

# Anvil Range Pit Lakes Assessment of Post Closure Conditions

*DRAFT*

Report Prepared for  
**Deloitte & Touch Inc**  
Interim Receiver of Anvil Range Mining Corporation

Report Prepared by



January 2004

# **Anvil Range Pit Lakes Assessment of Post Closure Conditions**

*DRAFT*

## **Deloitte & Touche Inc**

Interim Receiver of Anvil Range Mining Corporation

### **SRK Project Number 1CD003.38**

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# 1 Introduction

This project was initially identified in program planning sessions carried out in 2002. It was further discussed at the June 2003 planning workshop (Deloitte & Touche 2003). A scope of work for development of the pit lake water quality estimates was presented in a letter from SRK to Deloitte & Touche, dated September 8, 2003. The scope of work was authorized later in September 2003.

The purpose of this investigation is to establish the intermediate and long term water management and treatment requirements, and develop appropriate strategies for closure of the Faro and Vangorda pit lakes.

To meet this objective, the following assessments were completed:

- Evaluation of the potential for pit lake stratification (meromixis)
- Review of available in-situ pit lake treatment technologies; and,
- Pit lake water quality predictions.

The findings of these evaluations were considered in the evaluation for developing a 'clean' flow-through post closure pit lake system.

## 2 Pit Lake Water Column Stability

### 2.1 Introduction

The long-term behaviour of pit lakes depends on a complex interaction between physical and chemical processes. Of the physical processes, the most important is stratification, or the development of stable layers with potentially very different water quality.

Most natural lakes in Canada stratify during summer months. Heating of the surface water reduces its density, leading to development of a psuedo-stable layering, with the upper warmer water nearly completely isolated from the cooler lower layer. In late summer or autumn, cooling of the upper layer usually leads to the two layers reaching a similar density. As the denisty contrast decreases, winds are able to overturn the layering, resulting a complete mixing of the two layers. The sharp density contrast caused by a temperature difference between the two layers is known as a “thermocline”.

In pit lakes, other factors can lead to a possibility that the layering will be permanent. Pit lakes are generally much deeper and have less surface area than natural lakes. Both of these geometric factors tend to reduce the ability of winds to mix the lake. Another factor is chemistry. Water in pit lakes can carry very high levels of contaminants, in some cases enough to affect the water’s density. If the contaminantion is concentrated in the lower layer, or mor commonly diluted by rainfall and runoof into the upper layer, a density gradient known as a “chemocline” can result. Since the chemocline is unaffected by the late season cooling of the upper water, it has the potential to create a year-round stratification.

“Meromixis” is as the limnological term for the condition whereby a lake is permanently stratified. A condition of meromixis in any of the Anvil Range pits would have significant implications for water quality. For example, it might be possible to establish a ‘clean’ layer of water on the surface of a meromictic pit lake and thereby minimize the release of contaminants to downstream environments. Meromixis would also have implications for the storage of water treatment sludges in the lake bottom.

An assessment of the potential for a meromixis to develop in the in the Faro, Grum, and Vangorda Pit Lakes was undertaken by Dr. Greg Lawrence of the UBC Department of Civil Engineering. Dr. Lawrence is an internationally recognized expert in environmental hydrodynamics, and research into pit lake physics is one of his areas of specialization

Dr. Lawrence’s report is provided in Appendix A and the findings are summarised herein. Generally, limited information was available for the Faro, Grum, and Vangorda Pit Lakes. Consequently, data from the Equity Waterline pit lake located near Houston B.C. were used for comparing and modeling the three pit-lakes.

## 2.2 Results for Current Conditions

The annual cycles of the pit lakes can be divided into three periods including the ice cover (Nov. – May), warming (June – Aug.), and cooling (Sept. – Oct.). At the end of the warming period, the salinity stratification ( $St^*$ ) was compared with the reduction in salinity stability ( $\Delta St$ ) during the cooling period. The meromixis ratio  $M = St^*/\Delta St$  indicates the likelihood of meromixis. This is due to the exclusion of dissolved solids from the ice. The higher the  $M$  value, the higher the probability that the lake will be meromictic.

The modelling of the three pit lakes under current conditions, (i.e. with inflows diverted), and assuming an average ice thickness of about 3.5 to 4 ft resulted in meromictic ratios ( $M$ ) of 11, 6 and 5 for Faro, Grum and Vangorda pit lakes, respectively. These values would suggest that for current conditions meromixis could develop in the pit lakes. However, it should be noted that uncertainties remain due to the limited data availability.

The potential for meromixis for current conditions could be enhanced by several factors. The formation of ice drives salinity out of the upper water. Therefore the value of  $St^*$  increases as the thickness of the ice layer that forms on the pit lake increases. Significant salt input from waste rock and pit walls, and/or the concentration of salinity by evaporation, can also increase the potential for meromixis.

## 2.3 Results for Flow-Through Conditions

Modelling of the pit lakes in the event that local streams are diverted through the pit lakes considered the energy input from the streams. The energy input from the streams diverted into the pit lake was estimated from the flux of kinetic energy of a stream, which is given by:

$$P = 0.5 \rho Q u^2$$

Where  $\rho$  is the density,  $Q$  is the volumetric flow rate, and  $u$  is the average velocity. The analysis suggests that if local streams are allowed to enter the Pit-lakes, it would have a significant impact on the physical limnology of the lakes. First, the energy could result in mixing beyond the depth of the stratification zone. The results suggest that the energy provided by the stream would be greater than the salinity stability. Second, the resultant mixing and displacement would lead to the removal of salts from the stable layer, which would reduce its salinity and lead to a decrease in the meromictic ratio. The modelling results indicate that the Vangorda pit lake would be most affected due to the high flows and the Grum pit would be least affected.

## 2.4 Conclusions

The primary conclusions of Dr. Lawrence's work can be summarised as follows:

- In their current condition, i.e. with runoff diverted around the pits, there is a potential that meromixis may develop in the pit lakes, however additional monitoring of water column profiles through summer and winter would be required to confirm this conclusion.

- In the event runoff is allowed to flow through the pits, it is likely that completely mixed conditions will develop in the pit lakes.

To address the uncertainty with the first conclusion, Dr Lawrence recommends that ice thickness be monitored. He also recommends that the salinity stability be verified by conducting water column profiles for the cooling period (August to when ice develops), once the ice has been established, and as soon as ice melt occurs. A CTD meter would be required for this as it is more accurate than the Hydrolab that has been used in the past.

For the flow-through options, meromixis could only be retained if the inflow to the pit lake can be managed to limit the mixing effect. It may be worth considering engineering options to ensure that the inflow occurs near horizontally to limit disturbance of the hypolimnion.



## **3 Water Quality Assessment**

### **3.1 Introduction**

The water quality that will develop in the pit lakes in the long term will depend on the following factors:

- Pit lake limnology
- Hydrological inputs and outputs (water balance); and,
- Contaminant loadings.

The pit lake limnology is discussed in Section 2 for both current (diversions in place) and flow-through conditions. In this chapter water and load balances are developed for each of the pit lakes.

Contaminant sources that are considered include remaining or exposed wall rock above the pit lake level and waste rock piles that are within the current catchments of the pits.

The sections below present and discuss the modelling that was undertaken for each of the pit lakes respectively.

### **3.2 Faro Pit Lake**

#### **3.2.1 Current Pit Lake Water Quality**

In April 2003 Gartner Lee Limited (GLL) carried out a program of sampling and analysis to characterize water quality in the Faro Pit Lake. Complete results are presented in Appendix B and are summarised in Table 3.1.

The results show that the pit lake is at circum neutral pH, with slightly lower pH values at depth. Zinc concentrations are elevated in the surface layer at about 10 mg/L and decreases at depth. The elevated concentrations in the surface layer probably result from elevated concentrations in seepage and wall rock runoff that enters the upper part of the pit lake and is not well mixed through the water body.

In contrast, iron concentrations increase with depth. This is likely due to reducing conditions at depth which will result in ferric iron reduction to ferrous iron, which has a higher solubility. In the near surface layer, oxidizing conditions will result in the oxidation of iron to ferric, which will precipitate form solution and settle to the base of the pit.

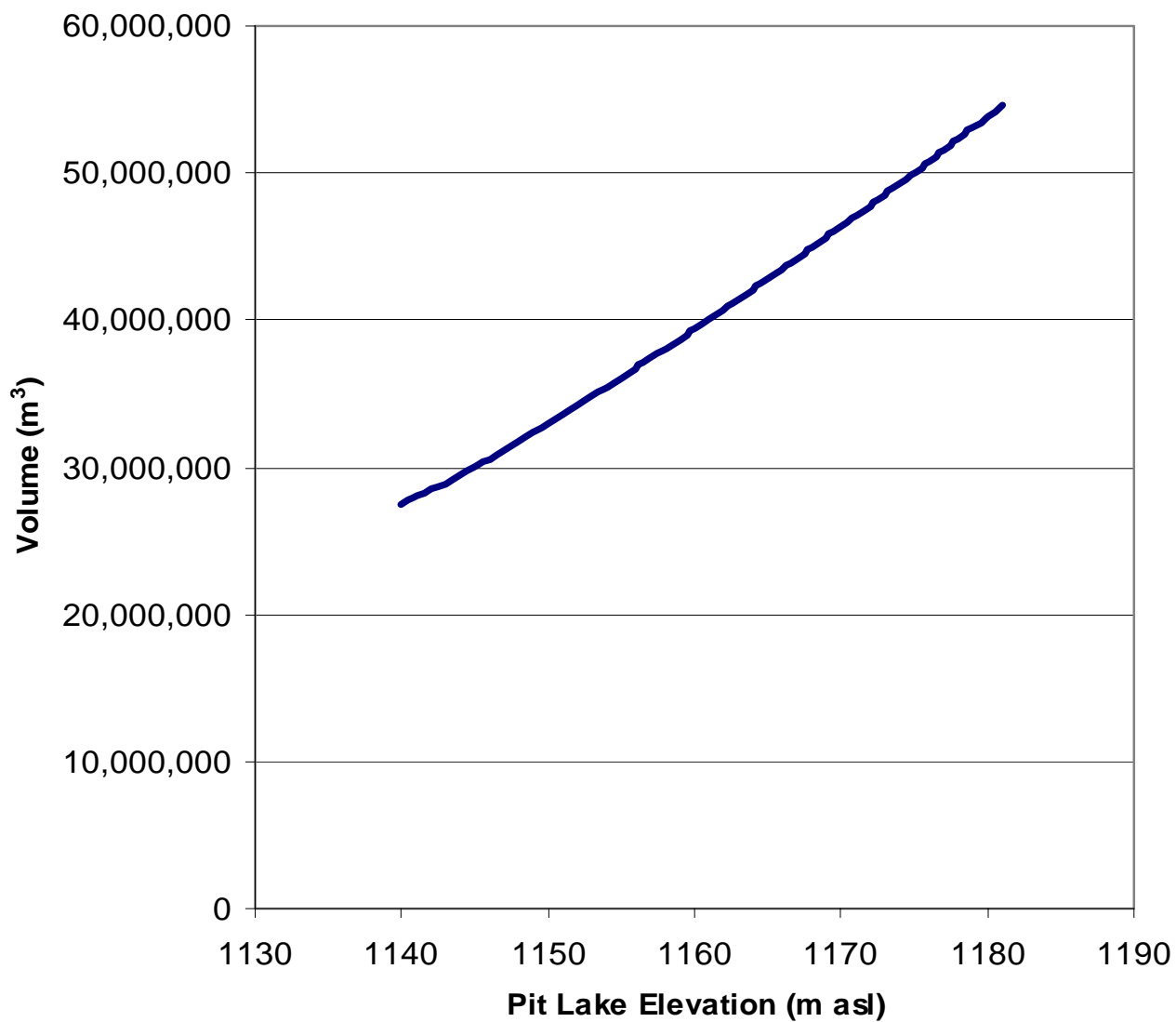
**Table 3.1 Summary of Current Faro Pit Lake Water Quality**

Parameter	Units	Faro Pit Lake Concentrations						
Depth	m	2	5	10	15	25	58	60
<b>Physical Tests</b>								
Conductivity	(uS/cm)	1070	1070	1200	1240	1330	1370	1390
pH		7.89	7.6	7.84	7.52	7.36	7.17	6.87
<b>Dissolved Anions</b>								
Acidity (to pH 8.3)	mg/L	18	39	27	25	35	42	65
Alkalinity- CaCO <sub>3</sub>	mg/L	97	98	108	108	100	96	100
Sulphate	mg/L	606	486	707	694	775	793	793
<b>Nutrients</b>								
Ammonia -N	mg/L	0.89	0.93	1.25	1.28	1.6	1.45	1.4
<b>Total Metals</b>								
Arsenic	mg/L	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Cadmium	mg/L	0.0129	0.0129	0.0111	0.0087	0.0003	<0.0003	<0.0003
Calcium	mg/L	133	133	156	163	178	180	185
Cobalt	mg/L	0.041	0.041	0.045	0.043	0.034	0.031	0.032
Copper	mg/L	0.008	0.008	0.008	0.007	<0.005	<0.005	<0.005
Iron	mg/L	0.05	0.04	0.04	0.15	11.8	20.4	21.8
Lead	mg/L	<0.003	<0.003	<0.003	<0.003	<0.003	0.003	<0.003
Manganese	mg/L	2.23	2.24	2.62	2.75	3.27	3.38	3.38
Nickel	mg/L	0.093	0.092	0.095	0.09	0.073	0.06	0.062
Selenium	mg/L	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Zinc	mg/L	11	11	10.3	8.39	3.04	1.42	1.4

### 3.2.2 Pit Lake Capacity and Hydrology

The volume-capacity curve for the Faro pit was re-assessed using the topography generated from the 2003 aerial photography. To include the volume of water below the current pit lake level, the new curve was 'meshed' with that presented in the ICAP(1996). The complete volume capacity curve is provided in Figure 3-1.

The overall water balance for the Faro pit lake is summarised in Table 3.2. The table shows conditions whereby Faro Creek is routed through the Pit Lake, making the total catchment about 17.3 km<sup>2</sup>. The mean annual runoff is estimated to be 341 mm and mean annual precipitation 400 mm. The evaporation rate is based on a fixed pit lake surface area of about 0.6 km<sup>2</sup>.



FILE REF: Figures 3-1\_3-14.xls



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**Faro Pit Volume Capacity Curve**

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FIGURE

**3-1**

**Table 3.2 Summary of Pit Lake Water Balance with Faro Creek Flow-Through**

Month	Days in month	INFLOWS		OUTFLOWS		
		Runoff	Direct Precip. on Lake	Lake Evap.	Discharge at Pit Outlet	
		(1000 m <sup>3</sup> )	(1000 m <sup>3</sup> )	(1000 m <sup>3</sup> )	(1000 m <sup>3</sup> )	(m <sup>3</sup> /s)
Jan	31	124	5	0.0	127	0.05
Feb	28.25	92	4	0.0	95	0.04
Mar	31	89	4	4.8	87	0.03
Apr	30	118	5	31.8	89	0.03
May	31	1097	45	54.0	1086	0.41
Jun	30	1892	77	67.2	1901	0.73
Jul	31	867	35	64.8	836	0.31
Aug	31	432	18	48.6	399	0.15
Sep	30	419	17	18.6	416	0.16
Oct	31	396	16	6.0	404	0.15
Nov	30	209	9	0.0	217	0.08
Dec	31	165	7	0.0	171	0.06
Annual	365.25	5899	240	296	5828	0.18

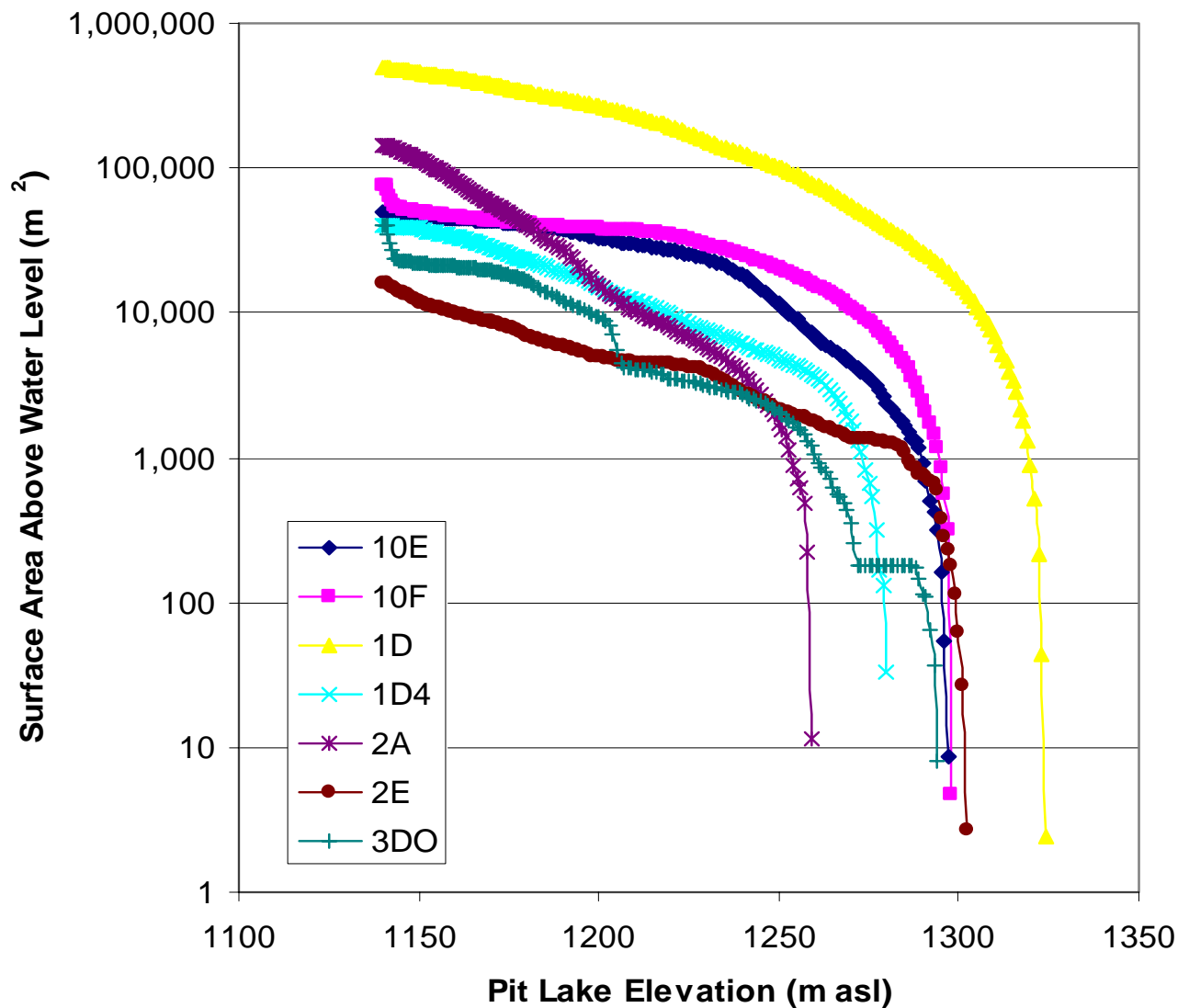
### 3.2.3 Contaminant Sources

Sources for contaminant loadings to the Faro pit lake include wall rock runoff and seepage from waste rock within the pit lake catchment.

#### Wall Rock Loadings

The potential contaminant loadings from the wall rock were estimated as follows. First, rough maps of the pit wall geology were derived from photos and previous mapping. The surface area of the exposed wall rock of each geological type was then determined. These inputs were then used to estimate the surface area of each type of wall rock above the water level as the pit lake rises. The wall rock type was then associated with a specific water quality as observed from the waste rock dumps and, together with the associated runoff estimates, was used to estimate the potential net loading to the pit lake.

The wall rock mapping results are provided in Appendix C, Figure C-1. The estimated surface area of each wall rock type is shown as functions of pit lake elevation in Figure 3-2. Note that the standard rock type notation that was developed for Faro rock types was utilised. Summary descriptions of the rock types are provided in Appendix C.



Estimates of contaminant concentrations in water that contacts each type of wall rock, were derived from the recent geochemical studies (SRK, 2003a). The water types are summarized in Table 3.3, and their assumed association with each rock type was as follows:

- 1D Schist - This rock type is probably non-acid generating. Assume water quality FT1 with no long term change.
- 1D4 Altered schist - This rock type is already acid generating. Assume water quality FT4 with no long term change.
- 2A Ribbon-banded graphitic quartzite – This rock type is already acid generating, slaking and reactive. Water quality FT5 may be too extreme as this was not an ore grade material. Assume water quality FT4 with no long term change.
- 2E Massive pyritic sulphides - This rock type is quartz rich and described as hard. It is potentially acid generating, so assume water quality FT4. however, kinetic testing indicates that it is less reactive than 2A and should not receive the same weight as 2A.
- 3DO - Calc-silicate. Assume water quality FT1 with no change.
- 10E/10F - These rock types are unlikely to be acid generating and have low sulphide. Assume water quality FT1.

The estimated average annual loading from the wall rocks are summarised in Table 3.4. The lower loadings after the pit is flooded are a result of the inundation of the more reactive wall rocks as the pit lake floods.

**Table 3.3 Summary of Waste Rock Seepage**

Parameter	Seepage Quality (mg/L except for pH)										
	Type 1	Type 2 Waste	Type 2 Ore	Type 3 Waste	Type 3 Ore	FD04	FD05 /06	FD14	FD19	FD37	FD40
Code	FT1	FT2	FT3	FT4	FT5	FT6	FT7	FT8	FT9	FT10	FT11
pH	7.3	6.7	6.5	3.9	3.4	2.4	7.2	7.6	7.1	2.4	4.3
Acidity	14.3	50.8	600.6	968.2	14469	30970	12.4	15.7	85.3	11700	98.3
Alk	184.7	137.4	242.1	15.7	5.5	1.0	204.1	111.3	397.5	1.0	10.3
Cl	1.6	1.6	11.7	3.1	125.8	342.1	1.9	0.8	2.1	0.5	0.6
SO4	722	1701	3783	1614	17107	35522	462	2050	3680	14850	386
Ca	153.7	287.8	490.5	173.2	305.2	377.8	132.5	210.7	601.3	242.0	42.2
Mg	114	231	504	161	727	1655	95.1	282	558	272	45.5
K	6.5	7.9	12.8	6.4	39.0	72.5	3.9	18.0	9.5	31.0	2.0
Na	28.9	15.9	48.8	7.5	44.1	72.5	6.9	121.0	19.5	31.0	2.7
Al	0.2	0.3	0.4	14.8	207.3	501.8	0.2	0.2	0.3	94.1	2.8
Cd	0.0	0.0	0.2	0.2	6.5	9.6	0.0	0.0	0.0	11.3	0.1
Co	0.0	0.1	0.4	0.3	5.0	10.6	0.0	0.0	0.1	4.0	0.1
Cu	0.0	0.0	0.1	2.1	92.2	186.7	0.0	0.0	0.0	126.5	0.4
Fe	0.0	1.9	33.3	76.3	2772	6747	0.0	0.3	0.8	1410	2.2
Pb	0.1	0.1	0.1	0.4	1.5	2.1	0.1	0.1	0.1	1.3	0.1
Mn	0.1	4.9	44.1	10.0	388	936	0.0	0.1	17.8	149	2.3
Ni	0.1	0.2	0.6	0.6	3.9	7.7	0.1	0.1	0.3	4.1	0.1
Zn	2.5	25.7	261	109	4259	6930	2.2	6.0	45.2	6985	35

**Table 3.4 Summary of Estimated Average Annual Loadings from Faro Pit Wall Rocks**

Parameter	Contaminant Loading (kg/year)	
	Initial	After Spill Elev. Reached
Cl	531	346
SO <sub>4</sub>	252,338	161,348
Ca	42,926	29,378
Mg	34,023	22,825
K	1,758	1,216
Na	6,500	4,804
Al	976	461
Cd	12	6
Co	21	10
Cu	132	61
Fe	4,827	2,222
Pb	35	19
Mn	653	307
Ni	47	25
Zn	7,430	3,572

### Waste Rock Seepage

Sources and catchments of waste rock piles that are within the catchment of the Main Zone Pit have been defined based on available pre-mining topography. A summary of the estimated proportions of the waste rock piles within the pit Lake Catchments is given Table 3.5. To be consistent with the assumptions for the wall rock runoff, it was assumed that all of the runoff (i.e. surface overflow and infiltration) would be contaminated.

**Table 3.5 Estimated Proportions of Waste Rock Piles in the Pit lake Catchment**

Waste Rock Pile	Proportion in Pit Lake Catchment
Faro Valley North	100%
Faro Valley South	100%
Southwest Pit Wall Dump	70%
Ranch Dump	20%
Ramp Zone Dump	20%
Outer Northeast Dump	100%
Lower Northeast Dump	30%
Upper Northeast Dump	40%

The water quality estimates derived in the waste dump and load balances (SRK 2003b) were used directly to estimate the corresponding contaminant loads to the pit lake. The estimated annual average loadings from waste rock piles are shown in Table 3.6.

**Table 3.6 Summary of Estimated Annual Contaminant Loadings From Waste Rock Piles**

Parameter	Loading (kg/year)
Cl	367
SO <sub>4</sub>	169058
Ca	23947
Mg	20656
K	856
Na	1662
Al	1141
Cd	13
Co	24
Cu	157
Fe	5822
Pb	31
Mn	781
Ni	47
Zn	8597

### 3.2.4 Faro Pit Lake Water Quality

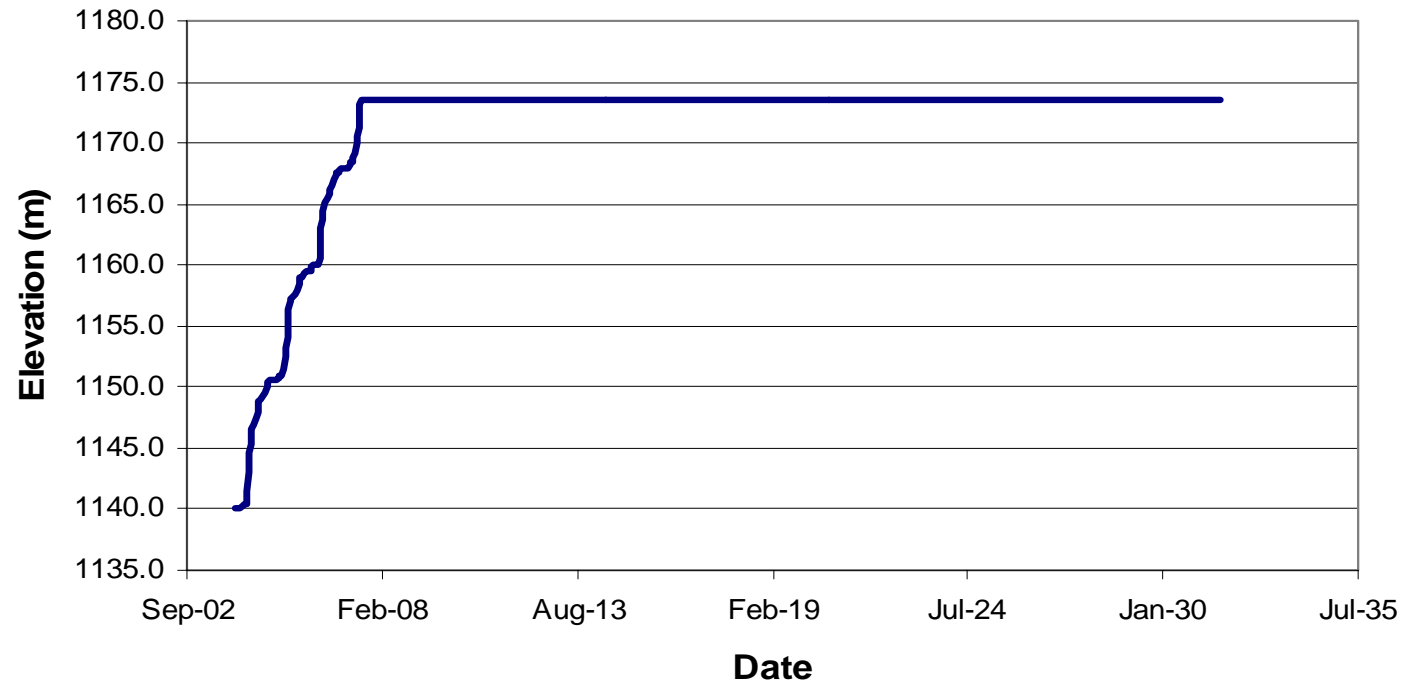
Contaminant concentrations in the pit lake were then estimated by simple mass balance calculations. Any geochemical (precipitation or sorption) reactions that may take place naturally or as a result of pit lake treatment were not accounted for.

It was assumed that a plug dam will be installed at the south east ramp, and the pit lake would be flooded to an elevation of about 1173.5 m asl. It was also assumed that the Faro Creek water would be diverted into the pit lake in 2004. Under this scenario, it is estimated that the pit will fill by about 2008, as shown in Figure 3-3. As noted in Section 2, the pit lake stability assessment indicates that if Faro Creek is diverted into the pit lake, the kinetic energy will likely result in a completely mixed system. Therefore it was assumed that the pit lake would be completely mixed for these calculations.

Two scenarios were modelled. In the first scenario, all of the loadings to the pit lake were considered. In the second scenario, only the effects of the pit wall rocks were assessed. The first scenario represents the case where there is no further remediation of the waste rock dumps. The second scenario represents a hypothetical case where the dumps are completely covered, so that all of the runoff from the dumps remains clean when it reaches the pit lake.

Figure 3-4 presents contaminant concentration estimates for the first scenario, with all of the waste rock seepage continuing to enter the pit lake. The most notable feature of the estimates is the decrease in acidity and zinc concentrations. This is attributable to the addition of clean water from Faro Creek. The modelling suggests that, at the time when the pit would first spill, the acidity would be about 22 mgCaCO<sub>3</sub> eq/L, the zinc about 5 mg/L, and the copper about 0.02 mg/L. After the pit starts to spill, zinc would continue to decrease to a long-term concentration of about 2.3 mg/L. Copper however would continue to increase to above about 0.04 mg/L.





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**Estimated Flooding Level for Faro Pit**

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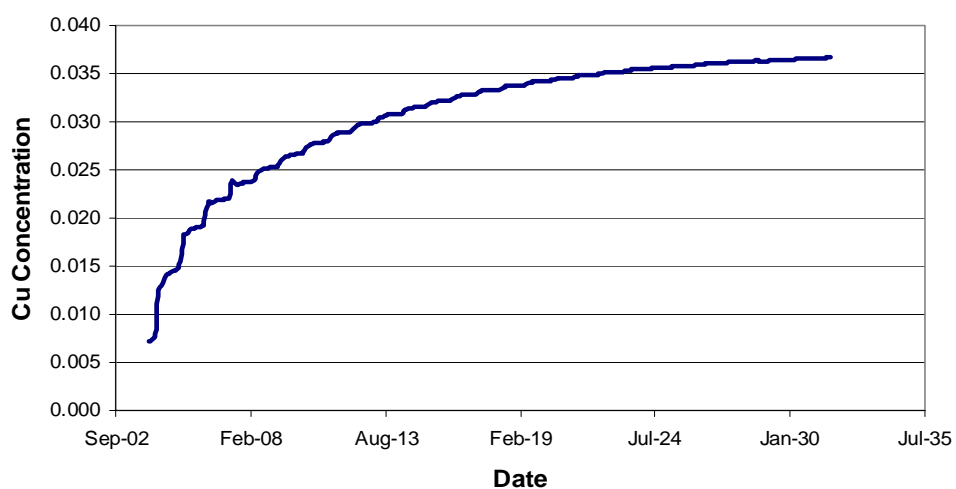
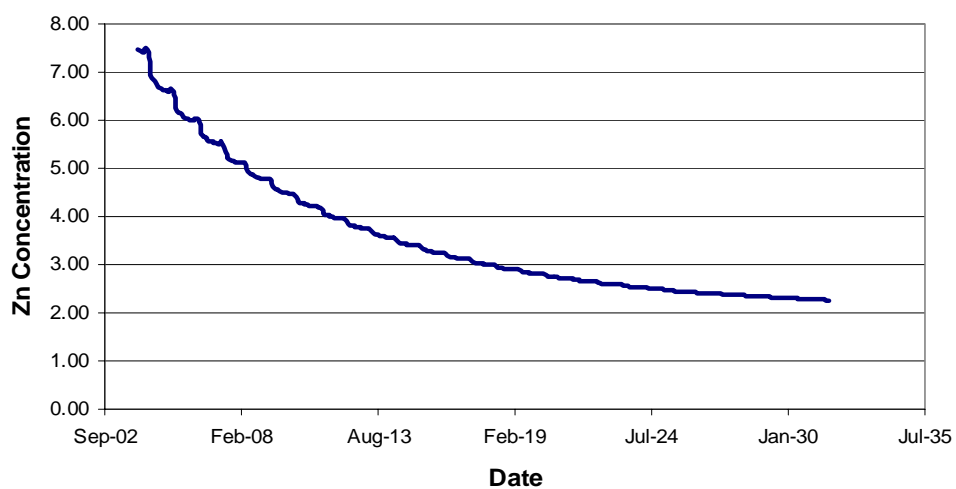
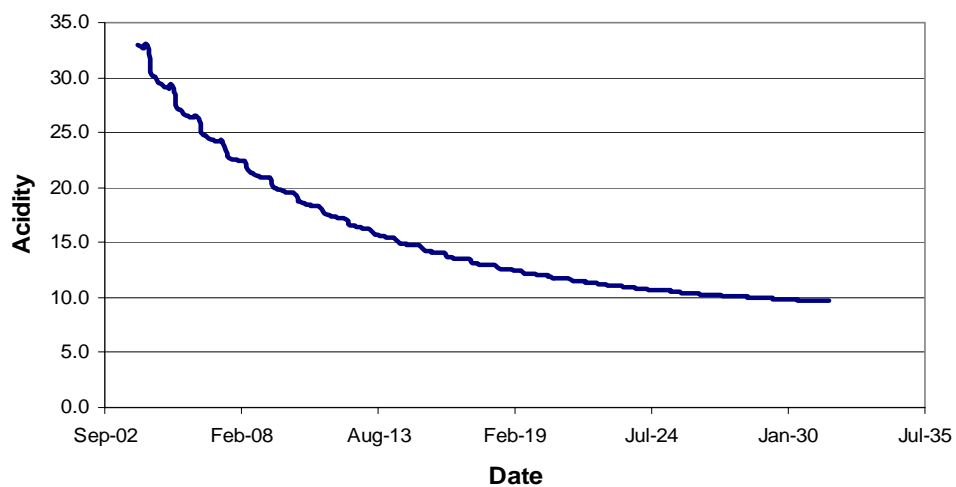
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FIGURE  
**3-3**

Figure 3-5 provides concentration estimates for the second scenario, where the waste rock loadings are completely eliminated. In this case, the acidity in the pit lake is predicted to decrease to about 20 mgCaCO<sub>3</sub>eq/L by 2008. At that time, the zinc concentration is predicted to be about 4 mg/L, and the copper concentration is predicted to be about 0.012 mg/L. Once the pit starts spilling, the predictions suggest that, copper concentrations would decrease to slightly above 0.01 mg/L, and zinc concentrations would decrease to less than 1 mg/L. these are significantly lower than the predictions for the first scenario and indicate the potential effects of waste dump remediation.

It should be noted that the model outputs shown here are illustrative only. The calculations are set up to facilitate easy change of the input assumptions, such as would be needed for sensitivity analyses.



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Assessment of Post Closure Conditions

**Estimated Future Faro Pit Lake Water  
Quality**

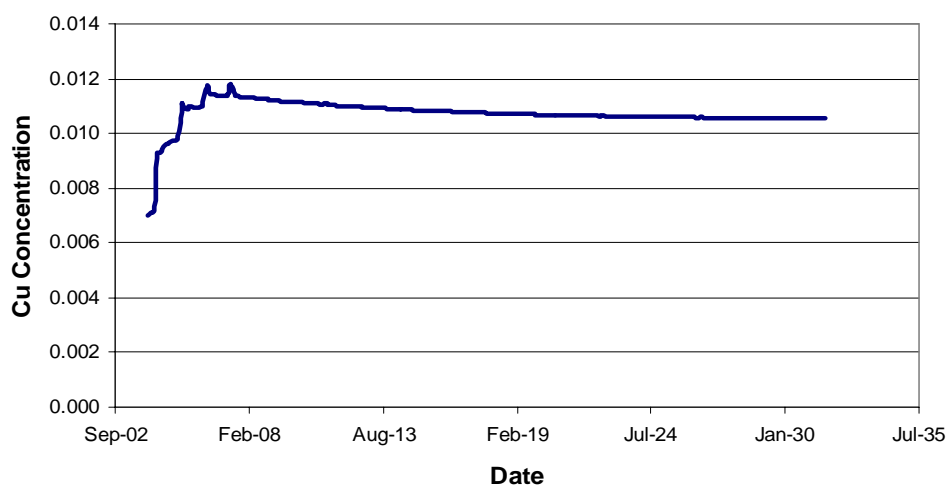
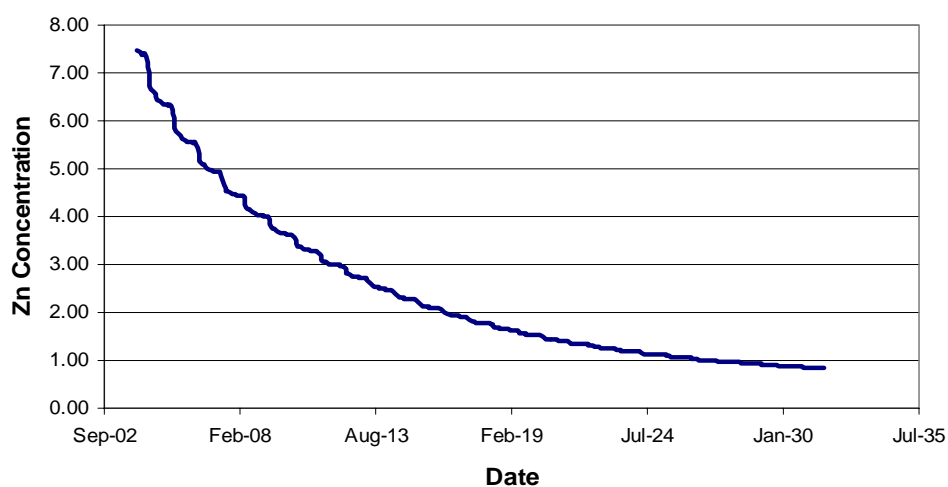
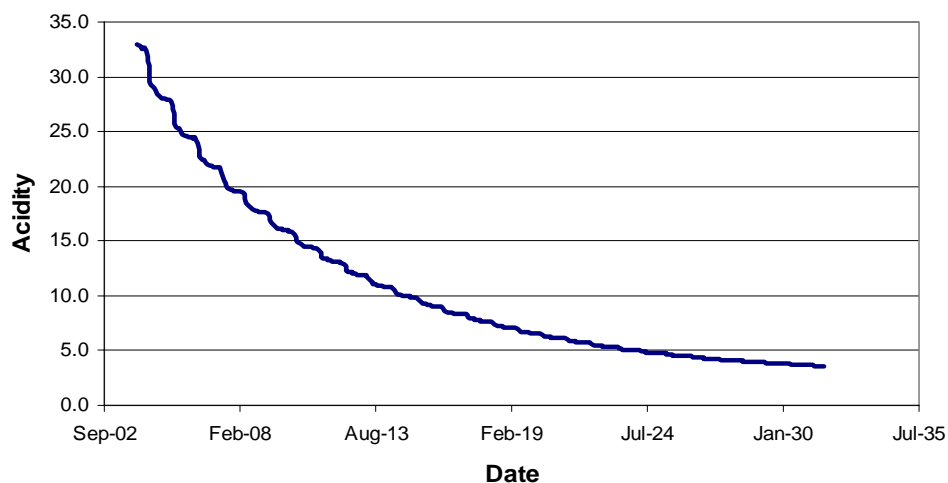
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FIGURE

**3-4**



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Assessment of Post Closure Conditions

**Estimated Faro Pit Lake Water Quality for  
Wall Rock Loadings Only**

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FIGURE

**3-5**

### 3.3 Grum Pit Lake

Gartner Lee Limited (GLL) completed an assessment of the Grum Pit Lake to evaluate short term management strategies that may be considered during the care and maintenance phase of the project. In the following sections the assessments that were completed to estimate the evolution of the water quality in the pit lake.

#### 3.3.1 Grum Pit Lake Water Quality

As noted above, GLL completed a water quality profile of the pit lake in August of 2003. The results are summarised in Table 3.7. At time the pit lake was thermally stratified, as noted in GLL (2003) and the surface layer of water had a lower concentration of zinc and sulphate, which suggests that the surface layer may have been diluted as a result of 'clean' precipitation and surface runoff. The remainder of the water column contained about 12 mg/L zinc.

**Table 3.7 Summary of Grum Pit Lake Water Quality at August 2003**

Parameter	Concentration (mg/L except for pH)				
Depth (m)	0	10	20	30	40
Conductivity (uS/cm)	955	1020	1050	1040	1060
pH	8.08	7.7	7.79	7.49	7.83
<b>Dissolved Anions</b>					
Acidity (CaCO <sub>3</sub> )	2	28	27	26	23
Alkalinity-T( CaCO <sub>3</sub> )	149	164	165	166	166
Sulphate	424	461	452	460	454
<b>Nutrients</b>					
Ammonia - N	0.03	0.02	<0.02	<0.02	0.08
<b>Total Metals</b>					
Aluminum	0.07	0.05	0.04	0.06	0.1
Cadmium	0.0097	0.0159	0.0159	0.0159	0.0159
Calcium	107	113	109	106	93.7
Cobalt	0.0349	0.046	0.046	0.047	0.045
Copper	<0.002	<0.005	<0.005	<0.005	<0.005
Iron	0.09	0.08	0.06	<0.03	0.17
Lead	0.002	<0.003	<0.003	<0.003	<0.003
Magnesium	64.6	67	65.2	62.9	55.6
Manganese	0.451	0.658	0.66	0.659	0.659
Nickel	0.187	0.263	0.269	0.27	0.265
Potassium	4	3	4	3	3
Sodium	11	11	11	11	9
Zinc	4.4	12	12.3	12.3	12

#### 3.3.2 Pit Lake Capacity and Hydrology

The volume-capacity curve for the Grum pit was re-assessed using the topography generated from the 2003 aerial photography. To include the volume of water below the current pit lake level, the new curve was 'meshed'

with that presented in the ICAP(1996). The complete volume capacity curve is provided in Figure 3-6.

The overall water balance for the Grum pit lake is summarised in Table 3.8. The table shows conditions whereby the Grum interceptor ditch is breached and surface runoff within the pit lake catchment is routed through the pit lake, making the total catchment about 1.3 km<sup>2</sup>. The mean annual runoff is estimated to be 270 mm and mean annual precipitation 450 mm. The evaporation rate is based on a fixed pit lake surface area of about 0.28 km<sup>2</sup>.

**Table 3.8 Summary of Grum Pit Lake Water Balance with Grum Interceptor Ditch Breached**

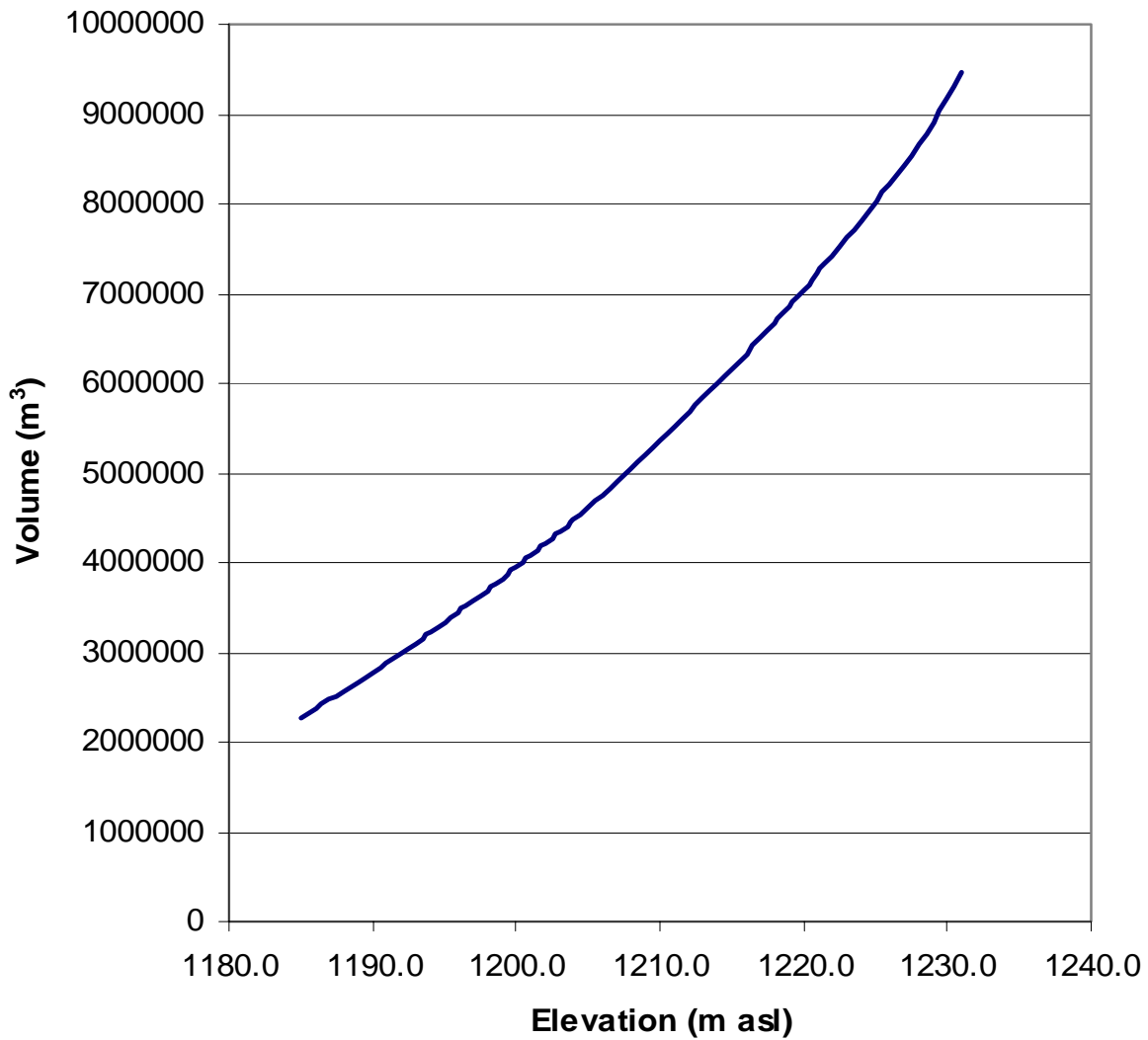
Month	Days in Month	Inflows		Outflows		
		Runoff (1000 m <sup>3</sup> )	Direct Precip. on Lake (1000 m <sup>3</sup> )	Lake Evaporation (1000 m <sup>3</sup> )	Discharge at Pit Outlet	
					(1000 m <sup>3</sup> )	(m <sup>3</sup> /s)
Jan	31	6	1	0.0	7	0.003
Feb	28.25	4	1	0.0	5	0.002
Mar	31	4	1	1.6	4	0.001
Apr	30	9	2	10.6	0	0.000
May	31	72	18	18.0	73	0.027
Jun	30	74	19	22.4	71	0.027
Jul	31	52	13	21.6	43	0.016
Aug	31	36	9	16.2	29	0.011
Sep	30	49	12	6.2	55	0.021
Oct	31	25	7	2.0	30	0.011
Nov	30	11	3	0.0	14	0.006
Dec	31	8	2	0.0	11	0.004
Annual	365.25	351	90	99	342	0.011

### 3.3.3 Contaminant Sources

The only source for contaminant loadings to the Grum pit lake that was considered was wall rock runoff and seepage.

The potential contaminant loadings from the wall rock were estimated as follows. First, rough maps of the pit wall geology were derived from photos and previous mapping. The surface area of the exposed wall rock of each geological type was then determined. These inputs were then used to estimate the surface area of each type of wall rock above the water level as the pit lake rises. The wall rock type was then associated with a specific water quality as observed from the waste rock dumps and, together with the associated runoff estimates, was used to estimate the potential net loading to the pit lake.

The wall rock mapping results are provided in Appendix C, Figure C-2. The estimated surface area of each wall rock type is shown as functions of pit lake elevation in Figure 3-7. Note that the standard rock type notation that was developed for Faro rock types was utilised. Summary descriptions of the rock types are provided in Appendix C.



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**Grum Pit Volume Capacity Curve**

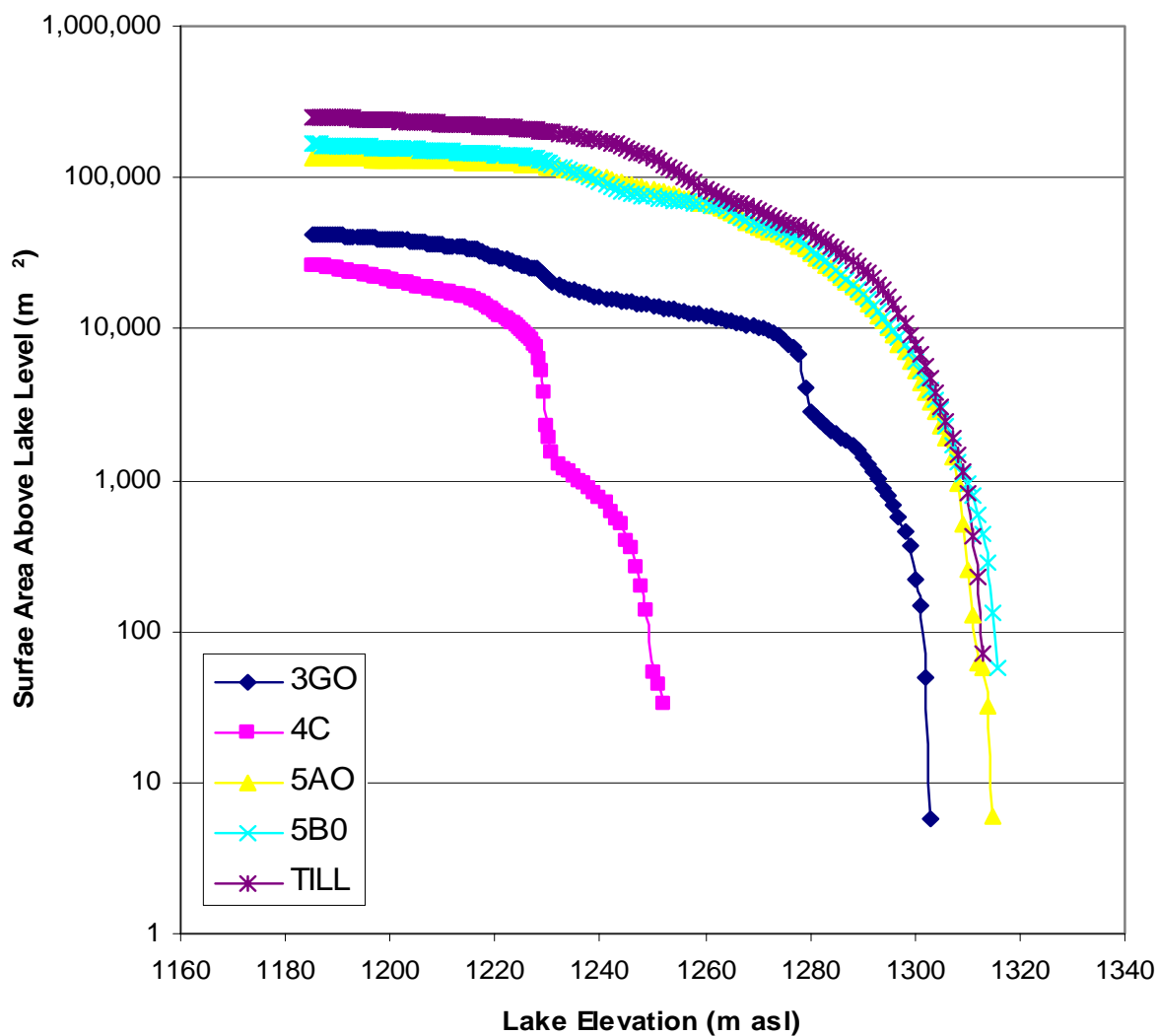
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FIGURE

**3-6**



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**Estimated Grum Pit Wall Rock  
Exposure**

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FIGURE

**3-7**



Estimates of contaminant concentrations in water that contacts each type of wall rock were derived from the recent geochemical studies (SRK, 2003a). The water types for the Grum and Vangorda waste rock are summarized in Table 3.9, and their assumed association with each rock type was as follows:

- 3GO - Non-calcareous phyllite - Non-acid generating. Assume water quality type VG1 with no change in the future.
- 4C - Pyritic quartzite - Potentially acid generating but not all currently acid generating. Assume VG2 possibly evolving to VG6. Small proportions may already be VG6 type.
- 5AO - Carbonaceous phyllite - Potentially acid generating. Assume VG2 evolving to VG6.
- 5B0 Calcareous Phyllite - Non-acid generating. Assume VG1 with no change in the future.
- TILL - Non-acid generating. Assume VG1 with no change in the future.

The estimated average annual loading from the wall rocks are summarised in Table 3.10. The decrease in loadings result from the decrease in exposed surface areas as the lake level rises.

**Table 3.9 Summary of Grum/Vangorda Waste Rock Seepage Water Quality Types Applied to Wall Rock Runoff**

Parameter	Seepage Quality (mg/L except for pH)					
	Vg/Grum Type 1a	Vg/Grum Type 1b	Vg/Grum Type 2	Vg/Grum Type 3	Faro Type 2 W	Faro Type 3 W
Code	VG1	VG2	VG3	VG4	VG5	VG6
pH	7.5	7.3	6.4	4.1	6.7	3.9
Acidity	10	23	352	6279	51	968
Alk	325	526	134	26	137	16
Cl	1.6	2.1	0.8	1.4	1.6	3.1
SO4	255	1093	2878	15482	1701	1614
Ca	137	323	351	432	288	173
Mg	56	205	374	1624	231	161
K	2.4	7.1	9.0	11.6	7.9	6.4
Na	2.6	10.4	8.2	8.7	15.9	7.5
Al	0.20	0.20	0.28	40.0	0.27	14.8
Cd	0.010	0.010	0.11	3.5	0.03	0.16
Co	0.010	0.011	1.4	9.5	0.052	0.30
Cu	0.010	0.010	0.014	29	0.04	2.1
Fe	0.030	0.030	40	706	1.9	76
Pb	0.050	0.050	0.077	1.0	0.064	0.36
Mn	0.16	0.10	67	996	4.9	10
Ni	0.052	0.38	2.6	8.0	0.17	0.56
Zn	0.009	3.0	184	2948	26	109

**Table 3.10 Summary of Estimated Grum Pit Wall Rock Contaminant Loadings**

Parameter	Loading (kg/year)	
	Initial	Final
Cl	256	190
SO <sub>4</sub>	73001	54483
Ca	27758	20677
Mg	14523	10833
K	547	408
Na	713	532
Al	29	21
Cd	1.4	1.1
Co	1.5	1.1
Cu	1.4	1.1
Fe	4.3	3.2
Pb	7.2	5.3
Mn	20	15
Ni	22	16
Zn	129	97

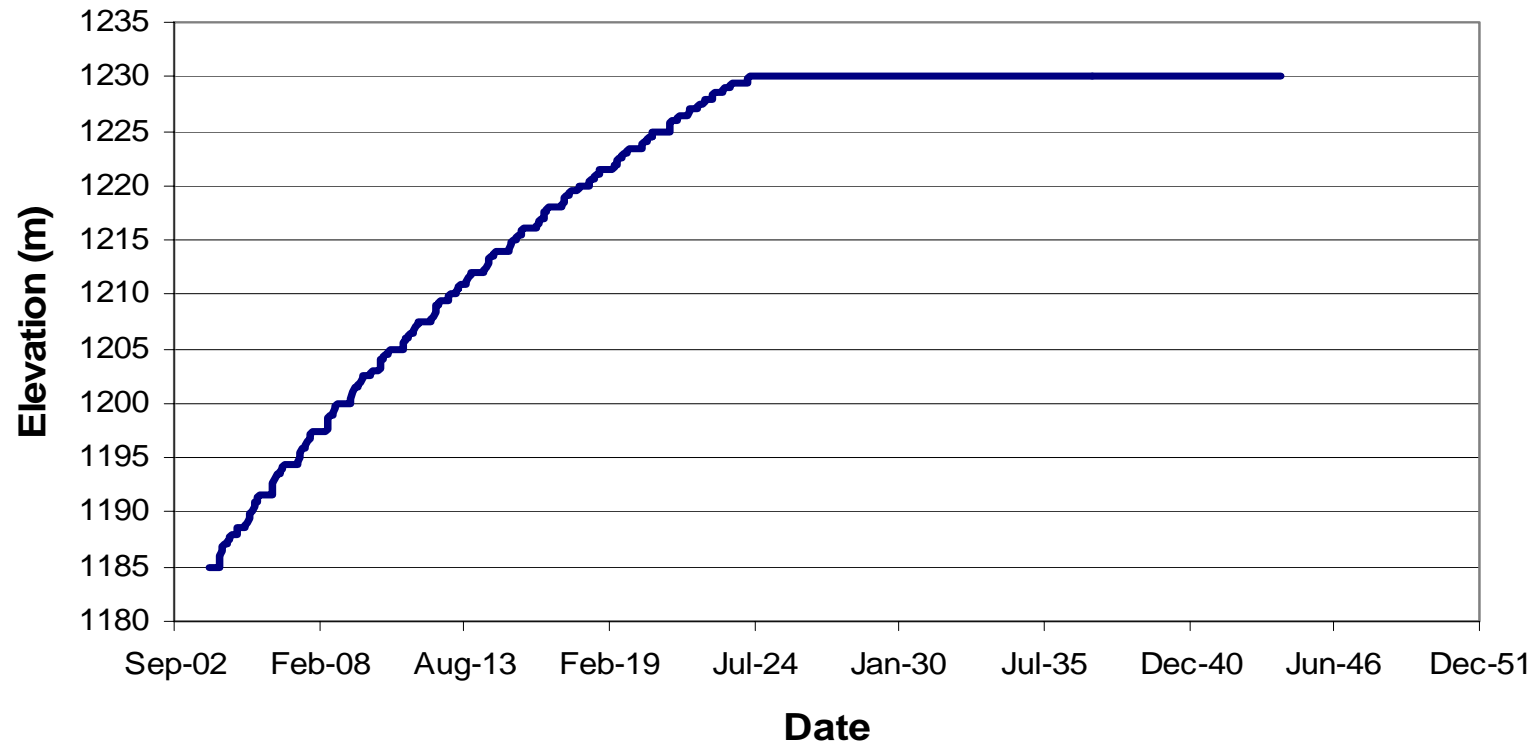
### 3.3.4 Grum Pit Lake Water Quality

As before, contaminant concentrations in the pit lake were then estimated by simple mass balance calculations. Any geochemical (precipitation or sorption) reactions that may take place naturally or as a result of pit lake treatment were not accounted for.

It was assumed that pit lake would be allowed to flood until it overtops at the access ramp. Unless a deeper slot-cut is made, the pit lake would be flooded to an elevation of about 1230 m asl. For the purpose of modeling it was also assumed that the Grum interceptor ditch would be breached in 2004. Under this scenario, it is estimated that the pit will fill by about 2024 or 2025, as shown in Figure 3-8. As noted in Section 2, the pit lake stability assessment indicates that if surface runoff is allowed to enter the pit lake, the kinetic energy will likely result in a completely mixed system. Therefore it was assumed that the pit lake would be completely mixed for these calculations.

Figure 3-9 presents contaminant concentration estimates for the Grum pit lake. The most notable feature of the estimates is the decrease in acidity and zinc concentrations. This is attributable to the addition of clean water to the pit lake. The modelling suggests that, at the time when the pit would first spill, the acidity would be about 5 mgCaCO<sub>3</sub> eq/L, the zinc about 3 mg/L, and the copper about 0.004 mg/L. After the pit starts to spill, zinc would continue to decrease to a long-term concentration of between 0.2 and 0.3 mg/L. However, due to the relatively low flow through the pit, the time before reaching this concentration would be several decades. Copper would continue to decrease to about 0.003 mg/L.

It should be noted that the model outputs shown here are illustrative only. The calculations are set up to facilitate easy change of the input assumptions, such as would be needed for sensitivity analyses.

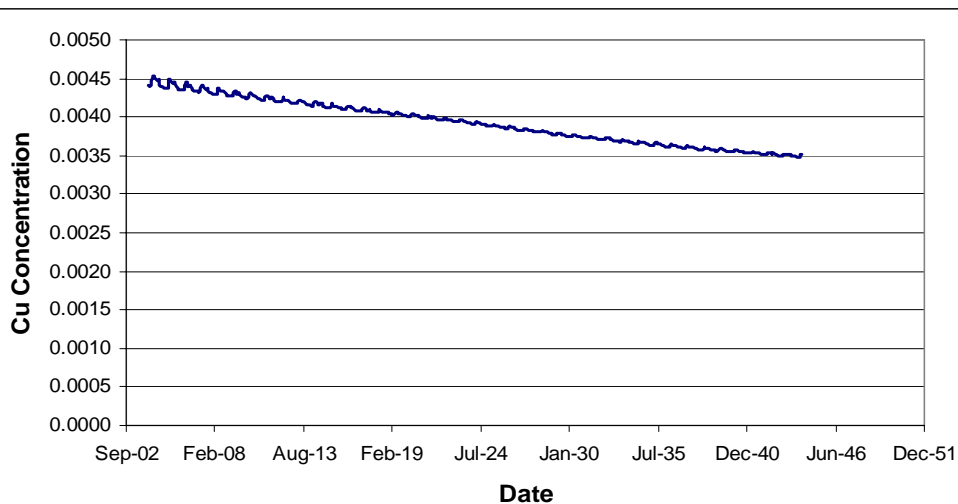
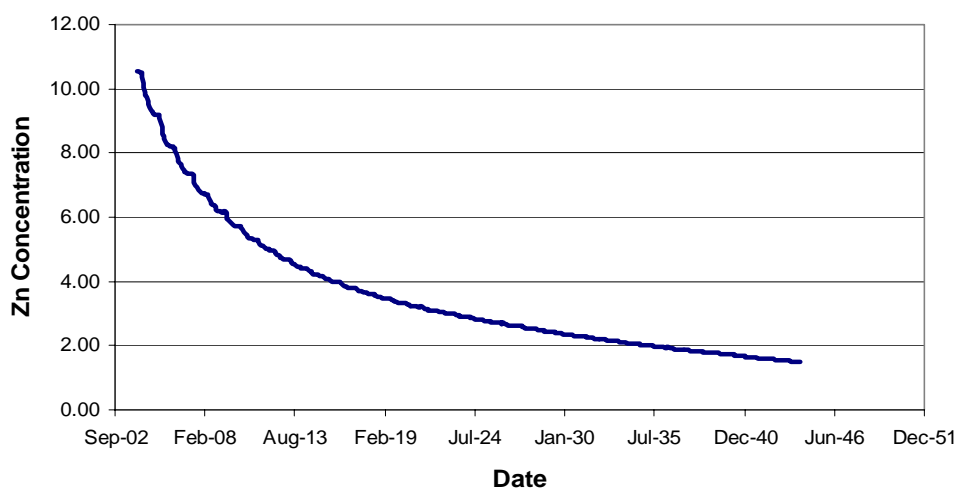
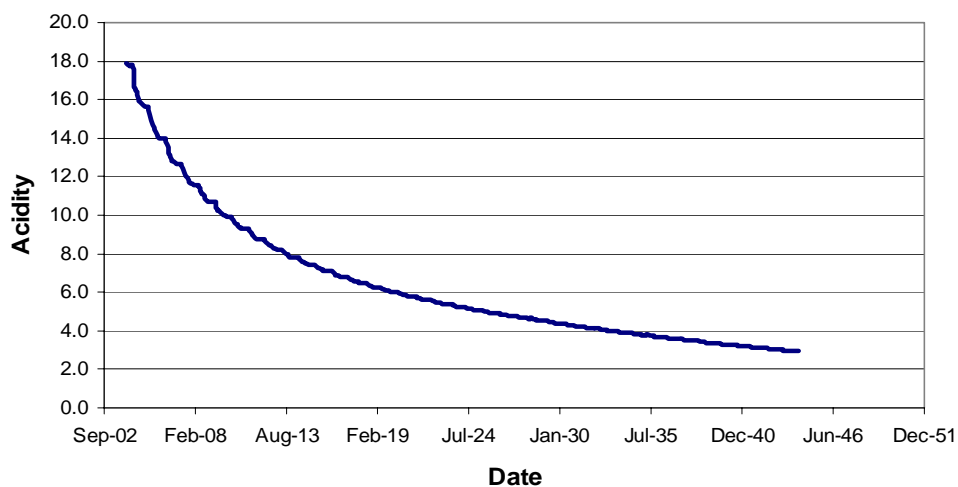


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**Estimated Flooding Rate of the Grum Pit**

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Anvil Range Pit Lakes  
Assessment of Post Closure Conditions

**Estimated Future Grum Pit Lake Water  
Quality**

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FIGURE

**3-9**

## 3.4 Vangorda Pit Lake

### 3.4.1 Pit Lake Water Quality

A water quality profile of the Vangorda pit lake was completed by SRK in September of 2003. Complete results are provided in Appendix D, and are summarised in Table 3.11. As with the other pit lakes, the Vangorda pit lake also had slightly lower contaminant concentration in the near surface. Zinc concentrations for example ranged from 91.5 mg/L near surface to a maximum of 124 mg/L at depth. Similarly, sulphate concentrations were lower in the surface water. It should however be noted that the Vangorda pit lake is utilized as a water storage facility and collected seepage water is pumped to the lake, and water is drawn from the lake and treated in the water treatment plant. Therefore, not all of contaminants in the pit lake are from the contaminant sources that are located within the pit lake catchment. In the past, water treatment sludge has also been disposed in the pit which may affect water quality at depth.

**Table 3.11 Summary of Current Vangorda Pit Lake Water Quality**

Parameter							
Depth (m)	1	3	5	10	20	30	40
Conductivity (uS/cm)	1710	1760	1930	1980	1980	1940	1990
pH	7.03	7.35	7.31	7.3	7.28	6.54	7.03
<b>Dissolved Anions</b>							
Acidity - CaCO <sub>3</sub>	151	162	194	210	212	217	221
Alkalinity-CaCO <sub>3</sub>	57	50	48	49	49	48	49
Chloride	0.7	1	0.9	1	0.9	1	0.6
Sulphate	1080	1100	1250	1280	1280	1250	1280
<b>Dissolved Metals</b>							
Aluminum	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Cadmium	0.08	0.08	0.08	0.08	0.07	0.08	0.08
Calcium	213	208	226	248	237	267	243
Cobalt	0.53	0.53	0.59	0.65	0.63	0.72	0.64
Copper	0.1	<0.01	0.01	<0.01	<0.01	<0.01	0.01
Iron	0.15	1.74	11.3	17.6	21.7	27.9	16.5
Lead	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Magnesium	85.1	84.4	92.6	103	98.2	112	100
Manganese	30.4	30.3	34.3	38.5	37.2	43	37.6
Nickel	0.5	0.51	0.57	0.62	0.59	0.66	0.62
Potassium	4	3	3	3	3	3	3
Sodium	5	6	6	6	5	6	6
Zinc	91.5	91.4	102	114	111	124	111

### 3.4.2 Vangorda Pit Lake Capacity and Hydrology

The volume-capacity curve for the Vangorda pit estimated using the topography generated from the 2003 aerial photography. To include the volume of water below the current pit lake level, the new curve was 'meshed'

with that presented in the ICAP(1996). The complete volume capacity curve is provided in Figure 3-10.

The overall water balance for the Vangorda pit lake is summarised in Table 3.12. The table shows conditions whereby the Vangorda Creek diversion is breached and routed through the pit lake. The total pit lake catchment becomes about 21.7 km<sup>2</sup>. The mean annual runoff is estimated to be 362 mm and mean annual precipitation 380 mm. The evaporation rate is based on a fixed pit lake surface area of about 0.12 km<sup>2</sup>.

**Table 3.12 Summary of Vangorda Pit Lake Water Balance**

Month	Days in month	INFLOWS		OUTFLOWS		
		Runoff (1000 m <sup>3</sup> )	Direct Precip. (1000 m <sup>3</sup> )	Lake Evaporation (1000 m <sup>3</sup> )	Discharge at Pit Outlet	
					(1000 m <sup>3</sup> )	(m <sup>3</sup> /s)
Jan	31	165	1	0.0	165	0.06
Feb	28.25	123	1	0.0	123	0.05
Mar	31	119	1	1.0	118	0.04
Apr	30	156	1	6.4	151	0.06
May	31	1458	8	10.8	1455	0.54
Jun	30	2515	15	13.4	2516	0.97
Jul	31	1152	7	13.0	1146	0.43
Aug	31	574	3	9.7	567	0.21
Sep	30	557	3	3.7	556	0.21
Oct	31	526	3	1.2	528	0.20
Nov	30	278	2	0.0	280	0.11
Dec	31	220	1	0.0	221	0.08
Annual	365.25	7841	46	59	7827	0.25

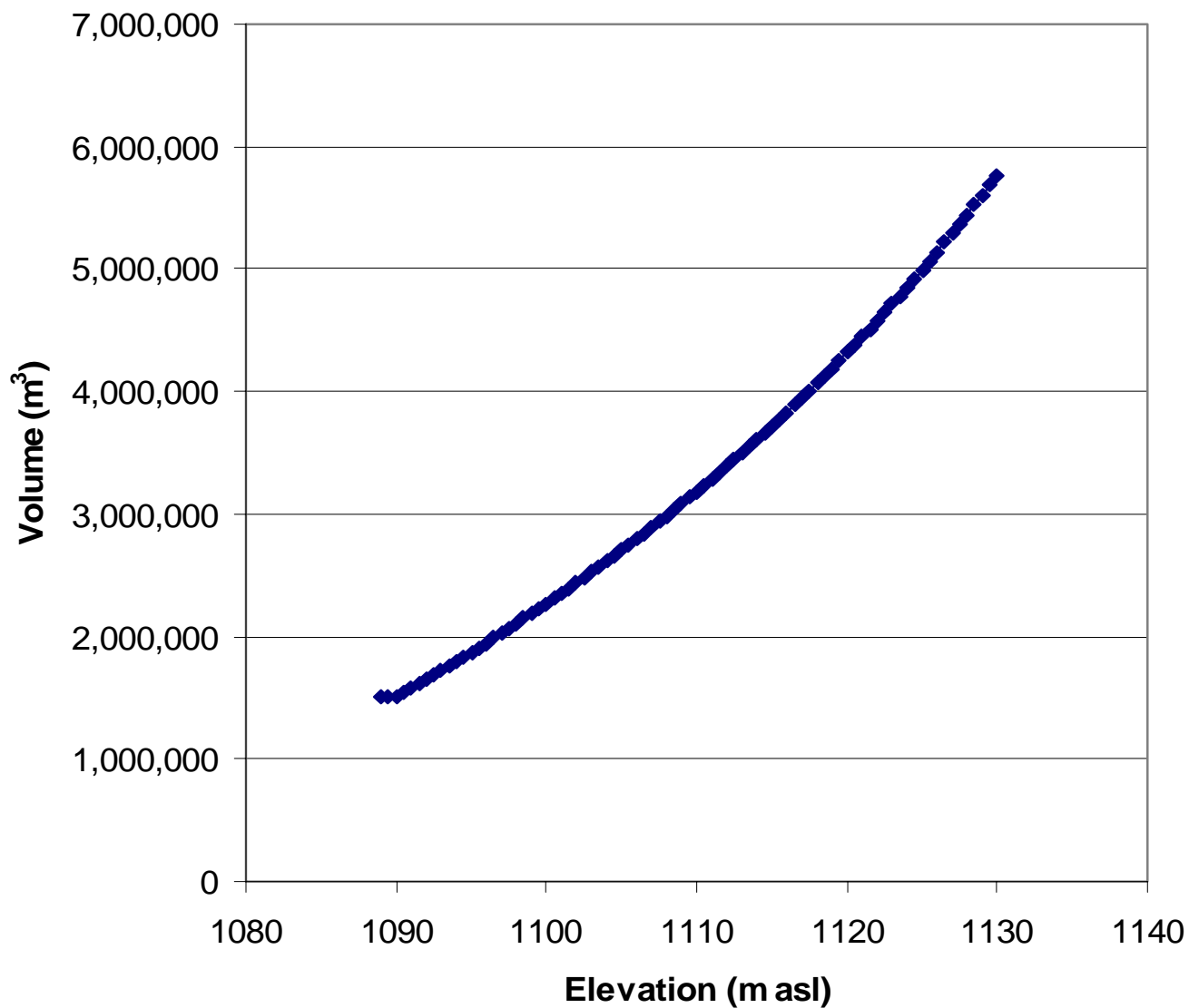
### 3.4.3 Contaminant Sources

Sources for contaminant loadings to the Vangorda pit lake include wall rock runoff and seepage from waste rock that has been placed within the ramp leading down to the pit.

#### Wall Rock Loadings

The potential contaminant loadings from the wall rock were estimated as as previously described for the Faro pit. In summary, surface area of the exposed wall rock of each geological type was determined from maps of the pit wall geology. These inputs were then used to estimate the surface area of each type of wall rock above the water level as the pit lake rises. The wall rock type was then associated with a specific water quality as observed from the waste rock dumps and, together with the associated runoff estimates, was used to estimate the potential net loading to the pit lake.

The wall rock mapping results are provided in Appendix C, Figure C-3. The estimated surface area of each wall rock type is shown as functions of pit lake elevation in Figure 3-11. Note that the standard rock type notation that was developed for Faro rock types was utilised. Summary descriptions of the rock types are provided in Appendix C.



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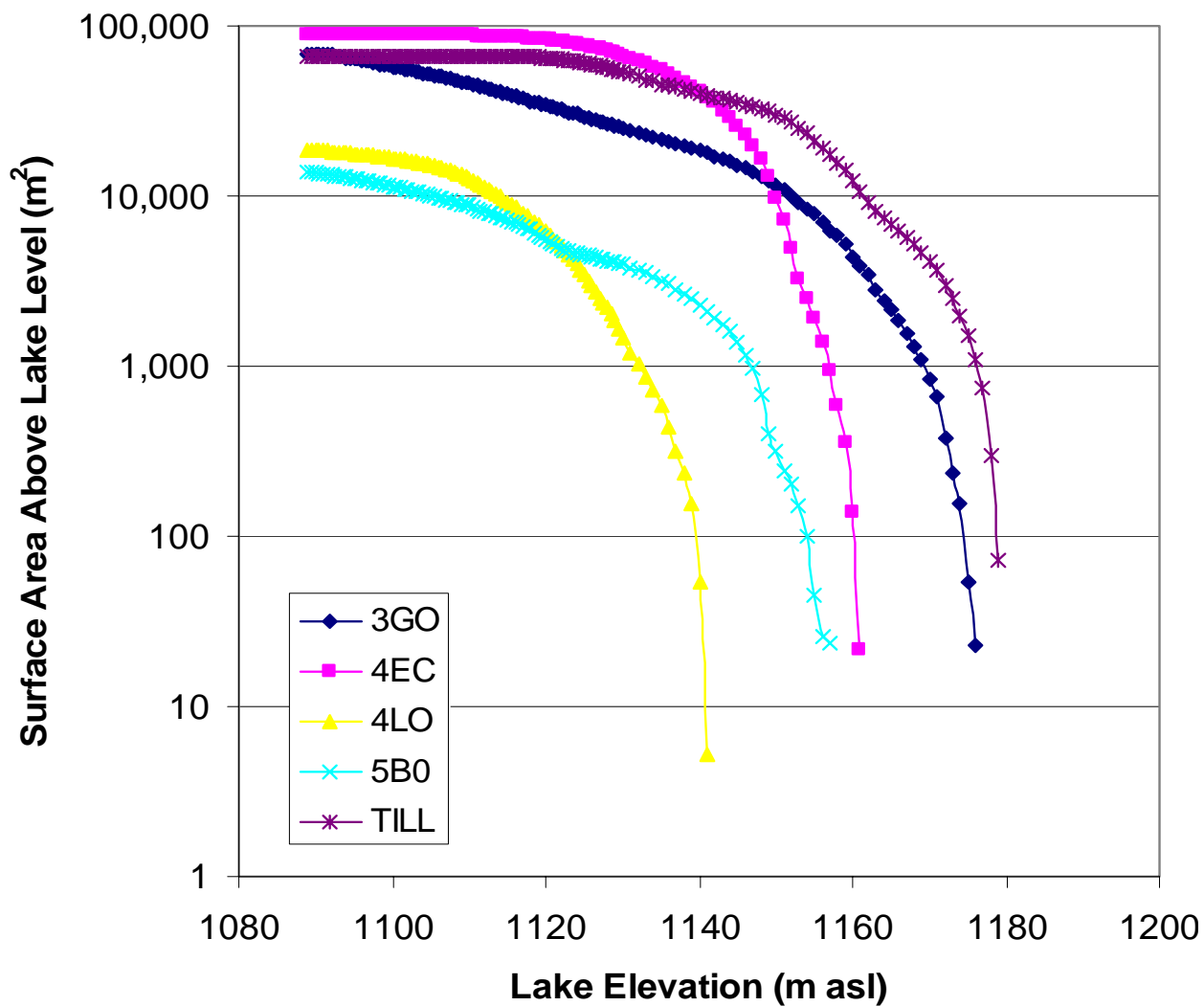
**Vangorda Pit Volume Capacity Curve**

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FIGURE  
**3-10**



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Assessment of Post Closure Conditions  
**Estimated Vangorda Pit Wall Rock  
Exposure**

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FIGURE  
**3-11**



Estimates of contaminant concentrations in water that contacts each type of wall rock were derived from the recent geochemical studies (SRK, 2003a). The water types utilized for the Vangorda pit are the same as for the Grum-Vangorda waste rock summarized in Table 3.9. Their assumed association with each rock type was as follows:

- 3GO - Non-calcareous phyllite. This rock is non-acid generating and therefore water type VG1 is assumed. No change is expected in the future.
- 4EC - Undifferentiated massive and disseminated sulphides. Potentially acid generating but not all currently acid generating. Assume VG3 evolving to VG4. Components may be at VG4 level already.
- 4LO Bleached pyritic phyllite. This rock is similar to 1D4 at Faro. Assume Faro FT4 (=VG4) water quality.
- 5B0 Calcareous Phyllite - Non-acid generating. This rock is non-acid generating and therefore water type VG1 is assumed. No change is expected in the future.
- TILL - Non-acid generating. Assume VG1 with no change.

The estimated average annual loading from the wall rocks are summarised in Table 3.13. As noted before, the decrease in loadings result from the decrease in exposed surface areas as the lake level rises.

**Table 3.13 Summary of Estimated Vangorda Pit Wall Rock Contaminant Loadings**

Parameter	Loadings (kg/year)	
	Initial	Final
Cl	91	68
SO <sub>4</sub>	140416	85868
Ca	16773	12848
Mg	17949	11636
K	387	296
Na	365	282
Al	139	34
Cd	14	4.8
Co	69	39
Cu	90	16
Fe	3340	1362
Pb	7.3	3.9
Mn	5015	2176
Ni	101	68
Zn	14393	6060

### Waste Rock Seepage

Waste rock has been placed within the Vangorda pit ramp area that leads down to the pit lake. Two waste rock piles are located in this area on either side of the access road. The smaller dump is located within the hairpin of the access road ('hairpin dump') and the second comprises waste rock that has been placed along the road to the south of the bend and to the east of the road as it descends to the pit lake. The hairpin dump represents an area of about 15,000 m<sup>2</sup> and the second dump an area of about 20,000 m<sup>2</sup>. To be consistent with the

assumptions for the wall rock runoff, it was assumed that all of the runoff (i.e. surface overflow and infiltration) would be contaminated.

The water quality estimates derived in the waste dump and load balances (SRK 2003b) were used directly to estimate the corresponding contaminant loads to the pit lake. The estimated annual average loadings from waste rock piles are shown in Table 3.14. The hairpin dump is expected to remain above the water level, however, a layer of about 10 m of waste rock in the second pile would remain above the lake level. Some reduction in the loadings may result from this which was not accounted for in the calculations.

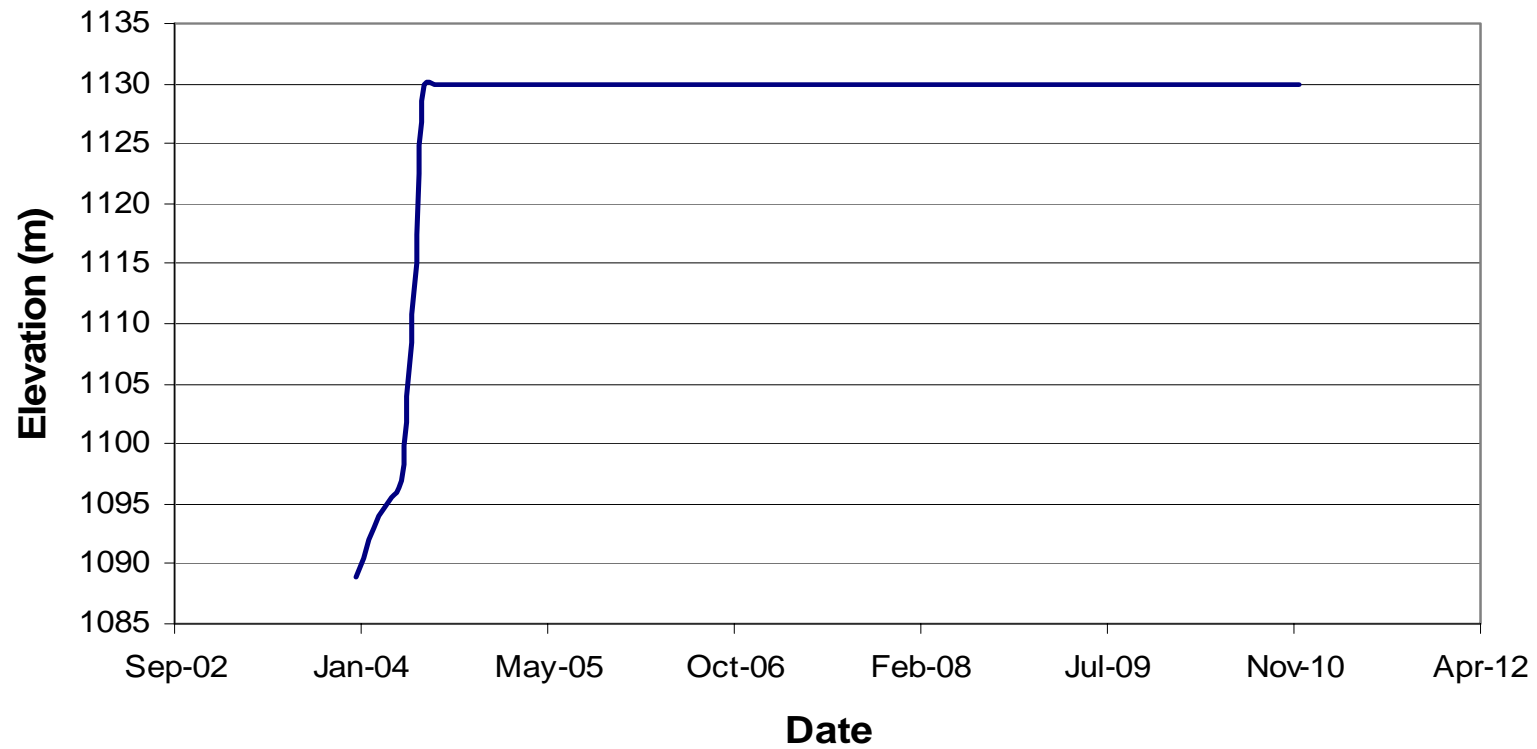
**Table 3.14 Summary of Estimated Annual Contaminant Loadings From Vangorda Waste Rock Piles**

Parameter	Loading (kg/year)
Cl	5
SO <sub>4</sub>	11,628
Ca	915
Mg	1,365
K	23
Na	35
Al	22
Cd	2.0
Co	5.3
Cu	16
Fe	388
Pb	0.72
Mn	552
Ni	4.9
Zn	1,649

### 3.4.4 Vangorda Pit Lake Water Quality

As before, contaminant concentrations in the pit lake were then estimated by simple mass balance calculations. Any geochemical (precipitation or sorption) reactions that may take place naturally or as a result of pit lake treatment were not accounted for.

It was assumed that the Vangorda Creek diversion would be breached and that the creek would flow into the pit lake in 2004. It was also assumed that the pit would fill to an elevation of about 1130 m, and would spill from the western side of the pit. Under this scenario, it is estimated that the pit will fill within one year as shown in Figure 3-12. As noted in Section 2, the pit lake stability assessment indicates that if the Vangorda Creek is diverted into the pit lake, the kinetic energy will likely result in a completely mixed system. Therefore it was assumed that the pit lake would be completely mixed for these calculations.



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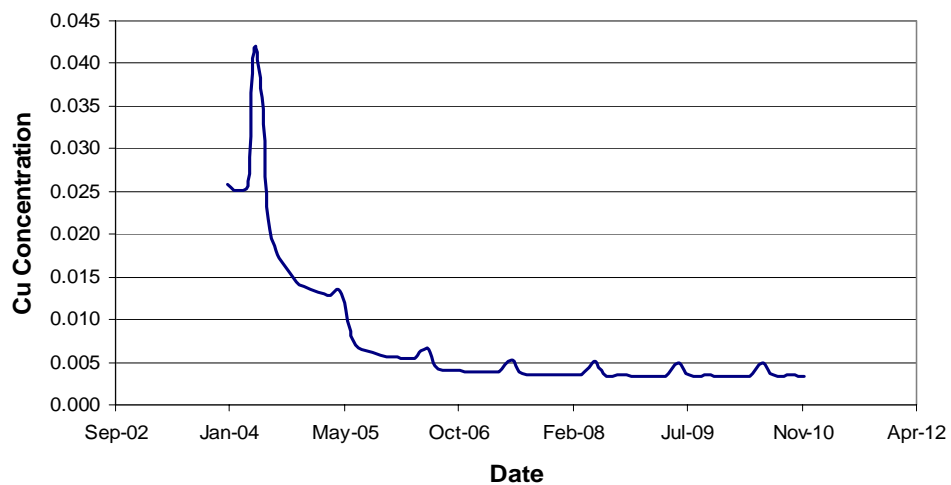
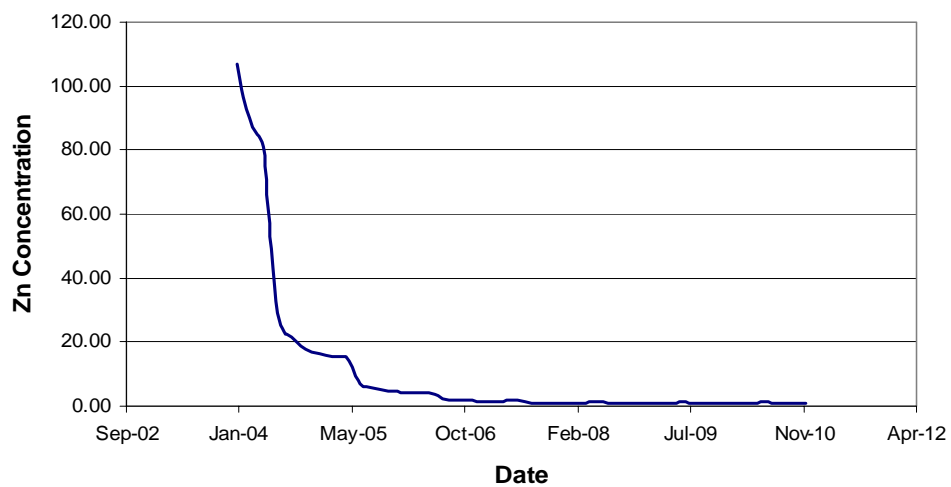
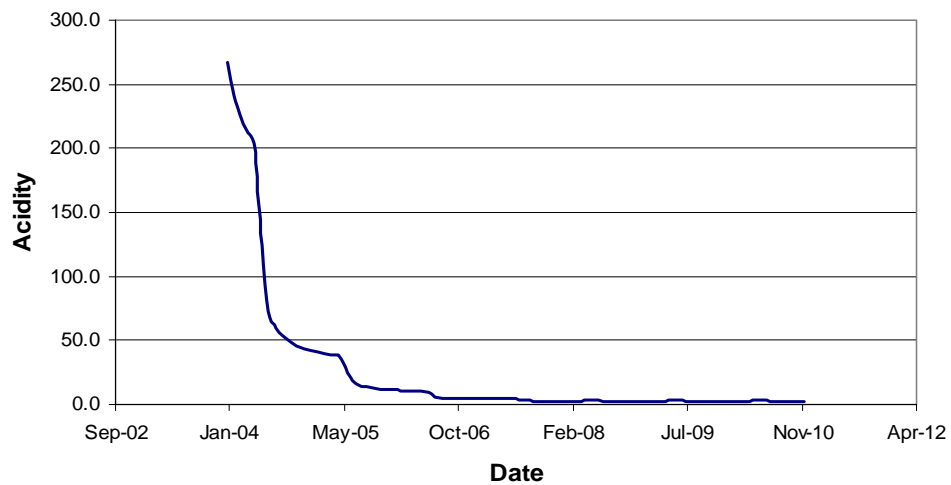
FIGURE  
**3-12**

Two scenarios were modelled. In the first scenario, all of the loadings to the pit lake were considered. In the second scenario, only the effects of the pit wall rocks were assessed. The first scenario represents the case where there is no further remediation of the waste rock dumps. The second scenario represents a hypothetical case where the waste rock would be moved down the ramp to below the flood level, and is isolated from the main lake with a low permeability cut off wall, so that all of the runoff from the dumps remains clean when it reaches the pit lake.

Figure 3-13 presents contaminant concentration estimates for the first scenario, with all of the waste rock seepage continuing to enter the pit lake. The most notable feature of the estimates is the decrease in acidity and zinc concentrations. This is attributable to the rapid addition of clean water from Vangorda creek, and the entire pit lake is rapidly flushed. The modelling suggests that, at the time when the pit would first spill, the acidity would be about 73 mgCaCO<sub>3</sub> eq/L, the zinc about 28 mg/L, and the copper about 0.02 mg/L. After the pit starts to spill, zinc would continue to decrease. Seasonally it would fluctuate between 0.8 and 1.2 mg/L in the long term. Copper decrease to less than 0.005 mg/L.

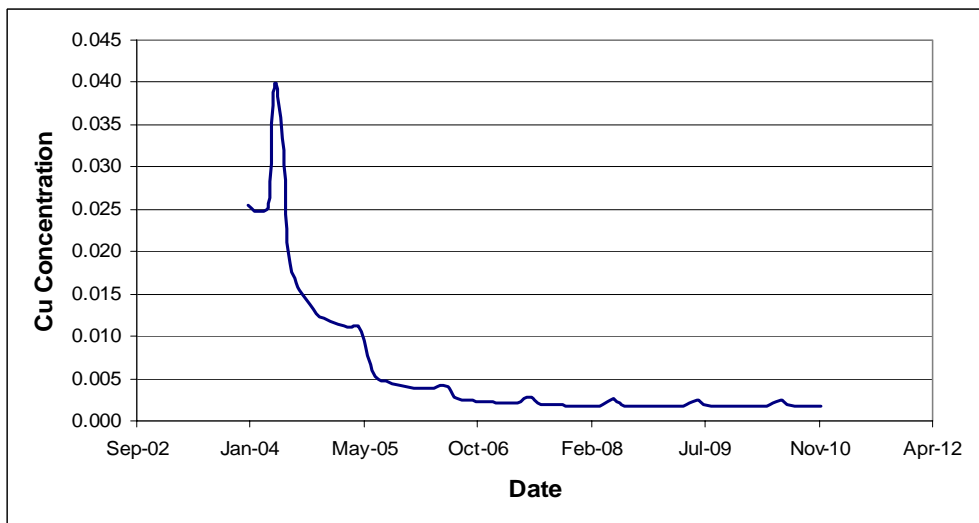
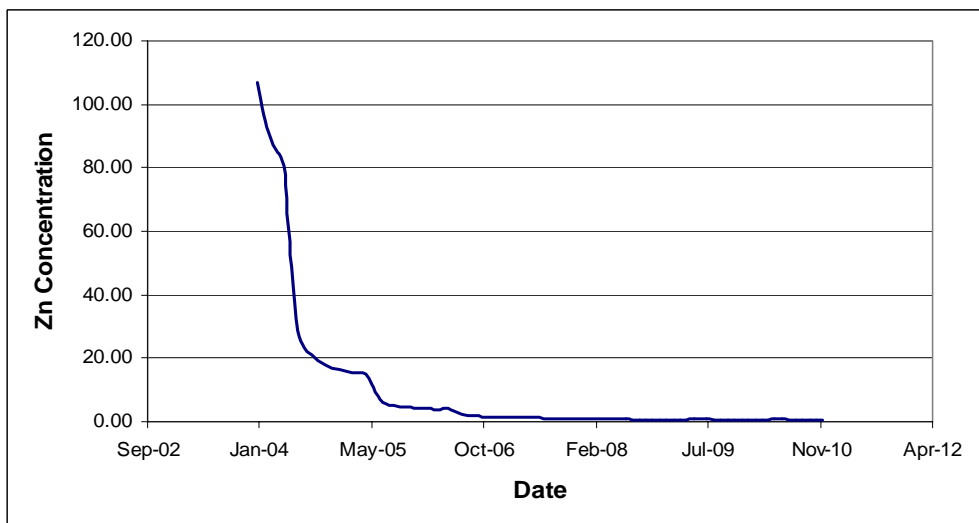
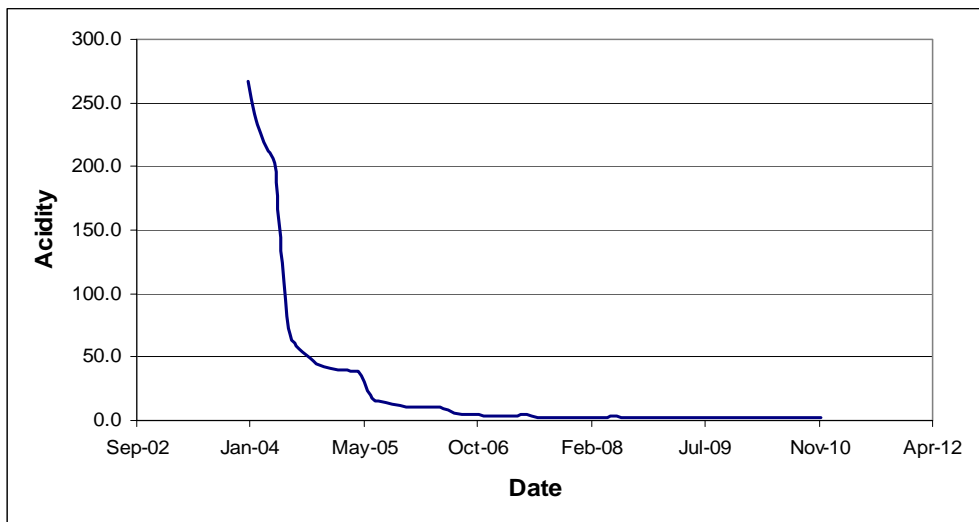
Figure 3-14 provides concentration estimates for the second scenario, where the waste rock loadings are completely eliminated. In this case, the acidity in the pit lake is predicted to decrease to about 60 mgCaCO<sub>3</sub>eq/L when the lake spills. At that time, the zinc concentration is predicted to be about 23 mg/L, and the copper concentration is predicted to be about 0.016 mg/L. Once the pit starts spilling, the predictions suggest that, copper concentrations would decrease to slightly above 0.003 mg/L. Zinc concentrations in the long term are expected to fluctuate seasonally between 0.6 and 0.9 mg/L.

It should be noted that the model outputs shown here are illustrative only. The calculations are set up to facilitate easy change of the input assumptions, such as would be needed for sensitivity analyses.



**Deloitte & Touche Inc.**

Anvil Range Pit Lakes Assessment of Post Closure Conditions			
<b>Estimated Future Vangprda Pit Lake Water Quality</b>			
PROJECT 1CD003.38	DATE January 2004	APPROVED	FIGURE <b>3-13</b>



**Deloitte & Touche Inc.**

Anvil Range Pit Lakes  
Assessment of Post Closure Conditions

**Estimated Vangorda Pit Lake Water Quality  
with Wall Rock Loadings Only**

PROJECT  
1CD003.38

DATE  
January 2004

APPROVED

FIGURE  
**3-14**

## 4 Pit Lake Water Treatment Review

### 4.1 Introduction

It is evident from the above predictions that the contaminant concentrations that will develop in the Anvil Range pit lakes may not be acceptable for discharge. One option in such cases would be to implement a program of treating the water in the pit lakes.

CANMET was commissioned to complete a review of the current state of the art of in-situ pit lake treatment. The assessment comprised a literature review and summation of the relevant information. The open literature was searched for references on treatment technologies for pit lake waters. The CANMET library carried out the search for the period 1980 through to 2003 using DialogWeb of twelve computerized databases.

The review addressed the following topics:

- application of technology to *in-situ* treatment of pit lake water;
- status of the technology (commercially available, pilot-scale, laboratory-scale and conceptual stage);
- effectiveness in removing dissolved metals;
- capital and operating costs; and
- sustainability of the effluent treatment process systems.

The complete report is provided in Appendix E, and the findings are summarized herein.

### 4.2 Summary of Available Technologies

A broad categorization of the applicable technologies, together with some examples, is presented in Table 4.1. In general, the technologies can be subdivided into biological and chemical. The level of success that has been achieved with each technology generally depends on site specific conditions which include the contaminant type, contaminant loadings and treatment objectives.

**Table 4.1 Summary of Potentially Applicable Technologies**

Technology	Amendment	Example
Bioremediation	fertilizer	Island Copper Mine pit lake
	sugar, alcohol phosphate	Sweetwater pit lake
	ethylene glycol	Sulphate Reduction Bacteria (SRB) Systems
Precipitation	lime	Neutra-mill - Anchor Hill Pit Lake
Precipitation/ adsorption	lime	Berkeley pit lake
Adsorption	Kaolin Amorphous Derivative (KAD)	Berkeley pit lake KAD process
	Ferric Oxyhydroxide	McLaughlin south pit lake
Cementation	Se removal	Berkeley pit lake

Five innovative technologies, that may be considered for reducing ARD from wall rock, were also identified in the Canmet review. These were field tested at the Golden Sunlight Mine, and included:

- A modified furfuryl alcohol resin sealant, utilising wood and agricultural by-product to coat the rock surface;
- EcobondARD is a phosphate-based AMD treatment process that reacts with Fe<sup>2+</sup> to form a stable, insoluble compound that coats the rock surface.
- Magnesium oxide (MgO) passivation technology in which an inert coating is formed when a magnesium oxide solution contacts the sulphide rock.
- Potassium permanganate passivation technology in which an inert coating is formed on the sulphide rock surface with basic permanganate solution.
- Furfuryl alcohol resin sealant (FARS) technology consists of a two-component, acid catalysed binder that produces a stable resistant polymer.

All methods showed a net reduction in ARD loads.

### 4.3 Estimated Treatment Costs

The available information on costs of the pit lake water treatment processes is summarized in Table 4.2. It should however be noted that the treatment costs are strongly dependant on site specifics, especially the contaminant levels in the water. The costs in Table 4.2 should therefore be seen as indicative only.



**Table 4.2 Summary of Unit Treatment Costs**

Location/Description	Process	Amendment	Volume	Cost (Can\$)
Island Copper Mine pit lake	bioremediation	fertilizer	3,760,000 m <sup>3</sup> /yr	\$0.026/m <sup>3</sup> (\$100,000/yr)
Sweetwater pit lake	bioremediation	sugar, alcohol phosphate		\$17.17/m <sup>3</sup>
Berkeley pit lake	Precipitation/adsorption	lime	28,300 m <sup>3</sup> /day	Plant: \$15.7-\$28.8 million Operational: \$2.6 million/yr
Berkeley pit lake KAD process	adsorption		11,355 m <sup>3</sup> /day	\$264/m <sup>3</sup>
Berkeley pit lake arsenatephosphate appetite	precipitation		1,635 m <sup>3</sup> /day with 500µg/L As	\$0.26/m <sup>3</sup>
Ferrihydrate Se removal	precipitation			\$4.75/m <sup>3</sup>
cementation of selenium	cementation			\$2.83/m <sup>3</sup>
Berkeley pit lake BSeR selenium removal	bioremediation			\$0.46/m <sup>3</sup>
CANMET1	precipitation	lime		\$0.012/m <sup>3</sup>
CANMET1	precipitation	limestone		\$0.003/m <sup>3</sup>
CANMET estimate	Bioremediation	ethylene glycol		\$0.21/m <sup>3</sup>

## 4.4 Assessment of Effectiveness

The CANMET review concluded that chemical treatment methods are technically feasible but depending on the volume of water to be treated, the cost may be high.

Lime treatment is a proven technology that can remove dissolved metals, indefinitely, from large volumes of water and provide long-term environmental protection. A potential drawback for lime treatment is that it may not meet permitted limits for water discharge to the environment where sulphate and/or hardness and pH are limiting factors.

Biological treatment methods are considered a promising new technology for *in-situ* mitigation of pit lakes in part because the implementation and operational costs calculated from *in-situ* tests are considerably lower compared to chemical treatment. While there are natural analogues, such as wetlands that remove drainage contaminants derived from nearby mineral outcrops that have performed for long periods of time and provide proof of concept, presently there are no long-term examples to show future reliability and costs of adsorption of metals by phytoplankton and bacterial-mediated precipitation of metal as sulphides. Biological processes do not respond well to sudden, rapid, changes to the system such as an increase in metal loading, water flow or loss of anoxic conditions in deep waters of the pit lake and they require a long time to re-establish equilibrium in the system.

Island Copper Mine is successfully using *in-situ* biogeochemical processes in the pit lake to meet permit water quality in the top water layer. However, the pit lake system is still in flux (Fisher and Lawrence 2002) and the long-term performance of biogeochemical processes is unknown. The Island Copper pit lake is also unique because seawater was used to establish meromixis in the lake.

## 4.5 Summary of Recommendations

Three pit-lake treatment methods were identified for further consideration:

- Lime or some other similar form of chemical treatment to raise the pH.
- Amendments with sugar and alcohol to create anoxic conditions under which SRB precipitate metals.
- Nutrient additions as means of creating algae and phytoplankton that remove metals such as Zn when they settle to the bottom.

Lime treatment has been used successfully in the past for pit lake treatment at Samatsum in B.C. and is still used for lake treatment at the Levack mining complex in Ontario. Issues that would need to be addressed with respect to lime treatment include:

- the lack of Fe in the drainage to co-precipitate trace metals such as Zn;
- whether treatment should occur in the pit or only to the overflow;
- whether additional measures will be required to lower the resulting pH prior to discharge; and
- how to prevent discharge of the resulting precipitates.

According to a paper by Harrington at the recent BC ARD workshop (2002), treatment of pit lakes with sugar, alcohol and proprietary amendments has been very successful in creating anoxic conditions under which SRB precipitate metals. A major limitation for SRB reactors is the input of oxygen in drainage or from surface processes such as wind action. Oxygen associated with the acid drainage at the the Island Copper is the likely reason SRB activity has been limited. Specific issues with respect to sulphate reduction that should be addressed include:

- compatibility with water management limitations and requirements;
- oxygen inputs;
- the quantity and frequency and method of amendment application, and the resulting costs; and
- measures required to address site-specific conditions.

Proprietary amendments (e.g., nutrients) may also represent an issue with respect to implementation and operation costs.

Nutrient additions as means of stimulating the growth of phytoplanktonic algae, is successful at least in the short-term both at the Island Copper and Landusky pit lakes (Adams, 2002). Successful results were also obtained from pilot-scale tests at Equity Silver mine. Equity has a cold climate that although not as harsh may be comparable to Faro. Issues that would need to be

addressed regarding metal removal by stimulating the growth of phytoplanktonic algae include:

- compatibility with water management limitations and requirements,
- the quantity, frequency and method of amendment application, and the associated costs,
- seasonal constraints on biological activity, and
- proprietary amendments (e.g., nutrients).

Temperature will be a concern at Faro, both from its potential impact on biological reactions and water management. One way to limit temperature concerns could be by treating the water during the summer and then pumping the pit lake down sufficiently so it can hold contaminated drainage during the rest of the year and there is no possibility of discharge until after the next summer treatment occurs.

All three treatment methods need to be tailored to site conditions. The CANMET review recommended laboratory and pilot scale testing before any of these treatment process is selected for large scale use. The laboratory and pilot scale testing should specifically address the following questions:

- At how high a metal load or flow rate can the method reliably meet permissible discharge concentrations, for how long and at what cost?
- What is required in terms of process control, waste disposal, equipment, personnel, power, amendments, monitoring and maintenance, and discharge?

## 5 Conclusions

Pit lake water quality assessments were completed for the Faro, Grum and Vangorda pit lakes. In all three cases, flow-through scenarios for completely mixed conditions were evaluated, and water quality was estimated as the pits filled. In the case of the Faro pit it was assumed that a plug dam would be constructed to maximise the flood elevation. For the Grum and Vangorda pits it was assumed that they would spill at the natural low points in the pit wall crests.

The predictions presented herein were set up to provide a better understanding of the likely evolution of water quality in the pit lakes. It should however be noted that sensitivity analyses will need to be completed to assess the complete range of conditions that may develop.

The modelling indicates that, at the time there were to spill, the water quality would be as shown in Table 5.1. The conditions shown in the table are, to a large extent, a result of the large inventories of contaminants that have already accumulated in the lakes due to current management practices.

**Table 5.1 Summary of Estimated Water Quality at Time of Spill**

Parameter	Units	Waste Rock Loads Included			Waste Rock Loads Removed	
		Faro	Grum	Vangorda	Faro	Vangorda
Acidity(CaCO <sub>3</sub> )	mg/L	23	5.2	73	20	73
SO <sub>4</sub>	mg/L	409	256	324	396	323
Al	mg/L	0.16	0.072	0.074	0.07	0.071
Cd	mg/L	0.006	0.006	0.022	0.005	0.022
Cu	mg/L	0.023	0.0039	0.022	0.011	0.020
Fe	mg/L	4.1	0.03	4.0	3.6	3.9
Pb	mg/L	0.0062	0.015	0.014	0.0038	0.014
Mn	mg/L	1.6	0.19	9.7	1.6	9.7
Ni	mg/L	0.05	0.11	0.16	0.05	0.16
Zn	mg/L	5.2	2.9	29	4.6	29

In the long term, steady state conditions will develop in the pit lake where the concentrations will be commensurate with the residual loads and the flow through the pits. These long term conditions are shown in Table 5.2.

**Table 5.2 Summary of Estimated Long Term (Steady State) water Quality**

Parameter	Units	Waste Rock Loads Included			Waste Rock Loads Removed	
		Faro	Grum	Vangorda	Faro	Vangorda
Acidity(CaCO <sub>3</sub> )	mg/L	9	1	2	3	2
SO <sub>4</sub>	mg/L	60	152	11	32	10
Al	mg/L	0.27	0.059	0.0064	0.08	0.0038
Cd	mg/L	0.0032	0.0030	0.00076	0.0011	0.00054
Cu	mg/L	0.037	0.0030	0.0036	0.011	0.0018
Fe	mg/L	1.4	0.0089	0.20	0.4	0.15
Pb	mg/L	0.0085	0.015	0.00052	0.0033	0.00044
Mn	mg/L	0.20	0.04	0.31	0.07	0.24
Ni	mg/L	0.013	0.045	0.0082	0.005	0.0077
Zn	mg/L	2.1	0.27	0.87	0.66	0.68

The time to attaining the long term conditions can be significantly reduced should the pit lakes be treated in-situ (chemically) to reduce contaminant inventories before the pits reach their spill elevations.

Assuming that the discharge objectives are similar to the water treatment objectives (EBA, 2003) as follows:

Zinc (Zn)	0.50 mg/L
Copper (Cu)	0.20 mg/L
Lead (Pb)	0.20 mg/L
Cadmium (Cd)	0.02 mg/L
Nickel (Ni)	0.50 mg/L

These discharge criteria would not be met without additional treatment.

In the long term, Grum lake water could meet these discharge criteria. The additional loading from waste rock at Faro would exceed the discharge criteria, as will Vangorda lake water quality. The removal of the waste rock loadings in both cases would be expected to reduce concentrations to near discharge standards.

The CANMET review of available in situ treatment technologies indicate that, with the waste rock source eliminated, the water quality would be within the range where in-situ treatment technologies may apply. It is therefore concluded that flow through pit options as a post closure management strategy should be considered a real possibility for all three pit lakes.

Stratification is unlikely to occur under flow-through pit conditions. Isolated pit conditions may lead to meromixis, however, this condition is not likely to be of long term benefit due to the risk of overturn that could occur due to unusual climatic conditions, seismic activity and the potential for groundwater losses.

## 6 References

SRK, 2003. Geochemical Studies of Waste Rock at the Anvil Range Mining Complex, SRK Draft Report 1CD003.11.610 prepared for Deloitte and Touche Inc., December 2003.

Deloitte & Touche 2003. Anvil Range Mine Complex Closure Planning Workshop June 2003, Deloitte & Touche Inc. report prepared for the Type II Mines Project Office, October 2003.

Integrated Comprehensive Abandonment and Reclamation Plan, Robertson GeoConsultants Inc., November, 1996

## **APPENDIX A**

### **Pit Lake Stability Assessment** (Report by Dr. Greg Lawrence)

# **Preliminary Evaluation of the Physical Stability of the Faro, Grum and Vangorda Pit Lakes**

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19 December 2003



## SCOPE OF WORK

This report attempts to assess the likelihood of meromixis in the Faro, Grum and Vangorda Pit-lakes. Lakes are generally density stratified due to vertical variations in temperature and the concentration of dissolved and suspended substances. This stratification can change with the seasons and from year to year. The first step in most limnological studies is to determine the regime of stratification of the lake(s) in question. The ratio of the surface area to the depth of most Pit-lakes is generally much higher than in natural lakes. Natural sources of mixing (typically wind and surface heating and cooling) are less likely to provide enough energy to destroy any density stratification that may occur. Therefore, Pit-lakes are often, but not always, *meromictic*, meaning they are permanently stratified.

A potential complication with the Faro, Grum and Vangorda Pit-lakes is the proposed routing of natural streams through them. These streams would be another potential source of mixing in the Pit-lakes, particularly if they enter the pits by cascading down steep pit walls. This study will estimate the magnitude of those factors enhancing the stability of the lake (e.g. the salinity of the water column; summertime heating; and the introduction of buoyant water at the surface by ice-melt, direct precipitation and runoff) and comparing them with those factors causing mixing (e.g. the energy of the streams, wind, and penetrative convection).

## INTRODUCTION

Three pit-lakes are located in the Faro area lead-zinc deposits about 360 km north east of Whitehorse. The physical characteristics of these pits are summarized in Table 1. Data for the Equity Waterline pit lake located near Houston B.C. are also presented for comparison in Table 1. There is a significant amount of important data available for the Waterline pit lake which is not available for the Faro pit lakes. The area of the pits as a function of depth is shown in the Appendix.

## Annual cycle

The annual cycle of the pit lakes can be broken into three periods: ice cover (November-May), warming (June-August) and cooling (September-October).

**Table 1.** Summary of available pit lake characteristics

PIT	FARO	GRUM	VANGORDA	WATERLINE
Ultimate water level (m ASL)	1158.2	1231	1122.5	1265
Depth (m)	182	90	96	40
Area (m <sup>2</sup> )*	5.96E+05	2.79E+05	1.23E+05	2.60E+04
Volume (m <sup>3</sup> )*	4.21E+07	9.31E+06	4.25E+06	4.80E+05
Annual Inflow (m)	9.9	1.3	63.7	
Precipitation (m)	0.4	0.3	0.4	
Evaporation (m)	0.5	0.4	0.5	
Surface outflow (m)	9.8	1.2	63.6	
Groundwater outflow (m)	0.0	0.0	0.0	
Retention time (yrs)	7.2	27.2	0.5	

\* computed from area data discussed in Appendix

Temperature and conductivity (salinity) profiles for the Equity Waterline pit-lake during the warming and cooling periods are plotted in Figure 1. There is little change in either temperature or salinity below 9 m. Important changes above this level do occur though. The epilimnetic temperature increases and decreases as we would expect. Through the warming period the salinity can either increase due to fresh inflow or decrease with wind mixing. Between June 29<sup>th</sup> and August 17<sup>th</sup> the epilimnetic salinity decreases slightly (Figure 1b).

In the Waterline Pit-lake, the surface layer cools from 15 °C on August 17<sup>th</sup> to a uniform temperature of around 5 °C on October 3<sup>rd</sup> (Figure 1c). During the cooling period the epilimnetic salinity decreases as a result of penetrative convection and wind mixing. The salinity of the epilimnion increases from August to October as it has mixed down into deeper water (Figure 1d).

Water below about 4 °C is buoyant and reverse stratification occurs as the surface cools and ice forms. The ice cover may be limited to 0.5 m if snow insulates, otherwise ice could be up to 2 m thick. We will model lake behaviour over this range of ice thickness. Ice expels much, but not all, of the salt providing increased salinity contrast and increased lake stability when it melts.

### **Salinity stability**

Mixing a stratified water body raises the center of mass of the water body and the work against gravity needed to lift the center of mass is the stability, given in  $\text{J/m}^2$ . Both warmer surface temperatures and lower salinities contribute to the buoyancy of the surface layer. To examine the possibility of meromixis we would like to remove the effect of temperature. To do this we define the salinity stability as the energy needed to mix the water body with a given salinity stratification while at a constant temperature.

Of particular interest is the salinity stratification at the end of the warming period (late August) defined as  $St^*$ . It varies from year to year, but for Waterline it is approximately  $200 \text{ J/m}^2$ . We compare  $St^*$  with the reduction in salinity stability during the cooling period  $\Delta St$ . During 2001,  $\Delta St$  for the Waterline Pit-lake was approximately  $13 \text{ J/m}^2$ . The meromictic ratio  $M = St^*/\Delta St$  (15 for Waterline) is an indicator of the likelihood of meromixis. The higher  $M$  the more likely the lake is to be meromictic. We have insufficient data to calculate  $\Delta St$  for the three Faro area pit lakes, so we shall use the Waterline value as a point of comparison.

### **Streampower**

If local streams are allowed to flow into the Pit-lakes they may have an important impact on lake stability. In particular, if a stream cascades down the pit wall into the lake, which is a possibility in Faro and Vangorda (J. Chapman, personal communication), it may plunge through the epilimnion and mix with hypolimnetic water before losing momentum.

The mixed water would eventually be flushed from the lake resulting in a decrease in the stability of the water column.

The power (flux of kinetic energy) of a stream is given by:

$$P = \frac{1}{2} \rho Q u^2 \quad (1)$$

where  $\rho$  is the density of water,  $Q$  is the volumetric flow rate, and  $u$  is the average velocity. Consider the stream draining the Vangorda catchment where  $Q \approx 1 \text{ m}^3/\text{s}$  for the month of June. If the stream were a “typical” natural river, then  $u \approx 0.5 \text{ m/s}$ . This is a conservative value, it is likely to be higher since the flow will be down a much higher slope than a “typical” natural stream (or even cascading). Substituting into (1) gives:

$$P = \frac{1}{2} (1000)(1)(0.5)^2 = 125 \text{ W} \quad (2)$$

The kinetic energy input per unit surface area for the month of June:

$$E_{JUNE} = \frac{PT}{A} = \frac{(125)(30)(24)(3600)}{123,000} = 2600 \text{ J/m}^2 \quad (3)$$

where  $T$  is the number of seconds in June and  $A$  is the surface area of the Vangorda pit. Following the same procedure for the Faro and Grum inflows (assuming  $u = 0.5 \text{ m/s}$  and  $0.3 \text{ m/s}$  respectively) gives  $E_{JUNE} = 400 \text{ J/m}^2$  and  $12 \text{ J/m}^2$  respectively.

Not all of this energy is available for mixing, as much of it will be dissipated as the stream passes through the epilimnion. On the other hand, the estimate of  $P$  is probably low for three reasons: the average velocity is probably underestimated; the appropriate velocity to use is the RMS velocity, which will be larger than the average; and stream inflows for the whole year should be considered. A more accurate estimate of  $E$  is beyond the scope of the present study, but the values given above are accurate enough to call into question the appropriateness of diverting the streams through the pit-lakes. For the present study we will just consider the scenario where the streams are diverted.

## Conceptual model

To investigate the possibility of meromixis in the Faro area pits we wish to estimate the salinity stability at the time of maximum heat content,  $St^*$ , and compare this to the change in salinity stability observed in the Waterline Pit-lake,  $\Delta St_{WL}$ .

## Model of warming period

A box model of the surface layer was run for the warming period. The salinity of the surface layer at the end of the warming period was used to compute the salinity stratification,  $St^*$ .

Following Gorham and Boyce (1989) we calculate the likely surface layer depth at the time of maximum heat content in late August. The surface layer depths in the absence of significant river flow-through were estimated to be 3.1 m for Grum, 3.8 m for Faro and 2.5 m for Vangorda using a surface temperature of 15 C and a mean wind speed for late summer storms of 5 m/s.

Two scenarios were run to bound the evolution of the surface layer through the warming period. The first assumed that the surface layer deepens to the maximum depth right after ice melt. The second assumed that the surface layer depth increases linearly from the depth at ice-off to the depth at maximum heat content. The differences between the model predictions for each scenario are negligible.

Important to the stability is the thickness of the initial layer of fresher water on the surface of the pit at the start of the warming period. This fresher layer is formed from a combination of spring freshet runoff and ice melt during the complex sequence of events that occurs during ice-off. We parameterize this process by considering an effective ice-thickness and the model is run over varying values of this thickness.

The model computes daily salinity for the warming period by conserving volume and salt and accounting for input of stream runoff and direct precipitation, outflow, evaporation and changes in surface layer depth. The runoff, precipitation and evaporation data are given in the Appendix. The salinity at the end of the model run is then used to compute the salinity stability as described earlier.

The following assumptions were made,

- The start of the warming period at ice-off is taken as June 1<sup>st</sup> and the end of the warming period at maximum heat content is taken as August 31<sup>st</sup>.
- The hypolimnion of each pit has a salinity of 600 mg/L. Of interest is the water density. Salinity, TDS or specific conductance is used to infer the density. Here salinity  $S$  [mg/L] is assumed to be  $0.5 \cdot C_{25}$  [mS/cm] and density is computed from salinity using Chen and Milero (1996).
- Local streams are diverted around the pit lakes.
- Direct precipitation has a salinity of 10 mg/L.
- Brine pockets form in the ice and the mean salinity of the ice melt is assumed to be 25% of the salinity of the surface waters, based on measurements from the Equity pit-lakes.

## **RESULTS AND CONCLUSIONS**

The results of the model for the three Pit-lakes, assuming the local streams are diverted, are plotted in Figure 2. The value of  $St^*$  increases as ice thickness increases. Typical ice thicknesses observed in the Faro area pits is approximately 3.5 to 4.0 feet (John Chapman, personal communication), comparable to that observed in the Equity Waterline Pit-lake. The meromictic ratio for 1 m of ice thickness is 11, 6 and 5 for Faro, Grum and Vangorda, respectively. Thus, if streams are diverted meromixis seems likely for all the pits, and in each case the likelihood increases with increasing ice thickness. Significant inaccuracies in the estimates remain and this should not be taken to indicate a guarantee of meromixis.

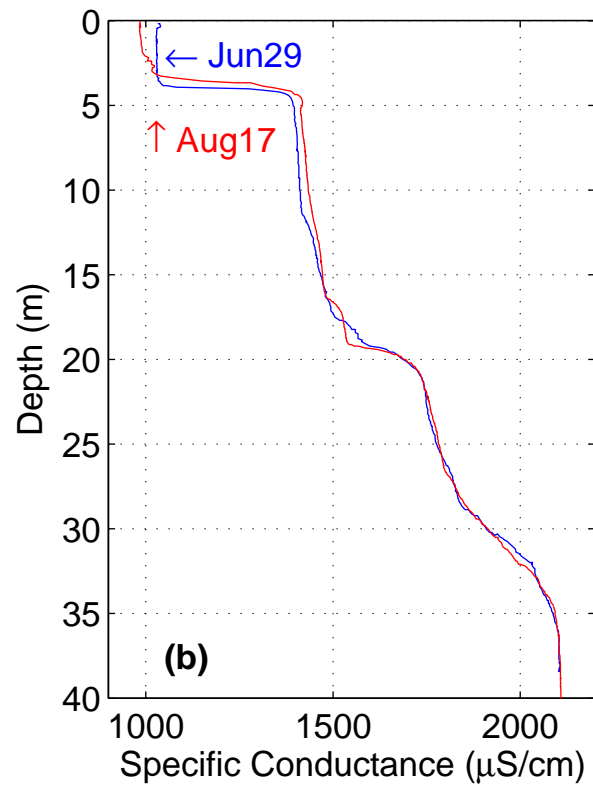
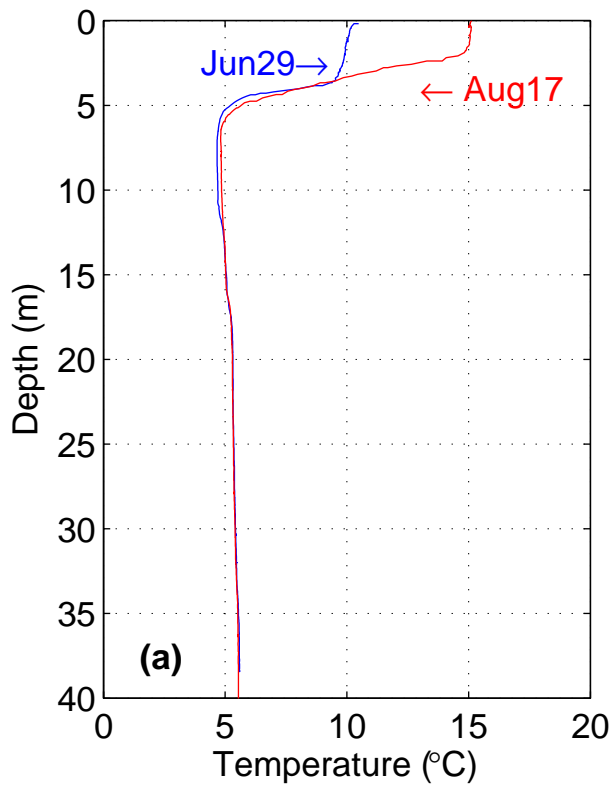
Meromixis can be enhanced by significant salt input such as the dissolution of salts from waste rock and pit walls. It can also occur where evaporation is the major outlet of water from a lake, resulting in concentration of salts. On the other hand flow of relatively fresh water from, for example the local catchment, can export salt and reduce the salinity contrast in the long term.

If the local streams are allowed to flow through the pit lakes they would have a major impact on the physical limnology of the Vangorda and Faro Pit-lakes, and a lesser impact on the Grum Pit-lake. For example, the stream flow into Vangorda would result in a bulk retention time of only 6 months and the surface layer would have a retention time of less than a week. In addition, the stream power would be much greater than the salinity stability of the pit lake. The model would have to be refined to include the effects of streamflow induced mixing. There is certainly the possibility that the flushing of mixed fluid from the lake would lower the salinity stability and reduce the likelihood of sustained meromixis.

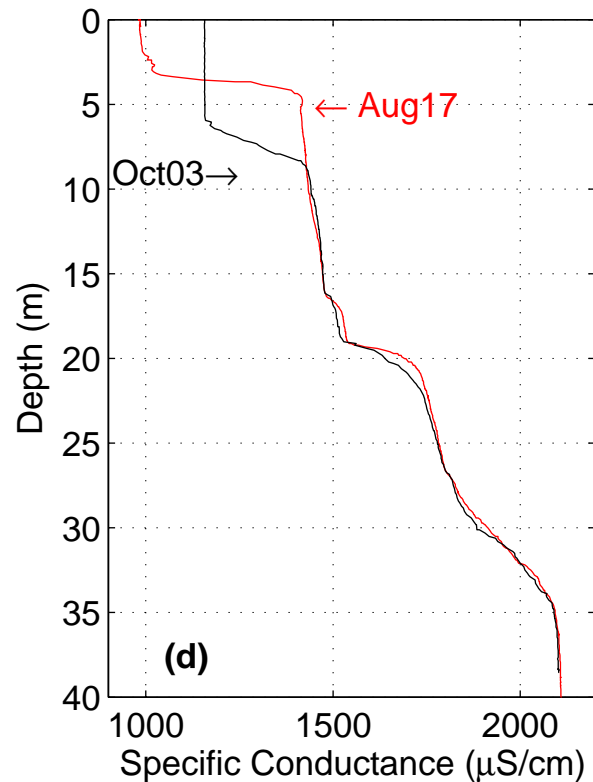
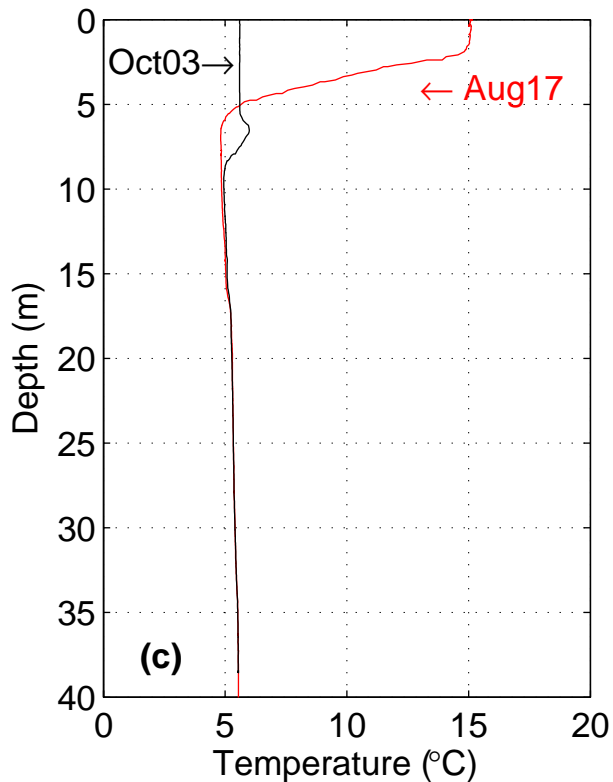
## REFERENCES

- Chen, C. A. and Millero, F. J., 1986. Precise thermodynamic properties for natural waters covering only the limnological range. *Limnology and Oceanography*, 31(3), 657-662.
- Gorham, E. and F. M. Boyce, 1989. Influence of lake surface area and depth upon thermal stratification and the deth of the summer thermocline. *Journal of Great Lakes Research*, 15(2), 233-245.

### Waterline Warming Period

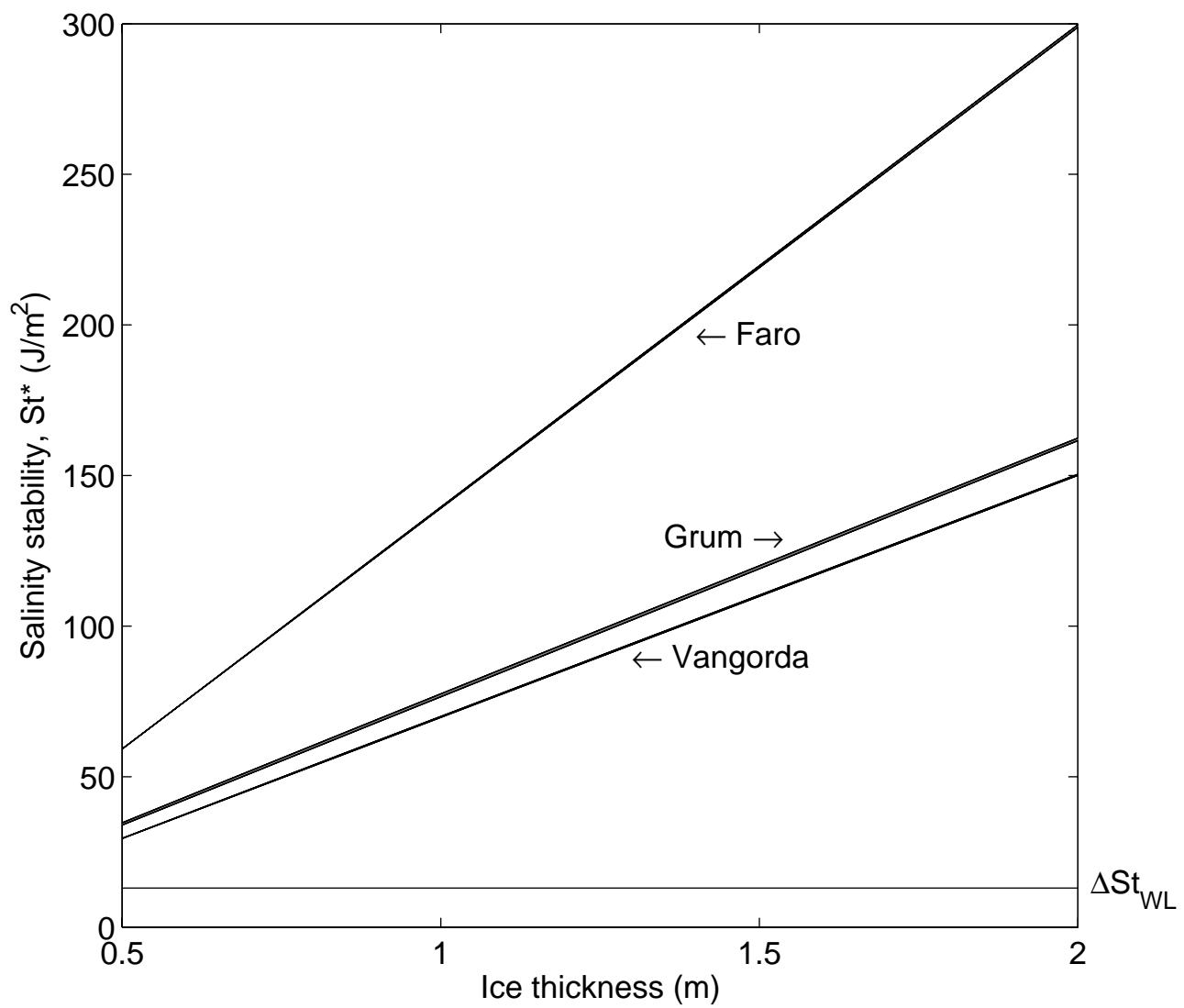


### Waterline Cooling Period



**Figure 1.** Waterline warming (Jun–Aug) and cooling (Aug–Oct) in 2001. The salinity stability was 194, 200 and 187 J/m<sup>2</sup> on Jun 29, Aug 17, and Oct 3, respectively.





**Figure 2.** Predicted salinity stability at time of maximum heat content,  $St^*$ , for Grum, Faro and Vangorda pits with stream water diverted.

## **Appendix Information provided**

The ultimate water level for each pit is given in Table 1. Two sets of area data were given for each pit:

1. DepthCapacityCurves.xls

Grum – Area and elevations very different than the new data. Not used.

Faro –The area is about 10% lower than the area from the surface region given in the new data set. This data was used, as it was a complete set.

Vangorda –The area in this data set is about 10% lower than the areas from the surface region given in the new data set. This data was used, as it was a complete set.

2. Pit Lake Volume Capacity Curves.xls, marked “New Data from Topographic Calc.”

Grum – Elevation matches ultimate water level. Data used.

Faro – partial data going only 30 m below ultimate water level. Not used.

Vangorda – partial data going only 30 m below ultimate water level. Not used.

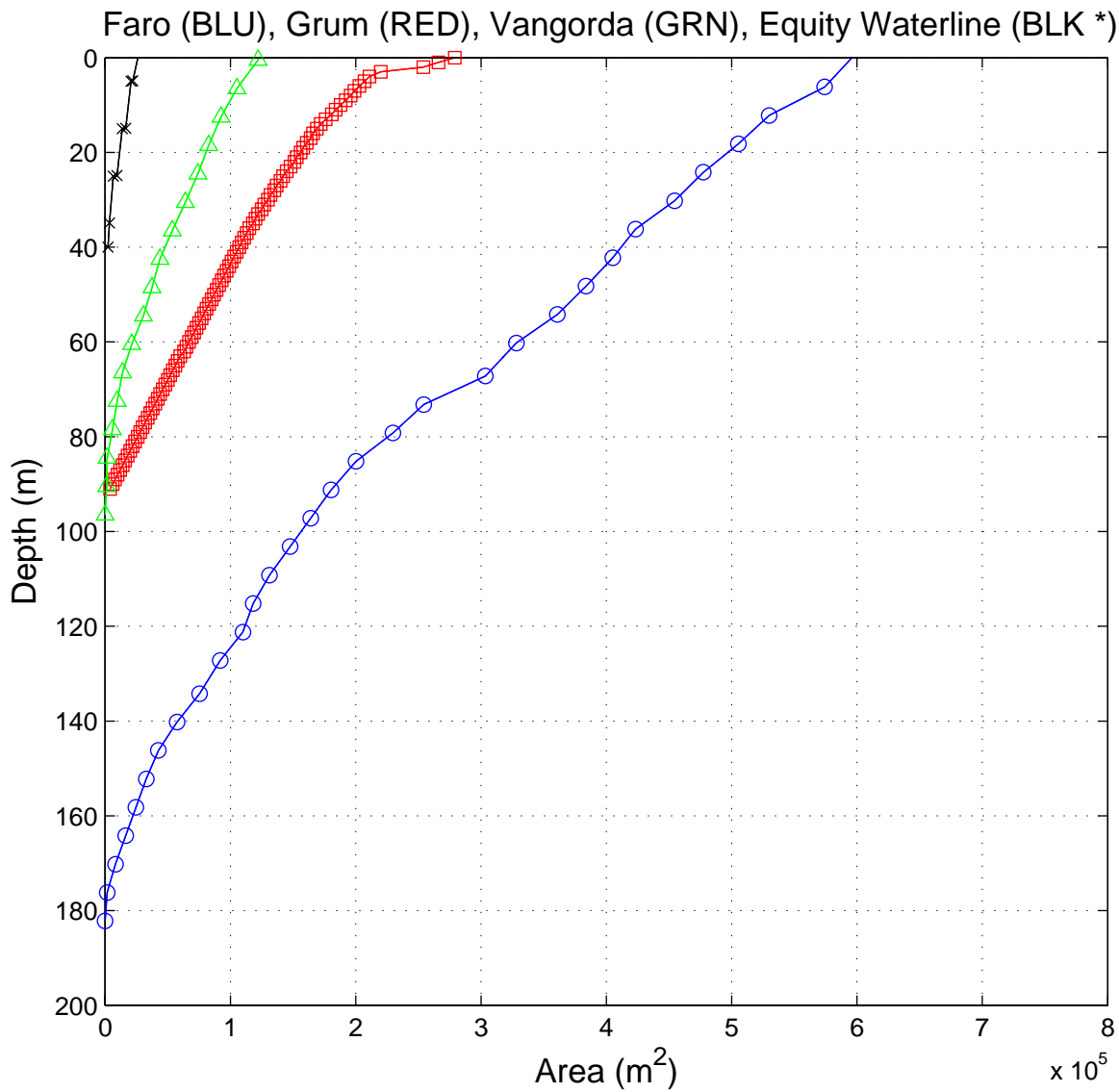
Attached are the following:

Figure showing area as a function of depth used for the pits

Grum: water balance

Faro: water balance

Vangorda: water balance



Area as a function of depth from ultimate water level for Faro area pits

## Grum Pit Average Water Balance

### Assumptions:

- 1) Grum Interceptor Ditch breached
- 2) Groundwater seepage from filled pit assumed negligible

Total catchment of Grum Pit (excl. pit lake surface) =	1.3 km <sup>2</sup>
Surface area of pit lake =	0.2 km <sup>2</sup> (guesstimate - to be checked)
Mean annual runoff of Grum Pit catchment =	270 mm
Mean annual precipitation at pit lake =	450 mm
Groundwater loss rate from open pit =	0 m <sup>3</sup> /s (assumed negligible)

Month	No. of days in month	INFLOWS		OUTFLOWS			
		Runoff (1000 m <sup>3</sup> )	Direct Precipitation on Lake Surface (1000 m <sup>3</sup> )	Groundwater Recharge (1000 m <sup>3</sup> )	Lake Evaporation (1000 m <sup>3</sup> )	Discharge at Pit Outlet	
						(1000 m <sup>3</sup> )	(m <sup>3</sup> /s)
Jan	31	6	1	0	0	7	0.003
Feb	28.25	4	1	0	0	5	0.002
Mar	31	4	1	0	2	4	0.001
Apr	30	9	2	0	11	0	0.000
May	31	72	18	0	18	73	0.027
Jun	30	74	19	0	22	71	0.027
Jul	31	52	13	0	22	43	0.016
Aug	31	36	9	0	16	29	0.011
Sep	30	49	12	0	6	55	0.021
Oct	31	25	7	0	2	30	0.011
Nov	30	11	3	0	0	14	0.006
Dec	31	8	2	0	0	11	0.004
Annual	365.25	351	90	0	99	342	0.011

## Faro Pit Average Water Balance

### Assumptions:

1) Faro Creek routed through Faro Pit

2) No dam constructed in SE access ramp, so pit fills to 1158.2 m (NAD 27) level and spills to buried Zone II Pit, which in turn spills to North Fork of Rose Creek.

The alternative is to construct the dam and force the spill to occur at the SW ramp.

Total catchment of Faro Pit (excl. pit lake surface) =	17.3 km <sup>2</sup>
Surface area of pit lake =	0.6 km <sup>2</sup>
Mean annual runoff of Faro Pit catchment =	341 mm
Mean annual precipitation at pit lake =	400 mm
Groundwater loss rate from open pit =	0.0005 m <sup>3</sup> /s (roughly based on calcs done by RGC)

Month	No. of days in month	INFLOWS		OUTFLOWS			
		Runoff (1000 m <sup>3</sup> )	Direct Precipitation on Lake Surface (1000 m <sup>3</sup> )	Groundwater Recharge (1000 m <sup>3</sup> )	Lake Evaporation (1000 m <sup>3</sup> )	Discharge at Pit Outlet	
						(1000 m <sup>3</sup> )	(m <sup>3</sup> /s)
Jan	31	124	5	1	0	127	0.05
Feb	28.25	92	4	1	0	95	0.04
Mar	31	89	4	1	5	87	0.03
Apr	30	118	5	1	32	89	0.03
May	31	1097	45	1	54	1086	0.41
Jun	30	1892	77	1	67	1901	0.73
Jul	31	867	35	1	65	836	0.31
Aug	31	432	18	1	49	399	0.15
Sep	30	419	17	1	19	416	0.16
Oct	31	396	16	1	6	404	0.15
Nov	30	209	9	1	0	217	0.08
Dec	31	165	7	1	0	171	0.06
Annual	365.25	5899	240	16	296	5828	0.18

## Vangorda Pit Average Water Balance

### Assumptions:

- 1) Vangorda Creek routed through Vangorda Pit and NE Interceptor Ditch breached
- 2) The spill point for the pit is at 1122.5 m (estimated point where old Vangorda Ck channel intercepts southern pit wall.

Total catchment of Vangorda Pit (excl. pit lake surface) =	21.66 km <sup>2</sup>
Surface area of pit lake =	0.12 km <sup>2</sup> (to be checked)
Mean annual runoff of Vangorda Pit catchment =	362 mm
Mean annual precipitation at pit lake =	380 mm
Groundwater loss rate from open pit =	0 m <sup>3</sup> /s (assumed negligible)

Month	No. of days in month	INFLOWS		OUTFLOWS			
		Runoff (1000 m <sup>3</sup> )	Direct Precipitation on Lake Surface (1000 m <sup>3</sup> )	Groundwater Recharge (1000 m <sup>3</sup> )	Lake Evaporation (1000 m <sup>3</sup> )	Discharge at Pit Outlet	
						(1000 m <sup>3</sup> )	(m <sup>3</sup> /s)
Jan	31	165	1	0	0	165	0.06
Feb	28.25	123	1	0	0	123	0.05
Mar	31	119	1	0	1	118	0.04
Apr	30	156	1	0	6	151	0.06
May	31	1458	8	0	11	1455	0.54
Jun	30	2515	15	0	13	2516	0.97
Jul	31	1152	7	0	13	1146	0.43
Aug	31	574	3	0	10	567	0.21
Sep	30	557	3	0	4	556	0.21
Oct	31	526	3	0	1	528	0.20
Nov	30	278	2	0	0	280	0.11
Dec	31	220	1	0	0	221	0.08
Annual	365.25	7841	46	0	59	7827	0.25

## **APPENDIX B**

### **Faro Pit Lake Water Quality**

**Project** Pit Sampling Water Analysis  
**Report to** Gartner Lee Ltd.  
**ALS File No.** T2499  
**Date Received** 12/08/2003  
**Date:** 14/08/2003

**RESULTS OF ANALYSIS**

<b>Sample ID</b>	FP1-5	FP1-10	FP1-15	FP1-58	FP2-5	FP2-10	FP2-25	FP2-60	FP1-10R
<b>Depth</b>	5	10	15	58	2	10	25	60	10
<b>Date Sampled</b>	09/08/2003	09/08/2003	09/08/2003	09/08/2003	09/08/2003	09/08/2003	09/08/2003	09/08/2003	09/08/2003
<b>Time Sampled</b>									
<b>ALS Sample ID</b>	1	2	3	4	5	6	7	8	9
<b>Nature</b>	Water	Water	Water	Water	Water	Water	Water	Water	Water
<b>Physical Tests</b>									
Conductivity (uS/cm)	1070	1200	1240	1370	1070	1200	1330	1390	1210
Hardness CaCO3	570	644	640	726	554	636	684	719	625
pH	7.6	7.84	7.52	7.17	7.89	7.86	7.36	6.87	7.38
<b>Dissolved Anions</b>									
Acidity (to pH 8.3) CaCO3	39	27	25	42	18	26	35	65	23
Alkalinity-Total CaCO3	98	108	108	96	97	97	100	100	103
Sulphate SO4	486	707	694	793	606	655	775	793	663
<b>Nutrients</b>									
Ammonia Nitrogen N	0.93	1.25	1.28	1.45	0.89	1.13	1.6	1.4	1.12
<b>Total Metals</b>									
Aluminum T-Al	<0.03	0.04	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Antimony T-Sb	0.004	0.004	<0.003	<0.003	0.003	0.004	<0.003	<0.003	0.004
Arsenic T-As	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Barium T-Ba	0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Beryllium T-Be	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Boron T-B	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Cadmium T-Cd	0.0129	0.0111	0.0087	<0.0003	0.0129	0.0111	0.0003	<0.0003	0.0115
Calcium T-Ca	133	156	163	180	133	157	178	185	152
Chromium T-Cr	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Cobalt T-Co	0.041	0.045	0.043	0.031	0.041	0.044	0.034	0.032	0.045
Copper T-Cu	0.008	0.008	0.007	<0.005	0.008	0.008	<0.005	<0.005	0.008
Iron T-Fe	0.04	0.04	0.15	20.4	0.05	0.06	11.8	21.8	0.04
Lead T-Pb	<0.003	<0.003	<0.003	0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Lithium T-Li	0.05	0.05	0.06	0.06	0.05	0.05	0.06	0.06	0.05
Magnesium T-Mg	57.9	63.5	63.9	63.7	57.8	64.2	63.9	65.8	62.4
Manganese T-Mn	2.24	2.62	2.75	3.38	2.23	2.58	3.27	3.38	2.63
Mercury T-Hg	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005
Molybdenum T-Mo	<0.005	<0.005	<0.005	0.005	<0.005	<0.005	0.005	0.005	0.005
Nickel T-Ni	0.092	0.095	0.09	0.06	0.093	0.094	0.073	0.062	0.096
Potassium T-K	9	11	13	15	9	12	15	15	12
Selenium T-Se	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Silver T-Ag	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Sodium T-Na	21	26	28	34	21	26	33	35	26
Thallium T-Tl	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Tin T-Sn	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Titanium T-Ti	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Uranium T-U	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Vanadium T-V	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Zinc T-Zn	11	10.3	8.39	1.42	11	10.2	3.04	1.4	10.3



**Project** Pit Sampling Water Analysis  
**Report to** Gartner Lee Ltd.  
**ALS File No.** T2499  
**Date Received** 12/08/2003  
**Date:** 14/08/2003

**RESULTS OF ANALYSIS**

<b>Sample ID</b>	FP1-5	FP1-10	FP1-15	FP1-58	FP2-5	FP2-10	FP2-25	FP2-60	FP1-10R
<b>Depth</b>	5	10	15	58	2	10	25	60	10
<b>Date Sampled</b>	09/08/2003	09/08/2003	09/08/2003	09/08/2003	09/08/2003	09/08/2003	09/08/2003	09/08/2003	09/08/2003
<b>Time Sampled</b>									
<b>ALS Sample ID</b>	1	2	3	4	5	6	7	8	9
<b>Nature</b>	Water	Water	Water	Water	Water	Water	Water	Water	Water
<b>Dissolved Metals</b>									
Aluminum D-Al	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Antimony D-Sb	0.004	0.004	<0.003	<0.003	0.003	0.004	<0.003	<0.003	0.004
Arsenic D-As	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Barium D-Ba	<0.02	<0.02	<0.02	<0.02	<0.02	0.02	<0.02	<0.02	0.02
Beryllium D-Be	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Boron D-B	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Cadmium D-Cd	0.0125	0.0114	0.0089	<0.0003	0.0126	0.0109	<0.0003	<0.0003	0.011
Calcium D-Ca	133	154	155	183	130	152	171	181	149
Chromium D-Cr	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Cobalt D-Co	0.04	0.045	0.044	0.033	0.041	0.044	0.034	0.033	0.044
Copper D-Cu	0.007	0.007	0.005	<0.005	0.007	0.006	<0.005	<0.005	0.006
Iron D-Fe	<0.03	<0.03	<0.03	20.5	<0.03	<0.03	11.1	21.2	<0.03
Lead D-Pb	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Lithium D-Li	0.05	0.06	0.06	0.07	0.05	0.05	0.06	0.07	0.05
Magnesium D-Mg	57.7	62.6	61.3	65.1	56	62.3	62.2	64.5	61.7
Manganese D-Mn	2.22	2.68	2.83	3.59	2.25	2.55	3.26	3.47	2.58
Mercury D-Hg	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005
Molybdenum D-Mo	<0.005	0.005	<0.005	0.006	<0.005	<0.005	0.005	0.006	0.005
Nickel D-Ni	0.09	0.095	0.093	0.064	0.091	0.093	0.072	0.063	0.092
Potassium D-K	10	11	12	15	10	10	15	15	11
Selenium D-Se	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Silver D-Ag	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Sodium D-Na	21	25	27	34	21	26	33	34	26
Thallium D-Tl	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Tin D-Sn	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Titanium D-Ti	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Uranium D-U	0.003	0.003	0.003	0.004	0.003	0.003	0.003	0.003	0.003
Vanadium D-V	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Zinc D-Zn	10.7	10.4	8.53	1.49	10.9	9.97	3.02	1.35	10.1

**Footnotes:** Results are expressed as milligrams per litre except where noted.  
< = Less than the detection limit indicated.

## **Appendix C**

### **Wall Rock Mapping**

## Geochemical Studies Logging Guide

### Faro Area Rock Types

- 1D Non-carbonaceous fine-grained schist containing muscovite, biotite and andalusite. Typically contains finely disseminated pyrite or pyrrhotite along foliations. May contain quartz veins with coarse grained pyrite and/or chalcopyrite. Occasionally contains calcite in fractures and along foliations. Often loose but sometimes cemented by white salts. May be blocky or fine-grained.

A variety of 1D is maroon-stained and typically contains more visible pyrite and calcite. Sometimes appears to be a transitional form between 1D and 1D4.

1C6 Same as above but with biotite and andalusite porphyroblasts along foliation

1D2 Carbonaceous fine-grained schist. Typically friable with abundant fines.

- 1D4 Quartz muscovite schist. In palest form, is extremely friable and decomposed. Fine-grained pyrite may be visible. Oxidized fines are pale yellow to orange brown. Quartz veins typically contain pyrite. Rinse pH is strongly acidic (pH<3). See comment about maroon stained variety of 1D.
- 2 Sulphide rock types. These include massive to semi-massive siliceous pyrite occurring as blocks (brown stained), massive crumbly pyrite occurring as blocks and fines (no stain), and massive sphalerite. Barite is common.
- 3D0 Amphibolite and calc-silicate schist. Distinctive centimetre-scale light and dark banding. Calcite is common both as a matrix component and as a fracture filling. Rare sulphides. Typically blocky.
- 6 Milky quartz. Informal name.
- 10E Hornblende biotite quartz diorite. Dark porphyritic rock type. Typically blocky and stable but also rapidly decomposing and fines forming.
- 10F Quartz feldspar porphyry. Distinctive white rock and 1 mm biotite and hornblende phenocrysts. Typically blocky and stable but also rapidly decomposing and fines forming.
- 5 or T Overburden. Till.

## Grum and Vangorda Area

### Units

### Symbols Used on Field Maps

#### *Vangorda Formation*

5C	Poorly foliated greenstone	
5D	Chlorite phyllite, calcareous	5D0, 5D4
5B0	Calcareous phyllite, silver to dark grey	5B
5A0	Carbonaceous phyllite, weakly calcareous	5A

#### *Mount Mye Formation*

3G0	Non-calcareous phyllite	3G
4EC	Undifferentiated massive and disseminated sulphides	
4E	Massive pyritic sulphides (60 to 100% pyrite)	
4C	Pyritic quartzite (<30% pyrite)	
4L0	Bleached phyllite, commonly pyritic	4L

### Modifiers

ca	Calcareous
py	Pyritic
ox	Oxidized
st	Visible salts (describe type in notes)
gn	Galena
sl	Sphalerite
bl	Blocky (describe in notes)
sk	Slaking (describe in notes)
ms	Massive sulphide


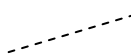

### Clast sizes

m>cm:	Coarse
cm/m:	Mixed metre and centimetre scale
mm>cm>>m	Fine Frained

### Mapping Conventions

3D0ox/10Fsk	About equal quantities.
10% 3D0ox/90% 10Fsk	Proportions indicated

### Symbols

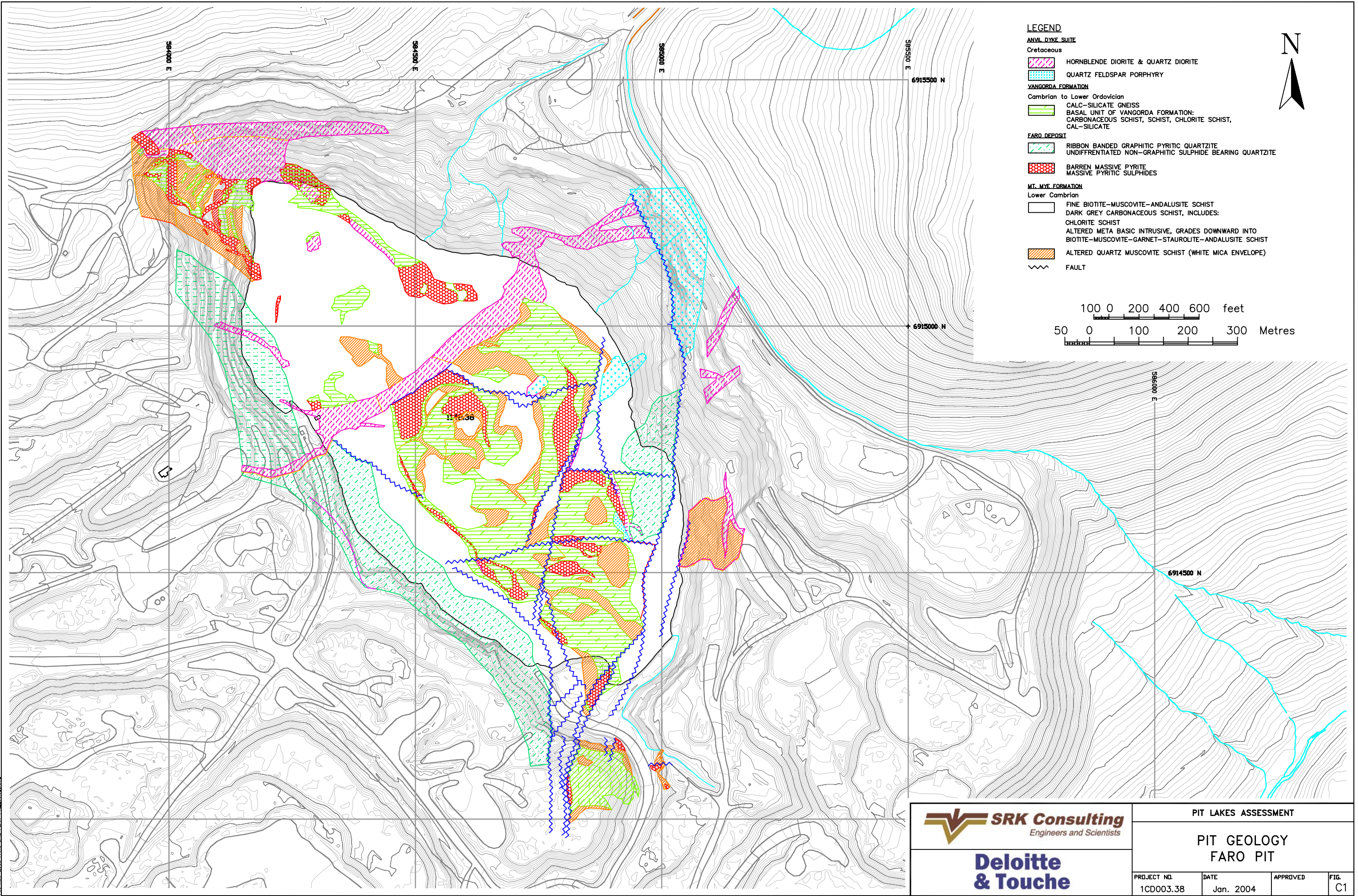
	Distinct contact
	Indistinct contact
	FD – Free dumped area


\* Small cluster of sulphide boulders

- GUS-01 Fine screened sample location for contact test

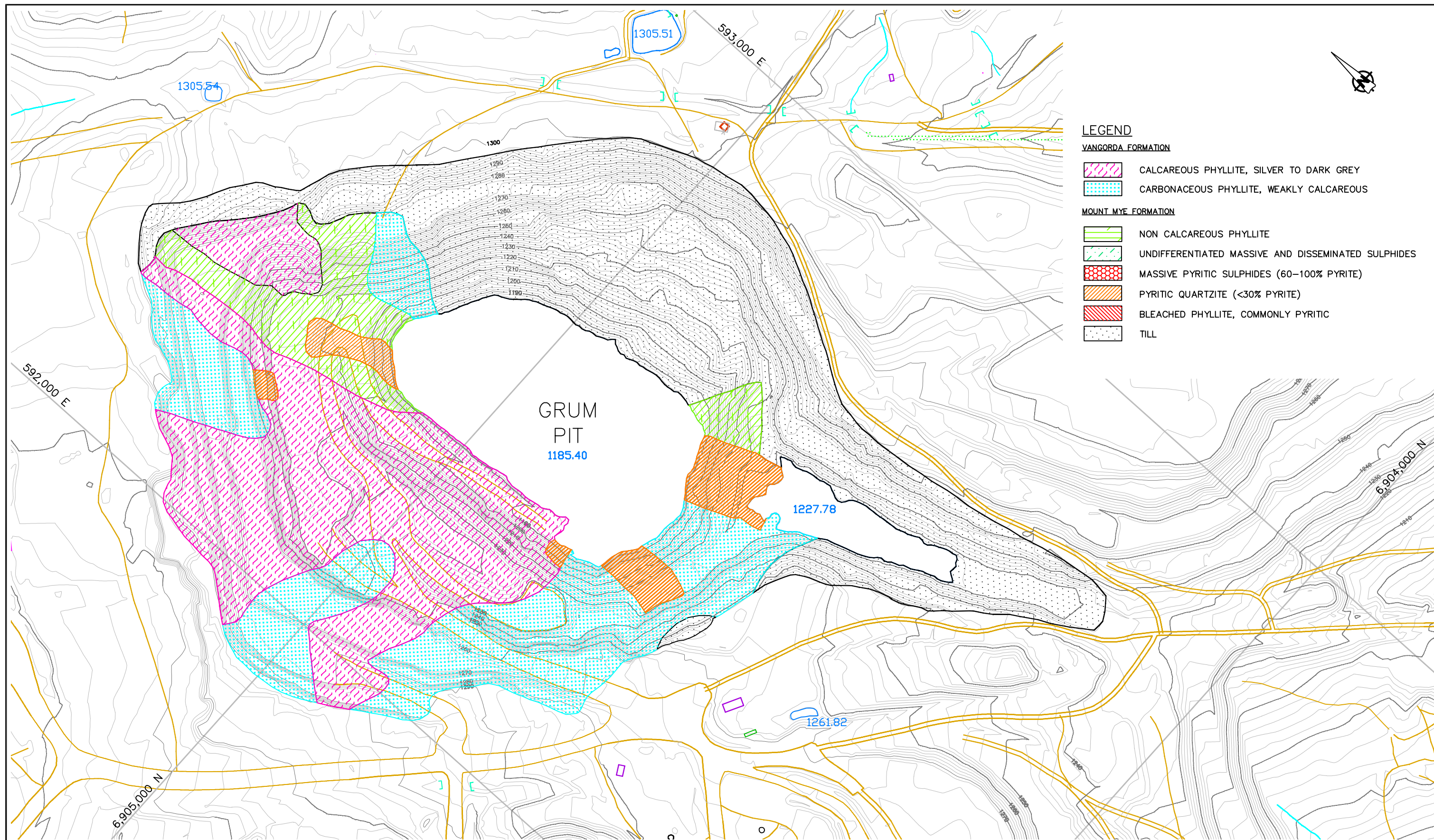


File Ref: 2003 FARO SITE PLAN-PIT-00000001.dwg



 <b>SRK Consulting</b> Engineers and Scientists		PIT LAKES ASSESSMENT	
		<b>PIT GEOLOGY FARO PIT</b>	
PROJECT NO. 1CD003.38	DATE Jan. 2004	APPROVED	FIG. C1





### LEGEND

#### VANGORDA FORMATION

- CALCAREOUS PHYLLITE, SILVER TO DARK GREY
- CARBONACEOUS PHYLLITE, WEAKLY CALCAREOUS

#### MOUNT MYE FORMATION

- NON CALCAREOUS PHYLLITE
- UNDIFFERENTIATED MASSIVE AND DISSEMINATED SULPHIDES
- MASSIVE PYRITIC SULPHIDES (60-100% PYRITE)
- PYRITIC QUARTZITE (<30% PYRITE)
- BLEACHED PHYLLITE, COMMONLY PYRITIC
- TILL

Map Scale: 1:5000  
Contour Interval: 2m  
Date of Photography: 03/07/25  
Scale of Photography: 1:20000  
Survey control derived from existing 1:20000 photography  
Survey control based on: UTM Projection, NAD27  
Compiled by The ORTHOSHOP, Calgary, September 2003  
WO 8856

0 25 50 75 100 125 150 175 200 225 250m  
Scale 1:5000



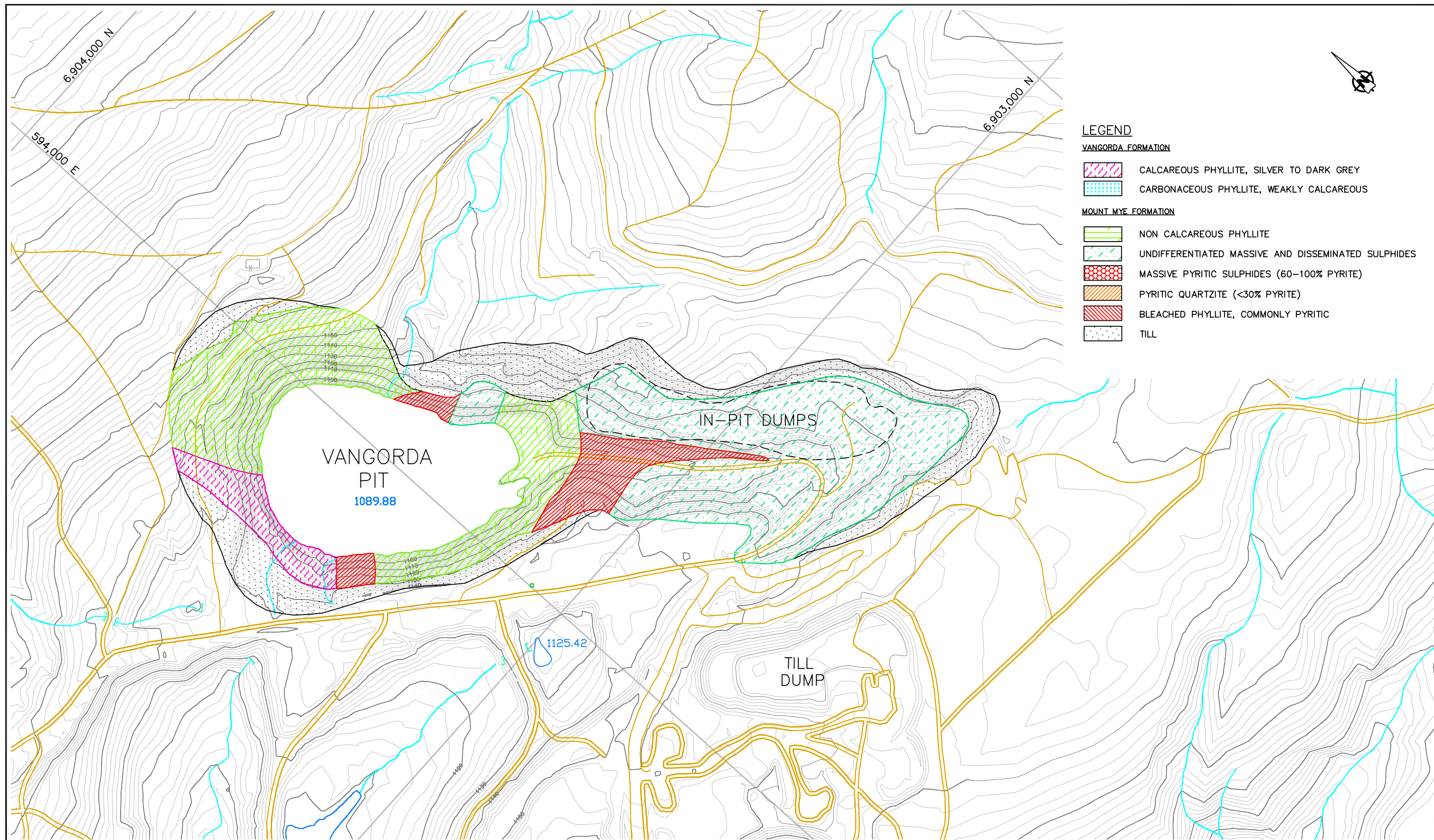
**Deloitte  
& Touche**

PIT LAKES ASSESSMENT

PIT GEOLOGY  
GRUM PIT

PROJECT NO. 1CD003.38	DATE Jan. 2004	APPROVED	FIG. C2
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**LEGEND**

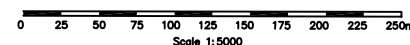
**VANGORDA FORMATION**

- CALCAREOUS PHYLLITE, SILVER TO DARK GREY
- CARBONACEOUS PHYLLITE, WEAKLY CALCAREOUS

**MOUNT MYE FORMATION**

- NON CALCAREOUS PHYLLITE
- UNDIFFERENTIATED MASSIVE AND DISSEMINATED SULPHIDES
- MASSIVE PYRITIC SULPHIDES (60–100% PYRITE)
- PYRITIC QUARTZITE (<30% PYRITE)
- BLEACHED PHYLLITE, COMMONLY PYRITIC
- TILL

Map Scale: 1:5000  
Contour Interval: 2m  
Date of Photography: 03/07/25  
Scale of Photography: 1:20000  
Survey control derived from existing 1:20000 photography  
Survey control based on: UTM Projection, NAD27  
Compiled by The ORTHOSHOP, Calgary, September 2003  
WO 8856



**Deloitte  
& Touche**

PIT LAKES ASSESSMENT

PIT GEOLOGY  
VANGORDA PIT

PROJECT NO. 1CD003.33	DATE Jan. 2004	APPROVED	FIG. C3
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## **APPENDIX D**

### Vangorda Pit Lake Water Quality



Vangorda Pit Water Quality 2003  
SRK Consulting  
T4224  
09/22/2003  
INTERIM

**RESULTS OF ANALYSIS**

Sampl Depth	1	3	5	10	20	30	40
<b>Sample ID</b>	VGPW- 1m	VGPW- 3m	VGPW- 5m	VGPW- 10m	VGPW- 20m	VGPW- 30m	VGPW- 40m
<b>Date Sampled</b>	09/15/2003	09/15/2003	09/15/2003	09/15/2003	09/15/2003	09/15/2003	09/15/2003
<b>Time Sampled</b>							
<b>ALS Sample ID</b>	1	2	3	4	5	6	7
<b>Nature</b>	Water	Water	Water	Water	Water	Water	Water

**Physical Tests**

Conductivity (uS/cm)	1710	1760	1930	1980	1980	1940	1990
pH	7.03	7.35	7.31	7.3	7.28	6.54	7.03

**Dissolved Anions**

Acidity (to pH 8.3) CaCO3	151	162	194	210	212	217	221
Alkalinity-Total CaCO3	57	50	48	49	49	48	49
Chloride Cl	0.7	1	0.9	1	0.9	1	0.6
Sulphate SO4	1080	1100	1250	1280	1280	1250	1280

**Dissolved Metals**

Aluminum D-Al	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Antimony D-Sb	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Arsenic D-As	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Barium D-Ba	0.01	0.01	0.01	0.01	<0.01	0.01	0.01
Beryllium D-Be	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Bismuth D-Bi	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Boron D-B	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Cadmium D-Cd	0.08	0.08	0.08	0.08	0.07	0.08	0.08
Calcium D-Ca	213	208	226	248	237	267	243
Chromium D-Cr	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cobalt D-Co	0.53	0.53	0.59	0.65	0.63	0.72	0.64
Copper D-Cu	0.1	<0.01	0.01	<0.01	<0.01	<0.01	0.01
Iron D-Fe	0.15	1.74	11.3	17.6	21.7	27.9	16.5
Lead D-Pb	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Lithium D-Li	0.04	0.04	0.04	0.05	0.05	0.05	0.05
Magnesium D-Mg	85.1	84.4	92.6	103	98.2	112	100
Manganese D-Mn	30.4	30.3	34.3	38.5	37.2	43	37.6
Molybdenum D-Mo	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Nickel D-Ni	0.5	0.51	0.57	0.62	0.59	0.66	0.62
Phosphorus D-P	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Potassium D-K	4	3	3	3	3	3	3
Selenium D-Se	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Silicon D-Si	2.97	2.91	3.04	3.37	3.19	3.58	3.23
Silver D-Ag	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sodium D-Na	5	6	6	6	5	6	6
Strontium D-Sr	1.22	1.19	1.24	1.35	1.26	1.43	1.33
Thallium D-Tl	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.2
Tin D-Sn	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Titanium D-Ti	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Vanadium D-V	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Zinc D-Zn	91.5	91.4	102	114	111	124	111

**Footnotes:**

Results are expressed as milligrams per litre except where noted.  
< = Less than the detection limit indicated.

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