

# BLACK HAWK NOVEMBER, 1998 FINAL REPORT DESCRIPTION

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Table 3	BlackHKtabs.xls	48.
Table 4	BlackHKtabs.xls	48.
Table 5	BlackHKtabs.xls	48.
Figure1a	BlackHKfigls.xls	48.1
Figure1b	BlackHKfigls.xls	48.1
Figure1c	BlackHKfigls.xls	48.1
Figure1d	BlackHKfigls.xls	48.1
Figure1e	BlackHKfigls.xls	48.
Figure2a	Figure2.doc	48.
Figure2b	Figure2.doc	48.
Figure2c	Figure2.doc	48.1
Content of App.	Bhapp.wpd	48.1
Map 1	copy (no file)	
Map 2	copy (no file)	
Appendix1	copy (no file)	
Appendix2	copy (no file)	
Appendix3	copy (no file)	
Appendix4		
Schematic	copy (no file)	



**Decommissioning Mine Waste Management Areas**

**Design Parameters for Utilizing Wetlands/Muskeg  
for the  
Farley Lake Mine Property  
Keystone Gold, Black Hawk Mining Inc.  
in the vicinity of  
Lynn Lake, Northern Manitoba**

**November 10.1998**

## TABLE OF CONTENTS

<b>1.0</b>	<b>INTRODUCTION</b> .....	<b>1</b>
<b>2.0</b>	<b>WATER CHARACTERISTICS</b> .....	<b>2</b>
<b>3.0</b>	<b>FLOWS AND DRAINAGE BASIN</b> .....	<b>6</b>
	<b>3.1 Toe Seepage Collection</b> .....	<b>11</b>
<b>4.0</b>	<b>GEOCHEMISTRY AND WEATHERING CRITERIA</b> .....	<b>12</b>
	<b>4.1 Weathering Rates and Contaminate Concentration</b> .....	<b>14</b>
	<b>4.2 Areas Required for Back Up Treatment</b> .....	<b>16</b>
<b>5.0</b>	<b>AREAS REQUIRED FOR BACKUP TREATMENT</b> .....	<b>17</b>
<b>6.0</b>	<b>ENVIRONMENTAL CONDITIONS OF THE DRAINAGE BASIN</b> .....	<b>17</b>
<b>7.0</b>	<b>RECOMMENDATIONS</b> .....	<b>26</b>

## LIST OF TABLES

Table 1	Inorganics of Water Samples from Black Hawk Inc. (Jul.-Aug. 1998) .....	3
Table 2	Elements of Water Samples from Black Hawk Mining Inc. (Sept.1998) .....	5
Table 3	Farley Lake Mine : Areas of Drainage Basin. Pits and Acid Waste Dump. ....	7
Table 4	Basic Statistics of Five Water Quality Parameters Examined over Nov. 1995 to Aug. 1998 .....	16
Table 5	Projected Toe Seepage Concentration .....	19

## LIST OF FIGURES

Figure 1 a	pH Change over Time .....	21
Figure 1b	Hardness Changes over Time .....	21
Figure 1c	Ammonium Changes over Time .....	22
Figure 1d	Iron Changes over Time .....	22
Figure 1 e	TSS Changes over Time .....	23

**Figure 2a: Cross Correlation Between pH and Ammonium at Ditch . . . . . 24**

**Figure 2b: Cross Correlation Between pH and Ammonium at Gordon Lake . . . . . 24**

**Figure 2c: Cross Correlation Between pH and Ammonium at Farley Lake . . . . . 25**

**LIST OF MAPS**

**Map 1 Farley Lake Black Hawk Mining . . . . . 9**

**Map 2 Farley Lake Project -EIA . . . . . 10**

## 1.0 INTRODUCTION

Boojum Research Limited was retained by Black Hawk Mining Inc. to develop a decommissioning plan which could be implemented in 1999. The objective of the decommissioning activities is to produce low maintenance or, possibly, walk-away conditions, for the site. The site contains two pits (which are to be flooded) and two waste rock piles; one potentially acid generating and the other consisting of non-acid generating waste rock.

The site is located in discontinuous permafrost and, at present, there appears to be no sign of acid generation after 5 years of mining. Based on humidity cell tests, several metals may be of concern in the long term, possibly justifying setting up a pilot constructed wetland facility on site.

A site assessment by M. Kalin was carried out to define the areas which require investigation prior to winter 1998. It included an examination of the conditions of the waste rock pile, the pit walls, diversion ditches and any running water/creek ponds or pools and muskeg areas. This led to the conclusion that the waste management area has well-documented data, and is extremely well-managed from an environmental perspective. A pilot facility was considered unnecessary by Boojum Research Ltd., given their extensive test results for similar situations. A brief technical summary of wetland applications and their stages of development is given in Appendix 1.

It was recommended that a series of water samples be collected to determine the present conditions of the site. The decommissioning plan would then be initiated with a step-wise construction of muskeg areas, if required. The aim would be to utilize existing ditches and settling ponds, as these represent reasonably well-defined zones where water could be retained. One of the most important tasks is to predict the locations where the toe seepages may emerge and ways in which they can be intercepted for treatment. Secondly, their metal loading has to be determined.

The water sampling covered locations where waste rock pile toe seepages could potentially occur, i.e., along both piles at the interface between muskeg and waste rock and seepages in the pit walls. The samples are used to describe the conditions existing after 5 years of waste deposition on the site. The water composition can be used to estimate the weathering rates of the waste rock, given the local climate. A site-specific data set is utilized to determine the expected loadings of potential contaminants in the long term.

## **2.0 WATER CHARACTERISTICS**

Water samples were taken in pools or seepages at the toes of the North waste rock dump (NWRD) and around the South waste rock dump (SWRD). Water was obtained at two locations, along with a general survey of pH levels in the muskeg area surrounding the NWRD. The sampling locations, NWRD#1 and NWRD #2, are given in the Appendix 2, and the results are listed in Table 1. The data from the North and South waste rock dumps are referred to as Ken's sample #1 and Ken # 2 respectively.

The differences in toe seepage characteristics should reflect the careful segregation of waste rock into the two piles. The weathering rate could then be estimated using the sulphate concentrations, relating it back to the mineralogy of the waste rock.

The pH values around the NWRD are all in the neutral range (also see other survey locations on the map in Appendix 2). The same holds true for the SWRD. The pH value is not a measure indicative of acid mine drainage, since neutralizing minerals which easily weather are contributing to the water chemistry. The seepage waters at the toe of the waste rock pile would also reflect reducing conditions in the boggy areas, similarly resulting in circum-neutral to alkaline pH values.

Table 1: Inorganics of Water Samples from Black Hawk Inc. (July-Aug., 1998)

Unit: mg/l

Inorganics	Ken's Samples #1 (SWRD) 16-Jul-98	Ken's Samples #2 (SWRD) 16-Jul-98	NWRD #1 20-Aug-98	NWRD #2 20-Aug-98	Detection Limit
pH	7.35	6.31	6.25	6.72	NG
Calcium	335	212	NM	NM	<b>NG</b>
Magnesium	163	87	NM	NM	<b>NG</b>
Sulfate	1210	919	725	959	NG
Total hardness	1510	886	NM	NM	NG
Ammonia as N	1.0	0.1	3.4	3.8	<b>NG</b>
Silver	LDL	LDL	LDL	LDL	0.001
Arsenic	LDL	LDL	0.0005	0.0026	0.0005
Cadmium	LDL	LDL	NM	NM	0.001
Copper	LDL	0.006	0.003	0.003	0.001
<b>Iron</b>	0.065	0.038	0.062	0.4	NG
Nickel	0.001	0.005	NM	NM	0.001
lead	LDL	LDL	LDL	LDL	0.002
Zinc	LDL	0.006	NM	NM	0.005

Note 1: **LDL**=Lower than Detection Limit; **SWRD**=South Waste Rock Dump; **NWRD**=North Waste Rock Dump; **NM**=Not Measured; **NG**=Not Given.

Note 2: The bold results in the table are add soluble.



Unfortunately, the elements in the water associated with the two types of waste rock piles are not the same, although the sulphate concentrations for both piles are in a similar range. While we expected the NWRD to have lower sulphate concentrations, it is possible that the sulphate from this pile is, in part, organic, but this is not yet determined. As planned, water samples from the drainage ditch, representing the characteristics of the toe seepages from the SWRD, were collected but the analytical results have not been received.

The pit wall seeps collected for the Wendy Pit are summarized in Table 2, and the locations are given in Appendix 2b. Seepages #1, 3 and 5 originate at the south to south-western wall, whereas seeps #8, 6 and 2 originate in the north-western wall and, finally, seeps #4 and 7 originate in the north-eastern corner of the Wendy Pit.

If the Wendy Pit seeps are connected to the SWRD, then their characteristics should indicate increased concentrations of the weathering elements. Table 2 shows the chemical composition of the pit wall seeps. The following elements in the Wendy Pit wall seeps are at or below the detection limit: P, Ag, Be, Cd, Co, Cr, Cu, Mo, Pb, Ti, V, Zn and Zr. Details are given in Appendix 2, along with the detection limits.

The seeps on the south-western wall would be those possibly affected by shallow ground water seepage from the SWRD. When comparing elemental concentrations, the data suggest that at least one of the three south-west wall seeps consistently contains the highest concentrations of sulphate, ammonia, aluminum, arsenic, barium, calcium, iron, potassium, manganese, nickel and strontium, compared to the other Wendy Pit seeps.

Although it is possible that the water of these seeps run through some mineralized ore zones, slightly increased concentrations of elements may originate from the SWRD. Based on the monitoring data, background concentrations of iron for Gordon Lake are 1.7-0.2 mg/L, and for Farley Lake they are 0.001-0.5 mg/L. For sulphate, based on

Table 2 Elements of Water Samples from Black Hawk Mining Inc. (Sept., 1998)

Unit: mg/l

Element	Southwest Wall Seeps		Northwest Wall Seeps				Northeast Wall Seeps		Detection Limit
	Wendy Pit Inflow #1	Wendy Pit Inflow #3	Wendy Pit Inflow #5	Wendy Pit Inflow #2	Wendy Pit Inflow #6	Wendy Pit Inflow #8	Wendy Pit Inflow #4	Wendy Pit Inflow #7	
Sulfate	52	104	58	67	34	37	53	71	NG
Ammonias N	0.08	0.12	0.29	0.09	0.13	0.15	0.1		
Boron	0.029	0.059	0.032	0.058	0.017	0.033	0.12		
Aluminum	0.49	0.48	0.019	0.028	LDL	LDL	0.01		5
Arsenic	0.0015	0.0023	0.0011	LDL	LDL	LDL	LDL		5
Barium	0.024	0.036	0.019	0.01	0.002	0.001	0.002	0.013	
Calcium	49	70	61	47	49	47	25		
Iron	1.6	1.3	0.18	0.02	0.085	0.17	0.094	0.016	
Potassium	4.9	7	3.5	5.3	2.2	1.8	2.5		
Magnesium	18	19	22	13	19	15	18		NG
Manganese	0.12	0.014	0.22	0.007	0.1	0.093	0.011	0.003	NG
Sodium	13	19	11	22	9.1	12	35		NG
Nickel	LDL	0.012	0.007	LDL	LDL	LDL	LDL	LDL	0.001
Silicon, soluble	6.1	6	6.5	4.9	6.3	6.1	5.1	4.8	NG
Strontium	0.12	0.2	0.14	0.12	0.091	0.098	0.098	0.12	NG
Flow Estimates (L/sec.)	15	4.56	5.3	5.3	7.6		1.88	3.0	-
pH	8.43	8.29	8.31	8.54	8.38	7.83	8.43	8.21	-

Note : LDL = Lower than Detection Limit. NG = Not Given.

information from the EIA, the reported background is less than 1-10 mg/L for Farley Lake and 6-10 mg/L for Gordon Lake. We recommend that the origin of these wall seeps be determined.

### **3. FLOWS AND DRAINAGE BASIN**

In order to determine both the water supply to the toe seepages and their flows, so that a loading could be estimated, flow estimates were derived using the parameters given for the drainage basin. In addition, it was necessary to consider the overall water balance of the waste management area, since a wetland requires a continuous supply of water.

The overall drainage basin of Gordon Lake leaves through the diversion ditch and flow values would be useful here, as well as for at the seepage collection ditch at the foot of the SWRD. These data do not appear to be available. Therefore, in order to estimate flows, values given in the EIA are used. Gordon Creek is reported to flow at 0.042 m<sup>3</sup>/s, which is assumed to be the flow in the diversion ditch for water leaving Gordon Lake for Farley Lake. During mine development, the water elevation of the lakes was altered, and the hydrological consequences of this are unclear at this point. Using the run-off coefficient given in the EIA, the flow estimates for the drainage basin are presented in Table 3. Using the same approach, flows from the drainage basin containing the SWRD are calculated.

If these assumptions are correct, then toe seepage flows can be expected at a maximum of 0.9 L/s (Subdrainage A and B, Table 3). This would result in an annual water volume (which might be contaminated) of 28,400 m<sup>3</sup> per year. The area below the waste rock pile (Area C) is estimated to be about 9.4 ha. With no evaporation, a very shallow cover of about 0.3 m could be maintained throughout the year. When the entire lowland area (Area D) is considered, the water cover is even shallower.

**Table 3: Farley Lake Mine: Areas of Drainage Basin, Pits and Acid Waste Dump.**

Area	Area ha	Volume m <sup>3</sup>	Note	Run-off*		Res. Time days
				m <sup>3</sup> .d <sup>-1</sup>	L.s <sup>-1</sup>	
<b>Gordon</b> Creek Watershed (7.1 km <sup>2</sup> )	<b>710</b>		run-off	<b>3.619</b>	<b>42</b>	
Gordon Lake		<b>13.2</b>				<b>18</b>
Sub-Drainage Basin (Appox.)	<b>36.2</b>		run-off	<b>185</b>	<b>2.1</b>	
Upland Area	<b>19.6</b>		run-off	<b>100</b>	<b>1.2</b>	
A Acid Waste Dump (AWD)		<b>2.7</b>	run-off	<b>14</b>	<b>0.16</b>	
			ll Infiltr.**	<b>37</b>	<b>0.43</b>	
B Fresh Water Input to AWD		<b>7.5</b>	run-off	<b>38</b>	<b>0.44</b>	
C Upland area below AWD		<b>9.4</b>	run-off	<b>48</b>	<b>0.6</b>	
Lowland Area	<b>16.6</b>		run-off	<b>85</b>	<b>1.0</b>	
Wendy PR		<b>3.3</b>	run-off	<b>17</b>	<b>0.19</b>	
East Pit		<b>3.7</b>	run-off	<b>19</b>	<b>0.27</b>	
D Muskeg (original Gordon L. discharge path)		<b>9.6</b>	run-off	<b>49</b>	<b>0.57</b>	

Run-off: Estimated run-off based on November, 1994 EIA value of 0.0059 m<sup>3</sup>.s<sup>-1</sup>.km<sup>-2</sup>, or 5.0976 m<sup>3</sup>.d<sup>-1</sup>.ha<sup>-1</sup>.

This run-off is equivalent to a net precipitation of 0.186 m.y<sup>-1</sup>

All infiltr.\*\*: All precipitation infiltrates into waste rock, no run-off or evaporation, only seepage.

Total Annual precipitation, 0.502 m

With evapo-transpiration of plants, such as alders, which are likely to invade the area, further reduction is expected. These hydrological conditions, along with changes in the drainage basin and the expected elevation of the ground water, need to be discussed with a hydrologist.

Based on these estimates, it is likely that not enough water exists to support a muskeg as a treatment option.

By increasing evapo-transpiration through establishment of an alder cover on the pile, flow of toe seepages would be further reduced, so it is recommended as the most reliable long-term approach to the SWRD stability.

With the flow of the Gordon Lake diversion ditch, it is estimated that about 1.3 million m<sup>3</sup>/year leave Gordon Lake. The EIA reports it's total volume as 66,000 m<sup>3</sup>, meaning Gordon Lake is flushed about every 18 days. If we assume the flow to be reduced or negligible during the winter period, the turnover rate would be further increased. In summary, if the flow of the diversion ditch is in the same order of magnitude as indicated by the EIA, then any discharge from Gordon Lake to Farley Lake via the diversion ditch, can be expected to experience a significant dilution.

The sub-drainage basin contains the SWRD and the open pits outlined in Map 1. It covers a total area of about 36.2 ha, which is a small fraction of the Gordon Lake Drainage basin (Map 2) and represents only 5% of the total area. The same calculations should be carried out for the NWRD to determine its potential impact on water quality, if any.

The hydrological conditions of the ground water table in the pits to be flooded and the true flow of the diversion ditch are relevant to any planning of the muskeg area. The hydrological conditions of the sub-drainage basin, in relation to the pits and the elevations to which the deep ground water level will rise, should be clarified.



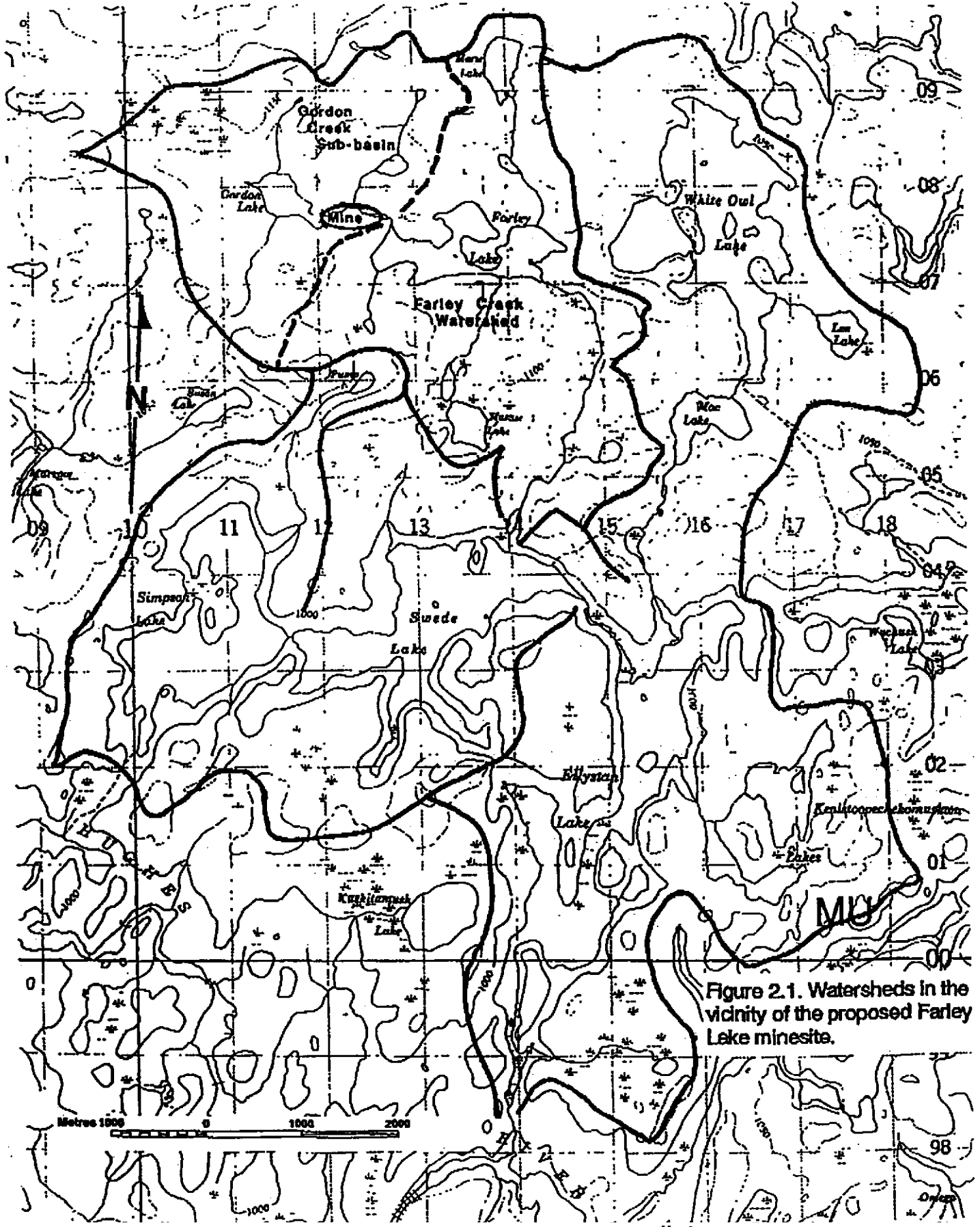


Figure 2.1. Watersheds in the vicinity of the proposed Farley Lake mine site.

In Map 1 the surface topography prior to mining was used to determine the likely drainage path of the shallow ground water and/or surface run-off. It is evident from the old contours that the likely origins of toe seepages are the north-west corner of the SWRD. It is suggested that this seepage may drain towards the east pit, and a second drainage path might run through the west ore pad towards Wendy Pit. The seepage locations in the Wendy Pit are given in the Appendix 2b. Seeps 1, 3 and 5 are located at the southern side of the pit, and may partly reflect the topographic contours prior to mining.

### 3.1 Toe seepage collection

With respect to wetland treatment requirements for the toe seepages which might arise from the SWRD, surface drainage could be collected in the existing ditch and a wetland treatment area established in the sedimentation pond.

Microbial treatment of acid mine drainage requires at least one meter of water to establish reducing conditions. In order to determine what fraction of the water will report to the collection ditch, the pumped water from the pit should be eliminated, which could likely be done at the time mining is completed. Together with the determination of the flow path of the Wendy seeps and the elevation of the expected water level in the pits, i.e., expected ground water table, the fraction of water reporting to the ditch can be estimated. If further assurances were needed, a polishing system could be promoted in the receiving section of Gordon Lake. There is already extensive cattail growth along the modified shores of Gordon Lake.

In fact, if it can be established that all the toe seeps report to the ditch, then Gordon Lake could be utilized to a larger extent.

Water was collected from the north-west corner of the SWRD, and a conductivity survey was carried out in the collection ditch running along the north side of the



SWRD. Those results are not yet available. If Ken's sample #1 and # 2 are indeed toe seeps, then the loading to the ditch could be established by installing some pedometers or stand pipes. Again , it is recommended that a hydrologist be consulted.

The survey of the seepage collection ditch has been carried out and the water has been submitted to SRC for chemical analysis, but the results have not yet been received. These samples, together with information on the collection points of Ken's samples and the pumping rate of the pit water, will provide input into the characteristics of the toe seepages. The chemistry of drainage ditch water is presently highly diluted by the pumping of ground water to de-water the pit. Thus it would not be representative of toe seepages which might require treatment in the muskeg.

As discussed previously, ground water conditions determined by the stratigraphy underlying the SWRD will be significant with respect to shallow toe seepages discharge.

#### **4.0 GEOCHEMISTRY AND WEATHERING CRITERIA**

One of the most important criteria is the prediction of the pH value which might be expected once the acid generation process is well established. The expected pH was calculated using a geochemical simulation model, PHREEQUE C.

The S content of the potentially acid-generating rock dump, SWRD, is estimated to be 0.43%, according to the senior geologist Kenneth Akin. Per kg of SWRD rock, this would results in the equivalent of 0.134 mol S or 0.067 mol FeS<sub>2</sub>. The model is set up to "dissolve" 1 kg SWRD material in an arbitrary amount of pure water (pH 7.0). In such a simulation, the following assumptions were made:

- the material was exposed to atmospheric conditions with 21% O<sub>2</sub> (max. oxidative conditions)

a maximum amount of 0.067 mol FeS<sub>2</sub> was allowed to dissolve/oxidize until saturation was reached with pyrite: Si(pyrite) = 0. It should be recognized that this condition would never take place, as the saturation index will never reach 0 when all the pyrite was oxidized.

- biotite, plagioclase, quartz and caressed were allowed to dissolve until their saturation indices reached 0.
- the 1 kg of SWRD was reacted with: 10ml - 100 ml - 1 L - 10 L - 100 L - 1000 L H<sub>2</sub>O.

Two scenarios were developed. In the first, iron and sulphate are not removed by precipitation of H<sub>2</sub>O, Gypsum or Jacobite, if their respective saturation indices exceed 0. This does not reflect reality, but is used as a check on the approach taken to predict the pH value. The second scenario is more realistic, in that the removal of iron and sulphate takes place by precipitation of H<sub>2</sub>O, Gypsum or Jacobite, if their respective saturation indices exceed 0.

The results of the geochemical modeling predicted the following iron and sulphate concentrations at different solid waste rock to water ratios:

Ratio	Scenario 1	Scenario 2		
SWRD:H <sub>2</sub> O	pH-1	pH-2	Fe-2	SO <sub>4</sub> -2
			mol./L	mol./L
1:1000	6.03	5.95	0.0002	0.13
1:100	5.40	5.32	0.0009	1.33
1:10	5.01	5.04	0.0019	9.01
1:1	4.72	4.93	0.0026	93.41
10:1	4.32	4.80	0.0040	936.2
100:1	2.00	4.46	0.0043	10050

In conclusion, and considering a wide range of SWRD material to H<sub>2</sub>O ratios, and the precipitation of relevant minerals if their saturation indices exceeded 0, the pH generated by oxidation of pyrite in the SWRD ranges between 4.5 and 6.0. Since these PHS were calculated with maximum pyrite oxidation, the actual pH at the various solid to water ratios will most likely be higher.

These simulations suggest that the toe seepages will not likely be of a low pH. This pH value appears reasonable, since the humidity cell test with Black Argillite alone produced a pH value of only 3.5. This represents water essentially sitting on the mineralized surface, and does not take into consideration any other processes, such as adsorption and precipitation.

#### 4.1 Weathering rates and contaminant concentrations

The mineralogy and geochemistry of the waste rock was obtained from Ken Akin, the mine site geologist, and the report is included in Appendix 1. Estimating the total contaminant mass in the waste rock pile is based on the concentrations of the element of concern, which are based on the mineralogy. For the Farley Lake site, these elements are As, Ni, Zn, Co and Pb. The derivation of the total mass of potential contaminants is based on total metal concentrations given in a table for the different geological formations at the Farley Lake project (Appendix 1).

In order to determine the concentrations of elements, a weathering rate must be estimated, but this requires making the unrealistic assumption that all of the waste rock would be exposed to weathering on a per weight basis. However, the weathering process is a function of the surface area exposed to weathering, which would require a void ratio to be determined. This in turn would assume that the waste rock pile has a uniform void ratio, which is not the case. In waste rock dumps, there are normally perched water tables forming, and only a limited number of seepage paths develop, from which toe seepages emerge. In Schematic 1 (Appendix 4), the functioning of a

waste rock pile is depicted, describing all of the ongoing processes. The assumptions made for the seepage contaminant load represent approximations, using the best available data sources.

To estimate the worst case scenario, the maximum concentrations of the elements in the geological formations were used, from the ranges given by Mr. Akin. The mass of each element in the waste rock dump (SWRD) was determined by using the % of Argillite and BIF given. In this manner the total mass of As was calculated as 479 tonnes. The second largest metal fraction which might be weathered was Zn.

Assuming that the  $SO_4$  concentrations measured in the SWRD seepage represent a 5-year average of  $SO_4$  concentrations in the SWRD, we first calculated the amount of S (tonnes) required to oxidize/weather over a 5-year period at conditions of **25%** and **75%** infiltration of the rainfall over the period. Knowing the amount of S oxidized over a period of **5** years (the age of SWRD), we could then calculate an (average, constant) oxidation rate of S (**mM**) for each infiltration scenario.

Applying the calculated S oxidation rate proportional to other S minerals (e.g.,  $AsFeS$ ) contributing to the total S content, and assuming an average water discharge rate of **6.45** L/min (**25%** infiltration) or 19.43L/min (**75%** infiltration), allowed us to calculate an average concentration of each element in the discharge. The latter was achieved by dividing the oxidation rate of each mineral (**mM**) by the discharge rate (L/min). The reported contaminant concentrations in the discharge are 1000 x smaller than calculated according to the above procedure. This factor 1000 has been used as the measured  $SO_4$  concentration in the seepage (11.1 mM) is about 1000 x smaller than the  $SO_4$  concentration calculated with PHREEQUE C (10,050 mM) at the appropriate SWRD:H<sub>2</sub>O ratio.

The estimated concentrations of elements in the toe seepages are given in Table 4. The arsenic concentrations are expected to reach 0.05 mg/L. A comparison of these concentrations to those reported in the Wendy wall seeps (where deeper ground and

Table 4: Projected Toe Seepage Concentration

	Argill. (31.6%)	BIF (68.4%)	SWRD	SWRD tonnes		%	Weath./Oxid. Rate*		Conc. In Discharge 25% infil. mg/L
							25% infil. mmol/min	75% infil. mmol/min	
<b>S (%)</b>			<b>0.43</b>	6675.28	sulfides	100	<b>0.071</b>	<b>0.215</b>	
<b>As (ppm)</b>	240	340	<b>308.40</b>	478.76	AsFeS	7.17			0.0595
<b>Cd (ppm)</b>	1.5	2	<b>1.84</b>	2.86	CdS	0.04			0.0005
<b>Cu (ppm)</b>	49	13	<b>24.38</b>	37.84	CuFeS2	0.57			0.0020
<b>Ni (ppm)</b>	83	21	<b>40.59</b>	63.01	Fe(Ni)S	0.94			0.0003
<b>Pb (ppm)</b>	39	21	<b>26.69</b>	41.43	PbS	0.62			0.0142
<b>Zn (ppm)</b>	106	110	<b>108.74</b>	168.80	ZnS	2.53			0.0183
Argillite	491,190 tonnes								
BIF	1,061,200 tonnes								
SWRD	1,552,390 tonnes								
<b>SWRD</b>	<b>2.7 ha</b> <b>502.1 mm/yr</b> <b>25% Inf.</b> <b>75% Inf</b>			<b>solid:H2O</b> (kg/kg)	<b>Q</b> m <sup>3</sup> /yr	<b>Q</b> L/min			
		3389.18 m <sup>3</sup>		458.04:1	3389.18	6.45			
		10167.53 m <sup>3</sup>		152.68:1	10167.53	19.34			
<b>SWRD seepage</b>	<b>SO4</b> (mg/L)	<b>SO4</b> (mmol/L)	<b>S</b> (mg/L)	<b>S (mean)</b> (mg/L)	<b>S (mean)</b> (mmol/L)		<b>Over 5 yr period: S=354.83 mg/L</b>		
	1210	12.60	403.33	354.83	11.09		25% Inf.	6.01 tonnes S/(5x3389.18) m <sup>3</sup>	
	919	9.57	306.33				75% Inf.	18.04 tonnes S/(5x10167.53) m <sup>3</sup>	

Note: Since the SO4 concentration (10050 mmol/L), calculated with PHREEQC at appropriate solid:water ratio, is about 1000x larger than the SO4 concentration (11.1 mmol/L) at the SWRD seepage, the calculated oxid./weath rates have been reduced by a factor 1000 (e.g. calibration of model with SO4 site data).

This factor may account for the effects of:

- reduced sulfide oxidation rates
- dilution by groundwater
- differences in infiltration and discharge

much higher flow rates cause few adsorption and precipitation processes), again indicates a relatively good relationship. The concentrations, lower by 10-fold, are likely a result of dilution of the water. In summary, it can be concluded that the rationale used to derive weathering processes, and contaminant loading to assess seepage concentrations, is reasonable.

## **5.0 AREAS REQUIRED FOR BACKUP TREATMENT**

Using these contaminant generation rates, the annual As load expected in toe seepages from the waste rock pile is 82 g in 150 days of snow-free season. (0.05mg/L reporting in 6.4 L/min using the infiltration rate of 25%). Using the established treatment capacity of a muskeg in northern Saskatchewan, an average load of 270 kg of As in a period of 113 snow-free days, required an area of 2.7 ha. Since the load expected from the SWRD is 3000 times lower, the area of 9 m<sup>2</sup> would be required. The present seepage diversion ditch and the sedimentation pond is, therefore, of sufficient area to accommodate the toe seepages with a significant safety factor.

Calculating the capacity of 100, which is likely closer to the area of the seepage collection ditch, field and laboratory studies determined that sediments in the muskeg pools have a removal capacity for nickel of between 0.07-0.1 g.m<sup>-2</sup>.d<sup>-1</sup>, and between 0.08-0.1 g.m<sup>-2</sup>.d<sup>-1</sup> for arsenic. During the summer, therefore, 100 m<sup>2</sup> effective pool sediment would remove 1.5 kg in the 150 days assumed to be snow-free, which represent a safety factor of 100.

## **6.0 ENVIRONMENTAL CONDITIONS OF THE DRAINAGE BASIN**

In this section, an evaluation is made of the existing conditions of the receiving environment, in order to establish the criteria against which the decommissioning measures can be evaluated.

Monitoring results on water quality have been obtained from three locations: (i) the Diversion Ditch at the foot of the SWRD, which discharges through a settling pond into Gordon Lake; (ii) Gordon Lake, which discharges through a diversion ditch into Farley Lake; and (iii) Farley Lake itself. The monitoring data, which cover the time period November, 1995 to July, 1998, are given in Appendix 3.

The elements which are monitored but do not vary in concentrations reported are As, Cu, Pb, Ni, and Zn. Their concentrations are very low or at the detection limit. However pH, hardness, ammonia, iron and TSS vary over time and are likely seasonal. Those parameters are used to understand the systems behavior. Water quality data from the three locations are available covering the time period of November, 1995 to August, 1998.

The basic statistics of these parameters are presented in Table 5. The data set covers a total of 34 months, but samples were not always collected every month. The data points which are missing for the same date for the three sampling stations are comparable with 29.4% for the collection ditch, but for Gordon Lake and Farley Lake, only 20% of the monthly intervals are missing. All parameters except pH have a high StDev/Average ratio, which suggests that they are highly unlikely to be normally distributed. This excludes the use of parametric statistics. In the absence of normality, the non-parametric Wilcoxon Test was used for testing for differences between the water characteristics.

In Table 5, the parameters which are used to determine the behavior of the system are compared to pre-mining conditions reported in the EIA. Also shown in Table 5 is water quality in a test pit, which was created to collect a 10,000 tonnes bulk sample in 1988, in order to represent the East pit. Although the hydrological conditions at the time are not known, this water may be representative of results of pit wall oxidation of the mineralization. Ground water was, however, reported to have overflowed the test pit and drained toward Farley Lake. As the dilution factor of the incoming ground

**Table 5: Basic Statistics of Five Water Quality Parameters Examined over Nov. 1995 to Aug. 1998**

**1995 - 1998**

	pH			Hardness (mg/L)			NH4 (mg/L)			Fe (mg/L)			TSS (mg/L)		
	Ditch	Gordon	Farley	Ditch	Gordon	Farley	Ditch	Gordon	Farley	Ditch	Gordon	Farley	Ditch	Gordon	Farley
No.	24	27	27	24	27	27	24	27	27	24	27	27	24	27	27
Data missing %	29.4	20.6	20.6	29.4	20.6	20.6	29.4	20.6	20.6	29.4	20.6	20.6	29.4	20.6	20.6
Max	9.3	10.3	9.5	205.0	223.0	182.0	0.5	1.1	0.2	0.8	1.7	0.5	9.7	50.0	6.0
Min	6.0	6.0	5.8	67.0	41.0	69.0	0.0	0.1	0.0	0.1	0.2	0.0	0.4	1.0	0.0
Average	6.9	7.1	6.9	124.0	137.5	97.9	0.1	0.3	0.1	0.2	0.6	0.1	2.4	9.1	1.6
StDev	0.8	0.9	0.8	37.0	45.2	21.5	0.1	0.2	0.1	0.2	0.3	0.1	2.4	10.2	1.4
Median	7.5	7.9	7.6	112.0	134.0	95.0	0.1	0.3	0.1	0.2	0.5	0.1	1.5	4.0	1.0

**1993-1994**

	pH			Hardness (mg/L)			NH4 (mg/L)			Fe (mg/L)			TSS (mg/L)		
	Test Pit	Gordon	Farley	Test Pit	Gordon	Farley	Test Pit	Gordon	Farley	Test Pit	Gordon	Farley	Test Pit	Gordon	Farley
No.	1	3	5	1	3	5	1	3	5	1	3	5	1	3	5
Average	7.7	7.7	7.8	83.2	63.2	71.4	0.034	0.1	0.1	0.3	0.1	0.1	5.0	7.7	2.6



water is unknown, the test pit water does not likely represent a reliable long-term projection of water quality, even though it is 5 years after flooding.

However from the parameters which change in the drainage basin summarized in Table 5, the comparison of these data lead to the valuable conclusion that these parameters have remained the same. It appears that the mining activity has had no environmental impact up to this point in time. If there had been an effect of the weathering products from the waste rock pile, then the hardness and iron, for example, would be expected to have increased.

The changes in all five parameters were examined over the sampling period, and these data are plotted in Figures 1 a-e. The pH value appears to be highly seasonal, with peaks in summer and lower values in winter/spring. This trend is particularly strong for Gordon Lake. The Wilcoxon Test indicated that pH in Gordon Lake was significantly higher than in either Farley Lake or the seepage collection ditch ( $P < 0.01$ ), while there was no significant difference between the seepage collection ditch and Farley Lake ( $P > 0.1$ ). As the seepage collection ditch mainly represents ground water pumped from the pit, it suggest that it might be Farley Lake water which is being pumped.

PH, however, co-varied strongly over the three locations, with Pearson correlation coefficients of  $r$  ranging from 0.82 to 0.95 ( $P < 0.01$ ). This means that the pH levels follow similar seasonal patterns at all three locations. There are no significant correlations between pH and the other four parameters at all locations. This indicates that the water from the drainage ditch is not affecting any of the parameters which were analyzed. This is to be expected, since pH is not affecting these variable.

Fig. 1a: pH Changes over Time

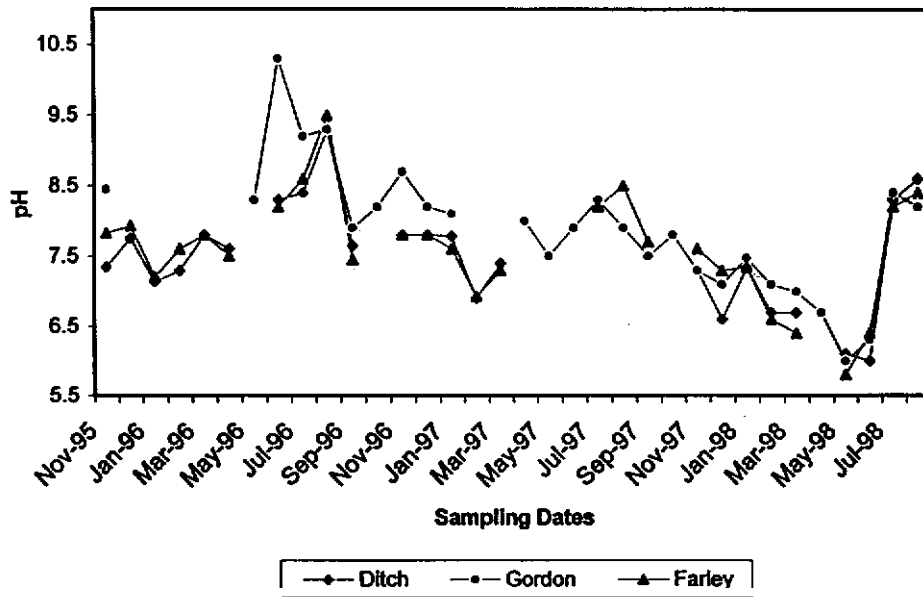


Fig. 1b: Hardness Changes over Time

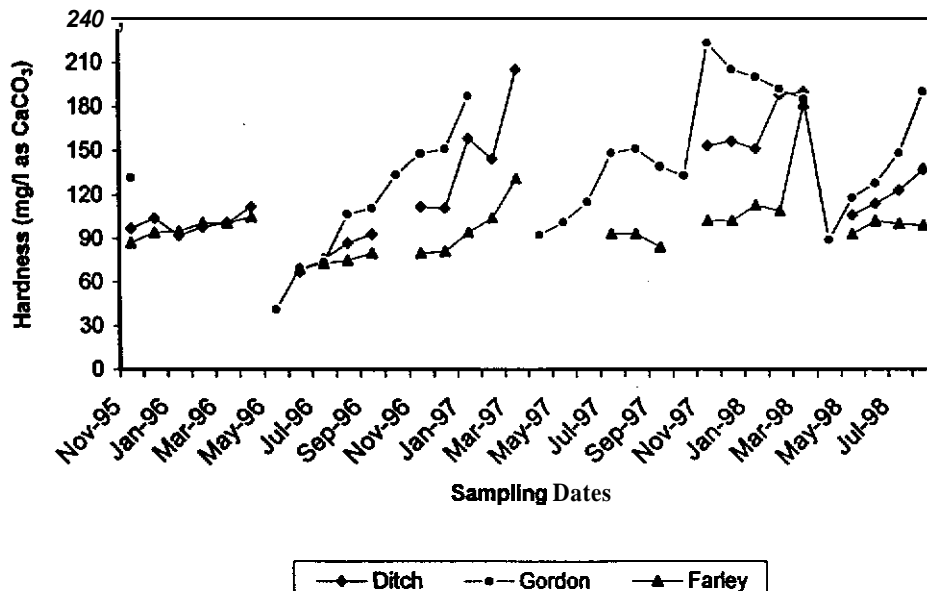


Fig. 1c: Ammonium Changes over Time

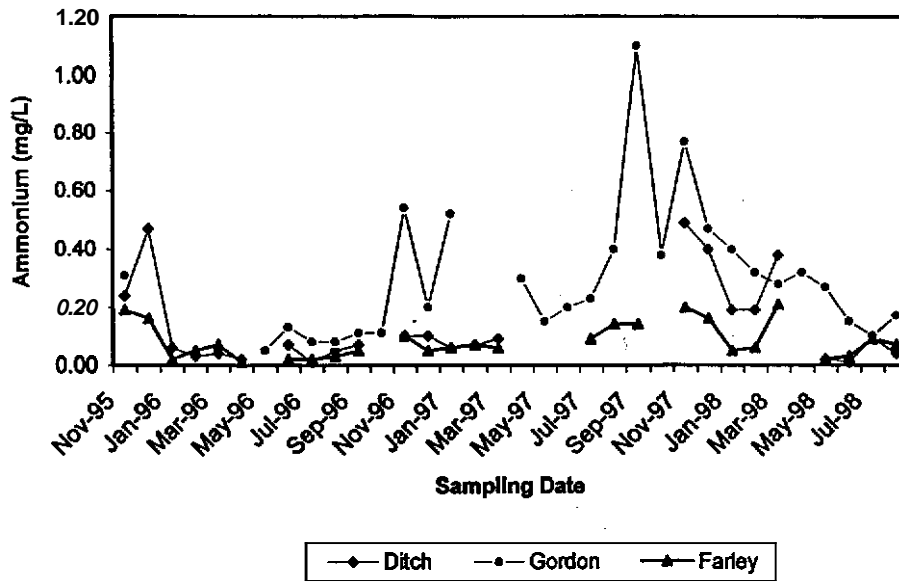
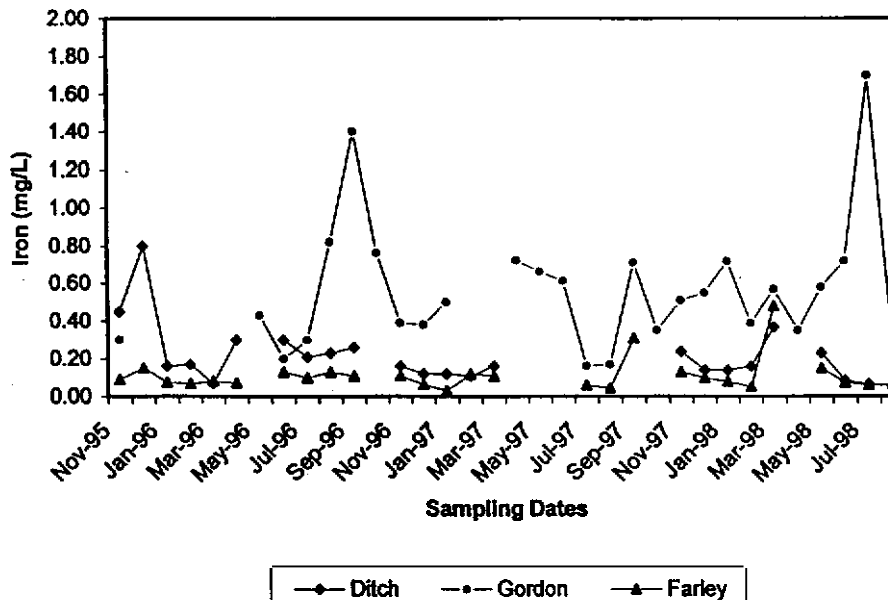
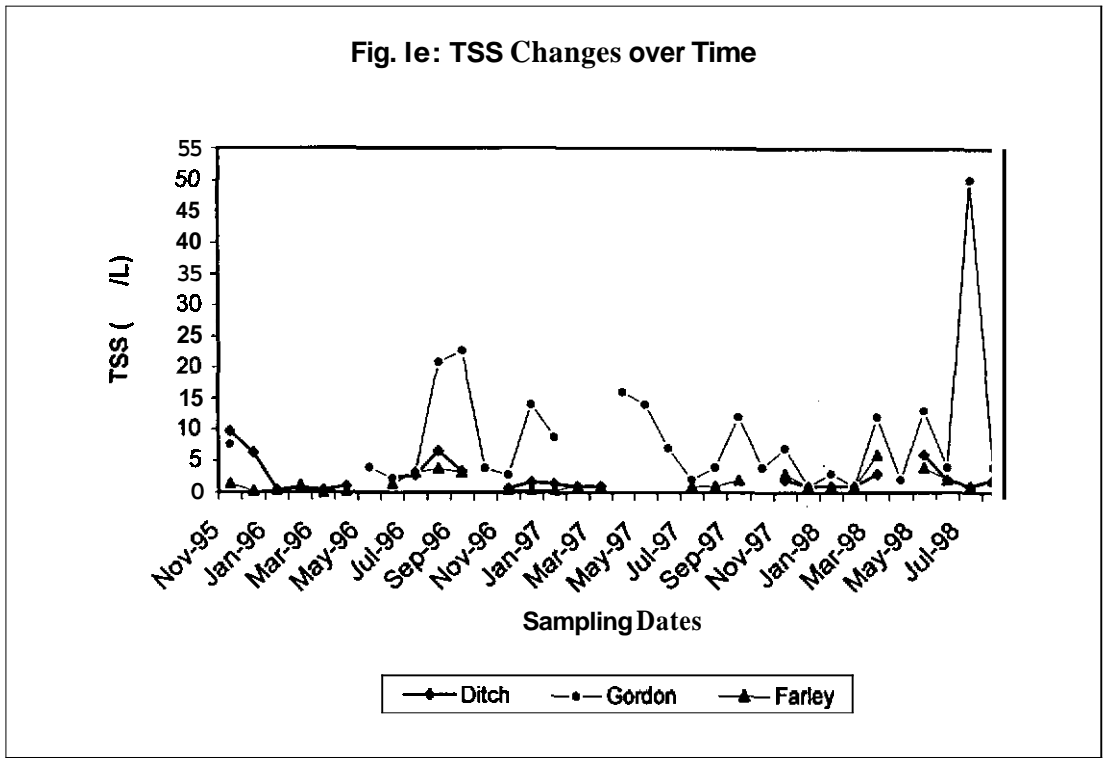


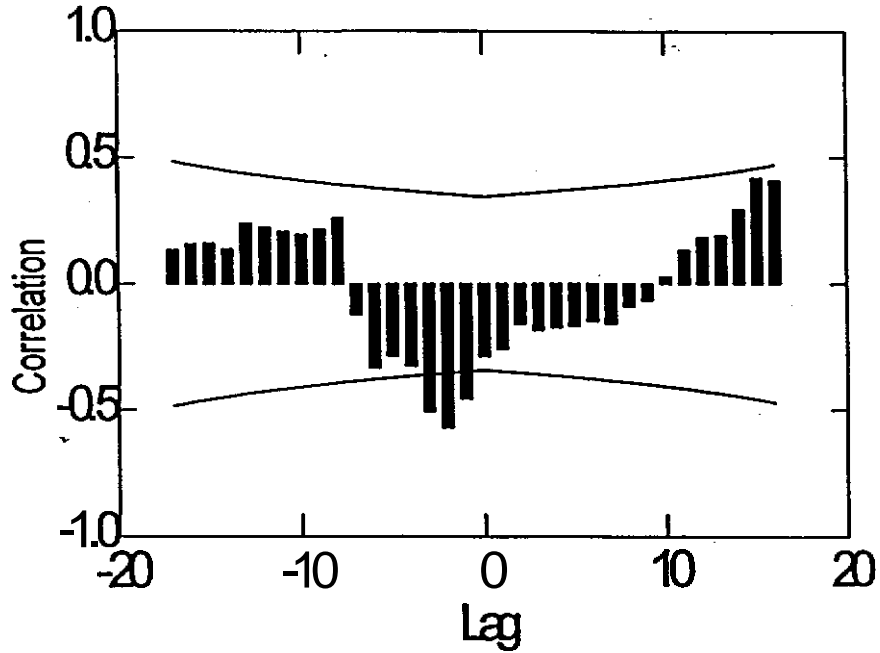
Fig. 1d: Iron Changes over Time



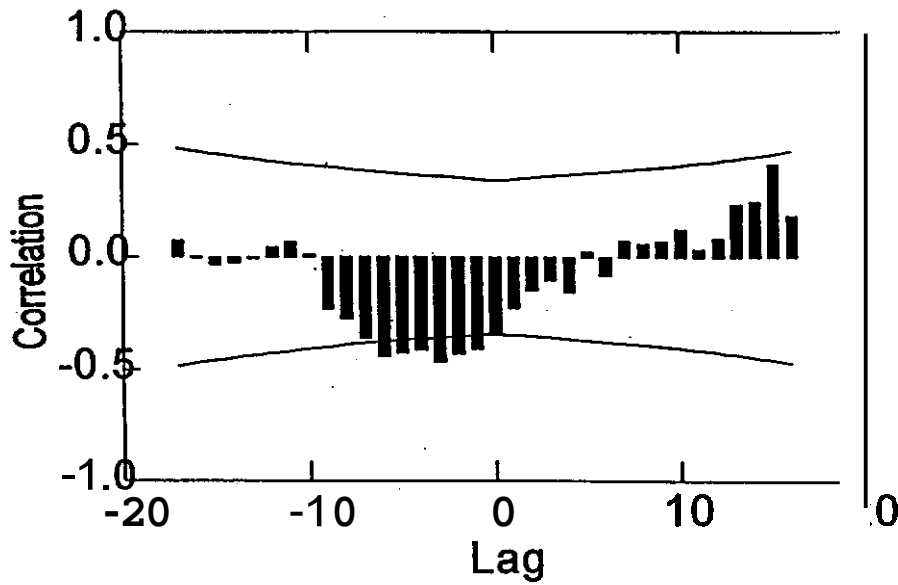


Examining the data using a cross correlation, which takes time lag into account showed that significant correlation exists between pH and the total ammonia of approximately two months earlier (Figure 2a-c). This time lag is due to biological activity in Gordon Lake, which has generally a higher concentration of ammonia than the diversion ditch. With the input of organic matter the microbial interactions with phytoplankton production could reflect biological cycling of CO<sub>2</sub> and ammonia over time. In the spring, high CO<sub>2</sub> and ammonia are accumulated because of the ice-cover, which results in the lower pH values and ammonia increases. In late spring/summer, temperature rapidly increases, and active phytoplankton photosynthesis can substantially consume CO<sub>2</sub> and ammonia, which lead to an increase in pH. The cross-correlation well reflects this limnological cycle.

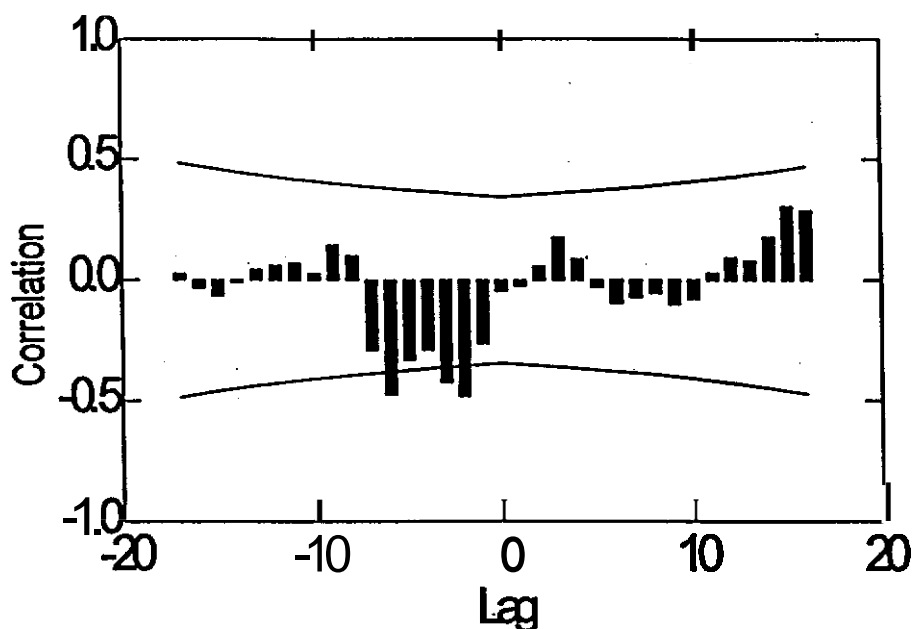
**Fig. 2a: Cross Correlation Between  
pH and Ammonium at Ditch**



**Fig. 2b: Cross Correlation Between  
pH and Ammonium at Gordon**



**Fig. 2c: Cross Correlation Between pH and Ammonium at Parley Lake**



Ammonia and hardness also co-varied at the three locations, with a Pearson  $r > 0.57$  ( $P < 0.05$ ). In the summer months, both hardness and ammonia are relatively low, while they reached higher levels in winter/spring. These parameters are also affected by biological activity, indicating a healthy ecosystem response. The two parameters were also significantly higher at Gordon Lake, Farley Lake and the Diversion Ditch (Wilcoxon Test,  $P < 0.01$ ). Although neither Fe nor TSS co-varied at the locations over time, both parameters reached higher levels in Gordon Lake than in either the Diversion Ditch or Farley Lake. As Gordon Lake is the smaller lake, it is reasonable to assume that it has higher phytoplankton biomass, given the large drainage basin. All parameters reflect biological processes such as iron oxidation/reduction and TSS production due to biomass growth, as indicated by the temporal changes in all the above parameters.

In conclusion, all of the five parameters showed significant spatial differences, with

Gordon Lake generally producing the highest values. Seasonal patterns were also clearly evident in all parameters; pH and TSS were higher in summer, while ammonia and hardness peaked in winter/spring. There is a strong cross-correlation between pH and ammonia, with a time lag of 2 months, suggesting the influence of phytoplankton production. The seasonal changes in water quality appear more prominent than any of the potential impacts from the discharge of the diversion ditch. The two-month lag likely reflects changes in temperature. It can be concluded that the drainage basin of Gordon Lake has not been affected in any way by the mining activities. With the proposed buffering capacity of muskeg, there will be no environmental impact after mining ceases.

## RECOMMENDATIONS

The hydrological conditions of the site should be clarified and the seepage paths from the SWRD to the pits determined, in order to increase the certainty that no short-circuiting of the toe seepage takes place.

The results of the analyses of water samples from the seepage collection ditch, which are currently being carried out, as well as the results of the water samples already analyzed, should be further examined in order to determine the origin of the elements. In order to do this, back-titration of rain water with the mineralogy would be carried out, using geochemical models. The results would provide a second verification of the oxidation rates and the seepage chemistry projection.

## Content

Appendix 1a: Geology Keystone Gold from Ken **Atkin**

Appendix 2a: Map of North Waste Rock Ditch, Sampling Location and Analytical Results SRC

Appendix 2b: Map of Wendy Pit and Analytical Results SRC

Appendix 3: Monitoring Data for Waters Gordon Lake, Ditch, Farley Lake 1995 - 1998 and Test Pit, Gordon Lake, Farley Lake 1993-1994

Appendix **4**: The Function of **Wetland/Muskeg** Decommissioning Mine Waste Management Areas

Proposed Waste Pock Pile Seepage Generation Pathway



# Keystone Gold

DATE: September 16, 1998  
TO: Dave Passfield, Mine Superintendent  
CC: Kevin Drover, General Mine Manager  
FROM: Ken Atkin, Senior Geologist  
RE: ABA and Geological Composition of the Acid Rock Dump

---

## DRAFT

The composition of the Potentially Acid Generating (PAG) rock dump, or south dump, is estimated to be:

Rock Type	Tonnes	Fizz	%Sulfur	
Wendy Black Argillite	491,190	1.41	0.26	Tonnes from Block Model Assays from 87 Bench Blastholes
Wendy BIF	339,745	1.36	0.43	Tonnes = Truck Count <b>Less</b> Black Argillite Assays from 87 Bench Blastholes
East Pit BIF	721,455	1.75	0.55	Tonnes from Truck Count Assays from 87 Bench Blastholes
<hr/>				
Total	1,552,390	1.56	0.43	

The dump was not sampled as it was constructed and much of the material sent to the dump was directed on the basis of visual estimates of the sulfur content. For this reason, blasthole assays from the 87 bench of each pit have been used to approximate the composition of the dump.

Black argillite is most common in the Wendy Pit, although minor occurrences are found in the East Pit. This rock type has a relatively low sulfur content but is essentially devoid of neutralizing minerals and is therefore considered as PAG. For practical purposes, it can be assumed that all black argillite reported to the PAG dump. Black argillite is a fine grained well foliated rock composed mostly of quartz, biotite, and

carbonaceous matter. Carbonate is essentially absent. Pyrite typically occurs as disseminations of tiny grains (2 to 30 microns) within the groundmass and also as coatings on fracture surfaces. The very fine grained nature of the pyrite should tend to make it more reactive. However, the even dispersal of pyrite grains within the relatively impermeable groundmass will impede the reactivity of pyrite. Pyrite fracture coatings would have a high reactivity, but likely constitute a minor portion of the total pyrite in the black argillite. A sample of the black argillite from the humidity cell test (5328 Reject) was examined in thin section and found to have the following composition.

Quartz	50%
Biotite	33%
Carbonaceous Matter	10% (?)
Sericite, Chlorite, and Plagioclase	5%
Pyrite	1.5%
Rutile	0.5%
Tourmaline	Trace
Carbonate	Trace
Pyrrhotite	Trace
Marcasite	Trace

Banded iron formation (BIF) reported to the PAG South waste rock dump as well as the NAG (Non Acid Generating) North waste rock dump Segregation of PAG from NAG banded iron formation was based on blasthole assays plus visual identification of sulfides. Guidelines for the identification of PAG are dependant upon the fizz rating (approximate net neutralizing potential) and sulfur content:

Fizz Rating	% Sulphur	Dump
1	NA	Acid
2	>0.3	Acid
	<0.3	Basic
3	>1.5	Acid
	<1.5	Basic
4	NA	Basic

Banded iron formation reporting to the PAG South waste rock dump had sulfur concentrations of 0.3 to 1.5% sulfur. More sulfur rich banded iron formation was taken as ore and reported to the mill Sulfur occurs in the form of iron sulfides, namely pyrite and pyrrhotite The Wendy Pit was dominated by pyrrhotite with lesser pyrite, whereas the East Pit is dominated by pyrite with lesser pyrrhotite Also, the banded iron formation in the East Pit is typically more finely crystalline and more chert rich than that of the Wendy Pit. These mineralogical factors result in blasted rock from the East Pit being more finely fragmented than that from the Wendy Pit Dye tests in the metallurgical test work suggest that there is very little permeability in the banded iron formation

Pyrite and pyrrhotite generally occur as liberated grains 50 to 300 microns or more in size These sulfides are commonly poikilitically sieved with fine grained silicate inclusions (e.g. the sulfide crystals

encapsulate numerous small silicate grains) The sulfides generally occur as discrete blebs within the silicate groundmass with the blebs being concentrated along preferred bedding planes Fracture fillings are **less** common. The poikilitic habit would increase the reactivity of the sulfides to weathering whereas the blebby nature of the sulfides would limit the reactivity to weathering because the sulfides are encapsulated within the impermeable, non-reactive silicates, The impermeable nature of the silicates has been confirmed by dye tests in the metallurgical testing

Thin sections are being prepared to better understand the detailed mineralogy of the banded iron formation in the two pits A single thin section has been prepared of ore taken from the 1989 Test Pit in the East Pit. The following minerals were identified in this sample:

Quartz	20%
Amphibole (hornblende and grunerite)	61%
Chlorite	<b>5.5%</b>
Carbonate	2.0%
Magnetite	7%
Pyrrhotite	<b>3%</b>
Pyrite	1.5%

Note. Albitic Feldspar was identified a major component in the metallurgical test work and further work is required to more fully document the mineralogy of the banded iron formation Lesser occurrences of tourmaline, tellurobismuthite, galena, chalcopyrite, covellite, tetrahedrite, ilmenite, and arsenopyrite were also identified in the metallurgical test work Geochemical studies suggest that these lesser occurrences must be particularly rare.

The geochemistry of the major rock units at the Farley Lake Property has been reviewed in the Environmental Impact Statement A summary table comparing the chemistry of Farley Lake rock units to that of "typical" rocks is attached. Only silver (Ag), arsenic (As), and cadmium (Cd) are enriched by a factor of **5** or more versus concentrations in "typical" **rock**. The geochemistry of ore, low grade ore, argillites, and iron formation are applicable to the PAG dump; mafic sill has a high neutralizing potential and reported mostly to the NAG dump.

Sincerely,

Kenneth T.J. Atkin  
Senior Geologist

File: ABA-0998.WP6

Element	Typical Concentrations in Rock	Ore (N=20)	Low-Grade Ore (N=10)	Argillites (N=10)	Iron Formation (N=10)	Mafic Sill (N=10)
Al	"Major"	14,600-36,100	9,100-42,500	35,300-85,600	6,700-31,500	46,900-83,900
Ag	0.04-0.1	2.0-3.5	1.5-2.5	1.5-2.5	1.5-2.5	1.5-2.5
As	1-13	<20-120	<20-40	<20-240	<20-340	<20-90
Ba	10-600	20-440	60-310	240-700	20-260	50-640
Be	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Ca		3,300-15,400	3,000-11,100	6,500-18,200	6,900-59,000	4,800-47,900
Cd	0.03-0.3	<0.5-2.5	<0.5-3.0	0.5-1.5	<0.5-2.0	<0.5-1.5
Co	0.1-48	3-12	<1-14	8-17	<1-12	3-33
Cr	11-170	54-172	43-111	89-343	39-121	28-152
Cu	2-87	14-117	3-43	8-49	3-13	5-45
Fe	"Major"	168000-239000	115500->250000	47800-192500	185000->250000	55500-136500
Hg	0.01-0.4	0.15-0.35	0.14-0.33	0.14-0.29	0.05-0.24	0.10-0.69
K		7,800-16,000	5,300-17,200	8,400-32,400	1,800-12,800	4,700-13,800
Mg		11,200-17,700	10,900-19,700	14,600-19,800	13,800-19,500	13,800-46,100
Mn	50-1500	780-5,010	675-4,950	150-1,105	1,315-4,690	245-2,870
Mo	0.2-2.6	<1-3	<1-2	<1-6	<1-2	<1-1

Element	Typical Concentrations in Rock <sup>1</sup>	Ore (N=201)	Low-Grade Ore (N=10)	Argillites (N=10)	Iron Formation (N=10)	Mafic Sill (N=10)
Na		200-5,700	200-8,800	200-20,800	500-9,500	14,200-46,900
Ni	2-130	8-22	2-23	23-83	4-21	2-80
P		910-3,120	750-2,360	590-1080	980-2,820	260-1360
Pb	6-20	9-33	12-27	14-39	14-21	17-29
Sr	20-600	12-74	14-107	47-192	39-215	84-603
Ti	"Major"	700-1,600	300-1,500	1,500-4,200	300-1,400	1,000-5,600
V	20-250	32-61	25-54	60-185	24-60	9-184
Zn	16-105	42-118	44-118	46-106	28-110	62-100

<sup>1</sup> From Drever, J.I. 1982. The Geochemistry of Natural Waters. Prentice-Hall Inc.; all concentrations in units of ppm

**Subject: Rare Mineral Occurrences in Farley Ore****Date:** Sat, 7 Nov 1998 10:30:25 -0500**From:** "Kennet t.J. Atkin" <kenatkin@cancom.net>**To:** "Margarete Kálin" <margarete.kalin@utoronto.ca>

Black Hawk Mining  
 BOX 2000  
 Lynn Lake, Manitoba  
 ROB OWO  
 Tel: (204) 356-2461  
 Fax: (204) 356-8372  
 Keystone Gold

**DATE:** November 5, 1998  
**TO:** Jan Gerits  
**cc:** Dave Passfield, Mine Superintendent  
 Kevin Drover, General Mine Manager  
**FROM:** Ken Atkin, Senior Geologist  
**RE:** Rare Mineral Occurrences in Farley Ore

The occurrence of rare minerals was omitted from the memo on the mineralogical composition of the south waste rock dump in an effort to avoid confusion. Metallurgy testing identified the presence of several minerals that are present in trace amount include:

Tourmaline	A complex botosilicate
Tellurobismutite	Bi <sub>4</sub> Te <sub>3</sub> ?
Galena	PbS
Chalcopyrite	CuFeS <sub>2</sub>
Covellite	cus
Tetrahedrite	(Cu,Fe) <sub>12</sub> Sb <sub>4</sub> S <sub>13</sub>
Ilmenite	FeTiO <sub>3</sub>
Arsenopyrite	FeAs <sub>2</sub>

The geochemistry of the Farley ore proves that these minerals are extremely rare (as from the same metallurgical study **as** the mineralogy):

cu	60	ppm
Pb	184	ppm
Zn	55	ppm
As	51	ppm
Sb	50	ppm
Bi	44	ppm
Hg	94	ppm

The concentration of these elements would be less in the south waste rock dump because only heavily diluted "ore" reported to the south waste rock dump.

This should address your needs for the trace element mineralogy of the south waste rock dump. I can be contacted the (204) 473-2490 should you require further information.

Sincerely,

Kenneth T.J. Atkin  
Senior Geologist

File: BOOJ1198.WP6

NW RD Water Survey

P<sup>u</sup> Temp  
Water Q. 10.1  
Aug 20/92  
1:00 pm

pH 6.80 @ 6.2°C  
in Bag at 50 and 100  
pH 6.25 @ 16.2°C Sample NURS-4  
pH 6.90 @ 9.8°C  
pH 6.79 @ 11.2°C  
Trench in Till  
Subs and green  
algae in water  
at dist. 1 m

SEDIMENTATION  
POND

7.75  
@ 16.4°C

7.57 pH  
@ 17.5°C

NW RD #2  
pH 6.72  
@ 17.2°C

Brown foam  
water from  
mussel bag

7.61 pH  
@ 18.2°C

6.70 pH  
@ 17.5°C  
6.75 pH  
@ 15.9°C

SEDIMENTATION  
POND

30HP

OVERBURDEN  
DUMP

81C



KEN

**SRC ANALYTICAL,**  
 101 Research Drive  
 Saskatoon, Saskatchewan S7N 3R2  
 (306) 933-6932 1-800-240-8808

Black Hawk Mining Inc.  
 Keystone Gold Mine  
 P.O. Box 2000  
 100 Camp Street  
 Lynn Lake, Manitoba R0B 0W0  
 Attn: James Armstrong

05-Aug-98 09:57

Date Samples Received: 20-Jul-98 Client P.O.:

SOUTH WASTE Rock dump

SAMPLE CLIENT DESCRIPTION  
 17297 KEN'S SAMPLE #1 JUL 16/98 \*WATER\*  
 17298 KEN'S SAMPLE #2 JUL 16/98 \*WATER\*

ANALYTE	UNITS	17297	17298
		PH	
		7.35	6.31
INORGANICS			
Calcium	mg/L	335	212
Magnesium	mg/L	163	87
Sulfate	mg/L	1210	919
Total hardness	mg/L	1510	886
Ammonia as nitrogen	mg/L	1.0	0.10
Silver	mg/L	<0.001	<0.001
Arsenic	ug/L	<0.5	<0.5
Cadmium	mg/L	<0.001	<0.001
Copper, acid soluble	mg/L	<0.001	0.006
nickel	mg/L	0.001	0.005
Lead, acid soluble	mg/L	<0.002	<0.002
Zinc	mg/L	<0.005	0.006

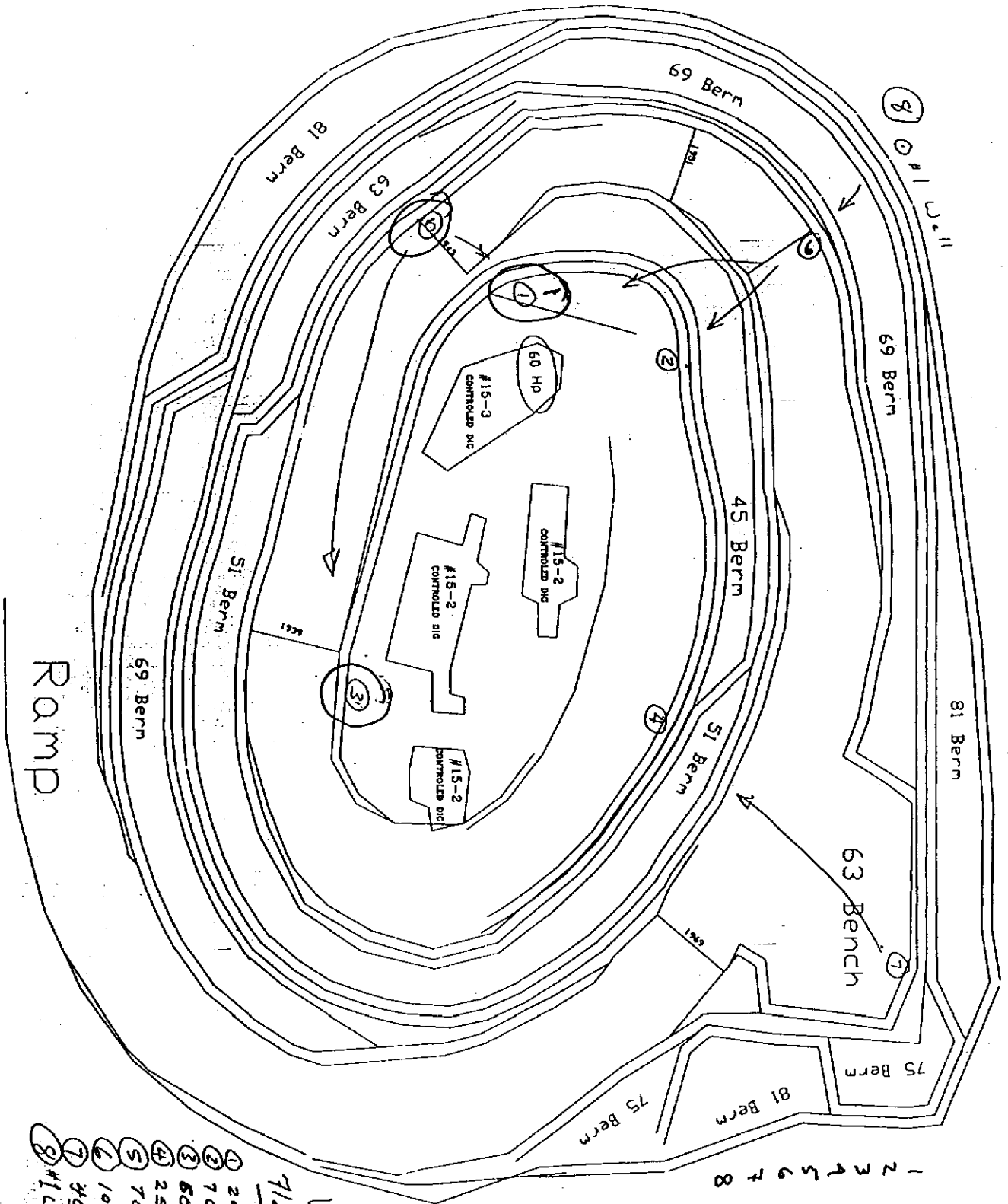
"<": not detected at level stated above.

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# WENDY PIT



	PH
1	8.43
2	8.54
3	8.29
4	8.43
5	8.31
6	8.38
7	8.21
8	7.83

Visual  
Flow Rate 5/yr  
IMPA

1	200
2	70'
3	60
4	25
5	70
6	100
7	30
8	#10.01

# TABULATION OF GORDON LAKE WATER QUALITY: FARLEY LAKE MINE

1995 - 1998

125

DATE	NOV 95	MAY 96	JUN 96	JUL 96	AUG 96	SEP 96	OCT 96	NOV 96	DEC 96	JAN 97	APR 97	MAY 97	JUN 97	JUL 97
PARAMETER														
pH	8.45	8.3	10.3	9.2	9.3	7.9	8.2	8.7	8.2	8.1	8	7.5	7.9	8.3
Field Temperature	1	5.1	16.3	18.1	14.7	12	2	2.2	2.7	0.5	2.2	13.7	12.3	18.7
Hardness	132	41	70	74	107	111	134	148	151	187	92	101	115	148
Total Ammonia	0.31	0.05	0.13	0.08	0.08	0.11	0.11	0.54	0.2	0.52	0.3	0.15	0.2	0.23
Total Arsenic	0.001	0.0006	0.0005	0.0023	0.0007	0.0007	0.0009	0.001	0.0016	0.0016	0.0005	0.0006	0.0015	0.0019
Acid-soluble Copper	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.003	0.001
Acid-soluble Lead	0.005	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Total Nickel	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.001
Total Iron	0.3	0.43	0.2	0.3	0.82	1.4	0.76	0.39	0.38	0.5	0.72	0.66	0.61	0.16
Total Zinc	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.009	0.005	0.005
Total Sus. Solids	7.6	4	2.2	3.2	20.8	22.6	3.8	2.8	14	8.8	16	14	7	2

DATE	AUG 97	SEP 97	OCT 97	NOV 97	DEC 97	JAN 98	FEB 98	MAR 98	APR 98	MAY 98	JUN 98	JUL 98	AUG 98
PARAMETER													
pH	7.9	7.5	7.8	7.3	7.1	7.48	7.1	7	6.7	6	6.3	8.4	8.2
Field Temperature	14.9	9.5	1.5	0.4	0.4	0.6	0	0.5	0.7	2.3	11	17.1	17
Hardness	151	139	133	223	205	200	192	185	89	118	128	148	190
Total Ammonia	0.4	1.1	0.38	0.77	0.47	0.4	0.32	0.28	0.32	0.27	0.15	0.1	0.17
Total Arsenic	0.0013	0.0006	0.0017	0.002	0.0011	0.0007	0.0017	0.0017	0.0005	0.0008	0.0007	0.0009	0.0016
Acid-soluble Copper	0.001	0.001	0.002	0.001	0.002	0.003	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Acid-soluble Lead	0.002	0.002	0.002	0.004	0.002	0.005	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Total Nickel	0.001	0.001	0.003	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Total Iron	0.17	0.71	0.35	0.51	0.55	0.72	0.39	0.57	0.35	0.58	0.72	1.7	0.3
Total Zinc	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Total Sus. Solids	4	12	4	7	1	3	1	12	2	13	4	50	4

Parameters	Units	Limit
pH		n/a
Field Temperature	celcius	n/a
Hardness	(mg/L)	1
Total Ammonia	(mg/L)	0.01
Total Arsenic	(mg/L)	0.0005
Acid-soluble Copper	(mg/L)	0.001
Acid-soluble Lead	(mg/L)	0.002
Total Nickel	(mg/L)	0.001
Total Iron	(mg/L)	0.001
Total Zinc	(mg/L)	0.005
Total Sus. Solids	(mg/L)	1

# TABULATION OF DIVERSION DITCH DISCHARGE TO FARLEY LAKE WATER QUALITY: FARLEY LAKE MINE

1995 - 1998

138

DATE →	NOV 95	DEC 95	JAN 96	FEB 96	MAR 96	APR 96	JUN 96	JUL 96	AUG 96	SEP 96	NOV 96	DEC 96	JAN 97	FEB 97
PARAMETER														
pH	7.35	7.75	7.14	7.3	7.8	7.6	8.3	8.4	9.3	7.65	7.8	7.8	7.78	6.9
Field Temperature	0	0	0	0.6	1.5	1.6	16.7	19.5	15.6	14	0.7	1.7	0.6	0.7
Hardness	97	104	92	98	101	112	67	76	87	93	112	111	158	144
Total Ammonia	0.24	0.47	0.06	0.03	0.04	0.02	0.07	0.01	0.05	0.07	0.1	0.1	0.06	0.07
Total Arsenic	0.0008	0.0009	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0007	0.0005	0.0005	0.0005	0.0006	0.0005
Acid-soluble Copper	0.001	0.001	0.002	0.001	0.001	0.001	0.003	0.001	0.001	0.001	0.002	0.002	0.001	0.001
Acid-soluble Lead	0.005	0.005	0.005	0.005	0.002	0.002	0.002	0.002	0.002	0.006	0.002	0.002	0.002	0.002
Total Nickel	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Total Iron	0.45	0.8	0.16	0.17	0.068	0.3	0.3	0.21	0.23	0.26	0.16	0.12	0.12	0.11
Total Zinc	0.007	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Total Sus. Solids	9.7	6.3	0.4	0.8	0.4	1	2.4	2.8	6.6	3.4	0.6	1.6	1.4	1

DATE →	MAR 97	NOV 97	DEC 97	JAN 98	FEB 98	MAR 98	MAY 98	JUN 98	JUL 98	AUG 98			
PARAMETER													
pH	7.4	7.3	6.6	7.34	6.7	6.7	6.1	6	8.3	8.6			
Field Temperature	0.7	0.4	0.4	0.4	0.4	0	9.1	14.3	19.3	20.2			
Hardness	205	153	156	151	188	190	106	114	123	137			
Total Ammonia	0.09	0.49	0.4	0.19	0.19	0.38	0.02	0.01	0.09	0.04			
Total Arsenic	0.0008	0.0009	0.0006	0.0005	0.0006	0.0013	0.0005	0.0005	0.0005	0.0005			
Acid-soluble Copper	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001			
Acid-soluble Lead	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002			
Total Nickel	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001			
Total Iron	0.16	0.24	0.14	0.14	0.16	0.37	0.23	0.086	0.065	0.057			
Total Zinc	0.005	0.005	0.005	0.005	0.005	0.01	0.005	0.005	0.005	0.005			
Total Sus. Solids	1	2	1	1	1	3	6	2	1	2			

Parameters	Units	Limit
pH		n/a
Field Temperature	celcius	n/a
Hardness	(mg/L)	1
Total Ammonia	(mg/L)	0.01
Total Arsenic	(mg/L)	0.0005
Acid-soluble Copper	(mg/L)	0.001
Acid-soluble Lead	(mg/L)	0.002
Total Nickel	(mg/L)	0.001
Total Iron	(mg/L)	0.001
Total Zinc	(mg/L)	0.005
Total Sus. Solids	(mg/L)	1

# TABULATION OF WEST DEEP BASIN FARLEY LAKE WATER QUALITY: FARLEY LAKE MINE

1995 - 1998

19

DATE	NOV 95	DEC 95	JAN 96	FEB 96	MAR 96	APR 96	JUN 96	JUL 96	AUG 96	SEP 96	NOV 96	DEC 96	JAN 97	FEB 97
PARAMETER														
pH	7.83	7.93	7.21	7.6	7.8	7.5	8.2	8.6	9.5	7.45	7.8	7.8	7.6	6.93
Field Temperature	0	0	0	0.8	1.5	1.9	16.9	20.3	15.6	15	0.7	1.1	0.4	0.7
Hardness	87	94	95	101	101	105	69	73	75	80	80	81	94	104
Total Ammonia	0.19	0.16	0.02	0.05	0.07	0.01	0.02	0.02	0.03	0.05	0.1	0.05	0.06	0.07
Total Arsenic	0.0007	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Acid-soluble Copper	0.001	0.002	0.003	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.004	0.002	0.001	0.001
Acid-soluble Lead	0.005	0.005	0.005	0.005	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Total Nickel	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Total Iron	0.09	0.15	0.076	0.068	0.082	0.072	0.13	0.1	0.13	0.11	0.11	0.064	0.03	0.12
Total Zinc	0.006	0.005	0.005	0.005	0.005	0.005	0.005	0.007	0.005	0.005	0.005	0.005	0.005	0.005
Total Sus. Solids	1.4	0.2	0.4	1.2	0	0.2	1.4	3.2	3.8	3.2	0.4	0.4	0.4	1

DATE	MAR 97	JUL 97	AUG 97	SEP 97	NOV 97	DEC 97	JAN 98	FEB 98	MAR 98	MAY 98	JUN 98	JUL 98	AUG 98
PARAMETER													
pH	7.3	8.2	8.5	7.7	7.6	7.3	7.35	6.6	6.4	5.8	6.4	8.2	8.4
Field Temperature	0.7	22.1	17.1	9.6	0.4	0.4	0.4	0.4	0	8.7	14	19.3	20
Hardness	131	93	93	84	102	102	113	109	182	93	102	100	99
Total Ammonia	0.06	0.09	0.14	0.14	0.2	0.16	0.05	0.06	0.21	0.02	0.03	0.09	0.07
Total Arsenic	0.0005	0.0005	0.0005	0.0005	0.0006	0.0005	0.0005	0.0005	0.0006	0.0005	0.0005	0.0005	0.0005
Acid-soluble Copper	0.002	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.002
Acid-soluble Lead	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.003
Total Nickel	0.001	0.001	0.001	0.001	0.001	0.01	0.001	0.001	0.002	0.001	0.001	0.001	0.001
Total Iron	0.11	0.059	0.045	0.31	0.13	0.1	0.08	0.052	0.48	0.15	0.073	0.059	0.062
Total Zinc	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.011	0.005	0.005	0.005	0.005
Total Sus. Solids	1	1	1	2	3	1	1	1	6	4	2	1	2

Parameters	Units	Limit
pH		n/a
Field Temperature	celcius	n/a
Hardness	(mg/L)	1
Total Ammonia	(mg/L)	0.01
Total Arsenic	(mg/L)	0.0005
Acid-soluble Copper	(mg/L)	0.001
Acid-soluble Lead	(mg/L)	0.002
Total Nickel	(mg/L)	0.001
Total Iron	(mg/L)	0.001
Total Zinc	(mg/L)	0.005
Total Sus. Solids	(mg/L)	1

**Imperial Gallons per minut L per second**

**IGPM**

**L.s<sup>-1</sup>**

1 IG = 4.54596L

1	0.076
10	0.76
20	1.5
50	3.8
100	7.6
200	15
500	38
1000	76

**U.S. Gallons per minute L per second**

**USGPM**

**L.s<sup>-1</sup>**

1 USG = 3.785306L

1	0.063
10	0.63
20	1.3
50	3.2
100	6.3
200	13
500	32
1000	63



SRC Group: 98-4589

# SRC ANALYTICAL

Black Hawk Mining Inc.

28-Sep-98 14:38

SAMPLE	CLIXNT DESCRIPTION			
23050	WENDY PIT INFLOW #1	*WATER*		
23051	WENDY PIT INFLOW #2	*WATER*		
23052	WENDY PIT INFLOW #3	*WATER*		

ANALYTE	UNITS	23050	23051	23052
INORGANICS				
Sulfata	mg/L	52	67	104
Ammonia as nitrogen	mg/L	0.08	0.09	0.12
Boron	mg/L	0.029	0.058	0.059
Phosphorus	mg/L	<0.05	<0.05	<0.05
Silver	mg/L	<0.001	<0.001	<0.001
Aluminum	mg/L	0.49	0.028	0.48
Arsenic	ug/L	1.5	<0.5	2.3
Barium	mg/L	0.024	0.010	0.036
Beryllium	mg/L	<0.001	<0.001	<0.001
Calcium	mg/L	49	47	70
Cadmium	mg/L	<0.001	so.001	<0.001
Cobalt	mg/L	<0.001	<0.001	<0.001
Chromium	mg/L	<0.001	<0.001	so.001
Copper	mg/L	<0.001	<0.001	<0.001
Iron	mg/L	1.6	0.020	1.3
Potassium	mg/L	4.9	5.3	7.0
Magnesium	mg/L	18	13	19
Manganese	mg/L	0.12	0.007	0.014
Molybdenum	mg/L	<0.001	<0.001	<0.001
Sodium	mg/L	13	22	19
nickel	mg/L	<0.001	<0.001	0.012
Lead	mg/L	<0.002	<0.002	<0.002
Silicon, soluble	mg/L	6.1	4.9	6.0
Strontium	mg/L	0.12	0.12	0.10
Titanium	mg/L	0.030	<0.001	0.029
Vanadium	mg/L	<0.001	<0.001	<0.001
Zinc	mg/L	SO.005	<0.005	<0.005
Zirconium	mg/L	<0.001	<0.001	<0.001

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## SRC ANALYTICAL

Black Hawk Mining Inc.

28-Sep-98 14:38

SAMPLE CLIENT DESCRIPTION  
 23053 WENDY PIT INFLOW #4 \*WATER\*  
 23054 WENDY PIT INFLOW #5 +WATER+  
 23055 WENDY PIT INFLOW #6 \*WATER\*

#6

ANALYTE	UNITS	23053	23054	23055
INORQANICS				
Sulfate	mg/L	53	58	34
Ammonia as nitrogen	mg/L	0.10	0.29	0.13
Boron	mg/L	0.12	0.032	0.017
Phosphorus	mg/L	<0.05	<0.05	<0.05
Silver	mg/L	<0.001	<0.001	<0.001
Aluminum	mg/L	0.010	0.019	<0.005
Arsenic	ug/L	0.5	1.1	<0.5
Barium	mg/L	0.002	0.019	0.002
Beryllium	mg/L	<0.001	<0.001	<0.001
Calcium	mg/L	25	61	49
Cadmium	mg/L	<0.001	<0.001	<0.001
Cobalt	mg/L	<0.001	<0.001	<0.001
Chromium	mg/L	<0.001	<0.001	<0.001
Copper	mg/L	<0.001	<0.001	<0.001
Iron	mg/L	0.094	0.18	0.085
Potassium	mg/L	2.5	3.5	2.2
Magnesium	mg/L	18	22	19
Manganese	mg/L	0.011	0.22	0.10
Molybdenum	mg/L	<0.001	<0.001	<0.001
Sodium	mg/L	35	11	9.1
Nickel	mg/L	<0.001	0.007	<0.001
Lead	mg/L	<0.002	<0.002	<0.002
Silicon, soluble	mg/L	5.1	6.5	6.3
Strontium	mg/L	0.098	0.14	0.091
Titanium	mg/L	<0.001	<0.001	<0.001
vanadium	mg/L	<0.001	<0.001	<0.001
Zinc	mg/L	<0.005	<0.005	<0.005
zirconium	mg/L	<0.001	<0.001	<0.001

## SRC ANALYTICAL

Black Hawk Mining Inc.

28-Sep-98 14:38

SAMPLE	CLIXNT	DESCRIPTION	
23056	WENDY	PIT INFLOW #7	*WATER*
23057	WENDY	PIT INFLOW #8	*WATER*

ANALYTE	UNITS	23056	23057
INORGANICS			
Sulfate	mg/L	71	31
Ammonia as nitrogen	mg/L	0.13	0.15
Boron	mg/L	0.041	0.033
Phosphorus	mg/L	<0.05	<0.05
Silver	mg/L	<0.001	<0.001
Aluminum	mg/L	0.012	<0.005
Arsenic	ug/L	co.5	co.5
Barium	mg/L	0.013	0.001
Beryllium	mg/L	<0.001	<0.001
Calcium	mg/L	55	47
Cadmium	mg/L	<0.001	<0.001
Cobalt	mg/L	<0.001	<0.001
Chromium	mg/L	<0.001	<0.001
Copper	mg/L	<0.001	<0.001
Iron	mg/L	0.016	0.17
Potassium	mg/L	4.1	1.8
Magnesium	mg/L	14	15
Manganese	mg/L	0.003	0.093
Molybdenum	mg/L	<0.001	<0.001
Sodium	mg/L	16	12
Nickel	mg/L	<0.001	<0.001
Lead	mg/L	<0.002	<0.002
Silicon, soluble	mg/L	4.8	6.1
Strontium	mg/L	0.12	0.098
Titanium	mg/L	<0.001	<0.001
Vanadium	mg/L	<0.001	<0.001
Zinc	mg/L	<0.005	<0.005
Zirconium	mg/L	<0.001	<0.001

\*<\*: not detected at level stated above.

**Table 1: Elements of Water Samples from Black Hawk Mining Inc. (Sept., 1998)**

Unit: mg/l

Element	Wendy Pit Inflow #1	Wendy Pit Inflow #2	Wendy Pit Inflow #3	Wendy Pit Inflow #4	Wendy Pit Inflow #5	Wendy Pit Inflow #6	Wendy Pit inflow #7	Wendy Pit Inflow #8	Detection Lim
Phosphorous	LDL	LDL	LDL	LDL	LDL	LDL	LDL	LDL	0.05
Silver	LDL	LDL	LDL	LDL	LDL	LDL	LDL	LDL	0.001
Beryllium	LDL	LDL	LDL	LDL	LDL	LDL	LDL	LDL	0.001
Cadmium	LDL	LDL	LDL	LDL	LDL	LDL	LDL	LDL	0.001
Cobalt	LDL	LDL	LDL	LDL	LDL	LDL	LDL	LDL	0.001
Chromium	LDL	LDL	LDL	LDL	LDL	LDL	LDL	LDL	0.001
Copper	LDL	LDL	LDL	LDL	LDL	LDL	LDL	LDL	0.001
Molybdenum	LDL	LDL	LDL	LDL	LDL	LDL	LDL	LDL	0.001
Lead	LDL	LDL	LDL	LDL	LDL	LDL	LDL	LDL	0.002
Titanium	0.03	LDL	0.029	LDL	LDL	LDL	LDL	LDL	0.001
Vanadium	LDL	LDL	LDL	LDL	LDL	LDL	LDL	LDL	0.001
Zinc	LDL	LDL	LDL	LDL	LDL	LDL	LDL	LDL	0.005
Zirconium	LDL	LDL	LDL	LDL	LDL	LDL	LDL	LDL	0.001

Note : LDL = Lower than Detection Limit.

Table 211. Current (September 1993 and May 1994) water quality in Gordon and Farley lakes and in the East Zone Test Pit

Site Station Date	Test Pit 30/5/94	Gordon Lake			Farley Lake				
		GL-2 23/9/93	GL-2 23/9/93	GL-2 30/5/94	FL-1 23/9/93	FL-2 23/9/93	FL-3 23/9/93	FL-4 23/9/93	FL-4 30/5/94
Secchi (m)	NA	<0.4	NA	NA	NA	NA	2.00	NA	NA
pH	7.7	7.7	7.7	7.7	7.9	7.4	7.9	8.1	7.9
Conductivity (uS/cm)	179	123	135	96.3	153	71	159	155	123
Alkalinity (mg/L as CaCO <sub>3</sub> )	80	63	63	40	73	43	77	81	50
Bicarbonate (mg/L as HCO <sub>3</sub> )	97.6	76.3	76.3	48.5	88.5	51.9	93.3	98.8	61.0
Hardness (mg/L as CaCO <sub>3</sub> )	83.2	68.5	75.7	45.3	84.9	40.5	88.4	86.8	56.6
TDS (mg/L)	98	73	78	51	89	45	92	95	62
TSS (mg/L)	5	4	14	5	<1	<1	<1	4	6
Turbidity (NTU)	29	2.2	4.0	2.2	2.1	0.4	1.5	20	3.8
True Colour	100	100	60	100	60	100	40	40	80
<b>Major Ions (mg/L)</b>									
Ca (ext)	22.8	19.6	21.3	13.0	23.9	127	25.2	24.5	16.0
Mg (ext)	6.4	4.7	5.5	3.1	6.1	2.1	6.2	62	4.0
Na (ext)	3	2	2	1	3	2	3	3	2
K (ext)	2.8	0.80	1.21	2.1	0.87	0.62	1.13	1.21	1.8
SO <sub>4</sub> (diss)	13.4	7.8	10.3	6.3	10.2	<1.0	9.1	10.6	6.5
Cl (diss)	1.6	0.6	0.5	1.0	1.1	0.7	1.2	1.2	1.2
<b>Nutrients (mg/L)</b>									
TKN	0.71	0.39	0.40	0.50	0.25	0.44	0.69	0.64	0.58
NH <sub>3</sub> -NH <sub>4</sub> -N	0.034	0.05	0.26	0.018	0.18	0.03	0.05	0.14	0.017
NO <sub>3</sub> -NO <sub>2</sub> -N	<0.005	<0.05	<0.05	<0.005	<0.05	<0.05	<0.05	<0.05	<0.005
Total P	0.060	0.014	a.m.	0.050	0.036	0.014	0.018	0.009	0.050
<b>Extractable Metals (mg/L)</b>									
Al	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Ba	0.023	0.013	0.013	0.015	0.014	0.007	0.016	0.016	0.021
Be	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Bo	0.05	<0.01	<0.01	<0.01	<0.01	<0.01	0.10	<0.01	0.01
Cr	<0.02	<0.015	<0.015	<0.02	<0.015	<0.015	<0.015	<0.015	<0.02
Co	<0.01	<0.01	<0.01	<0.01	4.01	<0.01	<0.01	<0.01	<0.01
Fe	0.29	0.06	0.09	0.17	0.08	0.13	0.03	0.06	0.21
Mb	<0.01	<0.01	0.02	<0.01	0.02	<0.01	0.02	<0.01	<0.01
Ag	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Si	1.9	2.62	2.51	1.0	1.62	2.67	0.36	0.66	1.3
Ti	<0.05	<0.050	<0.050	<0.050	<0.050	<0.050	<0.050	<0.050	<0.050
Th	<0.3	<0.3	<0.3	<0.3	<0.3	d.3	<0.3	<0.3	d.3
V	<0.01	<0.014	<0.014	<0.01	<0.014	<0.014	<0.014	<0.014	<0.01
<b>Total Metals (mg/L)</b>									
As	0.0007	<0.0002	<0.0002	0.0003	<0.0002	<0.0002	<0.0002	<0.0002	0.0006
Cd	<0.0002	<0.0002	0.0005	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Cu	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Pb	<0.001	0.001	<0.001	<0.001	<0.001	4.m	<0.001	<0.001	<0.001
Mn	a037	0.008	0.014	0.011	0.018	0.018	0.014	0.013	0.063
Ni	<0.002	0.006	0.005	<0.002	0.005	0.011	0.004	<0.002	<0.002
Zn	<0.004	<0.004	<0.004	<0.004	4.m	<0.004	<0.004	<0.004	<0.004

# The Function of Wetlands/Muskeg in Decommissioning Mine Waste Management Areas

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## Introduction

Ten to fifteen years ago, reports started to appear in the environmental literature (mine waste management) which suggested that wetlands could be useful in treating acid mine drainage (AMD). Evidence was provided that cattails could survive the harsh conditions in tailings ponds and AMD seepages. There were also encouraging improvements in water quality when AMD passed through constructed wetlands. The concept “let nature do the work” started to attract some mine operators, and more test systems were constructed. As the number of these wetland treatment systems in mining applications grew, so did the number of sceptics. Criticisms included: “Wetlands can only deal with small seeps, or with low flows”; “What about the winter?”, “We don’t know how it works” and; “It cannot be designed or controlled and, therefore, it cannot be reliable.”

This paper attempts to address the concerns of sceptics by discussing the important ecological/wetland processes which must be taken into consideration when muskegs or wetlands are used in decommissioning mining waste management areas. The wetland/muskeg sediment contains the microbial processes which define the treatment capacity. For some wetlands/muskeg pools in northern Saskatchewan, for example, it was determined with field and laboratory studies that the sediments have a removal capacity for nickel of between  $0.07 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  and  $0.1 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  and between  $0.08 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  and  $0.1 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  for arsenic.

Weathering rates of mining wastes, together with climatic conditions and the physical layout of the mine site, define contaminant loadings. A 5.6 million  $\text{m}^3$  waste rock pile in northern Saskatchewan, generated between 1984 and 1991, is estimated to contain a total contaminant mass ranging between 240 t and 403 t of arsenic and 357 t and 447 t of nickel. The annual release rates are estimated to be  $1.7 \text{ t}\cdot\text{y}^{-1}$  and  $4.9 \text{ t}\cdot\text{y}^{-1}$  respectively. This estimation was based on toe seepage flow, concentrations of contaminants in the toe seepages and atmospheric precipitation.

The physical layout of the waste management area also defines where best the ecological processes can be promoted. Data are presented which suggest that passive treatment approaches must also consider changes due to iron oxidation/reduction in the design stage. Recent publications on flooded-lake chemistry, as well as the results of investigations into pit lakes undertaken by the author for the past five years, are discussed. When taking geochemical, hydrological and ecological factors into account, an ecological treatment system can be defined and designed to meet almost any decommissioning scenario.

## Designing for the Use of Ecological Processes in Decommissioning

Decommissioning design criteria for waste management are derived from the geochemical (mineralogy and weathering rate of the rocks) and hydrological (ground water, surface water and climate) characteristics of the site. The geochemistry and mineralogy of the waste rock will determine the contaminants of concern which must be retained inside the waste management area. These two criteria are accompanied by a third criterium, the environmental conditions inside and outside the waste management area. The integration of all three criteria will lead to a restoration approach which will require minimum maintenance and, in some cases, will be self-sustaining.

In a feasibility study, where ecological processes to decommission a waste management area are under consideration, data on the three criteria must be synthesized, focusing on decommissioning. While some data may be missing, they can be obtained through one or several rounds of targeted sample collection. A data *summary* is then used to project the expected contaminant load leaving the waste area (tailings, waste rock pile and pit walls) over the long term. Each of the three design criteria are discussed below, with examples of the nature of the data which are obtained. In effect, this constitutes a feasibility study which integrates the ecological or wetland treatment approaches.

### Geochemistry and Weathering Criteria

The mineralogy and geochemistry of the waste rock or tailings can be obtained from the mine geologist. Estimating the total contaminant mass in the waste rock pile is based on the concentrations of the element of concern, which is likely one that was part of the monitoring requirement and related to the mineral-bearing rock. The total ~~mass~~ is derived from its fraction occurring in the waste rock pile. These numbers are, in turn, estimated from geological records and, if available, drill cores of the waste rock pile. Information on the waste rock, along with actual chemical characteristics, can be utilized to determine the chemical characteristics of the toe seeps.

For example, located in northern Saskatchewan, a **5.6** million m<sup>3</sup> waste rock pile, generated between 1984 and 1991, is projected to produce a total contaminant mass ranging between 240-403 t of arsenic and 357-447 t of nickel. The annual release rate of the contaminants is estimated to be 1.7 t.y<sup>-1</sup> for arsenic and 4.9 t.y<sup>-1</sup> for nickel, based on toe seepage flows, concentrations of contaminants in the toe seepages and atmospheric precipitation, surface and shallow ground water hydrology.

### Environmental Ecological Criteria

An ecologist/limnologist is able to determine the environmental conditions of an ecosystem, its productivity and its growth behavior. Generally, Environmental Impact Assessments provide good summaries of the relevant components of an environment which need to be utilized and restored.

Muskeg ecosystems have very low productivity. In open pools or shallow lakes, microbial decomposition of vegetation is slow, resulting in the accumulation of peat and the typical fine-grained sediments of muskeg lakes. While the choice of vegetation type should always be indigenous, species which promote high evaporation rates (cattails, sedges, alders and willows) should be selected, thus reducing infiltration of atmospheric precipitation.

The productivity of the ecosystem is determined by ecological criteria. It should be noted that, due to the use of explosives, many mining waste management areas are no longer of **low** productivity, since explosives serve as nutrients. Should **this** not be the case, however, many different organic materials have been used in constructed wetlands, although for large-scale decommissioning problems, organic matter needs to be inexpensive, locally available and biodegradable. Also, the organic substrates should degrade slowly in order to minimize the need for additional applications. Presently, dosage rates which appear to last for at least 3-5 years are being tested. A detailed review of the materials used in constructed wetlands and associated experiments is given in Kalin et al. (1998).

The best solution to solving the problem of providing organic matter is to generate it **on** site. Smith and Kalin (1991) have reported that cattails can be rafted over the top of a flow-**through** system, enhancing anaerobic zones, reducing surface turbulence and providing a stable, long-term carbon source. **Only** 30% of *Typha* litter produced each **year** is consumed by the microbial community over the ice-free season (ibid). With floating wetland islands, the microbially-active sediment area can be increased through enhancement of the cattail raft root zone.

### **Hydrological and Climate Criteria**

Hydrological ground water conditions can be derived from pit development and stratigraphy, which can be obtained from the exploration works. It is important to differentiate between shallow ground water movement in the overburden and deeper ground water moving in fractures in the bedrock, because the shallow ground water conditions affect the choice of approach required for restoration.

In the Canadian context, muskeg or peat areas often develop in terrain with low permeability and, frequently, this results in a perched water table. Thus, for a waste rock pile placed on muskeg or peat, the movement of seepages through the waste rock piles into the ground water is not frequent, and toe seepages represent the contaminant weathering and release rates. They are not often a source of shallow ground water contamination, but this possibility has to be considered during the decommissioning design. Waste rock piles are frequently surrounded by, or placed on top of, muskeg/wetlands, which can be utilized as part of the waste management area in decommissioning.

The restoration of shallow ground water *can* utilize the sediments of the muskeg lakes, whereas deeper ground water requires nutrients for alkalinity generation that are delivered to microbes in the ground water itself, or to the potential contaminant plume. Understanding the hydrological conditions surrounding the waste rock pile is key to successfully integrating the



wetland/ecological processes into the decommissioning activities.

During operations, toe seepages from tailings ponds and waste rock piles are channeled into ditches and ponds, which are constructed for holding and particle settling, followed by chemical treatment, if required. However, “pump and treat” scenarios at the time of decommissioning are economically and environmentally unattractive. To utilize these ditches and ponds for treatment in conjunction with wetlands and muskeg, they often must be reshaped and expanded.

### The Ecological Treatment Process and Removal Capacity

Sulfur-containing mine wastes generate acid mine drainage (AMD) as a byproduct of microbial metabolism on weathered rock surfaces. The generation of AMD or ARD is an aerobic process, similar to, if not the same as, the process that takes place during bioleaching. The natural counterpart to the oxidative weathering of rocks is biomineralisation under anaerobic conditions. Here, microbes generate alkalinity and precipitate metals in the sediments, removing the metals and the sulphate from the AMD.

The main goal in the ecological approach to AMD remediation is to provide the proper anaerobic conditions for the microbes to generate alkalinity. The required conditions are: first, the presence of an organic sediment with the proper microbial flora; second, the presence of anaerobic conditions necessary for sulfate- and iron-reducing bacteria; and third, the proper mix of carbon sources for short- and long-term microbial growth. Removal rates for acidity and other contaminants are summarized in Kalin et al. (1998). The presence of sulfate-reducing bacteria (SRB) in test systems from which the rates were determined has been confirmed by inference from the strong hydrogen sulfide smell, as well as from samples which have been provided for genetic studies on SRBs by Telang et al. (1994).

Removal rates in reactors containing the AMD and sediment from a northern Ontario lake contaminated with ground water seepage from a tailings pond, were tested at 5°C and 22°C. The results, as expected, indicated that the removal rates are temperature dependent, i.e., higher microbial activity take place at higher temperatures. It follows, therefore, that for the implementation of removal rates from the sediment, temperatures of the muskeg must register around 3-5°C, equivalent to winter temperatures. It is important, therefore, that the muskeg sediment should not freeze, and so appropriate vegetation must provide insulation to the sediments. An ice cover over the lake during winter reduces wind turbulence and complete mixing occurs in shallow muskeg lakes only during the summer. The effects of ice cover on pH have been documented for the lake in Northern Ontario; the pH increased during winter from 3 - 6.5 (Kalin et al 1997).

Sulfate-reduction rates from AMD field systems range from a high of 15 to a low of 0.5 g m<sup>-3</sup> d<sup>-1</sup>, depending on the type of AMD and the physical conditions of the system such as retention time (Kalin et al. 1998). Rates of sulfate reduction reported in the literature, where rates are determined in ideal conditions, for example, test tubes, pure culture and field conditions in non-AMD water, vary from 17 to 964 g m<sup>-3</sup> d<sup>-1</sup> (Spratt et al. 1987; Herlihy and

Mills 1985). Extremely high-rate sulfate reductions are reported for annular biofilm lab reactors with  $214,000 \text{ g m}^{-3} \text{ d}^{-1}$  (Nielsen 1987) and  $2300 \text{ g m}^{-3} \text{ d}^{-1}$  (Maree et al. 1987). While the rates of sulphate reduction reported for the AMD system by Kalin et al. (1998) are, as expected, at the low end of the scale, they are nevertheless in a range which supports an economically viable natural treatment system.

### The Required Area for Muskeg/Wetland Treatment

Design criteria for the construction of wetlands are generally based on the performance of test systems (Brodie 1991). Wetland size is based on the area estimated to be necessary to remove a specific quantity of iron to some acceptable level. Hedin et al. (1994) have also recommended criteria for selecting wetland types, differentiating flow conditions and oxygen supply. For example, for water which is net-alkaline, passive systems with aerobic wetlands are to be sized based on  $20 \text{ g.m}^{-2}.\text{day}^{-1}$  Fe and  $0.5 \text{ g.m}^{-2}.\text{day}^{-1}$  Mn. These authors, in their approach to sizing wetlands for AMD treatment, rely on bulk removal processes, which include adsorption and precipitation processes. Those processes, however, often lead to the clogging of systems with hydroxides of iron or aluminum (Fyson and Kalin, 1996), particularly if the seepages contain high iron or aluminum concentrations. These must be precipitated through oxidation leading to the formation natural yellowboy, prior to the actual microbial treatment. This can be done, most often, in the existing collection ditches of the waste management area. More importantly, the bulk removal process approach to sizing **does** not consider the microbial activity of the sediments, which is the key process leading to the fixation or re-mineralization of metals in AMD.

**As** discussed earlier, the principal function of microbial activity in a passive treatment system is the generation of alkalinity in the sediment, which in turn alters the pH and leads to metal precipitation in the sediment (Kalin 1991). To maintain microbial activity, organic matter to provide the microbes as a source of energy may have to be added in low productivity systems.

The design of the decommissioning plan must take into consideration the contaminant loading to be retained on site, because this will determine the area of muskeg/wetlands which needs to be utilized, extended or constructed. Over the past 10 years, field experiments and laboratory studies have proven that wetland/muskeg sediments can remove contaminants.

For some wetlands/muskeg pools in northern Saskatchewan, for example, field and laboratory studies determined that their sediments have a removal capacity for nickel of between  $0.07\text{-}0.1 \text{ g.m}^{-2}.\text{d}^{-1}$ , and between  $0.08\text{-}0.1 \text{ g.m}^{-2}.\text{d}^{-1}$  for arsenic. Based on these removal rates, it was determined that a maximum of 16 ha of wetland was required which, during the ice-free season, would accommodate the seepage accumulation from spring run-off and summer-generated flows. During the winter, the seepage flow was negligible.

If the loading of contaminants from the waste is too high in relation to the removal rates or area of sediment, **then** contaminant generation or the weathering rate **has** to be curtailed. This can be achieved by using natural phosphate, which reduces the corrosion, or acid generation process. Fundamentally, when sedimentary phosphate is weathered together with waste rock,

rain water carries the phosphate to the rock surface where the acid is generated, and an encrustation takes place on the pyrite-waste rock surfaces. This encrustation reduces the rate at which weathering products are released from waste rock piles. Work in this area **has** been described in detail in Kalin et al. (1998).

### **The Flooding of Open Pits in Decommissioning**

Open pits are generally flooded at the time of decommissioning, and the new water body is referred to as a pit lake. Recently, pit lakes have received attention with respect to water quality, and reviews of pit lakes summarize the experience of several flooded pits. Authors caution that decommissioning by flooding can be a liability with respect to water quality. Doyle and Runnels (1997) review the conditions of several flooded pits and suggest that, possibly, meromictic conditions might predominate in pit lakes. Meromixis is a rare limnological condition, where the surface water is physically, chemically and biologically separated from the deeper waters. In case of pits, a stable meromixis would segregate contaminants from the surface water and containing them in the deeper waters of the pit lake. In theory, *this* would be a very desirable condition to achieve if the meromixis is completely stable. However, stable meromixis is a very rare condition and thus contaminants can be brought to the surface with one complete mixing of the pit *lake*. The data from pit lakes discussed by Doyle and Runnels, as well as the review by Miller et al. (1996), suggest that there is little evidence of meromixis and, even if it can be considered meromictic, it is unlikely to be stable.

Natural lakes and decommissioned pit lakes stratify seasonally. The depth of the stratification is dependent on the latitude and the physical shape of the lake. The thermocline will vary seasonally, depending on the physical forces mixing the water body. In most lakes in higher latitudes, a thermocline forms in spring, just after ice breakup, and disappears with fall storms, before ice cover. During the time of mixing, the entire lake becomes thoroughly mixed.

The physical components of a lake are determined by factors such as fetch (length along the predominant wind direction - which controls large-scale water movements), light penetration and ground water table. **Thus**, the physical shape of the pit and conditions of the seeps prior to flooding will determine the chemical and biological processes taking place in the new pit lake. While waste rock placed in the open pit will alter water movement patterns, it will not eliminate them. Weathering processes and the associated contaminant generation will, therefore, continue, albeit at a slower rate due to the lower oxygen availability in ground water.

When open pits are used for tailings disposal, a pervious surround is constructed along the pit walls, forcing the natural ground water to flow around the tailings deposit. Pervious surrounds have been used in the **uranium** sector, where the tailings mass has a low permeability, and generally is not acid generating.

Several flooded open pits have been investigated by Boojum Research in the course of

decommissioning mine sites using ecological engineering techniques, and large data sets on the limnological behavior of these pits have accumulated over the last five years. Data for these pit lakes have been collected as though the lakes were natural in origin and will evolve to become natural lakes. At the time of flooding, pit lakes are simply holes in the ground water table. Natural lakes, on the other hand, are fed by ground and surface water, which provide nutrients and sediments. These inputs provide the basis for lacustrine biology, which is sediment-driven, and healthy lake sediments are an essential component of a living lake system. In pit lakes, shorelines and bottom sediments are not present and so inputs from, and interactions with them, are impossible.

From investigations of open pits made over the past 5 years, Boojum has recorded contaminant removal to the bottom of a 45m-deep pit. Suspended solids relegated adsorbed contaminants to the pit bottom and the erosion of pit walls and algal growth produced particles to which contaminants were adsorbed. As the particles settled out of the water column, contaminants were relegated to the newly-forming, organic sediments. It is important to realize, however, that not all particles settle to these sediments. Total Suspended Solids (TSS) consist of particles of various sizes, and the smaller particle fraction may stay suspended in the water column. Some of the contaminants adsorbed onto biological TSS can be released at the thermocline due to microbial degradation of the organic carbon in the algae.

As already stressed, all aspects of a pit prior to flooding should be known or, minimally, should be recorded during the flooding stage, when the most effective remedial measures can be operationalized. If the pit is force-flooded, the water body has to be studied in detail in order to determine which possible measures to improve water quality support either biological or geochemical (or both) natural removal processes. With this knowledge, recommendations about particle formation can be made, utilizing either fertilizer to stimulate algal blooms or surface reactive materials, such as bentonite, to flocculate and relegate contaminants to the sediments. Methods of decommissioning pits need to be evaluated based on their success in supporting contaminant removal processes, such that biomineralisation can take place in sediments forming in the flooded pit. For example, sediments *can* be installed prior to flooding, while the pit is flooding naturally, or by clay caps which are installed in trouble spots identified prior to flooding.

In *summary*, decisions about decommissioning open pits should be based on their flooded characteristics, including their biological, chemical and physical features. If handled correctly, pit lakes will evolve into natural lakes where water quality parameters can be predicted, and the objectives of decommissioning - environmentally sustainable water quality - are achieved. Moreover, the process is economical.

## **Conclusion**

This discussion has attempted to show that successful applications of ecological processes rely on evaluating and integrating the hydrological, geochemical and original (i.e., prior to mining) environmental conditions surrounding the waste management area. The necessary treatment processes exist naturally in muskeg/wetland sediments and, if utilized appropriately, nature's

restoration and cleansing processes will lead to sustainable, low-maintenance decommissioned mining areas.

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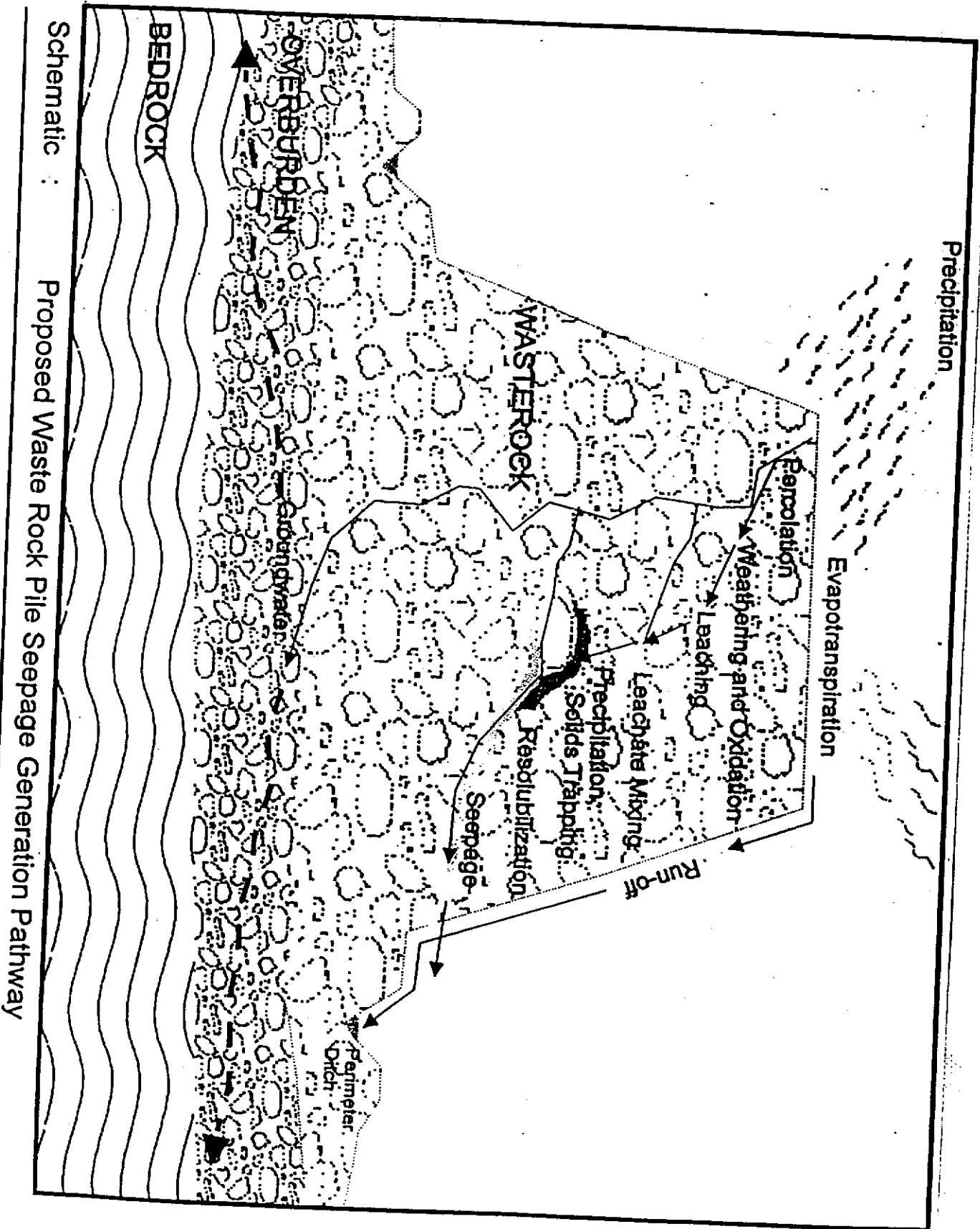
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Schematic :

Proposed Waste Rock Pile Seepage Generation Pathway