GEOCHEMICAL CONTROLS ON WASTE-ROCK DUMP SEEPAGE CHEMISTRY AT SEVERAL PORPHYRY MINES IN THE CANADIAN CORDILLERAN[1]

Stephen Day, and Ben Rees[2]

Abstract. In 2003, Red Chris Development Company started collecting baseline data to support its application for environmental approvals to mine the Red Chris porphyry copper-gold deposit located in northwestern British Columbia, Canada. An extensive geochemical testing program revealed that the majority of the waste rock has the potential to generate acid. However, the presence of significant quantities of carbonate minerals indicated that most of the rock would probably take several decades to generate acid. This precluded determination of which rock components would leach under acidic conditions using conventional laboratory methods. This information was required to predict future water chemistry and potential requirements for water treatment. As an alternative, waste-rock seepage chemistry data from six operating or recently closed porphyry mines in British Columbia were compiled and evaluated to investigate common hydrogeochemical features which could be used to predict water chemistry at Red Chris. The resulting database contains dissolved ion chemistry spanning the full range of pH conditions.

The database indicated that dissolution of aluminum minerals such as biotite and chlorite exert a strong consistent pH control which can be explained by the solubility of basic aluminum sulfates and hydroxide. Likewise, iron concentrations were similar at all sites and appear to follow the solubility of ferric hydroxide. Dissolved concentrations of copper, zinc, cadmium, and molybdenum in waters were related to pH but reflected the variable presence of minerals such as chalcopyrite, sphalerite (zinc, cadmium) and molybdenite (molybdenum). In conclusion, concentrations of major ions affecting drainage acidity (sulfate, aluminum, and iron) are very similar at different sites, but concentrations of other elements depend on the abundance of their sulfide minerals.

Additional Keywords: Acid rock drainage, prediction, metals.

Introduction

In 2003, Red Chris Development Company (RCDC), a subsidiary of bcMetals Corporation, began collecting data needed to support an application for an Environmental Assessment Certificate, required under the British Columbia Environmental Assessment Act, as part of development of the Red Chris Project in northwestern British Columbia (B.C.), Canada. Static geochemical data (acid-base accounting) collected for the project in the 1990s indicated that the majority of the rock had the potential to generate acid due to pyrite concentrations in several percent and insufficient carbonate buffering capacity. Information on metal leaching rates was required to complete water chemistry predictions. However, the presence of carbonate minerals and the low rate of oxidation under non-acidic conditions indicated by kinetic testing (Red Chris Development Company, 2004) showed that acid generation would be delayed for many years beyond a reasonable time frame for assessment of potential environmental impacts, permitting, and development of the project. As a result, comparison of mine drainage from analogous mineral deposits in B.C. was considered as a possible approach to predict future weathering behavior of the waste rock and mine walls at the Red Chris Deposit.

The concept of using data from other mineral deposits is not new. Both geographical and geological bases for comparisons have been suggested (Steffen, Robertson and Kirsten et al., 1989; Plumlee and Nash, 1995) and Carrucio and Ferm (1974) showed that coal deposits formed under similar paleo-environmental conditions would show similar weathering behavior. It is now generally well known that coal swamps with a sea water influence incorporated sulfate from the water, which would subsequently be reduced to sulfide and converted to iron sulfide (pyrite and marcasite) during diagenesis. Coals formed in freshwater environments have lower sulfide content due to the typically much lower concentrations of sulfate in freshwater. The approach is reasonable for coal deposits because the environmental conditions of formation are near ambient and the rocks associated with the coals undergo limited changes during diagenesis and burial.

Application of this approach to hard rock mines requires extreme caution. The geological conditions of formation can vary widely from near surface to great depths in the earth's crust. Many base and precious metal deposits are formed by circulating hot waters of highly variable compositions that may interact with all conceivable rock types. The resulting mineralogy produced by these interactions can be highly variable in terms of mineral type, abundance, composition, and occurrence. Economic geologists have been able to group mineral deposits into common types based on similar characteristics. Approximately, twelve types have been recognized (Guilbert and Park, 1986). Most classifications are based on inferred genetic similarities that result in similar mineral assemblages. Since rock weathering during mining is also a function of mineralogy (as well as environmental and mining factors), mineral deposit classifications represent a possible basis for comparisons in environmental studies of mining projects (Bowell et al., 2000).

Porphyries are one mineral deposit type that has been extensively studied because these deposits contain large inventories of base (Cu, Mo) and precious (Au, Ag) metals. Numerous global studies of porphyry deposits (e.g. McMillan and Panteleyev, 1988) have shown that common large geological conditions such as primarily rock alteration can be recognized. Red Chris is well-defined as a porphyry deposit, and therefore represented a good candidate for a comparative study of rock weathering characteristics.

This paper describes assessment of water chemistry data for several porphyry deposits in the Cordillera of British Columbia and the possible application of the data to predictive studies at other mine sites.

Background

Porphyry deposits are typically found in island arc environments where they form in the root of volcanoes as a result of hot circulating waters. The host rocks for porphyry deposits are variable and depend on the composition of the volcanic pile, but some common features include: intermediate plutonic rocks, such as diorites, quartz diorites, and granodiorites, and intermediate volcanic rocks like andesites.

The distinctive feature of porphyry deposits is the presence of hydrothermal alteration that may occur in broad concentric zones named for their distinctive mineralogical assemblages. These zones represent evolution of hydrothermal fluid chemistry and the temperature and pressure of fluids. Economic mineralization including Cu and/or Mo is typically associated with high temperature potassic alteration which is typified by the presence of secondary K-feldspar and/or biotite. Copper mineralization is usually present as chalcopyrite or bornite, and Mo occurs as molybdenite. Pyrite concentrations may be relatively low compared to other sulfide minerals. This zone is often surrounded by phyllic alteration which is characterized by sericite (fine-grained muscovite/secondary feldpsar), low grades of economic minerals, and more abundant pyrite. This zone is sometimes referred to as a "pyrite halo" since it surrounds the copper and molybdenum mineralization. Depending on overall grades and mining method, rock from the pyrite halo can be an important component of waste rock and pit walls but it may also contain elevated Cu and Au grades. Beyond the phyllic zone is the propylitic alteration zone typified by minerals such as chlorite, epidote, and carbonates. Pyrite concentrations often continue to be elevated but generally decrease as the overall intensity of alteration decreases into the surrounding country rocks. Veins containing minerals such as galena and sphalerite may be present in the propylitic zone distant from the copper, molybdenum, and gold mineralization.

Numerous and complex variations of this simple pattern of alteration occur at all porphyry deposits. Some alteration types are completely absent and other features may be present such as argillic alteration (typified by kaolinite alteration of feldspars), silicic alteration (quartz flooding) and breccia bodies. In some cases, multiple alteration phases occurred during deposit formation, over-printing earlier alteration zones. Alteration zoning is commonly apparent at many scales. The above description of alteration implies pervasive alteration of the rock but alteration also occurs at small scales as hot waters moved along fractures, resulting in centimeter scale zoning around veins.

At least 29 porphyry deposits have been identified in B.C. and 13 of these have been developed into open pit mines. Studies of these deposits in B.C. have shown that they contain features identified elsewhere. Different classification schemes are used to divide porphyry deposits into sub-types. Sutherland Brown (1976) developed a classification scheme based on morphology, rock associations, and depth. In this scheme, the three types are referred to as volcanic, plutonic, and classic. The volcanic type indicates an association with small intrusions such as stocks, sills, and dyke swarms. Ore is hosted mainly in the volcanic country rocks that consist of volcanic flows, pyroclastics, and breccias. Plutonic deposits form at greater depth and

are associated with plutons. Classic deposits are related to multiple sub-volcanic intrusions and host rocks may be volcanic or sedimentary.

Host rock chemistry differences have led to two sub-types referred to as alkalic and calc-alkalic, which refers to the composition of the intrusive rocks (McMillan and Panteleyev, 1988). Although alkalic deposits are mainly of the volcanic type and tend to have higher Cu and Au grades than calc-alkalic deposits, these two classification systems overlap. Calc-alkalic deposits may be volcanic, plutonic, or classic. Additional discussion of the porphyry deposit classification systems can be found in Guilbert and Park (1986).

Objectives

The objective of the study was to compile drainage water chemistry data from porphyry mines in British Columbia and evaluate common chemical and mineralogical controls on concentrations of major and trace ions in solutions. At the same time, explanations for substantial differences in drainage chemistry were to be identified by referring to known variations in porphyry geological features such as differences in hydrothermal alteration type and the occurrence of Pb and Zn mineralization distal from the Cu-Mo-Au mineralization. Following recognition and explanation of similarities and differences, the findings were to be applied to water chemistry predictons for the Red Chris Project.

Methods

Site Selection and Data Control

Site selection was largely based on the suitability of water chemistry monitoring locations; author Day's knowledge of the sites, access to and quality of data, and permission from the site owners to use their data. The primary criterion was for monitoring locations to be true toe seeps representing water draining directly from waste-rock dumps. Toe seeps are not completely pore water because they may include influences from groundwater and waste-rock surface runoff. Monitoring data were not included because these locations certainly contain dilute runoff, groundwater, and direct precipitation. It was expected that these data would add "noise" to the dataset and obscure relationships between parameters. The requirement for analyses from filtered water samples was set as a criterion to avoid variability caused by suspended solids. In addition, field pH measurements were preferred but this was removed as a criterion because the data were generally not available. The authors relied on data collected prior to this study and as such the use of different sampling protocols represents a possible source of unquantifiable data variability in the study. The authors did not collect additional water samples.

Five porphyry deposits (Gibraltar Mine, Island Copper Mine, Kitsault Mine, Mount Polley Mine, and Mine C) yielded suitable data (Fig. 1). The owner of "Mine C" requested that the mine not be named. It is included in the overall discussion of data trends but is not specifically described. Suitable site monitoring data were not available for the Huckleberry Mine but a long term laboratory test on a slowly leaching (58 mL/week) 2 kg column was included. These data provided an opportunity to compare laboratory test results with full-scale field data. Table 1 summarizes the available data for each site. The largest dataset in terms of number of monitoring points was Gibraltar Mine. Although Table 1 implies that a large number of parameters have been monitored over time, in some cases spanning the late 1980s to the present, many parameters were analyzed using detection limits that were too high. Due to the problems of mixing detection limits, non-detection results were removed from the database. As a result,

442

As, Hg, Sb, Ag and K could not be evaluated. Only one of the sites reported field measurements of oxidation-reduction potential therefore correlations of metal concentrations with this parameter could not be considered.

Figure 1. Location of British Columbia porphyry deposits used in this study. G = Gibraltar; H = Huckleberry; I = Island Copper; K = Kitsault; M = Mount Polley; R = Red Chris.

Table 1. Number of stations and individual water sample results for mine sites in this study.

Mine	Stations	Acidity	Alkalinity	SO$_4$	Al	Cd	Ca	Cu	Fe	Mg	Mn	Mo	K	Se	Na	Zn
Island Copper	19	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Gibraltar	48	90	43	124	91	1	39	91	91	39	39	91	1	1	37	39
C	1	0	0	57	17	17	17	65	64	17	17	66	17	17	17	17
Mount Polley	1	0	27	27	26	25	25	26	26	25	25	25	25	25	25	25
Huckleberry	1	34	38	70	69	69	69	69	69	69	69	69	69	69	69	69
Kitsault	26	0	212	213	36	27	80	27	35	80	27	27	69	27	77	27

Data Evaluation

Data interpretation involved two steps. First, scatter plots were prepared to compare pH with concentrations of ions because it was expected that pH would be the primary control on the

solubility of most ions. Then, based on the trends observed, the equilibrium speciation model MINTEQA2 (Allison et al., 1991) was used to evaluate possible secondary mineral controls on trends. Using a typical feed water chemistry and the presence of an assumed infinite supply of selected secondary Al, Fe and Cu minerals, MINTEQA2 was used to calculate the theoretical variation of metal concentrations with pH. Major element ion chemistry was also used to evaluate silicate minerals that might be influencing trace metal dispersion.

Results

Characteristics of Individual Deposits

Table 2 shows the main characteristics of the five identified and mined porphyry deposits, and the Red Chris Deposit. The following sections describe the characteristics along with features unique to these deposits that might affect interpretation of drainage chemistry. All deposits described are porphyries but differences are observed in alteration types and intensity. Two of the mines (Island Copper and Kitsault) are located in coastal areas and receive very high levels of precipitation. Island Copper Mine receives most of its precipitation in the form of rain. The other porphyry deposits are located in the interior of B.C. and experience cold winters during which snow accumulates, followed by melting of the snowpack during the spring.

Gibraltar Mine. Copper and Mo were extracted from a composite batholith composed of tonalite and trondhjemite (Bysouth et al., 1995). Mining began in 1972 and is ongoing. Hydrothermal alteration is primarily propylitic and dominated by chlorite. The mineral deposit was deformed after formation which complicates interpretation of the hydrothermal alteration. The widespread propylitic alteration may reflect regional greenschist metamorphism. The porphyry mineralization is dominated by pyrite and chalcopyrite but distinctive Mo and Zn zoning is observed. High temperature sections of the ore body are copper-molybdenum rich whereas low temperature sections are Zn-Cu rich. Pyrite is ubiquitous in the deposit.

Huckleberry Mine. Copper, Au and Mo are extracted from ore hosted by both granodiorite and a fine-grained crystaline tuff of andesite and dacite composition (Jackson and Illerbrun 1995). Mining began in 1997 and is ongoing. Hydrothermal alteration minerals include zoned biotite, sericite, epidote, amphibole, chlorite, magnetite, and hematite. Gypsum is an abundant late stage alteration product. The dominant sulfides are pyrite and chalcopyrite with minor molybdenite and bornite. Rock at Huckleberry varies from potentially acid generating to not potentially acid generating. The mine was specifically designed to prevent ARD from developing by ensuring that all potentially acid generating (PAG) rock will be submerged at mine closure. The data used for this study was obtained from a leach column containing fresh PAG rock that generated acid after several years in the column.

Island Copper Mine. Copper, Au and Mo were extracted from mineralized andesite and basalt and intrusive rhyodacite (Perelló et al., 1995). Mining began in 1971 and the mine is now closed. Hydrothermal alteration is zoned and consists dominantly of magnetite, bioite, quartz, sericite, and epidote. The rock is dominantly potentially acid generating. The main sulfide minerals are pyrite and chalcopyrite; however, molybdenite and sphalerite occur in the ore and host rock.

Kitsault Mine. Molybdenum mineralization is developed in a quartz monzonite to quartz diorite stock which intrudes siltstones and greywackes (Hodgson, 1995). Alteration is dominantly potassic (K-feldspar and minor biotite). The sulfide mineral suite is complex and includes

Table 2. Characteristics of porphyry deposits used in this study.

Name and Status	Class[1]		Commodities	Rock Types	Alteration Types[2]					Sulfides[3]						Reference
	Chem	Morph			Potassic	Phyllic	Argillic	Propylitic	Other	py	cpy	bo	sl	gn	mo	
Gibraltar Operating	CA	P	Cu, Mo, Au	Tonalite		Ser, q		q, ser, chl, ep, carb		M	M	m	m		m	Bysouth et al. (1995)
Huckleberry Operating	CA	C	Cu, Mo, Au	Andesite, dacite, granodiorite	bi, amph, k-sp, ab	chl, ser		chl, ep, py, ab	anh, zeo, carb	M	M	tr			m	Jackson and Illerbrun (1995)
Island Copper Closed	CA	V	Cu, Mo, Au	Andesite, basalt, rhyodacite porphyry, hydrothermal breccias	bi, mag, q, amph, k-sp	q, ser, chl, py	ser, ill, chl, py	ep, chl, mag, carb, py	zeo	M	M	m	m	m	M	Perelló et al. (1995). MINFILE
Kitsault Closed	CA	?	Mo	Diorite, quartz monzonite, greywacke, argillite	k-sp	present	present			M	m		m	m	M	Hodgson (1995)
Mount Polley Operating	A	V	Cu-Au	Diorite, plagioclase porphyry, hydrothernal breccia	bi, k-sp			ep, py, ab, cal	gt, ep, ab, k-sp	M	M	m				Fraser et al (1995)
Red Chris Proposed	CA	V	Cu, Au, Ag	Hornblende monzonite, volcanic wackes, siltstone, basalt	k-sp, bi, mag, hem	q, chl, ser, ank, py	Kaol	ep, py		M	M	M	tr	tr	m	Newell and Peatfield (1995)

Notes
1. CA – Calc-alkalic, A – Alkalic, P – Plutonic, V – Volcanic, C- Classic
2. ser – sericite, q – quartz, chl – chlorite, ep – epidite, carb – carbonates, bi – biotite, amph – amphibole, k-sp – potassium feldspar, py – pyrite, ill – illite, mag – magnetite, gt – garnet, ab – albite, hem – hematite, ank – ankerite, kaol – kaolonite, cal – calcite, present – alteration type noted but no mineralogical data.
3. py – pyrite, cp – chalcopyrite, bo – bornite, sl – sphalerite, gn – galena, mo – molybdenite, M – Major, m – minor, tr – trace.

molybdenite, pyrite, galena, sphalerite, chalcopyrite and tetrahedrite. Sulfur content of the waste rock is relatively low but components of the rock are potentially acid generating. Waste-rock seepage has been monitored since the 1980s.

Mount Polley Mine. Copper is extracted from altered brecciated felsic intrusions in alkali basalts in central British Columbia. Unlike the other mineral deposits considered in this study, Mount Polley is classified as an alkalic porphyry. Alteration includes a central potassic core surrounded by a garnet-epidote zone, and an outer propyltic rim (Fraser et al., 1995). The dominant sulfides are pyrite, chalcopyrite, and lesser bornite. Calcite is the dominant carbonate mineral. No acidic drainage is present at the site due to the buffering capacity provided by abundant calcite.

Red Chris Project. The Red Chris deposit is hosted by a small monzonite stock intruded into volcanic and sedimentary rocks (Newell and Peatfield 1995). The strongest alteration type is phyllic (quartz-sercite-pyrite) grading into propylitic in the country rocks. Potassic and argillic alteration is only locally present. Sulfide mineralization consists primarily of pyrite, chalcopyrite and bornite, but molybdenite and traces of galena and sphalerite are also present. No mining has taken place at Red Chris but the project received its Environmental Assessment Certificate in August 2005.

Drainage Chemistry Relationships

Metal concentrations as a function of pH are shown in Figs. 2 to 4. Sulfate concentrations (Fig. 2) show a slight increasing trend with decreasing pH for pH values of less than 5. At very low pH's (<3), SO_4^{-2} concentrations increase rapidly. The highest concentrations in the database are from Gibraltar Mine. This overall trend is shown by data for five sites including the Huckleberry Mine laboratory test. The SO_4^{-2} concentrations are generally lower at Kitsault Mine and did not increase as pH decreases.

Aluminum shows a very strong negative correlation with pH that is well defined by all sites except Mine C (Fig. 2). Again, the Huckleberry Mine leach column shows the same trend as monitoring data from the full-scale mine sites.
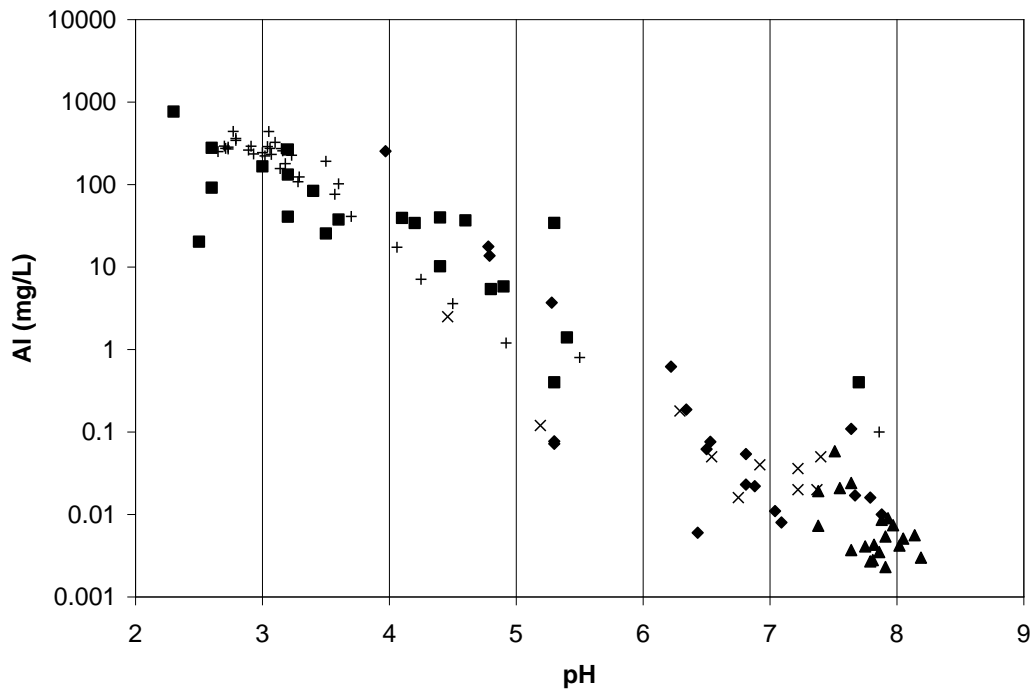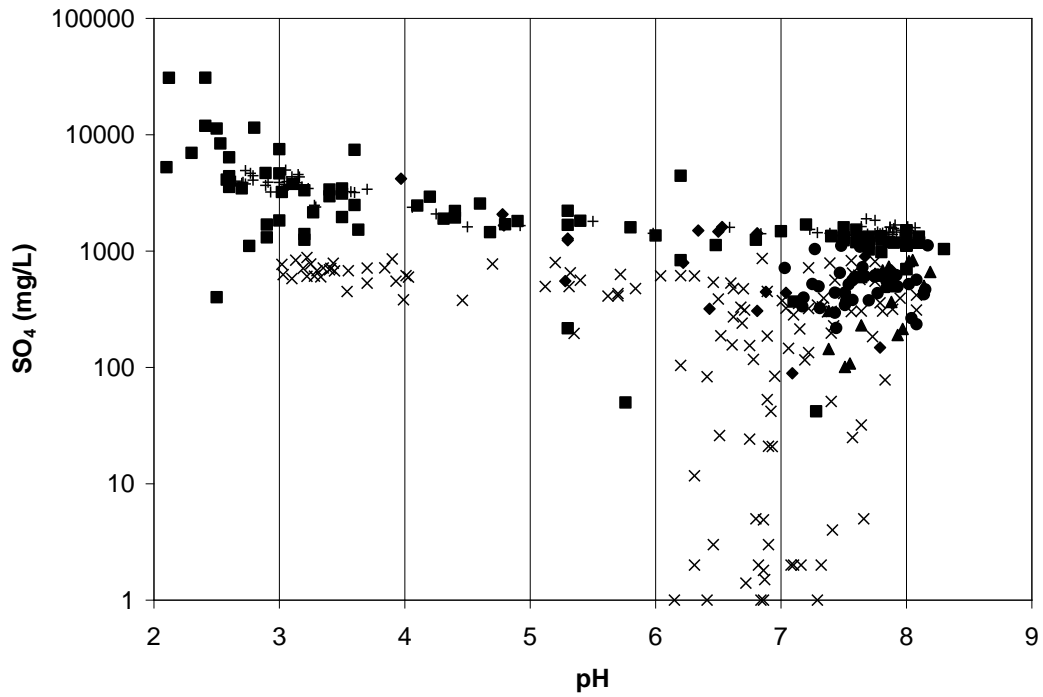
Figure 2. Scatter plots for SO_4^{-2} and Al as a function of pH. Diamonds – Island Copper; Squares - Gibraltar; Circles – Mine C; Triangle – Mount Polley; Cross – Huckleberry leach column; Diagonal Cross - Kitsault.
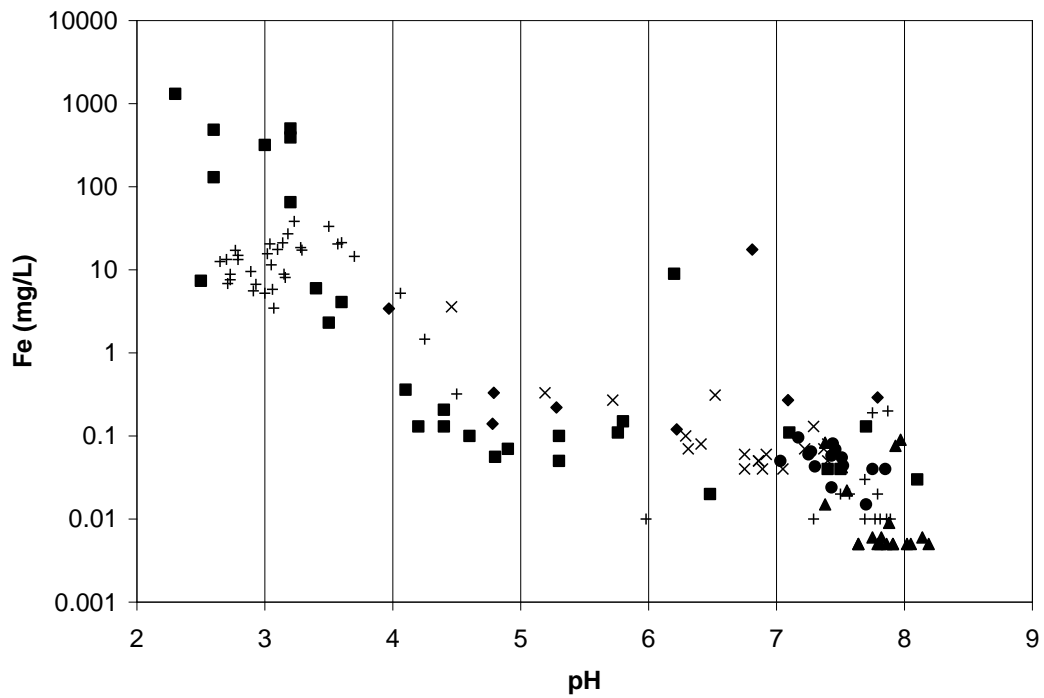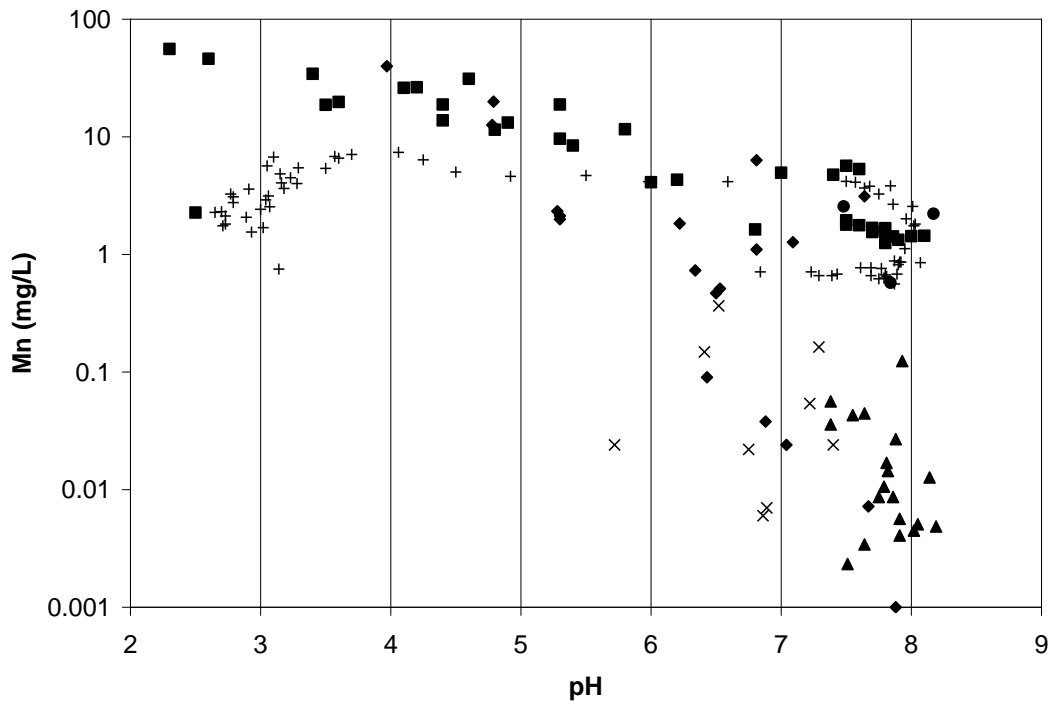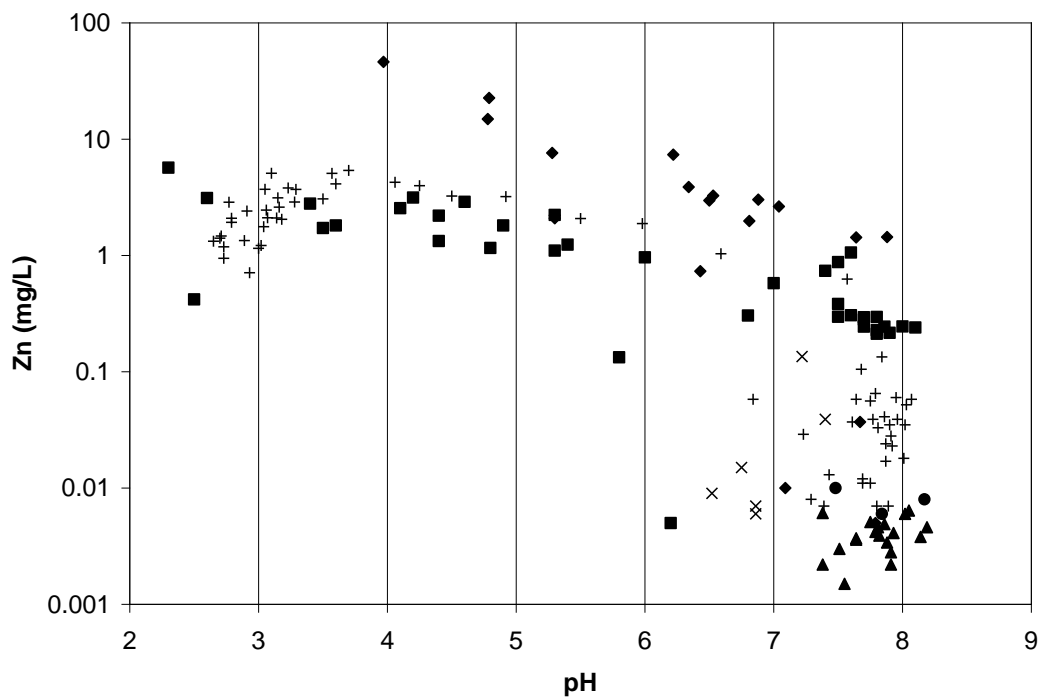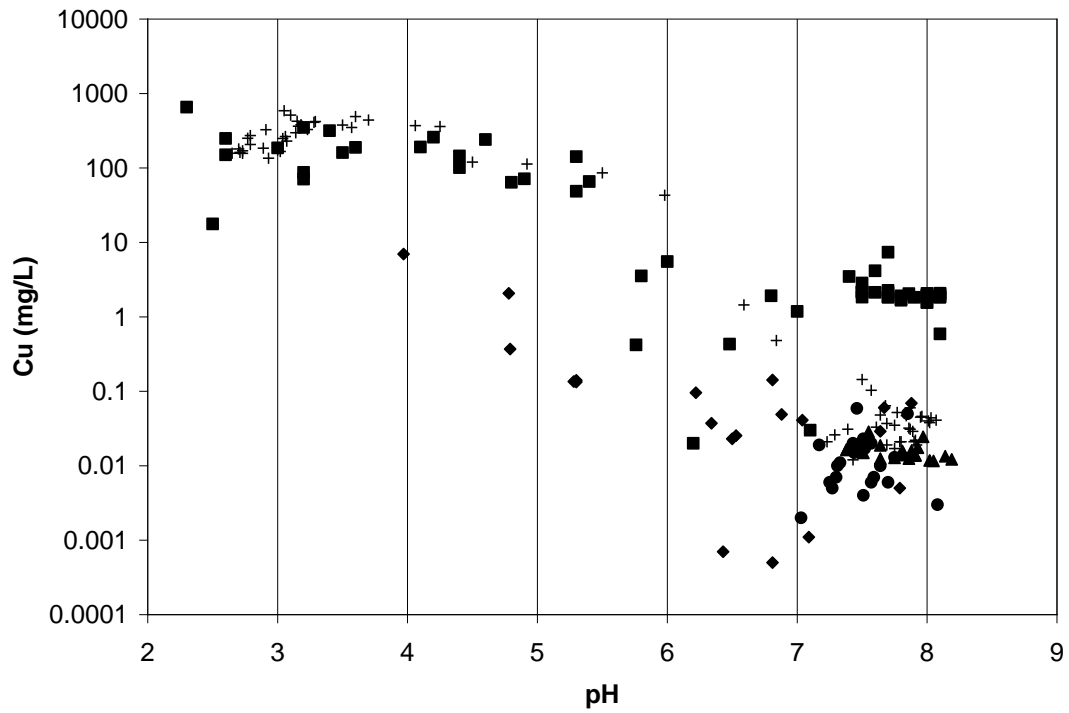
Figure 3. Scatter plots for Mn and Fe as a function of pH. Diamonds – Island Copper; Squares - Gibraltar; Circles – Mine C; Triangle – Mount Polley; Cross – Huckleberry leach column; Diagonal Cross - Kitsault.

Figure 4. Scatter plots for Cu and Zn as a function of pH. Diamonds – Island Copper; Squares - Gibraltar; Circles – Mine C; Triangle – Mount Polley; Cross – Huckleberry leach column; Diagonal Cross - Kitsault.

449

Iron concentrations do not vary substantially with pH above 4.5 (Fig. 2). Although below pH 4.5, a general negative correlation is shown for all sites. Most Huckleberry Mine leach column data are scattered near pH 3. This scatter is a result of decreasing Fe concentrations in leachate accompanied by steady pH below 3 following peak Fe release. Two points are well outside the main F trend at pH values between 6 and 7. The Island Copper Mine data point represents an Fe-rich seep discharging from a swamp buried by waste rock. The source of the single high Fe concentration from Gibraltar Mine is not known.

Manganese concentrations show a strong negative correlation with pH defined by Gibraltar Mine and Island Copper Mine (Fig. 2). Data from the Huckleberry Mine leach column show the same trend above pH 6, but generally lower Mn concentrations below pH 6. Like Fe, the positive correlation with pH near pH 3 reflects decreasing concentrations following a peak as pH continued to decrease. Mount Polley Mine and Kitsault Mine both had relatively low Mn concentrations.

A generally negative correlation with pH is shown by Cu (Fig. 3). The highest Cu concentrations are in samples from the Gibraltar Mine and Huckleberry Mine leach column. The trend is well-defined below pH 7 but becomes scattered for pH values above neutral. A group of Gibraltar Mine samples had Cu concentrations above 1 mg/L for pH between 7.5 and 8. The Cu concentrations in samples from the Island Copper Mine followed an increasing trend with decreasing pH, but at lower Cu concentrations. Copper concentrations in Kitsault Mine waters were either non-detectable (<0.01 mg/L) or not determined.

Fig. 3 shows a negative correlation between pH and Zn for samples from the Huckleberry Mine leach column and the Gibraltar Mine. Samples from the Island Copper Mine contain higher Zn concentrations than the other sites. Zinc concentrations in samples from the Mount Polley Mine and Kitsault Mine were relatively low (generally less than 0.02 mg/L). Cadmium concentrations also showed a similar relationship. Trends for Pb and Ni, defined by only a few data points, also display a negative correlation with pH.

Molybdenum concentrations (not shown) were highly scattered. Data from individual mine sites showed a positive correlation with pH but the relationship was different for each site. Gibraltar Mine and Kitsault Mine showed the highest Mo concentrations followed by Mount Polley, Huckleberry and Island Copper Mine.

Discussion

Sulfate Chemistry

At near neutral pH, sulfate concentrations are well-constrained at near 1,600 mg/L by the solubility of gypsum in the presence of Ca released by neutralization of acid by carbonates. The lack of significant scatter at near neutral pH indicates $CaCO_3$ is an important buffer in these waters. Higher SO_4^{-2} concentrations would be apparent if magnesium carbonates were significant neutralizing minerals. At lower pH, SO_4^{-2} concentrations increase due to the depletion of calcite and dissolution of minerals containing elements such as Al, Fe, Mg, K, and Na. The sulfates of these elements are more soluble than gypsum at low pH's and support higher SO_4^{-2} concentrations.

Aluminum Chemistry

The very strong relationship between Al and pH was evaluated using the solubilities of various basic aluminum sulfates and alunite in the MINTEQA2 thermodynamic database.

Aluminum concentrations above pH 4.5 are clearly explicable by the formation of either $Al(OH)_3$, alunite ($KAl_3(SO_4)_2(OH)_6$), or $Al_4(OH)_{10}SO_4$, but not $Al(OH)SO_4$ (Fig. 4). The latter mineral has greater solubility under all pH conditions than indicated by the Al concentrations in mine drainages. These findings are consistent with the observed formation of Al precipitates in drainage ditches at Island Copper Mine. This also indicates that Al minerals present as hydrothermal alteration products are reactive pH buffers.

Indications of the minerals involved are provided by the relationship between K and Mg (Fig. 5). For the Huckleberry Mine leach column data, the ratio of K/Mg is close to 1 whereas for the full-scale mine data it is generally lower than 0.08. The Huckleberry Mine data is consistent with dissolution of biotite ($KMgFe_2AlSi_3O_{10}(OH)_2$). The chemistry of drainage waters from the mine sites show that more Mg is released than would be expected if even if phlogopite ($KMg_3AlSi_3O_{10}(OH)_2$) was dissolving. This implies that either K is being removed, for example by the formation of alunite or jarosite, or that Mg is being contributed by the dissolution of another mineral, for example chlorite ($(Fe,Mg,Al)_6(Si,Al)_4O_{10}(OH)_8$). Dissolution of carbonates containing Mg could also be occurring.
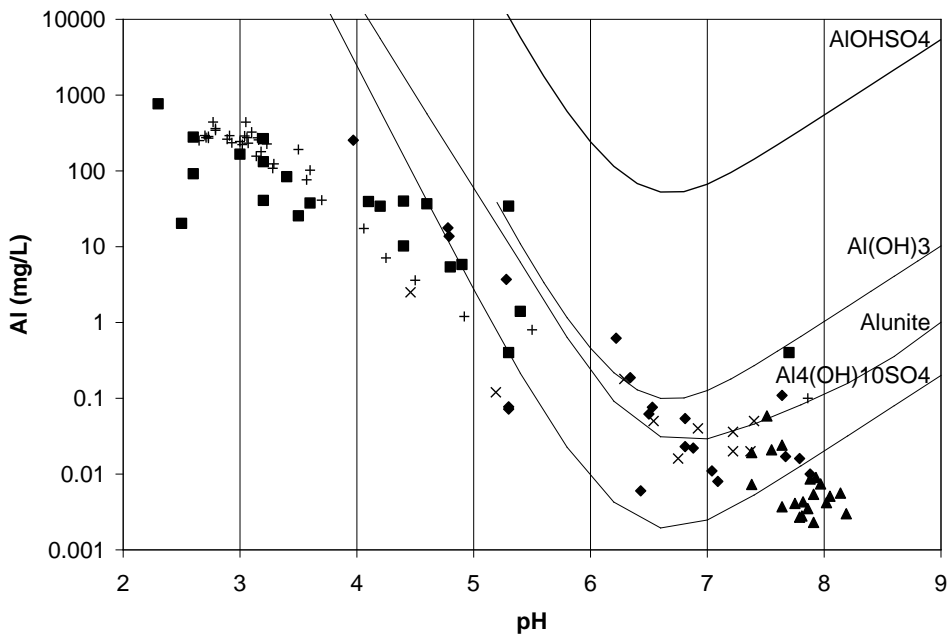

Figure 5. Comparison of monitoring data with solubility of Al minerals. Symbols for waters are same as in Figs. 2 to 4.
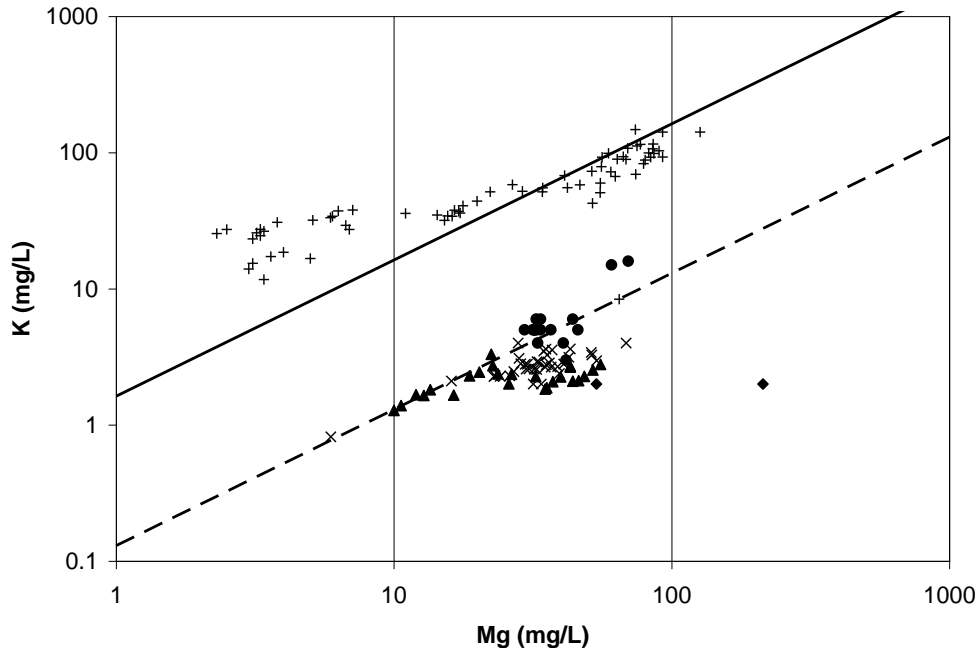
Figure 6. Comparison of K and Mg concentrations in mine drainage (solid line K/Mg = 1 (molar basis); dashed line K/Mg=0.08). Symbols for waters are same as in Figs. 2 to 4.

Iron Chemistry

Fig. 6 shows Fe concentrations in the database compared to the dissolution curve for $Fe(OH)_3$ calculated using MINTEQA2. Modeling of Fe concentrations was based on the assumption that all Fe is in the Fe^{+3} state because no Fe speciation data or oxidation-reduction potential measurements are available in the database. This curve provides a good fit to the data below pH 5. Iron concentrations above this line could be due to the presence of dissolved Fe^{+2}, which becomes important at lower pH and is more soluble than Fe^{+3} Fe. Overall, the data show that precipitation and dissolution of $Fe(OH)_3$ is an important control on Fe chemistry.

The solubility line for $Fe(OH)_3$ poorly fits the Fe concentrations above pH 5. Except in the case of the two Fe concentrations near 10 mg/L, this may be a result of concentrations near the detection limit and colloidal $Fe(OH)_3$. As indicated previously, the elevated Fe concentration at Island Copper Mine above pH 6 are probably due to Fe^{+2} Fe released in a reducing environment. No explanation is available for the single elevated Fe concentration above pH 6 at Gibraltar Mine.

In general, the similar Fe distribution for several different mines (including a laboratory test) indicates that common pH controls on Fe chemistry exist and can be applied to other sites.
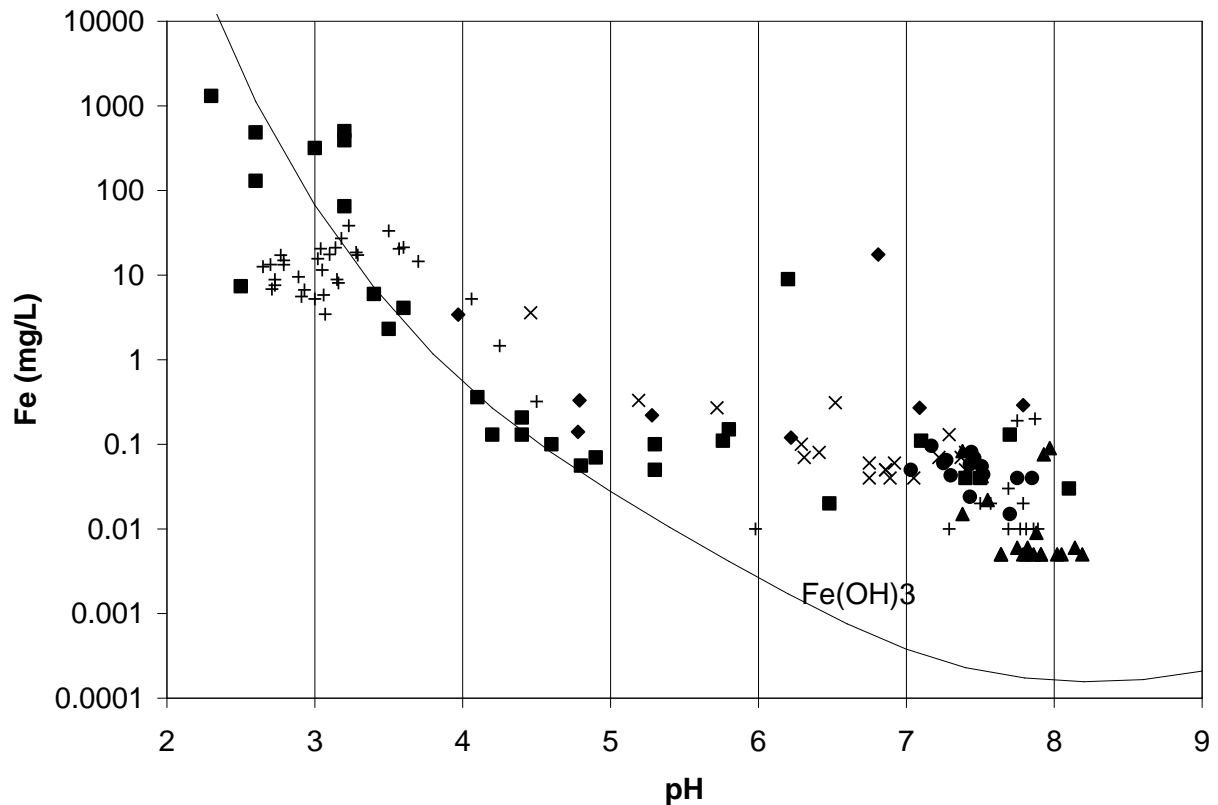
Figure 7. Comparison of Fe concentrations in monitoring database with the theoretical solubility of Fe(OH)$_3$.

Other Elements

At higher pH's, Cu concentrations are most likely limited by the dissolution of Cu carbonate such as malachite formed during oxidation of chalcopyrite and bornite under non-acidic conditions. MINTEQA2 indicates that Cu solubility at neutral pH (pH greater than 7) is between 0.5 and 1 mg/L. Copper concentrations in Huckleberry Mine column leachate were consistent with dissolution of malachite as pH decreased. Similarly, Gibraltar Mine waste-rock seepage is also consistent with this effect, though the cluster of data above 1 mg/L is anomalous (Fig. 3).

Copper concentrations in drainage from Island Copper, Mine C and Mount Polley are well below expected concentrations based on CuCO$_3$ minerals. This may be due to dissolution of Fe and Al co-precipitates such as woodwardite (Cu$_4$Al$_2$(SO$_4$)(OH)$_{12}$·2-4H$_2$O) which may have similar solubility controls to Al. It is not clear why Cu concentrations are much lower at Island Copper where chalcopyrite is present. Mine C, Kitsault Mine, and Mount Polley all had low Cu concentrations in drainage. For the first two, Cu concentrations in drainage may be low due to the limited chalcopyrite mineralization. Mount Polley is a Cu mine but the acid generation potential due to the weathering of pyrite is low which limits the locally acidic and oxidizing conditions required to oxidize chalcopyrite.

Zinc concentrations are well below concentrations expected if controlled by the dissolution of $ZnCO_3$, a common control for Zn (Day and Bowell, 2005). Zinc concentrations can generally be related to the presence of Zn mineralization as sphalerite. Island Copper Mine has the most ubiquitous sphalerite occurrence of the six mine sites and has the highest Zn concentrations in drainage. Sphalerite has not been reported at Huckleberry Mine and occurs in one zone at the Gibraltar Mine. It is present at Mine C and Kitsault Mine but not at Mount Polley Mine which shows the lowest Zn concentrations. Overall, the occurrence of Zn in drainage is not correlated with the presence or absence of reported sphalerite (except for Island Copper Mine), which limits the use of the database for prediction of Zn concentrations. Likewise, it is also not clear how cadmium concentrations are controlled.

Finally, Mn concentrations from Huckleberry Mine, Gibraltar Mine, Island Copper Mine, and Mine C at near neutral pH are roughly consistent with the dissolution of $MnCO_3$. At lower pH, the solubility of Mn increases perhaps due to the dissolution of manganese oxides.

Conclusions

Overall, SO_4^{-2}, Al, and Fe concentrations are consistent for all mine sites and the leach column in the study. This reflects solubility control by simple minerals such as gypsum, basic Al sulfates, and Fe hydroxides. This indicates that factors controlling the concentrations of these elements and the acidity in drainage waters are similar and predictable.

Concentrations of other metals in drainage waters appear to be controlled by site specific factors. For example, leaching of Cu appears to require the presence of chalcopyrite and sufficiently oxidizing conditions. Likewise, elevated Zn concentrations can be related to the presence of sphalerite. Prediction of metal concentrations using this dataset may lead to over-estimating concentrations if the mineralogy of the deposit is not well known.

The database was used to predict future metal concentrations in ARD from waste rock and the open pit at the Red Chris Project as part of the environmental impact assessment. The predictions were input into a site wide water quality model which in turn was used to determine needs for water treatment.

Acknowledgements

Literature Cited

Allison, J.D., D.S. Brown, and K.J. Novo-Gradac, 1991. MINTEQA2/PRODEFA2, A geochemical assessment model for environmental systems: Version 3.0 User's Manual, EPA/600/3-91/021. U.S. Environmental Protection Agency, Environ. Res. Lab., Athens, Ga.

Bowell, R.J., S.B. Rees, and J. Parshley, 2000. Geochemical predictions of metal leaching and acid generation: geologic controls and baseline assessment. p. 99–823. *In* R.F. Hardyman and C.L. Morris (eds.). Geology and ore deposits 2000: The Great Basin and beyond. Geological Society of Nevada Symposium Proceedings, Reno / Sparks, May 2000,.

Bysouth, G.D., K.V. Campbell, G.E. Barker, and G.K. Gagnier, 1995. Tonalite-trodhjemite fractionation of a peraluminous magma and the formation of syntectonic porphyry copper mineralization. p.201-213. *In* T.G. Schroeter (ed.). Porphyry deposits of the Northwestern Cordillera of North America. Canadian Institute of Mining and Metallurgy, Special Volume 46.

Caruccio, F.T., and J.C Ferm, 1974. Paleoenvironment – Predictor of acid mine drainage problems: National Coal Association/ Bituminous Coal Research Inc. p. 5-9. 5th Symposium on Coal Mine Drainage Research, Louisville, Ky.

Day, S.J. and R.J. Bowell. 2005. Atypical and typical zinc geochemistry in a carbonate setting, Sä Dena Hes Mine, Yukon Territory, Canada. p. 255–266. Geochemistry: Exploration, Environment, Analysis, v. 5. http://dx.doi.org/10.1144/1467-7873/03-046.

Fraser, T.M., C.R. Stanley, Z.T. Nikic, R. Pesalj and D. Gorc. 1995. The Mount Polley alkalic porphyry copper-gold deposit, south-central British Columbia. p.609-622. *In* T.G. Schroeter (ed.). Porphyry Deposits of the Northwestern Cordillera of the North America. Canadian Institute of Mining and Metallurgy, Special Volume 46.

Guilbert, J. M. and C.F. Park, Jr. 1986. The geology of ore deposits: W.H. Freeman and Company, New York.

Hodgson, C.J. 1995. Kitsault (Lime Creek) molybdenum mine, northwestern British Columbia. p.708-711. *In* T.G. Schroeter (ed.). Porphyry deposits of the Northwestern Cordillera of North America. Canadian Institute of Mining and Metallurgy, Special Volume 46.

Jackson, A. and K. Illerbrun. 1995. Huckleberry porphyry copper desposit, Tahtsa Lake district, west central British Columbia. p.313-321. *In* T.G. Schroeter (ed.). Porphyry deposits of the Northwestern Cordillera of North America. Canadian Institute of Mining and Metallurgy, Special Volume 46.

McMillan, W.J. and A. Panteleyev. 1988. Porphyry copper deposits. p. 45-58. *In* R.G. Roberts and P.A. Sheahan (eds.). Ore deposit models. Geoscience Canada Reprint Series 3.

Newel, J.M. and G.R. Peatfield, 1995. The Red Chris porphyry copper-gold deposit, northwestern British Colunbia. p. 674-690. *In* T.G. Schroeter (ed.). Porphyry deposits of the Northwestern Cordillera of North America. Canadian Institute of Mining and Metallurgy, Special Volume 46.

Perelló, J.A., J.A. Fleming, K.P. O'Kane, P.D. Burt, G.A. Clarke, M.D. Himes and A.T. Reeves. 1995. Porphyry copper-gold-molybdenum deposits in the Island Copper cluster, northern Vancouver Island. p. 214-238. *In* T.G. Schroeter (ed.). Porphyry deposits of the Northwestern Cordillera of North America. Canadian Institute of Mining and Metallurgy, Special Volume 46.

Plumlee, G.S. and J.T. Nash. 1995. Geoenvironmental models of mineral deposits – fundamentals and applications. p. 1-9. *In* E.A. du Bray (ed.). Preliminary compilation of descriptive geoenvironmental mineral deposit models. United States Geological Survey. Open File Report 95-831.

Red Chris Development Company Limited. 2004. Application for Environmental Assessment Certificate for the Red Chris Porphyry Project (October 2004). Volumes 1 to IV. Submitted to the British Columbia Environmental Assessment Office, October 2004.

Steffen, Robertson and Kirsten (B.C.) Inc., in association with Norecol Environmental Consultants and Gormley Process Engineering. 1989. Draft acid rock drainage technical guide, vols. 1 and 2. ISBN 0-7718-8893-7. Prepared for the British Columbia Acid Mine Drainage Task Force. BiTech Publishers, Richmond, British Columbia, Canada

Sutherland Brown, A. 1976. Morphology and classification. p. 44-51. *In* A. Sutherland Brown (ed.). Porphyry deposits of the Canadian Cordilleran: Canadian Institute of Mining and Metallurgy Special Volume 15.