GEOLOGY AND GEOCHEMISTRY: KEY TOOLS FOR SUSTAINABLE MINING

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ABSTRACT

There is no doubt about the importance of geology and geochemistry in the exploration of new ore deposits. But additionally, there are many other parts of the mining process, which need more input from geology and geochemistry than they receive today, as these processes are mainly controlled by the mineralogical composition of the ore and therefore, the geologist has to play a key role in the optimization of the mining process. This paper has the objective to explore the importance of these disciplines not only in the exploration of new ore deposits (the traditional task of the geologist), but also in the extraction process (geometallurgy) and in the environmental management of the mine waste material. As mining has to deal with complex environmental problems like SO_2 and CO_2 emissions and acid mine drainage (AMD) formation, strong efforts have to be undertaken towards more sustainable mining operations with focus on enhanced and optimized metal recovery systems in combination with a minimization of the environmental impact.

INTRODUCTION

Metal production and the associated exploration for new metal resources has experienced an enormous boost in the last years due to the rising demands for metals from developing countries like China and India. However, nowadays not only does the economic gain of metal production has to be considered for the development of a mining project, but also the environmental impact of the mining activities has to be evaluated before, during and after operation. This has to be seen especially in the context of socio-economic pressures toward the mining industry for a more sustainable and clean metal production. The main environmental problem of mining activity is the contamination of other vital resources, like water, soils and air. According to the United States Environmental Protection Agency (EPA), water contamination from mining is one of the top three ecological-security threats in the world. In fact, the competition for water use, especially between agricultural and mining in areas with scarce water resources is very pronounced, as for example in the Atacama desert of Chile and in Peru. There is an endless list of very promising and economically interesting mining projects, which were not able to enter into production or had to stop production due to the opposition of local communities and environmental problems.

The purpose of this paper is to analyze trends for future changes in the metal production process with focus on increasing and optimizing metal recovery combined with a minimization of environmental impact, i.e. more sustainable mining operations, and the importance of geological and geochemical information in these processes.

ROLE OF GEOLOGY AND GEOCHEMISTRY IN MINING AND ITS ENVIRONMENTAL PROBLEMS

An ore deposit is a natural enrichment of a certain element of economic interest in the earth's crust, which is present in a mineralogical form, able to be recovered by state-of-the-art techniques available at the moment of mining (Table 1).

Metal	Ø Crust (wt%)	Ø by mineral exploitation (wt%)	Enrichment Factor	Ø In mine tailings	Enrichment Factor tailings
Cu	0.005	0.4	80	0.1 – 0.3	20 - 60

Ni	0.007	0.5	71	0.2	28.4
Zn	0.007	4	571	2 – 4	275 - 571
Mn	0.09	35	389		
Sb	0.0002	0.5	2500		
Cr	0.01	30	3000		
Pb	0.001	4	4000	1 - 2	1000- 2000
Au	0.0000004	0.0001	250		

Ø = average

Table 1: Average concentrations of metals in the earth's crust with average concentrations exploited by mining and enrichment factors. Some concentrations of elements still present in mine tailings are shown to highlight the still strong enrichment of these elements in the waste material. Modified after (Evans, 1993).

During exploitation, for example due to selective sulfide flotation, the none economic part or the ore mineralogy, which represents, in case of copper ores, about 99 % and in case of gold deposits 99.99 % of the treated material is classified as waste and in the particular case of flotation is named "tailings". These mine tailings are usually deposited in constructed tailings impoundments (Dold and Fontboté, 2001) or natural depressions like lakes or lagoons (Dold et al., 2008), as well into the sea (Dold, 2006) for final deposition. Although this material has no economic metal concentrations at the moment of mining, it still represents a strong enrichment of these metals in relation to the earth's crust (Table 1) and contains other sulfide minerals like pyrite, arsenopyrite (FeAsS), enargite (Cu_3AsS_4), galena (PbS), sphalerite (ZnS), which can be the source for a future uncontrolled metal liberation. The problem of sulfide mine waste material is its uncontrolled exposure to oxidizing conditions at the earth's surface during the mining process. Sulfide minerals like pyrite were formed under reducing conditions in the earth's crust. Once exposed to oxidizing conditions at the surface they are no longer stable and undergo oxidation with the formation of sulfuric acid (equation 1) and the liberation of heavy metals and other toxic elements like arsenic to the environment. Equation (1) describes the initial step of pyrite oxidation, when this material is exposed for example to atmospheric oxygen at the surface of a tailings impoundment. Once ferric iron is produced by oxidation of ferrous iron (equation 2), oxidation which may be, especially at low pH conditions, strongly accelerated by microbiological activity, ferric iron will be the primary oxidant (equation 3) of pyrite (Nordstrom, 1982). Due to the acidic conditions established during these processes, most of the heavy metals are mobile and can pollute surface and groundwater resources, a phenomena better known as acid mine drainage (AMD).

$$FeS_2 + {}^7/_2\,O_2 + H_2O \qquad Fe^{2+} + 2\,SO_4^{2-} + 2\,H^+ \qquad (1)$$

$$Fe^{2+} + {}^1/_4\,O_2 + H^+ \qquad Fe^{3+} + {}^1/_2\,H_2O \qquad (2)$$

reaction rates strongly increased at low pH (< 4) by
microbial activity (e.g., *Acidithiobacillus spp., Leptospirillum spp.*)

$$FeS_2 + 14\,Fe^{3+} + 8\,H_2O \qquad 15\,Fe^{2+} + 2\,SO_4^{2-} + 16\,H^+ \qquad (3)$$

The complexity of defining if a material is classified waste or ore in a mine site is highlighted by the following example. At the moment there are still very rich porphyry copper mines (1- 2 wt% Cu), which have a cut off ore grade of 0.6 wt% Cu (i.e. material with less of 0.6 wt% is not considered as ore), while other less rich porphyry copper mines operate very successfully with a total ore grade of 0.6-0.7 wt% Cu. Exploration for new discoveries targets at the moment even ore bodies with 0.4 wt% Cu. Therefore, the decision if a certain material is classified as waste-material or ore depends on many factors including the actual metal price during mining, ore grade of the deposit, personal decisions of the management, local priorities, technique available, complexity of the ore mineralogy, geometallurgical behavior of the ore and recovery, etc.

SUSTAINABILITY IN MINING

Mining is and will always be a destructive activity with a high environmental impact. Therefore, a sustainable mining approach can only have the goal to optimize the metal extraction from the ore, which by it self means to increase the financial benefits, in combination with the minimization of the environmental impact, and also minimizes remediation costs. Mining history has shown, that material which was regarded as waste in the past, can today be a profitable resource due to improvement of extraction techniques and changes in the economic environment. Therefore, with this lesson in mind, any material of a mining area should be considered in a long-term vision as resource, as long as it represents an enrichment of the metals relative to the average concentration in the earth's crust.

EXPLORATION

The decision as to what kind of ore deposit is explored and if it can be exploited from an economic and an environmental point of view starts with the exploration of the ore deposit type. There are some ore deposits types, which have higher tendency to produce negative environmental impacts like acid mine drainage than other deposits (Plumlee, 1999). Massive, pyrite-rich ore bodies like those present in the Iberian Pyrite Belt of Spain (Sanchez Espana et al., 2005) or in Cerro de Pasco, Peru (Dold et al., 2008; Smuda et al., 2007) represent a high environmental risk due to the enormous amount of pyrite and the presence of other hazardous elements like arsenic. There are many examples of economically feasible ore deposits, which did not enter into operation due to the presence of high concentrations of arsenic or other toxic elements, especially those, which form oxyanions in solution and are therefore highly mobile even under neutral pH conditions (e.g. As, Mo, Cr, Se). This limitation of exploitation due to environmental concerns occurs mainly in more developed societies (e.g. Europe, Northern America, Australia), which do not depend wholly on the exploitation of their primary resources. In developing countries, the dependence of income from primary resources like the mineral industry is very high and downgrade environmental problems to a secondary priority. However, future exploration research should take this problem into account and focus on exploration pattern search for so called "clean ores", which have better chance to be developed and have lower environmental risks and costs.

EXPLOITATION

Once an ore deposit is found and is planed to start operation, it is crucial to perform, beside the obligatory environmental impact study, a detailed baseline study of the natural pre-mining conditions. This has to include an evaluation of the speciation of the element, in order to address the potential mobility of the elements to the environment, as well a detailed knowledge of the hydrogeological system in which mining will take place and in the areas of the potential waste or operation facilities. Ore deposits are natural enrichment zones of elements and therefore the natural background levels in soils and water in these areas are also in general higher than elsewhere. Thus the legal exigencies for the lower permitted concentrations of the elements have to be adapted to the local natural situation.

In order to increase the metal recovery of the total metal mass present in the ore and to minimize the elements, which can escape uncontrolled during the mining operation, a detailed mineralogical and geochemical classification of all rock units in the mining area should be performed. This classification of the rock-units should include metal concentrations (not only the economic elements, but also the hazardous), their speciation (mineralogical phases they are associated with) and the potential to produce acidity or neutralize acidity (acid-base accounting; ABA), in combination with tests to predict the kinetics of element release. Classification into ore, low-grade ore and very low-grade ore can promote the formation of end-products which can be treated upon their mineralogical composition and predicted kinetics of element liberation by the optimized combination of benefaction processes.

BENEFACTION PROCESSES

The choice of the benefaction process in a mining operation depends upon parameters like mineralogy, climate, economic considerations, infrastructure, etc., and has to be evaluated in each case specifically. It is clear that in a mining operation, the main part of the gain is needed at the moment of operation in order to compensate for the enormous amounts of investments needed for the mining activity.

Therefore, there will always be a combination of processes, which permit a fast and efficient concentration of the main ore minerals from the high-grade ore (e.g. flotation, magnetic separation, etc. and smelting), and slower processes for low-grade ores such as in heap leach operation (0.4 – 0.7 wt% Cu), as is practiced at the Escondida mine, Chile (Domic, 2007). If the very low-grade flotation tailings (0.1 wt% Cu) together with other very-low grade material from the ore (0.1-0.4 wt% Cu) can be blended, this could produce a material, which can be deposited and processed with slower reaction rates. If these operations are constructed to recover the pregnant liquor solution (PLS) and to prevent infiltrations of any PLS to the groundwater (i.e. with impermeable basement), these operations can bring economic benefit to future generations instead of high remediation cost (Fig. 1). This procedure would make the "waste material" with 0.1-0.4 wt% Cu, which still represents an enrichment factor of 20-80 (Table 1) accessible as metal source, instead of being classified and deposited as waste.

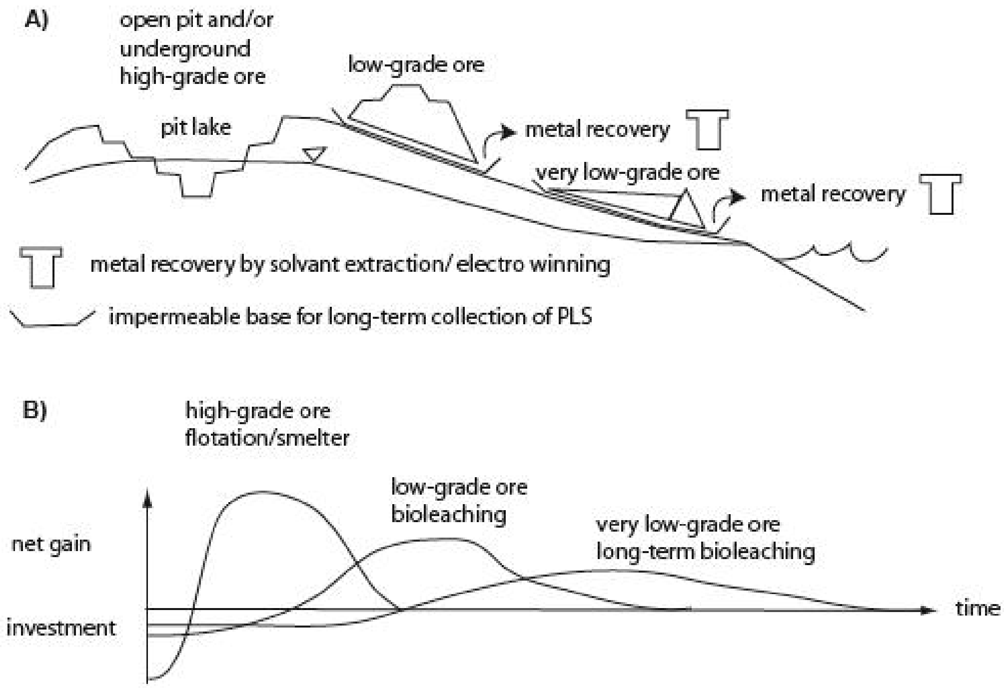

Fig. 1: A) During a sustainable mining operation, no material is exposed without control of the material deposited and possible element flows. The material is classified, registered, and extracted in order to optimize the economic gain for the mining company during operation and to ensure that the low and very low-grade material is managed in terms of kinetics needed for the metal recovery. The great difference in this scenery is that future generations will not receive an extremely expensive environmental problem as heritage, but a system, which will deliver slow but sure net gains in the future. Therefore, in the planning and operation a complete interdisciplinary approach from exploration, economic planning, exploitation and metal recovery process toward to final deposition of the materials has to be applied. B) Simplified schematic view of the financial outcome and investment costs of a sustainable mining operation associated to the different ore grades in a mining operation versus time.

FINAL WASTE MANAGEMENT

Once the complete acid potential of the sulfide mineralogy is liberated and the metal release is completed, a final conditioning of the material can bring the surface back to a final land use. However, depending on the mineralogy of the final waste material in combination with the climatic conditions an evaluation of the risk of further element release has to be performed. For example if arsenic or other elements present in form of oxyanions are associated to secondary Fe(III) hydroxides, the material should be maintained in oxic condition. In contrast, there would be a risk of release of these

elements due to reductive dissolution of the host minerals (e.g. schwertmannite or jarosite), if a standard cover would be implemented. In this case an inert gravel cover would prevent eolic transport and would ensure the oxic conditions.
In any mining process, there will be always a certain amount of waste material which has to be deposited as final waste and will have to be confined in special sealed waste disposal areas. The goal here must always be to minimize the size of this waste in order to minimize the final disposal costs.

CONCLUSIONS

Metal and coal mining has produced in the last century enormous amounts of waste material that resulted in severe environmental problems. The remediation of mining sites costs society great sums of taxpayer money. The past knowledge of the effects of uncontrolled waste disposal from mining must lead to a change in mentality towards prevention of uncontrolled metal release to the environment. A key for future sustainable mining activities will be that mineralogical, geochemical and geological information is used in all steps of the mining process (i.e. exploration, geometallurgy, biomining, final mine waste management). It is also crucial that all parties involved in the mining process (Industry, governmental agency (e.g. EPA, ministries, geological surveys), stakeholder) have the knowledge about the geochemical processes leading to these problems and the best-available techniques to control these systems. It is important that each party accepts that every mining site is unique and that there cannot be a world wide recipe to handle these problems.
The greater knowledge in the understanding of biogeochemical processes leading to sulfide oxidation and subsequent formation of acid mine drainage is more and more applied for bioleaching operations for low-grade ore material for metal recovery. The application of these principles to very low-grade material will be a major challenge in big mining operations with an enormous potential in the industrial application. This will give the possibility to improve the economic outcome of an ore deposit on the long-term perspective by extracting the complete metal content and prevent the uncontrolled release of contaminants to the environment, i.e. the sustainable mining approach has a double positive effect.

REFERENCES

Dold, B., 2006. Element flows associated with marine shore mine tailings deposits. Environmental Science and Technology, 40: p. 752-758.

Dold, B. and Fontboté, L., 2001. Element cycling and secondary mineralogy in porphyry copper tailings as a function of climate, primary mineralogy, and mineral processing. Journal of Geochemical Exploration, 74(1-3): p. 3-55.

Dold, B., Wade, C. and Fontbote, L., 2008. Water Management for Acid Mine Drainage Control at the Polymetallic Zn-Pb-(Ag-Bi-Cu) Deposit Cerro de Pasco, Peru. Journal of Geochemical Exploration, in press.

Domic, E.M., 2007. A review of the development and current status of copper bioleaching operations in Chile: 25 years of successful comercial implementation. In: D.E. Rawlings and D.B. Johnson (Editors), Biomining. Springer, Berlin Heidelberg, p. 81-96.

Evans, A.M., 1993. Ore Geology and Industrial Minerals. Blackwell Scientific Publications, p. 390.

Nordstrom, D.K., 1982. Aqueous pyrite oxidation and the consequent formation of secondary iron minerals. In: J.A. Kittrick and D.S. Fanning (Editors), Acid sulfate weathering. Soil Sci. Soc. Am. J., p. 37-56.

Plumlee, G.S., 1999. The environmental geology of mineral deposits. In: G.S. Plumlee and M.J. Logsdon (Editors), The environmental geochemistry of ore deposits. Part A: Processes, techniques, and health issues. Reviews in Economic Geology, p. 71-116.

Sanchez Espana, J. et al., 2005. Acid mine drainage in the Iberian Pyrite Belt (Odiel river watershed, Huelva, SW Spain): Geochemistry, mineralogy and environmental implications. Applied Geochemistry, 20(7): 1320-1356.

Smuda, J., Dold, B., Friese, K., Morgenstern, P. and Glaesser, W., 2007. Mineralogical and geochemical study of element mobility at the sulfide-rich Excelsior waste rock dump from the polymetallic Zn-Pb-(Ag-Bi-Cu) deposit, Cerro de Pasco, Peru. Journal of Geochemical Exploration, 92(2-3): p. 97-110.