Project Number: 48-EMP-HGMW

Mining and Metallurgy to the Renaissance

An Interactive Qualifying Project Report

submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

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Date: July 22, 1999

Project Abstract

The Higgins Armory staff are interested in the processing of metals before they reach the hands of the armor-maker. This project is a collection of some of the information available on mining, metal-working, and the early metal industry of Europe up to the Renaissance. It is intended to serve as an introduction for staff, and to provide information that they can incorporate into their guided tours of the museum.

Acknowledgements

The project team would like to thank the following people for their assistance and efforts.

Professor E. Malcolm Parkinson, our project advisor, for his guidance, patience, and instruction on this project.

Linda Honan, the former Director of Instruction, and Kent dur Russell, the Director of the Higgins Armory Museum, Worcester, for their support and interest in this project.

Georgius Agricola and Vannoccio Biringuccio, long deceased, without whose work this project could not have been undertaken.

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De Re Metallica

Introduction

The Higgins Armory Museum staff has a need for information relating to the production of arms and armor. Much is known about the use of the armor and weapons, some about the original ownership of individual pieces, but often knowledge is limited about the process used in the creation of the collection pieces. Compared with the knowledge of the finished weapon or suit of armor, much less is known about the origins of the material used to make these items and the techniques used in producing them by craftsmen of the time. Little is known about the skills of craftsmen who mined the raw ore from the ground and refined it into workable metals. It is the goal of this research to begin the process of presenting some of this limited knowledge into a form that will benefit the museum's staff in their general knowledge and in the information presented in their gallery tours.

This report covers the very beginning of the production of weapons and armor, focusing on what is known of mining, assaying, and smelting, from the removal of metal ores from the ground to the point where an armorer or sword maker would purchase the pure and refined metals. The methods of mining, assaying, and smelting in Europe from the beginning of the Iron Age through the Renaissance have been included as well as a summary of the properties of these metals, common beliefs about them for the time, and a focus on the two major metallurgical writers of the Renaissance.

Any summary or discussion of the mining process must contain at least the following topics. Firstly, the ore must be located within the earth and mined. After this a small portion is taken to the assay to determine what metals are present within the ore.

Finally, the ores are smelted and refined into their pure states where they may be shaped into useful items or combined to create alloyed metals. To compile this information in such a way as to be clear and easy to follow, the following chronological order to the chapters has been given. The chapters will proceed forward in time from the ancient period to the time of the Roman Empire, through the medieval period, and finally into the Renaissance. Within each of these time periods the work done by laborers and skilled craftsmen has been broken into three distinct sections; the methods, tools, and machinery utilized for mining, followed by the techniques of the assaying of metals, and finally the large-scale smelting of metals to make them pure.

Research for this project was difficult due to the scarcity of resources. Linguistic difficulties arose due to the lack of English translations of much of the relevant work. Translation into English from many of the Renaissance and late medieval texts has never often been performed; as none of the group members have attained fluency in the languages necessary, utilising these texts proved impossible. In particular, the medieval period presented difficulties, not only due to the aforementioned challenge provided by the language, but also due to the lack of facts written down in any language.[1] The lack of surviving Greek and Roman treatises on metallurgy, combined with the changes in the meanings of words throughout time, has created discrepancies in understanding the concepts presented by the remaining works. Given these limitations, the work presented here is as complete as possible, but is by no means an unabridged reference to the theory and practice of metallurgic science throughout the time span of the museum's collection.

[1] See sections on "Distribution of Information".

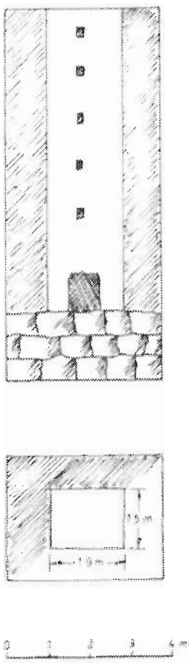
Ancient sources

There is a general lack of original material--especially witness accounts--dealing with ancient mining and metallurgical practices. This is partly due to the fact that not all the materials written on the subjects have survived to the present day. It is also attributable to the disdain with which the Romans regarded manual labor. Consequently writings on the practices are few and less concerned with methodology then with the results of mining and metalworking processes.

Another problem with ancient sources is the fact that translation is limited by the dilemma of translating technological terminology to the closest modern equivalents. In some cases, the ancients made distinctions that do not coincide with modern concepts and terms, making translation difficult.

Ancient and Roman Mining Technique

Figure 1: Shaft[1]



Opencast and underground mining techniques were known to be used as far back as the Stone Age, in the form of simple surface stripping or shallow pits. By the Bronze Age, these simple techniques were replaced with more ambitious methods of adits for pitting and simple shaft and gallery workings. An adit is a sloping tunnel cut from the surface, typically into a hillside. Pitting an adit is simply the digging of shallow excavations in the floor of the tunnel, for the removal of ore. A shaft is a vertical excavation cut to provide access to ore that is located below the surface. Galleries are the horizontal tunnelings from a shaft that provide access to the ore itself, via overhand or underhand stoping; removal from the ceiling or floor, respectively.

Greek Mining

Prospecting

The ancient Greeks are not credited with extensive knowledge of geology, and are thought to have relied largely on visual signs of ore at the surface. Exposure of a mineral at the surface or fragments of it are prime indicators of its existence, as the mineral ores that the ancients were seeking were typically brighter in coloration than the surrounding rock. The density of ore minerals is also typically higher than that of the surrounding rock, and when washed downstream ore will gather in areas of low movement, forming

[1] Shepard, Ancient Mining (London and New York: Institution of Mining and Metallurgy, 1993).

alluvial deposits or placers that could be distinguished easily and gathered readily. These deposits could sometimes be traced back to the original source. The state of the vegetation above an ore deposit is also an indication of its presence. Many plants cannot tolerate certain minerals, for example copper, and so would not be found in abundance or health above such a deposit, whereas those plants that are tolerant of the mineral would be flourishing.

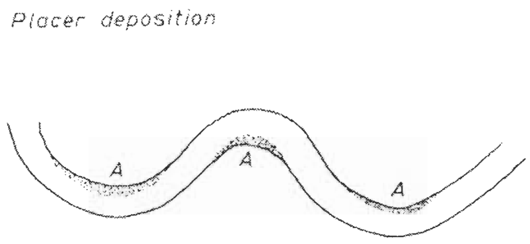


Figure 2: Formation of alluvial deposits[2]

Placer Mining or Panning

The first deposits exploited by the Greeks were alluvial, or placer deposits, left along the path of water carrying fragments of ore, especially in the curvature of rivers. As placers, the deposits could simply be gathered up by panning, which exploits the higher density of ore, or by simple gathering, if the fragments were large enough.

The Pactolus and Hermus rivers both had formed placers that were mined by the Greeks. It is believed that the alluvial deposits of the region were exhausted by the 5th century B.C.

Opencast Mining

Opencast mining refers to any mining operation that penetrates the earth but does not have a ceiling[3]. Large pits and trenches fall in this category, as well as more modern

[2] Ancient Mining, 6.

strip-mining techniques. Opencast mines are used when the ore outcrops at the surface or is covered by a thin layer of intervening material, known as overburden. The opencast mines operated by the ancient Greeks are believed to be a response to the depletion of placer deposits.

Underground Mining

The principal underground mining technique used by the Greeks was a simple shaft and gallery system, in which a single shaft is cut from the surface down to the level of the ore deposit, and then galleries that follow the ore are cut radiating out from the shaft. The galleries made by the Greeks were square or rectangular in section, unless cut to follow the ore bodies exactly, in which case they would be irregular. If the gallery was cut in soft rock, wooden post and lintel supports were added to reinforce the roof and walls against collapse. If wood was not available, columns of ore were left uncut as supports instead.

Another technique that has been in use since approximately 3000 B.C. is the technique of fire-setting, in which the rock face that is intended to be worked is treated by the setting of a large fire against it. This causes fracturing and splitting of the rock, if left to burn overnight, which makes the rock brittle and much more workable for up to a depth of 30 cm.

A principal difficulty faced by Greek miners was the provision of adequate ventilation. The heat of the depth, which increased by 1°C every 30 meters[4], as well as

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[3] Ancient Mining 11, 192: Shepard states at length that this is an incorrect usage of the terminology **opencast**, which should only refer to the modern opencast technique developed in the late 19th century.
[4] Ibid. This figure varies per mine. Shepard indicates that Ardallion generated the one included, in his study of Laurion.

the workers' breathing, the mineral dust, the decay of support timbers, and the smoke from light sources all combined to make the air foul, if not poisonous as in the case of cinnabar (mercury ore) mines. This limited the maximum depth of workings, as well as the maximum length of galleries.

It is theorized that the Greeks may have used shaken linen cloths to move the air manually, as well as cloth windscoops, similar to the sails used on the ships of the time. The use of the fire-setting technique may also have provided ventilation, due to the convection of hot air, and the draw of air to feed oxygen to the combustion.

Another difficulty of underground mining is lighting, which the Greeks solved with adaptations of domestic and urban lighting fixtures. Torches of resinous wood, skins soaked in oils, and simple oil lamps all provided smoky light.

The final difficulty in underground mining is the drainage of water, which becomes necessary if the mine penetrates the level of the local water table. The Greeks typically employed manual baling to remove water, which is slow and inefficient, and so they rarely penetrated below water level at all.

The removal of ore in ancient mines was also done manually, by workers specifically designated for the task. Diodorus Siculus wrote that boys were hired to do this work, while Pliny wrote that the miners carried it out on their backs.

Roman Mining

The Romans inherited many of their basic mining techniques from the Greeks and Egyptians, though they did add some new techniques, as well as making a general improvement to existing technologies.

Prospecting

The Romans are credited with a greater knowledge of general geology, though it is believed that they still relied heavily on visual surface indications. The lead mine at Bottino suggests that the Romans did have enough understanding of the nature of faults in rock to know when to pursue a vein of ore beyond one.

Placer Mining

By the time of the Romans, many alluvial deposits were exhausted. The Romans began to search further for such readily accessible deposits, including Britain and Spain, which both became important sources of ore.

Opencast Mining

The Romans added a significant contribution to mining with the introduction of hushing. Chiefly used for gold mining, hushing is a technique by which a large volume of water is suddenly released from reservoirs over the area to be worked, removing the overburden and allowing the miners to gather up the relevant ore pieces and pick larger rocks apart to test for ore. The process is then repeated until the deposit is exhausted.

Opencast mining techniques were still in use by the Romans, though contemporary scholars gave it little discussion. The iron mines on Elba, an island off of Italy, were almost entirely opencast operations, except for one short gallery.

Underground Mining

Roman underground mining was still a system of shafts and galleries, but the Romans often incorporated multiple shafts into their workings, and generally had more complex workings than were created previously. Though they still followed the form of the ore body closely, much more planning is evident, and many of the earlier limitations on ventilation and drainage were overcome. The basic methods of fire-setting and pick and chisel work remained in use, but iron tools gained prevalence over bronze.

The shafts of Roman mines were normally regular in section, square if lined with wood or circular if lined with stone. The holes sometimes cut into the sides of the shafts could either have been steps for the miners, or used to hold supports for a ladder. They were kept to one side to leave room for buckets to haul ore to the surface.

The galleries of Roman mines were driven from one or more central shafts, following the body of the ore closely and interconnecting. Roman mines were generally more ambitious than Greek ones, and multiple levels of gallery systems were created. Though the more ambitious and complex Roman mines showed evidence of some planning, few were extensively planned as compared with modern works, and some were disorderly mazes that could not have been intentionally designed. Like the Greeks, the galleries of the Romans had relatively small cross-sections, and were typically square or rectangular in section, though the Romans are known to have used a trapezoidal shape, narrower at the top, to reduce the horizontal compression of the workings by the weight of the surrounding rock.

On very rare occasions, natural underground galleries were found and worked.

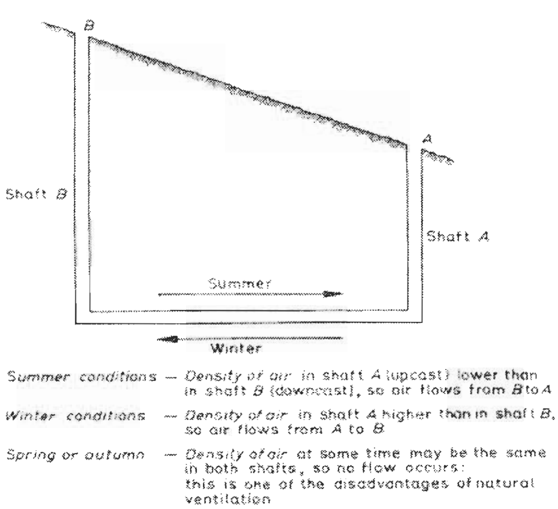
Surveying

The Romans encountered great difficulty surveying underground, mostly owing to the poor quality of tools available at the time. To guide the creation of long adits, they used shafts set at regular intervals of 30 meters. If the work was closer to the surface, the interval was shortened to 20 meters.

Ventilation

The Romans made significant improvements in the understanding of ventilation in underground mining, though they still had considerable difficulties in their deeper workings. All of the techniques employed by the Romans are based on the understanding of the natural circulation of air and convection.

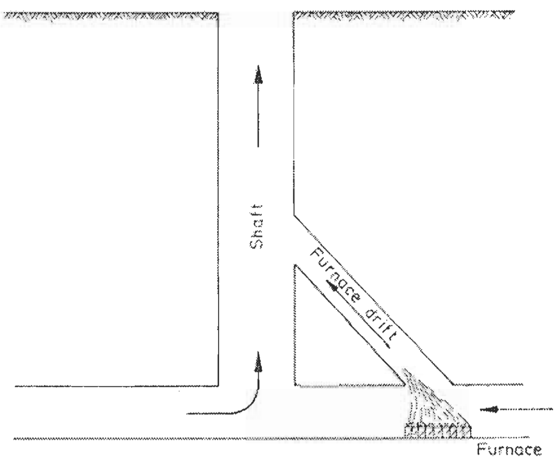
Figure 3: Natural Ventilation[5]



The draughts from firesetting were controlled by strategic placement of waste materials, doors, and shutters over old workings, which directed the air to the current work area.

[5] Ancient Mining, 31.

Figure 4: Draught Ventilation[6]



The Romans also used a technique of paired shafts to provide air circulation. If set at differing elevations, the difference in air pressures would move air between the two in summer or winter. They also used the convection of hot air from a fire at the bottom of one of the shafts to draw air down the opposite. This method could also be used in a single shaft by partitioning that shaft down the middle with wooden planks, with half for the upward draught, and half for the downward ventilation.

Drainage

The dry climates of Sinai and Egypt eliminated the need for drainage in the few Roman mines in those locations, allowing for much deeper systems. The porous rock at Laurion also eliminated the need for drainage, but prevented any mining below the water level.

The Romans used three main drainage devices. Cross cuts are channels to divert the flow of water to an alternate path, which was particularly useful when they encountered underground streams. Baling remained a slow and inefficient method, but was still used.

The Romans introduced two mechanical devices designed for the task of drainage. The Archimedean (or Egyptian) screw, originally used for irrigation in Egypt, was a

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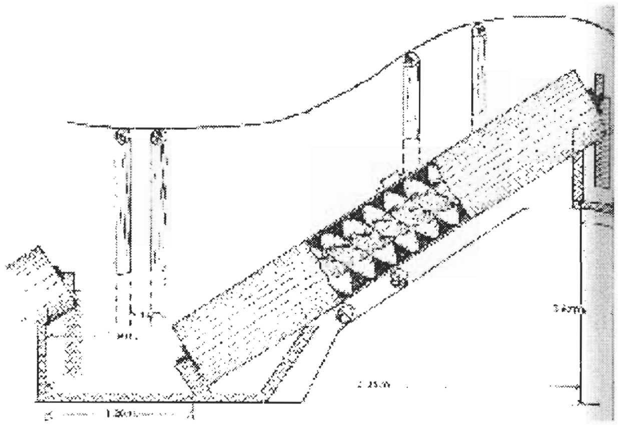
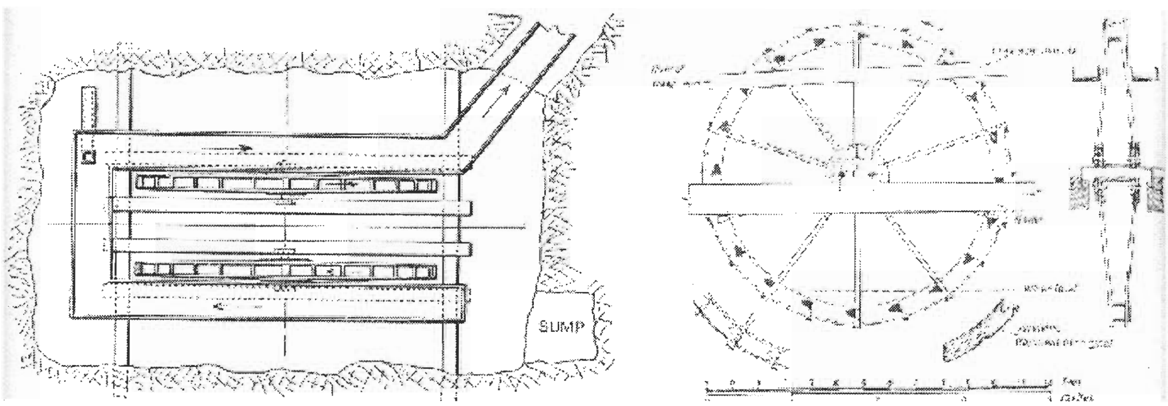
[6] Ibid., 33.

Figure 5: Archimedes' screw[7]



cylindrical device containing a threaded central axle fit inside a hollow tube. A handle on the top allowed the axle to be rotated and moved water with much less effort than simple baling. The Roman wheel for water removal is a predominantly wooden construction consisting of a circle of bucket-like chambers forming a wheel large enough to raise water 2 or 3 meters. It was operated by a person walking along the wheel, and removed water from a lower sump and deposited it near its apex in a channel that would lead to the next sump.

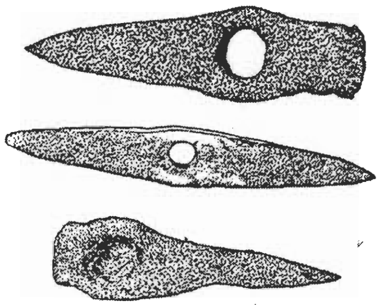
Figure 6: Roman water removal wheel[8]



[7] Healy, Mining and Metallurgy in the Greek and Roman World (Thames and Hudson, 1978), 96-97
[8] Ibid., 98-99.

Tools and Equipment

Figure 7: Mining picks[9]



The Romans used iron extensively for their mining tools, which consisted of a relatively simple set of items, including: a single or double-headed hammer, between 5 and 10 pounds weight, with a wooden handle; a pick for use with softer rock or earth overburden; an iron gad, intended to be struck by hammer, for the removal of harder stone; and an iron crowbar. They had also developed a specialized gad for use on the ceiling of a gallery.

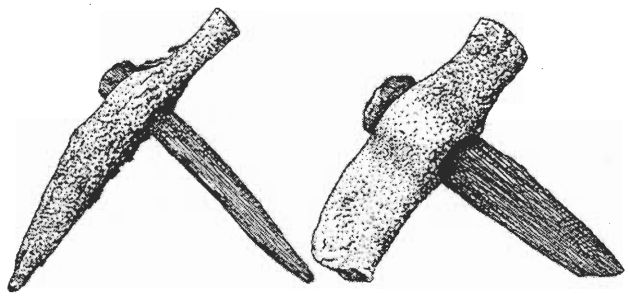


Figure 8: Mining hammers[10]

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[9] Bromehead, "Mining to the 17th Century", in Singer, History of Technology, Vol. 2
[10] Ibid.

Processing and Refining

Metallurgy

Metal-working began with the collection of native metals from surface deposits, and actually predates mining. The definition of metallurgy includes the methods used for extracting metal from ore via refining processes like smelting, the study of the principles involved and the properties of the subject metals, and the application of knowledge discovered via experience or investigation.[11]

Preliminary Processing

The processing of the raw ore, known as ore dressing, is the preparatory step where the metal-bearing ore is separated from the waste material, or gangue. This step significantly reduces the volume of the subject material, leaving a more concentrated valuable material. The processes of concentration used by the Greeks and Romans were entirely mechanical, and had no chemical processes taking place. There is no evidence that the Romans examined the texture of the ore prior to processing, and so therefore missed out on valuable information regarding the composition and properties of the specific ore being worked.

Ore not immediately suitable for smelting was first crushed by mortars and then milled for fineness and sieved to ensure a uniform grain. The mortars used consisted of a large hollowed thimble shape made of very hard volcanic stone, a stone cover of the same material, and an iron pestle that fit through a gap in the cover. The mills used were made from a cone-shaped central stone, and an enclosing ring of stones, with holes presumably

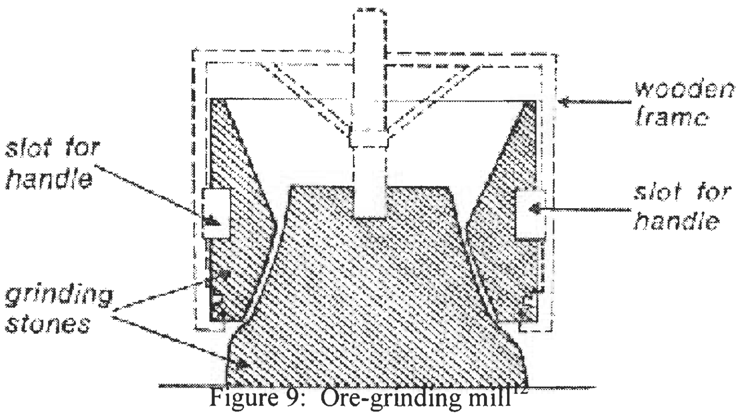
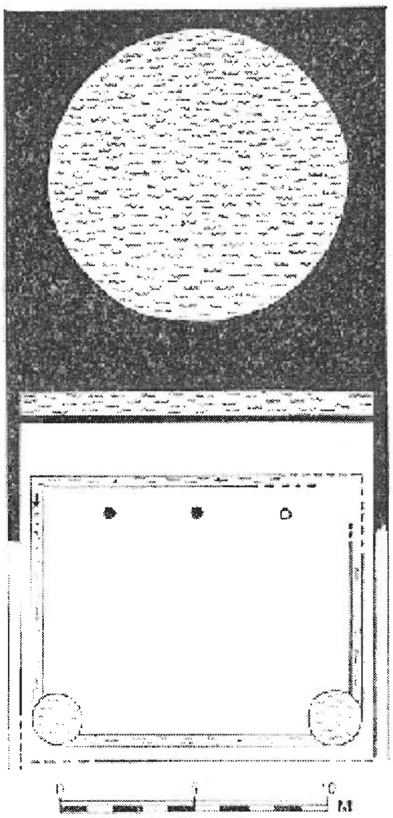


Figure 9: Ore-grinding mill[12]

for handles so that it could be pushed manually. The sieving was done on a stone with sloping inner sides leading to a hole along the length just wide enough for sufficiently small grains of ore to flow through. The sieve also had an iron ring on each side used for suspending the sieve so that it could be operated by oscillation. Any pieces of ore too large to pass through the sieve could be re-ground.

Figure 10: Plan of washery at Laurion[13]



Washing is an additional technique used for gold and silver processing. One method of washing is to operate the sieve underwater. The gold or silver will be pulled downward by gravity, while the lighter gangue will wash away.

Another method that relies on the greater density of metals, and additionally exploits this fact to determine purity of an ore, is the washing table, an example of which is found on the site of the Greek mine of Laurion. It is a compact operation that fits in a double square area. One square contains a large cistern,

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[11] Mining and Metallurgy.
[12] Ibid., 143.
[13] Ibid., 146.

which holds the water supply for the operation and feeds into a water tank that empties via three holes that function as jets of water to wash ore. These jets fall upon corresponding trenches in a plastered, inclined table where the properly crushed ore is placed. This table empties into a rectangle of water channels that surround a larger, plastered table. The corners opposite the inclined table are round settling tanks to gather the ore. The ore is deposited along the channels and in the settling tanks according to density automatically, allowing for an easy determination of purity of ore.

Refining

Refining is the process of purification of the ore, which is typically a heat-based chemical reaction that eliminates the materials compounded--or chemically joined--to the metal. Refining requires a processed ore, a furnace employing natural draught or blast air (forced air) to provide the oxygen necessary to reach sufficiently high temperatures, fuel for the furnace to be used, a crucible (a fire-resistant container), and various tools and ancillary equipment.

The availability of furnace fuels and refining agents affects the potential temperature that can be reached, which in turn affects which ores can be worked, and how efficiently. Deforestation or scarcity could limit the effective use of otherwise valuable deposits. Wood is incapable of reaching smelting temperatures, but charcoal created from wood is the single most important furnace fuel and reducing agent. Charcoal is 2/3 the volume and 1/4 the weight of the corresponding wood used to make it, but an equal weight of charcoal creates twice the heat as the same weight of wood. Charcoal is capable of reaching 900°C, and this can be increased by using blast air.

Charcoal was a chief export of Magna Graecia, Macedonia, Mt Ida and Gaul during Roman times.

Furnace Methods

Furnace reduction methods rely on the chemical reactions of high temperatures. The intent of smelting is to remove the impurities that mechanical processing or washing cannot.

Iron

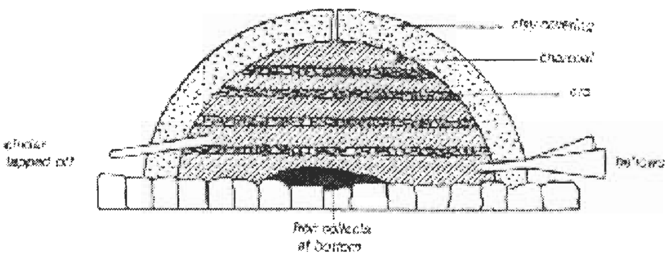
Iron deposits can be found in many regions. It is a very common element, numbering among the ten most common terrestrial elements, and makes up a full 5.06% of the earth's crust. The ancients could not make use of all of the iron deposits extant, however. Due to technological limitations, the mineral chromite could not be refined by the Romans.

There are three main sources of iron:
Meteoric iron was known only as a phenomenon, as recorded by Pliny. Telluric iron was unusable by the ancients. The high nickel content made smelting impossible. The remaining sources—the iron ores--can be divided into oxides: magnetite, haematite, limonite (oölitic and bog ore) and carbonates: spathic iron ore, sphaerosiderite, and blackband ores.

The difficulty of mining and refining varies with composition, as does the purity of the yield. This is illustrated at the mines of Noricum province, where the Romans ignored spathic iron ores in favor of limonites, even though the latter sometimes contained titanium, an excellent component of steel.

The preliminary roasting of an iron ore removes CO_2 from carbonates, and H_2O from limonates. It also makes the ores more porous, and therefore easily reducible. Roasting differs from smelting in that it employs a more moderate temperature and often oxidizing. There is therefore no need to keep out excess air.

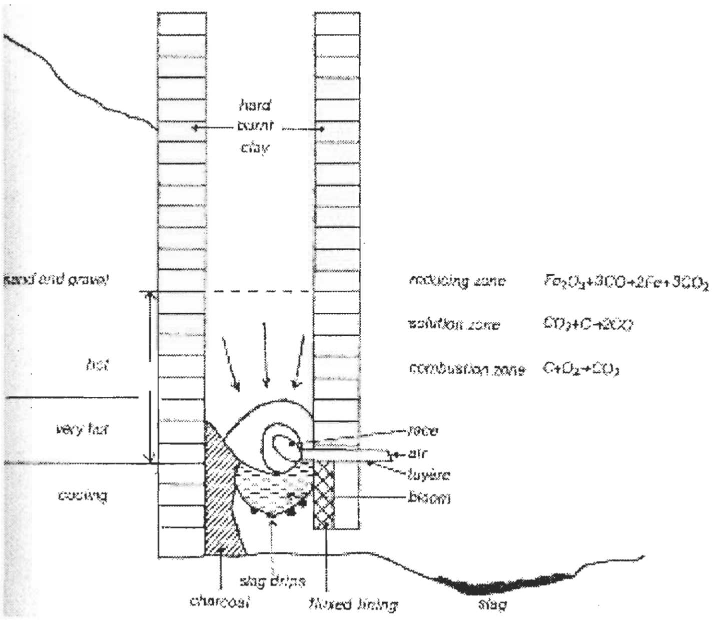
Figure 11: Bloomery hearth[14]



In contrast with copper and lead, no amount of heat alone is sufficient to reduce iron. Instead, carbon, iron oxide ore, and heat must be present for reduction to take place. The carbon plays an essential role in the properties of the resultant iron. Since washing is unsuitable for iron ores, the removal of gangue must be incorporated into the smelting process as slagging. Slags of gangue form with sufficient temperature, well below the melting point of iron, and then partly drain away from the iron ore. This partial slagging leaves a spongy bloom of impure iron. The remaining slag must be removed via a repeated process of heating and hammering while the slag is still in a liquid state.

The smelting of iron is a more complex issue than with other metals, because of the relatively high melting point, which requires greater heat. To generate the needed heat, more air must be supplied, which speeds oxidation and reduces the efficiency of the smelting process as the iron content of the slag increases. To reduce oxidation, more fuel

Figure 12: Shaft furnace[15]



must be used, which increases the mass of the charge over which the heat must be increased. In the end, the furnace must be constructed to trap the heat more efficiently. This spurred the development of more sophisticated furnaces that were specialized for iron smelting processes.

<u>Copper</u>

Copper oxides, carbonates, silicates and sulfides were all viable ores to the Romans. Because of the high melting point of copper (1083°C), copper ores were typically smelted into ingots formed in the smelting furnaces.

The early smelting furnaces were crude operations that consisted of a small hole in the ground in the center of a large depression which was filled with a mix of copper ore and charcoal. This was set ablaze and the copper would then drip into the hole underneath. This method could be enhanced with the addition of a bellows to supply blast air, increasing the heat over natural draught. This method developed into the bowl furnace, which was filled with a charge of fuel and ore in alternating layers, which meant

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[14] Ibid., 185.
[15] Ibid., 189.

that the bowl was built upwards around the charge. This upward extension eventually led to the development of the shaft furnace. The bowl furnace also evolved into the bun ingot furnace.

Tin

The Romans' primary source of tin was alluvial deposits. The vein ore could not be directly refined, but was reduced by a preliminary roasting, then a series of crushings and washings. The ancients did not need to achieve modern levels of purity, as tin was largely used for alloys, either with copper, in bronze, or with lead, in pewter.

One innovation used for tin smelting was the slag hearth, which was basically a trench in the ground which was filled with ore and heated with wood. The slag was tapped via a hole and drained, and the tin ladled out.

Lead

Lead was most commonly produced from argentiferous galena, which is a silver-bearing ore of lead sulphide. The smelting of galena produces the odious pollutant sulphur dioxide, and a crude lead that typically contains silver and other impurities. The crude lead could then be liquefied, leaving a dross of impurities behind, or purified by exploiting the fact that the impurities oxidize first, leaving a more pure lead yield. If the lead is high enough in silver content, it would be de-silvered in a cupellation process, or possibly the Pattinson process[16], though scholars debate the fact that the Romans knew this idiosyncrasy of lead-silver mixes.

[16] Mining and Metallurgy, 180. Healy describes the process as follows:

Zinc

Zinc ores were used with copper ores or metallic copper to make brass directly, but no evidence exists for the Roman use or refinement of metallic zinc. Its relatively low boiling point of 907°C meant that common furnaces would vaporize too much for smelting to yield an appreciable result.

Mercury

The mineral cinnabar was valued both as a pigment and for its mercury content. The mercury could be extracted by mixing cinnabar with vinegar using a copper mortar and pestle. This has been shown by experiment to be a viable chemical reaction, whereby the mercury amalgamates with the copper, leaving the need for additional distillation, which is heating that volatilizes the mercury in solution.

Tools and Equipment

Bellows – the Celts seem to have been leading the development of the bellows, possibly inventing the water-driven version. The bellows was first known in Egypt, where the earliest examples of this device were made of hide. As the demand for temperature grew, so too did the size of bellows being built, to provide greater drafts of blast air.

The Pattinson process… utilizes a peculiar physical property of lead-silver mixtures. If melted and cooled again, the first crystals formed consist of pure lead and the remaining solution will, therefore, become richer in silver. This formation of pure lead crystals will go on until the remaining lead contains about 2.4% of silver. Then the remaining molten metal will set all at once. By pouring off the molten metal before this happens the silver is concentrated as far as possible and the lead thus enriched can be desilvered by cupellation.

Tuyere – A clay nozzle that directs the input of blast air, substantiating its early use in many furnaces.

Crucibles – stone, refractory clay or sand, used for refining gold or steelmaking.

Forceps and Tongs – A pair of forceps are made by bending a metal strip until the ends can be touched together. Hinged tongs replaced forceps as the standard way to handle heated material or crucibles.

Roman mineral sources

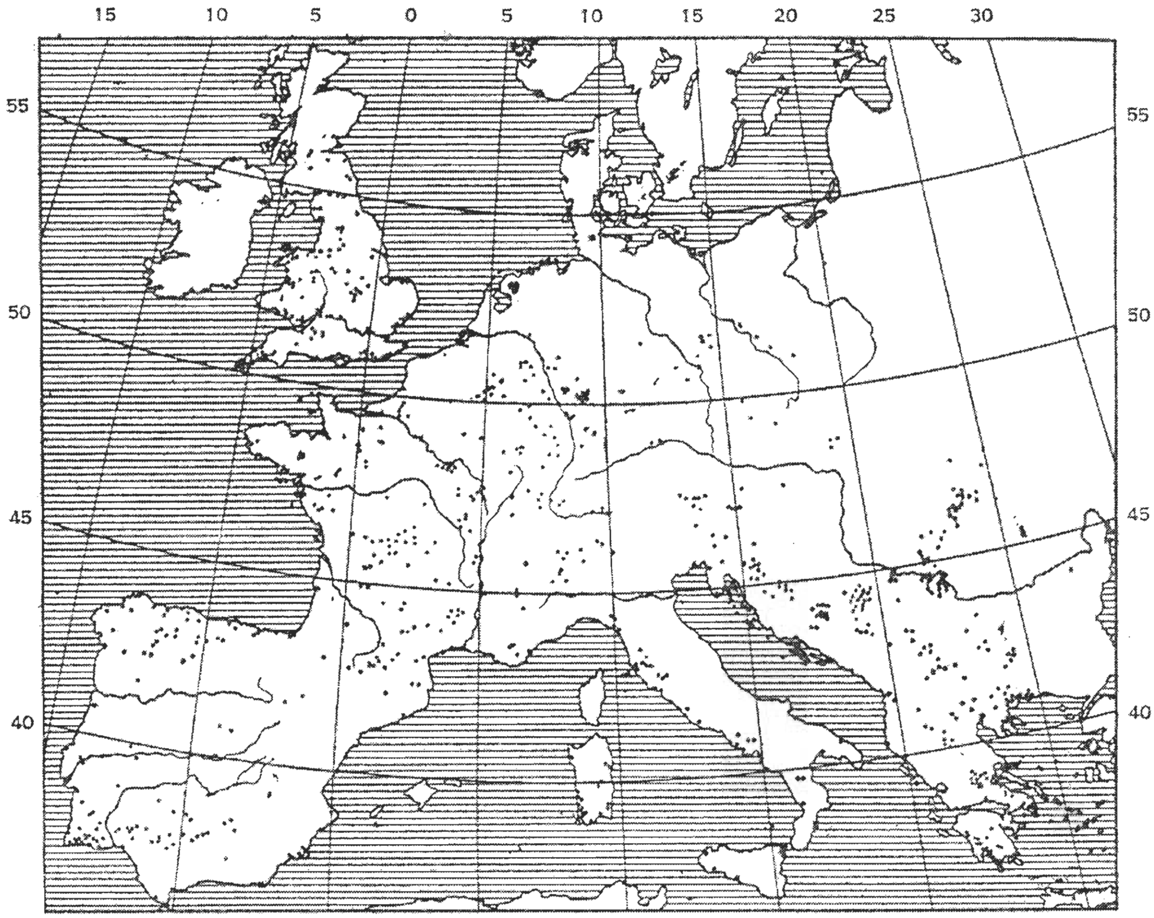

Figure 13: Position of Roman Mines in Europe[17]

Greece: Laurion

Though this is a survey of Roman mining activity, we should not overlook the best known area of Greek mining, the silver mines of the Attica region. The most famous of these is the mine at Laurion. The silver from this mine was a contributing factor to the early prosperity of Athens.[18]

[17] Bromehead, "Mining to the Seventeenth Century" in Singer, History of Technology.
[18] Ancient Mining, 73.

When the mine was re-opened in 1860, many of the old workings were destroyed, but due to modern workers' investigations more is known about Laurion than any other Greek mine. One scholar did attempt a study prior to the commencement of the modern workings, and the work of Ardallion remains a principal source for archaeological information about Laurion.[19]

Roman Ore Sources: Italy

Figure 14: Italy[20]

Italy has few natural resources. Additionally, Rome placed a restriction on mining in Italy, limiting it to activity in Cisalpine Gaul, the Pennine Alps, Elba, Etruria, Campania, and Sardinia. This restriction may have been placed to keep valuable reserves of minerals in case of the loss of important provinces to barbarians.

There are no workable minerals in Central Italy, but a metal-working industry did exist in that region.

[19] Ibid.
[20] Ancient Mining, 140.

Cisalpine Gaul

The segment of Gaul that lies on the side of the Alps adjoining Italy was one of the more productive areas in that region, though it was never worked as enthusiastically as Transalpine Gaul or Iberia, probably due to the relatively high profitability of those regions. Specifically, the area west of L. Maggiore, including the Val d'Aosta district was a center of mining activity.

Elba

Elba was known for having a rich deposit of iron, even before Rome acquired it. Once taken, it became a prominent source of iron ore. Originally, the iron was smelted on the island, but after fuel ran out the ore was shipped to Puteoli. The majority of workings on Elba were open-pit operations using iron tools.

Tuscany

The city of Populonia was the receiving point for Elba's iron ore during the time of the Etruscans. When the Romans razed the city, and the region ravaged by barbarians, all mining in the region ceased, and did not resume in quantity until the late Republic.

Campania and Calabria

These regions contained few deposits of workable quantity or quality, though the city of Puteoli inherited the iron works formerly located in Populonia, Tuscany.

Sardinia

This region is known to have contained Roman silver mines around Iglesias in the southwest, as well as mining of deposits of argentiferous galena (Silver-bearing lead sulfate) that produced lead and additional silver. This region may also have contained copper, iron and gold mines.

Sicily

This island contained few mines of importance to this survey.

Roman Provinces

Many of these regions were taken by military action, including Britain, Gaul and Iberia, though some, like Noricum, were added to the Empire by treaty. Until A.D. 270, gold and silver production in the provinces was relatively low, though Laurion had virtually dried up.

Noricum

Figure 15: Noricum[21]

This region comprises the greater part of modern Austria. It contained immense iron ore deposits that made it a prominent producer of

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21 Ancient Mining, 154.

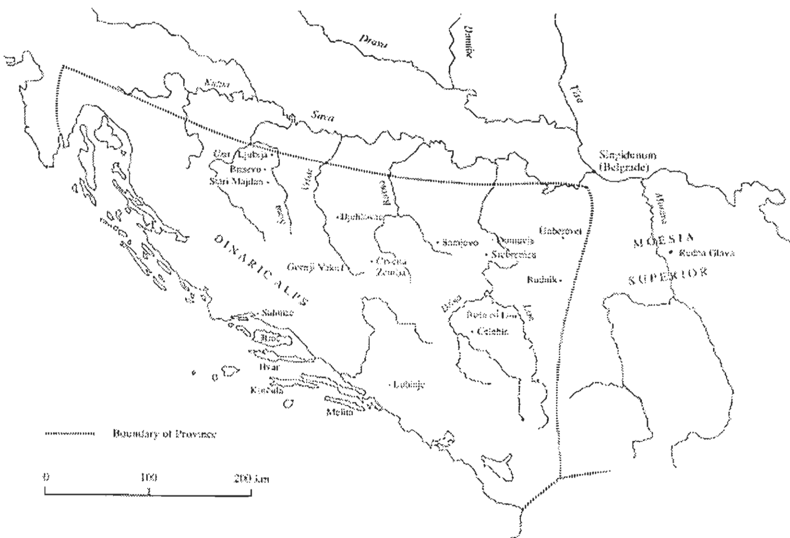
iron far beyond the time of the Romans. The Romans began relations with this region by establishing a trade center in Aquilea in 181 B.C. The area north of Klagenfurt was the center of iron production and the original center of power for the Noric kings. It was a Roman colony from 100 B.C.

The iron from Noricum was possibly the best in ancient times. Conditions were just right for steel production, given the availability of fuel and the resultant carbon content of the iron produced.

The high profitability of Noricum's iron operations resulted in an eventual increase in the use of free workers, and an elimination of the use of slaves for mining in this region.[22] This region also included mining activity yielding gold, copper, lead and zinc.

Dalmatia

Figure 16: Dalmatia[23]



This region encompassed about 1/3 of the former Yugoslavia area. It was an economically motivated conquest for the valuable gold, silver, lead and iron deposits known to exist in this area. Some of

[22] Ancient Mining, 157.
[23] Ibid., 159.

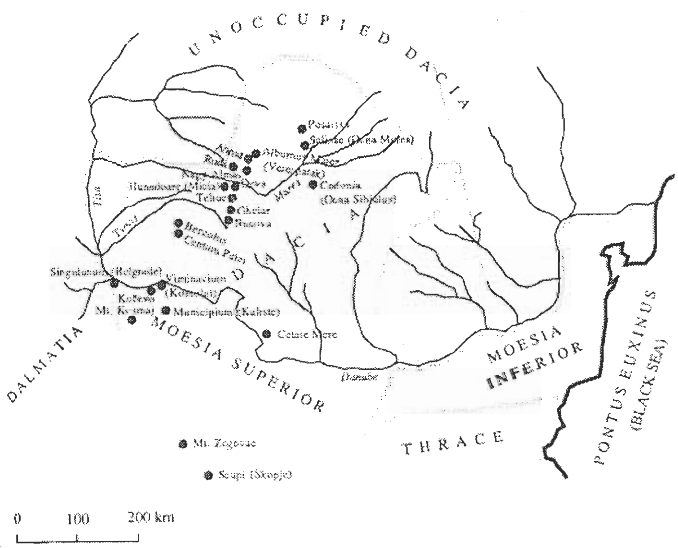
these mines are still active today. The center of iron production was in the Sana valley, near Stari Majdan.

Pannonia

There is little evidence of Roman mining activity in this region, though some authors refer to iron and silver mining activity. There is no modern archaeological evidence to support these claims.

Dacia

Figure 17: Dacia and Moesia Superior[24]



This area possessed great material wealth, and was fast developing as a powerful kingdom. It could have been a threat, but instead was conquered and became highly profitable under Roman rule, although slavery intensified to field the necessary labor force, at the expense of the native population.

Moesia

The northern half of Moesia Superior was abundant with gold, copper, iron and lead deposits worked by the Romans.

[24] Ibid, 165.

Outer Territories

Gaul

Figure 18: Gaul[25]

Iron mining existed in this region prior to Roman conquest, and iron was worked here continuously until the Middle Ages. There is little modern evidence of Roman mining activity left, most having been destroyed by later workings, so investigators look for evidence of smelting operations. The probable center of iron production was the Rhineland area, though widespread evidence of iron processing has been found.

Evidence for the mining of copper is likewise scarce. Due to the value of copper, any ancient workings would likely have been destroyed by later works.

Gaul was one of the few Mediterranean countries to use an independent gold currency prior to Roman rule. Most of the gold worked by the Romans in Gaul would have been alluvial deposits, leaving little modern evidence. The gold mines near Toulouse may have been the richest of Roman times.

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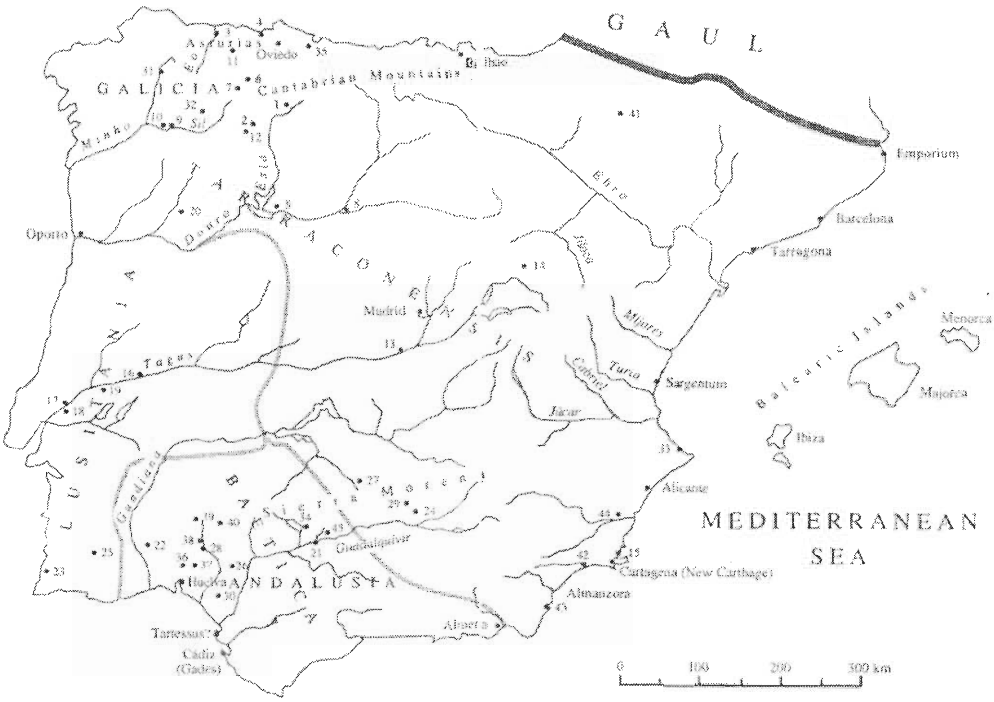
[25] Ibid., 172-173.

Debate exists over the mining of lead and silver in ancient Gaul. There is some evidence of Roman mining of these metals, and little evidence for pre-Roman working.

<u>Iberia</u>

Figure 19: Iberia[26]



This region is known as having been one of the richest acquisitions of the Romans. Natural gold, silver, copper, and iron were all found in significant amounts, as well as the respective ores and lead ore.

There is little evidence of Roman iron mining in Spain or Portugal, though ancient sources cite the region as rich in iron. Shepard contends that this is incorrect, and the product of optimism on the part of the ancient scholars.

Tin mining in Iberia probably largely consisted of placer mining, though some evidence of underground works exists in Lusitania, now North and Central Spain and

[26] Ibid., 196-197.

Northern Portugal, and in Gallaecia, now northwestern Spain. The tin produced in these regions seems to have monopolized the Roman markets up to 200AD.

Gold mining, for which Iberia seems to have been known, was located mostly in the northwest, with lesser amounts located in the south and southwest, and in the east.

Lead and silver production began before the arrival of the Romans, and helped to feed the high demands placed by the Romans for these materials. The ore worked here was also argentiferous galena, smelted by cupellation.

Copper is still mined in isolated areas of the Iberian Peninsula today. The main production in ancient times was in the southwest area of Baetica, in the Rio Tinto valley. Many of the ancient workings were destroyed when the Rio Tinto area was reopened for modern zinc mining. This destruction is still occurring. In ancient times, Rio Tinto was also a major source of silver, and the main center for silver smelting, given the relatively low amounts of lead slag at other locations.

Iberia also produced cinnabar, an ore of mercury valued both as a pigment and for its mercury content. There was a cinnabar mine noted at Almaden, in Baetica, now modern Sisapo.

Britain

Figure 20: Britain[27]

Iron working was introduced to the Britons by the Hallstatt people, and was already in progress when the Romans arrived. British iron was generally inferior to the ores of other locations, given that the slag has a high iron content in both Pre-Roman and Roman-era workings.

Tin is not distributed widely in Britain, and although it is an important metal for the production of the alloys bronze and pewter, locating sources in Britain was a problem.

Lead mining was a high-production industry, and may have even been worked before the arrival of the Romans, who created a high demand for it.

Copper mining in Britain was of little interest to the Romans, who had more plentiful alternative sources. However, there is evidence that pre-Roman mining of copper was done.

Gold was in scarce supply in Britain, and Dolocauthi is the only working we have proof of.

[27] Ibid., 272.

There is no evidence for the extraction or processing of zinc ores in Roman Britain; though many artifacts contain high proportions of zinc, these are most likely accidental.

Medieval Mining

The early Medieval period--the time after the fall of the Roman Empire--is a time notorious for its lack of information on the subject of mining. There is little in the way of written works on mining from this time. This lack of information makes it difficult to say exactly what the practices are that were in use because there were no scholars who would write on the subject as they have done before and after. Most of the knowledge gained on the subject of mining and metallurgy has been taken from archaeological digs of the mines and refineries.

Mining, during the early medieval period was just a continuation of the practices used by the Romans, but when the Roman Empire fell, so did the mining technologies used. Miners began digging shallower mines and more primitive methods of working the mines came into use. Over the seven centuries, from A.D. 300 to A.D. 1000, the Roman methods of mining were lost as the population in Europe declined and towns were abandoned as well as the mines. The production of metals fell drastically as trade stopped. The Germanic invaders who settled in the regions of the fallen Roman Empire settled for ores that could be reached easily and were near the surface of old mines. They did not bother with the sinking of new shafts or finding new veins of ore to follow.[1]

As production of metals declined over this period, iron declined the least. It become a needed metal for tools such as axes, spades, knives, plowshares, and of course weapons. Iron could be mined easier than the others due to its abundance and was the most common metal produced during this time period. The production of iron and most of the active mining occurred in Germany, the Harz region, and the Alps. By the 800's, trade in iron had been reestablished between Venice and the Near East.

Other metal production, such as bronze seems to have died out all together until the 1400's, while the production of copper, tin, lead, silver, and gold fell to almost nothing. It wasn't until the 900's that these metals began to be mined again and produced in significant amounts. Several new mines were discovered, rich in copper and silver-bearing lead ores, and opened in Germany, the Harz region, and the Alps. By the middle of the 1100's mining began to spread throughout Europe once more and by the 1400's metal production increased substantially every decade.[2] This increase was broken only by the plague in the 1350's. With over one-third of the work force deceased, the mining of metals, other than iron, decreased significantly in most areas and almost came to a stop where the plague hit hardest.

It was because of the plague and the reduction of the work force that other means of mining had to be found, means that were more efficient and less dependant on a large amount of human labor. The use of water wheels and mining machinery not seen since the height of the Roman Empire came back into use and with these innovations the cost of mining rose. Miners began to sell shares of their work and become dependant on banks, merchants or town funding. Thus began the rise in capitalist mining that is seen commonly in the Renaissance.[3]

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[1] John Nef, The Conquest of the Material World,(Cleveland and New York: The World Publishing Company, 1964), 7-8.
[2] The Conquest of the Material World, 9-10.
[3] Cedric E.Gregory, A Concise History of Mining, (New York, Oxford, Toronto, Sydney, Paris, Frankfurt: Pergamon Press Inc.,), 95.

Introduction to the Renaissance

The early Renaissance was witness to great growth in mining and metallurgy. The metal production at this time was the greatest the world had ever seen and the technologies used were being improved continuously. Also seen was the change from the mines being owned and operated by the miners to the mines being owned by merchants, monasteries, and town councils or anyone who could put up enough capital to fund the new expensive mining technologies. With this change to capitalism, there was a need for information on mining and metallurgy that was previously kept private by the workers and craftsmen. The profitability of the mines was the main concern and, if the profits were low, experts on mining would be sent to improve them. Mining was seen as a business that could make men rich if they could afford the cost of starting a mine.[1]

There was now a desire for information on mining and metallurgy, and filling this need were authors such as Vannoccio Biringuccio and Georgius Agricola. Together, their two main works, Pirotechnia and De Re Metallica, they cover most of the subjects relating to mining and metallurgy. Their works were considered the authority on these subjects through the next two centuries.

For these reasons, the lives and major works of Biringuccio and Agricola have been included here to represent the advance of mining technologies and metallurgy for the Renaissance. Presented first is Agricola's De Re Metallica with its focus on the mining of metals, followed by Biringuccio's Pirotechnia which has more to do with the assaying and refining of ores.

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[1] A Concise History of Mining, 95.

Georgius Agricola

On March 24, 1494 in the small town of Glauchau, Georgius Agricola, then Georg Pawer, was born, the son of a clothier Gregor Pawer and a mother whose name is unrecorded. One of seven children, four sons and three daughters, Georg was born into a well-to-do family, allowing three of the sons to study and all of the daughters to marry well regarded burghers of Glauchau.[1]

It was in his hometown that he began his education, learning to read, write and calculate. At the age of ten or twelve he attended a grammar school in Chemnitz, where he was taught the fundamentals of Latin and possibly Greek as well. At the age of twenty he began studying at the University of Leipzig. He continued his education in Greek under the teaching of Professor Richard Crocus and began speaking with Professor Petrus Mosellanus. Only a year older than Georg, he became Georg's idol and openly shared his views of the intellectual independence of man and free will, with the teachings Erasmus of Rotterdam, the major basis of his arguments. Georg took this view also and remained "Erasmian" all of his life. In 1598 he graduated from the university and latinized his name to Georgius Agricola, as was the custom of the time.

Agricola went to teach at the town of Zwickau in the Electorate of Saxony at the request of Stephen Roth, an old friend from Chemnitz, and a recommendation from Mosellanus. Zwickau was a town disturbed by various social forces and after a brief period of open support Agricola busied himself in the daily business of his school. In 1520 he published his first work, a Latin grammar for beginners and taught at a newly founded Greek school until it was combined with the older Latin school and he took the position of headmaster. On May 1, 1522 he happily

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[1] The material taken on Agricolas life can be found in:Prescher, Hans. "DR. Georgius Agricola 1494-1555 A European Scientist and Humanist from Saxony," *GeoJournal* 32 (1994). and, Charles Coulston Gillispie, Dictionary of Scientific Biography, (New York: Charles Scribner's Sons, 1970).

relinquished his position of headmaster due to problems that arose between the town and the lofty educational aims Agricola tried to establish.

He then moved to Leipzig, staying with Heinrich Stromer von Auerbach, a professor of medicine. This is where he may have begun his study of medicine. In 1524 he traveled to Italy, the "beloved land of science and art" and took lodging with A. Asulanus, a renowned publisher and printer. At some time during his stay in Italy Agricola achieved the title of Doctor of Medicine. In 1526 he moved back to Saxony where he married Anna ne' Arnold, the rich widow of Matthias Meyner, the state ducal tithe gatherer for Schneeberg.

It was at this time that he accepted the position of town doctor and apothecary in St. Joachimsthal (now Jachymov), a town in one of the richest mining areas of Central Europe. It was here that he studied the techniques of mining and smelting, then considered one trade, and could talk with miners from the already developed mining towns of the Harz, Bohemia, Tyrol, Saxony, and present-day Slovakia. As town doctor he learned the techniques of mining from mining officers, often traveling with them through the pits, shafts and galleries. Here he found that the miners knew more of minerals, rock, and mining machinery and practice than all previous authors of the subject combined. From his observations and experiences with the miners he wrote a small work called "*Bermannus sive de re metallica,*" which was a dialogue on mining. He dedicated this work to Lorenz Wermann, the mine's clerk. In it he created his own method of presentation different from what had been done traditionally. He named the materials as ores, earths, and calces and also gave names to more than thirty minerals and two rocks. By making reference to seven classical mining areas and forty-one other mineral working areas, he contributed to one of the first collections of regional mineralogy. He went on to attack the alchemists and astrologists as intentionally confusing, liars, and cheats. The alchemists methods of keeping secrets, or at least written in such a manner as to be confusing at best, were the opposite of what Agricola believed.

Due to his interest in politics Agricola published a work titled " *Rede von der Notwendigkeit des Krieges gegen die Turken,*" an address on the need for war against the Turks which was published when the Osman Turks were at the gates of Vienna in 1529.

In 1531 Agricola moved back to Chemnitz, giving up his position in St. Joachimsthal for unknown reasons. In Chemnitz he was again active as a town doctor but also focused on his scientific work. As a doctor he noticed that each country and even every large town had its own standard measurements. Due to the confusion this would create he looked to the classical authorities for a common basis and wrote "*De mensuris et ponderibus Romanorum et Graecorum,*" a Roman and Greek measurements of mass and weight. This book was published in 1533.

At the beginning of the 1540's Agricola's wife died and he married Anna Schutz, age 17. She was the daughter of Ulric Schutz, the deceased owner of a copper smelting furnace in Chemnitz. His second wife gave birth to two sons and four daughters.

During this period of his life, Agricola began compiling all the known writings of the classical authors Theophrastus, Pliny, and Aristotle, adding his own experience and observations. His five major works of this period were completed on the dates given:

De ortu et causis subterraneorum or The development of subteranian materials on the 1st of March 1544.

De naturaeorum quae effluent ex terra or The Nature of Materials Coming from the Inner Earth, October 21, 1545;

De natura fossilium or Minerals, February13, 1546;

De veteribus et novis metallis or Ore Bodies and Mining in the Ancient and Modern Times, March 7, 1546;

and *Epistula ad Meurerum* or letter to Wolfgang Meurer, March 21, 1546.

Also in 1546 Duke Moritz of Saxony gave Agricola the position of burgomaster during the Schmalkaldic war and in 1547 called him into the field. He was part of the military campaign that ended with the victory of the Emperor at Muhlberg. Agricola remained in office until 1548.

Also in 1548, Agricola finished his work "*De animantibus subterraneis*" an subterranean life which was published in 1549. Five more works were completed in 1549 on the subject of mass, weight and coinage and published in 1550.

Up to the end of his life, Agricola's scientific activity was constantly interrupted. Twice more he had to take on the responsibility of burgomaster during the ducal rebellion of Elector Moritz and his duties of town doctor interfered during the plague in Saxony in 1552. By instituting a social hygiene program for the town of Chemnitz and isolating its sick out of town, he was able to keep the plague from Chemnitz. His methods were printed in *De Peste* or The Plague, in1554. Finally, his research into writing a history of the Wettin dynasty diverted him from his usual studies; the completed history was presented to Elector August on October 1, 1555.

In November of 1555 Agricola became unwell and died on November 21, 1555. He was buried in the monastic church of Zeitz and never saw the publication *of De Re Metallica* in 1556 which he had sent for printing in Switzerland in 1553.

Vannoccio Biringuccio

Biringuccio was born in the year 1480 in Siena, Italy to Paolo and Lucrezia di Bartolommeo Biringuccio. Later that year he was baptized Vannoccio Vincenzio Austino Luca on October 20. Paolo appears to have been an architect and a public servant as well as a supporter of the Petrucci family of Siena. [1]

Biringuccio's allegiance to Pandolfo Petrucci, head of the Petrucci family, gave him a protection and patronage that allowed him to travel throughout Italy and Germany. Durring 1507 he traveled through Friuli and Carnia in northern Italy, Milan and Germany before his return to Siena.After his return, it was in fact Pandolfo who sent him to direct the mines and forge in the nearby town of Boccheggiano

In 1512 both Paolo and Pandolfo died, but Biringuccio's allegiance did not waver. He warmly supported Pandolfo's son Borghese who continued the rule of the Petrucci family. In 1513 Borghese appointed Biringuccio to a position in the Armoury of the Siena Commune where he directed the mint. During a popular uprising 1515 Biringuccio and Francesco Castori were accused of debasing the coinage alloy with the consent of Borghese Petrucci. This forced them to leave Siena and when he did not return to face the charges against him in 1516 Biringuccio was exiled as a rebel and a traitor to the Republic. It is possible that these charges may have been invented by an opposing political faction.

Pope Clement VII reinstated Fabio Petrucci, the younger son of Pandolfo, in 1523 to Siena. The charges against Biringuccio were lifted and his property and position at the Armoury

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[1] The material taken on Biringuccio's life can be found in:Biringuccio, Vannoccio. *Pirotechnia*, Cambridge, Mass. For the American Institute of Mining and Metallurgical Engineers, 1966. and Gillispie, Charles Coulston. *Dictionary of Scientific Biography Vol. 2* New York Charles Scribner's Sons 1970.

were regained. In 1524 he was given a monopoly on the production of saltpeter in the Sienese dominion. But, two years later in 1526, the people of Siena once again arose while Biringuccio was in Florence. The Petrucci Family was expelled from Siena forever. Biringuccio was once again called a rebel and his property was confiscated on 20 May. A later assault on Siena aided by soldiers from Florence proved unsuccessful.

Between 1526 and 1529 he traveled to Germany and returned to Italy in the service of Alfonso I d'Este, lord of Ferrara, Modena, and Reggio. There he cast the enormous culverin for the Florentine Republic.

By 1530 the opposing political factions had made their peace and Biringuccio once again returned to Siena. In 1531 he held office as a senator of the city and in 1535 succeeded Baldassare Peruzzi as architect and director of the Opera del Duomo. In 1536 he was offered a post in Rome by Monsignor Claudio Tolomei and in 1538 became head of the papal foundry and director of papal munitions.

It is not known when he died in Rome but it was some time before April 30, 1540 because a dated document exists concerned with debts owed to his surviving heirs.

Pirotechnia was printed in Venice, from Biringuccio's observations and research as taken down in note, after his death in 1540. It is commonly recognized as the earliest printed work to cover the whole field of metallurgy and was in use among metallurgists for the next 150 years. No fewer than nine editions were printed over a period of 138 years. Pirotechnia never gained the recognition of Agricola's De Re Metallica due to its practical aspects of metalwork being of little interest for several generations and his choice of writing in his native Italian instead of Latin was seen as unscholarly.

De Re Metallica

In 1556, almost one year after the death of its author[1], De Re Metallica[2] was published in Basel. The publication of this book marked the beginning of the transition of metallurgy from a speculative philosophy to an observation-based, empirically determined science. De Re Metallica is the first attempt at describing the nature, location, properties, means of acquiring, and purification of metal derived from actual experience and experimentation. This is reflected in the ability to duplicate the processes and experiments described, and the precision and detail with which they are described.[3]

Mining

Origin of Metal and Types of Veins

Up until and during the 1500s, three theories regarding the nature of ore deposits had been formulated.[4] The Biblical view, that all deposits were created at the same time, during the creation of the universe, was the first and predominant view of the time. The Aristotlean Greek view was the presence of four basic elements--earth, air, water, and fire--which were never found pure and which would, in the presence of others, transmute into baser substances. These elements were modified by four properties--hot, cold, damp, and dry--which affected their transformations. The process of the transformations produced "exhalations," one of which became metal. The final view

[1] Completion of the woodcut illustrations was the major reason for the delay in publishing.
[2] Georgius Agricola, De Re Metallica, trans. Herbert Clark Hoover and Lou Henry Hoover (London: The Mining Magazine, 1912; reprint, New York: Dover Publications Inc., 1950). (All page references are to reprint edition.)
[3] Bern Dibner, Agricola On Metals (Norwalk, CT: Burndy Library, 1958), 25-26.

was that of the alchemists and astrologers, which held to the basics of the Greek view but added that metals were produced by the influence of the planets upon these elements, in combination with "spiritual" sulphur, mercury, and salt.

Agricola held to a modified Greek view of the origin. He strongly believed in the existence of the four basic elements and four modifying properties; however, he made many arguments against the validity of "exhalations" as the cause of metals.[5]

Agricola defines metal as "a mineral body, by nature either liquid or somewhat hard. The latter may be melted by the heat of the fire, but when it has cooled down again and lost all heat, it becomes hard again and resumes its proper form. In this respect it differs from the stone which melts in the fire, for although the latter regain its hardness, yet it loses its pristine form and properties. Traditionally there are six different kinds of metal, namely gold, silver, copper, iron, tin, and lead. There are really others, for quicksilver is a metal, although the Alchemists disagree with us on this subject, and bismuth is also...Metal, therefore, is by nature either solid, as I have stated, or fluid, as in the unique case of quicksilver."[6]

Agricola classified three types of veins within *canales*,[7] ore channels: *vena profundae*, or fissure veins; *vena dilatatae*, or bedded deposits; and *vena cumulatae*, accumulations of an ore without form. The space between veins was dubbed *intervenium*, which usually would not be visible until excavation. He also identified five types of stringers, or veinlets: *fibrae transversae*, *fibrae obliquae*, *fibrae sociae*, *fibrae dilatatae*, and *fibrae incumbentes*. One last, mysterious type, *called commissurae saxorum*, defined as seams or cracks in the rock.[8]

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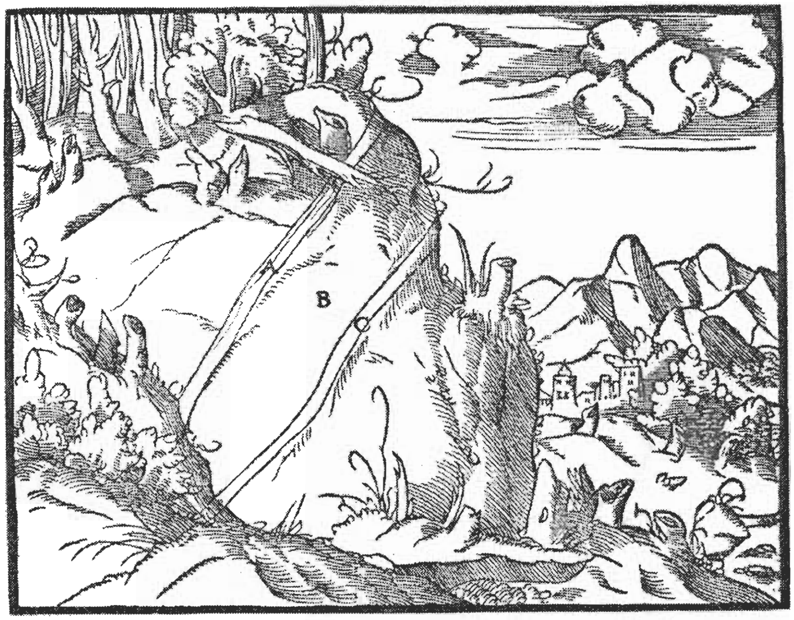
[4] Agricola On Metal, 5-7, 20-22.
[5] More information regarding Agricola's views on geological phenomena, metallurgy, and mineralogy may be found in De Natura Fossilium and De Ortu Et Causis Subterraneorum.
[6] Georgius Agricola, De Natura Fossilum, (Privately printed, 1546), 180; quoted in De Re Metallica, 2.



A—*Vena profunda*. B—*Intervenium*. C—ANOTHER *vena profunda*.

Figure 1: Vena profunda[9]

Vena profundae are visible from the earth's surface, and descend from there into the depths. These exist mostly along the vertical plane; their width varies from a mere two fingers to several fathoms. Because of the huge size variation, the classifications "wide vein" and "narrow vein" were region dependent. A normally "wide" vein would be anything larger than a half foot; however, in areas where there are veins tens of fathoms across, even a foot-long vein would be "narrow". *Vena profundae* were also classified by their direction, based upon the direction the *commissurae saxorum* travel in as the vein descends. If the *commissurae* travel westward, then the associated *vena profunda* is said to run east to west; likewise, if the *commissurae* travel north, the *vena profunda* is said to run south to north. These veins are not always straight, though; they could be inclined, crooked, and sometimes curved. All *vena profundae* are visible from the surface; all the differences are underground.

Vena dilatatae are not visible from the surface; instead, they exist as a horizontal disc underground. They differ in thickness as the *vena profundae* differ in width, but over a much smaller range. A "thick vein" would be a *vena dilatata* over a half-foot; anything smaller than that

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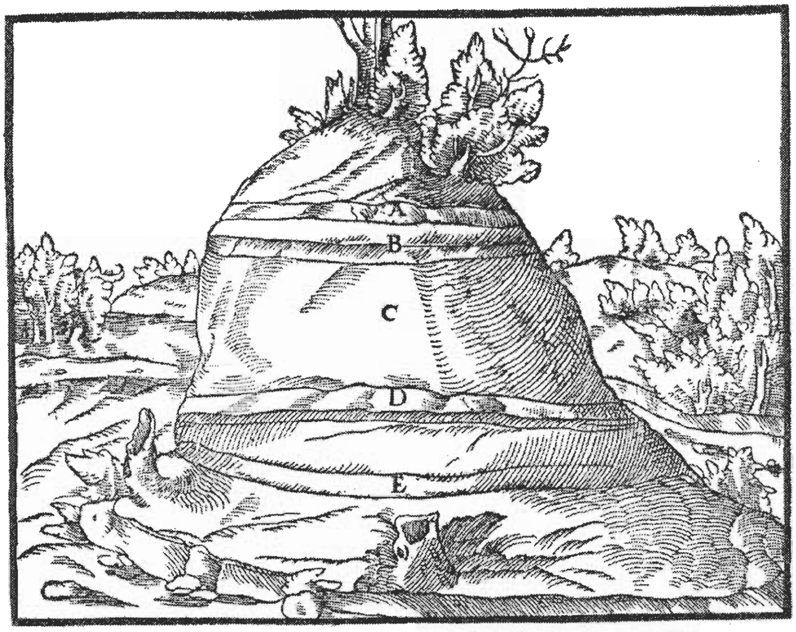
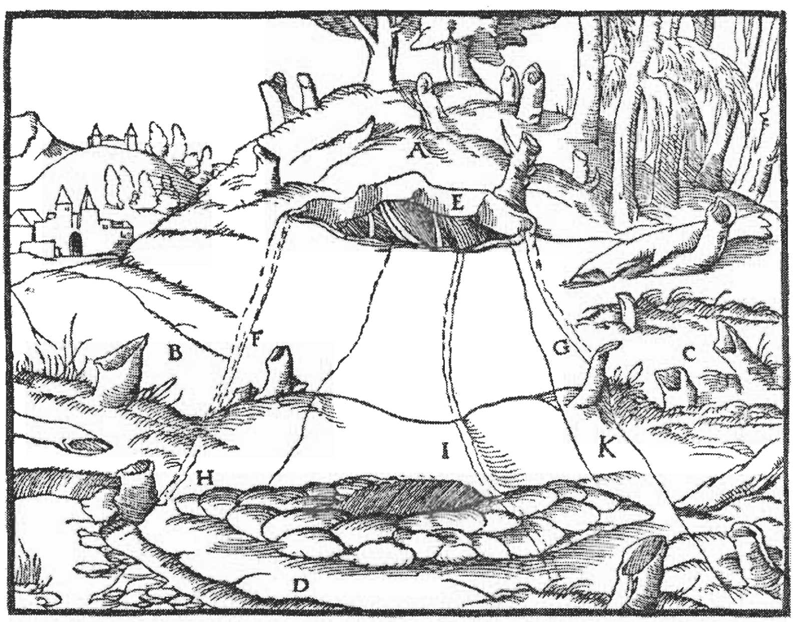
[7] Italics indicate literal Latin from the original text.
[8] Book 3 of De Re Metallica gives more detailed, technical descriptions of the vein types. See De Re Metallica, 43-76.
[9] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 50.



A & B—*Venae dilatatae.* C—*Intervenium.* D & E—OTHER *venae dilatatae.*

Figure 2: Vena dilatatae[10]

would generally be a "thin vein". These, too, are classified based upon direction; however, their directional qualifier determines which way they extend into the earth. If the *commissurae saxorum* incline eastward, then the associated *vena dilatata* is said to go from west to east; the same holds true for the *commussurae* heading north, except that it goes from south to north. A *vena dilatata* may be perfectly horizontal, inclined, or be curved and uneven. In all cases, though, the *vena dilatata* will not break the surface of the earth.



A, B, C, D—THE MOUNTAIN. E, F, G, H, I, K—*Vena cumulata.*

Figure 3: Vena cumulatae[11]

The *vena cumulatae* are huge accumulations of any type of mineral in a subterranean pocket. Agricola theorizes that they were caverns completely filled with ore. Occasionally, several *vena cumulatae* will be grouped near (within a few fathoms) of each other; however, due to their size

[10] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 50.

and shape, this is very rare. These do not have directional qualifiers, nor do they have the same types of variations as the other two veins. *Vena cumulatae* have a distinct "beginning" (one side of the cavern), "end", (the opposing side), "head" (the top of the vein), and "tail" (the bottom). The *vena profunda* also has these distinctions, but it is not as important for a miner to define these; anywhere a *vena profunda* surfaces, mining may commence.

Intervenia are simply the rock between veins. If the *intervenium* occurs between two *vena dilatatae*, the lower one will not be visible, nor will the *intervenium* until the upper vena *dilatata* is mined. (Therefore, it will not be immediately apparent that it is an *intervenium* at all.) However, if an *intervenium* occurs between two *vena profundae*, both of the *vena profundae* will be visible, as will the top (surface) of the *intervenium*.

The stringers (or veinlets) are classified solely by their means of contact with the vein. *Fibrae transversae* cross the vein at a perpendicular, with a distinct point of entry and a distinct point of egress. *Fibrae obliquae* are similar to *fibrae transversae*, but intersect at a diagonal. A *fibra socia* joins with the vein upon contact; there is a point of entry, but no exit. *Fibrae dilatatae* act much as *vena dilatatae*, penetrating through a vein horizontally (at a cross-section with it). The last type, *fibrae incumbens*, only travels the (comparatively) short distance between a vein and the surface. The only major distinction between a vein and a stringer is size.

Commissurae saxorum are exceedingly thin veinlets, or seams. They occur at random frequencies along true *vena*. They tend to travel in the opposite direction as the vein they follow, but can be diverted by larger and/or harder veins or stringers. Therefore, in plotting vein direction, one must observe many seams and follow the majority, rather than take a small sampling; a compass is also of use.[12]

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[11] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 49.
[12] See following section "Tools Of The Miner".

Veins may be solid, near-solid, or barren.[13] A solid vein is one that contains no water and little to no air, but has much ore. Near-solid veins very rarely have water, but frequently carry air. Barren veins have no mineral, but often conduct water. The only truly useful type of vein to the miner is the former.

A—Solid vein. B—Solid stringer. C—Cavernous vein. D—Cavernous stringer. E—Barren vein. F—Barren stringer

Figure 4: Different types of veins[14]

Types of Ores and Means of Removal

Up to and during Agricola's lifetime, only sixty mineral species had been classified. Agricola's experimentation and research led him to discover twenty new minerals, increasing the list of known compounds by a third.[15] In Book V of De Re Metallica, Agricola lists and classifies several types of ore by purity, colour, and certain physical properties.[16]

[13] De Re Metallica, 72-75.
[14] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 73.
[15] Agricola On Metals, 25.
[16] It is worth noting that in De Natura Fossilium Agricola gives much more detailed physical descriptions of the various ores. De Re Metallica is more concerned with the value to the miner than the value to the mineralogist.

Gold is one of the eight metals that are "often found native;"[17] that is, in pure form. After pure gold comes "*rudis*, of yellowish green, yellow, purple, black, or outside red and inside gold colour."[18] *Rudis* and native gold are considered the best ores, because the gold weight to stone weight ratio is in favour of the gold. After these comes any ore in which "one hundred *librae* contains more than three *unciae* of gold."[19] While not as rich as the *rudis* or native gold ore, the high value of gold in comparison with other metals still makes this worthwhile. Anything less than this is considered poor, and not worth mining. However, gold may also be found in marble, quartz, azure, and certain other stones in great enough quantities as to be worth noting.

Silver is often found in pure, native state. Rich silver ores, however, must contain at least three *librae* of silver for every one hundred *librae* of ore.[20] Any silver ore with this purity is considered *rudis* and of the highest value to the miner. Many species of silver ore fall into this category: silver glance, ruby silver, white, black, grey, purple, yellow, and liver-coloured silver.[21] Like gold, silver may be found in quartz, schist, and marble, but the amount of silver in these compounds is usually far higher than the amount of gold.

Interestingly, Agricola does not believe that any other kinds of ore are worth mining. "As regards other kinds of metal, although some rich ores are found, still, unless the veins contain a large quantity of ore, it is very rarely worth while [sic] to dig them."[22] He does note, however, that gems may be found, and that "extraordinary earths"[23] and "solidified juices"[24] should not be ignored, if found in a worthwhile mine.

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[17] De Re Metallica, 107.
[18] De Re Metallica, 108.
[19] De Re Metallica, 108. This is equivalent to 72 ounces 18 pennyweights of gold per short tonne of ore.
[20] De Re Metallica, 112. This is equivalent to 875 ounces of silver per short tonne of ore.
[21] De Re Metallica, 112-113.
[22] De Re Metallica, 115.
[23] De Re Metallica, 115. Extraordinary earths would be useful clays and similar substances.
[24] De Re Metallica, 116. Solidified juices are another type of mineral body. Agricola defines and details all types of mineral bodies in De Natura Fossilium.

Agricola defines four consistencies of ore: crumbling ore consists of earth and "soft solidified juices"[25]; hard ore, which is made of "metallic minerals and moderately hard stones,"[26] which would easily melt in a low fire; harder ore, made of minerals mixed with quartz, pyrites, or very hard marble; and hardest ore, where vein is composed throughout of only "hard stones and compounds".[27] Each type, having different physical properties, had slightly different means of extraction.

Crumbling ore could be removed utilising only a pick.[28] First, the hangingwall[29] rock would be torn away, then the vein would be separated from the footwall[30] with a pick "into a dish placed underneath to prevent any of the metal from falling to the ground."[31] "Hard" ore, and its hangingwall, require the use of a hammer and the "first kind of iron tool,"[32] and the rock of the hangingwall would need to be removed entirely from a section before attacking the vein and footwall. The "harder" and "hardest" ores would sometimes be removable with iron tools; however, this would be at great expense. Agricola then describes two alternate processes for mining difficult veins: "fracturing"[33] and fire-setting. If these methods fail to work on an extremely hard area of the vein, the only other option is to cut around it.

"Fracturing" is to be used when the owners of the neighbouring mines refuse to give permission for fire-setting.[34] This process involves using a wedge to apply stress beyond the breaking point of the mineral involved. "Then they place timbers set in hitches in the hanging or

[25] De Re Metallica, 117.
[26] De Re Metallica, 117.
[27] De Re Metallica, 117.
[28] All tools referenced are separately detailed in the section "Tools of the Miner".
[29] The hangingwall would correspond to the wall in the direction of the "tail" of a vein. This would be the rock over a vein.
[30] The footwall would correspond to the wall in the direction of the "head" of a vein. The vein would lie over this.
[31] De Re Metallica, 118.
[32] De Re Metallica, 118. This would be a specific type of wedge. See section "Tools of the Miner".
[33] Agricola describes a process without labeling it. The label "fracturing" is the design of the present author, and will appear only in quotes.

footwall, a little above the vein, and from the front and upper part, where the vein is seen to be seamed with small cracks, they drive into one of the little cracks one of the iron tools which I have mentioned; then in each fracture they place four thin iron blocks, and in order to hold them more firmly, if necessary, they place as many thin iron plates back to back…and strike and drive them by turns with hammers, whereby the vein rings with a shrill sound; and the moment when it begins to be detached from the hangingwall or footwall rock, a tearing sound is heard. As soon as this grows distinct the miners hastily flee away; then a great crash is heard as the vein is broken and torn, and falls down."[35] This method apparently caused approximately one hundred pounds of ore to collapse, which would then be picked through by the previous-described methods.

A—Kindled logs. B—Sticks shaved down fan-shaped. C—Tunnel.

Figure 5: Fire-setting[37]

Fire-setting is given more attention by Agricola, as it is a more effective, albeit difficult, method of breaking up particularly hard rock.[36] As there are many possibilities of tunnel and vein structure, each scenario is touched upon lightly by Agricola; however, all involve the common element of placing a pile of logs against the vein, or piece of vein,

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[34] As the process of fire-setting would give off poisonous fumes and vapours, permission from the owners of the neighbouring mines, and from the *Bergmeister*, needed to be obtained.
[35] De Re Metallica, 118.
[36] Fire-setting also has several historical notes of some interest to the researcher. The Hoovers give quotes and explanations in their footnote to De Re Metallica, 118-119.
[37] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 120.

to be shattered, and setting fire to the pile. "While the heated veins and rock are giving forth a foetid [sic] vapour and the shafts or tunnels are emitting fumes, the miners and other workmen do not go down in the mines lest the stench affect their health or actually kill them."[38] After the vapours clear, the miners re-enter and gather up the fallen mineral. The ore deposits remaining in the walls are softened as well, and can easily be removed with crowbars and picks. Both the useless rock and the ore are then filled into separate buckets and pulled up a shaft.[39]

<u>Role of the Miner and Mining</u>

The role of the miner and mining as a relevant and important part of society is the issue addressed by the first book of <u>De Re Metallica</u>. Instead of a "kind of business requiring not so much skill as labour,"[40] it is proposed that a great deal of varied and sophisticated knowledge is required in order to be a successful miner. The miner must be familiar with the type of area he is to mine: to understand the nature of the minerals, the specific forms that the minerals will occur in, and the most efficient means of removing them from the earth. He also must be educated in the sciences and arts: philosophy, for understanding the origin, cause, and nature of subterranean things; medicine, in order to recognise the specific pitfalls of the trade, and to be able to communicate effectively with doctors in treating these; astronomy, to utilise the stars in plotting vein directions; surveying, so that he can construct an efficient set of shafts and tunnels; mathematics, for cost calculations; architecture and drawing, in order to construct and design his own machinery for assisting the mine; and law, so as not to infringe on others' rights, nor lose his

[38] De Re Metallica, 120. Again, as he does many other places, Agricola shows his schooling as a doctor. His continuing commentary on pg. 121 describes, in almost clinical detail, symptoms of carbon monoxide poisoning.
[39] The details of this may be found in the section "Technology and Machinery of Mining".
[40] <u>De Re Metallica</u>, 1.

own advantage.[41] Since it is not necessarily possible to gain such a body of knowledge, the concept of consulting experts is recommended.[42] Specialisation in specific areas is a natural thing; to continually try to expand one's knowledge while working with those more knowledgable than oneself is perceived as an important matter in the profession of mining.

Agricola follows with a point-by-point analysis of the benefits of mining. The utility of the mining industry is first addressed, both on a personal level (for the miner) and for mankind as a whole. The differences between an educated miner, as described previously, and an ignorant, unskilled amateur are drawn out; while someone without knowledge and experience may be lucky, such an occurence is rare. To gain personal benefit from mining, education and experimentation are again stressed, with history[43] demonstrating the gains available to those who pursue mining in a learned, orderly fashion.

The desirability of mining as a profession is debated in much detail. Criticism of the stability and sustainability of mines is justified, as the pursuits of farmers and shepherds yield a constant crop perennially, while a mine will eventually be exhausted, leaving the miner without work. However, many mines remain active for centuries, and the possible financial profits from mining far exceed those of agriculture.[44] That mining can be a perilous occupation is true, as there are many types of accidents, diseases, and afflictions particular to the environment of a mine. These dangers are real and everpresent, but foresight and caution are enough to prevent most

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41 De Re Metallica, 1-4.
42 De Re Metallica, 4. This concept is strikingly modern; at a time when the flow of information was carefully controlled by families and guilds, Agricola's suggestion is almost heresy. See following section "Distribution of Information"; compare similar section in Alchemy.
43 De Re Metallica, 5. This references a previous work by Agricola (De Veteribus Et Novis Metallis) in which specific examples are given.
44 Mines in Meissen, Schemnitz, Cremnitz, and Freiberg had been active for hundreds of years. See De Re Metallica, 5, and De Veteribus Et Novis Metallis.

mishaps. These possibilities should no more deter a miner than the possibility of falling from a high building should deter a carpenter.[45]

The chief issue of the first book of De Re Metallica is the moral justification for metals and mining. The position that minerals, gems, and metals are worthless in and of themselves is an ancient one, supported even by such men as Ovid, and the idea that the soul and body neither need nor benefit from them is similarly established. The consequences of mining for the land, water, and forests can be disastrous, not only affecting human life, but in many cases destroying all of the environment.[46] Many historical and mythical examples[47] of the opposition of virtue and metal are given, culminating in the concept of gold as money, and the evils done for its sake. Of course, injurious iron, used to propagate war since time immemorial, especially with the new invention of the cannon, and copper and tin, cast into muskets, are not spared from condemnation by those speaking ill of metal.

However, to declare all metal to be inherently evil would be equivalent to stating that the Creator of these substances is evil, and the concept of God creating "vainly and without good cause" is an opinion "certainly not worthly of pious and sensible men".[48] Metals are hidden within the earth because this is the right and proper place for them to be. To not mine them would be the same as not fishing, for the fish do not live on the land and need to be drawn out from the depths. While there is no direct benefit for the body from metals, they enable humanity to live in a more comfortable, pleasant fashion. Without the use of metal tools, farming, hunting, fishing, and building is impossible. Metals can be formed into things of use and value, not only into utensils of destruction. Metal is proposed as being fundamental to the evolution of life; without it, "men

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[45] Even today in 1999, mining is a hazardous occupation.
[46] Again, Agricola shows a surprisingly "modern" outlook on a major issue of today: environmental pollution.
[47] The specific people, works, and anecdotes cited may be found in De Re Metallica, 6-12.
[48] De Re Metallica, 12.

would pass a horrible and wretched existence in the midst of wild beasts; they would return to the acorns and fruits and berries of the forest".[49] Book I concludes with a rebuttal against all historical precedents cited on the evils of metal, and the reaffirmation of the peculiar dignity of the calling of the miner.[50]

Locating Mines

Book II explores means of locating and identifying mines. There are seven major factors to be considered: the situation, the conditions, the water, the roads, the climate, the right of ownership, and the neighbours.[51]

There are four types of situations: mountains, hills, valleys, and plains. Of these, mountains and hills are preferable, for tunnels can be bored into them, allowing not only easier access to the vein, but also strongly aiding in the draining of water. In any one of these locales, though, a prudent miner will look for evidence of veins in places where a current will have exposed it. Great detail is paid to the different shapes and layouts of mountains; the best possibility for a rich find is in a series of connected mountains, of varying sizes. The different possible shapes for plains and valleys are also explored, and it is recommended that one avoid plains surrounded by mountains, or deep valleys between mountains, unless a vein is found to extend there, since the mountains offer more advantages in terms of mine structure. The primary use of the situation factor is to determine the most likely area within a region to be productive.

The condition of a region involves the forestation over that area. Since timber is vital to mining most metals, a bare area is a major disadvantage unless there is some other means of

[49] De Re Metallica, 14.
[50] De Re Metallica, 13-24.

transporting the wood. However, if gold or gems are to be mined in that region, timber is of lesser importance, as "gems need only to be polished and the gold to be purified".[52] Water also forms one of the most important resources, as a power supplier, means of transportation, and aid to processing the ores. However, caution is advised as the expense of moving the water via artificial means increases greatly with proportion to the distance from the mine.

Since a mining region is unlikely to also be supporting agricultural facilities, the conditions of the roads must be assessed before undertaking an excavation. Bad roads mean increased difficulty in bringing necessities in, which leads to increased prices, which forces increased wages, and therefore a mine would be less profitable.[53] The general health and prosperity of the region must also be assessed; mining has its own set of dangers, and the added risk of sudden disease is quite serious.[54]

Politics of the potential area must also be noted. Unfriendly or tyrannical lords of the realm make for unprofitable and unsafe mining, for they will attack and seize goods not rightfully theirs. In addition, the rights of others in the area must be respected. A single rich vein often draws others to the area in
hopes of similar fortune, and it is important to establish legal rights and boundaries early.[55]

"The miner should try to obtain a mine, to which access is not difficult, in a mountainous region, gently sloping, wooded, healthy, safe, and not far distant from a river or stream by means of which he may convey his mining products to be washed and smelted. This indeed, is the best

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[51] De Re Metallica, 30.
[52] De Re Metallica, 31.
[53] De Re Metallica, 32.
[54] Agricola's background as a physician makes him especially wary of disease possibilities. He addresses this subject further in De Natura Eorum Quae Effluunt Ex Terra.
[55] Dividing up a mining region and the hierarchy necessary to effectively maintain it is addressed in Book IV of De Re Metallica.

position. As for the others, the nearer they approximate to this position the better they are; the further removed, the worse."[56]

Before selecting a location in which to attempt to mine, veins must be sought out to confirm the validity of the locale. There are two basic ways in which a vein may be found: it may be exposed naturally through some phenomena, or it may lie buried in the earth. Various phenomena can reveal veins, including water flow, high winds, lightning, fires, rockslides, and earthquakes. Finding naturally exposed ore is a matter of chance and not to be relied upon. With careful observation and knowledge of the possible effects of the ore, however, buried deposits may be discovered.

A—Twig. B—Trench.

Figure 6: Methods of finding mineral veins[57]

Bubbling springs may be tested for the presence of certain minerals by their taste: salty water indicates the presence of salt, nitrous water indicates soda, etc. Vein fragments may have been broken off by the force of the water as well, and their smoothness can help the astute observer in

[56] De Re Metallica, 33.
[57] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 40.

finding the nearness of the vein. A very rough or fixed fragment indicates the presence of the ore nearby, whereas a smooth or round fragment usually indicates that it has moved some distance. The colouring of plant life, especially if there is an extreme variation over a space, may signal ore to be nearby, as will certain unusual frost patterns. By carefully observing the effects of natural cycles, an experienced miner should be able to successfully determine the optimal location for beginning excavation.[58]

The tradition of the "divining rod" is addressed quite seriously. This may seem a bit unusual in a revolutionary book of this type, but the belief in divining rods holds up into this century. Furthermore, while arguing that it does seem to be a valid means of locating ore in the hands of certain people, he states that "since we think he ought to be a good and serious man, should not make use of an enchanted twig, because if he is prudent and skilled in the natural signs, he understands that a forked stick is of no use to him, for as I have said before, there are the natural indications of the veins which he can see for himself without the help of twigs. So if Nature or chance should indicate a locality suitable for mining, the miner should dig his trenches there; if no vein appears he must dig numerous trenches until he discovers an outcrop of a vein. So if Nature or chance should indicate a locality suitable for mining, the miner should dig his trenches there; if no vein appears he must dig numerous trenches until he discovers an outcrop of a vein".[59]

Shafts, Tunnels, and Drifts

A tunnel is a horizontal passage that serves as an outlet to the mine. Agricola defines a tunnel as “a subterranean ditch driven lengthwise”, and states that it should be “nearly twice as high

[58] De Re Metallica, 33-38.
[59] De Re Metallica, 41.

as it is broad, and wide enough that workmen and others may be able to pass and carry their loads."[60] To dig a tunnel, two miners would work in tandem; one would dig out the top part, and the other would dig the bottom, slightly behind the former. The miners would use the tunnel as their primary entry and exit point, and it would also be the principal area of excavation.

THREE VERTICAL SHAFTS, OF WHICH THE FIRST, A, DOES NOT REACH THE TUNNEL; THE SECOND, B, REACHES THE TUNNEL; TO THE THIRD, C, THE TUNNEL HAS NOT YET BEEN [illegible]

Shafts are vertical or inclined passages through which materials may be transferred.[61] "Now a shaft is dug, usually two fathoms long, two-thirds of a fathom wide, and thirteen fathoms deep,"[62] except when the shaft is driven for the express purpose of connecting with a tunnel, in which case the depth would vary. Over each shaft, a windlass[63] would be placed, and a shed would be built over it "to prevent the rain from falling in, lest the men who turn the windlass

Figure 7: Shafts and tunnel[64]

[60] De Re Metallica, 102. The dimensions given for a normal tunnel are one and a quarter fathoms high, and three and three quarters feet wide.
[61] Other uses of shafts for ventilation, drainage, etc. are explored in Book VI of De Re Metallica and are discussed in the section "Technology and Machinery of Mining".
[62] De Re Metallica, 102.
[63] See section "Technology and Machinery of Mining".
[64] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 103.

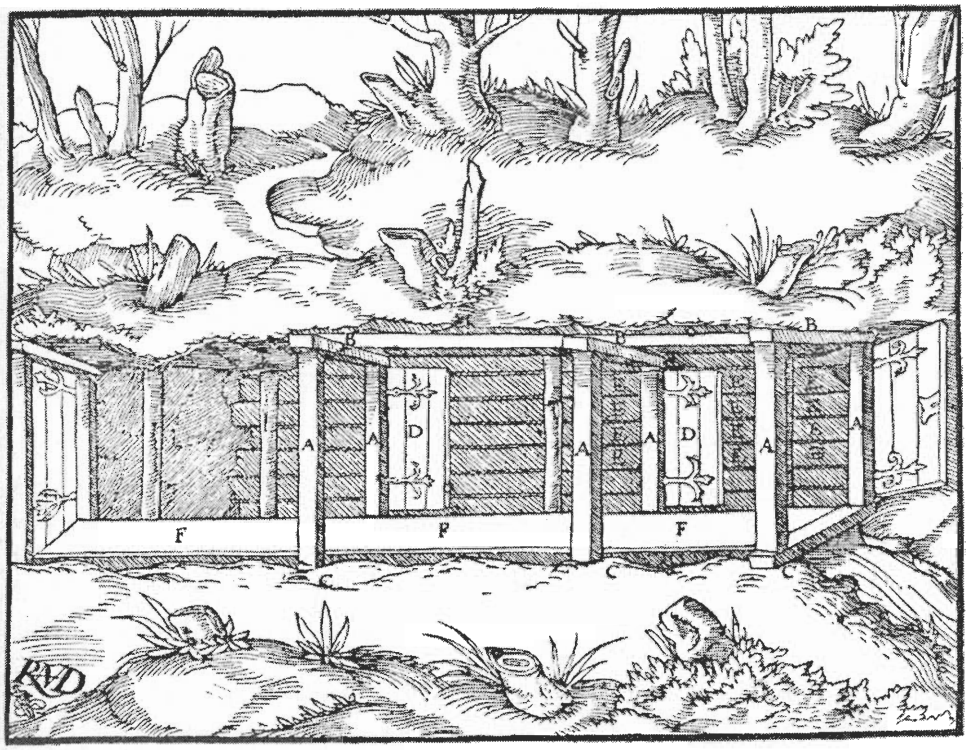
be numbed by the cold and rain."[65] Three possibilities occur when sinking a shaft: it may connect to the tunnel, it may not connect to the tunnel, or it may reach a level where the tunnel will reach it after further extension. To connect with the tunnel is usually optimal; the shaft and windlass make mining easier by reducing the distance ore would need to be carried.[66] However, it was not unusual for a shaft to "drift" off of the path to the tunnel while being dug out; these deviations were useful in determining the existance and location of veins and stringers that would intersect the primary vein.

A drift is a horizontal passage similar to a tunnel, but without a surface endpoint. When the excavation of a shaft "drifts" and happens upon a rich vein or stringer, a drift is burrowed, so that the ore may be mined more easily and effectively. "This kind of opening, however, differs from a tunnel in that it is dark throughout its length, whereas a tunnel has a mouth open to daylight."[67]

All three types of passages may require extra support systems to keep them from

Figure 8: Shaft and drift tunnel[68]

[65] De Re Metallica, 102. The shed would also be used for storage, but not for living quarters, because of the possibility that "boys and other living things" may fall into it. As a doctor, Agricola frequently notes health and safety concerns. See footnote 25.
[66] Shafts also aid ventilation and the removal of water. The details of this are given in the section "Technology and Machinery of Mining".
[67] De Re Metallica, 105.
[68] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 105.



A—Posts. B—Caps. C—Sills. D—Doors. E—Lagging. F—Drains.

Figure 9: Structural supports[69]

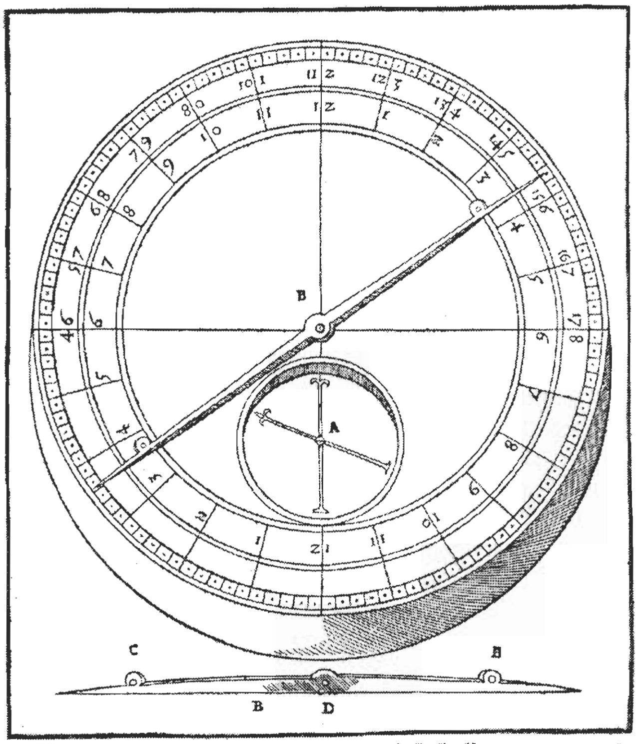
collapsing under the weight of the earth. A tunnel, shaft, or drift through a particularly hard vein with hard walls would not need timbering; all other possibilities require at least a minimal set of structural supports. Timbering a shaft involves placing wooden beams along its corners, buttressed by cross-beams along both the walls and the center space. In weaker or less stable shafts, the walls, in addition to the corners, of the shaft would be timbered; this would prevent loose rubble from falling and causing injury to the miners below. If the shaft were particularly deep, the bottom of the shaft would be covered except for the ladder area and the space for the bucket in order to prevent injury to the miners from falling debris.[70] Timbering a tunnel was a bit simpler; basic post-and-lintel structures, with planks on both floor and ceiling supported by each set, would suffice to stabalise it. Drifts, essentially being tunnels, are timbered in much the same manner.[71]

[69] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 125.
[70] De Re Metallica, 122-124. Agricola notes several other safety benefits and concerns involved with timbering shafts. See note <x>.
[71] De Re Metallica, 125-126. Some minute differences do exist between Agricola's description of the timbering of a tunnel and a drift, but they are technical in nature and are irrelevant to this text.

Tools of the Miner

The compass was indispensable for plotting vein direction and size. Agricola describes the means of making a compass:

Figure 10: Compass[72]



A—Needle of the instrument. B—Its tongue. C, D, E—Holes in the tongue.

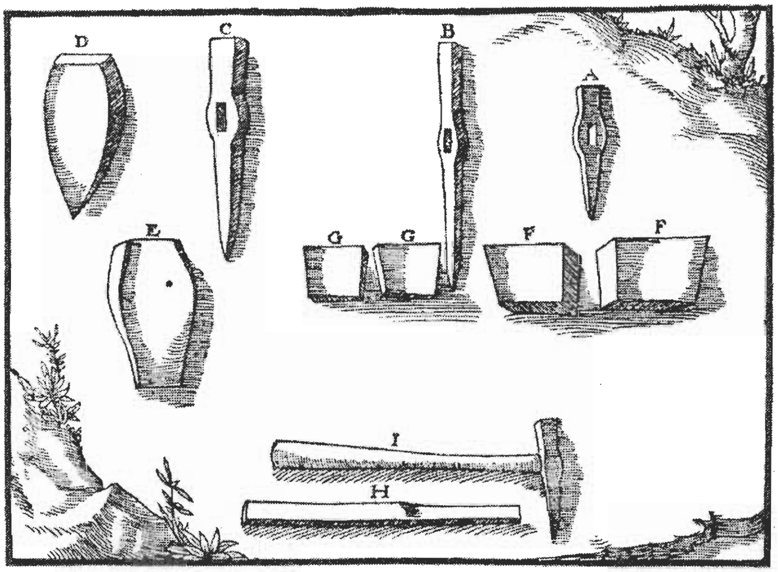
The instrument which indicates these directions is thus constructed. First a circle is made; then at equal intervals on one half portion of it right through to the other, twelve straight lines called by the Greeks diametroi, and in the Latin dimetientes, are drawn through a center point which the Greeks call kentron, so that the circle is thus divided into twenty four divisions, all being of an equal size. Then, within the circle are inscribed three other circles, the outermost of which has cross-lines dividing it into twenty-four equal parts; the space between it and the next circle contains two sets of twelve numbers, inscribed on the lines called "diameters"; while within the innermost circle it is hollowed out to contain a magnetic needle. The needle lies directly over that one of the twelve lines called "diameters" on which the number XII is inscribed at both ends.[73]

This instrument was invaluable for not only finding iron ore, but also for determining the exact direction the vein travels. "One who wishes to know the direction of the veins underground,

[72] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 142.
[73] De Re Metallica, 56-57.

places over the vein the instrument just described; and the needle, as soon as it becomes quiet, will indicate the course of the vein."[74] Agricola also describes the use of a compass in surveying, where it will aid measurements through the use of its exact angles.[75]

Figure 11: Tools[76]



A—First "iron tool." B—Second. C—Third. D—Fourth.³ E—Wedge. F—Iron block. G—Iron plate. H—Wooden handle. I—Handle inserted in first tool.

The first category of tools addressed in Book VI of De Re Metallica are "iron tools", which are separated into four categories by length and thickness.[77] However, all four types share a similar shape; one end (the "upper" end) is "broad and square, so that it can be struck by the hammer,"[78] while the other end is "pointed so as to split the hard rocks and veins with its point."[79] As Figure 3.N illustrates, these seems to be chisel-like in both use and appearance. The first one is "in daily use among miners, three-quarters of a foot long, a digit and a half wide, and a digit thick."[80] The second is identical to the first, but twice as long. It is used to "shatter the hardest veins in such a way that they crack open."[81] The third is similar to the second, but slightly wider and thicker; its use is to "dig the bottom of those shafts which slowly accumulate water."[82] Each of these has an "eye"; a hole where

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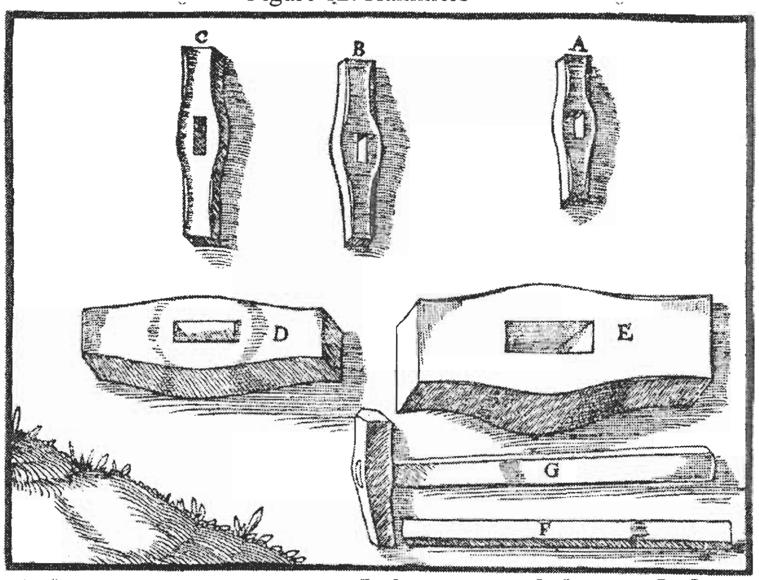
[74] De Re Metallica, 58.
[75] The subject of surveying is dealt with extensively by the latter part of Book V. Agricola details this subject quite exhaustively and it is beyond the scope of this paper to relay it. See De Re Metallica, 128-148.
[76] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 150.
[77] De Re Metallica, 149.
[78] De Re Metallica, 149-150.
[79] De Re Metallica, 150.
[80] De Re Metallica, 150.
[81] De Re Metallica, 150.
[82] De Re Metallica, 150.

a handle may be attached. The fourth type, however, does not have this hole; it is "nearly three palms and one digit long, two digits thick, and in the upper end it is three digits wide, in the middle it is one palm wide, and at the lower end it is pointed like the others; with this they cut out the harder veins."[83] The first three "iron tools", when fitted with handles, are akin to the modern pickaxe; the fourth seems to resemble Agricola's later description of the wedge.

The wedge was only briefly noted by Agricola; its measurements were "usually three palms and two digits long and six digits wide; at the upper end, for a distance of a palm, it is three digist thick, and beyond that point it becomes thinner by degrees, until finally it is quite sharp."[84] Iron blocks, utilised in the "fracturing" process,[85] are wide-angle wedges; six digits long and wide, and sloping from two digits thick at one end to one and one half digits thick at the other. Iron plates[86] have the same width and length, but are much thinner. Agricola ends the descriptions of these three types of tools with the note that they may be made larger or smaller to fit the task.[87]

Figure 12: Hammers[88]



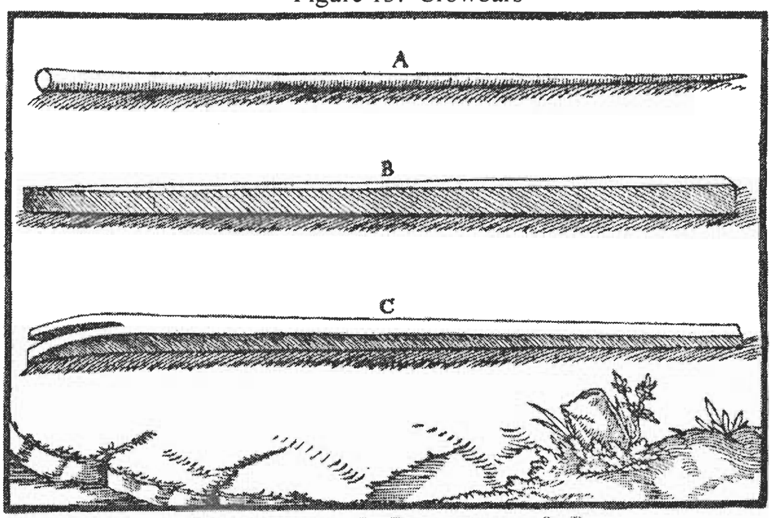
A—Smallest of the smaller hammers. B—Intermediate. C—Largest. D—Small kind of the larger hammer. E—Large kind. F—Wooden handle. G—Handle fixed in the smallest hammer.

Hammers are divided into those wielded with one hand and those wielded with both. Single-handed hammers come in three sizes, each corresponding with one of the "iron tools" in usage: the smallest (lightest) with the second "iron tool"; the middle

[83] De Re Metallica, 150.
[84] De Re Metallica, 150.
[85] See section "Types of Ores and Means of Removal".
[86] These were also used in the "fracturing" process. See section "Types of Ores and Means of Removal".
[87] De Re Metallica, 151.
[88] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 151.

with the first "iron tool"; and the largest with the third "iron tool". The greater hammers are separated into two categories, and, like the single-handed hammers, are paired with other tools; the smaller two-handed hammers strike the fourth "iron tool, while the larger ones are used in conjunction with the wedge. "All swell out in their middle, in which there is an eye for a handle, but in most cases the handles are somewhat light, in order that the workmen may be able to strike more powerful blows by the hammer's full weight being thus concentrated."[89] The only difference between each type of hammer is its size; this varies from under two digits wide and thick to "five digits wide and thick, and a foot long."[90]

Figure 13: Crowbars[91]



A—ROUND CROWBAR. B—FLAT CROWBAR. C—PIKE.

Crowbars are iron bars with one flat end and one point. There are two divisions of crowbars: round ones, with which "they pierce to a shaft full of water when a tunnel reaches to it"[92]; and flat ones, for prying out fire-softened ore that cannot be removed via the pike. A pike is simply a bar with a flat end and a slightly forked end.[93] Picks are used for digging out softer ores, and they only "differ from a peasant's pick in that the latter is wide at the bottom and sharp, but the former is pointed."[94] Hoes and shovels are "in now

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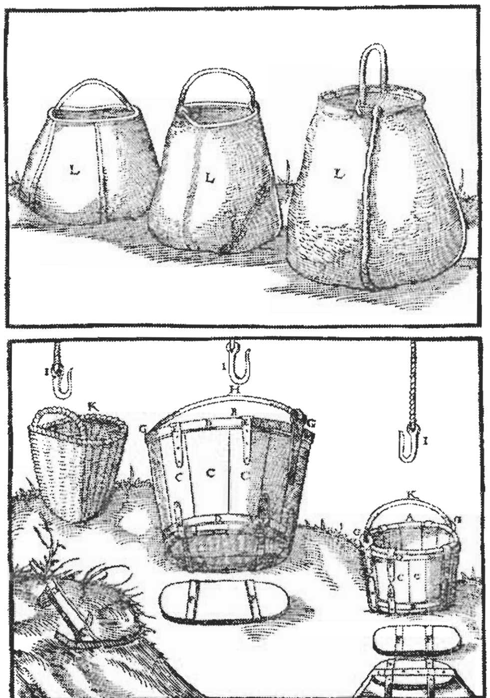
[89] De Re Metallica, 151.
[90] De Re Metallica, 151.
[91] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 152.
[92] De Re Metallica, 152. The meaning of this is somewhat unclear.
[93] See Figure 3.N.
[94] De Re Metallica, 153. See Figure 3.N.



A—Small bucket. B—Large bucket. C—Staves. D—Iron hoops. E—Iron straps. F—Iron straps on the bottom. G—Hafts. H—Iron bale. I—Hook of drawing-rope. K—Basket. L—Hide bucket or sack.

Figure 14: Buckets[98]

way different from the common articles"[95] and serve the obvious purpose of scooping up loose earth and depositing it elsewhere.

Buckets[96] are the prime vessels with which ore is hauled out of a tunnel or drift through a shaft. Agricola describes two types of buckets, of identical shape and material, but of differing size.[97] A bucket is "made of staves circled with hoops, one of which binds the top and the other the bottom. The hoops are sometimes made of hazel and oak, but these are easily broken by dashing against the shaft, while those made of iron are more durable. In the larger buckets the staves are theicker and wider, as also are both hoops, and in order that the buckets may be more firm and strong, they have eight iron straps, somewhat broad, four of which run from the upper hoop downwards, and four from the lower hoop upwards, as if to meet each other. The bottom of each bucket, both inside and outside, is furnished with two or three straps of iron, which run from one side of the lower hoop to the other, but the straps which are on the outside are fixed crosswise. Each bucket has two iron hafts which project above the edge, and it has an iron semi-circular bail whose lower ends are fixed directly into the hafts, that the bucket may be handled more easily. Each kind of bucket is much deeper than it is wide, and each is wider at the top, in order that the

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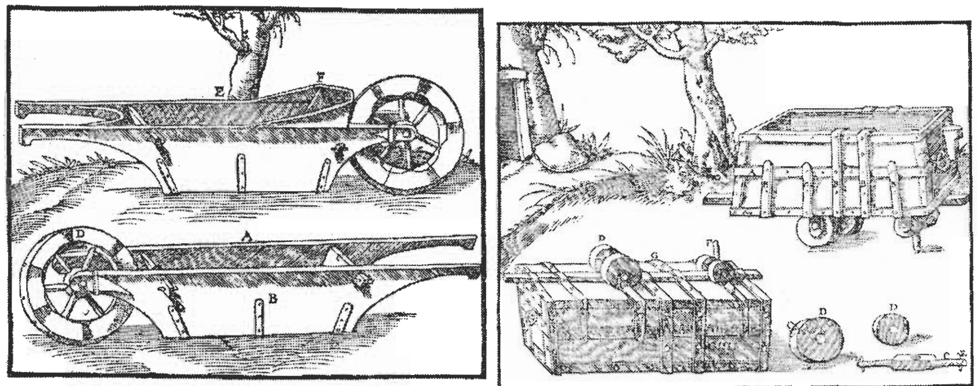
[95] De Re Metallica, 153.

[96] Agricola defines "buckets" only for carrying ore and earth (solids). Buckets for transporting water are called "water-buckets". "Water-buckets" are discussed later.

[97] The translation by the Hoovers of the volume measurements given by Agricola of the buckets are inconsistent with the text. See De Re Metallica, 153.

[98] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 154.

material which is dug out may be the more easily poured in and poured out again."[99] Slight note is given to baskets and hide sacks; these being only variations of the bucket design previously mentioned. Agricola suggests using any combination of buckets, hide sacks, and baskets in an efficient combination, where "three of these filled with excavated material are drawn up at the same time as three are being lowered and three are being filled."[100]



A—Small wheelbarrow. B—Long planks thereof. C—End-boards. D—Small wheel. E—Larger barrow. F—Front end-board thereof.

A—Rectangular iron bands on truck. B—Its iron straps. C—Iron axle. D—Wooden rollers. E—Small iron keys. F—Large blunt iron pin. G—Same truck upside down.

Figure 15: Wheelbarrows[101]

Detailed plans[102] for wheelbarrows and trucks follow the descriptions of buckets in the text. While buckets would serve as the most efficient means of drawing ore up through a shaft, wheelbarrows and carts serve the same purpose for tunnels. One specialised type of wheelbarrow, for the washing of "earth mixed with tin-stone,"[103] is larger and deeper than the ordinary transportation wheelbarrows, so that metal would not wash out of the basin accidentally. Trucks are only half the capacity of wheelbarrows, but it "is used when they draw loads out of the longest tunnels, both because it is moved more easily and because a heavier load can be placed in it."[104]

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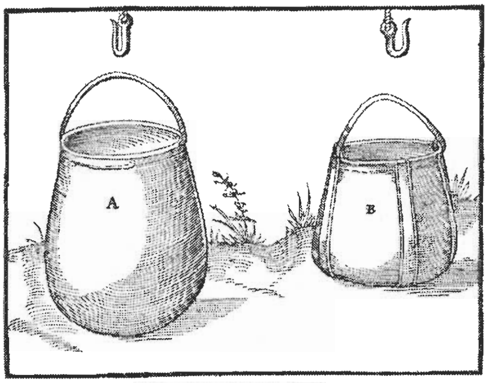
[99] De Re Metallica, 153.
[100] De Re Metallica, 153. Another "futuristic" concept, the assembly line, is hinted at here.
[101] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 155, 156.
[102] Descriptions of the construction of trucks and wheelbarrows is extensive, with the same level of detail as in the bucket described above. As the full process is unlikely to be of use or interest to the staff, only the diagram of the completed product is given here. See De Re Metallica, 154-156, and Fig. 3.N.
[103] De Re Metallica, 155. See section "Extraction and Smelting".
[104] De Re Metallica, 156.

Bateas,[105] hollowed-out wooden planks, were the least efficient way to transport ore, as they could only be carried out by men, either on their shoulders or from a rope over their necks.[106]

Figure 16: Water bags[107]



A—Water-bag which takes in water by itself. B—Water-bag into which water pours when it is pushed with a shovel.

Vessels for the removal of water from the mine were water-buckets, water-bags, and dippers. The water-buckets were different from their dry counterparts in that their tops were much narrower, "in order that the water may not be spilled by being bumped against the timbers when they are being drawn out of the shafts, especially those considerably inclined."[108] Dippers were not actually used for transporting water from a mine; their purpose was auxiliary in nature. Essentially small buckets, they were bound with hazel (instead of iron) and were used only for pouring water into the water-buckets. Water-bags were of two types: those that take in water by themselves, and those that take in water only when "pushed in a certain way by a wooden shovel."[109] Both kinds are "very large skins for carrying water which are made of two, or two and a half, ox-hides."[110] Once the water had been drawn out of the mine, it would be poured into a hopper, a simple rectangular basin, and from there flow along a trough, away from the mine.

[105] These are the "plates" placed below the vein to prevent any ore from being lost, and also where ore would be washed for testing. See sections "Types of Ore and Means of Removal" and "Techniques of the Assayer".
[106] Agricola also notes, on the authority of Pliny, that the only method known by the Ancients of transporting raw ore from the mine was to be carried in the fashion of bateas.
[107] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 158.
[108] De Re Metallica, 157.
[109] De Re Metallica, 159.

Technology and Machinery of Mining

Agricola separates mining machines into three categories: hauling machines, ventilating machines, and ladders. Hauling machines are those that draw loads out from shafts; ventilating machines "receive the air through their mouths and blow it into shafts or tunnels, for if this is note done, diggers cannot carry on their labour without great difficulty in breathing"[111]; and ladders are the means by which a miner may enter a shaft or leave it.

Hauling machines are divided into two main classifications: those for removing excavated material and those for removing water in order to drain a mine. Those for removing ore and earth, also called by the name "windlass", are of five types: the simple crank, shaft, and rope design, operated by two men; a larger version of the same, with a wheel replacing the second man, for deeper shafts; a slower, circular treadmill windlass, operated by two men, with an upright axle and gear mechanism; a large, horse-driven cross-wheel, similar in concept to the treadmill; and an intricate, very large drum and brake windlass, needing a minimum of two men and a horse to drive it. The first of these is simply

Figure 17: Windlass I[112]

[110] De Re Metallica, 159.
[111] De Re Metallica, 160.
[112] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 161.

an axle supported on two beams, with cranks on either end and a rope attached to its center.[113] Two men would "turn the windlass, each having a wheelbarrow near him, into which he unloads the bucket which is drawn up nearest to him."[114] This design is most useful for a shaft that is not too long, nor too quickly worked. The second type of machine is more useful for a deeper shaft, as its inertia[115] makes drawing up a load quicker. However, "all windlass workers, whatsoever kind of a machine they may turn, are necessarily robust that they can sustain such great toil."[116] To make the labour less arduous, and to raise larger loads, Agricola defined a third type of machine, driven by foot-power. While the design for this machine shows remarkable engineering ability[117], this arrangement was much slower. To solve this problem, and to raise "burdens once and a half as large again as the two machines first explained"[118], the fourth machine is driven by horses. Harnesses were

A—Barrel. B—Straight levers. C—Usual crank. D—Spokes of wheel. E—Rim of the same wheel.

Figure 18: Windlass II[119]

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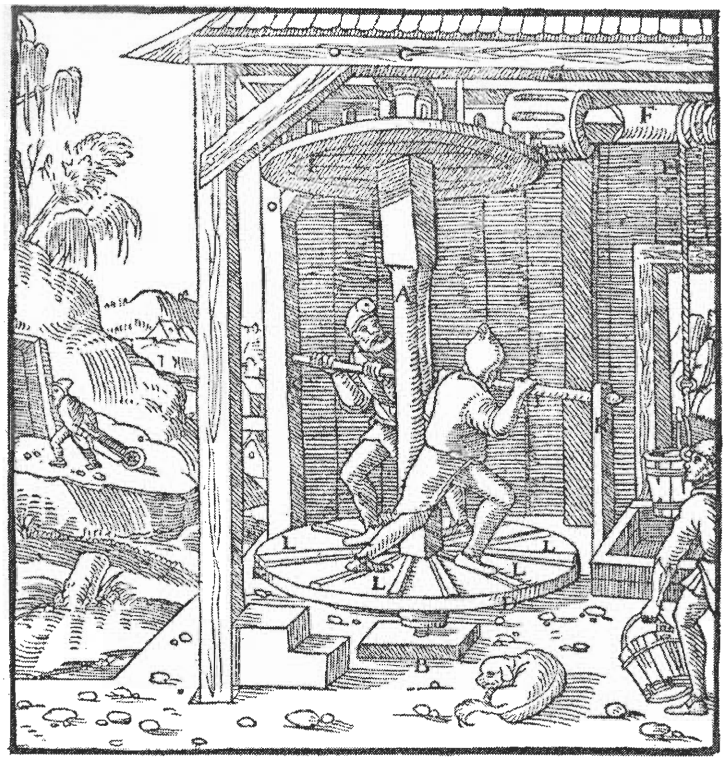
[113] As with his description of the tools, Agricola describes the materials and construction of these machines in great detail. As this detail gives a great deal of length without giving a great deal of information, the accompanying illustrations are provided instead. See Figs. 3.N...
[114] De Re Metallica, 160.
[115] Agricola describes lead masses being attached to the wheel to keep it moving. See De Re Metallica, 161-162.
[116] De Re Metallica, 162.
[117] See Fig. 3.N.
[118] De Re Metallica, 163.
[119] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 162.



A—Upright axle. B—Block. C—Roof beam. D—Wheel. E—Toothed-drum F—Horizontal axle. G—Drum composed of rundles. H—Drawing rope. I—Pole. K—Upright posts. L—Cleats on the wheel.

Figure 19: Windlass III[124]

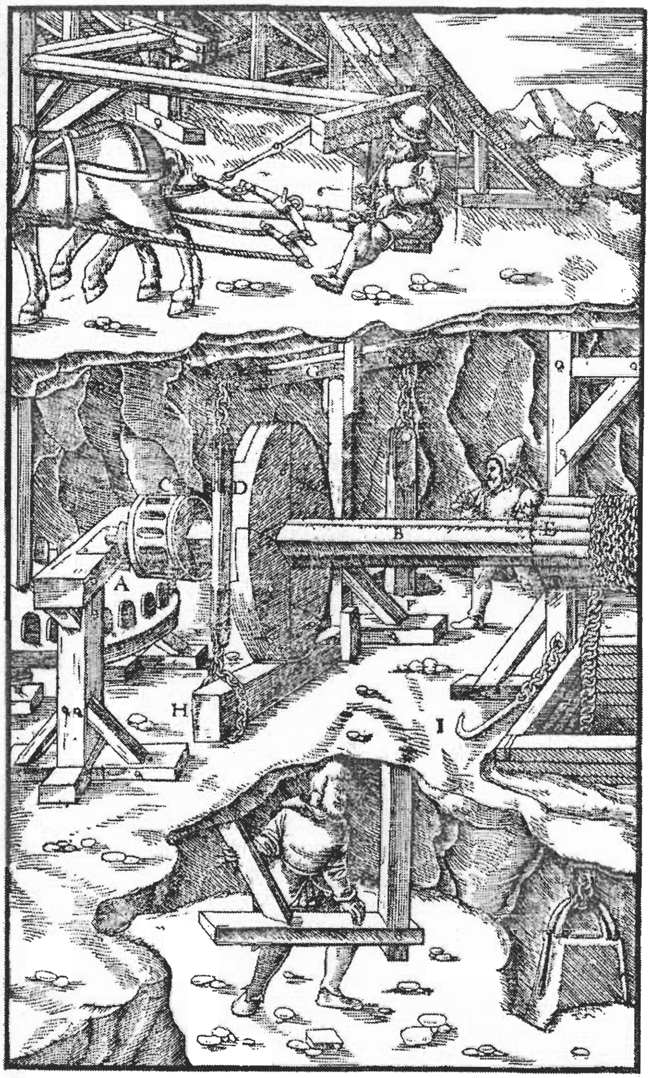
attached to a cross raised on a central axle; this pivot is connected to an intricate system of gears[120] that drive the horizontal shaft.[121] The final machine combines a whim with a braking mechanism[122]; a miner sitting on the brake-beam would force the wheel to halt, which was "necessary when the hide buckets are emptied after being drawn up full of rock fragments or earth."[123] The increasing level of technological development[125] between the designs presented by Agricola is readily apparent.

While any of the above machines may be used for hoisting water in buckets, Agricola describes three types of hauling machines specifically for pumping water from a mine: chains of dippers, suction pumps, and "rag and chain"[126] pumps. Three types of chains of dippers are described: a man-driven chain, made up entirely of buckets with an iron frame linking them; a tread-driven set of buckets, held together only by thick chains, without a frame; and a water-wheel powered version of the second. In the first, a linked frame is set against two toothed wheels, one at

[120] See De Re Metallica, 163-200, and Agricola on Metals, 46-66, for a more detailed discussion of the gear systems involved in the various hauling machines.
[121] An animal-driven windlass such as this is referred to as a "whim".
[122] See Fig. 3.N.
[123] De Re Metallica, 166.
[124] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 163.
[125] Agricola notes that the Ancients had no knowledge of this type of machinery.
[126] The literal Latin for this is "machine which draws water with balls". The Hoovers adapt the term used by Cornish miners contemparary with Agricola for ease of understanding.

A—Upright beams. B—Sills laid flat upon the ground. C—Posts. D—Area. E—Sill set at the bottom of the hole. F—Axle. G—Double cross-beams. H—Drum. I—Winding-ropes. K—Bucket. L—Small pieces of wood hanging from double cross-beams. M—Short wooden block. N—Chain. O—Pole bar. P—Grappling hook. (Some members mentioned in the text are not shown).

Figure 20: Windlass IV[127]

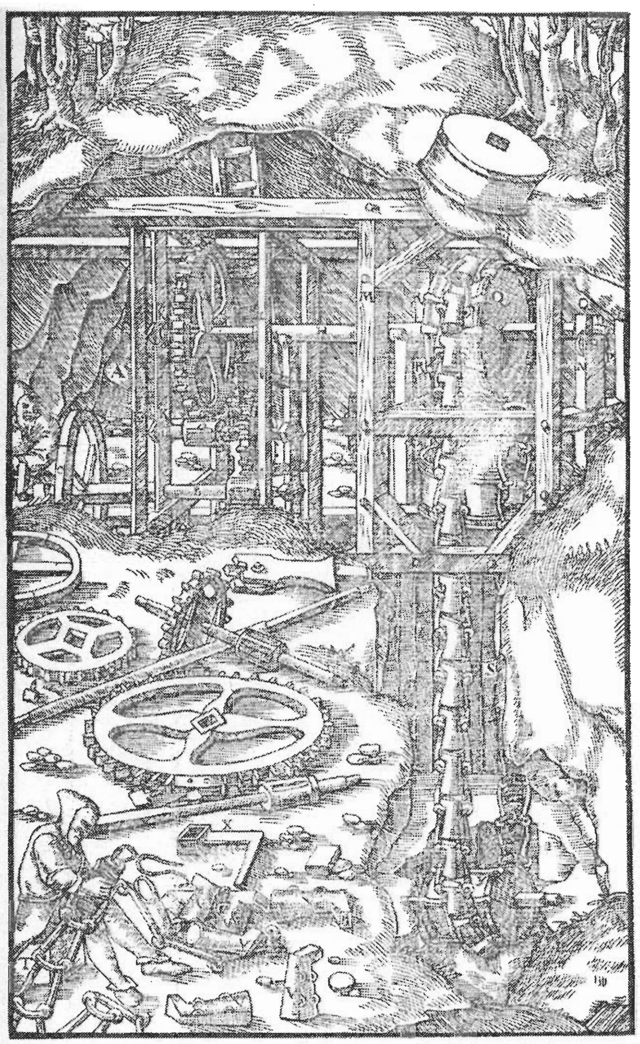


A—Toothed drum which is on the upright axle. B—Horizontal axle. C—Drum which is made of rundles. D—Wheel near it. E—Drum made of hubs. F—Brake. G—Oscillating beam. H—Short beam. I—Hook.

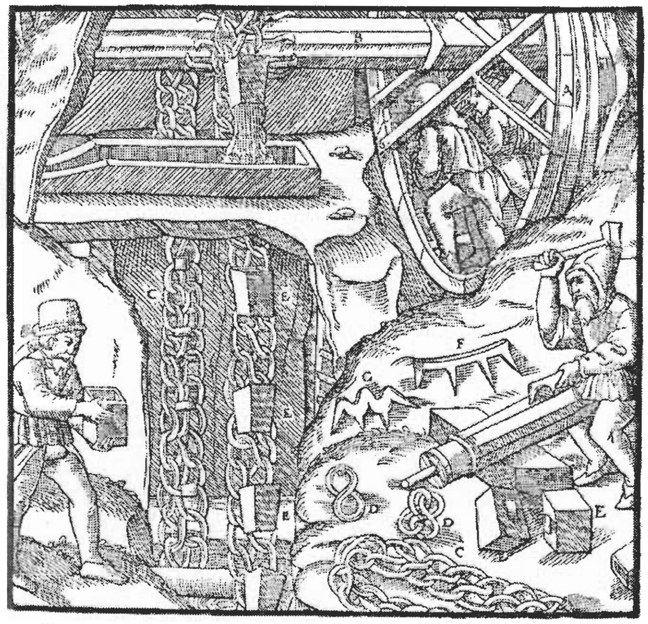
Figure 21: Windlass V[128]

the top and one on bottom. Buckets fastened within the frame fit between the teeth, and a miner operates this machine via a hand-turned crank. This machine is not recommended, as "it cannot be constructed without great expense, and it carries off but little water and is somewhat slow."[129] The second machine described by Agricola is faster and simpler than the first. A large wheel, in which a miner walks, is attached to a large axle, from which buckets linked by chain is suspended. It does

[127] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 165.
[128] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 167.
[129] De Re Metallica, 174.



A—Iron frame. B—Lowest axle. C—Fly-wheel. D—Smaller drum made of bundles. E—Second axle. F—Smaller toothed wheel. G—Larger drum made of bundles. H—Upper axle. I—Larger toothed wheel. K—Bearings L—Pillow. M—Framework N—Oak timber O—Support of iron bearing P—Roller. Q—Upper drum. R—Clamps. S—Chain. T—Links. V—Dippers X—Crank. Y—Lower drum or balance weight

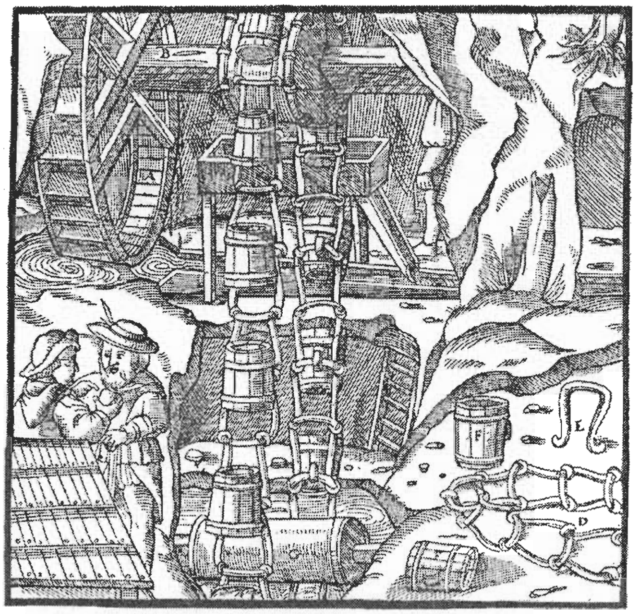


A—Wheel which is turned by treading. B—Axle. C—Double chain. D—Link of double chain. E—Dippers. F—Simple clamps. G—Clamp with triple curves.

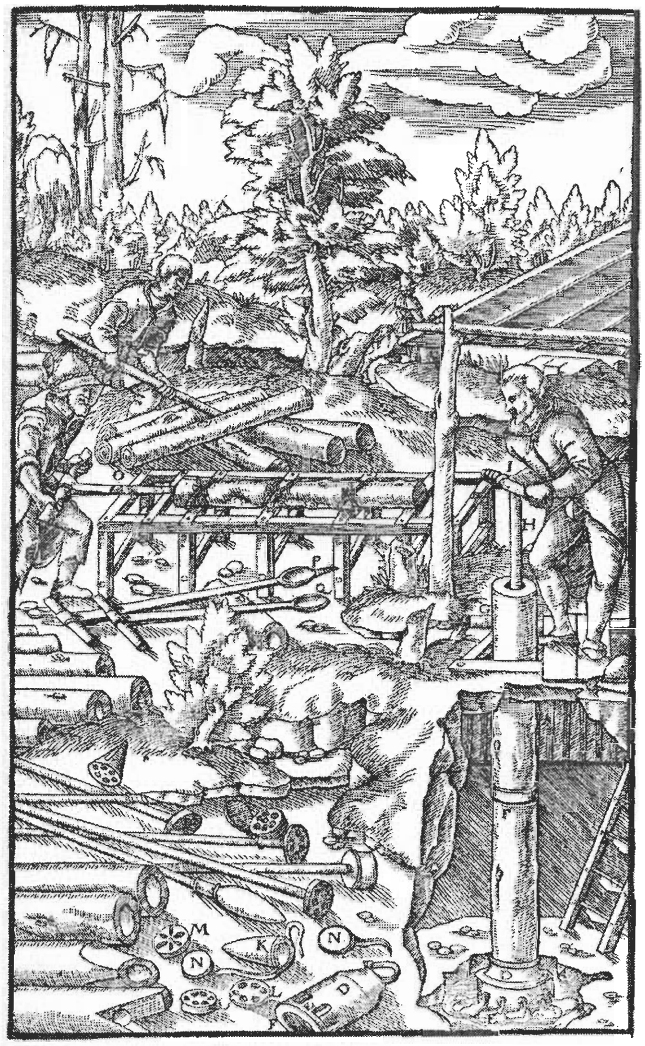
not involve as complicated of a gear mechanism, nor does it require the large amount of iron for building the frame, but the axle does not last as long due to its constant wear. The third type is the most efficient, being similar in design to the second but driven by a water-wheel instead of the labour of a miner.

Figure 22: Dipper pumps (above and above right)[130]

However, as the dippers on this model are as fragile as those on the others, this general design is not used often in practice. Suction pumps are of seven varieties: a single, direct, hand-worked pump; a single pump, hand driven by lever instead of directly; a labour-saving variation of the second where the water flows out from its own weight; a double pump, crank-driven; a triple pump, driven by an axle and piston setup; a water-wheel variation of the fifth; and a multi-level, water-driven pump, useful for pulling water from even the deepest of mines. The simplest pump is a



A—Wheel whose paddles are turned by the force of the stream. B—Axle. C—Drum of axle, to which clamps are fixed. D—Chain. E—Link. F—Dippers. G—Balance drum.



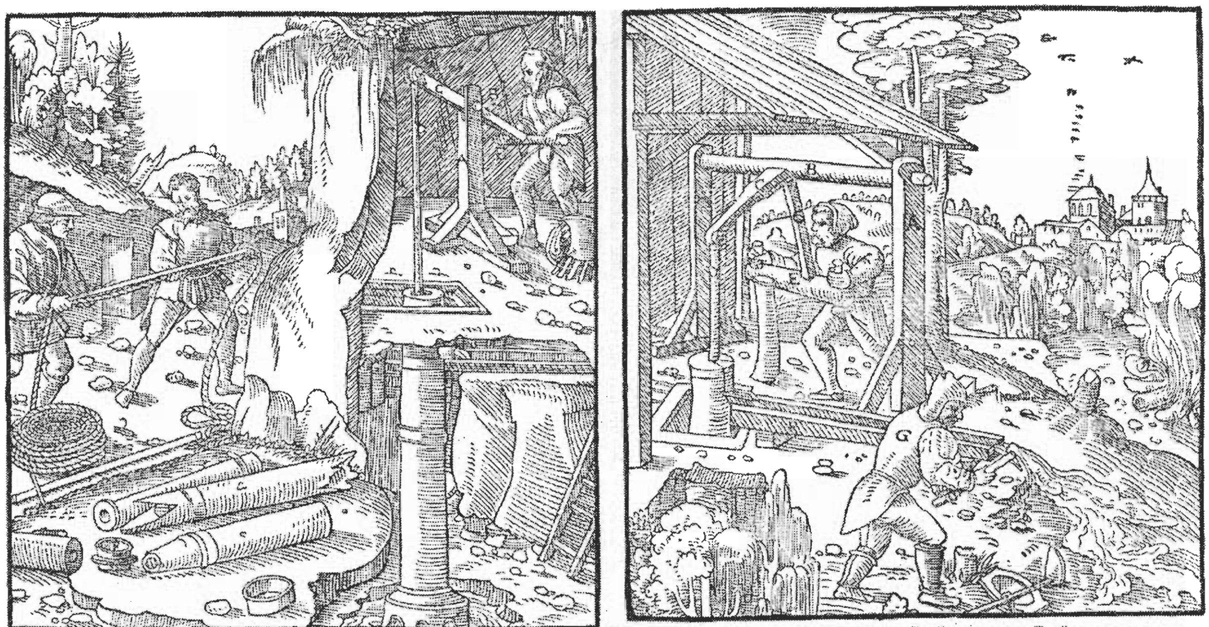
A—Sump. B—Pipes. C—Flooring. D—Trunk. E—Perforations of trunk. F—Valve. G—Spout. H—Piston-rod. I—Hand-bar of piston. K—Shoe. L—Disc with round openings. M—Disc with oval openings. N—Cover. O—This man is boring logs and making them into pipes. P—Borer with auger. Q—Wider borer.

Figure 23: Dipper (above left) and suction (right) pumps[131]

pipe, with a one-way valve on the bototm, so that when a piston is pulled up, the pipe is filled with water; but when the piston is pushed down, the valve remains closed, so that the water instead flows out of a spigot at the top. The second suction pump is a simple variation on this; instead of the strain of pushing the piston-shaft up and down, a lever on a fulcrum is attached to the piston. By working the simpler motion of the lever, the piston is manipulated.[132] The third is an even more efficient revision, where the upright lever is replaced by an axle-mounted lever; the simpler pushing motion is even less fatiguing to the miner. The fourth pump is a departure from the previous models; a double pump, attached to a holding

[130] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 173, 174.
[131] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 175, 177.
[132] Put in the pictures pages 176-185. Should make sense.

box, is filled via a third pump, operated by a crank. This would pull water much faster, but has a



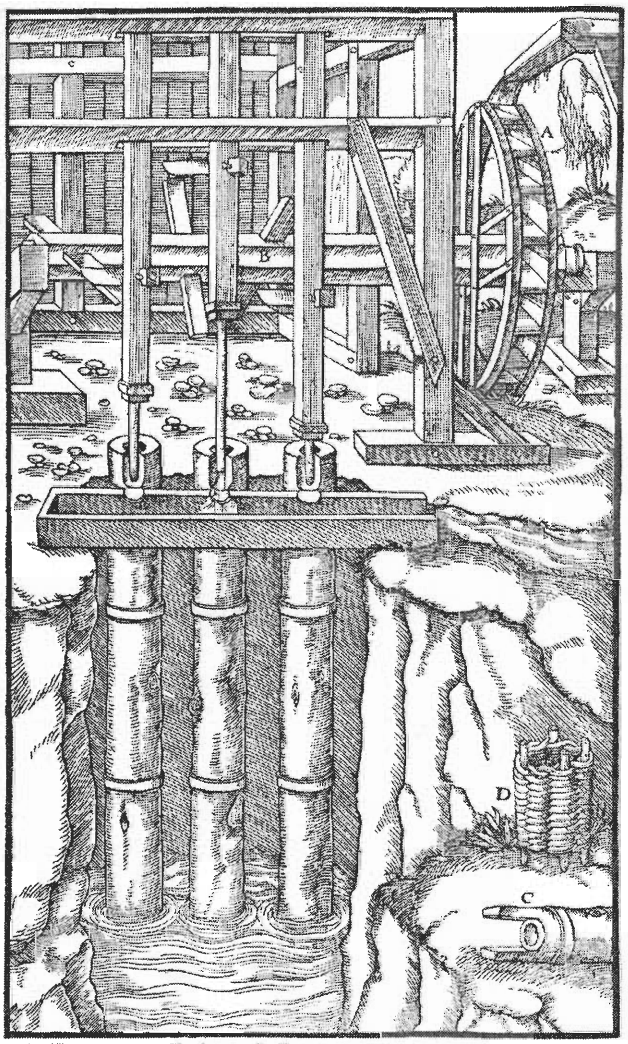
A—Erect timber. B—Axle. C—Sweep which turns about the axle. D—Piston rod. E—Cross-bar. F—Ring with which two pipes are generally joined.

A—Posts. B—Axle. C—Wooden bars. D—Piston rod. E—Short piece of wood. F—Drain. G—This man is diverting the water which is flowing out of the drain, to prevent it from flowing into the trenches which are being dug.

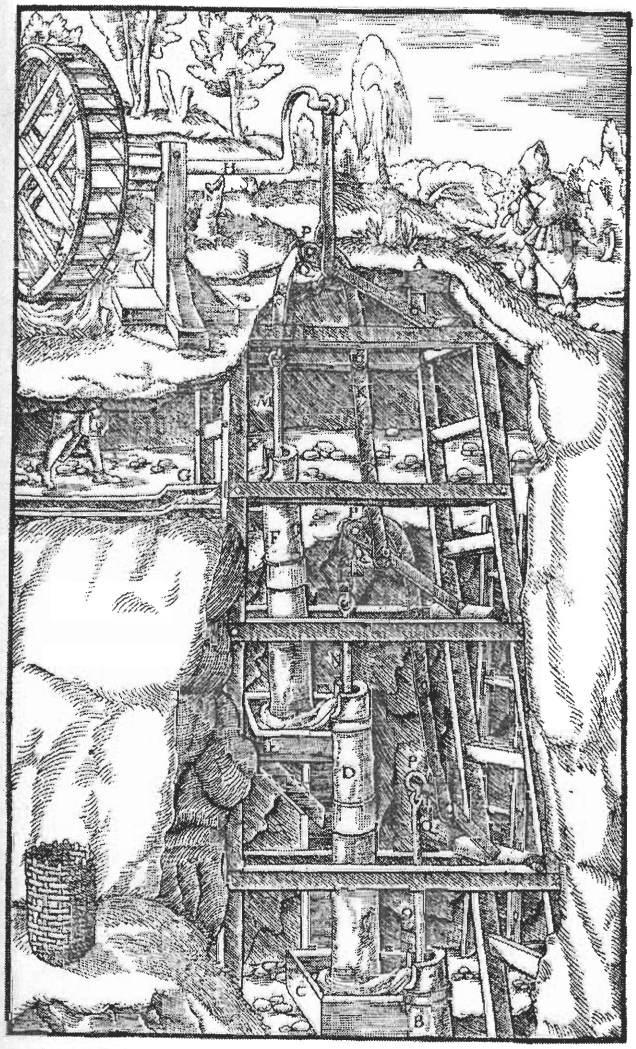
Figure 24: Suction pumps with axle lever (left) and crankshaft (right)[133]

much higher construction cost. The fifth type is even more complex, consisting of three or more pipes with an axle-turned crankshaft, to toggle the motion of each piston individually, but work them simultaneously. The sixth is identical to the fifth, except that instead of being turned by a crank operated by men, it is turned by a water-wheel. The seventh type is "the most ingenious, durable, and useful of all"[134], and the cheapest; it was an innovation of Agricola's, being invented only ten years before the book was published. It consists of several layers of pipes, operated by a single water-wheel; each one raises water to the next level, which is pumped to the next level by the pipe at that level, and so on. The major advantages of this design is that it combines the relative simplicity and low cost of the first three types of suction pumps with the power of a water wheel and it also allows a greater depth from which the water may be pumped.

[133] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 178, 179.



A—WATER-WHEEL. B—AXLE. C—TRUNK ON WHICH THE LOWEST PIPE STANDS. D—BASKET SURROUNDING TRUNK. (Sixth kind of pump—see p. 184.)



A—SHAFT. B—BOTTOM PUMP. C—FIRST TANK. D—SECOND PUMP. E—SECOND TANK. F—THIRD PUMP. G—TROUGH. H—THE IRON SET IN THE AXLE. I—FIRST PUMP ROD. K—SECOND PUMP ROD. L—THIRD PUMP ROD. M—FIRST PISTON ROD. N—SECOND PISTON ROD. O—THIRD PISTON ROD. P—LITTLE AXLES. Q—"CLAWS."

Figure 25: Suction pumps, water powered (left) and Agricola's design (right)[135]

[134] De Re Metallica, 184.
[135] Reprinted from Georgius Agricola's De Re Metallica. (New York, 1950) 183, 185.

Pirotechnia

Vannoccio Biringuccio's work Pirotechnia is of great importance to historical knowledge of mining, assaying and smelting practices due to its being the first compilation of practical metallurgical knowledge to be printed and hence to achieve wide distribution.[1] First printed in 1540, this book is broken into ten smaller works that discuss the following: Book One: every kind of mineral; in general, Book Two: the semiminerals; Book Three: assaying and preparing ores for smelting; Book Four: the separation of gold from silver; Book Five: the alloys that are formed between metals; Book Six: the art of casting in general and particular; Book Seven: methods of melting metals; Book Eight: the small art of casting; Book Nine: the procedure of various works of fire; and finally Book Ten: on certain artificial combustible materials, and the procedures followed in making fireworks to be used in warfare and for festivals.

As can be seen, Biringuccio does not discuss in detail the methods of mining, but with the addition of a later text, Georgius Agricola's work De Re Metallica, virtually all the aspects of mining, assaying, and smelting, known at the time, have been recorded in text.[2] Agricola writes of Birringuccio in De Re Metallica, stating: " Recently Vannoccio Biringuccio of Siena, a wise man experienced in many matters, wrote in vernacular Italian on the subject of the melting, separating and alloying of metals. He touched briefly on the methods of smelting certain ores, and explained more fully the methods of making certain juices; by reading his directions, I have refreshed my memory of these things

[1] Pirotechnia, xix.
[2] This text was printed in 1556, 16 years after the printing of Pirotechnia and covers in more detail the mining process than does Biringuccio

which I saw in Italy; as for many matters on which I write he did not touch upon them at all, or touched but lightly."[3] This shows the use of Pirotechnia in De Re Metallica, but that most subjects covered in each work do not duplicate the others.

Mining

What Biringuccio has to say on the subject of mining is little and is contained mostly in his preface to Book One "Concerning the location of Ores" and focuses mostly on where and how ores are to be found in their natural state in the earth. He continues with the finding of locations for the mine and the necessities a mine will encounter with operation. This preface is written as if the reader was about to begin the business of operating a mine and he commonly writes of the wealth to be gained by doing so.[4]

Biringuccio begins by describing the ores that are to be found as "veins of blood in the bodies of animals, or the branches of trees spread out in different directions."[5] Where these branches reach the surface is where you will find the signs that an ore is present. To determine whether the region you are examining contains ore he says to carefully search for all appearances of the ores to predict where the most plentiful ores will be found. The signs to look for will be in broken pieces of rock from the highest peaks of the mountain, in the beds and courses of rivers, or in the sands of valleys and crevices. These leads should be followed back to the openings whence they came. Where fresh water issues forth with a mineral taste or changing qualities with the seasons,

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[3] Pirotechnia, xvii.
[4] Pirotechnia, 21: "For this reason all men who wish to have wealth should turn their attention to the excavation of mines rather than to warfare, with all its annoyances, or to commerce, which goes about outwitting the world and perhaps doing other tiresome things which may be illicit for honest men, or going on long and weary journeys over land and water- journeys full of annoyances and discomforts, among strange and unknown peoples who are often of animal like natures- or to applying oneself (as many do) to the fabulous philosopher's stone in the hope of enslaving its elusive service to make fixed silver or to perform magic rites, or to other things vain and without foundation."

becoming warm in the winter and cold in the summer, the presence of ores can be found. Rough and wild mountains with little soil and plant growth will commonly contain ores, although that is not always the case when ores are present. Ores have been found in the rock under soil-laden mountains where fruit trees grow and give no signs of its presence. To search these regions he suggests using the earlier mentioned methods. Also, he suggests talking to the local inhabitants of the countryside for more information.

Once the ores have been located, Biringuccio goes into detail on the location and construction of the mining site stating that the opening of the mine must be in a place where it is convenient for the miners and will present the shortest route to where the signs found earlier predict the greatest masses to be. In addition to this there must be a location near the mine where the construction of cabins can be built to house the miners, foodstuff, tools, and a place to work iron for the fixing or replacement of tools that have broken. Here he warns of mining through soft or weakened rock, because it is liable to collapse and most ores are not found in such material, and of using reinforcement archways or timbers if such digging is necessary. He mentions this so as not to risk the money you have put forth so far for the mine and the miners' safety as well. Finally, he warns not to give up too quickly if water, rock of unusual hardness, or lack of results

[5] Pirotechnia, 13. It was commonly believed that these veins of ore would grow and thicken much like the branches of trees and replenish themselves with time.

occurs.[6]

Fig. Miners workshop shown near mine entrance and housing.[7]

Once it is assumed that you have a mine location and have begun the excavation of ore, Biringuccio discusses the other needs that the mine will have. There must be an abundance of wood, water, and food. There must be enough wood for the needs of the mine. Charcoal must be produced for smelting, roasting, refining, and other fires. Timbers must be cut for the reinforcement of the mine, construction of housing, and fabrication on site of the machines necessary.[8] Water must also be present for the turning and operation of these machines. "But of all the inconveniences, shortage of water is most to be avoided, for it is a material of the utmost importance in such work because the wheels and other ingenious machines are driven by its power and weight."[9] It is

[6]Pirotechnia 21. I therefore conclude that whoever begins such an undertaking should follow it through with the greatest courage and patience, proceeding at least as far as seems necessary according to the signs, and hoping always that by going ahead the following day, as may easily happen, may be the one in which he will discover what he is seeking and so make himself rich and happy.

[7] Reprinted from Vannoccio Biringuccio. *Smithy and other buildings at the mine entrance.* Pirotechnia. (Cambridge, Mass., 1966.) 18.

[8] Biringuccio does not go into great detail, if any, on these machines but Agricola's De Re Metallica describes them well and includes multiple wood cuts to aid in the description.

[9] Pirotechnia 22.

convenient that these needs will be met in close proximity to each other in order to save time, effort, and expense. If you can not have all three as one unit, he states, you must decide which is more profitable to have near, the charcoal or the ore and to make this as convenient as possible.

Finally, Biringuccio briefly touches on the tools that will be needed for the mining operation. He states that because of the difference of mining in limestone, marble, travertine, or other hard stone you must vary the tools depending on which you find. For the excavation of large rock, hammers, iron picks, long thick crowbars, mattocks and strong spades, picks both with and without handles, and similar iron tools, all of fine and well-tempered steel will be needed, but ordinary tools are usable for softer stone. An

Fig.Mining tools. Picks, shovels, baskets, barrows.[10]

abundance of these tools is necessary so the workers will not lose time when encountering hard or soft stone. Also there must be large and small baskets, sacks of untanned skins, barrows for excavation, and oily liquids to burn for light in the darkness

[10] Reprinted from Vannoccio Biringuccio. *Miner's tools, ore barrows, and baskets*. Pirotechnia. (Cambridge, Mass., 1966.) 24.

of the mine. Unfortunately, he does not go into detail on the use of these tools in the mining process, but assumes the reader will know how to mine or the men hired will.

Assaying

The assaying process is used to determine what materials are present in the ore that has been removed from the earth. This was an important step in the mining industry because at this point you would decide whether or not the metal left after refining the ore is enough to balance the cost of removing it from the earth and whether or not the mine would ultimately be profitable. The assaying method described in Pirotechnia is that which would be used with silver. Biringuccio includes silver as his example due to its high value. "But the eye is turned with much more care to the assaying of silver and gold, since they are things of value, and one tries to have a more exact knowledge of them."[11]

Firstly, once a small sample of the ore has been collected, the minerals are present must be determined. Biringuccio writes "Thus, when you have found the mountain and the vein of ore in it, and have also uncovered it or extracted it from the mine, it is necessary to make an assay of it, for though it is often apparent to the experts what kind of metal it contains, nevertheless they do not know for sure what virtues or evilness it may have unless the light of the assay itself shows them."[12] To achieve this, the ore must be free of as much rock as possible and then placed into a smelting fire to determine if the ore will smelt by itself or will need some other fusible material to remove the ore from the earth. Such fusible materials are marble, ground glass, lead, iron scale, and the slag from other ores. These will soften and combine with the earth to remove it from the ore,

[11] Pirotechnia 136.
[12] Pirotechnia 136.

but you must determine which one is needed for the large scale refining of the ore. Most of the time adjusting the heat of your smelting fire and the amounts of your fusible materials will be enough to properly remove the ore from the earth.

If that does not work, though, due to some property of the ore or of the earth in which it is present, then a different approach is taken. The ore is roasted and quenched two or three times and then ground down and washed to remove as much of the earth from the ore as possible. The ores are once again placed in the fire and the assay is tried with the addition of mercury to melt the ore.

If this also does not work the assay can be achieved with the use of a cupel. A cupel is a small concave vessel ready to accept a predetermined amount of lead or other pre-melted material for the refining process. These are made from different types of ash, but young ram's horn is said to work the best.[13] The cupel is placed into a small brick furnace shaped like a tower with an opening at the base to allow air to reach the fire from beneath. Above, where the fire is located, a shelf with iron grating and a level surface of cut brick is located. This is the furnace and the cupel is placed here with a muffle over it. The muffle is an arch made of fire-resistant clay big enough to cover the cupel and perforated all over. The muffle is placed into the furnace, surrounded by charcoal, and heated to red-hot. Once heated, the cupel is placed in the furnace until it is white from the heat. Then the lead is added to the cupel until it turns from black to white, fine, and clear. At this point the ore is added, in this case silver, to the lead and allow the lead to evaporate leaving only pure silver. If the ore is difficult to melt or contains copper it is

[13] Biringuccio gives detailed instruction on the construction of these cupels as well as the dimensions of a small brick furnace with grating, shelf, and openings for smelting and alternatives to the use of these if they are not available. Pirotechnia 137-139.

recommended that you use twice the amount of lead to separate out the pure ore.[14]

Fig. Cupeling hearth with cupels, muffle, and balance for the assay.[15]

Once any of these have been accomplished, and you have the remaining pure ore, you would weigh the pure and compare the weight to the previously measured weight of the sample. With this done you should know how difficult or easy it will be to refine the ore and what percentage yield the raw ore will return after smelting which is the ultimate goal of the assay. With this knowledge you may determine if the mine you operate will be able to make a profit. "For this reason, it is necessary to come to assaying and, with the knowledge of experience, to weigh their virtues and to proceed with the work or withdraw from it and its expense".[16]

Smelting

[14] Pirotechnia 139-140.

[15] Reprinted from Vannoccio Biringuccio. *An assaying laboratory, showing balances, muffle, furnacefor cupeling, ingot mold,etc.* Pirotechnia. (Cambridge, Mass., 1966.) 140.

Without smelting, Biringuccio writes, all the ores mined would be mere useless stones. He says that anyone going about the smelting process use his wits and knowledge of the assay. He has mostly written on the smelting of gold, silver, and copper because of the high value of gold and silver and the tendency to find them present in copper.

The first step in the smelting process is to sort all the ore that has been mined. This should be done by people well experienced in the sorting of metals and earths so as to remove as much of the "evil" which afflicts the ore. Then one should remove as much of the earth accompanying the ore as possible by means of physically breaking away the earth or roasting, quenching, and reroasting, grinding all the material into a powder, and then washing it. In this washing the ore will settle to the bottom of the washing vessel, sometimes called a trencher or a washing boat, while the lighter earth is carried away by the flowing water. Either way, the purpose is to isolate ore that is free of the earth it was taken from and to separate it from other types of metals that may be present.[17]

The next step in the smelting of the ores is to add a fusible material such as mentioned previously in the assay. This is necessary if a particular ore is too earthy or contains another metal, mineral, or "evilness" that does not allow it to smelt in the furnace, but instead to burn. If a fusible material is not necessary, then the ore would be taken, separated or ground and washed, to a smelting furnace.

For iron the smelting furnace, or blast furnace,[18] was built of some stone that resists fire exceptionally well, such as black flintstone, peperino, or a stone that is almost

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[16] Pirotechnia 135.
[17] Pirotechnia, 141.
[18] The only differences between a blast furnace and a smelting furnace are few. The blast furnace is about twice the size, holds more charcoal, and attains higher temperatures to melt iron.

half talc.[19] It should be built in a location where water-powered machines can be built to power the bellows, grinding wheels, and other machines needed. The furnace is built as a square box bottom with a small opening and a trough to an open container called the forehearth. This is where the molten metals will run out of the furnace and collect. Above this square is a pyramidal opening wider and open at the top that holds the coal and allows for more to be added as necessary. In the middle, on the side, is a small recessed area with a stone door. This is where the ore can be placed in the furnace, rearranged as needed, or have more added for a continuos, more efficient smelting of more than one furnace load. At least two bellows should be used to create a continuos air flow to the fire.

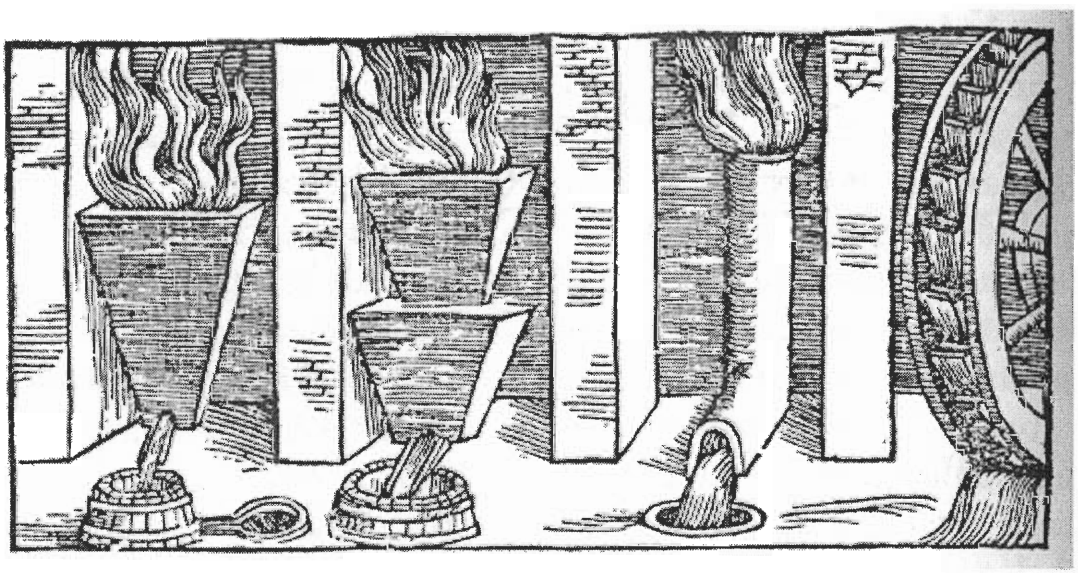

Fig. Different styles of smelting furnaces.[20]

The ore is prepared to go into the furnace by breaking it into small pieces described as the size of beans. These are placed on a bed of flat stones or bricks and

[19] Pirotechnia, 146.
[20] Reprinted from Vannoccio Biringuccio. *Various forms of blast furnaces*. Pirotechnia. (Cambridge, Mass., 1966.) 150.

covered with some fusible material such as galena.[21] Then iron slag, or a metal slag similar to what is being smelted, is added and all of these are prepared in layers.[22] Place this composition into the furnace and light the charcoal. Then add more charcoal to the fires and more ore as needed to smelt the desired amount or until the square chamber below he ore is full of molten materials.

Once the amount of ore to be smelted is reached and has been melted and collected in the square chamber, the small opening leading to the forehearth is opened and the molten material is allowed to run out. At this point the different materials begin to cool and solidify. The lighter materials, such as the slag that was added, will solidify first and they can be removed from the remaining pure metals with an iron fork fitted with a wooden handle. Once all the slag has been removed in this manner only the pure metals remain. If there is copper present, that will cool next and can be removed. This is called the matte. If there is silver or gold present in the ore it will have combined with the lead added to the prepared ore. When this solidifies it is called the work lead.[23]

The matte is then taken to be refined again. At this point the copper present would be useless because it is as brittle as glass. Lead is added to the matte until there is greater than 50 percent lead and cakes are made of the combination weighing 200 to 250 pounds. These are placed onto a table constructed of stone with a grove down the middle. Charcoal is placed surrounding the cakes and lit. The fire then brings the cakes to a glowing red temperature and the lead will flow out of the copper taking with it the last of

[21] Galena is a mineral found in nature that is abundant in lead and is where most lead is refined from.
[22] Pirotechnia, 153.
[23] Pirotechnia, 154.

the impurities.[24]

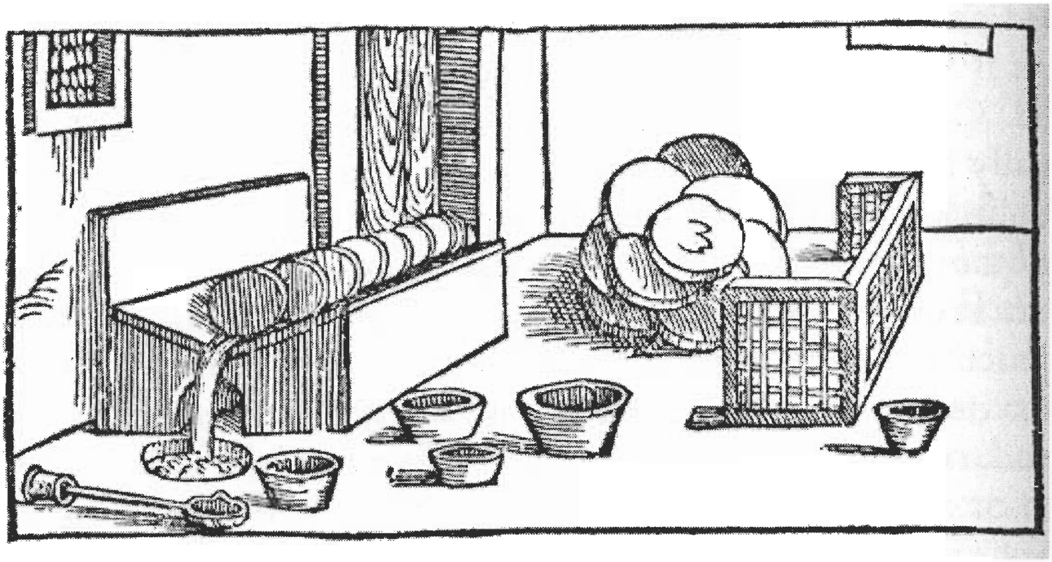

Fig. Smelting table for lead-copper cakes.[25]

The work lead and the run off from the matte may contain silver or gold. A second assay of this is made to see if there is enough present to warrant separating it from the lead. If there is, the lead is placed in a cupeling hearth as described in the section on assaying and all of the lead is removed leaving only the silver or gold.

Iron and Steel

Iron and steel are only mentioned briefly in Biringuccio's Pirotechnia and what he does mention is contained in his first book. It is worth mentioning all he has said on the subjects, in brief, due to their importance in the construction of weapons and plate armor in the Renaissance

[24] Pirotechnia, 156-158.
[25] Reprinted from Vannoccio Biringuccio. *Hearth for the liquidation of copper-lead cakes.* Pirotechnia. (Cambridge, Mass., 1966.) 158.

Biringuccio praises the properties of the iron ore found in Italy, that being his country, especially that of the iron mined from the island of Elba. This iron ore is of great purity and due to this is smelted with a normal smelting furnace and not a blast furnace as would normally be necessary if copper or some other mineral were present. The ore is broken into small pieces and placed in the center of a ring of rock and larger ore to hold the fire close to the ore that is to be smelted. This is covered with charcoal, lit, and blown upon with slightly larger than normal bellows than would be necessary for other metals, for eight to ten hours. The ore is then removed while still hot and broken into pieces. Then the pieces are reheated and brought to the forge hammer and made into blooms. These blooms have only lost 40 to 45 percent of their original weight and have been refined to pure iron.[26]

Of other iron ores, Biringuccio states that once you have roasted, sorted, re-roasted, well resorted and washed them to remove as much of the earthiness present the ore must be placed into a blast furnace. Here it must be smelted once or twice depending on the ore before it can be brought to the forge hammer. If the iron desired is to be soft and tough then the charcoal of soft wood should be used and if the iron desired is to be hard, strong, and less tough, then the charcoal of coarse wood should used in the blast

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[26] Pirotechnia, 61-63.

furnace.[27]

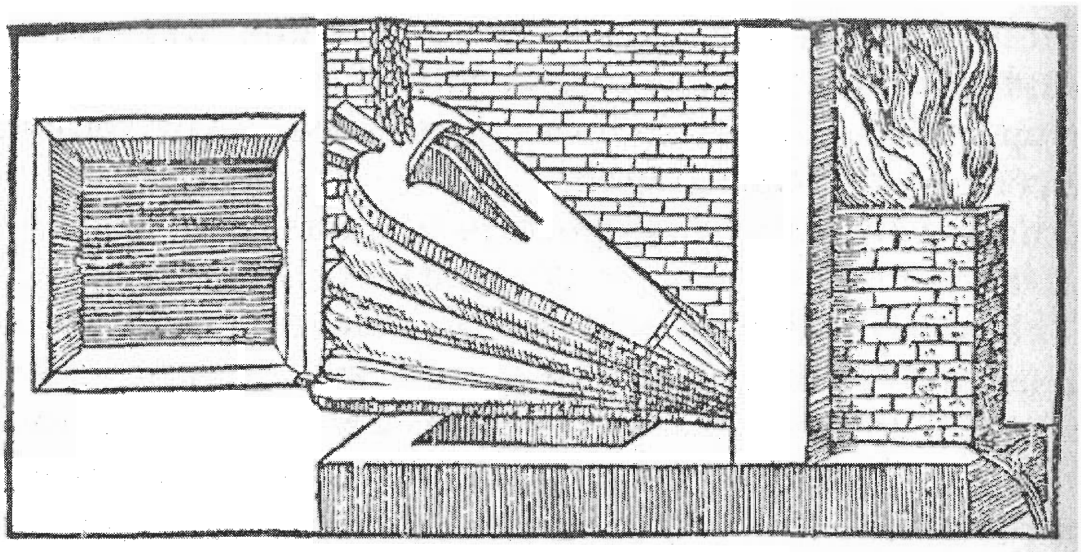

Fig. Blast furnace for smelting iron.[28]

Although others at the time of Biringuccio believed that steel was a different ore than iron only differentiable by its properties after the smelt, he did not believe this. "Therefore I wish to write of it [steel] here and tell you that steel is nothing other than iron, well purified by means of art and given a more perfect elemental mixture and quality by the great decoction of the fire than it had before."[29]

Firstly, when producing steel the better the quality and purity of the iron you start with, the better the results of the steel will be. To start you take the iron that has been refined and break it into small pieces. These pieces are placed into a round receptacle made of one part clay and two parts charcoal dust. This is placed into the furnace where

[27] Pirotechnia, 64-66.
[28] Reprinted from Vannoccio Biringuccio. *Blast furnace for smelting refractory iron ores*. Pirotechnia. (Cambridge, Mass., 1966.) 64.
[29] Pirotechnia, 67.

saline marble, crushed slag, or other fusible and nonearthy stones are added. This, once melted will be an iron bath in which the steel will be made.[30]

Next, three or four blooms of iron weighing thirty to forty pounds are added to the iron bath. Here the blooms are left for four to six hours. This is called "the art of iron." Then one of the blooms is removed, tempered in water, broken into pieces, and examined to make sure it has become steel through its entirety. If it has then the other blooms are removed and cut into six to eight smaller pieces and placed back into the iron bath with more crushed marble and iron. This second bath helps to refine the steel.

Once they have been reheated, the smaller pieces are removed from the bath, beaten at the forge hammer, and quenched in water as cold as possible. This is the tempering of the steel and is where it takes on the hardness associated with it. That completes the method for the making of steel in the Renaissance as recorded by Biringuccio.

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[30] Pirotechnia, 68.

Conclusion and Recommendations

The most prominent result of this study is a good illustration of the transition of mining and metallurgic practice from the Romans to the Renaissance, accompanied by a transition in scholastic thought about these subjects.

To the Romans, mining was a low, menial task not suited for scholastic study, so miners and metalworkers had to rely on the accumulated body of working experience to increase the productivity of their operations. The early medieval period saw a further retreat of even the classical approach, and the properties of ores and metals took on an almost mystical character with the belief in alchemical science. At the end of the medieval period mining enjoyed a resurgence and a renewed understanding of mining and metallurgical practices followed, though this information was not widely distributed due to the closed-mouth policy of the mining and metalworking guilds of the time. The Renaissance saw the introduction of analytical thought and the categorization and recording of experience-based knowledge into the beginnings of a science of metallurgy. The ancient scholars were still held in high regard, however, and the four-element model was still the prevalent view taken of material composition.

The technology employed in mining and metallurgy also improved greatly between ancient and Renaissance times. The Romans employed almost entirely manual labor for most aspects of mining, introducing machines only in the drainage facet of mine operation. Furnaces of the time were far simpler than the constructions that would evolve in later ages, as well. The Dark Ages saw a decline in the exploitation of mines, and in the ambition of the remaining mining attempts.[1] The plagues that swept Europe also made the operation of mining difficult, due to the sudden unavailability of a labor force. Once mining and metalworking increased in practice leading into the Renaissance, the technology employed again matched and surpassed that used by the Romans. Mechanical devices employed in all aspects of mining and more efficient and developed furnaces used for refining allowed the production levels of the ancients to be surpassed.

The most useful materials available, as recommended by the available English sources, are often Latin or German texts, only some of which have been translated. Agricola's De Re Metallica, translated by Hoover and Hoover, is generally regarded as a good indication of the technology of the time. It is well illustrated by a large series of woodcut drawings that aid description of the material discussed. Biringuccio's Pirotechnia is also a good source for the same time period, and covers the relevant metallurgical material that Agricola did not include.

Included in this project are illustrations, maps, and diagrams that can serve to educate both the Museum staff as well as visitors. The woodcuts from De Re Metallica and the illustrations from Pirotechnia are most indicative of the processes used in creating the pieces seen in the Armory collection.

[1] The Conquest of the Material World p29-30

Properties of Metals[1]

Included here is a listing of different metals and alloys common for the ancient period to the Renaissance. Their properties are well known and included here in a simplified form. This should add a greater understanding into the fundamentals of metals and their properties relevant to each other. Listed in this section are irons, steel, copper, brass, bronze, lead, tin, pewter, zinc, silver, and gold.

Iron is one of the most common of metals although it does not exist in nature in its pure form. It is usually found in the form of pyrites, magnetite, hematite, and carbonates. Iron, in its pure state, is gray and very ductile with a melting point of 2802 deg. F (1540 deg. C) with small amounts of carbon reducing its melting point. Iron, though, has not been used in its pure state until recently. Even a small amount of sulfur (0.03%) or phosphorous (0.25%) will make it brittle and hard. Iron containing more than 0.15% carbon is considered to be steel.

Cast irons are a group of alloyed metals including iron, carbon, and silicone. The difference between steel and cast iron is the cast iron is 2% to 4% carbon while steel falls below the 2% level. The cast iron is also much harder and brittle. Silicon is also present in it from 0.5 to 3.5%. Cast irons come in five different types depending on what form the

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[1] Information taken for this section can be found in
Brady, George S., Clauser, Henry R., *Materials Handbook.* New York , New York. McGraw-Hill, Inc. 1986.

carbon is present in and how much silicon there is when it is made. This includes white cast iron used in the production of wrought iron.

Wrought iron is created by placing white cast iron in an oxidizing flame, thus removing the silicon and carbon content. What is left is pure iron and iron slag, which is then rolled to unite it in one mass. It is a strong ductile metal that is corrosion resistant.

Steel is iron with at least 0.15% carbon content. At 0.15% to 0.30% it is considered low-carbon steel, from 0.30% to 0.60 is considered medium-carbon steel, from 0.60% to 0.90% is considered high-carbon steel, and from 0.90% to 1.5% carbon is considered very high-carbon steel. Any steel with above 1.25% carbon content becomes very brittle. Low-carbon steels are easy to forge and shape, where as high-carbon steels are difficult and would mainly be used in tools.

Copper is probably one of the first metals used by man. It is found in a large number of ores and it is easy to separate into a workable metal. It has a yellowish red color and is tough, ductile, and malleable. It has a melting point of 1981 deg. F (1083 deg. C). Copper is used in the production of brass and bronze.

Brass is an alloy of copper and zinc with the zinc present up to 40%. Its physical properties vary largely from the percentage of zinc present and other trace impurities although it can be said that it is a stronger metal than copper while retaining its ductility.

There are hundreds of brasses made with trace elements to change the properties and color of the metal.

Bronze is an alloy of copper and tin with around 10% tin present, though the term brass can be applied to any copper compound not including zinc or nickel. Bronze with copper above 90% appears to have a reddish color where less than 90% is orange yellow and is extremely brittle. Bronze is stronger than brass although not as malleable.

Lead is a soft bluish-gray metal obtained mostly from the mineral galena. It has a low melting point of 621 deg. F (327 deg. C). Lead has little strength and is very malleable, although it easily alloys with other metals.

Tin is a silvery-white metal with a bluish tinge that is slightly harder and stronger than lead although still very soft and malleable. Tin has a melting point of 450 deg. F (232 deg. C) and is commonly used in the production of bronze.

Pewter is a bluish-white alloy of tin and lead ranging from 30% to 10% lead throughout history. The later the time the less lead was used and the stronger and harder the pewter became. English pewter differs from others because it is a mix of tin and antimony at 9% antimony. Both the lead and antimony are poisonous, although pewter was commonly used for food containers.

Zinc is a bluish-white crystalline metal used to strengthen other metals. It is good at alloying with other metals, such as copper, and is seldom used alone. Zinc has a melting point of 786 deg. F (419 deg. C).

Silver is a white, very malleable, and ductile precious metal. It is commonly found with copper, lead or zinc ores. Seventy percent of all silver is found this way and removed from the other metals. Silver has a melting point of 1762 deg. F (964 deg. C).

Gold is a soft yellow precious metal known back to ancient times. It is commonly extracted from crushed gold ore with quicksilver. Native gold is usually alloyed with silver for higher strength. It is the most malleable of the metals and is easily hammered and shaped. Gold has a melting point of 943 deg. F (1062 deg. C).

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