

Review

Geology and Mining: A Symbiotic Cooperation?!

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Abstract: The challenge to maximize resource efficiency requires the optimal use of all products leaving a mine—not only ore but also waste products—and calls for contributions from and cooperation with every discipline involved as efficiently as possible. These interdisciplinary and transdisciplinary interactions between practitioners and scientists are also an act of learning and take time. They should be initiated at the start of the exploration phase and continue to the postmining stage. This paper focuses on the interactions of geologists and mining engineers, with examples in the exploration phase (preliminary economic evaluations at milestones using the rule of thumb), the feasibility and mine-design stage (bulk testing, test mining, mine design to minimize dilution and losses), the mining stage (grade control, selective mining, especially in smaller-scale deposit mining, and further exploration to extend a mine's life), waste management during the lifecycle of a mine, and the postmining closure and land-use stage. An additional section addresses the beneficial cooperation in helping small-scale and artisanal miners in developing nations to meet obligations under new laws in industrialized nations regarding due diligence in supply chains and, thereby, support them in retaining their markets and incomes.

Keywords: interdisciplinary cooperation between geology and mining; transdisciplinary cooperation between geology and mining; exploration; mining; after mining stage; small scale and artisanal mining



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1. Introduction

In September 2015, the United Nations Sustainable Development Summit adopted the 2030 Agenda for Sustainable Development with 17 sustainable development goals (SDGs) at its core [1]. With the exception of water, none of the SDGs specifically address raw materials; however, none of them can be achieved without these. SDG 4, Quality Education, for example, is scarcely imaginable without a computer, which needs chips. A chip today contains more than 60 elements [2] derived from ores of deposits that must be mined, smelted, and processed. The procedure from mining to processing has to be executed in a manner that is as safe as possible for the environment and the social structure of mining communities, regions, and countries, and a precondition for that is thorough and comprehensive deposit knowledge and development knowledge. Resource efficiency can only be optimized with a solid understanding of all the pertinent characteristics of a mineral resource, including its likely environmental impacts [3], process alternatives, and potential consequences. Maximizing mined materials while at the same time minimizing their impact presents an ethical challenge.

To access a mineral resource, numerous disciplines must contribute and cooperate, from the exploration and discovery stage of a mineral that could become an ore deposit and, potentially, a mine to the feasibility and later exploitation stage. This should not be a hierarchic stepwise process whereby, first, the geologist does his/her job, then the mining engineer takes over, and, in parallel, the metallurgical engineer for the task of designing an optimal process plan. Instead, the process should be an interdisciplinary one where each discipline learns from another. Ideally, it should also be a transdisciplinary process through which praxis, i.e., industry, learns from science and vice versa [4,5]. This is

particularly true for raw materials in lenticular deposits, often in complicated geological environments and frequently difficult metallurgy, such as base metal and precious metal deposits. For such interdisciplinary and transdisciplinary interaction and cooperation, the term “geometallurgy,” coined in 1968 by McQuiston and Bechaud [6], has come to mean fruitful interaction in the fields of mineralogy and metallurgy. Geometallurgy, in sensu strictu, means “understanding the complex nature of an ore deposit and translating this information into means of enhancing mining and metal extraction while reducing energy and reagent consumption, and the impacts of tailings” [7–9]. The term has been extended, however, to include other aspects of mine development as the “initiative to integrate geological knowledge into mining operations in order to increase their efficiency and effectiveness, enhance return on investment, and create opportunities for sustainable development” [9]. Hoal and Frenzel (2022) [9] provide references to numerous case studies.

In the present article, the author concentrates on the fruitful cooperation between geologists and mining engineers to optimize exploration, the feasibility and mine design stage, the mining stage itself, and the postmining stage with the overall goal of increasing resource efficiency, i.e., an area of geometallurgy in the wider sense is contemplated. Since transdisciplinary cooperation is a collaborative, participatory learning process that involves exploration also takes time, it is advisable that such cooperation starts from the beginning.

This paper primarily considers cooperation between geology and mining in established and ongoing mining operations for base metals and precious metals on land. Looking to the future, we must also consider marine mining operations not yet realized in the deep sea. The planning and execution of such operations will create a special challenge for teams of geoscientists, engineers, and biologists. Deep-sea marine mining operations might become important, especially with regard to increased metal demand due to the green-energy transition (energiewende). The consequence of this transition is higher material intensity per energy or another relevant unit, i.e., we will see growing consumption, disproportionately higher, of certain metals and minerals [10]. A recent study by the International Energy Agency (IEA) in Paris examined increased consumption of the metals and minerals copper, lithium, nickel, manganese, cobalt, graphite, and rare earth elements; not considered were steel and concrete. For example, the IEA concluded that the production of electric cars uses about six times more of the considered metals/minerals than that of conventional vehicles per vehicle, or an on-shore wind plant requires nine times more mineral resources than a gas-fired power plant [10] (pp. 5, 89). Copper, nickel, manganese, cobalt, and rare earth elements, as possible by-products, can be mined from manganese nodules of the deep sea. Other base metals such as zinc and by-products such as indium and germanium can be exploited from massive sulfide occurrences at extinct black smokers in the deep sea [11,12]. The increased demand combined with cost pressures related to the urgency to internalize environmental and social costs might lead to a new price plateau for many metals, making marine mining economically feasible [13]. Thus far, no marine deep-sea mining activities are in operation. The International Seabed Authority (ISA), with headquarters in Kingston, Jamaica, is responsible for future deep-sea mining activities in international waters.

On its website, the ISA states that it “... is mandated under the UN Convention on the Law of the Sea (UNCLOS) to organize, regulate, and control all mineral-related activities ... for the benefit of mankind as a whole (e.g., Art. 1, 136, 137, 140, 150). (...) In doing so, the ISA has the duty to ensure effective protection of the marine environment from the harmful effects that may arise from activities in the Area (The Area is the space in the open international sea beyond national jurisdiction in which, under the jurisdiction of the ISA, mineral rights are reserved and exploration rights granted.) (Art. 145 and UNCLOS Part XII)”. In fulfilling this mandate, the Council and Assembly of the ISA are supported by expert advice and recommendations from the Legal and Technical Commission (LTC) [14]. Deep-sea areas are currently being explored, but mine-planning approaches are still under development. To minimize environmental impacts but enable economic exploitation, particularly intensive cooperation between geologists, marine mining engineers, and biologists

is critical in order to design mining methods and mine plans and schedules and provide technical advice to the LTC of the ISA as “recognized experts”.

Another question not addressed in this article is why the constructive cooperation of the geologist and the mining engineer is often missing. An in-depth analysis from a psychological and sociological perspective is beyond the scope of this paper. From the extensive experience of the author and knowledge of mines and mining companies, the company philosophy and operational style, in addition to the complexity of the orebody, have a significant influence on such cooperative relationships. In mines with simple geology, such as that found in many coal mines, the philosophy of mining engineers is that they believe they can solve the geological problem on their own.

2. Exploration Stage

Exploration is connected with high-level risks. For potential base and precious metals, the chances of success in the detailed reconnaissance and prospecting stages are 1:700 to 1:800. If a successful drill intersection has been obtained, the chance of having finally discovered a successful mine is only 1:16, and even if an orebody is outlined, the chance of it becoming a successful, profit-generating mine is only 1:2 (Table 1). These are long-term averages based on the evaluations of many exploration projects [15]. Therefore, in addition, as an element of resource and monetary efficiency in this early stage, exploration activities have to be executed as efficiently as possible. Based on encouraging results, exploration proceeds in steps to increasingly costly stages, at the same time decreasing risks, as displayed in Figure 1. How difficult it can be from a geophysical perspective to move, for example, from the stage of geophysical investigations to the stage of more expensive drilling has been discussed by Harvey (2018) [16]. One tool to improve exploration efficiency is to continuously establish milestones for reviews, especially economic reviews. Milestones are decision points for determining whether the exploration results justify a continuation of activities, depending on the likelihood that the minimum economic objectives can be reached. The further advanced a project is, the more expensive exploration will be, with more detailed drilling, beneficiation tests, or even underground exploration and bulk sampling, with milestones at each stage. For this purpose, order-of-magnitude economic calculations are necessary using the rule of thumb [17]. Every exploration geologist should be able to perform such calculations, but doing so requires a basic understanding of mining and milling methods so that the appropriate rule of thumb can be applied to the right calculation.

Table 1. Probability of an exploration project becoming a profitable mine in the second half of the 20th century [15].

1. Detailed Reconnaissance	2. Detailed Surface Prospection	3. Drill Target Identified	4. New Mineralization	5. New Mineralization with Some Tonnage	6. Orebody Outlined	7. New Ore Deposit (Mineable)
1:800	1:700	1:90	1:16	1:3	1:2	1:1

Geometallurgy can be especially helpful in the early stages once a sufficient sample of the mineralization—potential ore—is available, mostly through a discovery drill hole, supplying sufficient material not only to prepare thin sections but also to execute a laboratory test for hardness, i.e., the Bond mill work index [19]. With thin sections, the intergrowth of the ore minerals can be determined; thereby, the grain size of the ore has to be ground in order to achieve a reasonable recovery. Using the Bond mill work index and the predetermined grain size to which the potential ore must be ground, milling costs can be estimated within a certain range that is exact enough to perform order-of-magnitude calculations in the prefeasibility stage at milestones M_1 to M_n , shown in Figure 1. This example clearly illustrates the beneficial coaction of geoscientists and engineers ([17] pp.

104–105): the mineralogist characterizes the grain size and intergrowth, the metallurgist the hardness via the Bond mill work index. With these data, the metallurgist can determine milling costs, one element for the exploration geologist to make stepwise preliminary cost estimations at milestones M_1 to M_n , described in the following.

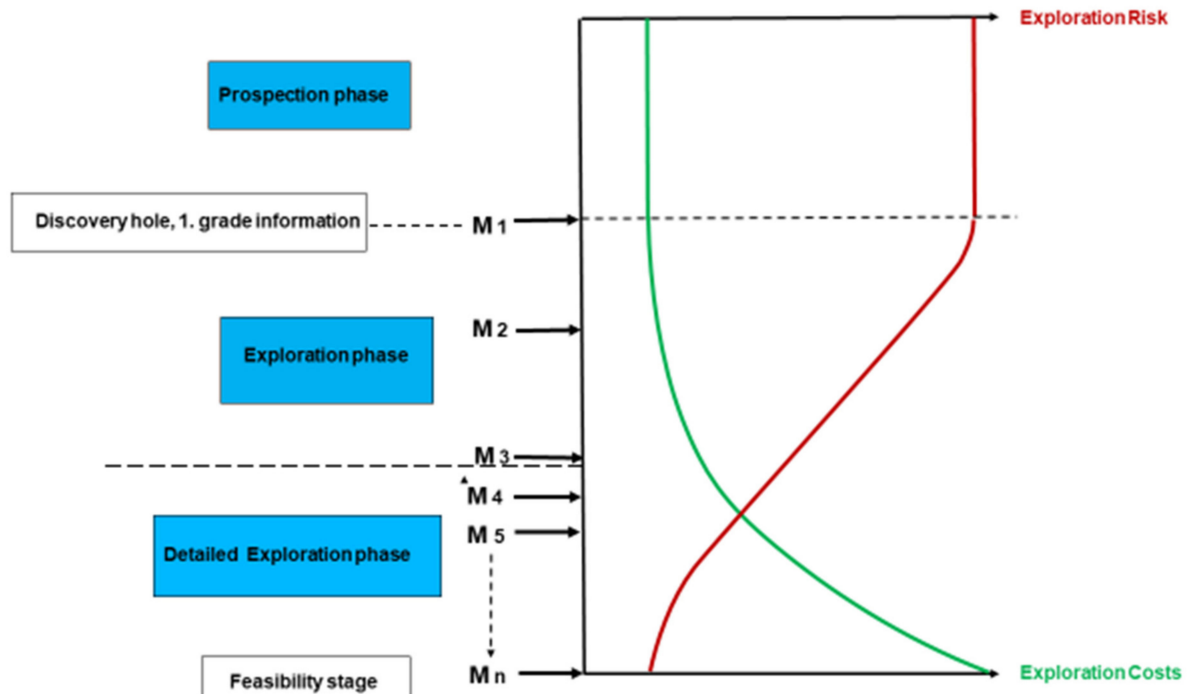


Figure 1. Progress of exploration with milestones, relative risks, and relative exploration costs [18] (with permission of Boletín Geológico y Minero).

Investment and operating costs are influenced by the economics of scale: with increasing capacity, the operating and specific investment costs decline. Figure 2 shows an example of operating costs for underground lead–zinc mines.

This shows that the exploration geologist needs not only an understanding of the mining methods to be applied later if the exploration is successful but also—and at an early stage—he/she needs to be able to derive an order of magnitude of the daily capacity of a hypothetical mining operation from the expected tonnage [21]. Taylor worked with reserves, and the exploration geologist can use the same equation for the expected resource.

$$\text{daily capacity in tons} = 0.014 \times \text{reserves}^{0.75} \quad (1)$$

Taylor did not distinguish between underground and open-pit mines. Taylor’s mathematical relationship was critically examined by Long (2009, 2016) [22,23], who concluded that there was a need to distinguish between more selective mining methods, i.e., underground mines, excluding block caving and mass mining methods, i.e., open-pit and block-caving mines.

Long [22] arrived at the following equations:

For open-pit and block caving:

$$\text{daily capacity in tones} = 0.123 \times \text{reserves}^{0.65} \quad (2)$$

For underground mines:

$$\text{daily capacity in tones} = 0.297 \times \text{reserves}^{0.56} \quad (3)$$

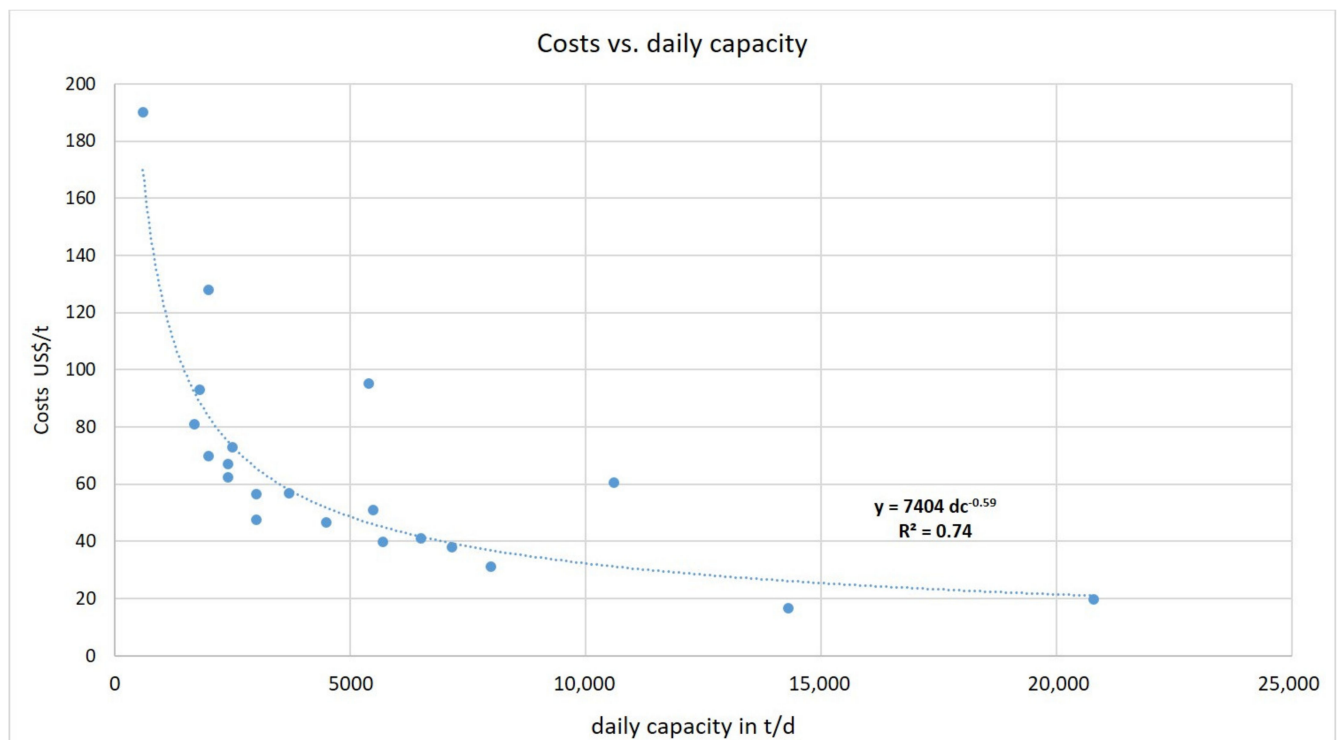


Figure 2. Operating costs as a function of daily capacity (dc) for underground lead–zinc mines (data source: [20]), [18] (with permission of Boletín Geológico y Minero).

A comparison of Taylor’s and Long’s relationships is given in Figure 3. It shows that for open-pit and block-caving mines, the optimal capacities are larger than those projected by Taylor for underground mines; however, the optimal capacities are significantly smaller. Wellmer and Drobe (2018) [18] tested these rules with actual data from mines established after 2011 and found good agreement with Long’s formula within an error of 10%, certainly within a range of error acceptable at the exploration stage for executing calculations by rule of thumb.

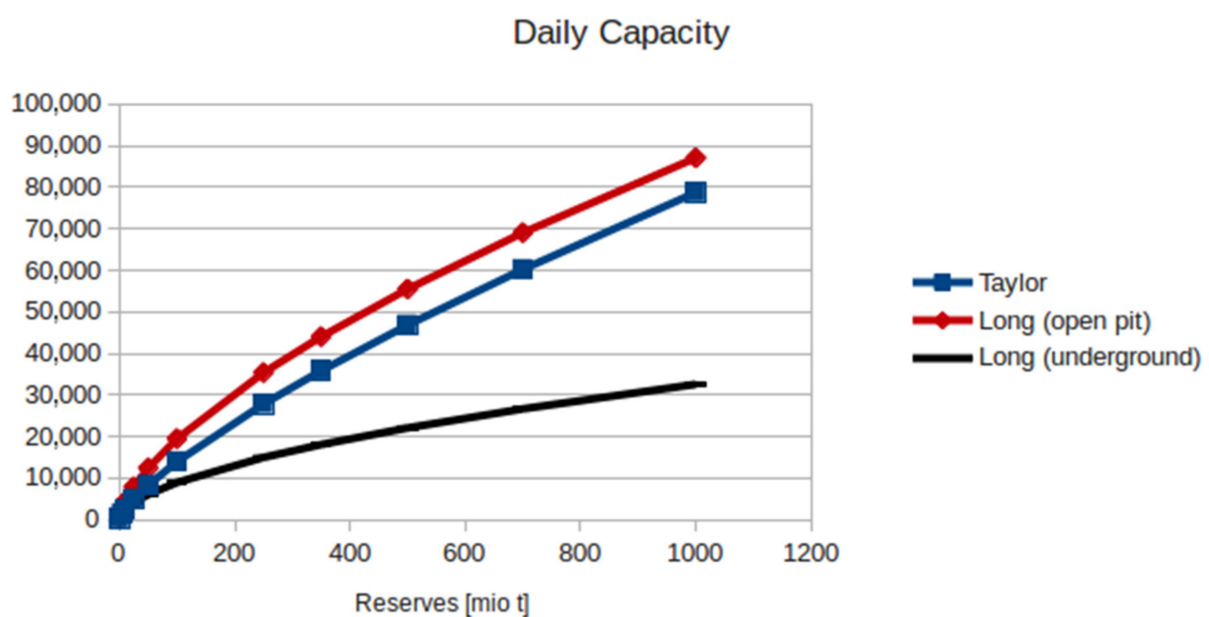


Figure 3. Comparison of Taylor’s and Long’s relationships between reserves and capacity [18] (with permission of Boletín Geológico y Minero).

This examination also shows that the exploration geologist should have interactions with the mining engineer at an early stage when the geometry of a potential orebody can be envisaged and the mining method determined in order to be able to use the appropriate equations for the geologist's milestone calculations.

3. Feasibility and Mine Design Stage

The procedure of applying geostatistical methods for an ore reserve calculation by geologists and supplying the mining engineers with a block model for their mine design is well-established. It uses, for example, Kriging and advanced Kriging methods such as the conditional geostatistical simulation of block compositions (e.g., [24–28]); thus, it is not discussed further in the present article. Frequently at this stage, bulk-sampling programs are undertaken to verify drilling results and, sometimes, to modify these results by upgrading or downgrading factors ([29], Section 11.3.2); this necessitates cooperation between mining engineers and geologists. In addition, when possible, at this bulk-sampling stage, the future mining method can be tested, such as selective mining in narrow gold-vein mining described below. The statistical problem requiring taking at least two bulk samples, one below the mean of the deposit and one above the mean, is explained in detail in Section 4.1, dealing with grade control.

Intensive interaction between geologists and mining engineers is necessary in order to design a method for minimizing dilution. Avoiding dilution with low-grade or sterile material and, at the same time, avoiding losses of ore reserves during exploitation is an ever-present problem (see, e.g., [30–32]). The amount of dilution is influenced by the shape of the orebody, the amount of internal waste, rock competency, and other factors. It makes a difference whether a vein is mined with well-defined straight foot and hanging walls, which can be mined with long-hole stoping, or an irregular ore shoot that has to be mined with a sublevel stoping method adapted to the irregularity of the orebody shape (Figure 4a,b).

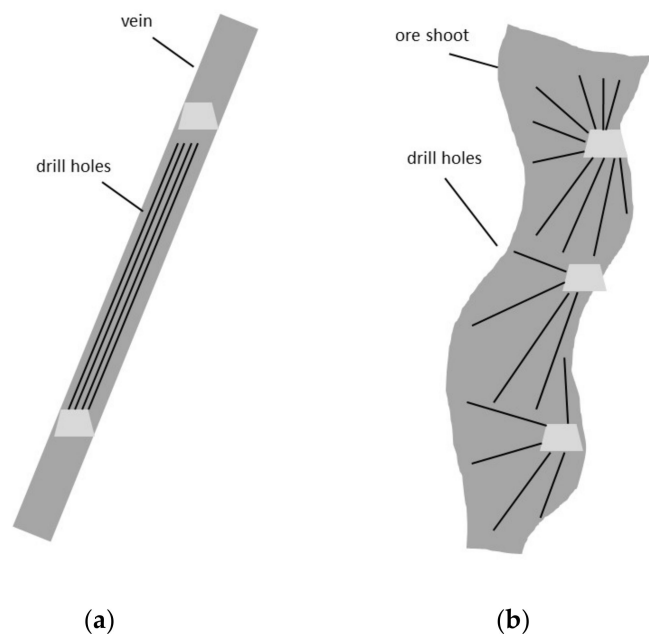


Figure 4. Schematic mining methods for (a) a narrow vein with clear hanging and foot walls and (b) an irregular ore shoot.

In open-pit mines, the rate of dilution is influenced by the number of contact areas between the ore and waste, as illustrated in Figure 5. For each case (compact orebody, ore blocks isolated in waste, waste block isolated in ore), there are 25 square ore blocks of length a . For case (a) compact orebody, there are 20 contact areas of length a ; in case (b) ore isolated in waste, there are 100 contact areas of length a ; and in case (c) waste isolated in ore,

there are 51 contact areas of length a . This is a significant factor if the cutoff grade has to be increased, for example, due to changing economics, and the orebody loses its cohesion.

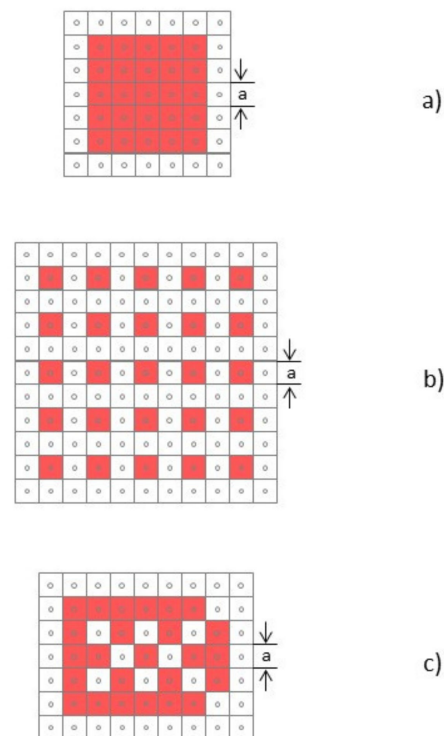


Figure 5. Three different types of ore deposits with respect to the relationship between ore and waste blocks: (a) compact ore body, (b) ore blocks isolated in waste, and (c) waste isolated in ore. Red: ore blocks above the cutoff, white: blocks below the cutoff [29].

A general rule of experience is that a large amount of geological and biological data is log-normally distributed [33]. Recent studies of more than 3000 well-explored distributions of 17 metals show that less than 10% of the grade distributions “fail to be fit by the lognormal distribution” [34]. Taylor (1972) [35] investigated porphyry copper deposits and was able to show that their grade distribution followed a log-normal distribution and, further, that the difference between the mined grade and the cutoff grade is a constant (Figure 6). David (1977) [36] (pp. 44–45) showed that this is a consequence of a log-normal grade distribution and a log-normal relationship between grade and tonnage. If, however, the internal waste problem becomes more severe (case c in Figure 5) or ore blocks become even more isolated in waste (case b in Figure 5), the dilution problem increases, and the grade development deviates significantly from the theoretical prediction (Figure 7), as experience has demonstrated. A geologist’s task is to alert the mining engineer about the behavior of the orebody in case the cutoff grade has to be raised and the sampling and mining procedures have to be changed and adapted.

Depending on the regularity or irregularity of the orebody, mining engineers and geologists must collaborate to design the appropriate drilling, sampling, and mining methods, selecting the appropriate mining equipment that makes the required selectivity possible. An extreme example is narrow-vein mining in open pits in Australia [29,37,38] (Figure 8); this is also a good example of how, through a continuing dialogue between geology and mining experts, the procedure is changed and improved. In the 1980s and 1990s, for sampling in oxidized, soft rock, it was common to use a Ditch Witch trenching instrument on lines 5 m to 10 m apart to a depth of about 1 m. High-grade and low-grade ore outlined using this method of sampling were then extracted by hydraulic shovel excavators (backhoes with a shovel width appropriate for the width of the ore zones), usually to a depth of 1.5 m, and then transported to two separate holding dumps. At the

holding dump, each truckload was sampled by two random grab samples. On the basis of the mean of these two samples, the truckload was classified either as ore and taken to the mill or as low-grade material and taken to the stockpile, where it could later be treated in the plant during periods of high gold prices. In most cases, the grade predictions based on the samples taken at the holding dumps correlated well with the yield from the mill. Experience from a gold-mining operation in Western Australia [39] showed that about 20% of the high-grade truckloads were reclassified at the holding dump as low-grade, and conversely, about 15% of the truckloads from the low-grade holding dumps were reclassified as high-grade and directed to the mill.

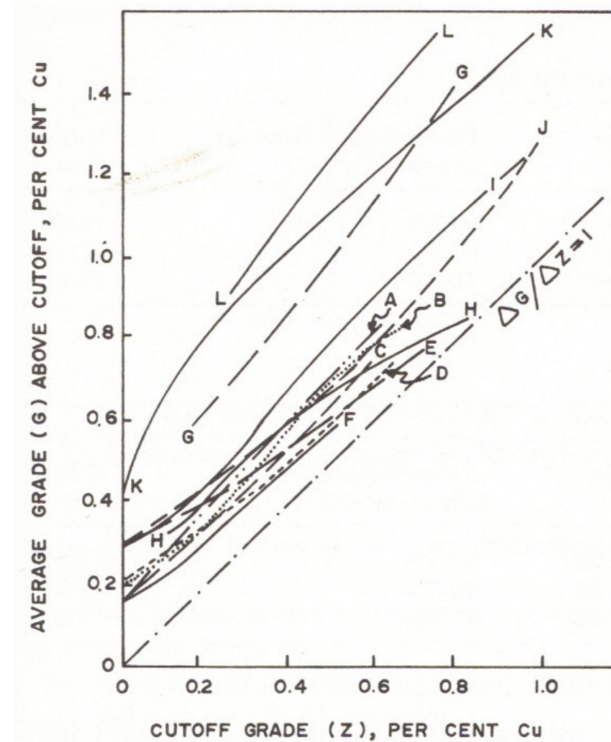


Figure 6. Average grade versus cutoff grade (bench height composited assays) for 12 North American copper prospects [35]. A–L are the 12 cases in the paper of Taylor [35].

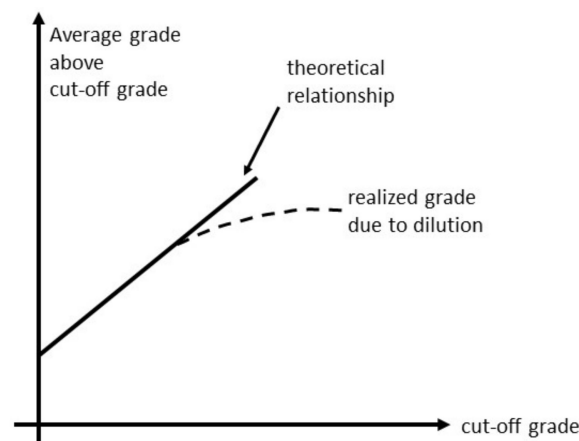


Figure 7. The theoretical relationship between cutoff grade and a grade above the cutoff grade, i.e., grade of run-of-mine (ROM) ore, according to Taylor (1972) [35] and David (1977) [36], and realized grade due to increasing dilution caused by raising the cutoff grade.

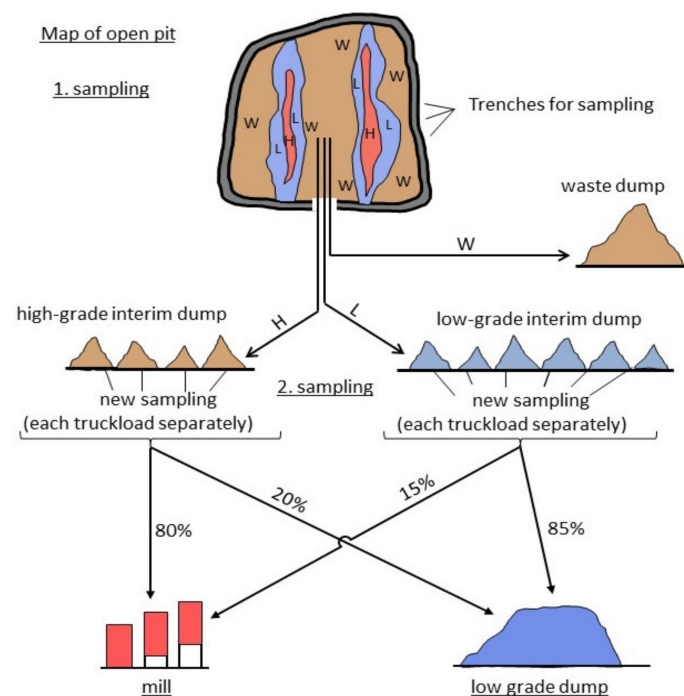


Figure 8. Principle of selective gold-mining open pits in Australia (after 29) (H = high grade ore, L = low grade ore, W = waste).

Later, Ditch Witch sampling was often replaced by Earth Saw sampling, a type of trenching equipment that could cut deeper and through harder rock [37] or, for example, reverse circulation drilling on a grid with inclined holes and experimented with using various grid and line spacings. According to the grade variability, truckload sampling was interposed or not [38]. Interestingly the lessons learned in grade control with reverse circulation drilling were also applied underground later to improve sampling in a complex underground operation [40].

The first case of sampling with the Ditch Witch (Figure 8) will be used to explain what happens during this sampling procedure from a statistical perspective. From the step of in situ sampling with a Ditch Witch [37,41] to the samples taken from the truckloads at the holding dumps, the support of the samples changed, meaning the variance was reduced. The quantities of the first and second samplings were approximately the same (2–3 kg). However, blending occurred as a result of the excavation, loading onto the trucks, and dumping onto the holding dumps; thus, the quality of the second sample was quite different. The variance of these samples was then much lower compared with the first set of samples. The lower the variance, the lower the probability of incorrectly classifying high-grade ore as low-grade ore and vice versa [29].

4. Mining Stage

In the mining stage, we distinguish two tasks of the mine geologist: the task of grade control and the task of finding additional ore; both require effective interaction with and the understanding of the mining engineer.

4.1. Grade Control

The statistical problem of grade control is that the blocks to be mined and the samples have different volumes, meaning different support. Figure 9 illustrates Krige's (1962) [24] classical investigation comparing mining blocks with samples in the South African gold-mining industry. If the sampling is properly conducted, the mean of the samples should be the mean of the blocks. However, because of the different support, below the overall mean, the group of samples is enclosed by blocks that have, on average, a higher grade than the

samples; above the overall mean, the group of samples is surrounded by blocks that have, on average, lower grades than the samples. This is theoretically explained in Figure 10. Therefore, the line of correlation between samples and blocks, KL in Figure 9, is lower than 45° . KL has been named by Wellmer (1996) [29] as the volume-variance comparison line or VVC line.

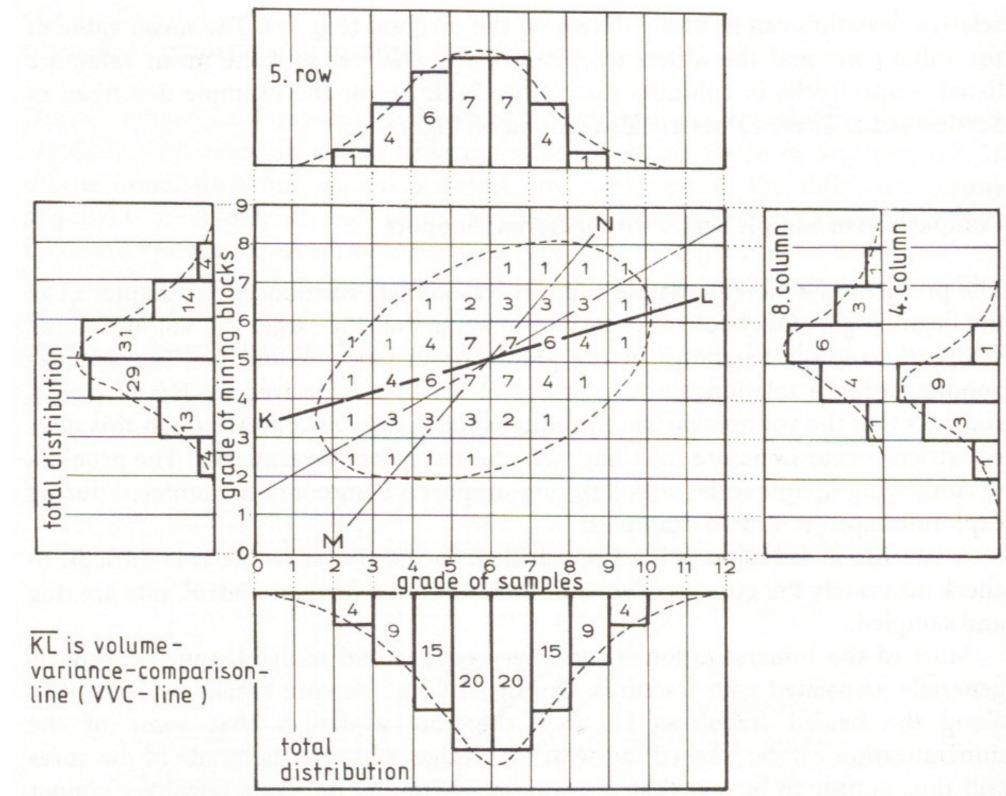


Figure 9. The classical Krigé diagram comparing mining blocks and samples from South African gold mining, illustrating the correlation between grades of samples with grades of corresponding mining blocks [24], with permission of the author, 1995; for use by Wellmer, 1996 [29]).

This understanding is critical for designing a bulk sampling and mining test program jointly between the geologist and mining engineer to determine the possibilities of selective mining and the reliability of drill programs with samples of lower support. The VVC line has to be determined, and a line is determined only by two points, i.e., at least two bulk samples are necessary, one above and one below the mean, to derive an upgrading (or downgrading) factor (Wellmer, 1996 [29], Chapter 11.3.2).

The challenge of grade control is explained in Figure 11 top and bottom figure). Taking Krige's (1962) [24] model from Figure 9 and applying a cutoff grade, four sectors in the ellipses of data of blocks and samples can be distinguished:

- Sector I: Correctly classified as economic; the blocks are mined as ore;
- Sector II: Incorrect classification since the blocks are classified as uneconomic (below the cutoff limit x_c) and are not mined, although their actual grades lie above the cutoff grade;
- Sector III: Correctly classified as uneconomic; the blocks are not mined;
- Sector IV: Incorrect classification since the blocks are classified as economic (above the cutoff x_c) and are mined, although they are uneconomic.

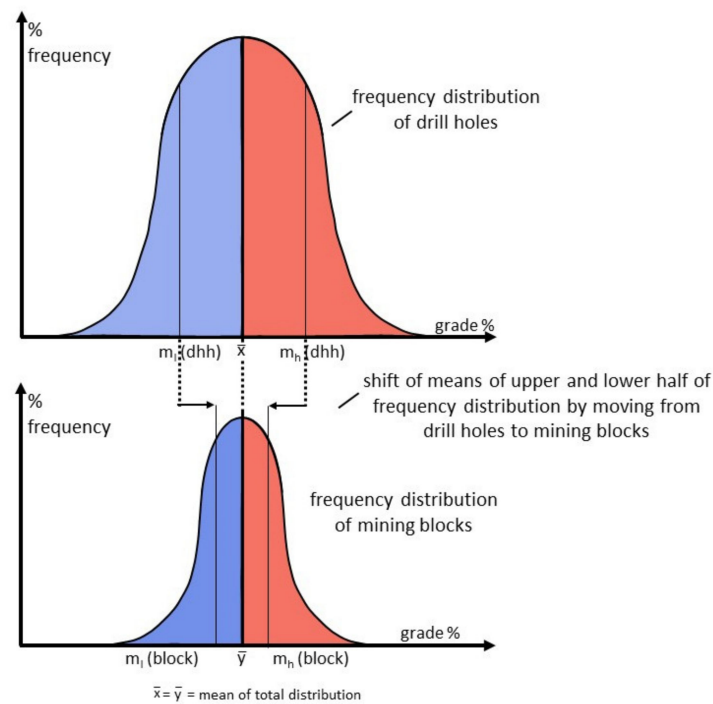


Figure 10. Hypothetical frequency distribution for drill-hole samples and corresponding mining blocks (from Wellmer, 1996 [29]). Because of the different support and larger variance of the drill holes than those of the blocks, the mean of the upper half of the frequency distribution of the drill holes, $m_h(dhh)$, is larger than the mean of the upper half of the blocks $m_h(blocks)$, and vice versa for the lower halves of the frequency distributions of drill holes and blocks, $m_l(dhh)$ vs. $m_l(blocks)$.

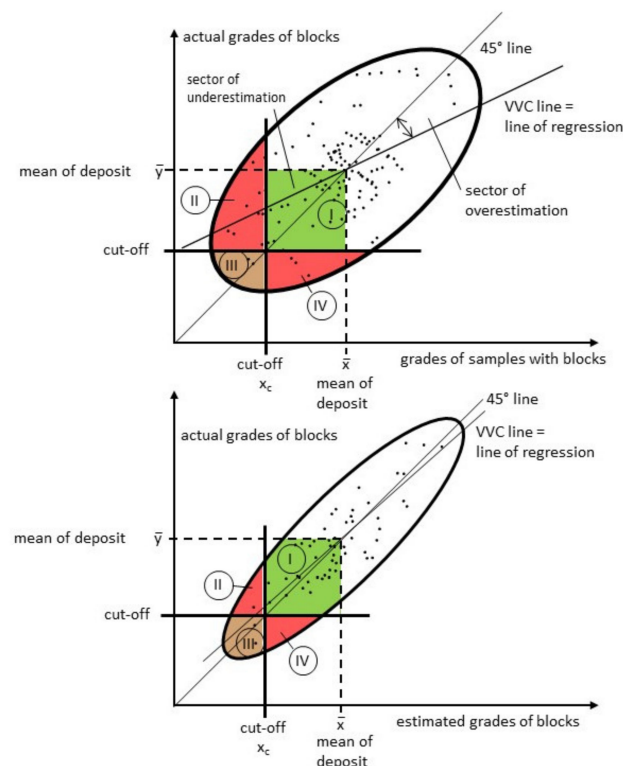


Figure 11. Ellipses of grade data of blocks and samples, the correlation between them, and the effect of the application of a cutoff grade x_c . Top: normal case, bottom: narrowed ellipse with the help of better grade-control methods.

The task of the geologists, with the help of geostatistical methods, is to narrow this ellipse (Figure 11 bottom) so that sectors II and IV of incorrectly assigned blocks become increasingly smaller (e.g., [26,42]). However, the sampling and the mining methods, i.e., the interactions of geologists and mining engineers, have an influence, as shown above with the example of narrow gold-vein mining in Australia. The more complex the grade distribution is, the more critical an effective interaction between geology and mining is. A good example is the former Mary Kathleen Mine, a low-grade uranium mine in Queensland, Australia, which had two operating phases from 1958 to 1963 and from 1976 to 1982 [43,44]. Prior to mining, the reserve grade was determined with 0.116% U_3O_8 . Finally, 9.2 million tons were mined with a production of 8882 tons of U_3O_8 , i.e., a recovered grade of 0.097% U_3O_8 [43]. The ore of the deposit consisted of lenses of allanite containing finely disseminated uraninite. At the beginning of the mining operation, the mine had experienced extreme grade-control problems. Finally, each blast hole was graded into six grade categories on the basis of averaging 1 m downhole measurements with a wireline scintillometer. Holes were then charged and blasted in a particular sequence to separate ore and waste in the blasted rock piles. The loaded trucks were then dispatched to a discriminator, i.e., a scintillometer, for further ore-grading prior to stockpiling ahead of crushing and subsequent radiometric ore sorting [44]. By following this procedure, the overestimation compared with the final recovered grade could be reduced to 7.8%. Other methods to optimize the grade of the ore and other chemical compositions influencing the beneficiation process of the run-of-mine ore by analyzing truckloads and determining the sequence of dumping and loading points have been described, for example, by Broicher (2000) [45] using the laser-induced fluorescence method.

A classical case history of considering not just one parameter but several is the geometallurgical grade control conducted at the Olympic Dam Mine in South Australia [46,47]. There, attempts were made to simultaneously optimize the recovery of copper, uranium oxide, acid consumption, net recovery, drop weight index, and the Bond mill work index.

Effective cooperation between the geologist and the mining engineer also helps to ease the daily conflicts between mine and mill, the conflict and tension caused by variations in the run of mine ore, and the possibilities of the mill to cope with variations in grade and other parameters such as the Bond mill work index, for example. The geologist can help the mining engineer keep variation at a tolerable level. An example is described in the next section.

4.2. Selective Underground Mining

In this section, two examples of how geologists and mining engineers can work together effectively to increase resource productivity and reduce the footprint of mining are provided. The first looks at the highly complex lead–zinc–silver mine, Song Toh in Thailand, owned by the Kanchanaburi Exploration and Mining Co. (KEMCO, Bangkok, Thailand), a subsidiary of the former German mining and smelting company Metallgesellschaft AG (Frankfurt am Main, Germany); Song Toh operated as an underground mine from 1979 to 2000 (Figure 12) [48]. Because of the intergrowth characteristic of the ore and the high-quality requirements for concentrates on the one hand, and on the other hand, the occurrence of mercury causing various penalties in the concentrates and limiting the amount of each concentrate type that could be accepted by the smelters, three concentrates had to be produced:

1. lead concentrate—good payment for lead and silver, progressively increasing penalties for mercury, a limited amount of concentrates acceptable by the smelter;
2. mixed lead–zinc concentrate—moderate payment for lead, silver, and zinc; moderate penalty for mercury, limitation of maximum mercury content and the amount of concentrates acceptable by the smelter;
3. zinc concentrate—good payment for zinc, moderate payment for silver, low penalty for mercury, no limitation in the amount of concentrates.

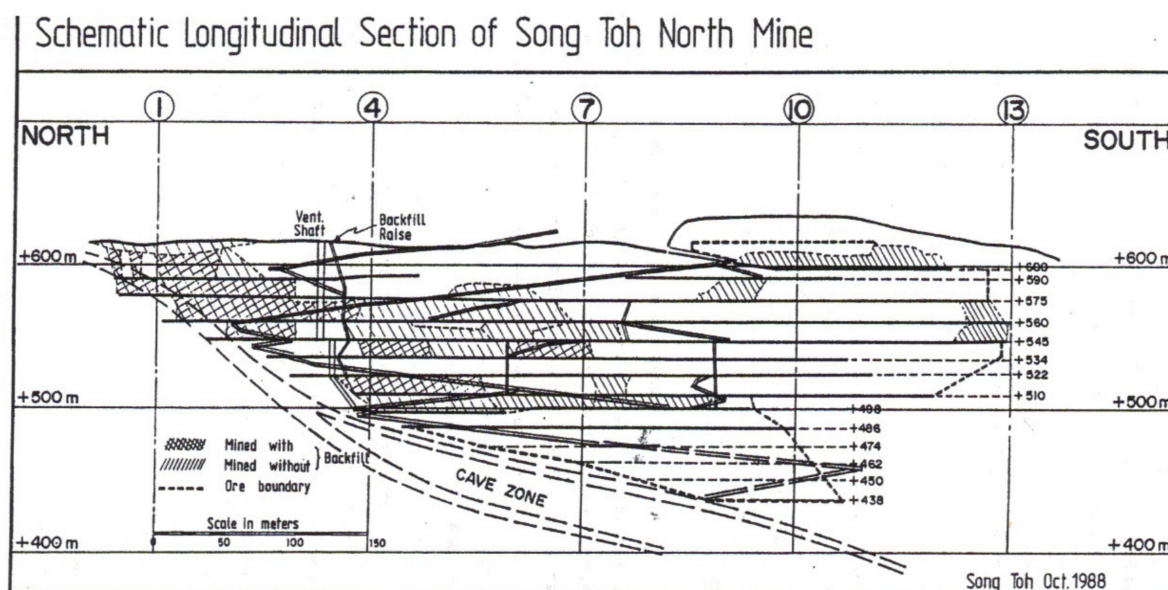


Figure 12. Cross section of the Song Toh Mine (status October 1988) (from [48] (with permission of the author).

To meet these quality and quantity limitation requirements, mining had to be quite selective; 20 to 25 stopes were in operation concurrently, and up to 40 ore dumps were needed for blending before the mixed run-of-mine ore could be sent to the mill. Figure 12 depicts how far spread out the mining sites had to be to enable the necessary quality control; the mining method was sublevel stoping. In 1989, the mine produced 350,000 t/a ore and 40,000 lead, zinc, and mixed lead-zinc concentrates.

The second example involves technologically advanced small-scale mines (SSMs), a category of mines that are often small deposit mines [49,50]. These must be clearly distinguished from small-scale artisanal mining (ASM), which will be discussed in Section 6. The SSMs produce in the order of 100,000 t/a or less, and typical examples are fluorite and barite vein mines. In this category, Moore et al. (2020) [50] included mines based on small deposits of antimony, rare earth minerals, tungsten, cobalt, and bismuth—commodities not required in large quantities such as the bulk metals iron or bauxite (aluminum), for example, or the classical base metals copper, lead, and zinc. These SSMs in industrialized countries like Germany are often highly mechanized and technologically well-advanced; an example is the Clara Mine for fluorite and barite near Oberwolfach in the Black Forest [51]. In addition, they serve as good test grounds for attempting to minimize mining's footprint. Economics of scale do not matter; an example could be not blasting underground waste material and ore at the same time but rather discriminating at the mining stage so that waste is left underground and, thus, does not have to be separated on the surface. Whereas in open pits, there is ample space, this is not the case underground; discrimination has to be accurate. This can be achieved using a reconnaissance vehicle equipped with sensors, hardware, and software for artificial intelligence and the automatic recognition of ore and waste. This, of course, requires the input of the geologist to “train” and control the vehicle [52]. This method can also be applied to continuously update a mine block model [53], a system that can also be applied to open pits [54] and blending stockpiles [55].

4.3. Further Exploration during the Exploitation Phase

During the exploitation phase, every responsible mine manager will attempt to extend the life of his/her mine. Therefore, the mine geologist will have the task of organizing an exploration program. This requires cooperation between the geologist and the mining engineer so that, in the development plan, the necessary drifts for drill locations are included. Depending on how far the manager is oriented toward purely economic thinking

or takes other aspects into consideration, a conflict of interest is possible (Figure 13). Today, the standard is for a project to be evaluated with dynamic economic assessment methods, taking into account the time value of money (TVM), such as the discounted cash flow (DCF) or internal rate of return (IRR) methods [17]. Discounting has the effect that the later the cash flow is achieved, the lower the present value is, thereby motivating the mine's manager to exploit an orebody as rapidly as possible. The geologist, however, needs time; exploration is a continual learning process, and learning always takes time. The longer the time span for learning, the higher the chances are of finding additional reserves. This presents a dilemma: Should one extend the operational lifetime of the mining operation in the expectation of additional reserves, or is it better to speed up the extraction process from the start-up of the mine in the interest of economic efficiency (Figure 13)? The result of exploration in and around a mine is normally a growth of the reserves. Cranstone (1988) [56] defined growth rates for specific ore types that were further refined by Wagner (1999) [57] when examining the question of what the optimal lifetime of a mine is under the aspect of time for learning [57,58]. Wagner (1999) [57] obtained the following multiplier factors; these are factors that the initial reserves have to be multiplied by in order to arrive at the final reserves, i.e., the growth rates. These are 1.6 for porphyry copper deposits, 1.8 for Mississippi Valley-type lead–zinc deposits, and 3 for volcanogenic base metal deposits. Earlier, Cranstone (1989) [56] had arrived at somewhat different factors: 2 for porphyry copper, copper–molybdenum, and molybdenum deposits; 2 for nonporphyry, nonvein base metal sulfide deposits (excluding nickel–copper deposits); 3 for vein deposits of gold, silver, and other metals; and 1.3 for nickel–copper deposits (other than those at Sudbury, Ontario, and the Thompson Nickel Belt in Manitoba). Regardless of the true multiplier factors, one result of Wagner's (1999) [57] study is quite remarkable: the critical point is arrived at when 60% of the initial reserves have been mined. This is the tipping point of a learning curve. In the studied cases, which are mostly from Canada, the reserve growth started at this point on average (Figure 14). Translated into the relationship between a mining engineer as a mine manager and a geologist, the mine manager has to understand this aspect and be prepared to be patient to have any chance of extending the lifetime of his or her mining operation. Time cannot be substituted by money, and a convincing example of this comes from petroleum exploration in Germany. Before and during World War II, Germany tried to mobilize every drop of oil to fuel its war machine. All means necessary—money, equipment, manpower—were available, yet the peak production was not achieved until 1968—23 years after the end of the war [59].

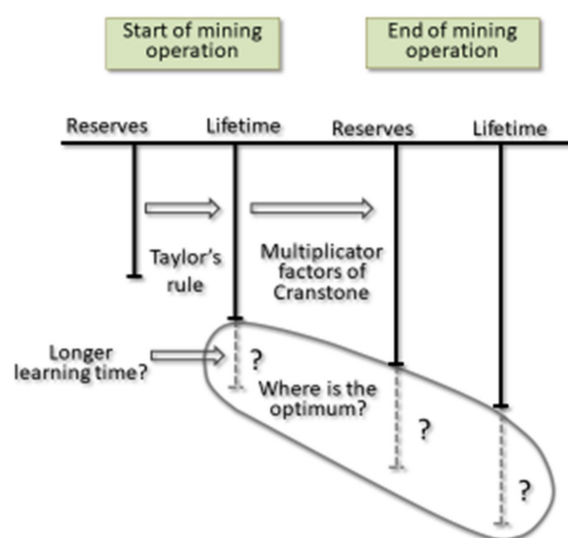


Figure 13. Schematic diagram: What is the optimal lifetime of a mine, taking into account learning effects? The vertical bars represent the sizes of reserves and lifetimes at the start and end of a mining operation [60].

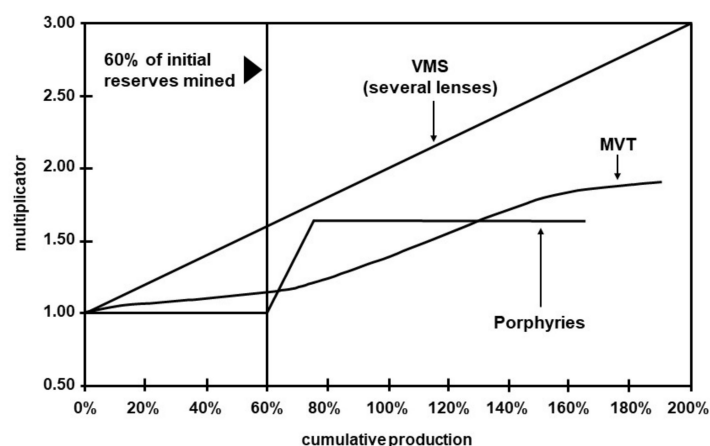


Figure 14. Development of reserves growth over time for porphyry copper deposits, Mississippi Valley-type lead-zinc deposits (MVT), and volcanogenic base metal deposits (VMS) (translated from Wagner, 1999 [57]).

5. Waste Management

In the introduction, it was stated that today's mineral resource development requires a comprehensive knowledge and solid understanding of all the pertinent characteristics of a mineral resource, including its likely environmental impacts [3]. Such an all-encompassing view should incorporate not only the ore but also waste rock from development work and, of course, the tailings after the beneficiation steps. For example, the geologist should have in mind how every product coming out of the mines can be used, not only out of the stopes but also from development work, which may be used, for example, in the construction industry, i.e., waste can be transformed into a commodity. Therefore, the geologist should consider the resource efficiency of every piece of rock that is mined. Examples of mines that utilize nearly everything can be found, one being the abovementioned fluorite and barite Clara Mine near Oberwolfach in the Black Forest, Germany ([61] p. 63). This mine demonstrates how mining can operate with minimal impact on the local environment, even in a sensitive scenic landscape. Practically all waste material is used either as a backfill, in road construction, or other applications.

Tailings are typically used underground to backfill mined-out spaces for stabilizing the mine and to provide the basis to be able to mine the next slice in a steeply dipping orebody, for example, with the cut-and-fill mining method shown in Figure 15. The example is from the Bad Grund Mine, exploiting a steeply dipping lead-zinc-silver mine in the Harz Mountains of Germany. The mine closed in 1992 after operating continuously for about 160 years. In the latest mining stage, the cut-and-fill stopes used load-haul-dump (LHD) equipment and concrete backfill with the coarse tailing fractions. Another example is the Lisheen Mine for lead–zinc, which closed in 2016. Here, 70% of the mining used efficient long-hole stoping. For about 20%, a drift-and-fill mining method was applied in areas where the host rock's strength was poor. A certain tailing fraction was used to produce a cement paste to fill mined-out portions of the deposit. Using this procedure, the structural integrity of the host rock could be maintained to allow mining to continue and to use the resource to its fullest extent [62]. When tailings cannot be used because they are too fine, the geologist, in collaboration with the mining and geotechnical engineers, has to find the appropriate foreign material close to the mine to prepare a suitable backfill. Such an example is the Rammelsberg Mine in the Harz Mountains, which closed in 1988. In operation for more than 1000 years, it mined a massive sulfidic sedimentary exhalative (SEDEX) copper–zinc–lead–silver orebody. The last mining method used was a room-and-pillar system with concrete backfill to mine pillars as well. The foreign material came from a nearby slate quarry [63].

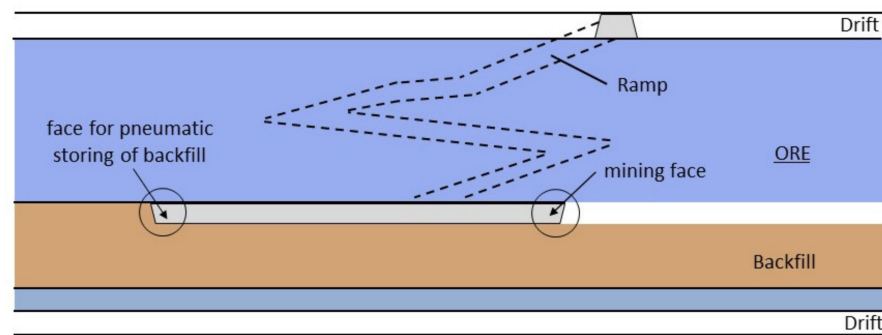


Figure 15. Longitudinal section: cut-and-fill mining with concrete backfill at the Bad Grund Mine for lead–zinc–silver in Germany (after Bartels, 1992 [64]).

Another example of utilizing tailings is related to the necessity to continuously raise the height of the dikes of the tailings dams during the operation of a mine (Figure 16). The first stage of the tailings pond starts with a dike of borrowed foreign material (starter dam). After filling this first pond stage with tailings material, the next dam is constructed using the coarse material from the tailings that have settled out close to the tailings discharge points (particle segregation), and so on with each subsequent lift of the tailings pond. This requires thorough and comprehensive interaction between geoscientists and engineers, particularly geotechnical engineers, to test the extent to which tailings are suitable or must be used in connection with other dike materials. Catastrophic dam failures such as the 2019 disaster in Brazil (Córrego do Feijão iron ore mine), the Mariana dam disaster (also in the Brazilian iron-mining industry) in 2015, or the dam breach in Spain in 1998 (Los Frailes Mine) demonstrate the need to use extreme caution when building dikes for tailing dams as well as the high level of responsibility of the professionals involved. This prohibits them from disregarding any advice from external actors and disregarding any detail [61].

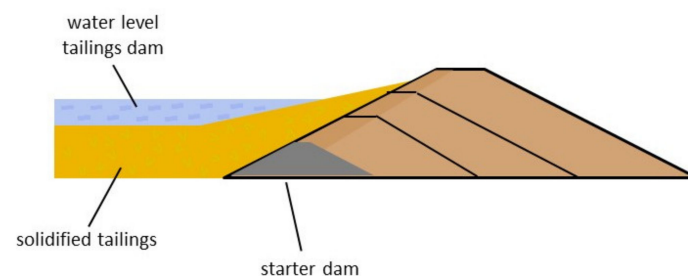


Figure 16. Schematic diagram of the structure of a tailings dam.

A particular problem involves concerns about the tailings after the mine has been closed and avoiding damage to the environment, due mostly to acid mine drainage (AMD). This is considered one of the major environmental challenges facing the mining industry worldwide [3,65]. The legacy accrued by historical mining activities is tremendous. Likely, the costs for AMD mitigation are estimated at AUD 300 million for Australia, USD 1900–5300 for Canada, USD 900 million for Sweden, and USD 32,000–72,000 million for the US [3]. For the most part, these costs are related to abandoned and orphaned mining and tailing sites, meaning the former mine owner and the operator can no longer be held responsible, and the taxpayer is responsible for the clean-up costs [66]. The challenge to prevent such neglect from recurring in the future calls for legal precautionary measures such as bonds and pooling state of the art and current knowledge of geoscientists and engineers, in addition to the most effective level of cooperation between science and practice, i.e., interdisciplinary and transdisciplinary groups. Such measures should be explicitly integrated to identify the optimal solution for care and management after mine closures and address repairs to orphaned sites. This is geomaterials in the broadest sense

of the term. Every mine produces its own unique waste requiring its own characterization, prediction, monitoring, treatment, and secure disposal [65].

In addition to the chemical pollution of AMD, there is the physical problem of the masses of waste and old tailings, remnant holes of open pits, and subsidence of abandoned underground mines. In regard to waste dumps in countries like Australia, mine owners, for example, are legally required to landscape the contours of waste dumps to fit into the general impression of the scenery in the area. It is surprising that after one of the worst human disasters in post-war Britain, the Aberfan disaster in South Wales in 1966 (a tip of dumped coal mine waste collapsed on a school building killing 140 people, mostly school children), it was discovered in a public inquiry that so far only in parts of Germany and South Africa there were any laws governing mine tips and their structure ([67] p. 392).

An especially challenging task has been, and still is, the recultivation and greening of tailing piles from potash and rock salt mining in Germany. Germany still is the fifth largest potash producer in the world [68]. Inter- and transdisciplinary teams of mining and geotechnical engineers, geoscientists including soil scientists, agricultural specialists, and botanists were created about 50 years ago to develop new technologies for greening salt dumps (Figure 17) [69,70].



Figure 17. Salt dump Wathlingen, about 30 km NE of Hannover/Germany, in the early stage of recultivation [70], with the permission of K + S Baustoffrecycling GmbH.

After German reunification in 1990, the eastern region of the country became a large experimental area for the reclamation of derelict mining sites of uranium and lignite. The former German Democratic Republic (GDR) was the largest lignite producer in the world and the fourth-largest uranium producer [71]. A number of new technologies had to be developed in a cooperative effort between geologists, soil scientists, and mining and geotechnical engineers, making the former GDR a role model for successful reclamation and, in the process, creating, for example, large lakeside areas attractive as recreational landscapes [72–75].

6. Artisanal and Small-Scale Mining

Artisanal and small-scale mining (ASM) have been defined by the OECD (2016) [76] as “formal or informal mining operations with predominantly simplified forms of exploration, extraction, processing and transportation, which is normally low capital intensive and uses high labour-intensive technology”. They must be clearly distinguished from advanced small-scale mines (SSMs), often applied to small deposits, as discussed in Section 4.2.

For some commodities, artisanal and small-scale mining not only plays a significant role in the worldwide supply (Table 2)—in 2017, it offered 40.5 million people a direct opportunity to earn a living [77]. This compares to only 7 million working in industrial mining in 2013. Considering the multiplier factor, i.e., the number of people depending indirectly on ASM, the number is estimated to be 150 million. In Africa, 40–50% of the ASM workforce are women [73]. It has been estimated that ASM makes a significant contribution to informal economies in as many as 55 countries [49,78,79]. The economic importance of mining in general for the economies of some developing nations is shown in Tables 3 and 4, in Table 3 for some countries with only an insignificant share of ASM, and in Table 4, the same statistical figures are shown for countries with an ASM share between 20 to <30% and 10 < 20%. So, the relevant importance of mining for the economy of many developing nations is much higher than even for the classical industrialized mining and mineral export countries Australia and Canada. For Australia, the relevant figures (share of GDP, share of exports) are 10.2/39.1, and for Canada, 2.9/9.1 [80].

Table 2. Approximate share of world production originating from ASM (sources: [77,79,81,82]).

Commodity	Estimated Share from ASM
Cobalt	10%
Gold	25%
Diamonds	20%
Sapphire	80%
Silver	7%
Tantalum	26%
Tin	25%
Tungsten	>6%

Table 3. Contribution of raw materials to the economies of selected developing nations with an ASM share of less than 5% for 2019 (source [79,80]).

Country	Mineral Raw Material Contribution to Gross Domestic Product	Mineral Raw Material Contribution to Exports
Botswana	19.2%	91.7%
Bolivia	12.1%	45.7%
Brazil	4.8%	7.3%
Chile	19.8%	53.4%

Table 4. Contribution of raw materials to the economies of selected developing nations with ASM share between 10% and 30% for 2019 (source [79,80]).

Country	Share of ASM in Mineral Production	Mineral Raw Material's Contribution to Gross Domestic Product	Mineral Raw Material's Contribution to Exports
Eritrea	20 to <30%	28.7%	42.2%
Central African Rep.	20 to <30%	0.6%	15.8%
Sierra Leone	20 to <30%	9.7%	50.8%
DR Congo	10 to <20%	42.4%	80.4%
Mongolia	10 to <20%	25.8%	45.3%
Zimbabwe	10 to <20%	18.8%	54.3%

International mineral supplies from small-scale and unregulated artisanal mining have come under sharp criticism worldwide for using child and forced labor and unsafe mining conditions. Examples include coltan mining in the Kivu Province of the Democratic Republic of Congo (DRC) as a source for tantalum, which is necessary for capacitors in many applications such as mobile phones, and the Copperbelt region of the DRC as a

source for cobalt, necessary for lithium ion batteries for electric mobility. ASM can also be used, especially in many African countries and regions such as the eastern provinces of the DRC, as a source for financing rebel armies, which have been known to forcibly recruit and use child soldiers (e.g., [81]). Responsible sourcing and due diligence concepts, therefore, are required. The due diligence concept for ASM was originally developed for the so-called conflict minerals—tin, tungsten, tantalum, and gold—defined in the US Dodd–Frank Act as related to conflict financing in the DRC [83]. The “conflict minerals” provision—commonly known as Section 1502 of the Dodd–Frank Act—requires US publicly listed companies to check their supply chains for tin, tungsten, tantalum, and gold to determine whether they might originate in the DRC or its neighbors, and to take steps to address any risks they find and file a report in regard to their efforts. Other countries are enacting laws whereby companies are responsible for controlling the supply chains [84]. In Germany, the Act on Corporate Due Diligence in Supply Chains was officially published on 22 July 2021 and will take effect on 1 January 2023 [85]. The law mandates companies with offices in Germany to conduct due diligence in regard to their supply chains to protect human rights and the environment in global supply chains, regardless of the location in the world. This applies to every industry and supply chain, not only mining but also, for example, textiles. Consequently, it is of great significance for ASM to be audited in order to keep its market share. Here, the cooperation of geologists and mining engineers can be significant, with mining engineers looking after safe and social mining conditions and geologists providing methods, for example, for tracing the ore or concentrate to audited mining sites, thus helping artisanal miners to maintain their markets and, thereby, their income. The German Federal Geological Survey BGR developed a fingerprinting method to trace the conflict mineral columbite-tantalite (“coltan”) back to mining localities, thus contributing to distinguishing legal from illegal mining operations [81,86].

There is another aspect where geologists and mining engineers can cooperate fruitfully to enable a peaceful coexistence of industrial mining and ASM. The ASM/large-scale mining relationship is often conflictual because both types of miners compete for the same resources or because they perceive each other as a threat [77,87]. Under the imperative of corporate social responsibility (CSR), creative solutions can be found. ASM zones could be outlined where small-scale miners can undertake mining gleaning activities on dumps or ASM small zones that are not lucrative for machine mining, e.g., small irregular gold veins [88]. Similar to the continuously occurring dilution of the ore by the waste in industrial mining, there is always—and inevitably—the complementary effect that some ore goes into the waste and upgrades it. In addition, there is the fact that ore can be erroneously classified as waste (see Sector II in Figure 11 top and bottom).

7. Conclusions

The interaction between miners and geologists should not be hierarchic but true, interdisciplinary and transdisciplinary cooperation through all stages, from exploration through exploitation and after mine closure to the post-mining stage. Through this continuing interaction, each side can learn from the other, efficiency can be increased, recoveries maximized, and losses minimized:

- In the exploration stage, the geologist has to grasp the relevance of rules of thumb for investment and operating costs in order to optimize these stages and arrive at the correct go/no-go decisions at every milestone. Similarly, in the production phase, the mining engineer has to understand the learning curve of exploring a deposit in production in order to identify the optimum between profitability and the lifetime of the mining operation;
- In the feasibility and mine design stage, close cooperation is essential in order to minimize losses and dilution.
- In the mining stage, interaction must continue to realize the estimated grade as closely as possible. The more complex the orebody and the more selective the exploitation, the closer this interaction must be;

- Geological and engineering aspects must be considered in order to minimize the environmental effects of managing waste and the potential effects of the mine site following its closure;
- Artisanal and small-scale mining (ASM) in developing countries, which provides work for many more people than industrial mining, is coming under increasing pressure due to the requirements of industrialized consumer countries to improve social and environmental standards along the trading chains. Here, geologists and mining engineers can assist jointly with audits to enable ASM to find markets for its production. They can also help diffuse the frequent tension between industrial mining and ASM and help determine strategies for their peaceful coexistence.

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