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The renaissance of minerals, mining and metallurgy in Tuscany: from Biringuccio's *Pirotechnia* (1540) to Cosimo I de' Medici

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Abstract. The 16th Century Renaissance marks the modern development of mining technology, mineral deposits prospecting and metallurgical practices. New tools and methods were introduced in tunneling and excavations, often paralleled and inspired by the development of siege warfare, as well as in metallurgical methods and ore processing. These are well recognized and documented in German-speaking areas as early as the first half of the 15th Century. Many practices had to be readapted or reinvented, and new metal smelting and refining processes were introduced, also as a systematization of alchemical practices based on the use of fire. The new metallurgical methods of that period are best described in Vannoccio Biringuccio's *Pirotechnia* (1540), while Georgius Agricola's *De Re Metallica* (1556) and *De Natura Fossilium* (1540) are the milestones of both mining/metallurgical technologies and geological/mineralogical studies, respectively.

In Italy, Biringuccio – native of Siena, central Tuscany – proposed a theory of metals formation based on an early concept of “particle structure”, an original synthesis between the Aristotelian doctrine of the elements and atomism. But it was with the weapon of experience that he criticized the opinions of philosophers and alchemists, contributing to the development of a scientific method in the field of geosciences. Biringuccio applies an early knowledge of rocks and minerals to practical problems, starting to shape in a modern way the concept of economic underground resources exploitation (the term “geology” was introduced only later, in 1603 by Ulisse Aldrovandi). He travelled extensively in the mining areas and metallurgical workshops of Tuscany, his homeland, but he also visited Carnia, Friuli, Tyrol, and probably he was twice in Germany.

The mining activity of Tuscany in the Middle Ages was indeed limited to a few mining sites, although some of them were very important; it is worth mentioning that one of the oldest compilations of medieval laws on mining, that guaranteed the freedom of ore prospecting, was written in Massa Marittima already in the 13th Century. The present study frames Biringuccio's activity, travels and studies, also in relation to the development of the mineral resources of Tuscany, linking them to the attempts of Cosimo I de' Medici to revive the mining and metallurgical industry of the Grand Duchy of Tuscany a few decades later. In 1542 Cosimo established a monopoly for the production of iron from Elba and in the 1550's called German miners to reactivate the copper/silver/lead mines of Campiglia Marittima, Pietrasanta and Montecatini.

Keywords: Renaissance mining – Mining history – Biringuccio – Metallurgy history – Cosimo I de' Medici – Tuscany mines.

Biringuccio's life and travels in Italy and Europe

Vannoccio Biringuccio (Siena 1480 - Rome circa 1537) was one of the most influential Italian scholars of the late Middle Ages and early modern age in the field of mining and metallurgy. Literature honors him as an engineer,

metallurgist, mechanic, bell and cannon smelter, armorer, master builder and architect as well as an applied chemist. However, he owes his fame to the posthumous publication of his only book *De la Pirotechnia libri X* (Biringuccio, 1540), one of the earliest mining and metallurgy handbook originally written in Sienese vernacular Italian.

Biringuccio belonged to one of the oldest noble families of the Republic of Siena. Born and

living in times of urban strife, he took an active part in the public affairs of his native city. His father Paolo di Vannoccio Biringuccio was an executive of the public administration and managed some mining activities in Southern Tuscany (Maremma). Very likely, Biringuccio's studies were in continuity with the profession of his father, and oriented to the career of a high-level mining technician. He would later begin his apprenticeship with his father and then in the mining activities of Pandolfo Petrucci. Pandolfo belonged to a rich family of merchants and continued to pursue his trades even when he effectively conquered the maximum political power in Siena, intertwining business and politics.

At that time the Republic of Siena, very sensitive to technological culture, built an impressive network of underground aqueducts for the city, an artificial lake, and stimulated private initiatives to intensify mining and metallurgical activities in order to renew and strengthen the military arsenal. Among the native technicians were Paolo Salvetti, an expert in minerals, and Francesco di Giorgio Martini (1439-1501), author of the *Trattato di architettura civile e militare* (late 15th Century manuscript), which deeply influenced the Italian cultural environment of the years to come. The young Biringuccio may have known Martini both through his collaborator Iacopo Cozzarelli, and for the professional relationships of his father, forging his intellectual profile and personality.

The Biringuccio's family belonged to the managerial class with an active role in the policy of the Republic of Siena. The family's active attendance of the *Camera del Comune* (Chamber of the Municipality, i.e., the administrative office that promoted and coordinated the design and construction of the architectural, hydraulic and military works of the city of Siena), certainly played an important role. Under the guidance of Petrucci, many prominent personalities from various cultural backgrounds had gathered in the *Camera*, forming a sort of technical oligarchy, whose interests ranged from civil and military engineering to architecture, scientific and humanistic studies to land management (Bernardoni, 2008).

In his youth, Biringuccio studied mathematics and natural sciences and learned metallurgy in various workshops as well as in several mines of the Republic of Siena territory. We know that around 1500 Biringuccio was sent to practice in the silver, copper and iron oxides/hydroxides mine of Boccheggiano, near Montieri. Shortly afterwards (1507-08) he was entrusted with the management of a company founded by various noble families for the exploitation of the silver, copper, lead and zinc mines of Monte Avanzo, in the Carnic Alps (Northern Italy, at the time under the control of the Republic of Venice). Biringuccio managed those mines until 1508, when hostilities began between the Republic of Venice and Maximilian I, the Holy Roman Emperor. As a consequence, Biringuccio moved to northern Europe to make at least two educational trips (1508-10) to the mines of Carinthia, Tyrol and probably also in the German areas of Saxony and Bohemia, although these journeys are not fully documented (Mieli, 1914). Visits to *Pleiper* (Bleiberg, Carinthia), *Sbozzo* (very likely Schwaz, Tyrol), *Alla* (Hall, Tyrol) and *Arottimberg* (Rattenberg, Tyrol) are cited in his *Pirotechnia*. It should be noted, however, that he never mentions any knowledge of the technical German language.

Back to Italy, between 1510 and 1512 Biringuccio was in Milan, where he studied the technical systems prepared by Leonardo for the casting of the bronze horse of the never executed colossal statue of Francesco Sforza and finally returned to Siena, with considerable knowledge in the field of bronze casting. In 1513 Petrucci appointed him both director of his iron mine at Boccheggiano, and specialized "workman" of the armory of Siena.

In modern terms, Biringuccio had a relatively short apprenticeship, just over 10 years. However, it seems that his father, Paolo di Vannoccio, owned an ironworks and had been involved by the Pandolfi family in various enterprises aimed at developing the whole technological chain, having also assisted Leonardo da Vinci, with whom in 1503 he was in the service of Cesare Borgia for the reconquest of Romagna. Therefore, by family tradition, by the conversations he heard at home and by personal

experience, Biringuccio had acquired a knowledge of metallurgy (and in particular of that of bronze and iron) superior to that of most of the Italians of his time.

Eventful and problematic times followed: after obtaining an exclusive contract to manage the Sienese mint in 1514, Biringuccio was accused of counterfeiting; he was then banished from Siena and fled to Rome, Naples and Sicily. A few years later he was rehabilitated and, back to Siena, in 1525 he obtained the monopoly for the production of saltpeter throughout the Republic of Siena territory, but this privilege only lasted for a short time. Flying again from the city, he worked as a cannon founder in Florence. Here in 1529, he built, among other things, a large cannon in a single cast, the *Liofante* (the elephant) or *Archibugio di Malatesta* (the harquebus of Malatesta, an Italian prominent family ruling part of the Romagna area at that time). This weapon was a gigantic double culverin, weighing over 6000 kg and almost 7 m long, with the breech decorated with an elephant head. In 1534 Pope Paolo III appointed Biringuccio captain of the artillery, master of foundries and director of the papal ammunitions. The advanced technologies described in the *Pirotechnia* (books 6, 7 and 8) demonstrate his extraordinary skills in the field of bronze casting technology, cannonballs production and explosives manufacturing (black powder).

Biringuccio died suddenly in Rome in August 1537. A more detailed biography based on archival resources is reported in Tucci (1968).

Biringuccio's *De la Pirotechnia* (1540)

The 16th Century Renaissance marks the modern development of mining technology, studies on mineral deposits prospecting and advancements in metallurgical practices. These are well recognized and documented in German-speaking areas as early as the first half of the 15th Century. In 1527, Rühle von Calw published *Ein nützlich Bergbüchlein* ("A useful booklet on mining"). Biringuccio knew Agricola's *Bermannus* (1530), and in his *Pirotechnia* he reports the almost miraculous finds of large blocks of native silver found in Saxony (Macini & Mesini, 2008). On the other hand, Agricola also mentions Biringuccio in his *De Re Metallica*: «Recently,

Vannoccio Biringuccio of Siena, a wise man and experienced in many matters, wrote in vernacular Italian on the subject of smelting, separating and alloying of metals. » (Agricola, 1556).

Bernardoni (2008) wrote that «Apparently, the differences between Agricola and Biringuccio are very marked: if the latter (who had a self-taught training) seems to adopt a purely operational perspective, Agricola instead moves in the most refined circles of scholars and humanists, and publishes his numerous writings and technical handbooks that constantly confronts with the classical tradition. However, while starting from very different cultural contexts and assumptions, Biringuccio and Agricola work in the same direction, that of a re-evaluation of the practical arts, and in particular of those of fire. Both Authors strongly pose the need for a linguistic revision (in open controversy with the obscure language of alchemists) as well as a clear codification of the metallurgical processes, in order to make them reproducible. »

In charge of the mines of the Republic of Siena, Biringuccio was interested in the study of minerals and metals and in investigating the most remote shapes and systems with which they hide in the bowels of the earth; he studied rocks and materials with which they mix, and clearly explained the fastest and cheapest ways to extract and refine them (Barzellotti, 1808).

De la Pirotechnia is considered the first book in the history of technology fully dedicated to metallurgy, characterized by a completely new concept. Published after the death of Biringuccio, the first edition (1540, *editio princeps*, Venice) is written in Sienese vernacular Italian. The work had numerous later editions, more or less modified (Mieli, 1914): we recall the four Italian editions (1550, Venice, which was slightly re-edited in Florentine vernacular; 1558, Venice; 1559, Venice; 1678, Bologna), the three French translations (1556, Paris; 1572, Paris; 1627 Rouen) and also the two Latin translations (1572, Paris; 1658, Köln). Finally, in the last century it was also translated in English (Smith & Gnudi, 1942-1943).

However, the *Pirotechnia* was rarely cited in books of history of metallurgy and mining technology until the end of 19th Century; unlike

his contemporaries who normally reported real or false observation and facts that they collected from ancient sources (Guareschi, 1904), Biringuccio had personally made observations and gathered first-hand experience in the field of metallurgy and mining production; on this basis, he attempted to systematize what he had collected on this subject into a sort of handbook conceived for practical uses. Biringuccio thus introduced a new methodology into the technical literature, as a sort of precursor of the modern experimental and scientific method. Again, unlike other contemporary treatises, the *Pirotechnia* is characterized by its extraordinary practical importance and by the intention of making the results accessible to a wide audience of specialists. A large number of illustration (the book contains 84 woodcuts) complete the descriptions, which are based mainly on Biringuccio's vast practical and experimental experience and are characterized by a clear and concrete representation. However, compared to Agricola's later treatise *De Re Metallica* (Agricola, 1556), Biringuccio refrained from describing some minor technical details, that he thought easily identifiable and understandable by the contemporary expert readers.

De la Pirotechnia collects and systematize most of the techniques related to metal, glass, ceramics, military and civil pyrotechnics, furnaces and castings technology, as well as mining engineering know-how of the time. The book also contains an analysis of distillation and sublimation techniques and theories of the alchemical tradition, analyzed and discussed in the light of a unitary theory of matter (Bernardoni, 2011; Bernardoni, 2014).

Biringuccio dissociates himself from the pure speculative approach of scholastic philosophers, and believes that knowledge of nature progresses towards an ever-deeper understanding of the mechanisms of natural phenomena through the continuous acquisition of new facts. In his view, the alchemists' failures confirmed the limits of artificial production and the superiority of natural products, but the technological progress resulting from alchemy seemed to bridge the gap between natural and artificial entities, leading to a deeper understanding of nature. In this regard,

Biringuccio expresses serious doubts about the regeneration of the alleged "inexhaustible" iron mines of the Elba Island, and does not trust the sulfur-mercury theory for the generation of metal deposits (on this subject, see also Halleux, 1974).

Mineral production in Biringuccio's homeland

The so-called "Metalliferous Hills" of Tuscany is an area strongly characterized by significant mining and metallurgical activities dating back to (at least) Etruscan times. In the past, iron, lead, zinc, tin, copper, and silver ore, together with sulfur, alum and coal, were mined and transformed here. Mining excavations and metal production sites still mark the territory, with hundreds of archaeological records and historical testimonies of great interest, sometimes impressive as for size and number. These activities date back from ancient times to the last decade of the 20th Century, albeit with many ups and downs in production, with a surprising continuity of mining and metallurgical activities that probably has no equal in Europe, maybe except for salt mining in Central Europe.

Evidences of mining and iron workings of the Etruscan and Roman period are documented since the 18th Century, and goes hand to hand with the modern archaeological sciences. In fact, there are many reports of discoveries of ceramic materials and mining tools in landfills containing mining wastes, located near the mining shafts and inside the ancient tunnels and excavations (Targioni Tozzetti, 1770; Lotti, 1893; Badii, 1931). Archaeological remains of iron metallurgy based on ores extracted from Elba Island can be found still today in many localities surrounding the Gulf of Follonica (continental Tuscany, in front of Elba Island), in the form of large piles of slag, sometimes associated with ceramic materials typical of the time (Benvenuti *et al.*, 2000).

In the Middle Ages the small town of today's Massa Marittima, the most important mining center of the Metalliferous Hills, drew great economic benefit from mining and metallurgical activities, witnessed by a remarkable urban and monumental development, which brought it on a par with the largest Tuscan cities. In that period there was a strong flow of immigration of

specialized workers from the German speaking area, expert in mining and metallurgical technologies, and in particular from Saxony and Bohemia.

Among the first to take advantage of the great mineral wealth of the Metalliferous Hills were the bishops of the diocese of Massa and Populonia, and then the people of the Republic of Massa (*Repubblica di Massa di Maremma*), hereinafter renamed as *Massa Metallorum*. Hundreds of mine shafts and tunnels were excavated around the town, and huge quantities of metals were extracted, such as copper and silver, then much more precious than today. The importance of mining activity in the town's economy was such that the oldest and most complete legal regulation of the mining matter existing today can be found in the ancient laws and statutes of the Republic of Massa, a document commonly known as the mining code of Massa Marittima (*Ordinamenta super arte fossarum rameriae et argenteriae civitatis Massae*), a collection of texts dating back to the 13th Century, updated and completed until to *circa* 1325. The extant manuscript is a true milestone in the field of European mining law, that guaranteed the freedom of ore prospecting. Undoubtedly one of the most significant mining documents left to us by medieval Italy, it can be regarded as the first European mining constitution that deals with the overall regulation of an entire mining district, both in terms of the discipline of mining and metalworking (Baldinacci & Fabretti, 1989).

The fortunes of the mining area of Massa (based on copper and silver), and more in general of Tuscany and Italy, decreased towards the second half of the 14th Century due, among others, to the plague of 1348, to famine, to the wars with the Republic of Siena and to a sharp drop in metal prices following the fast development of German and central European mines (Saxony, Bohemia, etc.). Other issues contributed to slow down the mineral production in Tuscany, and in particular the fast depletion of the most superficial parts of the very old mines (the rich gossan present in many mineral deposits), and the increasing difficulty in both deepening the excavation, and draining the underground structures (tunnels, shafts, etc.). Finally, many mining sites were more and more difficult to exploit due to the hardness of the host

rocks, which made the mining activities extremely difficult and poorly profitable.

However, the mining activities were never completely abandoned: in particular, a strategic iron production continued, and in 1377 Tollo Albizzeschi (uncle of St. Bernardino of Siena) obtained from the municipality of Massa the authorization to build an *edificio da foco* ("fire building", *i.e.* a blacksmith forge) to work the *vena del ferro* (iron ore) (Municipal Archive of Massa Marittima, *Riformagioni* 1376-1382). This is the framework in which developed Biringuccio's activity, *i.e.*, on one side the economic and strategic interest in maintaining the mineral production for the development of the Republic of Siena and on the other the ability to cope with old technologies that were no more adequate for the difficult geologic structures of the Tuscany mines.

Biringuccio's and the Tuscan mines in *De La Pirotechnia*

Undoubtedly, Biringuccio's *Pirotechnia* marks the modern development of mining technology, mineral deposits prospecting and metallurgical practices. New tools and methods were introduced in tunneling and excavations, often paralleled and inspired by the development of siege warfare, as well as new procedures in metallurgical methods and ore processing. Many practices had to be readapted or reinvented, and new metal smelting and refining processes were introduced, also as a systematization of alchemical practices based on the use of fire (Bernardoni, 2011). Biringuccio applies his knowledge of rocks and minerals to practical problems, starting to shape the modern concept of economic underground resources exploitation (it is worth mentioning that the term "geology" was introduced only later, in 1603 by Ulisse Aldrovandi in Bologna).

The first two books of *Pirotechnia* deals with metals and mineral ores. Biringuccio classifies the traditional six solid metals (gold, silver, copper, lead, tin, iron), the making of steel and brass, and many "semi-minerals" (sulfur, mercury, antimony, vitriol, alum, arsenic, orpiment, salt, calamine, manganese, ochre, bole, emery, borax, rock-crystal, gems, glass, etc.). For each mineral he describes the

properties, the principal mining sites, the rocks in which the mineral is contained, the clues to recognize the presence and the technology to produce useful metals or refined mineral products.

Unfortunately, the only solid metal largely produced in Tuscany and explicitly mentioned in De la Pirotechnia is iron. In the first book of *Pirotechnia* he does not report the existence of specific Tuscan mines of copper, silver, lead (although existing, and with a long mining tradition), but highlights the presence of iron only. Biringuccio says that Tuscany is very rich in iron, above all in the Elba Island, where it is so abundant that for its large quantity it spreads also in the surrounding territories on the mainland. But for its quality, abundance, ease of extraction, security of investment and supply in large quantity, one does not care to extract it into the mainland, despite the signs of presence and abundance. He notes that the amount of iron ore excavated in so many centuries is astonishing, and that it is still extracted even today, with a better quality compared to the past and with higher yields. Moreover, the iron ore of Elba is easy to work and melt, and easily provides a very soft and workable iron that make it suitable to any work of the blacksmith: according to Biringuccio, all the above demonstrates its purity. He observes that this does not happen in other mines such as in the ones of Val Camonica (near Brescia, northern Italy) where iron is “wild”, and it needs great fires to tame its wildness, resulting from the bad mixtures with other metals (of which it is so full) that it is purified with difficulty. Biringuccio wrote: « I saw this problem in Siena while I was still a young man, in the valley of Boccheggiano where many factories for making iron were constructed by the magnificent Pandolfo Petrucci. Since I was in charge of them, I took some of the iron ores which were found near there as well as that of Elba Island, and I came to be experienced in both » (Authors' translation, from 1540 edition, p. 16 *verso*).

The second book of *Pirotechnia* deals with the semi-minerals; according to Biringuccio, they are produced by nature neither as completely composed of stone, nor completely composed of metal. So, they are minerals in their “initial” stage of development, and thus they do not yield

metals or, if they do, these are only imperfect ones, such as mercury, which is liquid.

Among the semi-minerals contained and produced in Tuscany mines, Biringuccio mentions sulfur, antimony, vitriol, alum, salt, calamine and manganese. He states that sulfur is found in massive aggregates with earthy appearance in areas of hot water springs and volcanoes, such as at Bagni San Filippo in the territory of the Republic of Siena. On antimony, Biringuccio wrote: « There are several mines of this antimony ore in the region of Siena, among which one is near the city of Massa in the Maremma and another large mine near another city called Sovana. Practiced experimenters claim that the latter is the best they know. It is also found in the region of Santa Fiora, near a zone called Selvena » (Authors' translation, from 1540 edition, p. 28 *recto*).

Then, on the vitriol ore: « It is mined at Massa, powerful and beautiful as the *Ciprio* one, Travale and Monterotondo, at San Filippo, at Sovana and in many other places in the Sienese territory. It could also be mined in the region of Volterra; and in mount Amiata in the Santa Fiora region » (Authors' translation, from 1540 edition, p. 30 *verso*).

As for alum Biringuccio reports that in Italy its mines are located in Ischia and Pozzuoli near Naples, and in Tolfa near Civitavecchia; in this latter location, alunite was discovered during the papacy of Pius II in 1462. He wrote: « Alum ore is also found in the Republic of Siena at Massa and Monterotondo and in many other places in the same territory. Furthermore, it is found near Piombino at Montioni and in the territory of Volterra at Campiglia » (Authors' translation, from 1540 edition, p. 31 *recto*).

Biringuccio also describes salt production from sea water or salt springs by evaporation and crystallization, but also its extraction from underground mines in the form of stone. He describes the operation of coastal salterns (salt evaporation ponds), and the production of salt from salt-rich natural brines by means of large boilers, as in Halle (Tyrol). Then he writes: « The same procedure is used in Tuscany in Volterra, with a salt water extracted from some wells, which is evaporated by boiling in lead boilers

similar to those of vitriol. A very white salt is produced, like snow, and in such large quantity that not only the city of Volterra uses it, but also that of Florence and its neighboring territories » (Authors' translation, from 1540 edition, p.35 verso). Among the many other places where salts can be obtained from salt springs, he mentions also San Quirico d'Orcia.

Concerning brass, Biringuccio remind us that calamine, a mixture of zinc minerals useful for brass production, is located in Fosini (Montieri), in the territory of Siena, but he (wrongly) claims that calamine can be found associated with almost all types of mineral ores. About the semi-mineral manganese, he reports that: « It is found in Tuscany in the mountains of Viterbo », indeed a geographic mistake, since then (and still now) this area did not belong to Tuscany, but to present-time Lazio region, since long before under the dominion of the Papal States.

Finally, according to *Pirotechnia*, in 1540 the Tuscan mines in activity were very few, apart from those of iron. The lead-silver mine of Montieri had not yet been discovered; no copper mine was fully active, and Biringuccio observes that Italy was very rich in copper and silver, but it was not extracted for the laziness and fear of risk of the Italian entrepreneurs. Curiously, the cinnabar-mercury mines of Monte Amiata area are apparently unknown to Biringuccio. This area has always been characterized by research and extraction of cinnabar for the production of mercury. The characteristic purple-red color of cinnabar has attracted man since prehistoric times, when small surface excavations were made to extract small quantities of red powder used as a dye for clothes, for cosmetic uses and for its alleged medicinal properties. The first written document that clearly deals with cinnabar mines in the Amiata area is the deed of ownership sharing between the town of Sovana and Santa Fiora (1217), in which it was established that "the excavation of quicksilver" of Selvena will remain undivided and common property.

Cosimo I de' Medici and the Renaissance of mining in Tuscany

It is probable that the reading of Biringuccio's *Pirotechnia* was a stimulus for Grand Duke

Cosimo I de' Medici (1519-1574). He and his son, the second Grand Duke Francesco I (1541-1587), personally supervised the reviving of mining in Tuscany, with the interest of businessmen and the tenacity of investigators, stimulating researches in areas already exploited in the previous centuries (the Metalliferous Hills, Campiglia Marittima, Pietrasanta, etc.), as well as in new areas. He affirmed that «the intention to testing many places, to find and bring to light what is hidden underground, and by finding a good seam, one will pay for the expense, and whoever does not search does not find » (Fabretti & Guidarelli, 1980). In this regard, it is worth mentioning that probably Cosimo I proposed, or indirectly supported, the translation of Agricola's *De Re Metallica* into the Tuscan language. Even if this is not yet fully documented, the Italian translation of Agricola's masterpiece was printed in 1563, and was prepared and edited by the Florentine refugee Michelangelo Florio (Agricola, 1563). Moreover, already in 1547 Bolfo di Augusta, a scribe and secretary who came to Pietrasanta together with Christopher Degler (see below), translated numerous Germanic mining statutes on behalf of Cosimo. This is testified by numerous documents of the Historical Archives of Florence, mining section (Fabretti & Guidarelli, 1980).

The 19th Century mining engineer Theodor Haupt, in charge of re-evaluating the mineral resources of the Grand Duchy of Tuscany (see below), reports that in 1442 several iron mines were active in the territory of Pietrasanta (Apuan Alps, northern Tuscany), and in Montecatini Val di Cecina, near Volterra, many positive attempts to produce copper were carried out from 1469 to 1494. In 1584-1585 the silver mine of Montieri, in the territory of Massa Marittima, was reactivated (Haupt, 1847).

With full Renaissance spirit, the Medici government launched a policy of redevelopment of mining and industrial activities in the area of the Apuan Alps (territory of Pietrasanta, near Lucca), and Cosimo I reactivated the ancient "Argentiere" (silver mine) of Gallena and Farnocchia. The period of activity of the mines began in 1539 and ended in 1595. In the Gallena Silver Mine (today's Bottino mine) the mining activity was resumed with the help of German and Tyrolean mining and metallurgical experts,

given the absolute lack of specific knowledge on the part of local workers. In that period, 40 to 70 workers were employed on average, obtaining a moderate production of lead and silver. However, it was clear that smelting operations were critical due to the antimony and arsenic contents in that specific lead ore, which decreased the efficiency of metal separation resulting in economic losses (Fabretti & Guidarelli, 1980). As a reason for the crisis of this mining activity, we recall again that the end of the 15th Century coincides with the beginning of the arrival of large quantities of silver from the Americas, a fact which in general caused a crisis in all European mining activity, including the one of German mines.

The Medici's mining activities were headed by a technical manager, the *maestro generale* (master general), a position initially held by Christopher Degler, a mining expert hired from Nuremberg, and later by Johans (Hans) Gleggl, an experienced metallurgist from Schwaz (Tyrol, Austria), one of the most important silver and copper mining centers of Europe in the Middle Ages. The importation of skilled labor from northern Europe was possible thanks to the excellent business relationships existing between the Medici family and that of the Fuggers, the famous German bankers: Gleggl himself was one of the Fuggers' mines Director. As mentioned above, Cosimo I was also the promoter of a new mining enterprise in Campiglia Marittima, an area already known for lead/silver, copper and iron ores. This activity took place between 1548 and 1559, and it is well known and described in its specific phases through letters, documents, inventories and accounting records of the time. In the early stage of exploration some German miners, who were already working in the mines of the Apuan Alps, moved to Campiglia (1550-1555), and two hydraulic workshops were built to provide energy for ore processing. This activity was followed by the development of an autonomous mining company (1556-1559) with strong financial and workforce investments to increase production. Unfortunately, considerable difficulties arose in ore smelting, and very low yields were obtained, if compared to the metal content determined with laboratory essays on small samples. To overcome these difficulties, Cosimo I sent Johans Gleggl who brought with him 30 other specialized workers, but the master general and his metallurgists once again failed to

obtain satisfactory results from the smelting and refining of the ore. New smelting methods based on trial and error were widely attempted, but again without consistent results (Fabretti & Guidarelli, 1980). The insignificant production of good quality metals, the scarce water and energy availability, and the strong presence of malaria in this area led to the abandonment of the Campiglia mine (Farinelli, 2017).

Cosimo, still as Duke of Florence (the pope appointed him Grand Duke of Tuscany in 1569), in 1542 established the *Magona del ferro*, a central institution for the administration of the monopoly of the production and processing of iron, functional to the expansionist and reunifying policy of Tuscany. In order to obtain sufficient raw material, he signed an agreement with Iacopo V Appiano, Lord of Piombino (1480-1545), for the general contract of the iron ore of the Elba Island and the lease of their ironworks of Follonica. Cosimo I also reactivated numerous workshops (e.g., the ones of Forni di Accesa and Valpiana, near Massa Marittima) for the production of iron obtained from the processing of Elba Island iron ores (hematite, mixed with oxides and hydroxides of iron) and from the poorer and sporadic iron ore deposits of the Metalliferous Hills. With this domestic production, Cosimo I was able to develop his military industry, which led him to victory in the war with which he conquered Siena in 1555 and unified Tuscany.

Grand Duke Francesco I, son of Cosimo I, continued the intensification of the extraction of alunite at Monte Leo (near Montioni) for the production of alum. Moreover, he promoted exploration activities for copper production in Montecatini Val di Cecina (Volterra area, at present province of Pisa) and in 1585 he began the extraction of copper at the mine of Montecastelli Pisano, an activity that was abandoned after his death in 1587 (Delkeskamp, 1907). In the same period, the silver mine of Montieri was fully active, and it is documented that in 1584 a shaft was dug up to 45 meters, an outstanding depth for the time in this area, and in 1585 an old drainage tunnel reopened to serve the underground mining operations (Haupt 1847). In the light of the above, it is clear that, apart from alum, the only real success of the mining industry promoted by the Medici's in the second half of the 15th Century was in the production of iron,

while for copper and silver only poor and unsatisfactory results were obtained.

In the 17th and early 18th Century the Tuscan mines were neglected and mostly abandoned, as documented in Giovanni Targioni Tozzetti's letter to Richécourt "Short report of observations on mines in the municipal territories of Pisa, Volterra, Siena and Massa Marittima in the fall of 1742" (Targioni Tozzetti, 1743). In the same year he wrote a second letter "On the benefits that can be expected from the mines of Tuscany" attempting, with limited success, to stimulate the interest of the grand ducal administration in developing the mining business (Sammuri, 2021).

As a matter of fact, the Grand Duchy mostly favored the mining industry in the sector of non-metallic ores, and pushed for the search of coal to meet the increasing demand for energy in Tuscany; this is testified by studies carried out, among others, by Giovanni Fabbroni (1790) and Francesco Henrion (1792). After the Congress of Vienna (1815) the Grand Duchy was granted the sovereignty over the Principality of Piombino and thus incorporated in its territory the wealthy iron mines of the island of Elba and the alunite deposits of Montioni for the production of alum. However, the real rebirth of the mining activity in Tuscany will take place only at the end of the Napoleonic period, especially during the reign of Grand Duke Leopold II of Lorraine (1824-1859). In 1830 he invited Paolo Savi, naturalist and professor of the University of Pisa, to join him as an expert during a trip to Germany to study the coal districts of Saxony and Bohemia, during which they visited many mines and discussed with German geologists and mining engineers about the exploration and exploitation of mineral resources.

In the following years, numerous private mining companies tried to reactivate the old mines of the Grand Duchy of Tuscany, but with little financial resources and therefore using equipment and technologies of a typically pre-industrial period. However, Leopold II called from Saxony the aforementioned mining engineer Theodor Haupt and in 1844 appointed him as Royal Consultor for the affairs of the mines. In the following years, Haupt worked together with Belgian and Saxon mining experts to develop the

mining production, including the more and more strategic production of coal.

Conclusions

The mining activity of Tuscany in the Middle Ages encompassed a large number of small mining sites; some of them were very important, at least for the continuity of mining knowledge, sometimes dating back to Etruscan or even prehistorical times. This study frames Biringuccio's contribution in the field of mining and metallurgical developments that took place in Europe in the 15th and 16th Century, also in relation to the development of the mineral resources of Tuscany, linking them to the later efforts of Cosimo I de' Medici to revive the mining and metallurgical industry of the Grand Duchy of Tuscany. Biringuccio, in addition to a good knowledge of the literature of his time, also had direct experience of many mining and metallurgical procedures and practical methods adopted in numerous production sites that he visited and supervised both in Italy and in northern Europe. His descriptions of the single minerals, their aggregation, the typology of rocks in which they can be found, the methods of recognizing the metals and the metallurgical treatments to produce and refine them were a valuable guide for both mine managers and for the foundation of a scientific approach that drove the later development of modern mining and metallurgical engineering.

Probably, the grand ducal master generals who coordinated the activities of the Medici mining company knew Biringuccio's and the other almost-contemporary technical treatises on mining and metallurgy, and in particular the ones of Agricola. In fact, after *De la Pirotechnia* (1540), Agricola's *De Re Metallica* was published in 1556, and translated a few years later into the Tuscan language by Michelangelo Florio *De l'Arte de' Metallii* (Agricola, 1563).

In the second half of the 16th Century the Grand Duke of Tuscany Cosimo I and his son Francesco I, in addition to producing and using the very abundant iron ore of the Elba Island, reactivated several small mines and workshops for the production of iron from the poor and sporadic deposits of the Metalliferous Hills. It was a matter of a direct entrepreneurship of the

Grand Dukes, financed by the Grand Ducal Treasury, fostered by friendship and cooperation with the Fugger bankers who procured the expert German miners and mine managers necessary to this task.

The exploitation of alunite was also developed for the production of alum, a raw material very valuable and strategic at the time. Despite the many attempts and the investments, backed by the strong mining policy of the Grand Duchy, unfortunately there were no significant results in the attempt to increase the production of valuable metals for coins, such as silver and copper. Indeed, the mining policy of the Medici was a relatively short attempt, lasting a few decades, to satisfy the needs of the emerging Grand Duchy. Iron was produced for weapons, lead for bullets, silver and copper as precious metals, alum for dyeing fabrics and tanning leather.

Despite the great efforts and the great knowledge contained in Biringuccio and Agricola, apparently even the most qualified mining and

metallurgical experts did not obtain many results in relation to the metallurgical operations, indeed complex, of the Tuscan metal bearing ores. Here, the smelting of the metal was always considered as an adventure and a unique discovery, due to the variability of the composition of the minerals, and so the standard procedures reported in the contemporary literature have almost never worked properly.

At the end of the 15th Century, most of the Tuscan mines were once more abandoned, and remained substantially poorly exploited until the first half of the 19th Century, when an intense mining activity resumed in the area of the Metalliferous Hills, especially after the unification of Italy, also as a consequence of the need of both new materials, metals and energy for the newborn State. The mineral production in this area boomed during the first half of the 20th Century, mainly for the production of lignite, mercury and pyrite, this latter used as raw material for the production of sulfuric acid for the chemical industry.

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