Waste Rock Management at the Antamina Mine: Overall Strategy and Data Application in the Face of Continued Expansion

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Abstract

Based on the interpretation of a small dataset at mine start up, waste rock at the Antamina mine has been actively managed using three waste classes and two dump facilities. Geochemical testwork has been aimed at satisfying a detailed bottom-up approach; whereby, the database generated is used to estimate what the water quality could be both short- and long-term based on the current waste segregation. The program has expanded from the typical suite of laboratory testwork to large-scale instrumented waste rock test piles and cover studies as part of a joint University of British Columbia-Teck-ART-National Science and Engineering Research Council of Canada (NSERC)-Antamina research project.

This paper presents the overall strategy for the Antamina waste rock program, including the path forward for Phase II of the UBC research project. It examines how the wealth of geochemical data (from laboratory to field scale) has been applied to provide options for both short- and long-term water management strategies. Included, are examples of how the dataset generated by UBC is being incorporated into the site-wide Geochemical modelling and some of the strategies that are being developed to manage the waste rock expected from future expansions at Antamina.

Key Words: waste rock, geochemistry, strategy, water quality modelling

Introduction and Site Description

The Antamina mine is located in the Department of Ancash, approximately 270 km northeast of Lima (Figure 1). The elevation of the Antamina mine facilities ranges between 4200 and 4700 masl. The climate is marked by two distinct wet and dry seasons. Average annual precipitation ranges between 1200 and 1500 mm depending on the location on the site with average annual temperatures ranging between 5.4 to 8.5 ºC (Klohn Crippen Berger Ltd, (Klohn), 2010). Due to the marked seasonality and the resulting abundance of water, Antamina strives to divert clean water around the facilities while minimizing the use of clean water in the operational process.

Antamina is a polymetalic skarn deposit and produces copper, zinc, molybdenum concentrates by conventional open pit truck and shovel methods. The operation began in 2001 with a mill throughput of 70,000 tonnes per day (tpd) and recently ramped up to an average 104,000 tpd. The latest expansion will increase the mill throughput to 130,000 tpd in January 2012 and the next expansion will achieve on average, 145,000 tpd by January 2013. Waste rock production is on the order of 340,000 tpd and with higher production rates will increase. Under the current mine plan, Antamina is expected to generate 2.2 Bt of waste rock by closure at the end of 2029.

In addition to the property boundary which defines the legal limits of the operation, facility expansion is constrained both by the steep Andean terrain and karst features on the borders of both waste dumps and the tailings storage facility.

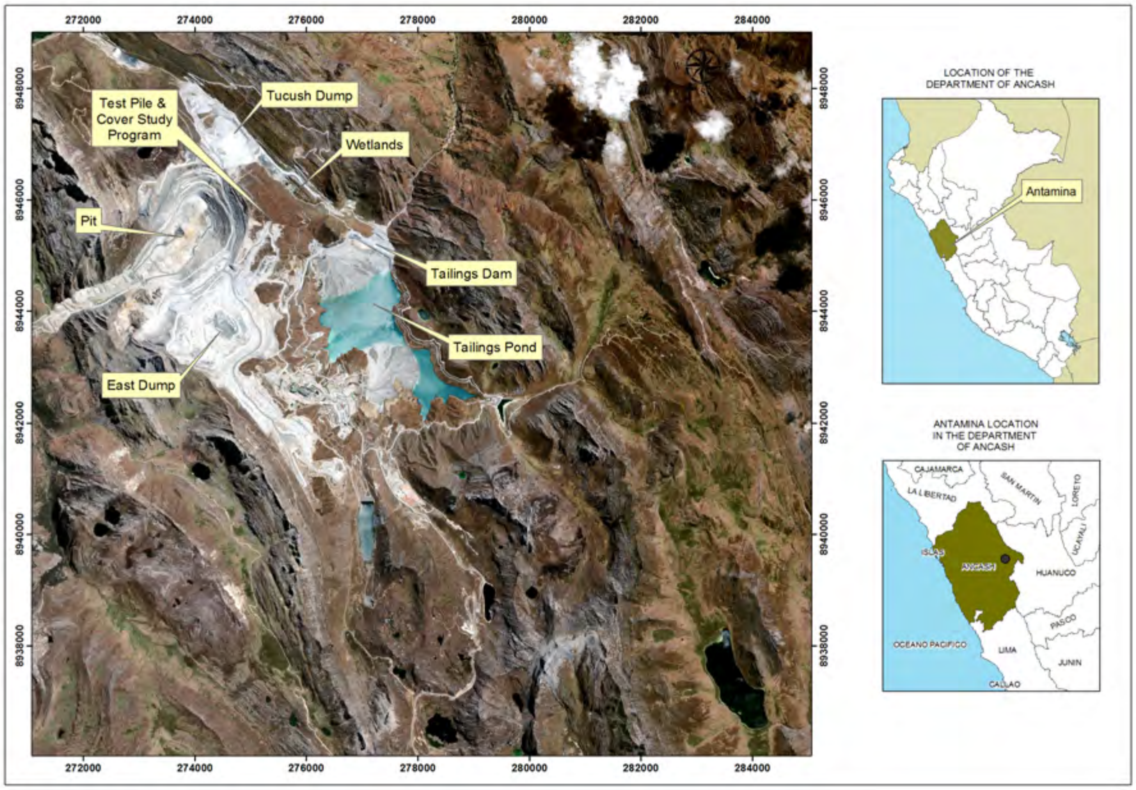

Figure 1. Mine Location

The Antamina deposit can be described as having five major rock lithologies: intrusive, skarn (distinguished as brown garnet endoskarn and green garnet exoskarn), hornfels, marble and limestone. Figure 2 shows a schematic of the Antamina deposit geology.

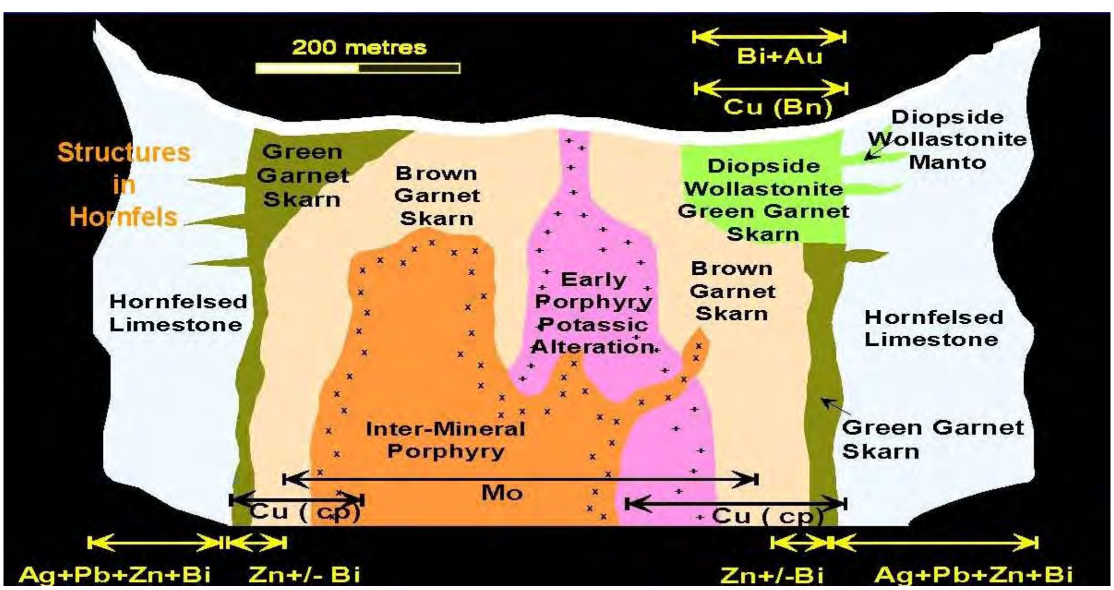

Figure 2. Deposit Geology

Baseline studies supporting the geochemical characterization of the waste conducted in 1997 showed that a majority of the samples selected to represent the Antamina waste rock (hornfels, marble/limestone and green garnet skarn) were Non-Potentially Acid Generating (Non-PAG) and neutral drainage metal leaching was expected. Samples selected from waste rock within the brown garnet endoskarn and intrusive were generally classified as Potentially Acid Generating (producing net acidity and higher metal loads). In 2001, Antamina implemented a waste classification system that segregated waste suitable for tailings dam construction from waste to be stored in the East Dump, the only active waste dump at the time. Refinements were made as more knowledge of rock leaching behaviour was gained through the geochemical testing program managed by Golder Associates Ltd (Golder). Once a level of comfort was reached, the limits of the waste classes were set to further manage the rock being allocated to the second waste dump Tucush dump commissioned in 2004. The classification system is shown in Table **1** (Compañía Minera Antamina, 2010).

Table 1. Antamina Waste Classification System

Waste Class	**Criteria**		**Waste Rock Dump**
A Most reactive	Exoskarn, Endoskarn, Intrusive Hornfels, Marble Limestone Zn > 1500 ppm or As > 400 ppm S >3%, visual oxides >10%		East Dump
B Slightly reactive	Zn 700-1500 ppm S <2-3%		East Dump and Tucush Dump
C Least reactive	Zn < 700 ppm As < 400 ppm S < 3%	<10% FeOx	Tailings Dam Construction
		Without restrictions on FeOx	Tucush Dump

Today, waste is actively segregated based on a rigorous method from blasthole assay analysis to polygon delineation and dispatch coordination. Depending on the material classification, waste rock is either sent to the East Dump, Tucush Dump or used in Tailings Dam construction. The East Dump receives the more reactive Class A rock as well as lesser quantities of Class B and C rock depending on its proximity to the polygon containing the reactive Class A waste within the waste block model and verified in the field. Drainage from the East Dump reports to the tailings pond where no active discharge occurs. Seepage from the tailings dam is pumped back in the dry season to maintain compliance with the internal Antamina standards which are generally more stringent than the legal limits applicable to Antamina, imposed by the Ministry of Energy and Mines for effluent discharge and in-stream compliance.

Class B and C waste are stored in the Tucush Dump. Drainage from this less reactive, dump is collected and routed through the Tucush Artificial Wetland (the wetland). The wetland was designed to investigate removal of TSS and reduction of ammonia as well as to a lesser extent reduction of copper, zinc and molybdenum reporting to the effluent compliance point located downstream of the wetland outlet.

From the description above, it can be seen that the current overall waste and water management strategy for the Antamina mine encompasses the following principal areas:

- Segregation. Separating the more reactive from less reactive waste rocks based on a classification system
- Placement. Storing the more reactive wastes in a waste dump that drains directly to the tailings pond and placing the less reactive waste in a waste dump where seepage is routed through a constructed passive treatment wetland; and
- Diversion. Separating as much clean runoff water away from the mine facilities as possible to minimize the amount of contact water affected by the operation.

The major changes affecting the way Antamina continues to operate are the new in-stream water quality standards effective for Antamina in early 2016. The sulphate limit of 300 mg/L is causing many mines, including Antamina, to relook at waste and water management. This paper summarizes the overall Antamina waste rock and water management strategy, including some of the recent changes, while also highlighting the areas where the large geochemical database is being integrated into operational practice.

Overall Waste Rock Management Strategy

Golder played an integral role in setting up and managing the waste rock strategy for Antamina, using data collected in the pre-mining baseline studies and data from the early years of mining. This strategy aimed initially at filling data gaps by collecting samples for static testing and setting up the on-site kinetic field cell program. Once a sufficient dataset of field cells was running, this program shifted focus to investigate the subtle differences between the marginally reactive rock groups with a simple water quality prediction component.

Recently the program has shifted focus again with the emphasis split into two major areas. This first area focuses on linking the geochemistry program with the mine planning process as well as generating data specifically applicable to water quality estimation. The second emphasis is on data application in the form of design. There are five major components of the current Antamina waste rock strategy. They are:

1. Waste block model and geochemical testing program;
2. Field cell kinetics program;
3. Test pile and cover study program;
4. Geochemical modelling for waste and water quality management; and,
5. Strategic planning for new regulations and closure.

The following subsections describe how each of these components are incorporated into the overall strategy to help minimize water quality impacts including specific discussion of how data collected from the field cell, test pile and cover study program have been used in water quality modelling estimates.

Waste Block Modelling and Static Testing

There have been approximately 160 waste rock types logged at Antamina. Of these, the five major lithologies in combination with the waste classes described above have been used to segregate rock.

A waste drilling program was initiated in 2008 and continued in 2010 and 2011 with a total of 38,100 m drilled. Antamina re-logged all previous drill-core and all new waste drill-core, expanding the original four waste lithologies into 22 waste lithologies to better define the material coming from the open pit. Using the re-logged drill-core and the new waste drilling information, the first waste rock block model was completed in 2010. The objective was to develop a five year waste management plan to optimize waste rock placement and to ensure sufficient Class C rock meeting dam construction criteria is available and stockpiled for future dam raises.

The static and on-site kinetic geochemical databases originally developed and maintained by Golder were re-logged based on the 22 waste lithologies. Approximately 350 samples from the 2010 and 2011 waste drilling programs were selected to (1) target under-represented waste units based on quantities expected out of the open pit in the next five years, (2) test the significance of the distribution and location of sulphides within the samples, and (3) continue to expand the database to understand the leaching variation that exists within each lithology. Upon the completion of the static tests from the 2010 and 2011 waste samples, field cells will be initiated to supplement the current field cell program. All of these objectives remain in-line with the objectives Golder developed and worked towards in the early stages of the Antamina waste rock geochemical program.

Waste drilling programs targeting approximately 13,000 m are now planned yearly. Each waste drilling campaign is coupled with a block model update and a complimentary selection of samples for geochemical static and then field cell kinetic testing. More emphasis will be placed on mineralogy, something identified both by Golder and the University of British Columbia (UBC) as a necessity in understanding the mechanisms contributing to the Antamina waste rock leaching characteristics. Antamina has now formally established a geochemical strategy to ensure a link exists between the waste rock volumes and lithologies coming from the open pit based on the medium-term 5- and 10-year mine plans.

Field Cell Kinetic Testing

There are currently 89 waste-rock field cells in the Antamina field cell program, including those set up specifically to compliment the test pile and cover study program. A description of the standardized method of the field cell construction and sampling at Antamina is included most recently in Hirsche et al. (2012). Over half of the field barrels set up by Golder were initiated between 2002 and 2004. Since 2006, the field cell program shifted focus. UBC and Antamina installed 50 field cells to meet the needs of the test pile program. As a result, less focus has recently been placed on continuing to install field cells to reflect the material expected from the mine plan. With the completion of the installation of the test piles, more emphasis has returned to implementing field cells in accordance with the strategy described above.

The field cell program plays an integral role in demonstrating the range in potential leaching rates from each of the different rock groups under site climatic conditions. The primary use of the leaching data is in support of the water quality prediction models. It is therefore crucial that the field cell program reflect the range of variation within the material types expected from the open pit in each of the mining phases throughout mine life.

Test Pile and Cover Study Program

In 2005 Antamina, Teck Cominco and UBC initiated discussions about a collaborative research study with the objective of understanding the potential long-term water quality originating from neutral waste rock at Antamina. Design and construction of the first waste rock pile was underway in November 2005. The program received a generous 5-year partial funding grant from the National Science and Engineering Research Council of Canada (NSERC) in April 2006 which finished in April 2011. In early 2011 Antamina, Teck-ART and UBC began reviewing the initial goals set out for Phase I of the program with the objective of determining if a Phase II would be warranted and what the second phase would aim to achieve.

The program consists of five large-scale instrumented waste rock test piles with complimentary field cells and laboratory humidity and column testing as well as five instrumented lysimeters for cover studies. Test pile construction details are summarized in Corazao (2007) and Bay (2009) and details of the cover study lysimeter design are described in Urruita (2011). The cover study construction was completed in December 2010 and the study is in the initial stages of data collection and interpretation. As a result, it has not yet yielded information that can be incorporated into the overall strategy as part of the water quality modelling described below.

The test pile program however, has amassed a wealth of flow and chemistry data critical to understanding wetting and drying cycles, waste rock runoff conditions and geochemical behaviour of the rock types (see Blackmore et al., 2012, Blaskovich et al., 2012, Peterson et al., 2012, Hirsche et al., 2012, Singundy et al., 2012 and Javadi et al., 2012 for specific study results). Details of how the results of these studies are being applied to the Antamina geochemistry strategy are touched upon in the modeling section of this paper.

The major objectives of Phase II of the test pile and cover study program are to directly link the test piles and the full-scale waste dumps. Antamina has committed to both drilling two sets of paired (deep and shallow) drillholes in closed areas of the existing East waste rock dump and instrumenting these holes to collect continuous temperature, gas and moisture content information. Details of the instrumentation and borehole design are being finalized and drilling is expected in the first part of 2012. The following summarize briefly the five Phase II studies aimed at linking the test pile program to the full scale Antamina operation (adapted from UBC, 2011):

- Scale-up from test pile to waste dump - The majority of this work is to integrate observations from the field-cell and test-pile scale with mechanistic models to provide insights into processes in the full-scale dumps and to build a framework to model full-scale dump behavior. This project is principally modeling and analysis of existing data. The link this study provides to the full-scale operation is key on many levels to validating the assumptions in the GoldSim geochemical model used for long-term prediction and planning (discussed in the following section of this paper). Samples collected during drilling can be analyzed for secondary minerals to determine geochemical processes occurring in full-scale piles.

- Gas analysis of the waste rock piles – A key uncertainty in the prediction of the behavior of full-scale dumps is the balance between oxygen supply and oxygen consumption. It is hypothesized that oxygen is being consumed at rates more quickly than it can be supplied from the ground surface. If this is true, then the release of metals through sulfide oxidation will be slower than predicted for a dump without oxygen limitations. Boreholes will be installed into inactive areas of the East Dump to measure gas composition, temperature and other parameters and use this information to constrain sulfide oxidation rates and geochemical behavior. Analysis and interpretation of the gas dynamics at both the test pile and waste dump scales will be done.

- Mixing at the base of the waste rock piles – The current conceptual model of full-scale dumps at Antamina hypothesizes that distinct rock types generate distinct leachate with distinct geochemistry. The various waters flow to the base of the waste-rock pile where they mix and equilibrate. The objective of this study is to understand what range of conditions and processes are possible at the base of the East Dump and the implications of the mixing on short and long-term discharge water quality. The work will integrate the field-cell and pile-scale geochemistry results, to understand mixing dynamics in the full-scale dumps.

- Alkaline weathering of metals from waste rock - The purpose is to understand the dynamics of metal release under neutral pH conditions. The work is motivated to understand processes likely to prevail in the Tucush Dump, where abundant class C is expected to maintain neutral-pH conditions. The research will leverage sequential leach studies conducted as part of the Phase I research.

- Cover study continuation – Phase I of the cover study examined the effects of material type and compaction on infiltration. A crucial gap in understanding is the effect of vegetation on the water balance. It is hypothesized that vegetation will enhance evapotranspiration and reduce infiltration. Data from existing test covers will be interpreted to assess the potential effects of covers on the full-scale waste dumps.

Geochemical Modelling for Water Quality Management

All of the data collection and interpretation with respect to waste rock quantities, characteristics and management come together in the modelling designed to manage current trends and plan for future changes in water quality at various locations around the site. Over the past year Antamina has developed a site-wide excel water and mass balance model as well as substantially advanced the existing GoldSim Geochemical model (Klohn Crippen Berger Ltd, 2011).

The objective of the excel water and mass balance developed in-house was to document Antamina's current understanding of water movement and usage around the operation. It takes the known volume and quality data since 2009 and projects the trends 5 years into the future. The results of the excel water and mass balance are used to monitor the effects operational changes will have on a day-to-day basis. In broader terms, the excel water balance is a calibration tool for the water management models used by various departments throughout Antamina. Specifically, it was used to calibrate the GoldSim Geochemical model built by Klohn and used by the Antamina Business Planning and Development Group for long-term site-wide water quality estimation, including post-closure.

The GoldSim Geochemical model is the long-term planning tool that brings the data from the various sources in the waste rock geochemical program, together. The steps vary slightly from mine component to component, but in the case of the waste rock dumps, they are generally as described below.

Rainfall data from the four climate stations located around the Antamina site are used in the stochastic rainfall simulations in the model. Waste dump runoff and infiltration are assumed to be 55% and 45%, respectively. Adoption of the 45% infiltration rate is based on results from the test pile program that generated a range of infiltration rates for the 10 m high test piles (UBC, 2010). Completions of the hydrogeologic studies currently underway as well as the scale up in Phase II of the test pile program are expected to refine these values for the full-scale waste rock dumps at Antamina.

Initial waste rock mass loads are calculated using data from both the test pile program and the kinetic field cell database discussed previously. Loads are applied to the tonnage of each waste lithology based on waste rock class and according to the life of mine plan based on the waste block model updates. In GoldSim terminology, the dump is considered a "reservoir" for both solutes and water. At each time step, the uncorrected water quality concentrations are calculated based on dividing the amount of mass of a particular parameter by the amount of water stored within the dump reservoir.

The model pH is adjusted based on the alkalinity-acidity balance at every timestep. Acidity generated from the oxidation of available sulphide minerals measured as sulphate in the field cell program and qualitatively identified in the mineralogical studies undertaken as part of the UBC tespile program (Aranda, 2009). These acidity production rates are scaled to the full scale dumps (taking into account factors such as grainsize, exposure to flushing water, etc). An additional source of acidity is noted from stored oxidation products as evidenced in the cyclical waste dump seep and field cell water quality results. These acidity sources are buffered primarily by the abundant limestone within the waste rock and which surrounds the site (calcite and dolomite). Additional buffering capacity is available and accounted for within the model siderite, the aluminosilicate minerals and by iron oxy-hydroxide minerals all of which are present in Antamina waste rock.

With the adjusted pH value determined from the alkalinity-acidity balance, the raw concentrations calculated based on the division of total mass by water volume are compared to solubility curves of known elements to determine theoretical solute concentrations. Adsorption, precipitation and complexation decrease the available mass within the solution resulting in the final equilibrated water quality that is then assigned to the dump drainage. A portion of the dump drainage reports to the dump toe and the remainder to the groundwater system. Details of how the model quantitatively determines each of these processes is described in Strand et al., 2010.

Future Challenges

Antamina is currently faced with short-term water management challenges due to its aggressive growth and expansion schedule and the newly imposed regulated limits for various parameters at the in-stream compliance points. Current trends modeled using the short-term excel water and mass balance model highlighted that Antamina should expect challenges with the newly regulated in-stream sulphate limit of 300 mg/L, applicable in 2016. Under current practice Antamina is able to meet this limit; however, as the waste dumps continue to expand and age, sulphate loads are projected to rise. With the most recent Environmental Impact Assessment submission (Klohn Crippen Berger Ltd., 2010), Antamina committed to provide either a water treatment plant strategy or an operational change to ensure compliance with the new in-stream limits

The short-term excel water balance was able to quickly pinpoint sulphate sources within the current waste and water management practices and estimate the short term increases. Using the GoldSim geochemical model, an options analysis is currently underway to look at ways of optimizing the current water management within the operation with the primary focus of averting the need for active water treatment, if possible. If optimization of the operation does not prove sufficient to manage future sulphate loads, the GoldSim Geochemical model has been adapted to evaluate treatment methods and removal rates.

Continued Geochemical Strategy Improvements

The first major strategy improvement recognized by Antamina is the development of a waste block model. After 10 years of operations, Antamina has begun to focus on quantifying and planning for the quantity and types of waste coming from the open pit. This is especially important as Antamina's future includes continued expansion and growth. With the development of the block model, the second improvement to the geochemical program is to maintain a link between the current field cell program and the rock coming from the open pit based on the medium-term mine plan. This was neglected in order to establish the UBC testpile program, but is now the focus of the field cell program. With the expansion from the five original waste classes to the 22 waste classes modeled in the geologic and geochemical block model and the known quantities of each, Antamina's efforts are being placed on assessing the ranges of leaching characteristics that fall within each rock class to better quantify the source terms used in the modeling and reflect the tonnages expected in the future.

The major area of uncertainty in any geochemical program is related to scaling factors that are applied to relate loading rates calculated from the field cell program to develop source terms applied to the full-scale waste rock dump leachate chemistry. In general to relate the concentrations in the leachate from the field cells to the dump seepage concentrations and to successfully model these, one needs to make assumptions on the effects of several interrelated characteristics including grainsize, temperature, oxygen diffusion, hydrologic properties within the dump and physical segregation due to mining and end-dumping. Though the use of the field cells at Antamina rather than conventional laboratory-scale humidity cell tests has reduced the need for some scaling factors with respect to climate, there remain significant differences between the internal heating mechanisms that control drainage in the field cells as compared with the test piles and again with the full-scale dumps.

Phase I of the test pile program has provided an intermediate scale between the field cells installed at the Antamina mine and the full-scale waste rock dump seepages measured as part of the routine water quality monitoring program. Preliminary results suggest that there is approximately a 5 to 15 times difference in sulphate loading rates between the field cells and the test piles based on direct leachate comparisons (UBC, 2010).

The saturated and unsaturated flow behaviour within the dumps has also been simplified to model the seepage from the dump toe. Complex internal hydrologic processes have not been accounted for. With the waste dump drilling programmed for Phase II of the test pile program, the unsaturated zones within the East Dump will be better understood. A gas monitoring system will be installed to monitor CO_2 and O_2

flux as well as temperature. The results will provide insight into how the water behaves within the dump. Combined with the hydrologic studies being conducted in the East Dump, Antamina will be able to fill some of the data gaps and uncertainties currently within the model.

Phase II of the test pile program is aimed at linking the wealth of data generated to the full-scale Antamina waste dumps. At the moment Geochemical GoldSim modelling uses literature values to scale between the results from the field cell and test pile programs to operations. Development of Antamina specific scaling factors will provide more certainty in the predictions made using the model.

The ultimate goal of the waste rock geochemical program is the ability to implement geochemical dump design to attenuate and reduce overall metal leaching from the Antamina was dumps. The dump design would explore the ability to use the results gained throughout the geochemical program to-date including for example results presented by Hirsche et al. (2012) in operational practice. With 160 rock lithologies, 22 major rock types and a complex mine plan, there is some doubt that mineable units will be available on the scale that Antamina moves rock. However, as part of the 2012 geochemical program, Antamina has committed to exploring the opportunity to integrate a design for metal leaching stability with physical stability.

Concluding Statements

The current waste segregation between more reactive and less reactive rock confines leaching to specific areas of the operation where it can be collected and managed. However, due to the aggressive growth path Antamina has adopted, the wealth of geochemical data from the field cell program and the understanding of water-rock interactions being developed as part of the testpile program will be required by Antamina to manage waste rock placement more actively.

The overall objectives for the next five years of the geochemical program at Antamina are to apply the data collected from the field cell and test pile program to the full-scale operation. This is a key step that confirms or helps refine the factors currently assumed within the GoldSim model with respect to the uncertainties in material behaviour. In addition, the commitment to investigate the ability to segregate rock beyond simple material segregation and in accordance with a dump design focussed on metal leaching attenuation, will advance the current practice at Antamina.

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