GEOCHEMICAL CHARACTERIZATION AND WATER QUALITY PREDICTION AT THE ANTAMINA MINE[1]

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Abstract. The Antamina mine, located in the Peruvian Andes, is one of the world's largest operating copper-zinc mines. A comprehensive geochemical characterization program of waste rock and low grade/marginal grade ore has been underway to fulfill a number of objectives. These objectives focus on developing an understanding of potential operational and post-closure impacts to the environment, assisting with identification and implementation of prevention/mitigation measures, and refinement of the current waste rock management program. The geochemical characterization program follows a multi-faceted approach, including extensive long-term laboratory and field testing and operational monitoring. This presentation will provide an overview of the geochemical characterization program at Antamina, including relationships between results from laboratory testing, field testing and operational monitoring, and water quality modeling.

Additional Key Words: metal leaching, neutral drainage, waste rock, sulfide

Introduction

The Compañía Minera Antamina (Antamina) Cu-Zn-Mo mine is located at an altitude of approximately 4,200 metres above sea level in the Perúvian Andes approximately 200 km west of the city of Huaraz (Fig. 1). The mine reached full production in the fall of 2001 and currently processes between 70,000 and 100,000 tonnes of ore per day. Approximately 300,000 tonnes of waste rock are also excavated daily and, depending on the waste rock classification, used either as construction material or placed in one of several waste rock piles. The current anticipated mine life is 23 years (i.e., until 2024).

The long-term environmental stability of various waste rock types at the Antamina Mine has important ramifications with respect to operational waste rock and water management and selection of closure alternatives. Previous geochemical testing (Golder Associates, 2004; Golder Associates, 2003; Klohn-Crippen, 1998) of rock has indicated that some rocks are potentially acid generating and that Zn and Mo leaching may occur under neutral conditions.
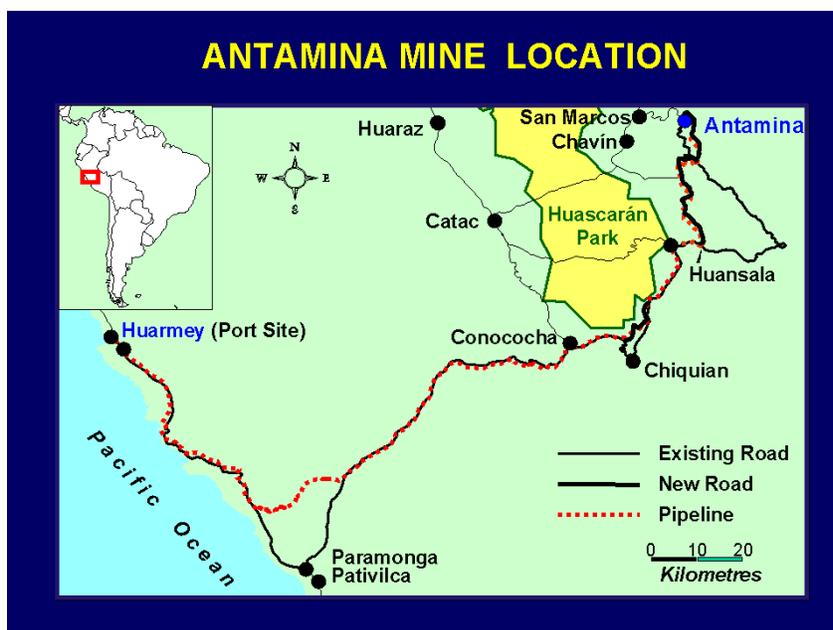
Figure 1: Antamina project location map (Antamina, 2003)

A comprehensive geochemical characterization program of waste rock and low grade/marginal grade (LG/MG) ore has been underway to fulfill a number of objectives. These objectives focus on developing an understanding of potential operational and post-closure impacts to the environment, assisting with identification and implementation of prevention/mitigation measures, and refinement of the current waste rock management program. The geochemical characterization program follows a multi-faceted approach, including extensive long-term laboratory and field testing and operational monitoring. This paper provides an overview of the geochemical characterization program at Antamina, including relationships between results from laboratory testing, field testing and operational monitoring, and water quality modeling.

Background

Deposit Geology

   The Antamina deposit is a large Cu skarn with Zn, Ag, Mo, and Bi formed by the intrusion of quartz monzonite into limestone (Antamina, 2003). The major rock types identified at the Antamina mine include: intrusives, endoskarn, exoskarn, hornfels, marble, and limestone. The Antamina deposit displays characteristics of both a Cu skarn and that of a Zn skarn deposit. Copper skarns normally form in proximal association with the intrusive that is the metal source, whereas Zn skarns usually form distal to the fluid source (Fig. 2). According to Antamina (2003), that fluid reaction occurred with both intrusives and limestones, forming endoskarn and exoskarn units. The previously implaced intrusives caused a thermal metamorphic event forming the hornfels that surround the deposit. These units then acted as barriers to successive mineralizing events, thereby forcing the fluids to react with the intrusives forming endoskarn and limited reaction into the country rock forming exoskarns (Antamina, 2003). Mineralization was able to extend significant distances from the deposit along thrust faults, fault planes, dike contacts and in favorable stratigraphic units.
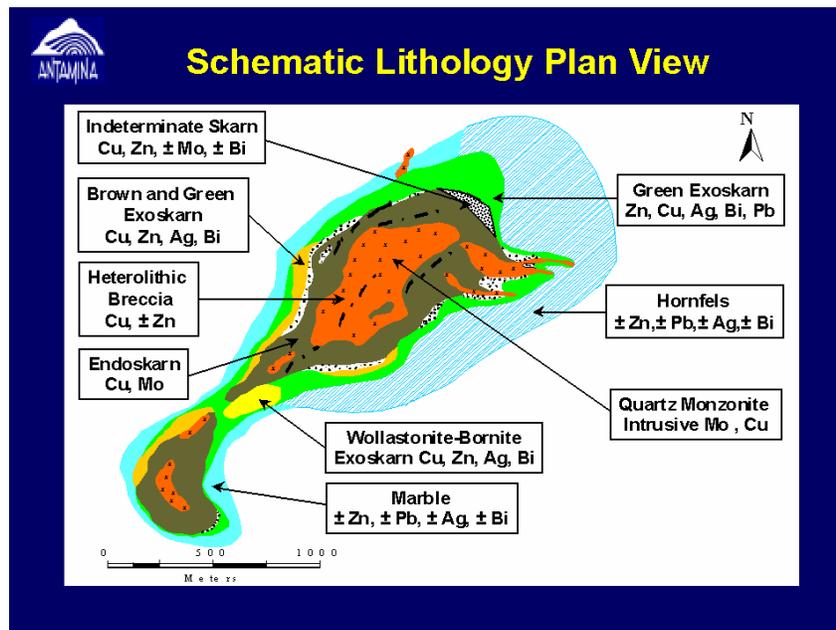
Figure 2: Schematic lithology plan view (Antamina, 2003)

Mineralogy

   Mineralogical analyses completed using x-ray diffraction spectrometry indicate that the general composition of the individual rock types is as follows (Golder, 2004):

- Hornfels – Mainly calcite with augite and minor amounts of quartz, muscovite, albite, rutile, microcline plagioclase, K feldspar, biotite, garnet, and trace amounts of pyrite, pyrrhotite, magnetite and covellite.

- Marble – Predominantly calcite with quartz, muscovite and plagioclase with minor amounts of mica and chlorite, pyrrhotite, diopside and traces of molybdenite.

- Intrusives – Mainly quartz and K feldspar with minor amounts of plagioclase, muscovite, biotite, calcite, and trace molybdenite and pyrite.

- Endoskarn - Mostly K feldspar, quartz, plagioclase, quartz, garnets (andradite and grossular), calcite, diopside with minor amounts of mica, chlorite, diopside, calcite, pyrrhotite, ilmenite, muscovite and montmorillonite and traces of molybdenite.

- Exoskarn – Mostly calcite and garnet with quartz and minor amounts of K feldspar, microcline, albite, muscovite, calcite, andradite, biotite, ilmenite, and traces of magnetite, fluorite, molybdenite, pyrite and possibly galena.

Waste Rock Classification

To prevent and minimize potential impacts from acid rock drainage and metal leaching (ARD/ML), Antamina developed an operational monitoring program for management of reactive and "non-reactive" waste rock. According to the current waste rock classification system (Antamina, 2002), three waste rock classes have been identified as follows:

- Class A is defined as mineralized / oxidized rock – endoskarn, exoskarn, and intrusive, and hornfels/marble/limestone with greater than 1,500 ppm Zn, greater than 400 ppm As, and greater than 3% sulfides.

- Class B is defined as hornfels, marble and limestone only, with Zn levels between 700 and 1,500 ppm, and sulfide content between 2 and 3%.

- Class C is defined as hornfels, marble and limestone only, with less than 700 ppm Zn, less than 400 ppm As, and less than 3 % sulfides.

Although the classification system does not contain a molybdenum criterion, Mo is associated with either the intrusives or endoskarn, which are designated as Class A material regardless of their Mo content.

Based on this classification system, waste rock is placed in designated piles or used for on-site construction material. Class C material only is considered suitable for use or placement in areas where downstream water treatment would not be required. This material has been used in construction of the Tailings Dam, water reservoir dam (Dam D), and for various access roads around the site or has been placed in a separate non-reactive dump. Runoff from piles containing Class A rock is captured for treatment via a pH adjustment system, or diverted to the tailings impoundment. Runoff from waste rock dumps containing Class B material will be monitored, and will be captured and managed accordingly.

In addition to waste rock, LG/MG ore is stockpiled in a separate pile and will not be processed until the later years of the operation.

Geochemical Characterization of Waste Rock

Methodology

Antamina and Golder Associates developed an assessment and monitoring program to evaluate and predict the long-term stability of waste rock and associated seepage quality (Golder, 2003, 2004). The key components of the long-term waste rock and ore stockpile monitoring plan include the following:

- Laboratory geochemical characterization (acid base accounting (ABA), metals analysis, and leach tests) of waste rock and LG/MG ore.

- Laboratory kinetic testing of selected waste rock and LG/MG ore.

- Construction and monitoring of field kinetic testing of selected waste rock and LG/MG ore.

- On-site monitoring of seepage/runoff quality and quantity from waste rock dumps and the LG/MG ore stockpile.

In addition, Antamina plans to initiate monitoring of several large, specially-constructed experimental waste rock piles (i.e., between 5,000 and 10,000 tonnes) and these data will become an integral component of the long-term monitoring program.

Construction and monitoring of field tests allowed for evaluation of the environmental stability of specific rock types under ambient but measured conditions. The field cells contain each of the major rock types currently present in the dumps as per the latest life of mine plan. The major individual rock groups (i.e., hornfels, marble, limestone, intrusives, endoskarn, and exoskarn) were sampled individually. For the hornfels, marble and limestone, representative samples of Class A, B, and C material were identified for testing. For the other rock types, which are all considered Class A per the current classification system, samples representing average and high metal and sulphur concentrations in drill core analyses were selected. In addition to cells for waste rock, field cells were constructed for the most important LG/MG ore types. Twenty-seven (27) field cells in total, each with a charge between 350 and 400 kg, are currently included in the testing program. Most cells have been operated for approximately 2.5 years.

Laboratory kinetic tests were also completed to provide additional information on the long-term weathering of waste rock and ore. For eight waste rock and LG/MG ore samples, laboratory kinetic tests were completed on a sub-sample of the same material placed in the field cell for at least one sample of each material type.

Field and Laboratory Cell Kinetic Results

Sulfate release rates and neutralization consumption rates from both field and laboratory kinetic tests were evaluated to provide a semi-quantitative estimate of the lag time for net acid generation. The rates were determined in accordance with the methodology provided in Price (1997). Based on these calculations, it is expected that acidic conditions will only arise in the intrusives sample (in approximately 15 years). In the remaining cells, the calculations indicate that sulfide minerals will be exhausted through oxidation prior to depletion of neutralization potential.

Results of the laboratory and field cell kinetic program were used to calculate loadings rates for various rocks types and, in turn, to develop water quality estimates. Golder (2004) provides a detailed review of field and laboratory kinetic loading rates. Zinc concentrations in leachate collected form the field cells are higher in the initial flushing and flushing at the beginning of each wet season. This is consistent with removal of stored, soluble reaction products resulting from sulfide oxidation. Although Zn concentrations are much higher in some of the field cells as compared to the laboratory cells, the calculated loading rates are similar after the initial flush at the beginning of the wet season (Fig. 3). These similar trends occur despite the fact that the

range of water to rock ratios in the laboratory cells is approximately two orders of magnitude greater than in the field cells.

Field cell monitoring data indicate that zinc is released from the LG/MG ore (Fig. 4). The pH of the field cell leachates varied between 6.7 and 8.9. The LGMG ore stockpile runoff/seepage is between 7 and 9.5 and, as illustrated on Fig. 4, zinc concentrations in the seepage/runoff show a high, and increasing, trend.
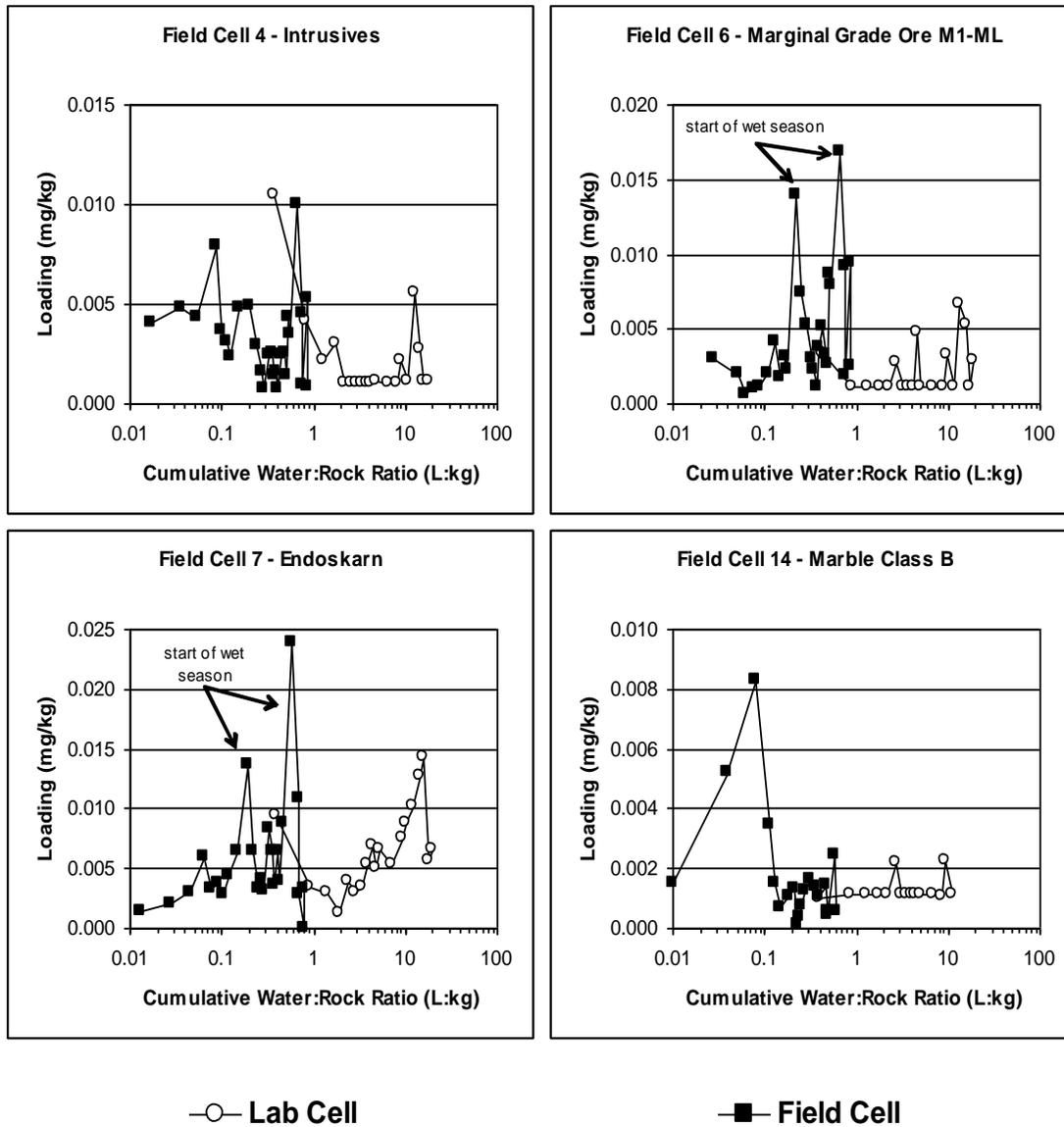
Figure 3: Comparison of zinc loading rates between field cell and laboratory kinetic tests

For samples in which molybdenum concentrations were greater than the detection limit, loadings for field and laboratory cells were similar. Molybdenum loadings are highest in leachate from the intrusives, skarn and LG/MG ore samples, which is consistent with the presence of molybdenite [MoS_2] identified in these samples.

Copper loadings are low, as concentrations of these parameters in the leachate from the both field and kinetic cells are near their method detection limits of 0.01 mg/L and 0.002 mg/L, respectively.
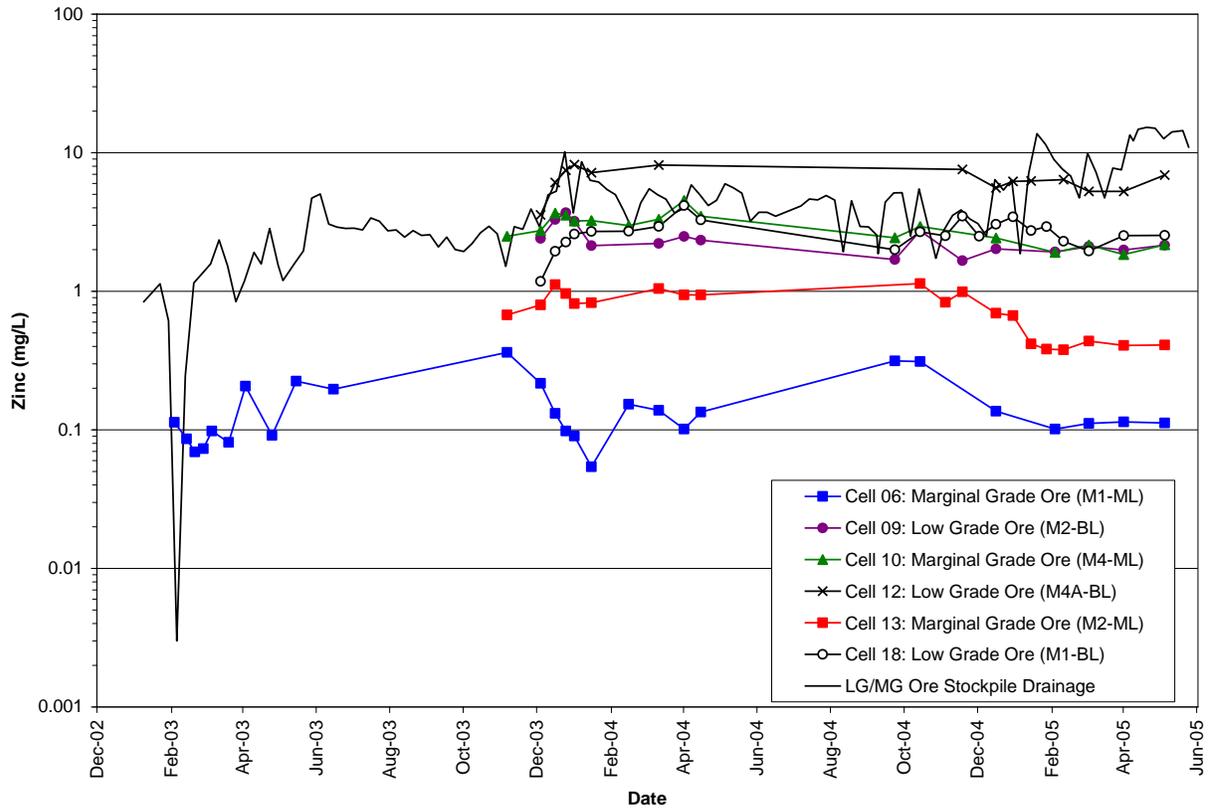
Figure 4:   Comparison of zinc concentrations from the LG/MG ore stockpile effluent and the LG/MG ore field cells

Sulphate concentrations are highest in leachates from the intrusives and LG/MG ore samples, with levels in several field cells approaching values that suggest a solubility control by gypsum. Sulfate, as well as dissolved Cu, Zn, Mo, Ca, and Mg concentrations, are higher in the initial flushing and flushing at the beginning of each wet season. This is consistent with removal of stored, soluble SO_4^{-2} reaction products resulting from sulfide oxidation. For field cells, elevated SO_4^{-2} concentrations in the initial flush at the beginning of the wet are consistent with observations in the laboratory kinetic cells. Sulphate concentrations in the field cells are greater than those observed in the laboratory tests, and remain at elevated concentrations throughout the monitoring period. However, SO_4^{-2} loadings from the field cells after the initial flush at the beginning of the wet season are similar to those for the laboratory cells after the initial flush at the start of the test (Fig. 5). This suggests that, despite the higher SO_4^{-2} concentrations in the leachates from the field cell, SO_4^{-2} is generated at a similar rate on a mass basis. This, in turn, means that the rate of sulfide oxidation is similar in the laboratory cells and field cells.

Data Limitations

As with any type of testing program, there are inherent difficulties in relating the test results from the laboratory and field cell programs to field conditions. The main uncertainty is that

neither the samples nor the test conditions may be truly representative of those occurring in the waste dumps and stockpiles at the Antamina site.

The laboratory test conditions are different from those observed in the field, including.

- Laboratory tests were conducted at room temperature which is higher than typical ambient temperatures at Antamina. Reaction rates are affected by temperature according to well-established geochemical principles.

- Humidity cells tests are conducted using a single, weekly flushing of a constant nature. However, precipitation at Antamina varies significantly during the wet and dry seasons.

- The humidity cell tests use a sufficiently-large volume of water that all reaction products can be reasonably expected to be removed. Removal of all reaction products may not occur in the field due to much lower water to rock ratios, incomplete flushing, and the occurrence of chemical reactions along the flow path. Also, the equilibrium conditions expected in the rock dumps and ore stockpile may not be realized in the test cells due to short contact times between solid and solution.
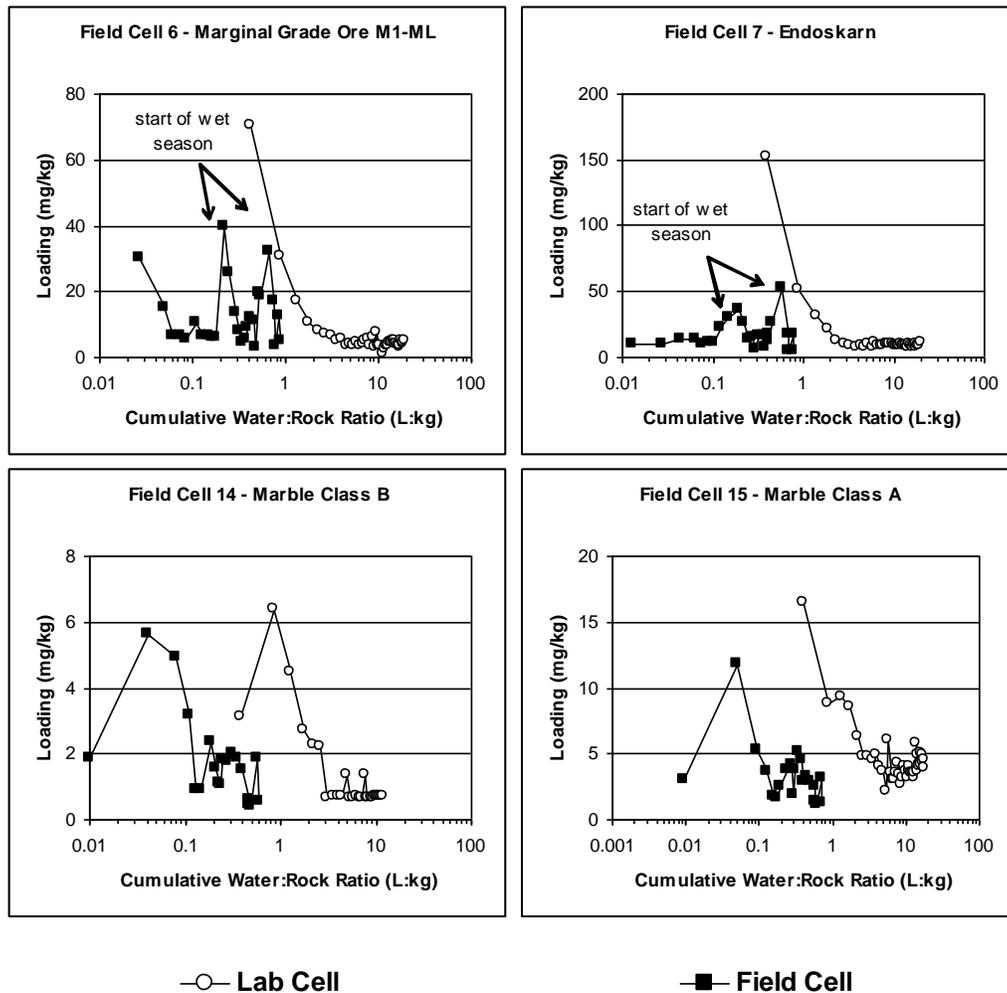
Figure 5: Comparison of SO_4^- loading rates between field cell and laboratory kinetic tests

Field cells were constructed to address the preceding issues. However, there are limitations with the field cells as well, including:

- Temperatures in the field cells will closely resemble ambient air temperatures. Therefore, temperature in the field cell may differ from those in the waste rock dumps, which, due to their larger mass, may contain portions that are relatively isolated from the atmosphere.

- Based on visual estimates of the particle size, it appears that the field cell samples contain a higher proportion of fine-grained materials than the dumps and stockpiles.

- Air completely infiltrates the field cells, which may not occur for the entire waste rock dump.

- It is expected that, due to physical containment within the field cell, infiltration contacts a higher proportion of the rock in the field cells than is the case in the dumps and stockpiles.

Consequently, there are some uncertainties associated with predicting sulphide oxidation, acid neutralization and metal release rates for the stockpiles and dumps using rates observed in laboratory and field tests. Nevertheless, it is believed that the field cell program represents a considerable improvement relative to the laboratory testing, and provides meaningful data which can be used to predict the long-term environmental stability of the waste rock dumps.

Water Quality Modelling

Model Development

Empirical water quality modelling was completed to evaluate relative changes in potential impacts to the receiving environment based on different mixes of rock types in the non-reactive waste rock dump. The water quality model discussed in this paper is not intended to provide definitive predictions of parameter concentrations. The non-reactive waste rock dump was initially modelled based on the current configuration and life of mine plan, which indicates that only Class C (~80%) and Class B (~20%) material are placed in the pile. In subsequent simulations, the rock classes were varied from the life of mine plan to determine the effect on water quality, with particular emphasis on placement of rock that is more environmental deleterious (i.e., Class A) than rock types intended for the waste rock disposal facility.

Metal release from LG/MG ore and waste rock was simulated using field cell loadings rates, supplemented by evaluation of data from laboratory kinetic testing and short-term leach testing.

Currently water quality monitoring data is available for the LG/MG ore stockpile. Thus, water quality simulations were completed for the existing LG/MG ore stockpile. Loading rates were initially applied to the LG/MG stockpile using data from the LG/MG field cells and based on the stockpile composition as presented in the life of mine plan. The annual loading was assumed to be distributed evenly on a monthly basis. Water quality data from monitoring of LG/MG ore stockpile runoff and seepage were used to calibrate the loading calculations. The modelling was conducted for a select set of parameters (included Cu, Mo, SO_4^{-2} and Zn), which have been determined to be the most sensitive in a regulatory context or the most important with respect to mine operations.

During the dry season, precipitation, and therefore dump seepage/runoff, is low. However, oxidation of sulfide minerals in the waste rock still occurs within the piles. Readily-soluble secondary minerals formed as a result of this oxidation are stored on the rock surface and are dissolved by infiltrating water at the beginning of the wet season. Water quality monitoring data for a complete dry and wet season suggest that there is an initial peak in concentrations followed by a decline to more stable levels in drainage from the LG/MG ore, skarn and intrusive field cells. However, for model simulations, loading rates were developed for the wet season after the initial flush, to represent average long-term conditions.

To bracket a range of possible loadings and seepage water qualities, two mechanisms of load release from the stockpile and dump were evaluated:

- The load release was based solely on the amount of material placed in a pile for the given year ("annual loading"). In this case, only the latest lift was considered chemically reactive, while the older material was assumed to not contribute any loading.

- The load release was based on the total amount of material in a pile for the given year ("cumulative loading"). This approach reflects cumulative leaching, where material deposited each year will continue to leach at those rates determined by leach tests until the end of the simulation or until all leachable mass has been removed. For this scenario, the annual mass leached each year is subtracted from the total amount of that parameter present in the solid phase (i.e. source term). For all simulations, the mass of parameter leached did not exceed the mass available in the solid phase.

Model Calibration and Correction Factors

Due to the inherent differences between field tests and the actual field setting, correction factors were applied to the loading rates as part of the model calibration. The differences in geochemical behaviour are influenced by particle size differences, water channelling, and geochemical reactions, as discussed below:

- Particle size differences - Smaller particles dominate weathering reactions. The smaller the particle, the larger the available surface area for weathering reactions to occur. The field cell sample collection is somewhat biased towards finer grain size than observed in the actual waste rock piles. Furthermore, some grain size reduction may occur during sample handling. Hence, the weathering reactions are expected to be faster in the field cells in than the dumps.

- Water channelling - Due to the heterogeneous nature of the stockpiles and waste dumps, void spaces may be isolated from the flow regime. Similarly, infiltration may flow through individual channels within the material rather than the entire volume of rock. Such isolated void spaces and segregated channel pathways are likely less prevalent in the smaller, field cells.

- Geochemical controls - The rate of mineral weathering within the dumps and stockpiles will be controlled by several factors (e.g., air infiltration, temperature) which are unique to each pile. Furthermore, attenuation (e.g., precipitation and adsorption reactions) of certain constituents may occur along the flow path through the piles. Due to the various differences between the field cells and the piles, geochemical controls may differ as well.

Both the particle size and channelling factor will vary from pile to pile due to the different characteristics of the various rock types, differences in placement strategies, and different post-

placement activities (e.g., use as a roadway which will lead to enhanced compaction). Geochemical controls will also vary depending on the dump composition, flow conditions, temperature and air entry. However, for purposes of determining loading rates, a uniform correction factor was applied for all waste rock and ore stockpiles throughout the life of mine. For each modelled parameter (SO_4^{-2}, Zn, Cu, and Mo), this uniform correction factor was varied to obtain modeled concentrations that are similar to observed concentrations in the drain from the LG/MG stockpile. Correction factors that were applied to the field cell loading rates in order to calibrate simulated water quality with that measured in the drainage from the LG/MG stockpile are presented in Table 1.

Table 1: Parameter specific loading rate correction factors

Parameter	Correction Factor	
	Annual Simulation	Cumulative Simulation
Zinc	2.5	0.1
Copper	30	1.1
Molybdenum	0.015	0.0005
Sulphate	0.5	0.015

Small calibration factors were required for zinc and sulphate for the approach using the annual load release (Fig. 6). A larger correction factor was required for the cumulative loading, which was expected as this approach assumes metal release within each annual stockpile volume throughout the life of mine and until depletion of available mass.
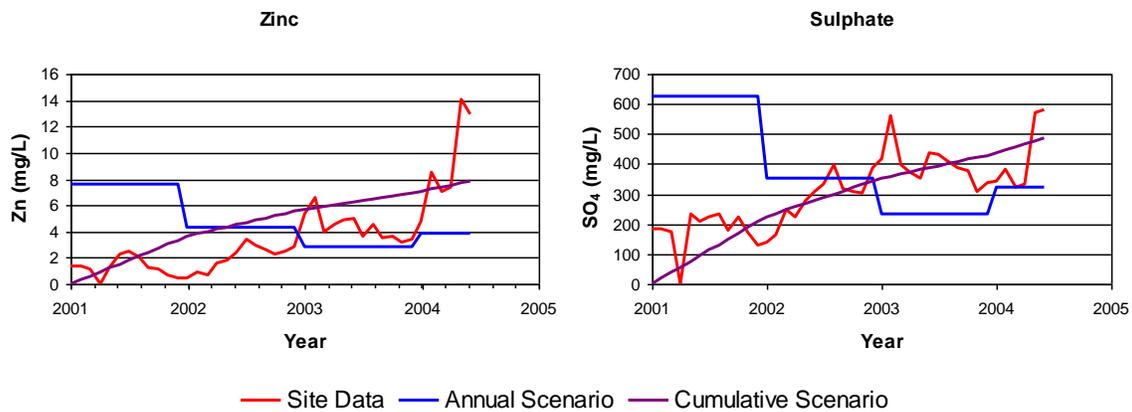
Figure 6: Zinc and sulfate model calibration for the LG/MG ore stockpile

Large correction factors were required for Cu and Mo (Table 1). Copper concentrations in the LG/MG ore field cells reach a maximum of 0.08 mg/L. However, Cu concentrations in the drainage from the LG/MG ore stockpile have continued to increase consistently from the early 2003 with an average monthly concentration of 1 mg/L at the end of the 2005 wet season. For Mo, concentrations observed in the effluent from the LG/MG ore field cells reach a maximum of 44 mg/L but concentrations in the LG/MG stockpile drainage are less than 0.4 mg/L.

There is a large difference in scale between the field cells and dumps or stockpiles. The field cells contain approximately 350 kg of material while the dumps and stockpiles consist of several

tens of millions to several hundred millions of tonnes of material. Due to the differences in tonnages, the overall distributions of waste may be different. If a material has mineralogical or weathering characteristics that are not typical of a class of material as a whole, the effects will be most pronounced in the field cell, whereas in the dumps, they will be dampened due to mixing with large volumes of other rock.

Model Simulation Key Findings

Varying the Class A skarn and intrusives portion has the greatest effect on the simulated Zn and Mo concentrations in the drainage from the non-reactive waste rock dump (Fig. 7). For example, inclusion of 10% Class A skarn and intrusives results in a more than 2-fold increase in zinc concentration. A 100-fold increase in Mo concentrations is observed with a 10% addition of Class A skarns and intrusives. Varying the proportion of Class A hornfels and marble, results in a slight increase in the simulated Zn concentrations in the discharge from the non-reactive waste rock dump (Fig. 8).
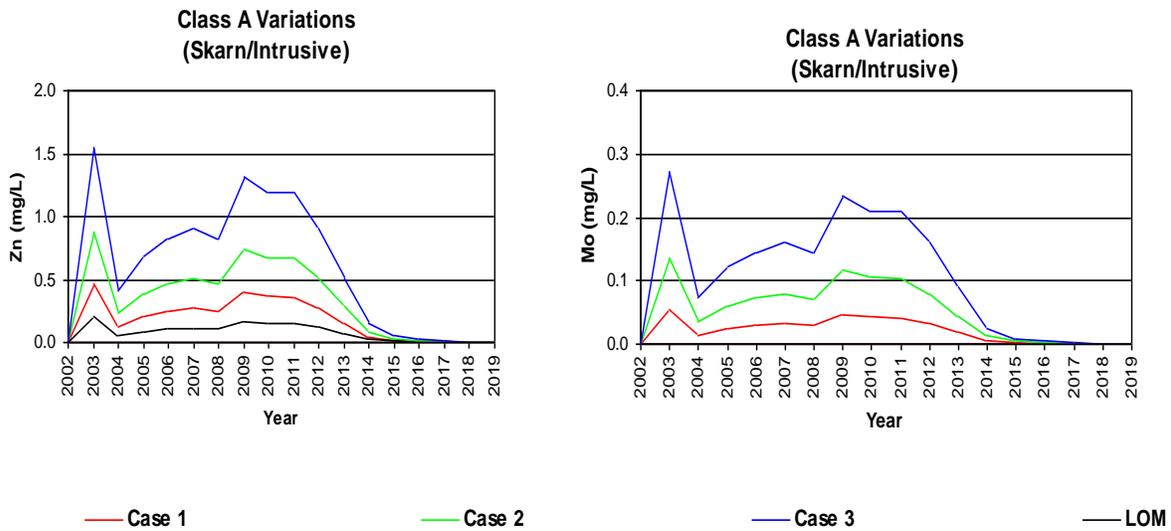
NOTES:
Case 1: Class A: 10%   Class B: 20%   Class C: 70%
Case 2: Class A: 25%   Class B: 20%   Class C: 55%
Case 3: Class A: 50%   Class B: 20%   Class C: 30%
LOM: As described in the life of mine plan.

Figure 7: Non-reactive dump water quality model Zn and Mo results for variations in Class A (skarn and intrusives) material content
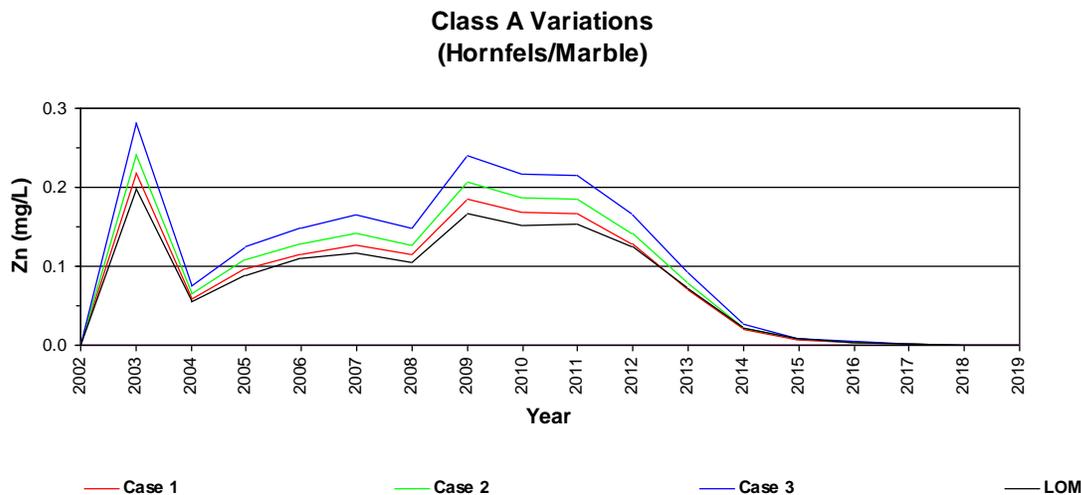
Class A Variations
(Hornfels/Marble)

NOTES:
Case 1: Class A: 10% Class B: 20% Class C: 70%
Case 2: Class A: 25% Class B: 20% Class C: 55%
Case 3: Class A: 50% Class B: 20% Class C: 30%
LOM: As described in the life of mine plan.

Figure 8: Non-reactive dump water quality model Zn results for variations in Class A (hornfels and marble) material content

To further assess waste rock management practices, water simulations were also completed by varying the proportion of Class B material in the non-reactive waste rock dump. For this assessment, Class A material is excluded from the dump (as is intended in the life of mine plan), while Class B material is increased from contents 10% to 75%. Class C material comprises the balance of the waste rock content. Loading rates are similar between Class B and Class C material and for illustration purposes simulations were only completed for zinc. Increasing the proportion of Class B material in the non-reactive waste rock dump does not produce significant differences in Zn concentrations (Fig. 9).

Closing

A comprehensive geochemical characterization program of waste rock and LG/MG ore was initiated to assist in developing an understanding of potential operational and post-closure impacts to the environment, identification and implementation of prevention/mitigation measures, and refinement of the current waste rock management program. The geochemical characterization program focused on water quality monitoring of field cells, waste rock dumps and ore stockpiles. Several years of data collection are needed from the field cells and waste rock piles to generate the information necessary to identify meaningful and defensible relationships between rock types and drainage quality. Therefore, it is considered essential to implement testing programs during the early stages of the mine life. However, as demonstrated by the results from water quality modelling presented in this paper, application of "initial" data (i.e., 2.5 years or less) has proven useful in developing predictive water quality trends and evaluation of waste rock management practices.

Class B Variations
(Hornfels/Marble)
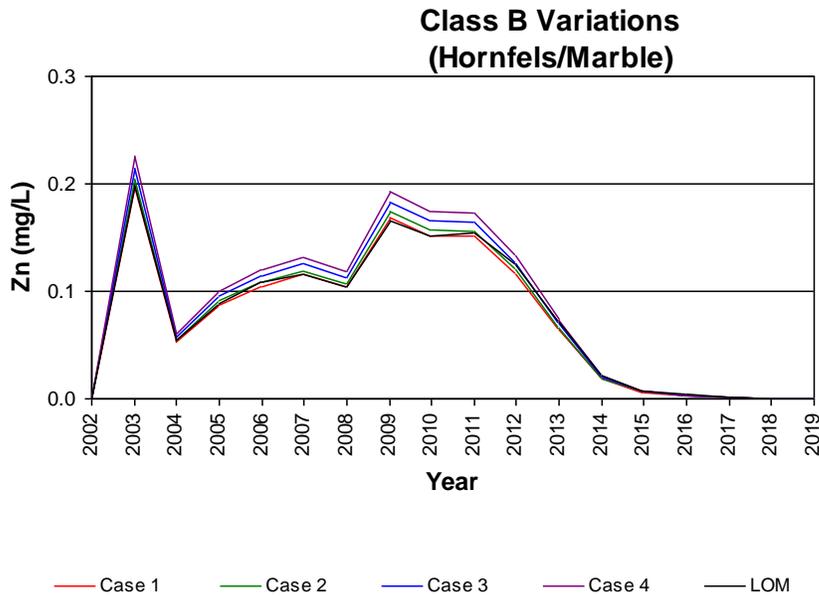
NOTES:
Case 1: Class B: 10%   Class C: 90%
Case 2: Class B: 25%   Class C: 75%
Case 3: Class B: 50%   Class C: 50%
Case 4: Class B: 75%   Class C: 25%
LOM: As described in the life of mine plan.

Figure 9: Non-reactive dump water quality model Zn results for variations in Class B material content

The results from the current water quality modelling are being used to develop waste rock and water management planning practices that enhance environmental protection. The water quality simulations based on the existing data are useful in evaluating potential impacts to the receiving environment from the existing waste rock classes and potential modifications to the waste rock classification system and placement strategies. For example, water quality simulations completed in this assessment indicate that water quality from the non-reactive dump is very sensitive to the amount of Class A skarn and intrusive material placed in the dump. Thus, quality control procedures will be developed to ensure that Class C and Class A blocks are better defined, that the classification of the material in the dig face is confirmed, and that the designation of the material placed in the non-reactive dump is confirmed. The water quality model will be updated as additional water quality and flow monitoring data become available from the field cells and the waste rock dumps and ore stockpiles, resulting in revisions of the waste rock and water management plan, as necessary.

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