an interesting iconography. The originality of this picture lies in its depiction of the workers as well as in the description of their activities and the installations used. Plate XXI of his book is perfectly clear and corresponds to what might have happened during classical times at Laurion. It shows from top to bottom:

- the water tank, here a wooden channel,
- the water streaming directly onto the washing area,
- the buddle or washing area,
- the two-part settling basin of concentration areas with an overflow and finally
- the water drain.

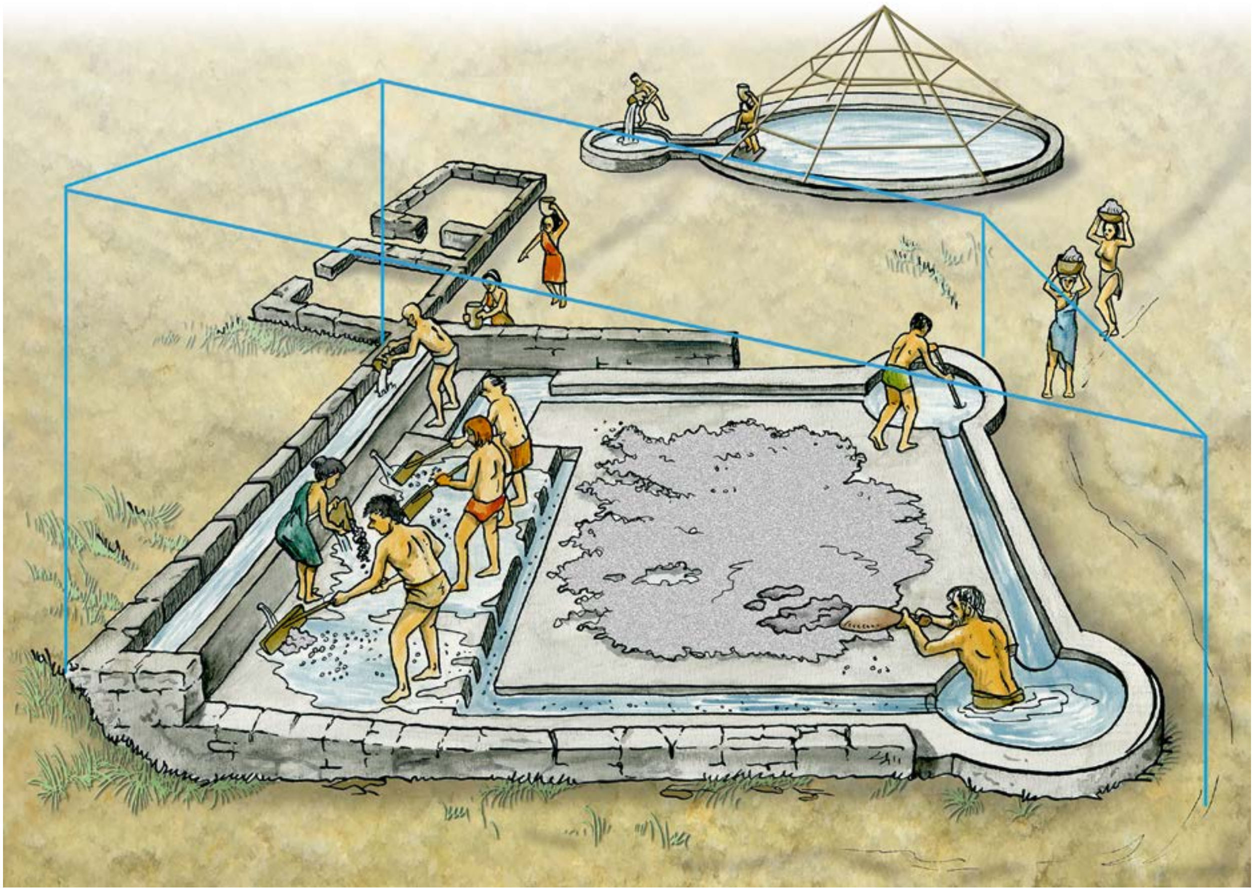


*Fig. 21: Laurion. Reconstruction of a flat-bedded washery in progress (Morin and Photiades, 2005, p.21). (Conception: Hélène Morin-Hamon, drawing: Bernard Nicolas, 2005).*

Crushed particles are stirred directly under the jet by means of wooden rakes before gradually flowing downstream into wooden settling or grading boxes. The waste water is finally released through a drainIn this case, the water is released into the environment. The concentration of the slime is carried out directly inside the boxes. The image reproduces here shows a dressing floor system and working postures identical to those found in the flat-bedded washeries at Laurion (Fig. 20).

## Discussion

### Ore-washing at Laurion: A classifying process

In the Laurion, various efficient devices were used to grind to obtain a powdered ore. However, the system described above is incomplete. Because it must admitted that the low-grade particles can hardly stabilize themselves on the flat surface if they are directly exposed to the water jets. Some elementary experiments confirm this. On the other hand, in the case of flat-bedded ore washeries, the water circulation around the square plants allows even the finest particles to settle, even those that slipped through during the first washing. The most plausible hypothesis is therefore here that of a so called labyrinth system. Willies (2007) writes:

> *"The typical length of surviving post-medieval buddles is around two meters, as is the floor at Laurium too. It is a very simple, effective process, capable of easy testing by experiment. Below the buddle-floor is a catch-channel for the water and sediment. This encircles the level drying-floor and seems to have functioned as a clarifying system like the labyrinth on many 19th century sites".*

First, it should be noted that these washing structures have been cleverly dispersed and perfectly adapted to the mining and geomorphological context. Some of them were entirely built, others were cut directly into the rock. This is the case of some ancient washing structures excavated by E. Kakavoyannis (2001) in the Bertseko valley. They all form a system of canals connecting several settling ponds, with an average length of 25 meters. Some of them may have been prototypes in terms of other morphology. Kakavoyannis (2001) writes:

> *"[…] Their channels and settling tanks had no definite number or particular positions in the body of the washery. They were all rather irregular and clearly showed thar their constructors were still at the stage of searching and experimentation, obviously in order to find the best shape and operating method for the construction, elements we see already existing in washereies for the Classical period […]".*

Flat-bedded washeries at Laurion are identical in every way: canal/stand supply tank upstream. The water is then sprayed on a surface or washing table. The supply tank ("a" in Fig. 5) serves exclusively as a water reservoir for the entire downstream system and never as a washing area as suggested by C. Domergue (1998) and J. Kepper (2004).

Thus, the system for washing fine particles used by the miners at Laurion was carried out in two stages in the same structure. Upstream, a regularly supplied water tank made it possible, via outlets or orifices placed at regular intervals, to wash the previously sorted and finely grounded material on a grinding tables: a buddling-floor (the Kepper's working floor) (Cordella, 1869).

In any event, contrary to what Cordella claims, the tank "a" found in all the washeries cannot be the basin where the work began, and thus served as a de-sludging box. This location found in all the washeries consists of a tank intended to supply the water distribution.

Washing was probably carried out using brushes. Here, the solid particles were stirred with the water counter to the current. This water loaded with gangue particles and ore then flowed directly into a first receptacle parallel to the axis of the tank "a" and the washing table, the surface of which was made of a particularly resistant hydraulic mortar.

Furthermore, there is no need for sluices arranged at the level of the orifices as Conophagos claims. Moreover, traces of such a device would obviously still be visible and would have left imprints on the washing floor, which is not the case. As Willies (2007) expresses, "(...) *flushes and jets of water in sluices, would destroy the differential settling required"*. The recovery of fine particles was carried out directly inside the bins and pipes according to a natural gravity classification.

The water loaded with the grinding products then gradually continued its course in the labyrinth system set up for this purpose. This channel is generally composed of two settling tanks preceded and accompanied by overflows designed to block the particles as the liquid progressed. The last basin is the sump where the settled water is completely recycled to be reintegrated into the supply tank. The cycle is thus perfectly closed. As shown by the layout of the channels and platforms, each element is inclined according to its own location. The gradient gradually decreases with the increasing distance from the water inlet.

These different channels and basins preceded by overflows functioned as a perfect classification device. In there, sediments were trapped by gravity. Depending on the concentrations, these sediments were evacuated outside, dried in the centre of the space or washed again to prevent any loss of material. The length of the channels was deliberately exaggerated so that the water, brought in for clarification, would flow clear for as long as possible over the reservoir or tailings pond, as the sludge would gradually fill up the basins from one end to the other.

Hypothesis of using sea water to feed the washeries has been mentioned. A laboratory study carried out at the *Ecole des Mines* at the beginning of the 20th century already evoked this hypothesis: sodium chloride is rarely an effective agent for both flaking and deflocculating and when added to water, in a special proportion, depending on the nature of the ore, it increases viscosity so that the particles settle slowly in some cases (Roux-Brahic, 1922).

## Conclusion

The flat-bedded washeries had a main tank in which a large volume of water could be stored. Water flowed out on a slightly inclined surface: a buddling floor. Water was distributed on a small amount of finely ground ore under the outlets, probably assisted by raking or brushing in order to separate the denser ore minerals from the less-dense gangue. Then, the particles were washed in a stream of water by depositing the heavier fine particles first (slime). Below this buddling floor was a catch-channel for water and sediment. This channel surrounds a central square plan, a drying floor, and it functioned as a clarifying system with overflow facilities like the so called labyrinths on many 19th century sites as described. The layout of the channels, with storage tanks at each corner and narrow inclined channels suggest that sedimentation was occurring gradually. Beyond the tank "a", the main process were the channel and the settling basin circuit.

The research carried out on ore-dressing complexes for alteration iron minerals in eastern France (Morin-Hamon, 1997, 2013a, 2013b) led us to make comparative observations with the Laurion washing facilities. The model proposed here is based on both field evidence and iconographic and documentary sources from 19th century mining engineers. Finally, it is based on the archaeological researches we have developed on the primary washing facilities of iron alterite (Morin-Hamon, ibid.).

Such hypothesis could be supported by future researches, particularly in terms of experimentation. We had already proposed a different method of operation from those usually presented, based on structures that have been widely used and described since the 16th century

(Morin-Hamon, 2005). An attempt at reconstitution thus suggests the specific activity in use in this type of washery.

Fig. 21 shows the reconstruction of the work process on a flat-bedded washery according to the results presented here. The water contained in a collector or tank "a" flows through several outlets to the head of a buddling floor. There, some workers spill in finely ground ore while others rake or brush. Below the buddling floor is a catch-channel for water and sediment. This channel, which encircles a square drying floor, functions as a clarification system like the labyrinths in use on many 19th century sites. The layout of the channels, connected through overflows, with basins or cisterns at each corner and narrow inclined bottom in the channels, suggests that sedimentation occurred in the equivalent of long buddling trenches (Willies, 2007).

The flat washers function here as a complete buddling device in order to catch the maximum amount of low-grade fine ore: at the bottom of the buddle and in the labyrinth below, and thus constitute a second element of buddling. The returned water at the end of the channel system is discharged into the stand-tank (Willies, 2007). The entire ingenious system thus allows the water to be completely recycled through an ingenious decanting system. Scrubbing sludge and mineral-rich sediments are collected directly at the bottom of the cisterns to be spread out and dried on a platform in the centre of the device. To prevent any infiltration, the entire system: tank, dressing floor, channels, and drying platform were carefully sealed with a special hydraulic lime coating.

The number of the flat-bedded washeries of Laurion is clearly related to the extent of the underground mining activities and the volume of material extracted there. The efficiency of ore dressing processes depends as much on the water supply as on the washing and settling structures, a perfect buddling device adapted to the technologies of the time and the particularly abundant and rich mineralogical context. The separation of ore particles from sterile particles depends on the architectural parameters of the device: tank "a", washing floor, outlet length, slope and overflows. Thereby the ingenuity of the ancient miners lies in the total control of hydraulics and particularly of the supply of washing systems in an arid context.

The enrichment model presented here corresponds to washing by stirring and settling. Thus, it was a simple, ingenious and effective process that made it possible to recycle water continuously in a closed system while achieving optimal separation of sediments and a progressive classification of low-grade ore to a precious material of galena and cerussite with high added value.

The buddle technique was mastered here in structures designed and built with perfect waterproofing and protected from the sun to avoid evaporation. This resulted in the quadrangular standard construction, which could be adapted in different proportions and to the volume to be treated, constituting a perfect engineering model.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## Notes

1 Many travel journals are now available online on the *Paris School of Mines* archives website (https://patrimoine.mines-paristech.fr/).

2 Journaux de voyages (in french).

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# APPENDIX

Extract from Cancrinus (1782):

*4) Man grabe stets zwei solcher Kasten, die man mit Letten umstampft, nebeneinander unter die Rinne a-b in die Erde, Tafel I, Figur 1, aber so, dass der Wasserstrahl c-g in die Mitte des Gefälles des Waschkastens fället, der ganze Kasten aber völlig steht. Über jeden Kasten nun lege man eine 1 ¼ Fuß breite Bohle h-i, die vorn mit einem 8 Zoll hohen gerade aufstehenden Seitenbrett vor das Spritzen des Wassers versehen ist, worauf dann der Wascher stehen und arbeiten kann. Man mache aber auch*
*5) vor jedem Kasten einen, und wenn dies nötig ist, an diesen noch einen anderen Sumpf, einen aus Bohlen zusammen gesetzten, und in die Erde gegrabenen Kasten k von vier Fuß lang, breit, und tief, damit sich hierinnen der etwa noch noch gehaltige Schlamm setzen, und dann durch den Graben l-m fortgehen möge: so ist die Wasche fertig, und man kann so viele Kasten machen, als nötig sind, der Raum n-o-p-q aber zwischen zwei Kasten, der 4 Fuß breit ist, dient dazu, das Erz mit einem Laufkarren, in die Wasche, und wieder davon führen zu können.*

*Der zweite Abschnitt der Verfahrungsart bei dem Waschen und Spülen der Erze*

*§10*
*Derbe oder blanke Erze von der Erde und dem Schlamm zu reinigen.*

*Auflösung*

*1) Man führe in das Gefülle g des Waschkastens, Tabelle1 Fig.1, einen bis zwei Laufkarren voll von dem zu spülenden Erz, und ziehe den Schieber c auf, damit das Wasser auf das Erz fällt.*
*2) man scheppe das Erz mit einer Schippe beständig um, so löst sich die Erde und der Schlamm in dem Wasser auf, und das Erz fällt, vermöge seiner größeren Schwere, stets zu Boden, die leichtere Erde hingegen wird von dem Wasser getragen, und fortgeführt (§205, 206, 207 und 208 und §214, 215, 216 und 217 der Bergmasch.). Bei alle dem richte man indessen die Stärke des Wasserstrahls c g durch das mehr oder wenigere Aufziehen des Schiebers so ein, dass die Erzstücken durch den starken Stoß des Wassers nicht heraus, und in den Kasten r unter den Schlamm geworfen werden.*
*3) Mit dem Umscheppen des Erzes halte man nun so lange an, bis dasselbe ganz rein, und das Wasser fast ganz hell wird. Ist*

English version:

*4) Two such caissons shall always be dug in the earth (see Table I, Fig. 1) side by side under channel a-b, and [sealed] with packed clay around them. They shall be dug in such a way that the water jet c-g falls in the middle of the fall (?) of the washing caisson, but the caisson remains full. On each caisson a 1-foot wide h-i plank ¼, with an 8-inch high side board at the front to protect from splashing water, will be placed on which the washer can stand and work standing. It will also*
*5) in front of each chamber a new chamber k, and if necessary another sump (?) against the previous one, dug into the ground and made of assembled planks of four feet in length, width and depth, so that the mud still contained can settle and then drain off through the ditch l-m: and the hand washing is then finished, and as many caissons as necessary can be made, however the 4-foot wide n-o-p-q space between two caissons, is used to supply the wash-house with ore, with a wheelbarrow, and to remove it from it.*

*The second part of the process is how to wash and rinse the ore.*

*§10*
*Cleaning coarse or raw minerals from soil and mud*

*Solution*

*1) One or two wheelbarrows full of ore to be rinsed are brought in g into the wash chamber, Table 1, Fig. 1, and the drawer c is opened so that the water falls on the ore.*
*2) The ore is worked continuously with a shovel, so that the earth and the mud dissolve in the water, and the ore always falls to the bottom, because of its higher weight, while the lighter earth is carried away by the water (§ 205, 206, 207, 208 and § 214, 215, 216, 217 of [the machines of the mines?] ). During the operation, the force of the water jet c-g is adjusted by opening the drawers more or less so that the ore pieces are not washed away by the force of the water but remain in the box r under the mud.*

*3) The ore is kept stirring until it is clean and the water is almost completely clear. When*

*4) dieses geschehen: so scheppe man das gespülte Erz aus dem Gefälle auf einen Laufkarren, und fahre solches an dem Ort, wo es zum Schmelzen aufbehalten werden soll, auf einen Haufen.*

*5) Man wiederhole die Arbeit so lang, bis der Kasten r mit Schlamm und kleinen Erzstücken angefüllt ist, alsdann aber schlage man diesen Kasten aus, das ist, man scheppe das kleine Erz mit dem Schlamm neben dem Kasten heraus und spüle dieses Zeug nochmals, man gebe aber nur wenig Wasser, man mache nämlich den Wasserstrahl klein: so bekommt man die groben Stücken alle allein, und das Erz ist von der Erde und dem Schlamm geschieden, also zum Rösten und Schmelzen geschickt.*

*6) Man schlage nunmehr den Kasten r, auch den Sumpf k, wenn solcher mit Schlamm angefüllt ist, wieder rein aus, man bringe aber jeden Ausschlag allein, weil der in dem Kasten reicher an Erz ist, als der in dem Sumpf, indem sich das gröbere und schwerere Erz eher zu Boden setzt, und im Wasser nicht so weit fortgeführt wird, als das kleinere und leichtere (§ 207 und 208 der Bergmasch.)*

*7) Diesen Auschlag nun, den Schlamm aus dem Kasten r und den Afterschlamm aus dem Sumpf k hebe man auf, und wasche ihn auf Graben und Heerden, wovon wir erst § 75, 90 und 91 bei dem Schlämmen und Waschen der Erze handeln können.*

*§11*

*Diese Wasche ist etwas besser, und vorteilhafter eingerichtet als die gewöhnlichen. Man bedient sich derselben gemeiniglich nur zu dem Eisenstein waschen, man kann aber auch alle Arten von anderen Erzen, besonders Graupen, die nur mit Erde und Schlamm vermengt sind, darauf waschen, nur muss man in diesem Fall die Graupen erst rädern, und das Wasser gleich über dem Kasten bei g in die Wasche führen, damit das zarte Erz nicht durch den Fall des Wassers aus dem Gefälle gespült werde.*

*Meist bedient man sich inzwischen bei dem Setzwerk eines Durchlassgrabens, den wir § 26 beschreiben, worinnen man die Setzgraupen, die wir § 35 zeigen, spült.*

*Außerdem kann man sich dieser Wasche auch zu dem Krätzwaschen bedienen, wovon wir in der Schmelzkunst*

*4) this is the case, the cleaned ore is taken out under the water jet with a shovel and transported in the wheelbarrow to a heap where it is to be kept for smelting.*

*5) The operation is repeated for as long as necessary until the caisson r is filled with mud and small pieces of ore. Then this caisson is emptied, i.e. the small ore with the mud next to the caisson is taken out with a shovel and rinsed again, giving little water, for this purpose the jet of water is reduced: so the coarse pieces are separated from the rest and the ore is separated from the earth and the mud and is ready to be roasted and melted.*

*6) The caisson r, and also the sump k, if it is filled with mud, is then emptied and cleaned, but the mud is kept separate, because the mud in the caisson is richer in ore than the mud in the sump, because the coarser and heavier ore falls to the bottom more quickly and is not carried along by the water like the smaller and lighter ore (§ 207 and 208 of the "Mining Machines").*

*7) The recovered sludge is kept in the r caisson and the sludge from the sump, and is washed on (?) ditches and ...(?) which we will only discuss in § 75, 90, and 91 concerning the washing of minerals.*

*§11*

*This washhouse is a little better, and better set up than regular laundries. It is usually used only for washing iron ore, but it can also wash all kinds of other ores, especially granular ores, which are mixed with soil and mud. However, first you have to wheel (grind?) the 'Graupen' and bring the water just above the g caisson into the washtub, so that the soft ore is not dragged out of the waterfall.*

*In the meantime, a drainage ditch, which we describe in § 26, is used to deposit the ore, in which the granular ore is washed, which we show in § 35.*

*In addition, this washhouse can be used for scraping (?) which we [...] in the art of smelting*

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