

COMPARISONS OF AMD PREDICTIONS WITH HISTORICAL RECORDS

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ABSTRACT

While many predictions of acidic drainage and metal leaching have been reasonably accurate when compared to historical monitoring data, there have also been some mistakes. To avoid these and similar mistakes in the future, several case studies from Canada are presented in this paper, including Equity Silver and Samatosum. The actual or potential mistakes involved either the underestimation or overestimation of acidic drainage and metal leaching. While the risk and liability of underestimation are obvious, overestimation can lead to unnecessary and expensive control measures and other long-term risks. In other words, a lack of accuracy in either direction leads to unwanted costs and concerns. The case studies show that the predictive techniques, which have been in use for decades, were not wrong, but that improper interpretations or unexpected complications led to the errors. For example, the interpretation of acid-base accounts (ABA) without the results of several other static and kinetic tests like mineralogy and humidity cells increases the potential for erroneous predictions. Also, predictions of drainage chemistry based on geochemical tests can err due to field-scale physical factors.

1.0 INTRODUCTION

The predictions of acidic drainage and of metal leaching at any pH are relatively simple under many conditions (Morin and Hutt, 1997a). For example, rock with a significantly negative NNP value or positive NAPP value, and low NPR value below 1.0, will likely generate net acidity at some point in time (see the Glossary for definitions). In contrast, tailings with a significantly positive NNP value or negative NAPP value, and elevated NPR value, will likely not generate net acidity. Predictions become much less certain at near-zero values of NNP and NAPP.

While the preceding paragraph describes simple scenarios that seem obvious, there have been situations in which these simple scenarios did not apply. This paper presents actual case studies involving those errors, or the potential for those errors. In some ways, this is not fair, because it gives the false impression that predictions of drainage chemistry are not often correct. In reality, most predictions have been reasonably accurate. However, from the viewpoint that we can learn and benefit from past mistakes, these case studies illustrate where predictions can go wrong. Such studies of past problems are one emphasis of the Canadian MEND Program (Feasby et al., 1997), which lowers drainage-control costs for, and increases public confidence in, mining companies within Canada and around the world.

In hindsight, the reasons for the actual or potential errors are clear, but they were not obvious to the mining companies and consultants at the time. In other words, there is no evidence that the people involved in these case studies were attempting to deceive anyone. They were, in fact, trying their best. No one purposely creates at any minesite a drainage-chemistry liability that is now often valued at US\$10,000,000 to \$100,000,000, with the highest reported cost currently reaching US\$7,000,000,000 (Jakubick et al., 1997).

2.0 CASE STUDY 1

The first case study is Equity Silver Mine in British Columbia, Canada (Aziz and Ferguson, 1997; Case Study 6.2-9 in Morin and Hutt, 1997). This gold-copper-silver property operated from 1980 to 1994, using open pits and underground workings to feed a mill at 9000 t/d.

The ore zones are contained in sequences of sedimentary, pyroclastic, and volcanic rocks (Aziz and Ferguson, 1997). The primary sulphide minerals are pyrite, chalcopyrite, and tetrahedrite, with lesser amounts of arsenopyrite, sphalerite, galena, and pyrrhotite. Pyrite is approximately 2-5 volume-% in waste rock and occurs as fine-grained disseminations, veins, and breccia infilling. However, pyrite can occur locally at much higher levels in massive sulphide zones.

During the design of the minesite, a few acid-base accounts (ABAs) were obtained for rock and these yielded negative NNP (positive NAPP) values (see the Glossary at the end for definitions). The company then concluded, "Drill core samples of ore were tested by B.C. Research to study the rock's acid producing potential. These tests indicate that under acidic conditions the rock has the potential of producing acid water. Because the rock will not be artificially acidified and the climate is not hot and humid, acid production from the dumps is not anticipated" (Equity Mining Capital Limited, 1976).

One year after the mine opened (1981), acidic drainage appeared from the waste rock. This error resulted in an environmental liability (closure costs including till covers over waste rock, plus bonding) of approximately US\$50,000,000 that may have been preventable. Operating costs for the collect-and-treat system are approximately US\$800,000/yr, with 70% representing lime costs (Aziz and Ferguson, 1997). There has been no significant decrease yet in annual lime consumption attributable to the till covers (Fig. 1).

It is now clear that a cold climate, even continuous permafrost, is not a deterrent to acidic drainage (Dawson and Morin, 1996; Case Study 4.2-4 in Morin and Hutt, 1997a). Despite this evidence from the field and laboratory, some still assume that cold conditions will prevent acid generation (e.g., Mine "B" in Price et al., 1997).

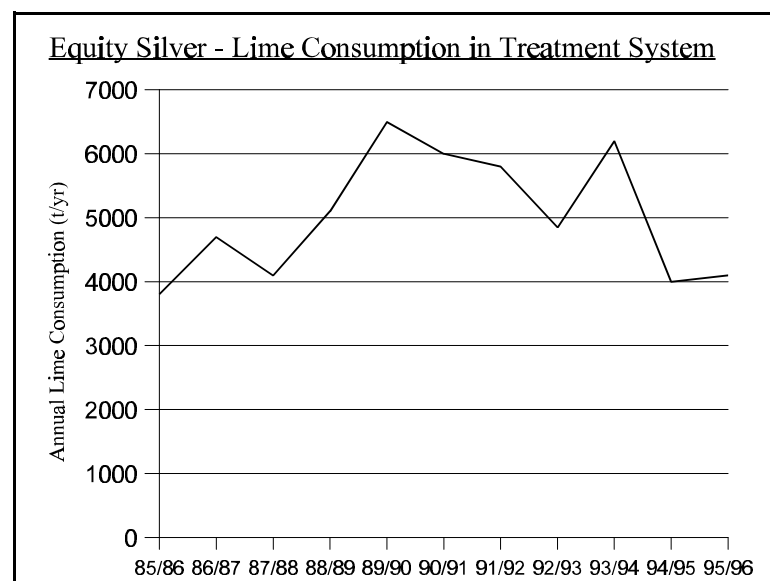


Fig. 1. Temporal Trend of Lime Consumption at Equity Silver Mine (adapted from Aziz and Ferguson, 1997).

3.0 CASE STUDY 2

This case study is the Samatosum Minesite in British Columbia (Denholm and Hallam, 1991; Case Study 6.4-5 in Morin and Hutt, 1997a; Morin and Hutt, 1997b; Mehling Environmental Management, 1997). The mine operated from May 1989 to September 1992, at an average rate of 465 t/d, for the recovery of silver, gold, copper, zinc, and lead. The mining method was originally open pit, turning to underground methods in 1991. The climate at Samatosum is cool and temperate with an average annual net precipitation of 0.940 m and snow cover during the winter months.

The Samatosum Deposit is primarily a stratabound quartz-carbonate vein within volcanic-related mafic pyroclastics, sericitic tuffs, cherts, muddy tuffs, argillite, mudstone, and greywacke. Some of this rock contains up to 60% syngenetic to diagenetic pyrite and up to 1-3% zinc, lead, and copper over distances of 10-15 m. The ore itself is predominantly comprised of 32% quartz, 19% dolomite (calcium-magnesium carbonate), and 11% pyrite, with some sphalerite, galena, chalcopyrite, electrum, and tetrahedrite (copper-iron-zinc-silver-antimony sulphide).

During the design of the mine, static and kinetic predictive tests indicated that most of the rock units and, by weighted average, 42% of total rock could generate net acidity (Table 1). The net-acid-generating rock was collectively called PAG (potentially acid generating), whereas the net-acid-neutralizing was labeled MAF (mafic pyroclastics).

Table 1. Predicted Tonnages and Weight-Averaged ABA Results for the Samatosum Minesite (adapted from Morin and Hutt, 1997b)

<u>Unit</u>	<u>Rock (t)</u>	<u>Total Acid Potential</u>		<u>Neutralization Potential</u>	
		<u>(t/1000 t)¹</u>	<u>(tonnes)</u>	<u>(t/1000 t)¹</u>	<u>(tonnes)</u>
<u>Net Acid Neutralizing (MAF)</u>					
Mafic Pyroclastics	5,300,000	73	387,000	377	2,000,000
<u>Net Acid Generating (PAG)</u>					
Sericite Tuffs	2,600,000	79	205,000	45	117,000
Muddy Tuffs	307,000	235	72,100	14	4,300
Quartzite & Qtz Vein	421,000	85	35,800	131	55,200
Cherts	9,540	250	2,390	23	219
Argillites	458,000	85	38,900	33	15,100
TOTAL PAG	3,800,000		354,000		192,000
<u>Overburden</u>					
Overburden	728,580	10	7,290	19	13,800
GRAND TOTAL	9,830,000		748,000		2,210,000

¹ mean values as CaCO₃ equivalent

The mining company and its consultants undertook a detailed program of laboratory-column testing (Fig. 2) to verify their control strategy of creating PAG and MAF layers within the waste-rock dump (Fig. 3). The strategy focused on ensuring any acidic waters in PAG layers would encounter sufficient neutralizing capacity in MAF layers. However, the columns contained cumulative ratios of neutralization potential (NP, predominantly dolomite) to acid potential (AP, calculated from sulphur) that were near or below 1:1, much lower than the overall 3:1 for the full-scale dump. As a result, the columns can be viewed as a worse-case analog to the dump.

The column effluents were not analyzed for all important parameters, like calcium and magnesium, and thus the consumption rate for the NP could not be determined. In the past, NP consumption in the Samatsum columns was estimated from effluent alkalinity, but a subsequent investigation found that this underestimated the actual NP consumption (Morin and Hutt, 1997b). As a result, although past work predicted no acidic drainage would drain from the columns, recent assessments indicated acidic drainage would have appeared after a few decades.

Although the revised predictions for the columns were not favourable, this did not affect the favourable predictions for the full-scale layered dump which contained excess NP at a ratio of 3:1 against AP. As a result, in comparison to the columns, the full-scale dump was not expected to release acidic drainage. However, acidic seeps were noted in places along the dump face by 1993, less than one year after mine closure.

The subsequent investigation reconciled the discrepancy between predictions and monitoring data through physical factors, primarily the short circuiting of drainage through specific layers so that the water did not encounter sufficient NP. As a result, geochemical principles did not fail at Samatsum, but complexities in physical hydrogeology overrode geochemical principles. This is interesting because it shows that failures in predictions of drainage chemistry are not necessarily due to failures in the predictive geochemical techniques.

Another interesting after-the-fact observation at Samatsum pertained to metal leaching. Although basal flow from the dump has been near-neutral, around pH 7-8, dissolved zinc concentrations have reached up to 23 mg/L. As a result, a water treatment plant had to be built to control this metal-bearing neutral drainage as well as any acidic drainage that will appear in the future.

4.0 CASE STUDY 3

The Huckleberry Minesite, currently under construction in British Columbia, is a reverse example of predictive problems, where an error resulted in the costly overestimation of the potential of acidic drainage (Mine "A" in Price et al., 1997; Case Study 5.2.1-8 in Morin and Hutt, 1997a). The Huckleberry Deposit is a hypogene porphyry copper-gold deposit that will be mined as an open pit. There are significant amounts of gypsum and other sulphate minerals in the deposit which complicate the determination of sulphide and acid generation.

During mine planning and public/government review, acid-base accounting (ABA) and kinetic tests were used to predict the potential for acidic drainage. This led to predictions that three of four rock units (approximately 100×10^6 t) and all tailings (approximately 70×10^6 t) were potentially net acid generating. This was based primarily on the ABA balance of:

$$\text{Acid-Generating Sulphide as \%S} = \text{Total Sulphur as \%S} - \text{Sulphate as \%S} \quad (1a)$$

or

$$\text{Acid-Generating Sulphide as \%S} = \text{Total Sulphur as \%S} - \text{Sulphate as \%SO}_4/3 \quad (1b)$$

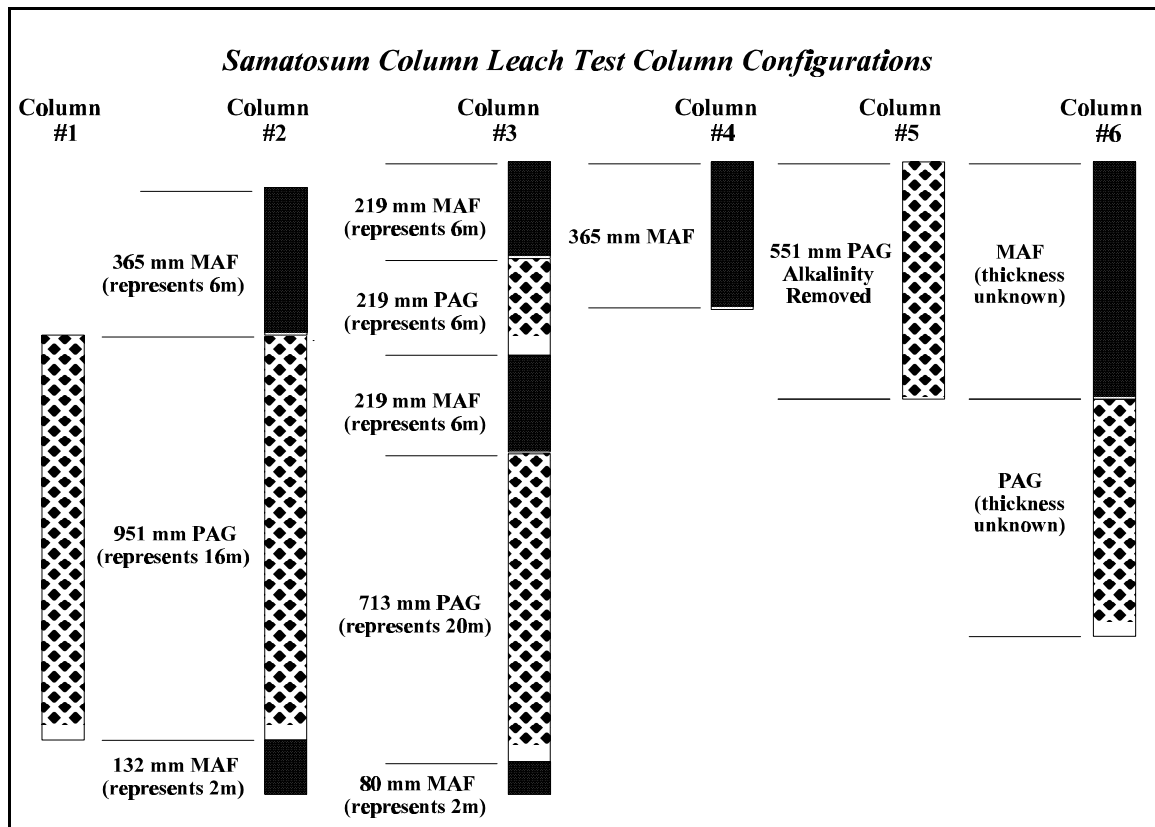


Fig. 2. Schematic Diagrams of the Samatosum Laboratory Columns (adapted from Denholm and Hallam, 1991).

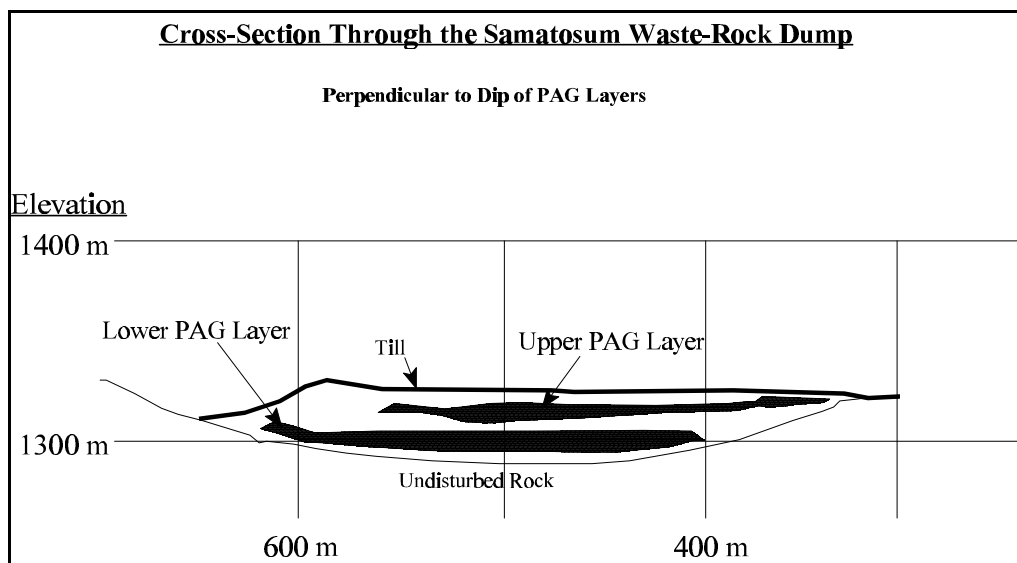


Fig. 3. Cross-Section Through the Samatosum Waste-Rock Dump Perpendicular to the Dip of PAG Layers (adapted from Morin and Hutt, 1997b).

Total sulphur and sulphate were measured and sulphide was calculated according to Eq. 1. In many studies, sulphide is often measured as part of the QA/QC procedures, but this was not done for Huckleberry. Therefore, a mathematical error occurred in calculating sulphide when the laboratory results for sulphate were divided by 3 in the mistaken belief that sulphate had been reported as %SO₄ rather than as %S. Due to the significant levels of sulphate in the deposit, this miscalculation greatly exaggerated the amount of acid-generating sulphide. Also, the average NNP value was used to describe the status of an entire rock unit, rather than proportions of each unit that were net acid generating.

When regulatory agencies recalculated the levels of sulphide and avoided the use of averages, up to 80% of each rock unit and all tailings were predicted to be net acid neutralizing. The mine plan was then adjusted to eliminate a large, expensive, water-retaining dam for waste rock and tailings and, instead, to have a flow-through dam built from the once acid-generating waste rock. This no doubt saved the mining company millions of dollars and long-term concerns over significant acidic drainage.

In addition to ABA problems, the kinetic tests used the sulphate production rate to estimate the rate of acid generating and the time to sulphide depletion, which is standard practice. However, because the sulphate in the tests was derived from gypsum dissolution and the effluents were gypsum saturated, no information on sulphide oxidation could be obtained. In other words, the rate of sulphide oxidation could have been very low or very high, and this would not have been detected because the effluent already carried as much sulphate as possible from the gypsum.

5.0 CASE STUDY 4

The Boss Mountain Minesite is located in British Columbia at the base of a glacial cirque (Morwijk Enterprises Ltd. 1993; Case Study 5.3.1-3 in Morin and Hutt, 1997a). This molybdenum deposit was discovered in 1917 and was mined from 1965 to 1972 and from 1974 to 1983 using underground and open-pit methods.

During a review of internal files in 1992, a regulatory agency located two ABAs for tailings collected in 1983, around the time of mine closure. The results indicated the tailings had the potential to generate net acidity (NNP = -13 and -42 t CaCO₃ equivalent/1000 t based on total sulphur; see the Glossary at the end of this paper for definitions). No further ABAs had been collected since that time. The agency then asked the mining company to undertake a detailed investigation involving various static and kinetic testwork.

Additional ABAs with an average NNP of -19 t/1000 t and average NPR ratio of 0.77 confirmed the potential for net acid generation (Fig. 4). However, there was a great deal of other information that contradicted the ABAs and pointed to no net acidity.

First, although the number of historical ABAs are limited, a comparison of NP values in 1983 and 1994 reveals that the average NP has not changed significantly although sulphide oxidation has been occurring. This points to additional NP not reliably detected in the laboratory analysis.

Second, the mineralogy of the tailings consisted of 50% feldspars, 35% quartz, and minor hornblende, biotite, epidote, and sphene, and several of these minerals can neutralize acidity at a relatively slow rate. Their full capacity to neutralize acidity is rarely detected in an NP analysis.

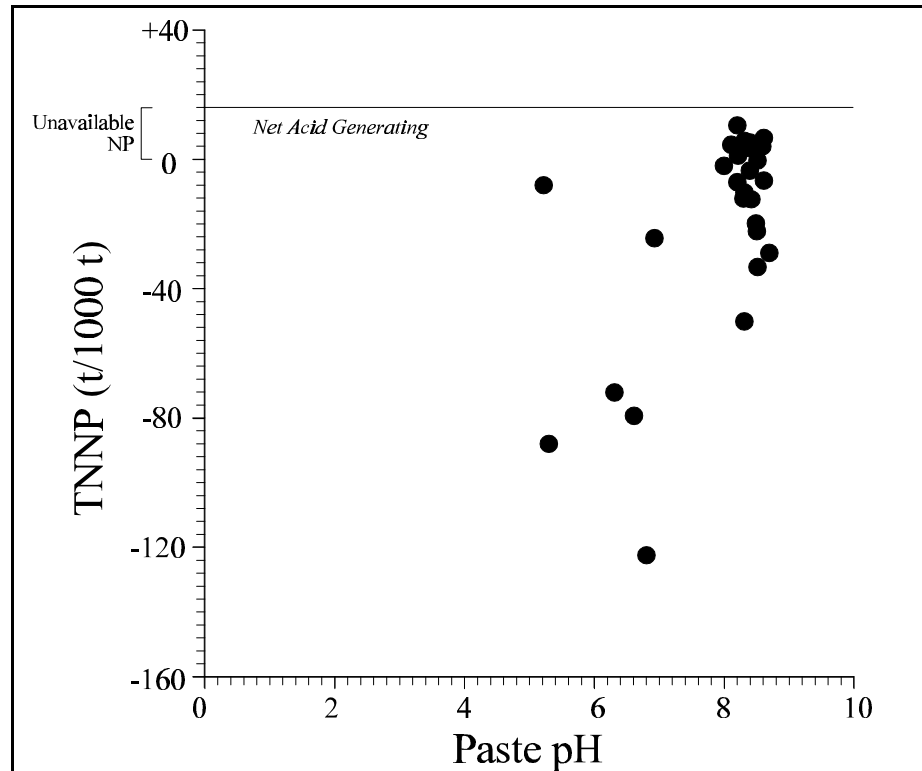


Fig. 4. Scatterplot of TNNP vs. Paste pH from Boss Mountain Tailings (adapted from Morwijk Enterprises Ltd., 1993).

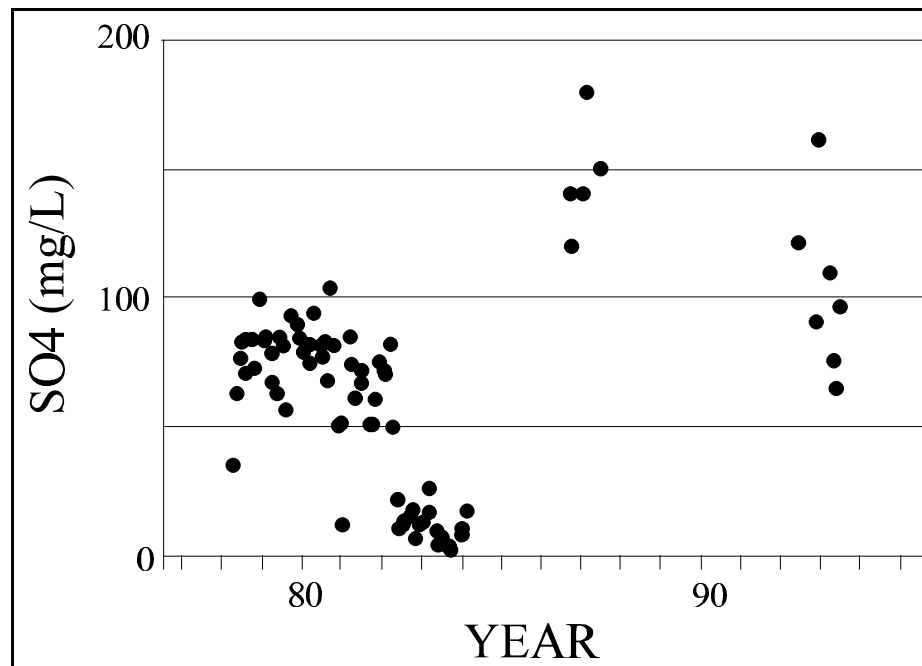


Fig. 5. Temporal Plot of Aqueous Sulphate from the Boss Mountain Tailings Impoundment (adapted from Morwijk Enterprises Ltd., 1993).

Third, although the pyrite in the tailings averaged around 1%S and was actively oxidizing and generating acidity on a local scale, it did not create net acidity on a large scale. A compilation and review of monitoring data at the site back to 1978 showed that all pH measurements have been and continue to be above 6.5. Also, aqueous sulphate concentrations are often near 100 mg/L (Fig. 5), which is far below gypsum saturation and indicates a relatively slow rate of oxidation around the site.

Fourth, a humidity cell which operated for 40 weeks showed that the rate of acid generation was low to moderate and that neutralization of the acidity was primarily attributable to one or more non-carbonate calcium-bearing minerals. These types of minerals do not often respond to chemical-equilibrium conditions and thus can provide a relatively steady rate of neutralization. Therefore, if the rate of sulphide oxidation at Boss Mountain had been significantly higher, the neutralizing minerals may not have been able to accelerate and thus acidic drainage would have appeared. This is an example of how the rate of oxidation can affect the relevant amount of NP in mined material and the pH of its drainage.

Fifth, the rate of NP consumption in the cell indicated all laboratory NP would be consumed in less than six years. Since all tailings have been exposed for a minimum of 15 years, this showed that there was additional field-scale NP not detected by the laboratory NP analysis.

Morin and Hutt (1997a) point out that the correct interpretation of ABA results requires input from many types of static and kinetic tests. For example, the laboratory NP value is only an approximate estimate of the on-site "effective NP" (ENP):

$$\text{ENP} = \text{laboratory NP} - \text{unavailable NP (UNP)} + \text{slow-reacting NP (SRNP)} \quad (3)$$

At Boss Mountain, kinetic and monitoring data showed that there was significant SRNP in the tailings. Upon mathematical conversion of a small amount of the calcium-bearing aluminosilicate minerals to an NP equivalent, the NNP values rise significantly into the positive range and NPR values rise above 2.0. The next case study also highlights the effect of high UNP and SRNP on predictions.

Therefore, the correct interpretation of ABA data using ENP shows that the Boss Mountain tailings are not expected to generate net acidity on a large scale at any time. As a safeguard, drainage is collected and analyzed regularly. If sulphate concentrations ever rise sharply, which is an indicator under field and laboratory conditions of impending net acidity (Morin and Hutt, 1997a), appropriate action can then be taken.

6.0 CASE STUDY 5

The Louvicourt Minesite in Quebec is one of Canada's newer minesites (Li, 1997). The potentially net-acid-generating tailings are discharged directly underwater into a flooded impoundment. However, because some tailings may be occasionally exposed to air, kinetic tests have been conducted to determine the lag time to net acid production (Fig. 6). This is critical for determining the lag time to net acidity and thus the maximum length of exposure before net acid generation.

The tested tailings sample had an initial Sobek NP of 75 t/1000 t. However, the initial Carbonate NP was 116 t/1000 t, indicating a significant portion of the carbonate minerals were not available for neutralization. This was consistent with mineralogical examinations which showed the presence of iron-based carbonate minerals which may provide little to no neutralization. The subtraction of the two values suggests that UNP (Eq. 3) of these tailings

is 41 t/1000 t. In reality, these tailings contain slow-reacting neutralizing minerals like muscovite and chlorite which provide SRNP (Eq. 3). In other words, the effective NP requires the laboratory value of 75 t/1000 t to be adjusted by subtracting some value (UNP) greater than 41 and adding on a value of SRNP. These missing values could only be obtained through kinetic testing and mineralogical assessments.

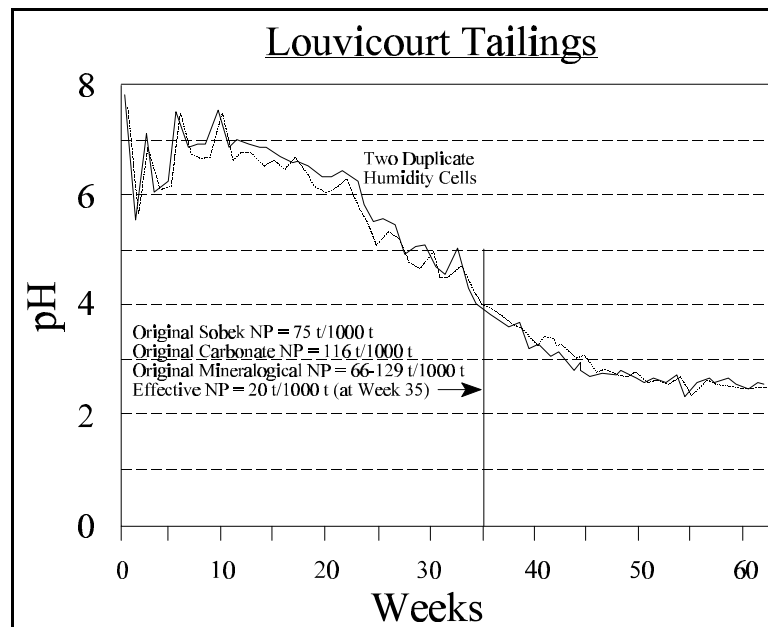


Fig. 6. Temporal Trends of pH in Duplicate Humidity Cells of Louvicourt Tailings (adapted from Li, 1997).

Two duplicate samples of Louvicourt tailings were tested in Sobek style humidity cells for 65 weeks (Fig. 6). Based on an aqueous pH of 4.0, the samples became acidic at Week 35. Calculations then revealed that only 20 t/1000 t of Sobek NP had been consumed. In other words, the effective NP was only 20 t/1000 t compared to a laboratory value of 75 t/1000 t. Li (1997) attributed this to a relatively rapid rate of acid generation that exceed the neutralizing rates of several minerals in the tailings. This is in contrast to the previous case study of Boss Mountain where the rate of acid generation was relatively slow and thus ENP was greater than the laboratory NP.

Because of the low ENP, Li (1997) explained that the lag time to net acidity in Louvicourt tailings is not around 2-4 years as expected from the basic testwork. The lag time was in fact around 0.7 years based on the integrated interpretation of all static and kinetic tests. Without this improved prediction, the minesite may have allowed tailings to be exposed too long and thus generate net acidity and enhance metal leaching into the water cover.

7.0 CASE STUDY 6

At a base-metal minesite in Canada, a consulting company conducted a geochemical survey of a waste-rock dump, tailings impoundment, and an open pit on behalf of the owner. This led

to a relatively inexpensive closure plan indicating no acidic drainage was expected from the waste rock. A year later, the same consulting company was hired by a potential buyer of the minesite to conduct an environmental-liability assessment. The consulting company then reported high liability costs because acidic drainage was issuing from portions of the waste-rock dump. In response, the owner considered legal action against the consulting company.

A subsequent examination of ABAs (see Glossary for definitions) for the waste-rock dump showed that the waste rock was net acid neutralizing on average, as recognized by the consulting company. However, at least three of the 15 ABAs were clearly net acid generating (a synthetic analog of the data is reproduced in Table 2). These three samples represented low-grade ore that was added to the waste-rock dump in later years, in two well-defined areas. The owner then removed this low-grade ore from the dump and drainage chemistry began to improve. Meanwhile, because the acidic ore consumed NP in the underlying waste rock, it was not clear if this waste rock would begin generating net acidity at a later time.

Table 2. ABA Data for a Waste-Rock Dump (values have been changed from the original, but the overall values and trends are similar)

<u>Total Sulphur (%S)</u>	<u>NP¹</u>	<u>Total Net Neutralization Potential¹</u>	<u>Total Net Potential Ratio</u>
1.1	74	+40	2.2
2.2	147	+78	2.1
3.7	149	+33	1.3
1.9	130	+71	2.2
0.3	122	+113	13.6
4.1	150	+22	1.2
1.4	88	+44	2.0
0.5	73	+57	4.6
0.8	81	+56	3.2
4.9	1	-152	0.01
1.7	145	+92	2.7
2.4	6	-70	0.08
2.1	197	+131	3.0
0.6	81	+62	4.3
2.6	2	-80	0.02
Avg = 2.0	96	+33	2.8
¹ values in units of t CaCO ₃ equivalent/1000 t; TNNP = NP - %S*31.25			

This case study illustrates the predictive error inherent in averages of static-test data. Averaging data for a rock unit or minesite component gives the impression that it behaves as one homogenous unit, which is rarely true (Morin and Hutt, 1997a). The better approach is to determine the portion of each unit or component that is net acid generating and net acid neutralizing. Additionally, averaging of NNP and NPR values, which are composites of two independent parameters, is statistically suspect. For example, in Table 2, the average NPR value is 2.8, whereas the NPR value of the average NP and AP is 1.5. In geostatistical modelling, NP and AP are best modelled separately and then combined at discrete locations to determine the values of NNP and NPR (Case Study 5.2.1-6 in Morin and Hutt, 1997a).

8.0 CONCLUSIONS

The objective of this paper was to compare predictive geochemical data with historical drainage-chemistry data based on several case studies. The case studies in this paper have focused on actual or potential errors in prediction in order to highlight weaknesses in predictive approaches. While in fact many predictions are reasonable and accurate, the case studies in this paper show that simple events like mathematical miscalculations, wishful thinking, and the lack of integrated interpretation of static and kinetic tests can lead to the multi-million-dollar liability of acidic or metal-laden drainage at a minesite. We hopefully can learn from others' mistakes.

9.0 REFERENCES

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10.0 GLOSSARY

ABA	Acid-Base Accounting; a series of laboratory analyses to determine a sample's AP and NP; includes "paste pH" which is the pH of a mixture of pulverized sample and distilled water
AP	Acid Potential; a sample's capacity to generate acidity from sulphur-based reactions
Carbonate NP	Carbonate Neutralization Potential; derived from a sample's carbonate content
ENP	Effective Neutralization Potential; see Eq. 3.
Kinetic Test	repetitive analysis of a sample or its effluent to determine its time-dependent behaviour
NAPP	Net Acid Producing Potential; $NAPP = AP - NP$; see NNP
NP	Neutralization Potential; a sample's bulk capacity to neutralize acidity
NNP	Net Neutralization Potential; $NNP = NP - AP$; often expressed in one of three equivalent units: kg $CaCO_3/t$, t $CaCO_3/1000$ t, or parts per thousand $CaCO_3$; may alternatively be expressed as H_2SO_4 which differs from $CaCO_3$ by only 2%
NPR	Net Potential Ratio; $NPR = NP/AP$; dimensionless
Static Test	a one-time analysis of some property of a sample, like ABA