Maqueda, Florence; Florsch, Nicolas; Téreygeol, Florian

The economics of medieval mining by firesetting or with chisel : the issue of energy

Archaeologia historica. 2024, vol. 49, iss. 1, pp. 193-208

ISSN 0231-5823 (print); ISSN 2336-4386 (online)

Stable URL (DOI): https://doi.org/10.5817/AH2024-1-7
Stable URL (handle): https://hdl.handle.net/11222.digilib/digilib.80162

Archaeologia historica 49, 1, 2024, 193–208
https://doi.org/10.5817/AH2024-1-7

THE ECONOMICS OF MEDIEVAL MINING BY FIRESETTING OR WITH CHISEL: THE ISSUE OF ENERGY

FLORENCE MAQUEDA – NICOLAS FLORSCH – FLORIAN TÉREYGEOL

Abstract: *Prior to the introduction of explosives in Europe, there were two primary methods of mining: firesetting and the use of tools, with the hammer and chisel being the most common. The use of wood, and therefore fire, can be traced back to protohistoric times. The choice between the two methods depended on the hardness of the rock being mined, as well as the source of energy used – either human energy or the thermal energy of wood. The issue of access to fuel is significant. The approach is based on experimental archaeology and involves tests carried out on various medieval mines, which permits the measures of energy. The thermal energy it correlated with to the mass of wood burnt. Human energy is measured using an accelerometer on the experimenter's wrist. This method helps to understand the technical and economical choices made in different geological, chronological and social environments.*

Key words: *mining – energy – firesetting – chisel.*

Ekonomika středověké těžby pomocí ohně či dláta: otázka energie

Abstrakt: *Před zavedením výbušnin v Evropě existovaly dva základní způsoby těžby: pomocí ohně a nástrojů, z nichž nejběžnější byly kladivo a dláto. Používání dřeva, a tedy i ohně, lze vysledovat až do protohistorických dob. Volba mezi oběma metodami závisela na tvrdosti těžené horniny a také na zdroji použité energie – buď energie lidské, nebo tepelné energie dřeva. Významná je otázka dostupnosti paliva. Přístup autorů je založen na experimentální archeologii a zahrnuje testy, prováděné v různých středověkých dolech, které umožňují měření energie. Množství tepelné energie se odvozuje z hmotnosti spáleného dřeva, lidská energie se měří pomocí akcelerometru na zápěstí experimentátora. Tato metoda pomáhá pochopit, jak se lidé rozhodovali s ohledem na technické a ekonomické podmínky v různých geologických, chronologických a sociálních prostředích.*

Klíčová slova: *těžba – energie – podpalování – dláto.*

Introduction

During the Middle Ages, wood and manpower were the primary sources of energy. Due to their cost and availability, both in terms of quantity and location, they played a crucial role in the development of industries. The choice of one energy source over another was a financial, societal, and technical decision that was closely linked to the amount of energy required to achieve a specific goal. Quantifying this energy provides a new perspective on technical solutions in constrained environments.

Medieval metallurgical production systems were highly sensitive to energy issues. According to Debeir et al. (2013), « Le manque de bois créait périodiquement […] des pénuries d'énergie thermique indispensable au traitement des métaux »[1]. These systems were particularly energy-intensive and were located as close as possible to mining resources, which sometimes resulted in a scarcity of certain energy resources. The Brandes-en-Oisans medieval mine (located in the French Alps) serves as a perfect example. Due to its high-altitude location in the Alps, the workforce had to reside far from the extraction site. It also meant that wood would need to be sourced and transported over long distances (Bailly-Maitre, 1993). Therefore, the selection of the ore extraction technique is not only a matter of energy but also a technical issue related to the nature of the rock.

Before the introduction of black powder in France in 1617 (Pierre 1991), two techniques coexisted for mining. The first technique was tool mining, which involved the use of a hammer

1 "The lack of wood periodically created [...] shortages of the heat energy essential for metal processing".

and handle chisel pair. The miner would place the handle chisel, on the wall and strike it with a hammer. This method is described in De Re Metallica (Agricola 1556) and is often depicted in ancient iconography (Kutnohorská iluminace 1490; Graduel de Saint-Dié 1510; La rouge myne de Sainct Nicolas 1525; Fig. 1). This pair of tools remains the most traditional symbol of the miners. Archaeological evidence of its use can be seen in the characteristic traces visible in certain galleries, or in the handle chisel found on mining sites such as Castel-Minier in Ariège, France (Méaudre, in press). It is rare to find miners' hammers due to the pragmatic reason that a miner would use a single hammer for a day's work, compared to a dozen handle chisel. In addition, the types of hammers used by the miners are similar to those used in other areas of metallurgical production. Schnitzler (1990) found some of these hammers in mines, providing insight into their size and weight. This initial mining method relied solely on human labour.

Figure 1. Illustration of mining with a hammer and a handle chisel. After Graduel de Saint-Dié 1510.

Obr. 1. Vyobrazení těžby s použitím kladiva a dláta s násadou. Podle Graduel de Saint-Dié 1510.

Mining by firesetting was another technique commonly used throughout the Middle Ages. This method involved weakening the rock using fire (Fig. 2). A pyre was set up against the work face. The heat from the fire would cause the rock to expand unevenly due to its heterogeneous composition, resulting in spalling. While thermal energy was an essential source of energy for firesetting mining, it was not the only one. The weakened rock is detached from the wall with a tool after the fire has died down (Agricola, 1556). This technique requires both thermal and human energy. It is typically used on hard rock where the tool is less effective. It is worth noting that some mines use both techniques, occasionally in the same gallery (Benoit, 1997).

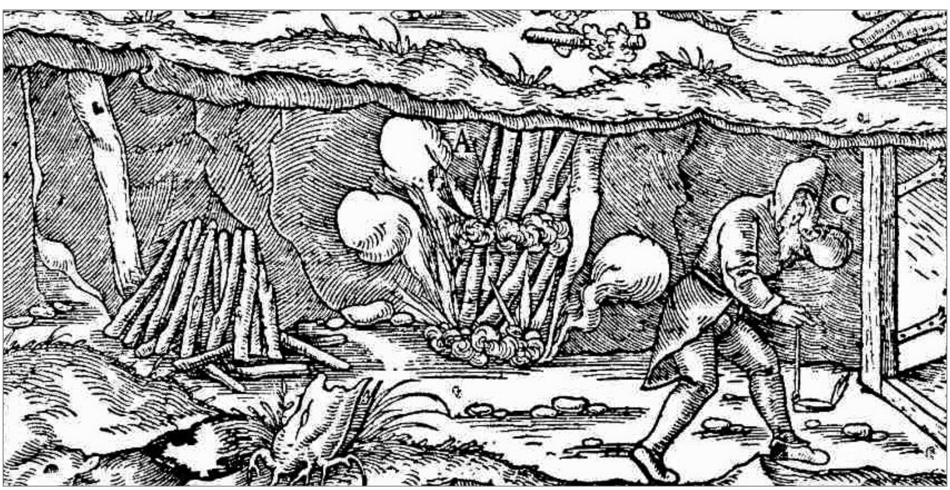

Figure 2. Firesetting engraving in De Re Metalica, Book V. After Agricola 1556.

Obr. 2. Rytina zobrazující podpalování v De Re Metalica, knize V. Podle Agricola 1556.

Experimental studies on firesetting have been conducted since the late 1980s. In the proceedings of the Early Mining in the British Isles conference, Welsh researchers published their first experiments on firesetting (Timberlake 1990; Lewis 1990; Crew 1990). The researchers were interested in the technique of firesetting in Bronze Age mines from a technical perspective. The studies focused on the method of making the pyre and the tools used to purge the rock. Researchers continue to be interested in extraction tools, and recent studies have provided a more precise understanding of their nature and usage within the production chain (Timberlake 2007).

At the same time, studies based on the extraction of ore by fire in historical periods began in France in the mid-1990s. These studies were complementary to those carried out previously, as the techniques for exposure to fire were similar. It is the use of the tool that differs. However, although it was taken into account, it was never the focus of these studies, which concentrated on the use of wood. This series of experiments begins with those carried out by Claude Dubois (Dubois 1996). He was interested in both the mining technique and the yield of rock spalled in relation to the mass of wood used, in order to obtain an estimate of the wooded area required for a mine to function properly. Although the four trials carried out do not address all the issues raised in his article, his work provides a basis for experimental mining.

Further work was carried out in the Melle mining district (in Deux-Sèvre, France). Firstly, it provided information on the use of fire in the mine (Téreygeol 1998). Secondly, a study was conducted on the temperature of the rock, which provided information on the timing of firesetting (Téreygeol 2000). Third study, carried out at Melle, provided data on the mass yield of firesetting, thanks to the large number of trials carried out (Téreygeol 2014). At the same time, mining trials were conducted at the Fournel mine in L'Argentière-La-Bessée (Hautes-Alpes), where 180 trials were carried out to measure the impact of parameters such as the type of wood, the mass of wood used and the way in which the pyre was set up (Py–Ancel 2006; Py et al. 2012). These experiments provide precious data through the repetition of firesetting.

Finally, a more archaeometric approach was taken to study firesetting and understand the changes in the mechanical properties of the rock after being subjected to fire. In 2014, a study analysed the rocks using thermogravimetry differential thermal analysis to compare the archaeological and experimental quarrying products (Popov et al. 2014). Another study proposed measuring the influence of temperature on the rock's elastic modulus to differentiate natural structures from those related to fire felling (Celauro–Maass 2019).

While the technique of firesetting has been extensively studied and understood for various periods, the same cannot be said for mining with a tool from an experimental perspective. It has been limited to wall clearing after the use of fire. This lack of experimental data on mining with tools hinders the understanding of technical choices made by ancient people, particularly in mines where both techniques coexist. Several factors influence the choice of a technique, such as the hardness of the rock, the ventilation present in the gallery, or the speed of advancement. Another factor, which is less discussed in the literature, is the energy expenditure. The concept of energy is anachronistic for the medieval world, and it was not scientifically defined until the 18th century (Debeir et al. 2013, 19). However, the ancients perceive it in their daily lives through the proxy of energy cost – financial cost, as well as through the finiteness of local resources, which is now referred to as the local energy mix. In this context, it can be defined as the set of locally available energy sources. For example, the abundance of wood resources allowed miners to continue using fire setting even after the introduction of black powder, as was the case in the Kongsberg mine in Norway. This study aims to quantify the energy expenditure of various mining techniques during the medieval period.

Archaeological remains are not always sufficient to estimate the energy expended to perform a given task. Only structures related to energy converters, such as a mill, or traces due to energy use, such as reddened earth under a hearth, are found. Experimentation is therefore a solution for quantifying this energy. It has the advantage of allowing measurements to be taken on converters while they are in operation, enabling direct measurement of energy. The traces and structures obtained in the course of the experiment make it possible, by comparison with the iconography and archaeological remains, to confirm the operational chain used.

Materials and methods

To enable a quantitative comparison of the two mining techniques from an energy perspective, a functional unit must be expounded. This unit must be measurable, precise, and additive. By using this unit, it is possible to compare the energy expended by two production systems. For this study, the functional unit will be one kilogram of extracted rock. Once the functional unit is given, the energy expended in the production processes can be compared. Only the energy consumed by the different production processes needs to be measured, and only then. The aim of the study is not to measure all the energy flows required to produce one kilogram of rock, but only those that differ between methods. The study quantifies the energy used when using the hammer and the handle chisel, but does not quantify the energy required to remove the rock and therefore the ore from the mine, which is identical in both cases. It is important to note that this study is limited to actions carried out in the mine.

Several methods exist for measuring an individual's energy expenditure, including the measurement of gaseous exchanges, global capture of movement by a set of cameras, or measurement of the individual's thermal exchanges (Levine 2005). While these methods are highly accurate, they are both costly and cumbersome, making them difficult to implement in a mining context. As a result, an alternative solution was chosen: the use of an accelerometer. However, it is important to note that this method has its limitations. It only provides an indirect measure of the energy produced by a limb. When mining with a tool, energy is mainly consumed by moving the arm holding the hammer. The accelerometer is therefore attached to the wrist of the experimenter holding the hammer.

The amount of thermal energy consumed during extraction is directly related to the mass and type of wood used. Based on these data and the calorific value of the wood, it is possible to calculate the energy released during combustion.

In this case, the accelerometer used is the METAMOTIONRL developed by MBientlab. It communicates with the MetaBase application via Bluetooth. For each experiment, accelerometer and gyroscope data were collected via Bluetooth at a frequency of 100 Hz. This method also requires the use of a camera that records the gesture at high speed, at least 60 frames per second. High-speed video makes it possible to use automatic gesture tracking in biomechanics software such as Kinovéa, facilitating the study of movement.

The tools used here are not exactly the same as those used by medieval miners. In this study, the hammer is a key element. It is the tool that consumes the most energy which is the only one measured. The four hammers identified as mining hammers, including the three found at Sainte-Marie-aux-Mines in Alsace (Schnitzler 1990, 498) and the one found in medieval Lorraine in the Mine de la Fontaine des Chouettes (Grandemange 1991, 94), weigh between 1.3 kg and 2 kg. For this experiment, we used a 2kg hammer due to tool availability. Handle chisels were not readily available and would need to be made. We chose to use a diamond-tipped chisel as we lacked the necessary skills and resources. This decision was made based on the understanding that it would not impact the results of our study.

Protocol

Tool mining

The mining experiments were conducted at the Castel-Minier site a metallurgical production site that was active between the 13th and 15th centuries, mainly for lead and silver metallurgy. Two sites were selected for the experiment: an outdoor quartzite wall and a shale working face

Figure 3. Mining with tools on a shale working face in the Lauqueille mine.
Obr. 3. Těžba s použitím nástrojů na břidlicovém povrchu v dole Lauqueille.

in the Lauqueille mine. For the Lauqueille mine, the selected working face had the benefit of direct contact with a window, enabling the experimenter to capture a profile video. This allowed for measurements to be taken on rocks of varying hardnesses. Shale has a hardness of 3.5 on the Mohs scale, while quartzite has a hardness of 7.

During this part of the study, a single experimenter carried out the various experimental sequences. He is an athletic man, which brings him closer to the endurance skills of the ancient miners. However, he had little training in mining techniques, which limited his ability to master the gesture.

The experiment necessitates the installation of a camera that films the experimenter in profile throughout the experiment at a frequency of 60 images per second. The accelerometer is placed on the wrist of the hand holding the hammer using a wristband. It is then connected via Bluetooth to the MetaBase application, where the required frequency and type of measurements are set. To use the accelerometer, initialization is needed: the experimenter holds his wrist horizontally for 10 seconds after starting the measurement on the application. Once completed, mining can begin (Fig. 3). The operator should place the handle chisel where they feel it is most appropriate, usually on a crack or hollow, and strike the tool with a hammer. Multiple strikes can be made without moving the handle chisel, and it is these various strikes that are measured.

To prevent excessive error accumulation, accelerometer measurements are restricted to a few minutes[2]. Therefore, it is necessary to take multiple measurements during the experiment. After approximately ten minutes of mining, the experiment is halted, and the collected rock is weighed.

2 The METAMOTIONRL sensor exhibits a significant time drift, which can result in substantial errors when the signal is integrated once or twice during data processing. To limit the extent of the time drift, it is recommended to use a short acquisition time.

Firesetting

The fire mining experiments took place on the experimental archaeology platform at Melle, which is also a former Carolingian silver-lead mine. The rock here is hard (silicified limestone), which historically meant that it had to be extracted by fire (Téreygeol 1998). The mining site was chosen to be outdoors, located in a recess that corresponds to an early medieval working face intersected by a 19th-century quarry face (Fig. 4).

Three trials were conducted for this experiment. In each trial, a 60kg[3] pile of wood was placed against the work face (Fig. 5). No action was taken until the fire burned out due to lack of fuel. The rock that had spalled off the wall was then collected and weighed. The rock was initially purged by hammering. The measurement did not include this human energy as it was insignificant compared to the other purge actions. Only fragile elements were detached at this point. The rock was then collected and weighed.

After this purge, the wall is worked on with a tool (Fig. 6) to remove the rock that has been weakened by the fire but is still properly attached to the wall (an essential step if only to return to unaltered rock that will be burnt again). The process of purging the wall using various tools is described in De Re Metallica: ‘Quae sic fractae decidunt: aut si etiam aliqua remanserit durities, eas ferramentis abrumpunt’[4] (Agricola 1556, 81). In this experimental sequence, mining stops when the rock is no longer detached from the wall by the stroke of the tool and when it produces a clear sound. The extracted rock is then collected and weighed, completing the fire mining sequence.

In this protocol there were two miner-experimenters. One carried out the first trial (Melle 1), and the second the other two trials (Melle 2 and Melle 3). Both were men who played sport and had some experience of mining at the Melle site. One of the experimenters, experimenter 1, carried out one of the fire tests and the two tool tests to ensure consistency in the measurements.

Figure 4. Experimental site for firesetting.

Obr. 4. Experimentální místo pro rozdělávání ohně.

3 The mass of wood making up the pyre is the highest permitting unidirectional tunneling. Additionally, a larger amount of wood would increase the cooling time of the rock surface (Téreygeol 2014).

4 ‘Thus broken off, the rock tumbles down; or if it still remains, they break it off with picks.’ Translation by H. C. Hoover and L. H. Hoover.

Figure 5. Pyre mounted on the working face.
Obr. 5. Oheň na opracovávaném povrchu.

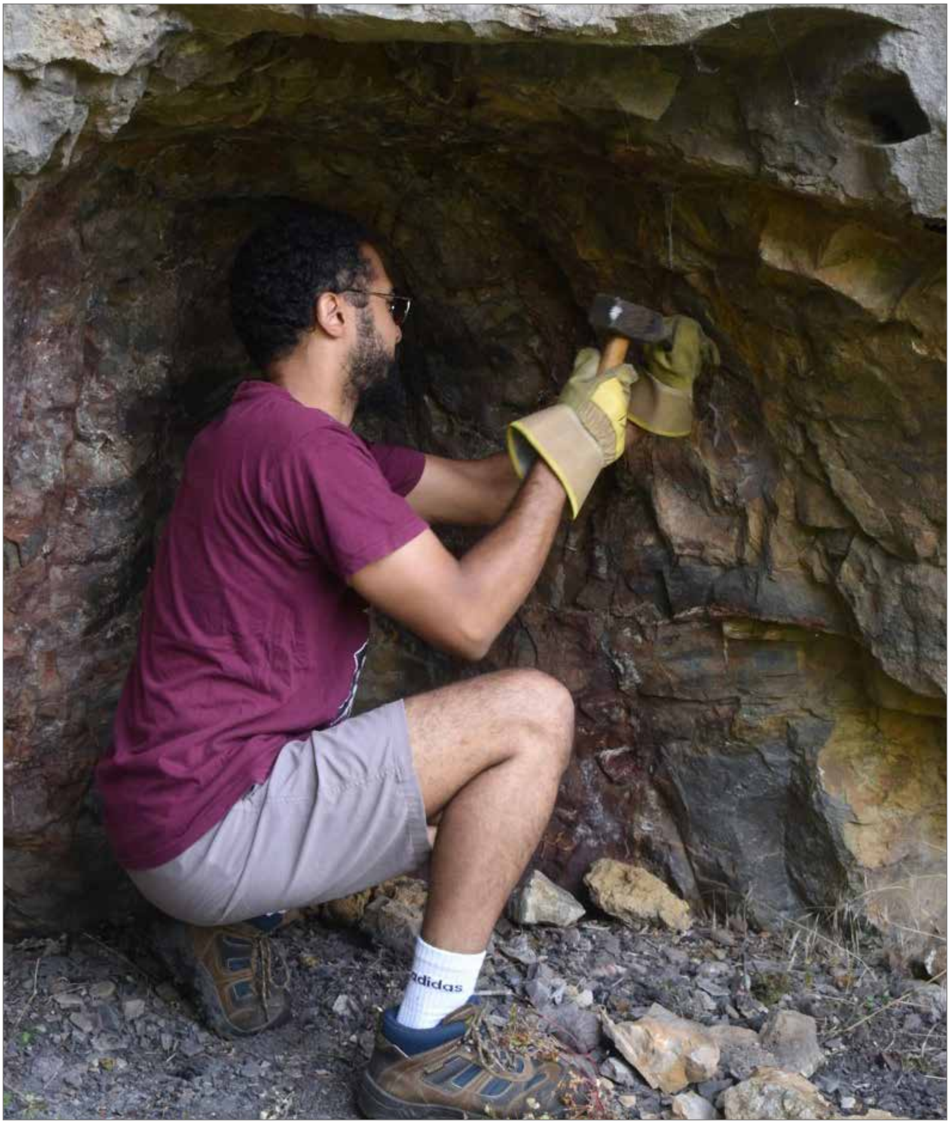

Figure 6. Removing the rock weakened by fire with tools.
Obr. 6. Odstraňování horniny oslabené ohněm pomocí nástrojů.

Data processing

The accelerometer data requires processing to obtain usable data and calculate the energy expended by the miner-experimenter. Due to sensor limitations, particularly some offset, accurately measuring the acceleration values of the experimenter's arm is complicated. However, as the experimenter's movement is periodic, we can deduce that the average acceleration value over a period is zero. By detecting each strike of the user on the chisel handle, we can eliminate the offset induced by time drift. This can be achieved by imposing a zero average acceleration over each period.

The video and gyroscopic data are used to detect 'strikes', corresponding to the miner's movement when striking the handle chisel with the hammer. The video is used to isolate the periods when the miner-experimenter was making this movement. Then, on this sequence, the gyroscope allows us to detect the strikes individually. A zero angular velocity indicates a change of direction in the movement. Given that the miner's movement is known, we can deduce a new strike when two changes in direction are detected by the gyroscope. The acceleration of each strike can then be determined. Before computer detection of the strikes, data processing is applied to the acceleration data to remove the gravitational component and express it in an appropriate frame of reference.

The energy supplied by the experimenter to make the strike can be calculated using the kinetic energy theorem. To apply this theorem, it is essential to know the mass set in motion during the strike. The scope of this study is limited to the use of one arm, and the system under consideration is therefore limited to the arm and the tool. The mass of this system is the sum of the mass of the tool and the experimenter's arm. The tool's mass is known, but the arm's mass must be calculated for each experimenter. As it cannot be measured, tables published in the literature must be consulted. In this case, we will use the tables proposed by Paolo De Leva (De Leva 1996), which show the mass percentage of each segment of the human body. For a man's upper limb, the mass percentage is 2.47 %.

Results

The experimental sequences carried out at the Castel-Minier site were used to measure the energy developed by the miner-experimenter during mining with a hammer and a handle chisel. The energy used for each strike was calculated, and the entire sequence was filmed to count the strikes. These data should be compared with the hardness of the rock and the mass detached during the experiment (Table 1).

In a similar way, the three experimental firesetting sequences carried out on the experimental archaeology platform at Melle were used to analyse the movements of the experimenters. Wood consumption was also measured. These data are summarised in table 2.

The experimental data allows for the calculation of thermal and human energy expended per kilogram of excavated rock. The thermal energy consumed during fire mining tests is calculated by multiplying the mass of burnt wood by the *calorific value* of the wood,

Table 1. Results of experimental sequences of mining with tool.

Tab. 1. Výsledky experimentálních sekvencí těžby pomocí nástrojů.

	CM Quartzite	CM Shale
Rock hardness	7	3.5–4
Number of strike	468	521
Average energy of a strike (J)	7.3	12
Mass of rock removed (kg)	10	12
Experimenter	1	1

Table 2. Results of experimental firesetting sequences.

Tab. 2. Výsledky experimentálních sekvencí těžby pomocí ohně.

	Melle 1	Melle 2	Melle 3
Mass of wood (kg)	46	60	60
Number of strike	1,439	788	859
Average energy of a strike (J)	22	9.6	13
Mass of rock removed (kg)	62	69	68
Experimenter	1	2	2

which is 14,400 kJ·kg^{-1} (Ollivier 2010, 170). Using this value, the total energy consumed in felling one kilogram of rock can be calculated (Table 3). This value is applicable to all mines with similar rock types, regardless of their location.

Table 3. Human and thermal energy consumed to obtain one kilogram of ore using fire and tools.

Tab. 3. Spotřeba lidské a tepelné energie k získání jednoho kilogramu rudy pomocí ohně a nástrojů.

	CM Quartzite	CM Shale	Melle 1	Melle 2	Melle 3
Human energy per kilogram (J·kg^{-1})	278	500	255	110	164
Thermal energy per kilogram (J·kg^{-1})	0	0	$1.07 \cdot 10^{7}$	$1.25 \cdot 10^{7}$	$1.27 \cdot 10^{7}$

Discussion

Mining with tools

The energy required to break down one kilogram of rock varied by a factor of two between the two tests carried out: 280 J·kg^{-1} compared with 500 J·kg^{-1}. Surprisingly, quartzite, a hard rock, requires less energy. There are two possible explanations for this difference. Firstly, the energy required to break the rock depends on its nature (Chamayou–Fages 2003, 379). The competence of a stone is its tendency to break rather than deform under stress, as it is easy to crush a piece of chocolate and almost impossible to do the same with a marshmallow. There is no quantitative value describing the competence of a rock. However, the Bond coefficient, which is used in an equation to calculate the energy required for comminution, can be used to specify this characteristic as it is linked to competence. For instance, quartzite has a Bond coefficient of 48,3 kJ·kg^{-1}, while shale has a Bond coefficient of 65 kJ·kg^{-1} (Valero et al. 2011). Therefore, quartzite is considered to be a more competent rock than shale and is therefore easier to extract.

The difference in energy can also be attributed to the state of the work faces where the experiments were conducted. The quartzite surface, being outside, was weathered, unlike the shale located 30 m underground, making it less energy-intensive to mine. Unfortunately, a quartzite working face accessible by mine was not available for a new measurement campaign. However, this should not obscure the fact that there is a difference in energy consumption whether or not the quartzite is weatheref.

As well as providing energy data, the experiments also allowed us to calculate the advancement speed of our experimental miners. Advancement speed is defined as the distance between the start and end face in a given time. By determining the power of the miner-experimenter from the accelerometer data, and knowing the energy required to remove one kilogram of rock and the average dimensions of a gallery (i.e. 2 m^2), we can calculate the theoretical advance of the miner-experimenter. This is between 14 cm and 20 cm, depending on the miner's working time (between 8 and 12 hours). The values obtained correspond to those recorded for the advance of miners in the dewatering gallery of the Pampailly mine: between 10 cm and 28 cm per day (Benoit 1997).

Firesetting

The total mass (fire and tool) felled in each trial was constant. It varies between 62 kg and 69 kg for the same mass of wood used in the pyre. This is not the case for human energy. Whether it is the energy expended to detach one kilogram of rock or the total energy, there is a variation between trials: from 110 J·kg^{-1} to 255 J·kg^{-1} and from 7.6 kJ to 16 kJ in total. This variation can be linked by the efficiency of the fire.

Although statistical confirmation of this trend is lacking due to insufficient data, studies on the mechanical properties of thermally damaged rock allow for the formulation of hypotheses regarding these variations. Heating a rock causes a decrease in its compressive strength due to micro fracturing and macro fracturing (Takarli et al. 2006, 7). The rock's fracture resistance decreases as the temperature increases. During certain mining operations, the rock temperature may not consistently reach the same maximum temperature. This can result in varying fracture strengths and, consequently, increased energy expenditure for certain essay (Table 4).

Table 4. Variation in the human energy required during the different firesetting tests in relation to fire performance.
Tab. 4. Rozdíly v lidské energii potřebné během různých testů podpalování v závislosti na výkonu ohně.

	Melle 1	Melle 2	Melle 3
Experimenter	1	2	2
Human energy per kilogram ($J \cdot kg^{-1}$)	255	110	164
Total human energy (kJ)	16	7,6	11
Mass of rock removed / Mass of wood	0.87	0.67	0.72

The energy required to transport the wood must then be added to the energy required to extract the firewood. Padlof's formula is used to estimate this energy (Looney et al. 2018). The formula is as follows:

$$P = 1.5m + 2(m + L) + \eta(m + L)(1.5S^2 + 0.35G)$$

Where P is the metabolic load of the individual (in W), m is his mass (in kg), L is the load (in kg), S is the speed (in $m \cdot s^{-1}$), G is the slope (in %) and η is a coefficient that takes into account the nature of the ground, here η = 1 for hard ground. We can then come back to the energy used for the round trip, with the outward journey carrying the wood and the return journey empty:

$$E = \frac{D}{S(P_o + P_w)}$$

Where D is the distance covered and E is the energy expended by the body, P_w is the internal power of the man transporting the wood, and P_o is the internal power of the man walking out of charge.

It is important to note that this is not the mechanical energy provided by the individual, but the energy associated with the metabolic load, i.e. the energy used by the human body to perform a task.

Let us assume that the miner weighs the same as our subject 2, that he moves at a speed of 4 $km.h^{-1}$, and that the mass transported is equal to the mass of wood of four log. We can then derive a formula that gives the energy consumed by the miner as a function of the distance travelled in the mine:

$$E = 861D$$

Where D is the distance covered in metres and E is the energy expended by the body in Joules.

The rate of advance per day is also a relevant indicator of the effectiveness of a mining technique. It certainly depends on the nature of the rock, but the same order of magnitude can be observed between the different experiments. The sources make no mention of the progress of fire mining. In general, they only mention the quantity of ore obtained, and fire is rarely used in the case of a strong vein, because fire alters the ore (Téreygeol 2000). The experimental approach is therefore the only one we can rely on, and the large number of fires carried out gives a good estimate of the average rate of advancement.

The first step is to determine the number of fires per day. Some literature suggests two fires per day (Dubois 1996, 44; Py et al. 2012). However, work carried out in a mine at the Melle site suggests a different time frame. Heat and smoke are difficult to dissipate in the mine and the working face is inaccessible for more than five hours (Téreygeol 2014, 68). In addition, the face is cleaned with the tool, the mined rock is sorted and transported out of the mine. On a working face, therefore, only one fire can be made per day, which runs counter to the figures proposed by Claude Dubois and Vanessa Py. These differences can be explained by the length of the working day proposed by Claude Dubois, which is based on a 24-hour day, and by the fact that the measurements carried out by Vanessa Py and Bruno Ancel at the Fournel mine, in Franch Alps, were made in a large room where cooling is much faster than in the old galleries. In this study, the calculations are carried out with one fire per day and the same assumptions as for tool mining: between 8 and 12 working hours per day and a working face of 2 m². Using these different data, we obtain (Table 5).

Table 5. Average advancement of the work face after firesetting.

Tab. 5. Průměrný postup u opracovávaného povrchu po zapálení ohně.

Mine	Advancement in cm per day	CM Shale
Melle (this study)	1.9	3.5–4
Melle (Téreygeol 2014)	2.5	521
Fournel (Py–Ancel 2012)	1.1	12
Mass of rock removed (kg)	10	12
Experimenter	1	1

Comparison

Firesetting is much more energy-intensive than tool mining. The pyre radiates heat in all directions; so much of the heat generated is lost by heating the surrounding air. In addition, all the rocks around the fire heat up, but not all of them reach the temperature required to make the rock brittle, which again leads to losses. The energy efficiency of firesetting is low. What's more, the energy required to transport the wood is considerable when the working face is far from the mine entrance. Finally, the rate of advance is between 4 and 30 times slower. Nevertheless, this technique was used in the Middle Ages. This raises the question of the reasons why it was used. Several hypotheses can be put forward. Firstly, the hardness of the rock may have influenced this choice. Some rocks are too hard to be quarried with a tool. This is the case in the Melle mining district. The energy that would be expended by a miner using a tool is not quantifiable; only the tool wears out and the rock is not excavated efficiently. The energy and financial costs are far too high to choose this technique. The second reason is resource availability. While the amount of energy may seem significant, when you come back to the mass of wood, it seems less so. In fact, the financial cost of resources and their availability play a role in the choice of technique.

Some mines show evidence of the use of both techniques, as priviously reminded, even in the same gallery (Benoit 1997; Téreygeol 2008), despite the technical difficulties, slow progress and high energy costs inherent in the use of fire in mining. The Pampailly mine in the Monts du Lyonnais and the Castel-Minier mine in the Pyrenees offer different interpretations of the almost simultaneous use of these techniques. In the Pampailly dewattering gallery, only a small part of the gallery was excavated by firesetting. The rest was mined using tools. The archives of the mine provide some clues. The part carved by fire was only a small part of the gallery. In this section of the gallery, the rock was too hard to be cut with a hammer and chisel. Despite the slow progress of fire mining, the high expenditure of thermal and human energy, and the long distance between the working face and the entrance to the gallery (about 200 m), the miners were forced to use firesetting for that part.

The case of Castel-Minier is different. The archaeological and geological evidence does not suggest that mining was difficult. Another hypothesis is that fire was used to save human energy. In fact, the extraction of one kilogram of rock with a tool requires 390 J of human energy. If fire is used, 180 J of human energy is consumed, plus the energy required to transport the wood to the mine. Thus, there is a distance limit below which fire mining requires less human energy. Knowing the total energy required to obtain one functional unit by mining with tools or by firesetting, as a function of the distance to be travelled in the mine, it is then possible to calculate the limit distance. Its value is such that the two energies are equal. After some calculations we have the following formula for the description of the distance limit.

$$D_{lim} = \frac{(E_t - E_f)SM_tM_f}{2P_oM_f - M_tN(P_w + P_o)}$$

Here D_{lim} is the limiting distance, E_t is the miner's internal energy expenditure to obtain one functional unit using tools, E_f is the miner's internal energy expenditure to obtain one functional unit using fire (not including the transport of the wood), S is the speed of the man transporting the wood, P_w is the internal power of the man transporting the wood, P_o is the internal power of the man walking out of charge, M_t is the total mass of rock obtain during one day of mining with tools, M_f is the total mass of rock obtain during one day of firesetting, N is the number of round trip needed to get all the wood near the work face (the assumption was made that a miner could carry four log).

Applying this formula to the case described in our study, the limiting distance for shale is 18m. Therefore, if the working face is less than 18 m from an access point, the use of firing saves human energy[5]. In the case of Castel-Minier, timber was not a limiting resource, so the hypothesis of saving human resources seems relevant. It should be noted, however, that the concept of energy is anachronistic. This limit is not clearly visible in the archaeological remains.

Conclusion

This study quantified the energy consumption of the two extraction methods used in ancient mines. The tool-only technique requires a lot of human energy. It takes about 400 J to extract one kilogram of rock. Depending on the nature of the rock and the technical skills of the miners, the working face can be advanced between 10 cm and 30 cm. The use of fire is more energy intensive. Mining by fire requires the combined use of two types of energy: about $1{,}2 \cdot 10^7$ J of thermal energy from burning wood and 200 J of human energy to extract one kilogram of rock. To this must be added the energy required to transport the wood to the mine. Mining by fire progresses at a rate of less than 3 cm per day.

So, from an energy point of view, it is more efficient to use tools if we look at global energy consumption, unless the rock does not allow it. However, a study of archaeological remains suggests that the use of fire may be preferred to the use of tools in order to save human energy. In fact, under certain conditions of access to the working face, mining with fire consumes less human energy than using a hammer and chisel for a functional unit. A greater number of studies on different types of rock could provide a better understanding of this condition. Even if this limitation influenced the decisions of the ancients, it was by no means perceived in quantitative terms of energy.

In addition, this study has made it possible to develop a new use for the accelerometer by using it in experimental archaeology to obtain quantitative measurements of the energy expended by humans. The energy approach offers new possibilities for the quantitative comparison of ancient techniques.

This energy approach can be extended to the whole mining and metallurgical production system, both through the use of accelerometers and through numerical simulations modelling energy converters. In the long term, this could lead to global energy modelling of the metallurgical production chain to understand technical decisions and resource management issues.

These results, measured for the Melle and Castel-Minier mines, can be applied to other ancient mining systems. The energy values obtained are of the same order of magnitude, as long as the nature of the rock remains similar. If there is a major difference, new experimental sequences can be carried out to obtain the missing data. In addition, these results can be extrapolated to all periods using these methods.

5 The measurement of human energy is influenced by the limits of the expert's abilities. Although the participants are sportsmen, they are not medieval miners. However, it is possible to estimate if their Metabolic Equivalent of Task (MET) is within the expected range. Human efficiency is 14 % (Lacour 2011), so for this study, the MET is approximately 2.6, which corresponds to the effort required for some household tasks. Although the value may seem low, it is important to consider that we only measured the energy of one arm.

Bibliography

AGRICOLA, G., 1556: De Re Metallica. In: De Re Metallica. Basel.

BAILLY-MAITRE, M. C., 1996: Brandes-en-Oisans: incidences d'un milieu alpin sur une exploitation minière médiévale. In: L'homme et la nature au Moyen Âge. Paléoenvironnement des sociétés occidentales. Actes du Ve Congrès international d'Archéologie Médiévale, 235–245. Caen.

BENOIT, P., ed., 1997: La mine de Pampailly, XVe–XVIIIe siècles: Brussieu–Rhône. In: La mine de Pampailly, XVe–XVIIIe siècles: Brussieu, Rhône, DARA. Lyon. https://doi.org/10.4000/books.alpara.1794

BRUN, T. A. et al., 1979: Brun, T. A.–Geissler, C. A.–Mirbagheri, I.–Hormozdiary, H.–Bastani, J.–Gedayat, H., The energy expenditure of Iranian agricultural workers, The American Journal of Clinical Nutrition 32, 2154–2161. https://doi.org/10.1093/ajcn/32.10.2154

CELAURO, A.–MAASS, A., 2019: The Variation of Elastic Modulus and Changes of Structures and Mineral Phases in Rocks as Parameters for the Identification of Fire-Setting in Ancient Mines, EXARC Journal Issue 1.

CHAMAYOU, A.–FAGES, J., 2003: Broyage dans les industries agroalimentaires. In: Technologie des pulvérulents dans les IAA, Sciences & Techniques Agroalimentaire (Melcion, J. P.–Ilari, J. L., edd.), 375–406.

CREW, P., 1990: Firesetting Experiments at Rhiw Goch, 1989. In: Early Mining in the British Isle, 57. Plas Tan y Bwlch.

DEBEIR, J.-C.–DELEAGE, J.-P.–HEMERY, D., edd., 2013: Une histoire de l'énergie: les servitudes de la puissance. In: Une histoire de l'énergie: les servitudes de la puissance. Paris. https://doi.org/10.14375/NP.9782081293618

DE LEVA, P., Adjustements to Zatsiorsky-Seluyanov's segment inertia parameters, J. Biomechanics 29(9), 1223–1230. https://doi.org/10.1016/0021-9290(95)00178-6

DUBOIS, C., 1996: L'ouverture par le feu dans les mines: histoire, archéologie et expérimentations, Revue d'Archéométrie, no. 20, 33–46. https://doi.org/10.3406/arsci.1996.935

GRANDEMANGE, J., ed., 1991: Les mines d'argent du duché de Lorraine au XVIe siècle Histoire et archéologie du Val de Lièpvre (Haut-Rhin). In: Les mines d'argent du duché de Lorraine au XVIe siècle Histoire et archéologie du Val de Lièpvre (Haut-Rhin), DaF. Paris. https://doi.org/10.4000/books.editionsmsh.36428

GROFF, H., c. 1530: La rouge myne de sainct Nicolas.

LACOUR, J.-C., 2011: Activité musculaire et dépense d'énergie. In: Revue des Maladies Respiratoires 28. Série exploration fonctionnelle à l'exercice. Paris. 1278–11292. https://doi.org/10.1016/j.rmr.2011.06.014

LEWIS, A., 1990: Firesetting Experiments on the Great Orme, 1989. In: Early Mining in the British Isle, 55–56. Plas Tan y Bwlch.

LOONEY, D. et al., 2018: Looney, D.–Santee, W.–Karis, A.–Blanchard, L.–Rome, M.–Carter, A.–Potter, A., Metabolic Costs of Military Load Carriage over Complex Terrain, Military Medicine 183, e357–e362. https://doi.org/10.1093/milmed/usx099

MEAUDRE, J.-C. et al., in print: Meaudre, J.-C.–Tereygeol, F.–Gosselin, M.–Dillmann, P., Study of the medieval mining tools of Castel-Minier (Pyrenees) in the European context between the 14th and 15th c. In: Acta rerum naturalium, 28. Jihlava.

OLLIVIER, P., 2010: Les différents types de bois énergie: caractéristiques et approvisionnement, Forêt Méditerranéenne XXXI(2), 169–176.

PIERRE, F., 1991: Vallée de la Moselle (Vosges). Mines d'argent et de cuivre, Archéologie médiévale 21(1), 409.

POPOV, H. et al., 2014: Popov, H.–Tsintsov, Z.–Jockenhovel, A.–Georgiev, P., Feuersetzen beim Abbau der goldhaltigen Quarzgänge im spätbronzezeitlichen Goldbergwerk auf dem Ada Tepe, Südbulgarien. In: Experimentelle Archäologie in Europa 13, 27–44. Unteruhldingen.

PY, V.–ANCEL, B., 2006: Archaeological experiments in fire-setting: protocol, fuel and anthracological approach, BAR International Series S, 1483, 71–82.

PY, V.–ANCEL, B.–MARCONNET, C., 2012: De l'usage minier du feu: sources et expérimentations, Cahier des Techniques de l'INRA, Des outils des machines et des hommes (8), 133–153.

SCHNITZLER, B., ed., 1990: Vivre au Moyen-Âge: 30 ans d'archéologie médiévale en Alsace. In: Vivre au Moyen-Âge: 30 ans d'archéologie médiévale en Alsace. Strasbourg.

TEREYGEOL, F., 1998: Les mines de Melle (Deux-Sèvres): une expérimentation d'attaque au feu insitu. In: L'innovation technique au Moyen Âge. In: L'innovation technique au Moyen Âge, Actes du Congrès de la Société d'Archéologie Médiévale, 111–133. Dijon.
– 2000: L'abattage au feu: étude des variations de température et de la nature des roches lors d'une attaque au feu. In: Actes des Rencontres Internationales d'Archéologie et d'Histoire d'Antibes, 531–544. Antibes.
– 2008: Le Castel-Minier (Aulus-les-Bains), Fouilles programmées. In: Rapport intermédiaire, tapuscrit, SRA Occitanie (Téreygeol, F., dir.).
– 2014: A la main ou au feu: les choix techniques pour l'extraction des minerais argentifères. In: Du monde franc aux califats omeyyade et abbasside: extraction et produits des mines d'argent de Melle et de Jabali (Téreygeol, F., ed.), 55–76.
– 2018: La place de l'expérimentation dans l'étude des procédés métallurgiques anciens. In: La place de l'expérimentation dans l'étude des procédés métallurgiques anciens, Mémoire HDR, Université de Haute-Alsace.
TAKARLI, M.–PRINCE, W.–MOLEZ, L., 2006: Etude expérimentale de l'endommagement thermique du granite: Mesures destructives et non destructives. In: 24èmes Rencontres de l'AUGC: « Construire: les nouveaux défis ». La Grande Motte.
TIMBERLAKE, S., 1990: Firesetting and Primitive Mining Experiment, Cwmystwyth, 1989. In: Early Mining in the British Isle, 53–54. Plas Tan y Bwlch.
– 2007: The use of experimental archaeology/archaeometallurgy for understanding and reconstructing early Bronze Age mining and smelting. In: Metals and Mines: Studies in Archaeometallurgy, 27–36. London.
VALERO, A.–CORTES, C., 2011: Exergy of comminution and the crepuscular planet. In: Proceedings of the 6th Dubrovnik Conference on Sustainable Development of Energy Water and Environmental Systems. 25–29. Dubrovnik.

Shrnutí

Ekonomika středověké těžby pomocí ohně či dláta: otázka energie

Před zavedením střelného prachu ve Francii v roce 1617 existovaly dvě techniky těžby. Jednou z nich byla těžba pomocí nástrojů, při níž se používaly kladivo a dláto s násadou. Archeologickými doklady jejich používání jsou charakteristické stopy v některých štolách nebo nálezy dlát s násadou v dolech. Tento způsob těžby byl založen výhradně na lidské práci. Další metoda, která se v průběhu času prosadila, spočívala v oslabování horniny za pomoci ohně. Na opracovávaném povrchu se zapálil oheň, přičemž teplo v důsledku heterogenního složení horniny způsobilo její nerovnoměrné rozpínání. Tepelná energie byla sice základním zdrojem energie pro těžbu za pomoci ohně, ale nikoli jediným. „Oslabená" hornina se následně oddělila od stěny nástrojem. Tato technika vyžadovala jak tepelnou, tak lidskou energii.

Volba mezi těmito dvěma metodami závisela na tvrdosti těžené horniny a také na zdroji použité energie – buď energie lidské, nebo tepelné energie dřeva. V druhém případě hraje významnou roli i dostupnost paliva. Abychom pochopili technická a ekonomická hlediska při rozhodování, kterou z metod použít, byla provedena studie zaměřená na množství vynaložené energie. Postup je založen na experimentální archeologii a zahrnuje testy, prováděné v různých středověkých dolech, umožňující měření energie. Množství tepelné energie je v korelaci s hmotností spáleného dřeva. Lidská energie se měří pomocí akcelerometru na zápěstí experimentátora.

Těžba pomocí nástrojů vyžaduje 300 až 500 joulů na kilogram vytěžené horniny, konkrétní množství energie závisí na povaze horniny a její náchylnosti k rozrušení při nárazu. Naproti tomu při těžbě ohněm je k získání jednoho kilogramu horniny zapotřebí přibližně $1{,}2 \cdot 10^7$ joulů tepelné energie a 110 až 255 joulů lidské energie, navíc je nutné připočíst energii potřebnou k dopravě dřeva do šachty. Pokud tedy není hornina tvrdá natolik, že se nedá použít nářadí, je užití ohně vždy energeticky náročnější.

Díky experimentům také bylo možné vypočítat rychlost, jakou horníci postupují štolou. U těžby za pomoci ohně jsou to 3 cm za den, zatímco při těžbě s nástroji je to 10 až 30 cm za den.

Ve většině případů se zdá, že těžba za pomoci ohně je nevýhodná. Archeologické nálezy však naznačují, že se používala k dobývání některých hornin, které se daly zpracovávat i nástroji. To lze vysvětlit, vezmeme-li v úvahu dostupnost energetických zdrojů. Některá místa oplývají dřevem, zatímco pracovní síla je vzácná a nákladná a za určitých podmínek se při těžbě ohněm spotřebuje méně lidské energie než při použití kladiva a dláta.

Z energetického hlediska je tedy efektivnější používat nástroje, když posuzujeme globální spotřebu energie – pokud to ovšem charakter horniny dovoluje. Studie archeologických nálezů však naznačuje, že v zájmu úspory lidské energie mohlo být používání ohně upřednostňováno. Tento přístup zohledňující vynaloženou energii lze rozšířit na celý systém důlní a hutní výroby, a to s využitím jak akcelerometrů, tak numerických simulací modelujících energetické konvertory. V dlouhodobém horizontu by mohl přinést globální energetickou modelaci metalurgického výrobního řetězce, aby bylo možné porozumět tomu, jak se lidé rozhodovali při výběru technického postupu a v otázkách využívání zdrojů.

Florence **Maqueda**, NIMBE, LAPA, Bat 637, CEA Saclay, 91191 Gif-sur-Yvette, France, *florence.maqueda@cea.fr*

Prof. Nicolas **Florsch**, Couloir 56-46, 3ème étage, case 105, 4, place Jussieu 75252, Paris cedex 05, France, *nicolas.florsch@sorbonne-universite.fr*

Florian **Téreygeol**, Senior Researcher, NIMBE, LAPA, Bat 637, CEA Saclay, 91191 Gif-sur-Yvette, France, *florian.tereygeol@cea.fr*