Characterization of an Existing Pit Lake as an *in situ* Model for Closure Planning for the Detour Gold Mine

Patrick Mueller[1], Alan Martin[1], Jim Robertson[2], David Flather[1], Colin Fraser[1], Mark Bednarz[3]

[1] Lorax Environmental Services Ltd., Vancouver, British Columbia, Canada, Alan.Martin@lorax.ca, David.Flather@lorax.ca, Colin.Fraser@lorax.ca, Patrick.Mueller@lorax.ca
[2] Detour Gold Corporation, Toronto, Ontario, Canada, JRobertson@detourgold.com
[3] BZ Environmental Consulting, Timmins, Ontario, Canada, markb@bzenvironmental.com

Abstract
The Detour Gold Mine is being redeveloped from the original mine which Placer Dome operated from 1983 to 1999. At closure of the original mine, the existing open pit was allowed to flood resulting in the development of an 80 m deep pit lake. As the original sulphide tailings had an ARD/ML risk, tailings were desulphurized with the resultant sulphide concentrate placed at the bottom of the flooded pit lake. Water quality monitoring indicates the pit lake has developed into meromictic system that is effective at controlling ARD/ML from the sulphide minerals contained within and on the walls of the flooded pit. Complex geochemical models are typically applied to justify mine closure plans. The Detour site has the unique feature of having an existing pit lake that serves as an *in situ* model to support future closure predictions. This paper describes the results of a twelve month study designed to characterize the physical and chemical structure of the existing pit lake for use as an analog for the future larger pit lake that will form at closure of the redeveloped mine.

Key Words: stratification, meromictic, anoxic, open pit, flooding

1. Introduction
Detour Gold Corporation has been exploring a previously developed gold property since early 2007. The Detour Lake property is located approximately 140 km northeast of Cochrane in northern Ontario (Figure 1). The Detour Lake deposit was discovered in 1974 and was operated as the Detour Lake Mine (DLM) by Placer Dome from 1983 to 1999 as an open pit and later underground mine. During later operations water was stored in the open pit for use in underground mining (Figure 2). The site was under a closure status from 2000 to 2010. The closure plan of the original mine included completely flooding the pit by passive infilling and this was accomplished by 2005 to establish the existing pit lake which now discharges to Karel Creek (Figure 2).

The tailing materials from the historic operations contained sulphide levels that exceeded the buffering capacity of the neutralizing minerals present in the material and hence were reactive to cause acid rock drainage (ARD). Assessment work determined that removal of the sulphides from the tailing yielded a material that was not acid generating. The mill had a deactivated flotation circuit from earlier operations that was reactivated for the last 18 months of the operation to yield a de-pyritized tailing and a sulphide-rich concentrate. A solid and aqueous cover system for the decommissioned tailing pond was implemented with the de-pyritized tailing spread over the western non-submerged areas of the decommissioned pond (Figure 1). Approximately 150,000 tonnes of sulphide-rich concentrate was produced (60,000 m^3) and deposited underwater on the pit bottom using an underwater discharge pipe located at the west end of the pit. This water cover has prevented the onset of ARD from sulphide-rich concentrate and pit walls and is expected to be a stable long term cover for both materials.

Detour Gold is redeveloping the DLM site, and proposes to construct, operate and eventually close the largest gold mine in Canada. The current project plan provides for a 16 year mine life with the development of an open pit mine and on-site ore processing plant at an approximate throughput of

55,000 tonnes per day (tpd). Construction commenced in late 2010 and will continue through 2012, with commissioning scheduled for late 2012, and full gold production to commence in early 2013.

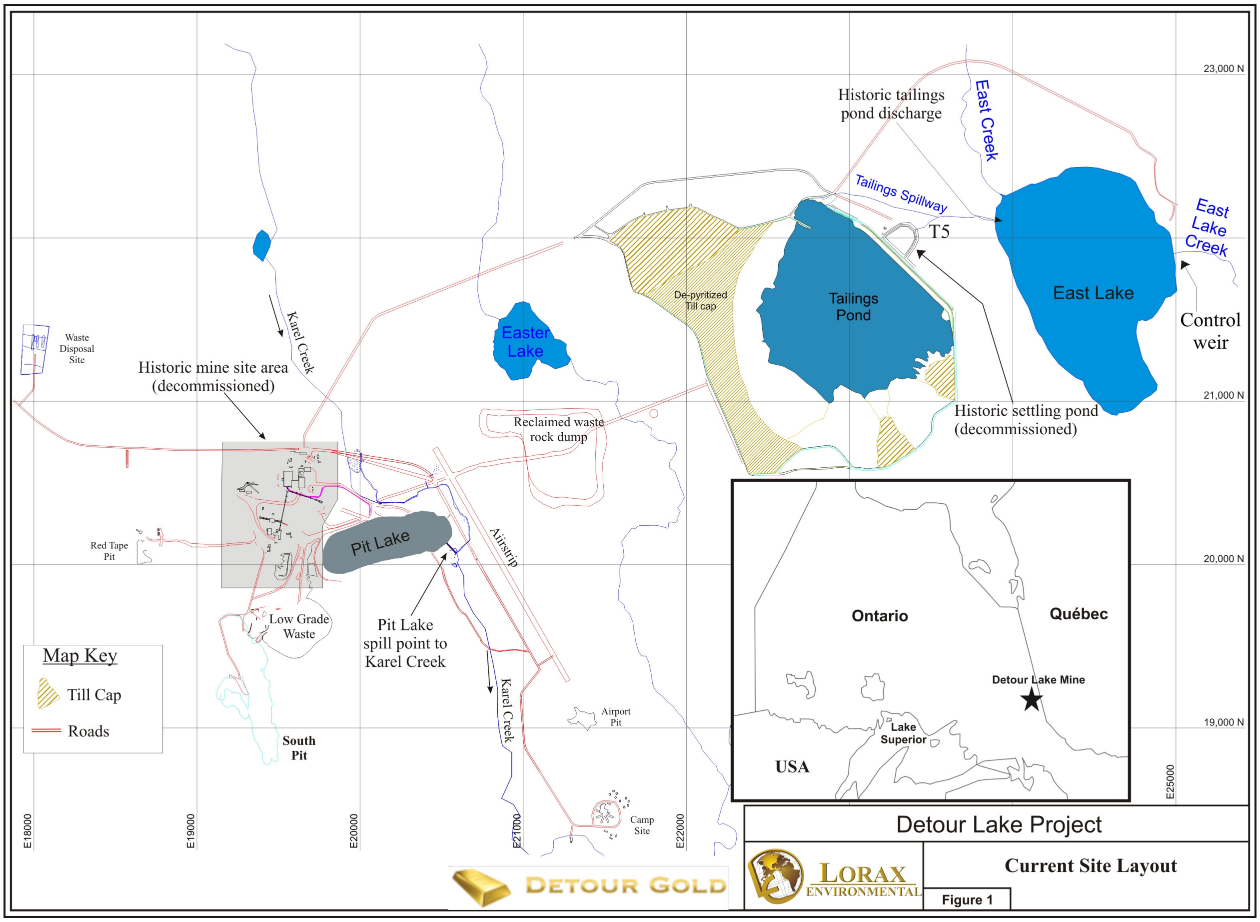

Figure 1: Location map and current site layout of the Detour Gold Mine

Figure 2: Photos looking west over the historic pit; left is the pit prior to closure and right is the partially flooded post-closure pit as observed July 2001.

The new mine reserves are located west of, and inclusive of, the existing pit lake and will yield a pit that is approximately 3000 m long, 1000 m wide and 600 m deep. Consequently, the existing pit lake water will be removed to allow future mining. As the new closure plan also includes a pit lake for the final configuration, it was determined that the chemical and physical limnology of existing pit lake would provide an excellent proxy for conditions of the final pit lake associated with the expanded mine. To this end, Lorax Environmental Services Ltd., with support from BZ Environmental Consulting, were engaged to assess and document the physical and chemical structure of the pit lake through a 12 month sampling program (June 2010 to June 2011). This paper describes the findings of this pit lake case history, and discusses the implications with respect to final closure of the expanded pit.

2. Study Program Overview

Characterization of the Detour Pit Lake included a combination continuous (data loggers) and discrete (monthly) monitoring between June 2010 and June 2011. The 2010-2011 monitoring program was established to monitor the physical and chemical structure of the pit lake water column through a full annual cycle, and to establish the physical and biogeochemical processes governing the behaviour of minor and major constituents. The program included the following elements:

- Monthly water quality profiling in the centre of the pit lake at specific depths (0, 5, 10, 20, 30, 40, 50 and 70 m) using an all-plastic Kemmerer sampler;
- Monthly water quality monitoring at the pit lake spill point to Karel Creek;
- Monthly *in situ* water column profiling (10 cm vertical resolution) of conductivity, temperature, and chlorophyll fluorescence (as proxy for algal biomass).
- Flow monitoring at the pit lake spill point to Karel Creek in July, August, September and October, 2010, and June 2011.
- Continuous temperature logging (every 2 hours) using HOBO Tidbit temperature loggers from June 2010 to June 2011 at specific depths (0.1, 2.5, 7.5, 17.5, 27.5, 37.5, 47.5 and 62.5 m).
- Continuous water level measurements in the pit lake (every 2 hours) using an HOBO water level logger for the period June 2010 to November 2010. Water level data were normalized against changes in barometric pressure, also recorded on site.
- Bathymetry: a one-time bathymetric survey was conducted in June 2010 using a depth sounder coupled to a GPS.

3. General Features of Meromictic Lakes

Meromictic lakes are permanently-stratified basins which typically comprise two dominant layers: 1) a more saline lower layer that is perennially stagnant (monimolimnion); and 2) an upper stratum of relatively fresh water which periodically circulates (epilimnion) (Fisher and Lawrence, 2006). The upper and lower strata are usually separated by an intermediate layer. This layer is characterized by steep physical and chemical gradients which represent the depth interval over which maximum changes in density are observed. This depth interval of maximal density change is referred to as the "pycnocline" (or transition zone). The Detour Pit Lake exhibits all of these characteristics. The physical stability of a stratified lake system can be described in terms of the tendency for the upper and lower strata to mix. The energy required to mix two water masses of differing density increases with increasing density gradient. The perennial stratification (*i.e.*, physical stability) in meromictic lakes results from the density differences between the upper and lower strata, whereby significant density changes across the pycnocline result in the virtual elimination of mixing of surface waters with the monimolimnion.

Vertical mixing in lakes, including pit lakes, can occur via wind action and through thermal turnover. Thermal turnover is common to temperate lakes in the fall and spring, and is a function of the temperature-dependent density properties of water. Freshwater is at its maximum density at ~4° C. Therefore, when surface waters cool to this mark, they sink to deeper depths which results in lake turnover. Wind-driven circulation influences both the horizontal and vertical migration of water in lake systems. The depth of wind mixing is a function of the wind speed, the duration of the wind event, and the distance over which the wind blows over water (fetch). In large temperate lakes, the depth of the mixed layer can vary seasonally and may range from a few metres to several tens of metres. In meromictic systems, only the epilimnion potentially experiences turnover as a result of thermal and/or wind mixing; the lower monimolimnion remains isolated from the surface. The permanency of stratification in meromictic lakes implies that the energy fostered by wind-driven or thermal influences is insufficient to overwhelm the density gradients in the water column.

The density structure of meromictic systems has important influences on the chemical and biological processes that occur in both the water column and sediments. In particular, the restricted exchange of constituents across the transition zone can result in the depletion of atmospheric-derived components (*i.e.,* oxygen) and the accumulation of other constituents associated with the breakdown of organic matter in the bottom layer (Castro and Moore, 2000). In natural aquatic systems, dissolved oxygen is consumed principally via the bacterially-mediated oxidation of organic matter (OM). OM produced in the surface waters (*i.e.,* plankton, zooplankton, *etc*.) is transported to the lake bottom via the settling of organic detritus. Due to the downward transport of OM, the oxidation reactions associated with its degradation occur throughout the water column. In shallow lakes, much of the oxidation of OM occurs at the sediment-water interface, while in deeper lakes, significant remineralization can occur in the lower portion of the water column. Collectively, such oxidation processes can result in the depletion of oxygen in bottom waters. In the absence of deep water mixing and associated replenishment of oxygen, as occurs in meromictic lakes, oxygen consuming reactions can result in the complete depletion of oxygen in the bottom waters (Suits and Wilkin, 1998).

The development of anoxic (*i.e.,* no oxygen) bottom waters can also influence the behaviour of trace elements. Specifically, the development of anoxia can lead to the dissolution of redox-sensitive species such as Fe- and Mn-oxides, resulting in increases in the concentrations of soluble Fe^{2+} and Mn^{2+} (Davision, 1993). Strongly reducing conditions can also result in sulphate reduction and the potential for trace element removal via sulphide mineral precipitation.

In comparison to natural lakes, pit lakes are typically characterized by a large water depth to surface area ratio. This tends to result in pit lakes experiencing relatively less wind-induced mixing than natural lakes which typically have much lower ratios of surface area to water depth. This morphometric feature of pit lakes makes them more amenable to the development of meromixis (Castro and Moore, 2000). Further, the mine-influenced nature of pit lake systems can also increase their tendency to form permanently stratified systems. Specifically, inputs of dissolved salts associated with the weathering of rock surfaces (*e.g*., waste rock, pit walls, *etc*.), waste management (*e.g.,* tailings disposal) or input of treated effluents (*e.g*., neutralization sludges) can have a marked influence of lake density characteristics. Under certain circumstances, such sources of salinity can contribute to the development and maintenance of permanent density gradients.

4. Pit Lake Characterization

4.1 Bathymetry and Hydrology

The layout of the reclaimed DLM site is shown in Figure 1. Karel Creek flows from north to south through the mine property. Water circumvention around the pit is achieved using a historical creek channel realignment that diverts the creek flow around the eastern margin of the open pit. Surface waters exit the pit via a southeastern spill point that feeds a small channel that merges with the Karel Creek diversion south of the pit. Water is assumed to collect in the pit through precipitation, runoff from the small pit catchment, and groundwater inflow. Groundwater flow into the pit was particularly evident on the southeast pit wall of the partially flooded pit prior to 2005, and is suspected to be a significant source of inflow. Flow measurements at the pit outflow have yielded surface water discharges ranging from 16 to 60 L/s.

Due to the pit lake access from Karel Creek local fish have moved from the streams into the pit lake. The lack of shallow areas for food supplies has likely limited the population and biological productivity. In preparation for removing the lake for mine development a fish capture campaign was conducted in the fall of 2011. As part of the project baseline, tissue samples from several captured walleye and pike are undergoing chemical analysis for trace metal concentrations to assess metal uptake rates. These chemical analyses are still in progress. As noted later, the lake water quality met virtually all PWQO levels but, due to depleted oxygen levels at depth, these fish occupied the upper 20 to 30 m of the lake.

The water level of Detour Pit Lake, corrected for changes in atmospheric pressure, was continuously monitored from June 2010 to November 2010 (Figure 3). Over the study period, the water level in the pit lake varied by less than 10 cm. Such small changes in lake level are consistent with the lake elevation control imposed by the spill point to Karel Creek and the relatively-low rates of inflow. The contours of the pit lake sub-surface were mapped with a sounder and are illustrated in Figure 4. Based on the bathymetric survey, the pit lake was calculated to have a volume of approximately 6,250,000 m^3, a maximum depth of roughly 80 m and a surface area of 20.4 ha. As previously noted, approximately 150,000 tonnes of sulphide-rich concentrate (60,000 m^3) was placed onto the pit lake bed by underwater discharge during closure operations and forms the current pit lake bottom.

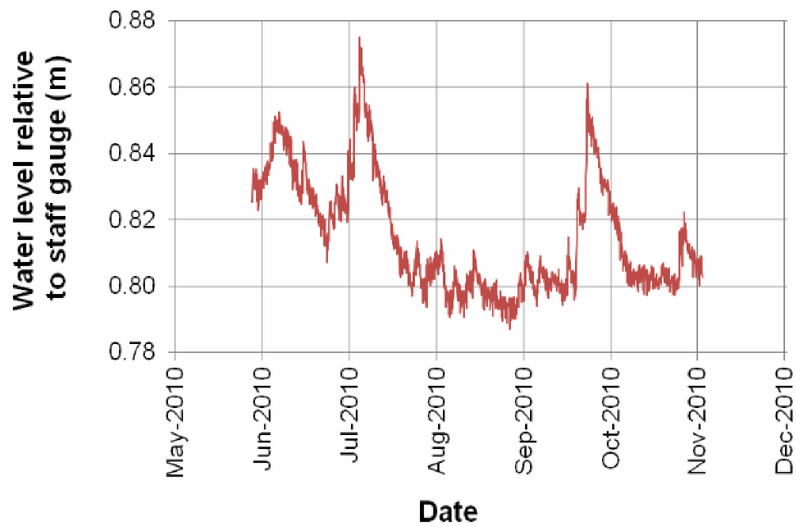

Figure 3: Pit lake water level fluctuations from May 2010 to October 2010.

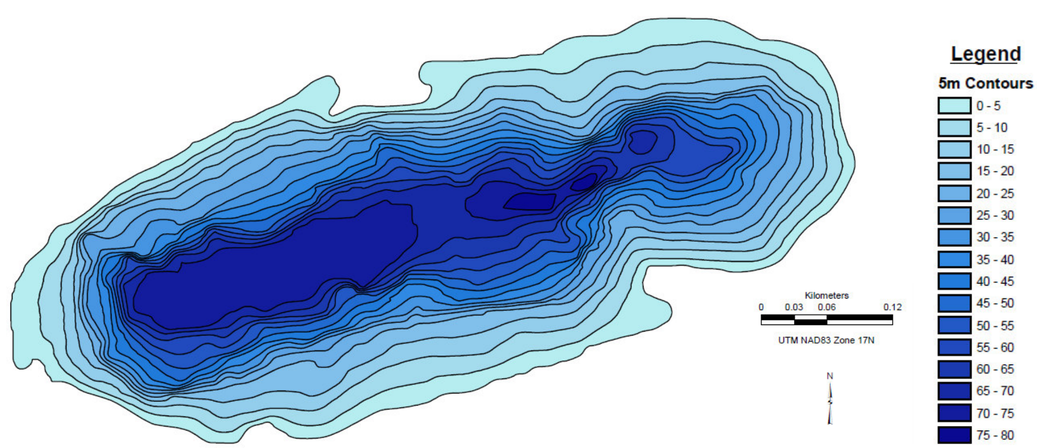

Figure 4: Detour Pit Lake bathymetry (5 m contour interval).

4.2 Physical Structure

Profiles of key parameters (temperature, conductivity and dissolved oxygen) depicting the physical structure of the Detour Pit Lake water column from June 2010 to June 2011 are presented in Figure 5. High-resolution temperature profiles indicate the presence of seasonal thermoclines to depths of 20 to 30 m, with relatively-uniform temperatures below the 30 m depth throughout the seasonal cycle. These data were used to generate temperature isopleths over the monitoring period that illustrate the seasonal changes in water column temperature in the surface layer (20 to 30 m) and the invariant thermal profile below this depth range (Figure 6). Surface temperatures ranged from summer highs of ~25°C to winter lows of 2 to 3°C, reflecting seasonal variations in air temperature. At a depth of 20 m, temperatures ranged from winter lows of approximately 3°C with to a high in November 2010 of 5.2°C, indicative of a fall turnover event in the uppermost 20 m of the water column. Temperatures were stable through the entire monitoring period at the 30 m depth, ranging from 4.4°C to 4.6°C. Below 30 m, water temperatures increase to 5.5°C and remained constant to pit bottom. This relict, higher temperature water signature suggests that vertical mixing of maximum density (*i.e.,* 4°C) water throughout the lake water column only occurs to a depth of 20 to 30 m, and that deeper penetration (mixing) does not occur appreciably below this depth.

The conductivity profiles for the Detour Pit Lake also indicate the absence of vertical mixing throughout the lower water column and illustrate the presence of a transition zone with a significant density gradient between 22 m and 50 m depth(pycnocline). This transition zone encompasses at least two pycnoclines occurring between 22-23 m and 37-43 m, respectively, reflecting historic variability in vertical mixing. Higher-salinity bottom waters are more dense than the overlying surface waters and this density difference is largely responsible for the apparent permanent stratification (meromixis) of the lake. This relatively strong chemical stratification has persisted since 2005 (data not shown) and likely reflects the presence of relict, higher salinity process water associated with the sulphide-rich concentrate that was discharged into the pit prior to cessation of operations.

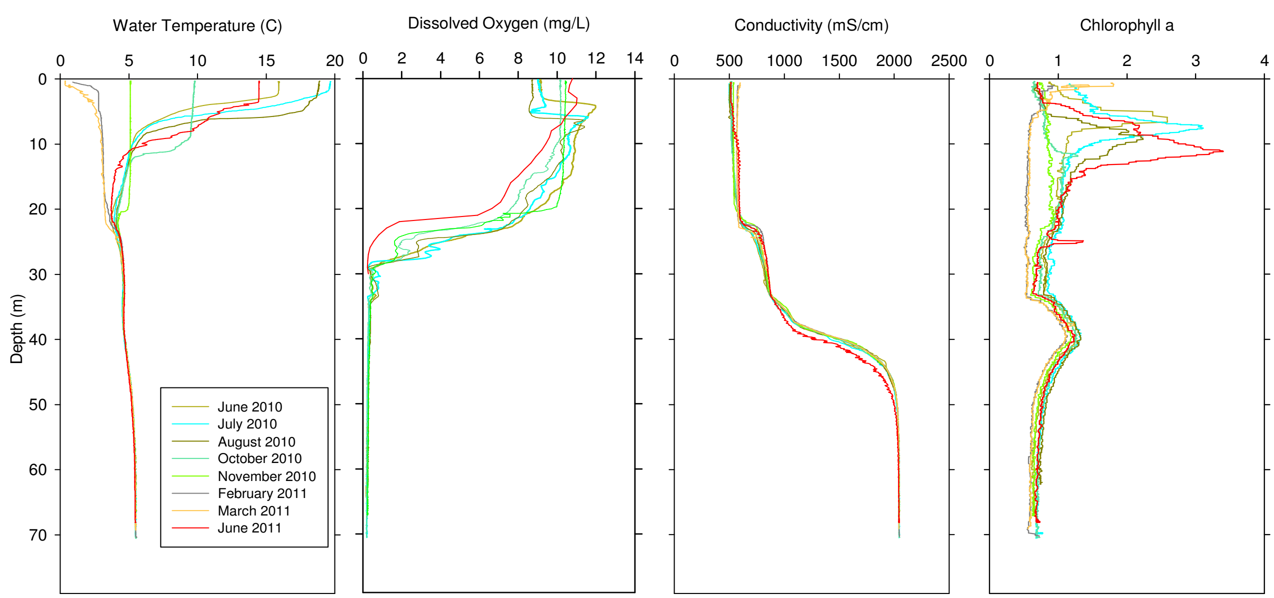

Figure 5: High resolution (10 cm) vertical profiles of temperature, dissolved oxygen, conductivity and chlorophyll a for the Detour Pit Lake (June 2010-June 2011 data).

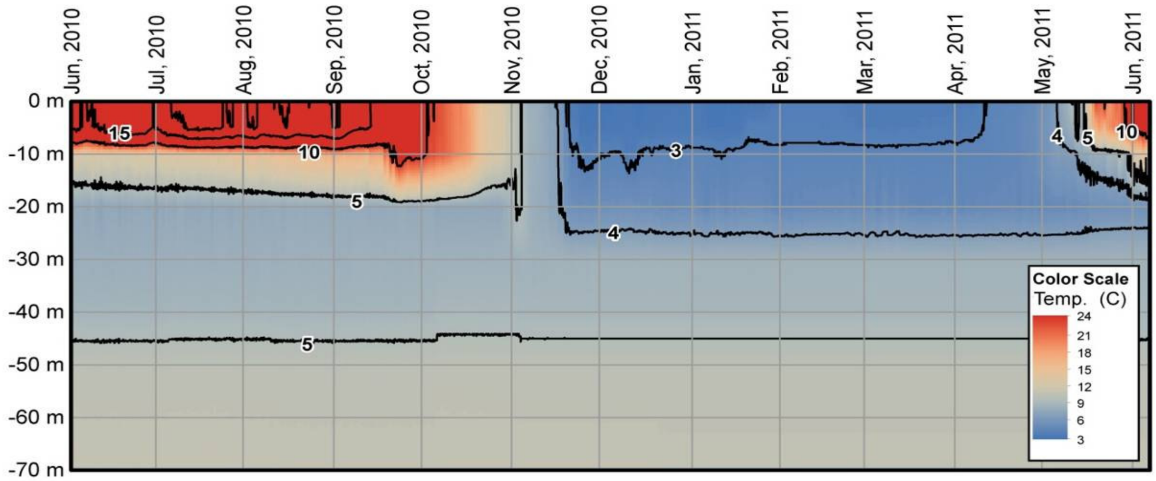

Figure 6: Temperature isopleths of the Detour Pit Lake from June 2010 to June 2011 showing seasonal variations in the 0-20 m depth range and relatively-stable conditions below 30 m.

The meromictic nature of the water column is further illustrated by the profiles of dissolved oxygen (DO) (Figure 5). Dissolved oxygen concentrations are highest in epilimnion where changes in DO are largely controlled by temperature-dependent saturation. In the June, July and August profiles (Figure 5), subsurface maxima in DO were also observed at approximately 6 m depth that coincided with peaks in chlorophyll (proxy for algal biomass), suggesting that the spikes in DO originate from the activities of primary producers. DO concentrations in the pit lake decline to near-zero at approximately 30 m depth (Figure 5), which is consistent with observations dating back to 2005. The presence of permanent bottom water anoxia below a depth of 30 m further supports the notion that mixing of oxygenated water in the pit lake is limited to the upper water column.

The persistence of anoxia over time in the below 30 m in the pit lake water column, in concert with the temperature and conductivity profiles, suggest that the Detour Pit Lake has evolved into a permanently stratified lake, exhibiting the characteristics of a meromictic system. Specifically, the data suggest that lake bottom waters remain chemically and physically isolated from surface waters by a relatively strong density gradient imposed by an increase in salinity with depth. A schematic of the Detour Pit Lake water column structure is provided in Figure 7.

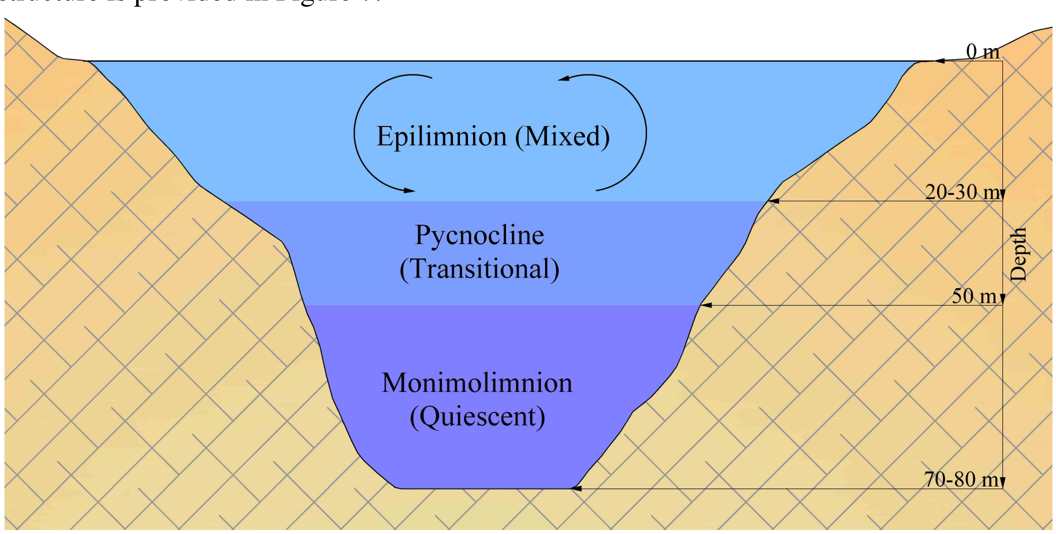

Figure 7: Cross-section of Detour Pit Lake illustrating primary features of water column structure.

4.3 Major Ions and pH

Although a full suite of major ion data was collected for the water quality samples, discussion is limited to those parameters most relevant to the characterization of the pit lake chemical and redox structure. The pH of the entire water column is relatively constant at pH 8 throughout the year (Figure 8). Such observations indicate that the weathering of pit wall exposures above the lake surface is not having a detrimental effect on lake pH through inputs of acidity. Sulphate concentrations in the Detour Pit Lake close mirror conductivity, with comparatively low values in the top 30 m of the water column (~150 mg/L) and concentrations increasing markedly across the transition zone to concentrations approaching 1,000 mg/L (Figure 8). The elevated concentrations of sulphate and calcium (not shown) in bottom waters are primarily responsible for the conductivity gradient observed in the water column and the associated persistent chemical stratification. Overall, the sulphate data reveal a high degree of temporal consistency, and support the notion of a stable water column structure.

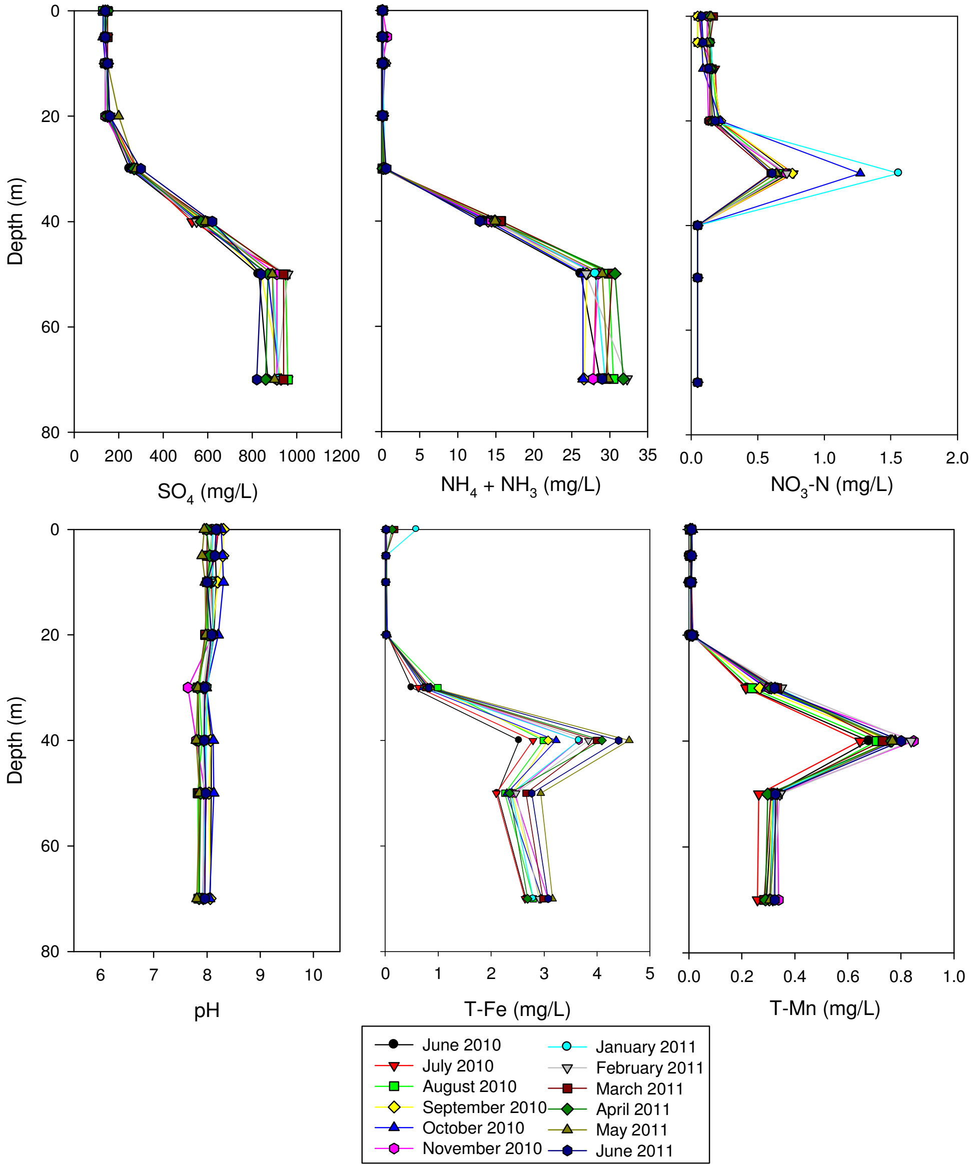

Figure 8: Pit lake vertical profiles of pH, sulphate, ammonia, nitrate, total iron (T-Fe) and total manganese (T-Mn).

The vertical distributions of ammonia and nitrate are also strongly influenced by the physical structure of the water column, and are consistent with dissolved oxygen profiles. Ammonia concentrations in the top 30 m of the water column are low (ranging from <0.1 mg/L to 0.7 mg/L) but increase sharply across the transition zone to concentrations ranging from 25 mg/L to 32 mg/L in the suboxic bottom waters (Figure 8). The presence of elevated ammonia in bottom waters represents a parameter of concern that needs to be duly considered when evaluating viable pit lake dewatering strategies. Ammonia is a redox sensitive species, and in oxic waters, is typically microbially oxidized via the process of nitrification to produce nitrate and acidity. In suboxic settings, however, ammonia can persist in the absence of oxidation mechanisms. Sources of ammonia in the monimolimnion may include the re-mineralized products of organic matter produced in the photic zone, residual blasting compounds, and possibly residual process waters introduced during the period of concentrate deposition. Nitrate shows concentration maxima at the base of the epilimnion at approximately 30 m depth; below this mid-depth peak, nitrate concentrations diminish to non-detectable values (Figure 8). The nitrate peak appears to be sustained through the nitrification of upward diffusing ammonia present in the transition zone. Below the transition zone, and within the anoxic zone of the Detour Pit Lake, nitrate is consumed via denitrification (*i.e.,* nitrate reduction) resulting in non-detectable concentrations below the 30 m depth. In this regard, nitrate is serving as a terminal electron acceptor in the oxidation of organic matter that is delivered to the lake bottom through the settling of organic detritus produced in the photic zone.

Iron and Mn profiles are consistent with the redox structure of the water column with low concentrations observed within the oxic epilimnion and concentrations increasing as dissolved oxygen concentrations are depleted below 30 m (Figure 8). Elevated concentrations in the monimolimnion are predicted to be sustained by the reductive dissolution of Fe and Mn oxides, which are delivered to the lake interior through particle settling (Davison, 1993). Fe and Mn oxides are unstable in suboxic settings, in which such phases undergo reductive dissolution to yield dissolved Fe^{2+} and Mn^{2+}. Since dissolved Fe cannot exist in significant concentrations in the presence of molecular O_2 at circumneutral pH, the abundance of the former (2.7 to 4.6 mg/L) in the monimolimnion provides conclusive evidence of bottom water suboxia (Stumm and Morgan, 1981).

4.4 Trace Elements

Key trace elements for the pit lake water column include Cu and Co, both of which show exceedences of their respective Ontario Provincial Water Quality Objectives (PWQO) of 0.005 and 0.0009 mg/L, respectively (Figure 9). Values for other trace elements (*e.g.,* As, Cd, Pb, Ni and Zn) are low (data not shown), with concentration levels within their respective PWQO limits (Table 1). The generally low levels of trace elements in surface waters are favourable as they indicate limited metal leaching from pit wall exposures above the pit lake surface.

Profiles of total Co show strong parallels to Fe and Mn. Co concentrations are lowest in surface waters (0.0003 to 0.002 mg/L) and increase across the transition zone to concentrations averaging 0.017 mg/L (Figure 9). Similar to Fe and Mn, the distribution of Co shows a peak within the transition zone, suggesting that the behaviour of Co is affected by the reductive dissolution of Fe- and/or Mn-oxide phases. Specifically, Co associated with Fe and Mn oxides would be expected to be released to solution commensurate with the reductive dissolution of the oxide phases (Laxen, 1985).

The profiles for dissolved Co show pronounced decreases in concentration below 40 m. The available data suggest that these decreases in Co concentration in pit bottom waters can be attributed to the precipitation of secondary Co-sulphides. Direct evidence of sulphate reduction in the monimolimnion was revealed by the presence of dissolved H_2S, with values ranging from 22 µg/L (20 m depth) to 100 µg/L (50 m depth). Many trace elements, including Co, form highly insoluble sulphide precipitates with HS^- (Huerta-Diaz *et al.,* 1998). It is unclear if Co in this system forms discrete Co-sulphide phases or co-precipitates with secondary pyrite. Sulphide precipitation mechanisms can be viewed as a natural form of bioremediation akin to other forms of biological treatment that involve sulphate reducing bacteria. In this system, the rates of sulphate reduction do not have a noticeable effect on the sulphate content in the lake bottom waters. The secondary sulphide controls invoked for Co likely also apply to Fe, which shows a decrease in concentration in the monimolimnion. Like Co, Fe readily forms secondary sulphide minerals in the presence of dissolved sulphide as Fe-monosulphides and/or pyrite.

Table 1: Provincial Water Quality Objectives (PWQO) for Trace Metals (Ontario, 1994).

Parameter	Guidelines (mg/L)		Parameter	Guidelines (mg/L)	
	PWQO	iPWQO		PWQO	iPWQO
Al		0.075^{pH}	**Fe**	0.3	
Sb		0.02	**Pb**	0.025^{Alk}	0.005^{H}
As	0.1	0.005	**Ni**	0.025	
Be	0.11 to 1.1^{H}		**P**		0.02
B		0.2	**Se**	0.1	
Cd	0.0002	0.0001^{H}	**Tl**		0.0003
Cr	0.001		**U**		0.005
Co	0.0009		**V**		0.006
Cu	0.005	0.005^{H}	**Zn**	0.03	0.02

^{H} PWQO is dependent on hardness (mg/L as CaCO3)
^{pH} PWQO is pH dependent
^{Alk} PWQO is dependent on alkalinity (mg/L as CaCO3)

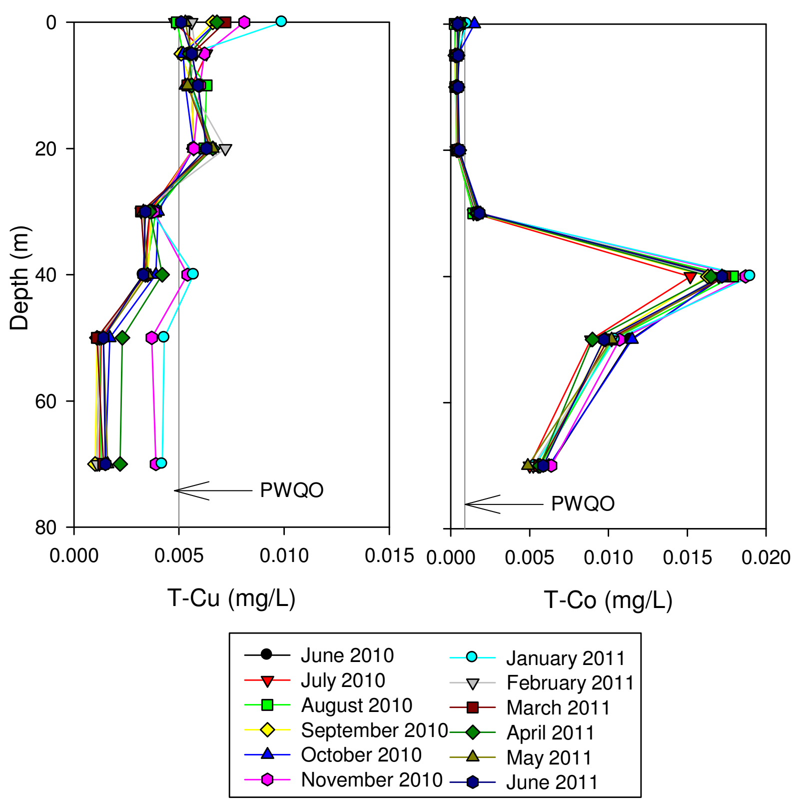

Figure 9: Detour Pit Lake profiles of total copper (T-Cu) and total cobalt (T-Co).

In contrast to Co, Cu exhibits the highest concentrations (0.0036 mg/L to 0.0099 mg/L) within the epilimnion (*e.g.*, top 30 m of the lake) with values decreasing to between 0.0010 mg/L to 0.006 mg/L in bottom waters (Figure 9). The absence of a Cu peak at the zone of Fe reduction suggests that Cu is not appreciably associated with Fe oxides, likely relating to its lower sorption affinity to Fe oxides in comparison to other trace elements such as Ni, Cd and Zn (Benjamin and Leckie, 1981). Based on the Cu profiles, and the presence of detectable dissolved sulphide in bottom waters, the depletion of Cu in the monimolimnion most likely relates to the formation of secondary Cu sulphides. Such mechanisms have been shown to occur in the anoxic sediments of near-by East Lake (Martin *et al.,* 2003).

4.5 Productivity and Trophic Status

In order to assess the trophic status of the pit lake, high resolution profiles of chlorophyll were collected in the water column using a fluorometer, which measures the fluorescence of photosynthetic pigments in the water column (chlorophyll *a*). In this manner, fluorescence provides a proxy for algal biomass. Profiles show two primary zones of photosynthetic activity, one in the top 15 m of the pit lake during ice-free months (May - October), and a secondary stratum of photosynthetic activity within the zone of anoxic bottom waters at depths ranging from 30 m to 50 m (Figure 5). This secondary layer of photosynthetic activity persists year round, and likely reflects the presence of an autotrophic bacterial assemblage that is preferentially occupying a specific redox regime. Overall, both zones of algal productivity are characterized by relatively-low levels of chlorophyll (<4 µg/L), reflecting oligotrophic conditions (Table 2). Oligotrophy is a common feature to pit lakes characterized by relatively small catchments and deep water depths, which act in concert to limit nutrient replenishment to surface waters.

Table 2: Classification of lakes into trophic state based on summer surface averages (thresholds from Yeasted and Morel, 1978).

Parameter	Oligotrophic	Mesotrophic	Eutrophic
TP (µg/L)	<10	10-20	>20
TN (µg/L)	<350	350-650	>650
Chl *a* (µg/L)	<4	4-10	>10

5. Conclusions and Implications for Closure Planning

Overall, the circum-neutral pH conditions of the water column and generally low levels of trace elements in surface waters reflect only minor loadings of metals and acidity from pit wall exposures above the pit lake surface. Assuming the future pit will exhibit similar geologic exposures and additions of process waters during closure, the final pit lake can be expected to develop into a meromictic system with similarly favourable water quality characteristics, with Cu and Co likely being the parameters of environmental interest in surface waters. Although site-specific pit lake modelling will be conducted to support the larger pit development, the current data provide a degree of confidence for the pit lake to serve as a viable closure component for the site.

In terms of lake physical structure, the existing Detour Pit Lake is a permanently stratified system that exhibits a well-mixed epilimnion extending to approximately 20 to 30 m. Below 30 m depth, a relatively steep density gradient exists, resulting in denser bottom waters being isolated from the surface mixed layer by this transition zone. The salinity gradient is induced largely by higher concentrations of calcium and sulphate in bottom waters as compared to surface waters. The physical isolation of bottom waters has resulted in the development of anoxia below depths of 30 m. The meromictic nature of the pit lake also results in a strong depth dependence on the concentrations of redox-sensitive species, including ammonia, nitrate, Fe and Mn. There is also evidence for sulphate reduction in the anoxic monimolimnion, and the removal of trace elements (Co and Cu) as secondary sulphide phases.

The source of increased salinity in the pit lake bottom waters is predicted to largely originate from the discharge of process-waters associated with the placement of sulphide-rich concentrate in the pit bottom during closure of the previous operations. Accordingly, the strong stratification currently observed in the

Detour Pit Lake is not necessarily a natural condition and may exist as a consequence of anthropogenic influences. Such considerations imply that the current meromictic condition within the Detour Pit Lake may not necessarily develop within the future, larger pit lake in the absence of similar anthropogenic inputs (*e.g.,* process water, tailings water or water treatment plant discharge). However, given the large dimensions of the proposed pit expansion, it is possible that permanently stratified conditions will evolve irrespective of mine-related factors.

Stratification of the ultimate pit lake may be a desired feature at closure, particularly if *in situ* bioremediation measures are considered for future water management. In this context, "bioremediation" may be in the form of lake fertilization to enhance algal productivity and metal scavenging. For this form of bioremediation, the advantages of a meromictic system are multifold. First, under conditions of permanent stratification, metals that are exported from the surface layer via particle settling are restricted from being recycled back into the lake surface (*i.e.,* uni-directional transport). Secondly, water column stratification is a prerequisite for the development of sulphate reduction, which can be used to scavenge metals from solution via the formation of insoluble sulphide minerals.

References

Benjamin M.M. and Leckie J.O. (1981). Multiple-site adsorption of Cd, Cu, Zn and Pb on amorphous iron oxyhydroxide. J. Colloid Interface Sci. 79, 209-221.

Castro J.M. and Moore J.N. (2000) Pit lakes: their characteristics and the potential for their remediation. Environmental Geology, Vol. 39, pp. 1254-1260.

Davison W. (1993) Iron and manganese in lakes. Earth Science Reviews, Vol. 34, pp. 119-163.

Fisher T. and Lawrence G. (2006) Treatment of Acid Rock Drainage in a Meromictic Mine Pit Lake. Journal of Environmental Engineering, Vol. 132(4), pp. 515-526.

Huerta-Diaz M.A., Tessier A. and Carignan R. (1998) Geochemistry of trace metals associated with reduced sulphur in freshwater sediments. Applied Geochemistry, Vol. 13, pp. 213-233.

Laxen D.P.H. (1985) Trace metal adsorption / coprecipitation on hydrous ferric oxide under realistic conditions. Water Research, Vol. 19, pp. 1229-1236.

Martin A. J., Jambor J. L., Pedersen T. F., and Crusius, J. (2003) Post-depositional mobility of Cu in a metal-mining polish pond (East Lake, Canada). Environmental Science and Technology, Vol. 37, pp. 4925-4933.

Suits N.S. and Wilkin R.T. (1998) Pyrite formation in the water column and sediments of a meromictic lake. Geology, Vol. 26, pp. 1099-1102.

Stumm W., Morgan J.J. (1981) *Aquatic Chemistry*. 2nd Edition ed. Wiley-Interscience, New York.

Yeasted J.G. and Morel F.M.M. (1978) Empirical insights into lake response to nutrient loadings, with application to models of phosphorus in lakes. Environmental Science and Technology, Vol. 12, pp. 195-201.