

Pre-mining Characterization of Ore Deposits: What Information Do We Need to Increase Sustainability of the Mining Process?

Bernhard Dold

SUMIRCO (Sustainable Mining Research & Consultancy), Chile

ABSTRACT

The efficiency of the metallurgical process can be increased by the incorporation of mineralogical data during the process. Moreover, mineralogy plays a key role in the efficiency of biomining operations and is necessary to predict the formation of acid mine drainage. Decision making in mining operations is currently mainly based on element concentrations (e.g. ore grade, cut-off, acid base accounting) assuming mineral associations of these elements (often with or without sufficient mineralogical data). This can lead to inefficiency of the mining process and environmental problems. Standard prediction methods for acid mine drainage are not accurate enough and there are no methods available, for example, to predict the stability of mine waste under reducing conditions as would apply to submarine tailings disposal (STD), a tailings management strategy that is seeing a revival in the mining industry. To overcome these problems, advanced methodologies have to be applied to characterize new ore deposits before exploitation starts. This approach gives the opportunity to design optimized processes for efficient metal recovery of the different mineral assemblages in an ore deposit and at the same time to minimize the future environmental impact and costs for mine waste management. Additionally, the whole economic potential is evaluated including strategic elements such as rare earth elements (REE). The methodology should integrate high-resolution geochemistry by sequential extractions and quantitative mineralogy in combination with optimized kinetic testing (oxidizing or reducing conditions, depending on the final waste deposition environment). The resulting data set allows the identification of units with similar geochemical behaviors in the ore deposit and to predict the behavior of each economically or environmentally relevant element throughout the mining process and in the final deposition site.

Keywords: process efficiency, acid mine drainage, prediction, geometallurgy, biogeometallurgy

INTRODUCTION

Metal mining is the base industry for the technological development of human society. However, metal mining has not always been very efficient in processing and has had many environmental problems associated. Therefore, it is necessary to predict and improve the efficiency of the mining process from the beginning of an operation through to the final closure plan including waste management and environmental protection (Dold and Weibel, 2013). Together with a social license to mine, these are the basic goals needed to achieve a more sustainable mining process (Dold, 2008; Dold and Weibel, 2013). Most of the problems concerning efficiency of the mineral processing is based on the use of incorrect parameters for decision making during mine operation, and also for the prediction of environmental problems such as acid mine drainage (AMD). This work highlights the problems associated to today's mining process and suggests a methodology to predict the geochemical behavior along the flow-path of the mineral during the mining process (Figure 1).

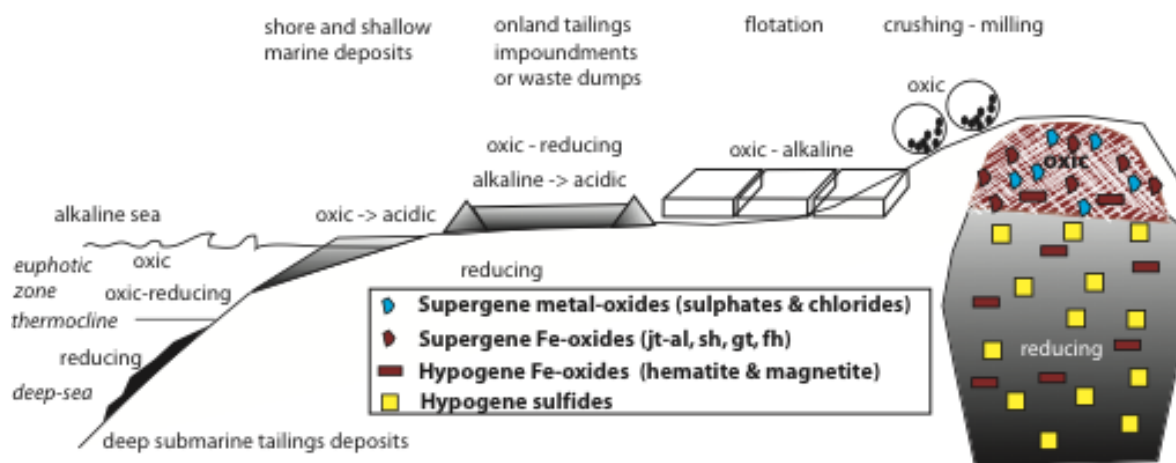


Figure 1 Overview of the flow path of the form the ore deposit with its different mineral associations through the mineral processing and the final mine waste deposition and the geochemical regimes in the different compartments of the process.

Currently, decision making is mostly based on element concentrations (e.g., cut-off grade, and acid-base account), but the metallurgical processes depend on the interactions between mineral surfaces and reagents, for example the flotation process and biomining operations (Dold, 2014b). For example, chalcocite is not acid leachable and it also is not efficiently oxidized by bacteria below 50°C, so that in most large scale bioleaching operations (dump leaching), chalcocite is not efficiently oxidized. However, this mineral responds well to flotation. In contrast, the presence of covellite and chalcocite in the mineral assemblage lowers the recovery of copper in the flotation, but these minerals are easily acid leachable (Dold, 2014b). Therefore it is crucial to know which minerals are sent to which processes in order to ensure the highest possible recovery rates. This goal is only possible if the mineralogical information is available.

The same is also true for acid mine drainage prediction, where currently very simple and mostly unsuitable tests are used to predict if a material will produce acid drainage and release certain elements into solution. Here, element concentrations such as from sulfur are also calculated as pyrite equivalent for the acid potential and a titration is used to calculate the neutralization potential. However, there are many other sulfide minerals that produce less acidity than pyrite and some even produce no acidity. On the other hand there are carbonates, such as siderite, that may even produce acidity due to hydrolysis of the iron ion. Iron hydroxides, such as ferrihydrite and goethite, and hydroxysulfates, such as jarosite and schwertmannite can acidify the system due to their dissolution chemistry (Alarcon et al., 2014). Thus, mineralogy is similarly key for the correct prediction of acid mine drainage (Dold, 2010).

Therefore, an advanced mineralogical and geochemical approach is suggested in order to predict accurately the behavior of the mineral assemblage throughout the mining process towards final deposition of the waste material.

METHODOLOGY

In order to predict accurately the geometallurgical, metallurgical, bioleaching, and environmental behavior, quantitative mineralogy is needed. This information allows for the possibility of predicting the behavior of the material in the comminution process (e.g. crushing, milling and flotation); during hydrometallurgy in the bioleaching process, or for the accurate prediction of acid mine drainage formation (acid-base accounting). Today advanced technologies are available for automated mineralogical analysis such as QEMSCAN® or MLA. If thoroughly calibrated with the ore mineralogy, these techniques give an accurate quantification of the complete mineral assemblage, degree of liberation, as well as grain size distributions, all of which are important to increase the efficiency of the extraction process. For example in case of the Andina Mine (CODELCO), the utilization of this information could increase the recovery by 2 % (Cruz et al., 2012).

However, this methodology does not give information on trace element associations to specific minerals or mineral groups. This information is crucial to predict if a certain contaminant may be liberated from its host mineral, or to develop a methodology for recovery of economically valuable trace elements such as rare earth elements (REE). Therefore, the mineralogical data are combined with high-resolution geochemical data from a seven-step sequential extraction procedure developed for the primary and secondary mineralogy present in typical porphyry copper deposits (Dold, 2003). These seven steps are as follows: step 1 liberates the water-soluble fraction (1.0 g sample into 50 mL deionized H₂O shake for 1 h at room temperature (RT)), step 2 liberates the exchangeable fraction (1 M NH₄-acetate, pH 4.5, shaken for 2 h, RT), step 3 addresses the Fe(III) oxyhydroxides fraction (0.2 M NH₄-oxalate, pH 3.0, shaken for 1 h in darkness, RT), step 4 dissolves the Fe(III) oxides fraction (0.2 M NH₄-oxalate, pH 3.0, heat in water bath 80 °C for 2 h), step 5 (35 % H₂O₂ heat in water bath for 1 h) dissolves organic matter and supergene Cu sulfides and partly primary sulfides, step 6 (KClO₃ and HCl, followed by 4 M HNO₃ boiling) dissolves more resistant primary sulfides, and step 7 (HCl, HF, HClO₄, HNO₃) dissolves the residual fraction (silicates). The leach solutions are then analyzed by inductively coupled plasma-atomic emission spectroscopy. In addition to the typical elements measured in the leachates, REE are analyzed in the different steps by inductively coupled plasma-mass spectroscopy (ICP-MS), in order to identify additional extractable byproduct commodities in the ore deposit and its mineralogical associations. The

sequential extraction data can additionally be used to perform a high-resolution acid-base account (ABA) (Dold 2010) and should be correlated with the mineralogical data for quality control, and in order to predict AMD formation and element liberation of any mined material. It is important to note that this extraction sequence must be adapted to the solubility of the specific minerals (primary and secondary) present in an ore deposit, as this may differ significantly among different ore deposit types.

RESULTS AND DISCUSSION

Exploitation efficiency

As described above, we extract minerals in the mining process, not elements, but the elements are associated with minerals. Therefore, we have to consider the mineralogy in order to develop efficient exploitation methods, to predict the stability of certain minerals during the extraction process, and in a long-term, for environmental protection.

Each mineral has a specific set of conditions where it remains stable. If we expose this mineral to other geochemical conditions, for example during the mining process (Figure 1), it will destabilize, resulting possibly in its oxidation, reduction, and/or dissolution. In these processes, associated trace elements from the mineral may be liberated and therefore possibly contaminate the process solution or the environment. Thus, if we know the exact mineralogy and the trace elements associated with those minerals prior to mining, we will be able to predict how these mineral will behave along the production flow-path, and we can even model this behavior with geochemical codes.

The evaluation process begins with the exploitation technique of the ore deposit. For example, it makes a difference if we exploit an open pit in the Atacama desert (e.g. Chuquicamata or Escondida) or if we exploit a porphyry deposit by block-caving in a more humid climate (e.g., El Teniente in Central Chile). In both cases, sulfide minerals are extracted. In the case of El Teniente, a slight pre-oxidation of the ore is observed (redox potential is slightly oxidizing and pH slightly acidic) due to the fracturing of the ore-body related to block caving and contact with rainwater percolating through the mineralization. These effects are evident in sequential extraction data for example through the association of Mo with secondary Fe(III)hydroxides (Dold and Weibel, 2013). In the crushing and milling process, water and reagents are added, so that the geochemical system then becomes more oxidizing before it is sent to an alkaline flotation process (Eh ~ 200-300 mV; pH ~ 9-11). Due to this geochemical change, secondary Fe(III) hydroxides are destabilized and may undergo reductive dissolution and adsorbed oxyanions such as molybdate or arsenate may be desorbed and enter into solution as a contaminant. This process can continue in an active tailings impoundment as the geochemical conditions maintain a reducing setting (Eh ~ 100-200 mV; pH ~ 8-10) at this stage (Smuda et al., 2014; Smuda et al., 2008). If operations then cease, the geochemical system of the tailings will change to oxidizing and acidic conditions may ensue due to sulfide oxidation (Dold, 2014a). Sulfides will be depleted in the oxidation zone and the iron will form secondary Fe(III)hydroxides, which serve as sorbents for oxyanions such as arsenate, molybdate, and sulfate at low pH condition (Dold and Fontboté, 2001). If we would now change again the geochemical system to reducing conditions by re-deposition of fresh tailings as in the case of Talabre/Chuquicamata (Smuda et al., 2014) or by an implementation of a cover system or flooding (Jenk et al., 2009), then the sorbent (Fe(III)hydroxides) will be destabilized and undergo reductive dissolution, liberating the adsorbed oxyanions into solution, possibly producing secondary

contamination (Jenk et al., 2009). A similar effect is observed when tailings containing Fe-oxides are deposited in the deep sea ($E_h \sim -200 - +100$ mV, pH 8) through submarine tailings disposal (Dold, 2014c). Thus, if we have exact knowledge before exploitation regarding which mineral contains which trace elements, we can predict their stability in the different geochemical systems during the exploitation process and thus increase exploitation efficiency and assess final and secure waste disposal scenarios.

Biomining

The relationship between ore and waste mineralogy and their fate has also been observed in the so called biomining operations, where in many giant mining operations, valuable metals can be recovered from the material that has an ore grade below cut-off but above the waste definition line (in case of porphyry copper systems usually between 0.1-0.2 and 0.3-0.6 wt.% Cu (Dold, 2014b)). The material of this grade is normally from the primary ore zone (without supergene enrichment with minerals such as covellite and chalcocite) and contains principally chalcopyrite as ore mineral. Chalcopyrite is not acid leachable and cannot be oxidized efficiently by the microbial community present at temperatures below 50°C. Thus the bioleaching process is very inefficient (10 - 20 % recovery). Recoveries can reach 40 % only if significant amounts of supergene Cu-sulfides are present, as in case of Escondida. However, this result is not due to efficient bioleaching, but to acid leaching of the supergene mineral assemblage. Thus, a thorough mineralogical characterization is also necessary in order to increase the efficiency of biomining. Here, the assessment of the presence of toxic trace elements in the ore minerals for the microbial community is also needed to predict efficiency of the bioleaching operation. These data can be obtained from sequential extractions.

Acid mine drainage (AMD) prediction and environmental assessment

As discussed above, standard AMD prediction, includes an acid-base accounting calculation based on sulfur concentrations, calculated as pyrite equivalent and neutralization potential, calculated based on a titration of the carbonate neutralization potential. All these calculations have many drawbacks and fundamental sources of error in the calculation (Dold, 2010). Therefore, if we rely on quantitative mineralogical data (such as optical microscopy, QEMSCAN or MLA), a more precise ABA can be estimated (Figure 2). A high resolution ABA can be performed even with sequential extraction data. If both methods are available, a thorough quality control is possible.

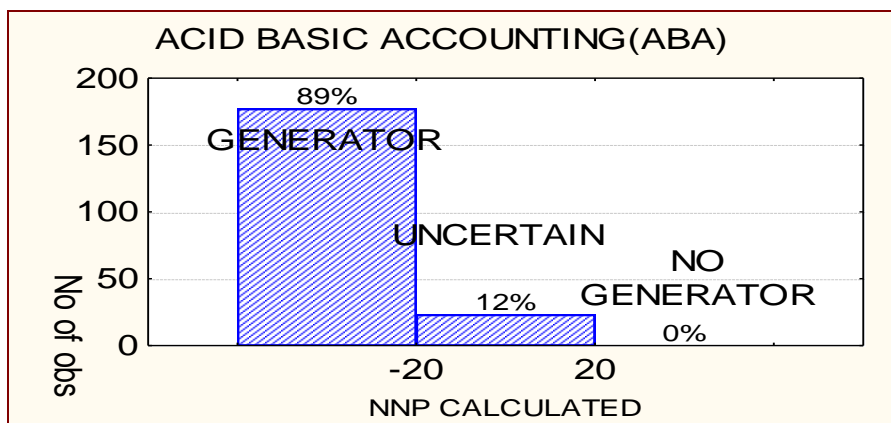


Figure 2 Example of the distribution of acid-base accounting data of a typical porphyry copper deposit calculated based on quantitative mineralogy, showing that 89 % of the samples are AMD generating and 12% range in uncertainty.

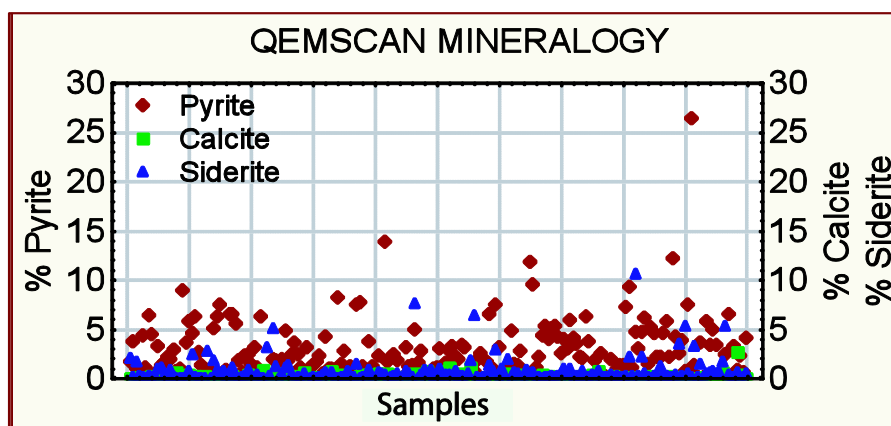


Figure 3 Quantitative mineralogy (QEMSCAN®) data for pyrite, calcite, and siderite of a typical porphyry copper deposit, showing the carbonate neutralization potential is mainly associated to siderite and not to calcite, so that standard ABA calculation would attribute higher neutralization potential, as the acid potential from the liberated iron from siderite (mobility of ferrous iron under reducing conditions or hydrolysis of ferric iron) is ignored.

For example, if unoxidized material from a porphyry copper deposit has 1.5 % pyrite (which has 1 % associated arsenic), 7 % siderite and 3 % anhydrite (Figure 3). A simple ABA would suggest that this material will not produce AMD. However, with the information given above based on quantitative mineralogy and sequential extractions, it can be predicted that this material in the active tailings impoundment will produce concentrations of approximately 1500 mg/L of SO₄ in solution due to equilibrium with gypsum (hydrated from anhydrite). Once operation has ceased, AMD will be produced, as siderite is not able to neutralize all the acidity produced by the pyrite oxidation. Siderite can be even a net acidity producer depending on the circumstances (Dold, 2010). Additionally, the AMD will carry significant amounts of arsenic.

CONCLUSION

The examples described above show that only if we rely on an accurate quantitative mineralogical characterization and chemical data on the trace elements with these minerals, can an accurate prediction of the behavior of the material in the different geochemical conditions during the extraction process, and during final deposition of the waste material be made. This approach is crucial to increase the efficiency of the extraction process, and to ensure environmentally sound waste management.

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