Two and Three Decades Post-Closure: Revisiting the ARD Predictions and Closure Plans for Two Copper Mines in British Columbia, Canada

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Abstract
Two porphyry copper mines located in British Columbia, Canada operated from 1966 for 16 years and from 1970 for 22 years before closing. The mines are 7 km apart, located on a peninsula and an island within Babine Lake, British Columbia. The closure plan objectives were to restore land use to wildlife habitat and to protect water quality in Babine Lake. Mine materials were assessed prior to closure at one mine and shortly after closure at the other. Most of the mine rock and some of the tailings were predicted to be potentially acid generating. Therefore, the closure plans included water collection and storage in the open pits, ongoing monitoring of water quality and surveillance of dams. Water stored in the pits will be treated in the future as storage capacity is approached. A review of site conditions was undertaken in 2009 to verify that closure predictions were realized after about 20 and 30 years since closure at each mine. This paper presents a review of the prediction programs completed in the early 1990s and compares the results with the observations in 2009 for acid conditions and water quality two and three decades after mine closure.

Keywords: acid drainage, metal leaching, water quality predictions, porphyry copper,

Introduction
The Bell and Granisle mines hosting calc-alkalicporphyry copper deposits are located on the Newman Peninsula and on McDonald Island, southeast of the Newman Peninsula, respectively, in Babine Lake near Granisle, BC (Figure 1). Both mines had similar mineralogy and host rock types with copper mineralization and varying sulphide mineral contents. Copper mineralization occurred in abiotite-feldspar-porphyry with chalcopyrite, bornite, and pyrite and lesser amounts of pyrrhotite, gold, silver,sphalerite and molybdenite. A supergene cap existed over the ore prior to mining. The similarity of the deposita provides an opportunity to compare long term water quality effects associated with these porphyry copper deposits.

The Bell Mine started operations in 1970 and milling started in 1972 with production rates as high as 15,500 tonnes per day, later in the operation. The Bell Mine operation was concluded in March 1992 when available ore was exhausted. The Granisle Mine began operation as an open pit mine in 1966 and had a milling rate as high as 12,000 tonnes/day by 1972. Operations at the Granisle mine permanently ceased in 1982 due to low copper prices.

Closure plans were developed for both sites in the early 1990s (Maclaren Forest Products 1990, Noranda 1993). Updates of the geochemical characterization were completed in the late 1990s (MDAG 1999, 2000, AMEC 2003). The closure plan status was reviewed and additional studies were completed in 2009 to 2010 to specifically address water quality and geochemistry at both sites (EcoMetrix 2010a, 2010b).

Objectives
Both mines started operations at a time when the challenges of potentially acid generating mine materials were not fully understood. Acid drainage at metal mines was only becoming recognized at

Canadian operations in the 1970s and was first noted in the published literature at the Elliot Lake uranium mining district in Ontario, Canada (Hawley, 1971). Much of what is now known about acid generation associated with sulphide mineral oxidation was learned in the 1980s through the 1990s through integrated programs such as the NUTP, RATS and MEND initiatives in Canada that focused on acid generation issues, as well as other research initiatives. The objective of this paper is to present a case study of predictions and to compare predictions from the 1990s to performance in 2011 at mines that closed in the early 1980s and 1990s. Both sites have been under care and management by the owner since closure.

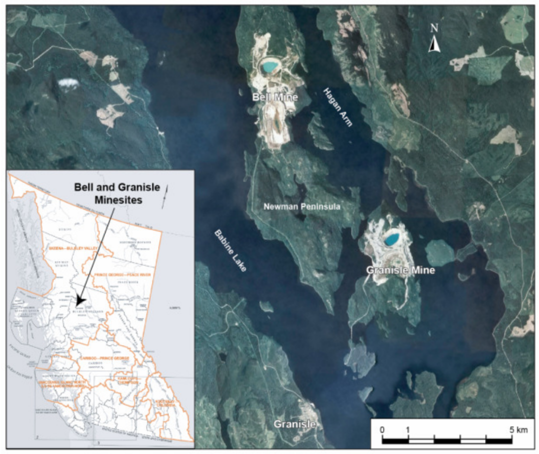

Figure 1: Location of the Bell and Granisle minesites near Smithers, British Columbia (Google Earth, under License).

Background

The total excavated volume of the Bell open pit is approximately 61.7Mm^3 representing about 143 Mt of material including 77 Mt of ore and 66 Mt of mine rock. The mine rock was used for construction of tailings dams and is also stored in two distinct stockpiles, one to the north and the other to the northeast of the pit (Figure 2). The tailings are stored in a management area (TMA) and a tailings extension area (TEX) south of the pit.

A total of 132 Mt of material was mined from the Granisle open pit including approximately 71 Mt of ore and low-grade material and 61 Mt of mine rock. The mill tailings are stored within Tailings Impoundments #1 and #2 and in the Emergency Tailings Impoundment (Figure 3). Approximately 16 Mt of low-grade material remains on site in the low-grade stockpiles. The majority of the mine rock was used for the construction of the tailings impoundment dams and very little was placed in rock stockpiles.

Near the end of operations at Bell in 1992, a closure plan was developed to guide long term reclamation and monitoring efforts at the site. Permitswere issued by the BC Ministry of Environment, Lands and Parks (now the Ministry of Environment) and the BC Ministry of Energy, Mines and Petroleum Resources (MEMPR), now the Ministry of Mines).

The original closure plan for the Granisle site was submitted to the MEMPR by Noranda Inc. (now Xstrata Copper) in August 1990. That plan was accepted by MEMPR in 1993. A series of studies was subsequently initiated by Noranda to obtain the data required to update the 1990 Reclamation Plan. Those studies resulted in an updated Closure Plan in 2003. Permit were also issued by the BC Ministry of the Environment(MOE) to address water monitoring requirements for the site and MEMPR for reclamation objectives and annual reports are prepared for each site and submitted to the respective regulatory bodies to demonstrate compliance.

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Figure 2: Configuration of the Bell minesite Figure 3: Configuration of the Granisle minesite

Proposed closure plan studies were reviewed by the public, the Northwest Mine Development Review Committee in Smithers, local government, and the First Nations communities. The key issues identified for consideration in the closure designs were:

- Thorough assessment of mine rock and tailings geochemistry;
- Prediction of long-term water chemistry;
- Establishment of historical and existing environmental conditions in the vicinity of the mines, and
- Environmental assessment of the closure approach.

Acid Base Accounting (ABA) analyses on mine rock samples was completed as part of the 1992 Bell Closure Plan and demonstrated that portions of most rock types are potentially capable of generating net acidity if stored on-land (Noranda, 1993). However, portions of some rock types were found to be capable of neutralizing a significant amount of acidity. In 1999, Minesite Drainage Assessment Group (MDAG) completed an update of the geochemistry at the Bell Mine (MDAG, 2000). That report provided an update and comparison of the predictions from the Closure Plan. It was found that static and kinetic geochemical data were generally consistent with those in the Closure Plan.

The original interpretation of acid rock drainage and metal leaching (ARD/ML) at the Granisle site was presented by SRK Consulting (SRK) inMaclaren Forest Products (1990). A review of past metal leaching and acid rock drainage characterization was completed by MDAG (1999). It was concluded that most of the mine rock was potentially acid generating when managed in on-land stockpiles or as construction material in dams.

Water quality was a major focus at the Bell Mine site where there were permitted discharges of clean water. As of 2011 there were three discharge locations that are monitored to ensure that the water quality leaving the site, either through seepage or permitted outfalls, meets required criteria. For locations where the discharge criteria are not met, water is collected in engineered ponds and pumped to the open pit for long-term storage. When the pit fills to capacity, the pit water will require management prior to release into Babine Lake.Monitoring at the Bell Mine has been ongoing since closure in the 1990s. A variety of monitoring programs have been created to aid in the continuous reclamation efforts and ongoing environmental protection at the site.

Monitoring at the Granisle Mine has been ongoing since closure in 1982. On- and off-site water management was and continues to be a priority and key activity at the Granisle Mine to ensure that contaminated water does not reach Babine Lake. Water is collected in ponds, monitored for quality and directed to the open pit for storage. The waters from some but not all monitoring locations have characteristics that are consistent with ARD. Other waters on site have characteristics that are consistent with ARD that has been neutralized *in-situ*.

Geochemistry of Rock and Tailings

Rock and tailings samples were anlaysed for ABA characteristics. The paste pH, net neutralization potential (NNP, or NP minus AP) and neutralization potential to acid potential ratios (NP/AP) for materials at the Bell site are summarized in Table1. The AP is represented by the sulphide content and the NP was determined by the standard Sobek acid titration method. The rock and tailings samples were collected from existing sources on site. The results show that some rock materials had become acidic with paste pH values as low as 2.4. The majority of the samples had negative NNP values indicating that the AP associated with sulphide contents exceeded the NP in samples. The NP/AP values were therefore typically less than 1. It was concluded that the majority of the rock and virtually all tailings at Bell were potentially acid generating. Similar results were found at the Granisle minesite.

Table 1: Summary of ABA data for the Bell minesite (MDAG, 2000).

Number of Samples	Material Type	Year	NNP ($kg-CaCO_3/t$)			Paste pH			NP/AP		
			Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
17	Rock	1987	-388	-44	+18	2.6	6.8	8.0	-0.2	0.8	2.6
7	Rock	1987	-141	-8	+42	1.8	5.6	7.2	-0.04	1.7	3.5
1	Rock	1990		-28			8.1			0.7	
16	Rock	1991	-86	-35	-5	7.9	8.1	8.2	0.3	0.6	0.9
5	Tailings	1991	-120	-96	-14	3.3	4.2	5.3	-0.1	-0.06	0.01
10	Rock	1991	-111	-43	-6	7.8	7.9	8.0	0.3	0.6	0.9
16	Rock	1991	-86	-35	-5	7.9	8.1	8.2	0.3	0.6	0.9
5	Tailings	1991	-120	-96	-14	3.3	4.2	5.3	-0.1	-0.06	0.01
10	Rock	1991	-111	-43	-6	7.8	7.9	8.0	0.3	0.6	0.9
38	Rock	1999	-87	-32	+13	2.4	7.5	9.2	-0.4	0.6	1.3

Kinetic tests on rock and tailings were also completed for both sites. The results from humidity cell tests were complemented with results from heap leach column and pilot-scale tests from the Bell mine,as well as monitoring data from both minesites. The two primary objectives of the kinetic tests were to estimate NP depletion rates, the time to onset of acidification, where applicable, and the chemistry of drainage from rock and tailings.

A summary of the kinetic test programs and field monitoring data used to estimate water quality is presented in Table 2. The kinetic tests forthe Bell Mine included results from 24 sulphuric acidleach (heap-leach) tests on ore and low grade ore, as well as seven humidity cell tests with weekly rinsing. The kinetic data forthe Granisle Minewas collected from eight column tests and complimented by long-term water quality monitoring data at 15 stations on site. The column tests contained mine rock materials from site and included weekly rinsing with water and collection of leachate. The conclusion of potentially acid generating materials was supported by some of the results from the kinetic test program and site monitoring data.

The sulphate generation rates from the kinetic tests were used to calculate sulphide depletion rates.(Noranda, 1993). The sulphate originates from all sulphide minerals present and no attempt was made to differentiate the sources such as pyrite from other sulphide minerals The average sulphide contents in various materials were applied to estimate the times to deplete sulphide minerals in various facilities at the Bell Mine. The acid generation rates from kinetic tests were similarly applied to estimate the times to deplete NP that were assumed to coincide with the potential onset of acidification. Table 3 presents the dates that were estimated for the onset of acid generation and for sulphide depletion in the various mine facilities assuming that reaction rates remain constant over time.

Table 2: Summary of Kinetic Test Programs for the Bell and Granisleminesites.

Minesite	Test	Materials	Mass (kg)	Initial Conditions
Bell	**Heap Leach**			
	4 Columns	Ore	25	Acidic
	12 Columns	Ore	2,500	Acidic
	8 Cribs	Ore	30,000	Acidic
	Humidity Cells			
	3	Rock	1	Neutral/Acidic
	4	Tailings	1	Neutral/Acidic
Granisle	8 Columns	Rock	50	Neutral/Acidic
	Site Monitoring Data	all		Neutral/Acidic

Table 3: Geochemistry and Predictionsforthe Bell minesite (Noranda, 2003)).

Location	Volume of Material	Geochemical Parameters			Predictions for	
		Paste pH	NNP ($kg\text{-}CaCO_3/t$)	NP/AP	Acid Drainage	Sulphide Depletion
	(Mm^3)	(mean)			(year)	
North Rock Dump	1987	7.7	-18	0.87	2020	2100
Dump 7	1987	7.7	+15.5	1.95	2020	2040
A-Frame Dump	1990	5.7	-34	0.38	2000	2070
Dam 1 and 2	1991	7.6	-8	1.16	2010	2060
South Dump Plant Site	1991	6.9	-17	0.90	2010	2060
Dam 3 and 4	1991	7.7	+15	1.39	2030	2060
Tailings	1999	6.5	-45	0.72	2000	NA

Tailings were also classified as potentially acid generating (PAG) at both sites and acidification in the shallow tailings was anticipated (MDAG 2000). However, the water table in the tailings was expected to remain within a few metres of the ground surface and all tailings below the water table were not expected to oxidize or acidify. Therefore, only tailings above the water table were expected to have the potential to generate acid. All water infiltrating the tailings moves vertically down from the vadose zone through the underlying tailings before migrating laterally. Therefore, all acidic water from the vadose zone will migrate through the tailings below the water table. An acid-base mass balance suggested that the net acid generated in the vadose zone would be consumed and neutralized by the NP in tailings below the water table. Therefore no net acidic water was expected to exit the tailings via groundwater (MDAG, 2000).

Predicted and Observed Water Quality

The water quality predictions were based on humidity cell loading rates with modifications related to empirical relationships between chemical parameters (MDAG, 2000). For example, sulphate loading rates derived from kinetic tests exhibited littltle to no scaling relationship between results for fine grained (minus 0.6 cm) material in humidity cells and heap leach tests in cribs with larger (minus 60 cm) material. Therefore particle size adjustment factors were not applied for scale-up. In the 1992 closure studies at Bell Mine, the only adjustment factor used to scale lab results to the field was the estimated quantity of rock in contact with water that infiltrates the stockpile or dam. A factor of 0.1 was used, assuming that only 10% of the rock was flushed by water infiltrating the rock pile. Predictions of water quality were later updated by considering empirical relationships such as concentrations versus pH for metals (MDAG, 2000). Ranges of concentrations were estimated for the constituents of potential concern (COPCs) at key locations. Concentrations were also estimated for conditions prior to the onset of acidic generation and after NP depletion. A summary of predicted values for chemical parameters at locations that had not yet become acidic is presented in Table 4 together with measured values in 1992 and 2011.

Table 4: Predicted (MDAG, 2000) and Measured Water Chemistry in Selected Collection Ponds at the Bell minesite.

Location	Condition	pH	Sulphate	Dissolved Copper	Dissolved Iron	Dissolved Zinc
		pH units	(mg/L)	(mg/L)	(mg/L)	(mg/L)
North Dump (CP 8)	Measured in 1992	7.0	2,000	<0.01	<0.03	<0.01
	Predicted at pH = 7.0	7.0	2,000	0.20	0.08	0.06
	Predicted for NP Depletion	2.5	10,000	800	500	5.0
	Measured in April 2011	6.6	6,170	1.1	<1.0	0.38
Dump 7 (CP D7)	Measured in 1992	7.0	2,000	<0.05	<0.03	<0.01
	Predicted at pH = 7.0	7.0	2,000	0.20	0.80	0.06
	Predicted for NP Depletion	2.5	10,000	800	500	5.0
	Measured in April 2011	6.0	3,960	0.05	<1.0	0.10
A-Frame Dump (CP 4 & CP 5)	Predicted at pH = 7.0	6.3	1,600	8.0	<0.03	0.07
	Predicted for NP Depletion	2.5	10,000	800	500	5.0
	Measured in April 2011 (CP 4)	3.5	2,880	67	130	5.6
	Measured in April 2011 (CP 5)	6.1	2,070	1.4	<1.0	0.60
Dam 1 & 2 (CP 1-3 & CP 1-5)	Measured in 1992	7.6	1,800	0.20	<0.03	0.07
	Predicted at pH = 7.0	7.0	2,000	0.20	0.08	0.06
	Predicted for NP Depletion	2.5	10,000	800	500	5.0
	Measured in April 2011 (CP 1-3)	6.8	2,770	0.75	<1.0	0.28
	Measured in April 2011 (CP 1-5)	6.5	2,200	6.8	<1.0	1.3
South Dump Plant Site (CP 2)	Measured in 1992	7.0	1,000	4.0	<0.03	0.40
	Predicted at pH = 7.0	7.0	2,000	0.20	0.08	0.06
	Predicted for NP Depletion	2.5	10,000	800	500	5.0
	Measured in April 2008[a]	5.8	5,230	10.8	2.0	0.9
Dam 3 & 4 (CP 3-1)	Measured in 1992	7.8	<2,000	<0.02	<0.03	<0.01
	Predicted at pH = 7.0	7.0	2,000	0.20	0.08	0.06
	Measured in April 2011	6.8	1,920	0.002	<1.0	<0.04
Tailings (Pond)	Measured in 1992	7.0	<2,000	<0.01	<0.03	<0.01
	Measured in April 2011	6.8	1,730	0.015	<1.0	<0.04

As shown in Table 4, where 1992 measurements were available, pH values were near neutral at all locations, sulphate was generally near 2,000 mg/L, as expected for gypsum solubility, and dissolved copper concentrations varied widely from less 0.01 to 4 mg/L.

The predicted concentrations of metals at neutral pH were orders of magnitude lower than those for acidic pH conditions. All waters, except for those at CP3-1, were predicted to eventually be acidic with sulphate and metal concentrations predicted to be about 10,000 mg/L and in the range of 10 to 800 mg/L, respectively.

Measured pH values in 2011 were generally in the range of 6 to 7 with the exception of CP4 that had a pH value of 3.5. Sulphate and copper concentrations in the neutral pH collection ponds in 2011 varied fromabout 2,000 to 6,100 mg/L and 0.002 to 6.8 mg/L, respectively, and those values were generally intermediate between values predicted for neutral pH and those predicted for acidic conditions.

The chemical trends for water in collection ponds that have not yet become acidic show pH values that have remained near-neutral, whereas sulphate and hardness values have apparent upward trendsupward since the mid-1990s. Trends for pH, sulphate, hardness and dissolved copper in CP 8 are plotted in Figure 4with trend lines that have lery low R^2 values that are not significant. Water quality at CP 8 exhibits characteristics that are consistent with neutralized ARD, with near-neutral pH values and high concentrations of sulphate, hardness and copper. There is substantial variability in the concentrations within the long term trends that likely result from hydrologic variations on site. The seasonal peak values evident in the copper plot correspond to spring freshet in either March or april of each year. Similar trends for sulphate and hardness are observed because sulphate results from ongoing sulphide oxidation and hardness represents the consumption of NP that occurs when the sulphuric acid from sulphide oxidation is neutralized.

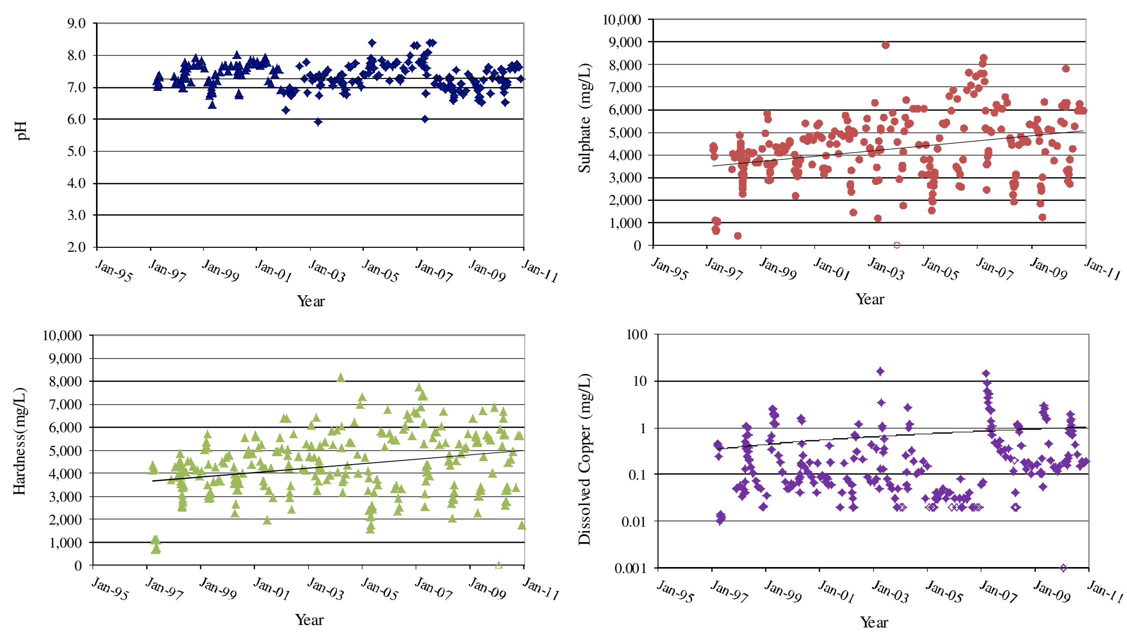

Figure 4: Water Chemistry Trends at CP 8 at the Bell minesite

The predicted values for water quality at the Bell minesite agree well with measured data indicating that after almost 20 years, the water quality predictions remain valid. The timeof onset of acidic conditions for some collection ponds was predicted to occur in 2010 and acid pH values have not yet been observed. However, the prediction that acidic conditions will occur is not contradicted by the data that have exhibited slight declines in pH values toward acidic conditions and increases in sulphate and copper concentrations between 1992 and 2011. Those trends indicate the evolution of acidic conditions and support the prediction that acidic conditions will occur in the future. The predicted times for the onset of acidic drainage were base on linear extrapolation of rates into the future and there may be som potential for refinement of those predictions if non-linear relationships were considered.

In practical terms, the water quality predictions do not need to be precise after certain threshold values are attained. For example, if discharge criteria are exceeded, water management and possibly treatment will be required whether the values are exceeded by a factor of ten or one-hundred. More precise estimates of water quality can be helpful for water treatment planning purposes, however. In either case, the water would require management prior to release to the environment. Therefore, a major concern for prediction of water quality is whether or not acidic conditions occur. If the water is acidic, then it will likely exceed at least one criterion for discharge. If the drainage remains neutral, then prediction of the concentrations of key COPCs may be more relevant in relation to discharge criteria and/or effects on the receiving environment. In a case in which exceedences are anticipated to be small, it may be relevant to have more precise estimates of expected concentrations in order to explore mitigation options other than treatment in a typical water treatment plant.

Many collection ponds at the Bell minesitethat have neutral pH also have dissolved copper concentrations that exceed the permit discharge limit of 0.15 mg/L. Of those listed in Table 4, only pond CP3-1 is approved for discharge to Babine Lake and only after permit requirements are met. The water from all collections ponds that do not meet permitted discharge limits for constituents is pumped to the pit and stored for future treatment before release to the environment.

Pit Water Quality

The quality of water in the pit will ultimately determine water treatment requirements. The pit water also represents an integrated water quality for site in this case, rather that worst or best case concentrations and is therefore relevant to understanding what quality of water will be subjected to treatment. Pit water samples have been analyzed annually in April since 1992 and the time trends display variability that suggested that near surface samples may be affected by temporal variations and seasonal stratification that was responsible for the large year to year variations. The pit water was sampled at multiple depths in October 2009 to assess water quality. The results showed that the pit water was well mixed over the entire depth of 150m. The results for selected constituents are summarized in Table 5. The pH of the pit water was near 4 with sulphate and hardness concentrations of about 3,000 mg/L. The concentrations of copper, iron and zinc were on the order of 10, 1 and 1 mg/L, respectively. This water quality reflects that of the mixture of waters that are collected and pumped to the pit. Dissolved aluminum and manganese, with concentrations of 12.6 and 7.5 mg/L, respectively represent about 72% of the stored acidity, and therefore, the majority of the lime demand if the water is treated by traditional pH adjustment. The detailed chemistry of the pit water, including profile sampling with depth, will be re-assessed in preparation for the planning and design for a water treatment system.

The pit water quality was predicted in the closure plan assessment by estimating the mixing of various collection pond waters together with fresh precipitation and runoff. The predicted pH was 5 and copper concentration was 10 mg/L andthose values are similar to those observed in the well mixed pit in 2009.

Table 5: Bell Mine Pit Water Chemistry Profile

Constituent	Units	□	Minimum	Maximum	Average
General Parameters					
pH	--	10	3.89	4.07	4.01
Hardness	mg/L as $CaCO_3$	10	2,770	3,010	2,844
Sulfate	mg/L	10	2,930	2,970	2,954
Dissolved Metals					
Aluminum	mg/L	10	12.1	13.2	12.6
Copper	mg/L	10	8.43	9.12	8.87
Manganese	mg/L	10	7.11	7.60	7.40
Iron	mg/L	10	0.296	0.707	0.62
Zinc	mg/L	10	1.22	1.32	1.29

Tailings

The closure plan studies suggested that tailings will become acidic near the surface and tailings below the water table were expected to remain neutral. Any acidic water generated above the water table was expected to be neutralized by the NP in the tailings below the water table and therefore, no net acidic water was expected to exit the tailings via groundwater. The closure plan studies in 1992also suggested that anacid front, with a pH of 4 or less, would migrate downward at a rate of about 0.2 m/a, or a total of 2 m in about 10 years or by 2002 in the tailings at Bell Mine (Noranda, 1992). The predictions were based on diffusion calculations to define oxygen flux and mass balance for sulphide and NP content. It was also predicted that the sulphide content in the tailings would deplete with depth at a rate of 0.7 m/a. While explicit predictions of acid generation and sulphide depletion rates were not made for the Granisle tailings, it was acknowledged that some tailings at the site were PAG.

Field investigations of tailings at both sites were completed in 2009 and results were compared to overall predictions (EcoMetrix 2010a, 2010b). Tailings samples were collected from a total 14 stations, with seven stations at both the Granisle and Bell minesites. Samples at each station were collected by hand coring at four to evaluate the profile to a depth of about 80 cm below surface. A follow up sampling in 2002 had showed that the depth of acidification was much shallower than originally predicted. The solids and pore waters were characterized in all samples.

The results for tailings samples from the Bell Mineexhibited rinse pH values of less than 5 at four stations (Figure 5) compared to pH values between 6.5 and 8 for unoxidized tailings. Only two of the stations exhibited pH values less than 5 at a depth of 0.8 m below surface. The depletion of NP to values less than 5 kg-$CaCO_3$/t occurred in samples with rinse pH values less than 5 and at two of those stations, depletion was evident at a depth of 0.8 m below surface. At other stations, the NP increased with depth to values near 30kg-$CaCO_3$/t at the 0.8 m depth. Although the sulphide contents in the tailings solids were lower at surface than at depth, only two stations exhibited values of less than 0.5%S in the top 0.1 m. Sulphide contents below 0.4 m varied between 1.5 and 3.2%S, values that were consistent with unoxidized tailings, indicating that sulphide depletion was not appreciable at depths below 0.5 m (Figure 5). Soluble sulphate concentrations were typically between 1,000 and 5,000 mg/kg at all depths. In contrast, soluble copper concentrations were in the range of 10 to 100 mg/kg in samples with rinse pH values less than 5. In samples with rinse pH values greater than 5, soluble copper concentrations were less than 0.2 mg/kg.

The variations in the pH as well as depletion of sulphide and NP are considered to be the result of variable moisture conditions of the tailings near surface. The impoundments have ponded water near the centres and more well drained conditions toward the edges. The higher water contents near the ponds result in lower oxygen fluxes into the tailings and reduce the rates of sulphide oxidation compared to lower water content areas that are better drained at surface away from the ponded water.

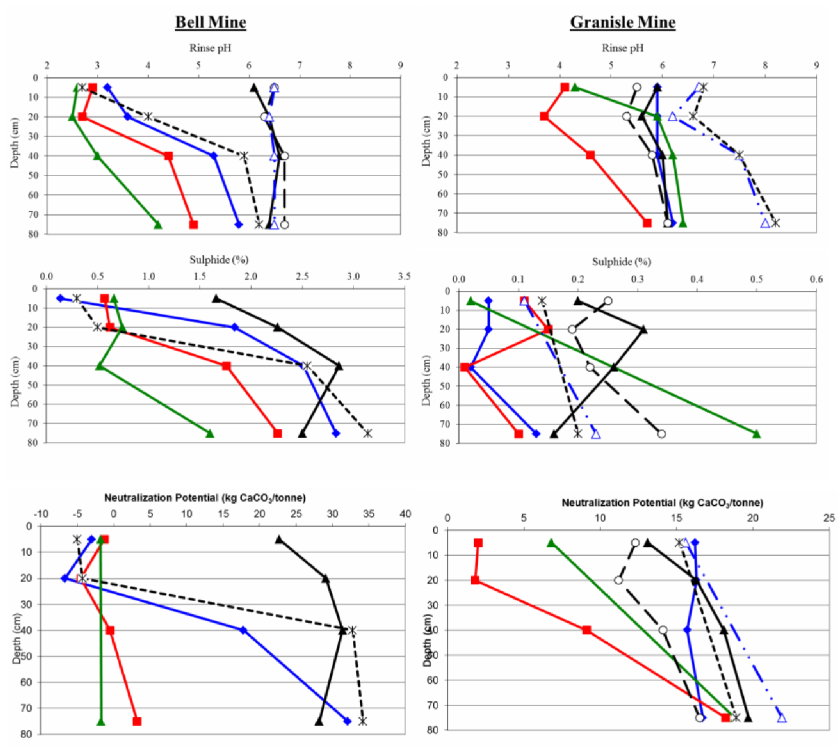

Figure 5: Results for Rinse pH and Sulphide and NP Contents from the 2009 Tailings Investigations at the Bell and Granisle minesites

These data clearly showed that acidic conditionsoccurred in shallow tailings at Bell Mine. However, no locations exhibited sulphide depletion below a depth of 0.4 m. Also, it is evident that the underlying tailings effectively neutralize acidity produced in the near surface zone even though pore water with pH less than five has evolved to depths greater than 0.8 m at some locations.

The tailings results at the Granisle Mine had rinse pH values less than 5 at only two locations. Those samples were from Impoundment #1. All other tailings samples exhibited pH values between about 5.5 and 8, with an average pH value near 6.5, at a depth of 0.8 m below surface (Figure 5). The NP values at all stations were greater at depth than at the surface, suggesting depletion in the shallow tailings. Only samples with rinse pH values less than 5 exhibited NP values less than 10 kg-$CaCO_3$/t. Samples with rinse pH values greater than 5 exhibited NP values between 12 and 20 kg-$CaCO_3$/t that generally increased with depth. The sulphide contents in tailings at Granisle varied from about 0.05 to 0.5% S with no obvious trends over depth (Figure 5). Soluble sulphate concentrations were between 100 and 700 mg/kg at stations with rinse pH values less than 5 and were between 10 and 50 mg/kg at other stations. Soluble copper was highest in samples with the lowest pH with values near 5 mg/kg. All other samples exhibited values between 0.1 and 0.8 mg/kg near surface and between 0.01 and 0.1 mg/kg at depth.

These data confirmed that only some tailings were generating acid near surface and that neutralization of infiltrating pore water was occurring in the top 1 m of tailings. Neutralization of the pore water with depth also resulted in natural attenuation of copper and other metals.

The tailings investigations showed that acidity, copper and other metals in pore waters are attenuated at depth in the tailings by neutralization reactions. Therefore, overall, the prediction in the closure plan of acid conditions in shallow tailings but not in tailings seepage that exits the tailings is supported by the 2009 data. However, the rates of the advancement of the acid front as well as that for sulphide depletion in the solids were largely over predicted in the original estimates (Noranda, 1993) likely as a result of the assumption of lower water contents that result in higher diffusion fluxes for oxygen. Revised estimates for sulphide depletion rates in the Bell mine update (MDAG, 2000) were lower than the original estimates but also overestimated depletion rates based on observations in 2009. The data show that rates of acid front migration and of sulphide depletion are highly variable and likely depend on the degrees of moisture in the tailings that controls the rate of oxygen entry or flux into the tailings, as expected. The over estimation of these rates, however, does not affect the overall conclusion that while some near surface tailings will generate acid, the underlying tailings, particularly the mass below the water table, will neutralize all of the acidity produced above the water table.

Conclusions

Extensive ABA and kinetic test data combined with available water quality data from 20 years of mine operations provided a strong basis for water quality predictions at the Bell and Granisle minesites. The results of the static tests correctly predicted acidic conditions in mine rock and tailings in the absence of mitigation. The kinetic results from a variety of tests assisted with the prediction of the time to onset of acidic conditions or the depletion of NP, estimates of the time to sulphide mineral depletion, as well as estimated concentrations of acidity, sulphate and metals at neutral and acidic pH values. The water quality predictions were adjusted to agree with empirical relationships with pH and other master variables observed in field data from both sites as well as laboratory results.

After almost 20 years at Bell and 30 years at Granisle, the water quality predictions associated with mine rock remain valid and agree with site data. Predictions of the onset of acidic conditions at previously neutralize drainage facilities were not contradicted by the data but many of the predicted dates for onset of acid conditions remain to be observed in the future. The overall prediction of acid conditions in the tailings was valid. However, the rates of acid front migration with depth were overestimated. The times for sulphide depletion in tailings were, therefore, underestimated. Nonetheless, the prediction that the tailings will not generate net acidity in groundwater seepage below the tailings currently appearsto be valid and is supported by the 2009 data.

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Acronyms

ABA	Acid Base Accounting
AP	Acid Potential
ARD/ML	Acid rock drainage and metal leaching
BC	British Columbia
COPCs	Constituents of potential concern
EEM	Environmental Effects Monitoring
MDAG	Minesite Drainage Assessment Group
MEMPR	Ministry of Energy, Mines and Petroleum Resources
MEND	Mine Environment Neutral Drainage
MOE	Ministry of Environment
NNP	Net neutralization potential
NP	Neutralization Potential
NUTP	National Uranium Tailings Program
PAG	Potentially Acid Generating
RATS	Reactive Acid Tailings Sulphides
SRK	SRK Consulting
TEX	Tailings Extension Area
TMA	Tailings Management Area