Innovations in Mining and Metal Production in Europe in the Late Middle Ages

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Histories of inventions tend necessarily to take the form of lists of the achievements of the human spirit and prize-rolls of individual genius classified by discipline and field of application. While this has certain lexographical functions, there are obvious short-comings. For the historian, invention poses a number of fundamental problems because it serves to introduce into the continuities of economic and technological history an element or a group of factors which may both change existing structures and speed up their development. And if the fact of invention stems from the realm of the individual, it provides an indication no less of the collective creative capacity of a given society. One field in which technological development, and hence technological innovation, played a major and fundamental role in economic change is provided by that complex of industrial activities known in German as *Montanwirtschaft* which embraced every aspect of mining and metal production from the casting of metallic ores to their transformation into marketable products.

At the close of the Middle Ages and the beginning of the modern period, roughly from the mid-XIVth to the mid-XVIth century, the German lands provided the European commercial economy with the bulk of the metals used for currency and military purposes by the different European states and societies. A first period of capitalism which had been based in the XIIIth century on high quality textile production gave way subsequently, in the region stretching from the Rhine to the Carpathians, to a new mining capitalism which led to the rise of new industrial sites that were carefully nurtured by rulers and specialist entrepreneurs, and were to provide the economic basis of Habsburg hegemony.

Although what Jacob Fugger described as this 'metallic blessing' has been studied in considerable depth, insufficient attention has hitherto been devoted to the technological basis of German supremacy in this field. This is illustrated by the case of the principal mines of Schwaz in the Tyrol, at Falkenstein — the production accounts of which have been preserved since 1480. These show a gradually increasing curve of silver production, but more importantly they show that production leapt from 6 to 11 tons per year within a very short period [1] This cannot be explained solely by reference to the expansion of the mine-works or the quantitative increase in the supply of silver-bearing ores, since the main cause lay in the changes that took place in the process of refining with the introduction of quite new methods for separating silver and copper.

Unless the economic historian is prepared to take note of the history of technology we run risks of explaining such increases in metal production simply in terms of increased investment in the mines and improved productivity, without being able to specify the role of individual factors and the ways in which they inter-acted on the process as a whole. Any history of mining

[1] *Landesregierungsarchiv Innsbruck, Leopoldina Litt. S, 102* et *Pestarchiv XIV, 897.* The numerical data are used in M. von Isser-Gaudenthurm, Schwazer Bergwerksgeschichte, *Berg- und Hüttenmännisches Jahrbuch52,* 1904, p. 407-478, p. 420-432; and more recently by E. Egg, "Das wirtschaftswunder im silbernen Schwaz," *Leobener Grüne Hefte, H. 31,* Vienne 1958, and by E. Westermann, *Das Eislebener Garkupfer und seine Bedeutung für den europäischen Kupfermarkt 1460-1560,* Cologne-Vienne 1971, appendice X.

and metal production must therefore take account of the history of technologies and applied science — of those factors which contemporary economists lump together under the heading 'research departments'. Throughout the workshops and construction sites of medieval Europe there were numerous local experts whose business it was to carry out research and experiments on the production in which they were engaged. Innovation was born, then, as a response, or an attempted response, by such local experts to the questions posed by entrepreneurs or public authorities whenever conditions seemed to favour new investment.

The documentary sources

Any research on technological innovation in mining and metal production in the Middle Ages has to be based on sources that pose major problems of interpretation — primarily theoretical treatises, practical descriptions and iconography. In the case of theoretical treatises, it is always difficult to ascertain to what extent they formed the technical background information in a given period, or to know how widely and by what groups they were used. The practical descriptions, on the other hand, generally contain indirect information on particular industries and their products, but are written in an administrative or notarial idiom that does not always lend itself well to the study of technology. And iconography of course poses endless problems regarding the realism of pictorial representations and the value of single examples.

Of the theoretical treatises, the mid-XVIth century encyclopaedias — Agricola's *De re metallica* and the *Schwazer Bergbuch* — offer two kinds of information,[2] and contain descriptions

[2] *De re metallica libri XII*: Latin edition (Bâle 1556), German (Bâle 1557), Italian (Bâle 1563); English C. and L.H. Hoover (London 1912, then New York 1950); Russian (Moscow 1962); new German edition by G. Fraustadt and H. Prescher (Berlin 1974), and paperback edition Société Georg Agricola du Deutsches Museum (Munich 1977).

of the scientific knowledge — mathematical, mechanical and chemical — applied in mining and metal producton, and also scrupulously detailed accounts of the technologies — from the pick to the endless chain — used in each phase of production. The authors of these tracts were at once humanists and technical experts, who were consciously attempting to provide a synthesis of the innovations made in nearly two centuries of development. But while the information is truly encyclopaedic, it is not always possible to identify what was new from what was not, and many of the machines that are described in minute detail were well known, at least in principle, to engineers of the time of Alexander and Vitruvius. The developments in the production of copper and silver that are described in the *Schwazer Bergbuch* and in the *Speculum metallorum* [3] and in other XVIth century treatises do not seem to be particularly original compared with the alchemic treatises of the XIIIth century or the writings of monk Theophilus which date from 1110-40; [4] the principles for roasting silver-bearing copper, for examples, seem to derive directly from the process of selective fusion described by Theophilus.

The main problem, however, is the connection between inherited scientific knowledge and practical application. The methods for extracting metals certainly derived from alchemy — but once the quantity of lead required to bring about the almost complete separation of copper and silver in industrial production had been established, then it was a matter of moving from theory to application, and of taking into account the behavioural characteristics of the ores, the investment capacity of a given enterprise, and market opportunities. In what ways was alchemic knowledge in fact translated into practice? How were master-miners and metallurgists trained, and what part was played in their train-

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Schwazer Bergbuch: based on the seven known manuscripts, edited by H. Winckelmann, Wethmar 1956.

[3] Ed. F. KIRNBAUER, *Leobener Grüne Hefte, H. 50*, Vienne 1961.

[4] *Des Theophilus Presbyter Diversarum Artium Schedula*, ed. W. Theobald, Berlin 1933.

ing by theoretical knowledge, what part by oral traditions? Despite the scarcity of written sources for such problems, it seems reasonably safe to suggest that there was an intermediary culture between science and practice, a sort of general know-how which was present in every metal workshop and plant. But since theoretical treatises were concerned above all to systematize, they paid no attention to the evolution of such ideas nor to the ways in which they were disseminated — they cannot help us establish, either, the social ladder of scientific knowledge, nor even the stages by which it developed.

The practical descriptions need to be very carefully interpreted, because in the hands of scribes and notaries the technical vocabulary used often served to disguise or simplify the real nature of the installations they were describing because terms were improperly applied, or given particular local colourings, or made misleadingly general. Let me take as an example a complex metallurgical establishment which some texts describe as a *fabrica* or factory; elsewhere it is described as a ' blowing machine ' (*follis*) in XIIIth century Hungary; as a ' wheel-house ' (*rad*) or a mill (*molendina que vulgo dicuntur Hutten*) in XIVth century Poland; or by the term tilt-hammer (' *martinet* '), which was used to describe a copper foundery with hydraulic wheel, bellows and blast furnaces on Jacques Coeur's mine in the Lynnais mountains in 1450.[5]

To move from the installations to their products necessitates comparing numerous different sources and relying on some guesswork as well. R. Sprandel has shown that in the Brescian Alps in the XIIIth century as well as the *furnus* that produced the *ferrum crudum* that was registered in the tax accounts, there was also the *fusina* which could be used to produce smelted ores (*vena rotura*) and crude iron (*ferrum ad coquendum*) and cast iron.

[5] Cf. G. Heckenast, "Die Verbreitung des Wasserradantriebs im Eisenhüttenwesen in Ungarn," *Nouvelles Etudes Historiques*, I, 1965, p. 159-179; R. Sprandel, *Das Eisengewerbe im Mittelalter*, Stuttgart 1968, p. 179 et seg. et 366-367; A.-Th. Rendu, *La mine de Pampailly d'après les comptes de Pierre Granier en 1455*, Mémoire de maitrise dactyl., p. 68 sgg.

This meant that the plant could be adapted to direct treatment or to the two methods of smelting which typified the indirect process.[6] A Friulian inventory dating from 1389 confirms this double utilization, referring to the *fusina ad faciendum et laborandum ferrum utriusque generis* (i.e fusina for making and working iron of other kinds.[7] We should bear in mind an important aspect of the origin of the indirect method — the innovation lay in adapting hydraulic energy not to the forge itself, but to the bellows. It was due to the very high temperatures that they were able to attain (over 1250⁰) that the metallurgists of Upper Italy, followed by those of central Austria, were able to be the first in Europe to produce molten iron in large quantities, and given the absence of phosphorus and the presence of magnesium this enabled them to specialize in the production of tempered steel from as early as the XIIIth century. On the island of Elba, where the ores contained a very high iron content, the direct process was retained since it was much less costly in timber — it was not so much a case of an unwillingness to innovate as a question of production costs and profits. Despite its importance for Europe as a whole, our chart of innovations in this field still shows many unexplored areas, and the practical descriptions we have used do not have sufficient clarity of terminology to provide unequivocal evidence on their own. However, it seems reasonable to suppose that the introduction of the hydraulic bellows is a fair guide for setting the European origins of the indirect process for the treatment of iron in the XIIIth century.

We have already mentioned the mining and metallurgical encyclopaedias of the XVIth century, and one of their most remarkable aims was to provide the cultured public with a mass of annotated visual information. In iconographical terms this means that we have a documentary source of inestimable impor-

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[6] Cf. R. SPRANDEL, *Das Eisengewerbe...*, p. 226 sgg.

[7] *Archivio di Stato di Udine, Comune di Venzone II, 9, Notaio Giovanni fu Ermano*, (1389/14/11 *m.v.*).

tance for the greater part of the German teritories, on the basis of which the study of innovation can attempt to draw comparisons between both place and time, and to analyse movements, tools, machinery and working conditions. A comparison of successive images makes it possible to establish lines of paternity, to analyse the process of imitation and to identify regional differences. But iconographical sources are of varying reliability — the images they provide are often stereotyped, romanticised, or anachronistic. They may well present a misleading reflection of reality, and in comparison with written sources do not always have the merit of antecedence. The oldest known representation of a horse-drawn windlass (*molette*) for raising standing water from mine shafts is a miniature painted at Kutna Hora (Kuttenberg) in 1490.[8] But had there been a depiction of the pumping of water out of the Falkenstein mines in the Tyrol in the early XVIth century, what we would see would be teams forming a chain to pass water in buckets out from the bottom of the shaft — in other words, one must be very careful about generalizing from a document describing a particular local practice at a particular time. In the case of mining, the earliest known engraving of a conveyor and mine-cars is in the altar-piece at St. Anne of Roznava (Rosenau) in the Carpathians, dating from 1513 [9] — but the accounts of the Pampailly mines in the Lyonnais mountains in the mid-XVth century show that the same innovations were already in use there.[10]

While making every allowance for differences in style and skill, one can still attribute considerable importance to the comparison of two contemporary — yet in spirit totally different — iconographical sources like the altar-piece at Annaberg in Saxony

[8] The original by the Prague master Mathias Illuminator has disappeared; reproduction in H. WINCKELMANN, *Der Bergbau in der Kunst*, Essen 1958, p. 97.

[9] The altar-piece is in the museum of mining at Rožnava; reproduction in H. WILSDORF-W. QUELLMALZ, *Bergwerke und Hüttenanlagen der Agricola-Zeit*, Berlin 1971, pl. XX.

[10] Cf. A. TH. RENDU, *La mine de Pampailly...*, p. 62.

and the series of drawings by Henrich Gross.[11] By 1520 Annaberg was a mining centre of long tradition with diggings juxtaposed pell-mell and little evident organisation of the underground workings — the mine provides a picturesque feature in the background of the altar-piece, but the antiquity of the type of mining used and of the organisation of the enterprise emerges clearly from the traditional fashion in which the space is utilized. In contrast, Henrich Gross had been commissioned to depict day to day life at the mine of St. Nicholas de la Croix-aux-Mines in the Vosges, and he portrays a rational and coherent mining enterprise with vertical shafts and horizontal galleries — the artist, in fact, captures live the image of a rational capitalism, which encouraged innovation and liked to progress in precise right-angles. Two different images, two different ages of mining, yet taken from two contemporary sites — the contrast can only be reconciled by reference to the *De re metallica* which will reduce them to a single common denominator.

Conditions favouring technological development and innovation

The expansion in the production of metal ores in Europe between 1450 and 1520 was in response to the intense demand for metal for coinage and military purposes — especially iron, copper and silver, but also tin and lead. Domestic consumption and exports to distant parts of the world (to balance trade with the East, and also with Africa) were the incentives for increasing production, and as the trade in metals became more dynamic

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[11] The 25 etchings by Heinrich Gross, have been kept since 1925 by the Ecole des Beaux-Arts de Paris, and have been reproduced in fac-simile with an introduction by A. Girodié, *Les mines d'argent de la Croix-aux-Mines en Lorraine*, Nancy 1909, and in H. Winckelmann, *Bergbuch des Leberthals*, Wethmar 1962, p. 157 et seg.; and in the Alsace journal *Pierres et Terre*, 25-26, 1982. On their interpretation, cf. P. Benoit, " Histoire des techniques et iconographie: la place du manuscrit de Heinrich Gross dans l'iconographie minière germanique," *Ibid.*, pp. 67-83.

so the whole complex system of production needed to be relaunched in more intensive form. First this took the form of reopening old mines, then prospecting for new ones, then a deepening of the shafts and the digging of drainage galleries. This systematic exploitation required heavy investment in the expectation of high profits — and as a result the bourgeoisie began to move from selling metal to refining it and then finally to investing in production by purchasing parts of the mines, or sharing in the cost of mining enterprises and in the profits on the sale of the proceeds; and they were soon followed by noblemen and ecclesiastics, like the dedicatee of the *Graduel de St. Die* [12] or Melchior of Meckau, bishop of Brixen.[13]

In this way the industrial regions — the Central Alps, Hungarian Slovakia, the Southern Vosges, and Ottoman Bosnia — were revitalized, and mining and metal working drew in large populations, transformed the countryside, and created closer links between the towns and the mining 'deserts'. Cities like Nuremberg, Cologne and Dresden became regional capitals, providing capital reserves, supplies of metals to specialist craftsmen, and the organisation of distribution networks.[14] The rulers also played a key role in this renaissance, and some of them — like

[12] In the Bibliothèque Municipale de St. Dié; this precious illuminated manuscript containing 364 folios was commissioned by the monks of the collegiate church of the town. Two of the pages were commissioned by the monk Vautrin Lud, who belonged to a family of mining entrepreneurs who were very active in Lorraine during the reign of René II; a connoisseur who in 1504 became director of the mines commissioned the drawing and painting of the particularly realistic scenes which postrary all the different stages of work in the mine and the metal works; cf. the analysis by A. Ronsin and H. Bari in *Pierres et Terre*, 25-26, 1982, pp. 51-60.

[13] Cf. G. von Pölnitz, "Jacob Fugger und der Streit um den Nachlass des Kardinals von Brixen," *Quellen und Forschungen aus italienischen Archiven und Bibliotheken*, XXX, 1940, pp. 223-294; L. Schick, *Un grand homme d'affaires au début du XVIe siècle: Jacob Fugger*, Paris 1957, pp. 89-101.

[14] On the relationship between a mercantile metropolis and its industrial neighbourhood, cf. the model study by F. Irsigler, *Die wirtschaftliche Stellung der Stadt Köln im 14. und 15. Jahrhundert. Strukturanalyse einer spätmittelalterlichen Exportgewerbe- und Fernhandelsstadt*, Wiesbaden 1979.

Duke George of Saxony who owned some 700 mining lots (*cuxen*) scattered over more than 40 workings in the Annaberg district in 1535 — were themselves producers. Others (often they were the same people) called on specialists to help them develop this vitally important form of production which would enrich their revenues — in Saxony, the regalian dues on the silver mines produced a quarter of the entire State revenue in 1470 and two-thirds in 1530.[15] Some of these rulers strongly encouraged innovation. like the Margrave of Meissen who had hydraulic workings (*Wasserkünste*) built in 1379; [16] the Count of Mansfeld who built furnaces for refining copper, which had been made at Nuremberg, in Schleusingen in 1461 and in Hohenkirken in 1462 [17]; and Mathias Corvin and Ladislas, Kings of Hungary who in 1475 and 1493 respectively conferred privileges on Hans Thurzo to build huge dams which were to be used — as we shall see shortly — to supply the hydraulic wheels in the mines of Slovakia.

The concession of special privileges was something that the ruler should do freely in order to attract skilled craftsmen to his state — this at least was the opinion expressed by the author of the *Schwazer Bergbuch* in 1556.[18] A mine, he argued, was a gift from God, but not for the benefit of any one individual, and for every ten men who grew rich thereby, there were always at least a hundred who were exhausted and impoverished; since few human enterprises collapsed as quickly as mines, all those who laboured with their hands should benefit from the social rewards that were the fruit of development and innovation.

It goes almost without saying that the process of gradual

[15] Cf. A. LAUBE, *Studien über den erzgebirgischen Silberbergbau von 1470 bis 1546*, Berlin 1976, p. 282.

[16] Cf. H. HELBIG, *Quellen zur älteren Wirtschaftsgeschichte Mitteldeutschlands*, IV, Weimar 1953, pp. 76-79.

[17] Cf. G. VON PÖLNITZ, *Jacob Fugger*, Tübingen 1951, II, p. 20 et 74.

[18] *Schwazer Bergbuch*..., p. 63: "Bergwerk ist eine Gottesgabe und nicht nur zum Nutzen einer Person, sondern zum Nutzen aller, die danach trachten und sich damit befassen, für niemand aber sicherer als für den Arbeiter etc..."

technological improvement and the adoption of innovations met numerous checks and set-backs during this period. Innovations were not disseminated uniformly to all mining regions at the same time, but it is too soon to start drawing distinctions between what Levi Struss has called ' hot ' and ' cold ' sectors — the disparities at this time were much more likely to be the result of different legal and social organization and of the ways in which the mining enterprises were set in the overall fabric of a local economy.

It was Marc Bloch who first suggested the general theory that any problems caused by the labour force will tend to increase the level of mechanization,[19] yet the situation at the Falkenstein mine in the Tyrol would appear to contradict this — since we find that there was an abundance of available labour and also a remarkable delay in taking up new technologies.[20] In 1532, wages totalling 15,000 florins were paid to the 600 men who took four-hour shifts to form a continuous human chain night and day to draw water off the mine shafts. It was not until 1553, three years before the publication of the *Schwazer Bergbuch*, that a horse-powered wheel for working a pump to drain the mine was built, which costed the Imperial exchequer 15,000 florins. And this was certainly no longer the heyday of the Schwaz mines. which had already begun to decline. But in comparison with the mines of Saxony or Kuttenberg and Ste. Marie-aux-Mines, the delay is surprising and shows the need for more detailed studies of the precise nature of the factors blocking the introduction of new technologies. In this particular case, it may well have resulted from the overmanning and cost in the Inn valley, but no less important must have been the limited investment capacity of the controllers of the mines.

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[19] M. Bloch, Les " inventions " médiévales, *Annales d'Histoire Economique et Sociale*, VII, 1935, pp. 634-643.

[20] *Schwazer Bergbuch...*, pp. 150-151.

Innovation in the mines

From the moment when the excavation of deep shafts met the limits of profitability, given the state of existing technologies and the level of financial investment possible, the most pressing problem facing every mine-owner and entrepreneur in Europe was the struggle with water and flooding. There were two ways of dealing with the problem. The first was simply to dig a pit at the lowest point of the working to form an unflooded gallery, which also had the additional advantage of providing ventilation and secondary access. Alternatively the water could be brought to the surface by some form of mechanical power.

The first solution was used in the lead mines at Olkusz in southern Poland for example, where the shafts were very shallow and had a maximum depth of 50 meters. Between the late XVth and the mid-XVIth centuries, an extremely large net-work of long but very low angled galleries was constructed.[21] At Pampailly, in the Lyonnais mountains, the royal administration decided to build a drainage channel 300 metres long, which had to be cut through extremely hard rock and progressed at the rate of only 2 or 3 metres a month: an undertaking that well illustrates the expectations of profit that were still aroused by Jacques Coeur's silver mine.[22]

The second alternative involved artificially raising the water by means of manpower, animal power or hydraulic machinery. The limits of human force applied to a windlass were reached at about 15 metres depth, and for anything deeper than that needed some form of horse or ox drawn winch (the *molette*); in some cases these employed teams of up to thirty horses at a time.[23] But by the second half of the XVth century the mining

[21] D. Molenda, "Investments in Ore Mining in Poland from the XIIIth to the XVIIth Centuries," *The Journal of European Economic History*, 5, 1976, p. 151-169, part., pp. 160-161.

[22] A. Th. Rendu, *La mine de Pampailly...*, p. 56.

[23] Ainsi à Olkusz: D. Molenda, *Investments...*, p. 159.

enterprises had wherever possible tried to fight 'water with water'. The treatise by Agricola minutely lists and describes the different water-powered machines that were used, which included piston pumps constructed in hollowed-out tree trunks, endless bucket chains that passed around a drum at the base of the mine and lifted the water off towards the surface and leather balls that were passed along tubular conduits (*Heinzenkunste*). But none of these devices could function at more than 70 metres depth, and in the case of the deeper mines that could not be drained by lower galleries it became necessary to construct the very costly reversible hydraulic wheel (rotam '*Kerrad*' dictam) — this was powered by a water head which activated bowls fixed to the wheel in two series, one forward and one in reverse: the wheel drove a windlass around which was wound a metal chain which lifted a huge leather sack made from the hides of four oxen. It seems quite likely that the system was devised by Johannes Thurzo, who was called on — we discover — in 1475 to oversee the installation of such machinery in seven mining towns in Slovakia: it was also Johannes Thurzo who was summoned in 1486 to Rammelsberg in the Harz mountains [24] and again in 1513 to the gold mines at Nagybanya in eastern Slovakia [25] to rescue flooded mines. A *Kerrad* wheel 10 metres in diameter was installed 65 metres underground at Nagybanya to drain a network of galleries which went down as far as 280 metres: it was driven by a 110 metre water head

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[24] E. Reinhardt, Johannes Thurzo von Bethlemfalva, Bütger und Konsul von Krakau in Goslar 1478-1496, *Beiträge zur Geschichte der Stadt Goslar*, 5, 1928, pp. 54-55, 78 segg.

[25] In addition to Georg Thurzo's *Mémorial* for Jacob Fugger (31 mai 1513), now at Dillingen, *Fuggerarchiv 37, 6*, cf. M. Skladaný, Nujstarši doklad o podniketelskej činnosti Jána Thurzu v stredoslovenských banských mestách (the earliest evidence on the activities of J. Thurzo in the mining towns of central Slovakia), *Historickè Študie* XIX, 1974, pp. 237-265; and O. Paulinyi, "Der erste Bau von Stauseen und des wassergetriebenen grossen Kehrrades zur Bekämpfung der Wassernot von Zechen: der Versuch einer Rekonstruktion des Bergbaues von Nagybánya- Ungarisch Neustadt in der Jahren 1506-1513 durch Johann und Georg Thurzo von Bethlenfalva," *Acta Historica Academiae Scientiarum Hungaricae* 24, 1978, pp. 109-130, part., pp. 121-126.

which caused the wheel to move so fast, according to an eyewitness, that the moving parts of the wood threatened to catch fire. To obtain the head of water a series of dams were built, for the first time in the history of European mining, in the mountains over 15 kilometres distant, from the mine. But this massive rescue operation organized by Thurzo, with the support of the King of Hungary and the Kremnica treasury, was frustrated by weather conditions — the long periods of continental aridity and the rigours of the winter meant that the machinery could only operate effectively for about half the year. As a result it proved necessary to institute two annual periods for draining the mines, the first at the end of the winter and the second with the onset of the autumn rains — each lasted for 15 days and thereby further reduced the time available for working the mines. The enterprise had reached its operational limits, since these massive infrastructural investments, which were financed largely by the Crown, were being made at a time when the output of the Nagybanya gold mine was well past its peak.

To summarize, therefore, at the close of the Middle Ages innovation in the mining industry consisted primarily in adapting to the needs of underground excavation techniques that had first been pioneered in agriculture, such as the mill-wheel and the drainage channel. As we have seen, the laws of engineering imposed well defined limits on the development of even the most ingenious of these devices: ropes and chains were all subject to the limits of tension they could bear, and often the tools used to work the hardest rocks like quarz had to be reforged daily. Gunpowder was first used experimentally in 1470 but was not used systematically for mining until the first half of the XVIIth century.[26] Similarly, there was to be no real improvement in

[26] Cf. A. Birembaut, *L'industrie minière, Histoire générale des Techniques*, sous la direction de M. Daumas, III, Paris 1968, p. 569: R. Vergani, " Gli inizi dell'uso della polvere da sparo nell'attività mineraria: il caso veneziano," *Studi Veneziani*, III, 1979, pp. 97-140, part., p. 123 etc.

drainage and pumping techniques until the second half of the XVIIIth century and the introduction of reinforced steel wire cables and steam pumping machines. But among the innovations that had been made in the late Middle Ages, there were two that were to remain widely in use right down to the XXth century — the reversible wheel and the system of mine carts known as ' mine dogs ' (*chiens de mine*) which were forerunners of the railways and their wagons.

Innovations in the metallurgy of silver-bearing copper

The heavy demand for silver throughout Europe provided the main incentive for a series of experiments which by the second half of the XVth century had led to the establishment of a chemical process for separating silver from silver-bearing copper ores that was almost complete and relied on the addition of lead: *ars conflatoria separantia argentum a cupro cum plumbo.*[27] The process had three stages.[28] In the first, black copper with a high silver content was melted at high temperatures (990°) to form an alloy. In a second stage, the different temperatures at which copper (1083°) and lead (327°) melt meant that as the ores cooled it was possible to obtain separate crystalization of the copper and the silver-bearing lead. When the silver-bearing lead was finally reheated in a 'roasting' oven the lead ores gave off trickles of copper crystals. The refining was then completed for the copper in a drying oven (*Darofen*) and for the silver in cupellation ovens.

The techniques for extracting silver from lead had been known in ancient times, and it seems likely that the system of ' industrial ' roasting had evolved from alchemic knowledge and the practical experience of the royal mints.[29] Various authors

[27] Cf. W. von Stromer, *Oberdeutsche Hochfinanz 1350-1450*, Wiesbaden 1970, I, p. 125.

[28] Cf. L. Suhling, *Der Seigerhüttenprozess. Die Technologie des Kupferseigerns nach dem frühen mettalurgischen Schrifttum*, Stuttgart 1976, p. 17-22.

[29] Cf. L. Suhling, " Technologische Entwicklungen in der mittelalterlichen Kupfermetallurgie," *Erzmetall* 31, 1978, pp. 348-353.

have dated this invention from the early XVth century and the late XIVth century, but it is Nuremburg — undeniably the centre of technological progress in virtually every sector of metallurgy [30] — that provides us with the first clearly documented case, contained in the inventory of the municipal foundry in 1453.[31] We should also add that the oldest representation of a cupellation oven also comes from southern Germany and dates from 1482.[32] By 1460 there were five refineries in which the 'industrial' roasting of copper ores was carried out in Nuremburg, and the technology was transferred first to the estates of the Count of Mansfeld in the Thuringian forest where the huge deposits of silver-bearing copper at Eisleben, the abundance of timber for the furnaces, and the traditional interests of the Nuremburg businessmen explain the rapid development of a number of mining factories, at Schleusingen in 1461, at Gräfenthal and Hohenkirchen in 1462, at Steinback in 1464.[33] The diffusion of new techniques was, of course, also taken up in refining silver: this was evident at Mogilà near Cracow in 1469,[34] at Chemnitz in Saxony in 1471 [35] and in the Tyrol [36] where the Archduke Sigismund in 1486 received from the town council of Nuremburg the details of the process of silver roasting — which demontrates clearly that at this date the process had still not been taken over by private entrepreneurs, but formed rather

[30] Tinned sheet metal and wire-drawing, as well as the pocket watch (1510) were all invented at Nuremburg — the best compasses and astrolabes in Europe were also produced there in the XVth century.

[31] L. Suhling, *Der Seigerhüttenprozess...*, p. 57.

[32] Cf. B. Neumann, "Die ältesten Zeichnungen eines mittelalterlichen Hüttenwerkes und die ältesten Angaben über den deutschen Kupferhüttenprozess," *Metall und Erz*, 1920, 15, pp. 333-339, and 16, p. 354-361; J. Waldburg-Wolfegg, *Das mittelalterliche Hausbuch*, Munich 1957.

[33] Cf. E. Westermann, *Das Eislebener Garkupfer...*, pp. 266-283.

[34] M. Skladany, Ján Thurzo v Mogile (1469-1496), *Zbornik Filozofickej Fakulty Univerzity Komenského, XXIV-XXV, Historica*, Bratislava 1973/1974, pp. 203-222; D. Molenda, W sprawie badań huty miedzi w Mogile pod Krakowem w XV i XVI wieku, *Przeglad Historyczny*, LXVI, 1975, pp. 369-382.

[35] L. Suhling, *Der Seigerhüttenprozess...*, p. 63.

[36] *Tiroler Landesmuseum Ferdinandeum Innsbruck, W 1516*; quoted by L. Suhling,

part of a form of economic diplomacy, since Nuremburg and its master craftsmen were still the only ones who could put it into practice. It was after his association with Hans Koler of Nuremburg at Mogilà that Hans Thurzo went into partnership in 1494 with Jacob Fugger thereby forming the famous 'Hungarian enterprise' and launching large-scale copper and silver refining at Neusohl (Banska Bystrica) and, Moschnitz (Mostenica) in Slovakia, at Hohenkirchen in Thuringia and Fuggerau in Carinthia.[37]

In contrast to the traditional methods of refining lead, the new method involved obtaining a separation as the temperature rose and from an identical quality of lead extracted over 60-70% more silver. It was the increased profits from the greater silver yield that explains the intensive mining for silver-bearing ores at Eisleben and in the Schwaz, where from 100 kilogrammes of ore 1380 grammes of silver were extracted in 1490 as opposed to only 790 grammes in 1480.

But the new method ('*die neue Künst*') could not be adapted with equal ease to every form of silver-bearing ore. Peter Rummel of Nuremburg, for example, who was director of finances first for Archduke Sigismund and later for the Emperor Maximilian, invented a process to meet the specific requirements of the ores of the Falkenstein mines, which involved a combination of roasting and grilling:[38] the copper ore was melted four times over, on each occasion with additives of lead and slag enriched with lead. This was essentially a Tyrolian adaptation of a process invented

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Bergbau, Territorialherrschaft und technologischer Wandel. Prozessinnovationen im Montanwesen der Renaissance am Beispiel der mitteleuropäischen Silberproduktion, in U. Troitzsch and C. Wohlauf, *Technik-Geschichte. Historische Beiträge und neuere Ansätze*, Francfort 1980, p. 139-179, part., p. 157.

[37] There is a general picture in L. Schick, *Un grand homme d'affaires...*, pp. 52-55.

[38] On Peter Rummel of Lichtenau, cf. Ch. Schaper, Die Ratsfamilie Rummel — Kaufleute, Finanziers und Unternehmer, *Mitteilungen des Vereins für Geschichte der Stadt Nürnberg*, 68, 1981, pp. 1-107, part., pp. 59 et seg. On his role as innovator, cf. L. Suhling, Innovationsversuche in der nordalpinen Metallhüttentechnik des späten 15. Jahrhunderts, *Technikgeschichte*, 45, 1978, p. 144.

in central Germany, and described in its Saxon form in the *De re metallica.*

It is the practical and precisely dated local application of a given innovation that enables us to see the links between the work of the metallurgist, the market incentives and the aspirations of those rulers like the Duke of Saxony or the Austrian Archduke who were keenly drawn to supporting such developments. The activities of Hans and George Thurzo throughout Slovakia and Thuringia, or of Antoni von Ross or Peter Rummel of Nuremburg were not inspired by the mysteries of experimental science, but rather by the search for profit in which they all had a direct interest as advisers to rulers, as mining entrepreneurs and dealers in precious metals. A striking example of this concern to find profitable returns on investment is provided by the correspondence of duke Louis IX of Bavaria with the specialists in his iron works.[39] In 1467/8 the duke had encouraged the goldsmith Hans Lochhauser and Heinrich Rummel (III) of Nuremburg, a widely respected metallurgist and cousin of Peter Rummel, to build a copper refinery at Brixlegg, near Rattenberg, which was to employ the new process. Preliminary experiments were carried out in Nuremburg on samples of the ores excavated in the Bavarian Tyrol, and the duke was kept continuously informed of the results of these experiments, which were initially rather mediocre but then began to improve. But before it became fully established at Brixlegg at the end of the XVth century [40] the new processes of roasting and refining had already caused a major transformation of the conditions of production some few kilometres away at Schwaz in the Austrian Tyrol.

The correspondence, which breaks off before the experiments

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[39] This file in the Munich State Archives was discovered and analysed by L. Suhling, "Herzog Ludwig der Reiche von Bayern als Montanunternehmer am unteren Inn," *Veröffentlichungen des Museum Ferdinandeum Innsbruck*, 57, 1977, pp. 119-136.

[40] The refinery where the essays were made had been built by Duke Louis in 1463; and the enterprise celebrated its 500th anniversary by publishing *Kupferhütte Brixlegg 1463-1963.*

were finally concluded, show clearly that this German prince at any rate had a very precise awareness of his role and capacity as an innovator. Following the details of the technical discussion, it also becomes clear that if the high price of silver encouraged the adoption of new methods, the market also at the same time acted as a restraint due to the high price of the lead needed in the process which had to be purchased from Cologne, Frankfurt and Cracow. The solution reached in the Tyrol was to use lead enriched slag from earlier castings in each smelting of the copper — an innovation which, as we have already seen, had already been tried at Rattenberg in around 1468.

Mining and metallurgy constituted branches of industry where, in today's terms, applied and theoretical science were combined. But it is rare that we possess sources for studying the ways in which innovations that had major impact on the whole system of production were put into practice — the correspondence of a ruler who had a passion for all forms of innovation, or the letters of Hans Stockl who compares his experience as a Tyrolian metallurgist with the traditional methods based on handed-down knowledge are really exceptional. Knowledge and know-how constituted the limits within which the search for higher and better yields was carried on. The land and the natural qualities of the minerals established another set of rules of the game, while the game itself was dominated by the laws of the market. By bringing together the as yet unstudied documentary sources, by mapping out more clearly the things that are already known and established, and by studying the careers of these expert metallurgists and mining entrepreneurs who travelled throughout Europe, we can hope to set the history of innovation into the broader context of economic and social history, and also to make a contribution thereby to a better understanding of that multifaceted phenomenon known as the Renaissance.