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Disposal of Acid Drainage Generating Mine Tailings in Lakes and Man-Made Reservoirs

By:

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I. DATA COLLECTION FOR MODELLING PURPOSES

and

II. EVALUATION OF MEROMICTIC STATUS OF A MAN-MADE PIT

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MANAGEMENT PERSPECTIVE

Disposal of acid drainage generating mine tailings and waste rock has been intensively investigated in the past ten years. Recent research of economical and environmentally safe disposal of the tailings and waste rock indicated subaqueous disposal of these materials as a possible solution. However, the research also identified negative effects of the tailings disposed on the bottom of temperature-stratified lakes on biota and water quality.

One of the major tasks in the subaqueous disposal of acid generating tailings and waste rock is to prevent oxidation of sulfides in disposed material with the subsequent migration of metals and trace elements into lake water. Consequently, subaqueous disposal of acid generating tailings and waste rock into chemically stratified lakes with an anoxic layer of bottom water appears to be a suitable technique.

A study was initiated at the National Water Research Institute, to evaluate the economical and environmental feasibility of the disposal of acid generating mine tailings and waste rock into natural meromictic lakes and man-made reservoirs. The objectives of the study were i) to carry out a comprehensive baseline study to investigate the physico-chemical characteristics of an abandoned mine pit and confirm its meromictic nature; and ii) to collect sufficient data for future development of a model for the estimation of the capacity of a well characterized meromictic water body to contain acid drainage generating mine tailings, and to predict the changes that would occur in water chemistry and the tailings after their disposal.

At three sites in Crown Pillar pit at Ignace, Ontario, continuous surface-to-bottom depth profiles of pH, specific conductivity, dissolved oxygen, and temperature were recorded in the spring and fall, from 1993 through to 1995. The results of the study clearly indicated that the pit has the characteristics of a meromictic water body. Consequently, the pit would provide ideal conditions for the subaqueous disposal of acid drainage generating mine tailings and waste rock. Further, data collected during the study are sufficient for the modelling of changes of water quality in the pit and oxydation of the tailings after their disposal into the pit.

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INTRODUCTION

Many base and precious metal ores and surrounding rock contain sulfide minerals. Tailings and waste rock generated by mining and extraction of the metals from these ores contain different quantities of sulfides. During exposure to air and water, the water insoluble sulfides in the tailings and waste rock become converted to water soluble sulfates. These sulfates acidify surface and groundwater which subsequently become contaminated by different metals and trace elements leached from the tailings and waste rock.

Uncollected and untreated acid drainage can further contaminate surface and groundwater and negatively affect the receiving ecosystem at the mining area.

For several past years, the Canadian mining industry, in cooperation with federal and provincial government agencies, has sponsored research of economical and environmentally safe disposal of acid generating mine tailings and waste rock. Results of the research indicate that the subaqueous disposal of acid generating mine tailings is a possible solution. However, some problems, such as the effects of tailings disposed on the bottom of the lake on benthic organisms and other biota and food chain in the lake, resuspension and transport of tailing particles, etc., remain to be solved before the technique for the subaqueous disposal of the tailings and waste rock into lakes and man-made reservoirs can be accepted as the final solution for the prevention of acid mine drainage.

One of the major tasks in the subaqueous disposal of acid generating tailings and waste rock is to prevent oxidation of sulfides in disposed material with the subsequent migration of metals and trace elements into lake water. Consequently, suitable conditions for subaqueous disposal of tailings would be in a lake (or a man-made reservoir) with a sufficiently deep layer of permanently anoxic bottom water (MEROMIXIS) containing high concentrations of sulfides and a sulfate-reducing microbial population to maintain an equilibrium between the sulfides in disposed tailings on the lake bottom and those in the overlying water. Such conditions exist in natural meromictic lakes.

Generally, meromictic lakes differ from others in a) being permanently stratified, and b) having a high concentration of dissolved salts. Three distinctive segments in a meromictic lake are (1) the surface water (also referred to as epilimnion), often resembling the water quality of a eutrophic lake; (2) the chemocline, a segment of water separating the epilimnion from the bottom water; and (3) the monimolimnion, a segment of anoxic water above the lake bottom containing relatively high concentrations of disolved salts. Although temperature changes and mixing of the epilimnion can occur, the monimolimnion is stabilized by its density derived from dissolved salts, and full circulation happens rarely in a meromictic lake.

Meromictic lakes can support dense populations of anaerobic, photosynthetic sulfur bacteria. Permanently stagnant bottom waters of the monimolimnion are often rich in nitrogen, phosphorus and sulfide necessary for bacterial growth. The light requirement results in the positioning of the photosynthetic bacteria at the top of the monimolimnion (Fry, 1986).

Numerous lakes in Canada, particularly at high latitudes, are stratified with respect to temperature and salt content (Jeffries et al., 1984). Radiocarbon dating of one of these lakes on Ellesmere Island in the Canadian Arctic determined the age of its deepest water to be over 4,000 years (Lyons and Mielke, 1973). The surface fresh water overlies the deeper, trapped seawater in the lake (Krouse, 1970). In further studies of the lake, a marked depletion of sulfates coupled with isotopic data on sulfur species indicated that anaerobic activity has been extensive during the lake's history.

Meromictic lakes exist in the temperate zone of the North American continent. Studies of a meromictic lake near Syracuse, New York, revealed high concentrations of nitrogen, phosphorus, sulfate and sulfide in anoxic bottom waters (Deevey _et al._, 1963; Turano and Rand, 1967; Torgersen _et al._, 1981). In the 45-m deep lake, the monimolimnion extended from about 20 m water depth to the bottom. Below 17 m, oxygen was absent and sulfide present in the water. The studies indicated that a large standing stock of bacterioplankton and zooplankton at the top of the monimolimnion and base of the epilimnion existed as relatively isolated units in the lake food chain, and that the food webs in the epilimnion closely resembled those in non-meromictic lakes (Fry, 1986).

Results of the above studies indicate that meromictic lakes provide suitable conditions for the subaqueous disposal of acid generating mine tailings and waste rock. Surface waters unaffected by materials disposed on the bottom of a meromictic lake can be managed to continue to support plankton and fish population similar to a non-meromictic (monomictic and dimictic) lake. The knowledge of the biogeochemical processes in a natural meromictic lake before and after the disposal of mine tailings will allow the modelling and design of man-made reservoirs managed as meromictic lakes which can be used for the disposal of the mine tailings.

Many pits have been generated by surface mining. For example, Lyons _et al_. (1994) anticipated between twenty and fourty completed open pit mines in Nevada within the next twenty years. After filling with water, these "pit lakes" will contain over one billion m^3 of water and their unusual shape will have a profound effect on their physical limnology and hence their biogeochemical dynamics. Once filled with water, deep pits with relatively small surface area may become meromictic and therefore suitable for the disposal of acid drainage generating mine tailings and waste rock.

Acid generation from tailings and waste rock disposed on land is mainly the result of the oxidation of sulphide minerals. The oxidation of pyrite (FeS_2) or other sulphide minerals can be generalized by the following equation:

$$(Fe,Pb)S_2 + H_2O + 3.5\ O_2 \dashrightarrow (Fe,Pb)SO_4 + H_2SO_4$$

In order to minimize oxidation of sulphide minerals, underwater disposal of mining wastes has been considered an option for permanent storage of these wastes. Although some uncertainty still exists on whether reactivity of the sulphides in the tailings and waste rock is completely inhibited by underwater storage, such storage is the most preferred long-term disposal option. Complete inhibition can only be expected in underwater environments which are anoxic (i.e., void of oxygen) throughout the year.

A study was carried out to estimate the quantity of acid drainage generating mine tailings which can be safely disposed on the bottom of a meromictic pit, and to assess the rate at which the tailings will become oxidized after their disposal. The objectives of the study were: I) to carry out a comprehensive baseline study to investigate the physico-chemical characteristics of an abandoned surface mine pit, filled with water and confirm its meromictic nature. One site was chosen for future tests for inhibition of chemical reactivity of submerged mine tailings in *anoxic* environments. The test will include the evaluation of the processes affecting the potential of long-term underwater disposal of the tailings. Total inhibition of chemical reactivity of the tailings is necessary to minimize oxydation processes, resulting in acid generation; and II) to collect data for the development of a model for the estimation of the capacity of a well characterized meromictic water body to contain acid drainage generating mine tailings, and to predict the changes that would occur in water chemistry and the tailings after their disposal. This report summarizes and interprets the data collected in the first part of the study of a meromictic pit, and lake, and streams in a base metal mine site in northern Ontario during 1993, 1994 and 1995.

TABLE OF NOTATIONS

B-1	1m above the bottom sediments
BR	Bell River
CHLA.C	chlorophyll (corrected)
CHLA.U	chlorophyll (uncorrected)
COND	specific conductance
CPP	Crown Pillar pit
DIC	dissolved inorganic carbon
DO	dissolved oxygen
DOC	dissolved organic carbon
ICP	inductive coupled plasma
ISM	inorganic suspended matter
LC	Lyon Creek
LL	Lyon Lake
LOI	loss on ignition
NH_4^+	ammonia
OSM	organic suspended matter
PPB	µg/L in dissolved phase and µg/kg in solid phase
PPM	mg/L in dissolved phase and µg/g in solid phase
PW	pit water
Si	silicon
SiO_2	silica
SO_4	sulphate
SOP	soluble organic phosphorous
SRP	soluble reactive phosphorous
TDC	total dissolved carbon
Temp	temperature (°C)
TFP	total filtered phosphorous
TP	total phosphorous
TPP	total particulate phosphorous
TSM	total suspended matter
TW	trap water
TWC	trap water concentrate

PARAMETERS AND DETECTION LIMITS

Parameter	Detection limits in : Water	Detection limits in : Sediment and Tailings
As	0.1 $\mu g \cdot L^{-1}$	5$\mu g \cdot g^{-1}$
Zn	1 $\mu g \cdot L^{-1}$	1 $\mu g \cdot g^{-1}$
Cu	1 $\mu g \cdot L^{-1}$	1 $\mu g \cdot g^{-1}$
Ni	2 $\mu g \cdot L^{-1}$	1 $\mu g \cdot g^{-1}$
Fe	1 $\mu g \cdot L^{-1}$	0.01 %
Cd	1 $\mu g \cdot L^{-1}$	0.2 $\mu g \cdot g^{-1}$
Co	1 $\mu g \cdot L^{-1}$	1 $\mu g \cdot g^{-1}$
Mn	0.5 $\mu g \cdot L^{-1}$	1 $\mu g \cdot g^{-1}$
Pb	5 $\mu g \cdot L^{-1}$	2 $\mu g \cdot g^{-1}$
Cr	1 $\mu g \cdot L^{-1}$	1 $\mu g \cdot g^{-1}$
Al	10 $\mu g \cdot L^{-1}$	
Ba	1 $\mu g \cdot L^{-1}$	
Be	1 $\mu g \cdot L^{-1}$	
Ca	100 $\mu g \cdot L^{-1}$	
K	100 $\mu g \cdot L^{-1}$	
Mg	100 $\mu g \cdot L^{-1}$	
Na	100 $\mu g \cdot L^{-1}$	
Si	10 $\mu g \cdot L^{-1}$	
Sr	1 $\mu g \cdot L^{-1}$	
V	1 $\mu g \cdot L^{-1}$	
TSM	10 $\mu g \cdot L^{-1}$	
ISM	10 $\mu g \cdot L^{-1}$	
OSM	10 $\mu g \cdot L^{-1}$	
LOI	0.1 %	0.1%
CHLA	0.1 $\mu g \cdot L^{-1}$	
CHLA.U	0.1 $\mu g \cdot L^{-1}$	
CHLA.C	0.1 $\mu g \cdot L^{-1}$	
POC	10 $\mu g \cdot L^{-1}$	
PN	2 $\mu g \cdot L^{-1}$	
TP	0.2 $\mu g \cdot L^{-1}$	
TPP	0.1 $\mu g \cdot L^{-1}$	
SRP	0.2 $\mu g \cdot L^{-1}$	
SOP	0.2 $\mu g \cdot L^{-1}$	
NH_4^+	5 $\mu g \cdot L^{-1}$	
NO_3 + NO_2	10 $\mu g \cdot L^{-1}$	
DIC	0.1 mg/l	
DOC	0.1 mg/l	
TDC	0.14 mg/l	
TKN	0.014 mg/l	
CL	0.06 mg/l	
SIO_2	0.01 mg/l	
SO_4	0.3 mg/l	

MATERIALS AND METHODS

Description and mining history at the Mattabi Mine site

Physiography, Geology and Hydrology

The Mattabi site straddles the boundary between the District of Kenora and the District of Thunder Bay and is located at approximate 91° west longitude and 49.5° north latitude. The site is located in the Sturgeon Lake area, approximately 80 km northeast of Ignace, Ontario.

Geologically, the mine sites are located within the Canadian Shield. Surficial geology is characterized by glacial sediments and occasional bedrock outcrops. Eskers and deposits of glacial till are also common features. Locally, the till deposits may be quite thick. Sources of till and granular materials have been identified in the vicinity of the site.

The mean annual precipitation at the station closest to the Mattabi site (Sturgeon Lake) is about 750 mm, with approximately 64% as rainfall and 36% as snowfall.

Mine History

The original discovery of the Mattabi Mine orebody was made in 1969 by Mattagami Lake Exploration Limited. Mattabi operations involved mining and milling zinc, copper, silver, and lead ore. Mining at Mattabi Mine was carried out between 1972 and 1988. Until 1980, all ore was supplied from the Mattabi open pit. Mining of the underground orebody started in late 1980, with supplementary mining from the open pit. The Crown Pit opening was originally excavated in order to remove the crown pillar. Overburden at this site is approximately 25 m deep and was slurried into the nearby Sturgeon Lake Pit prior to removal of the crown pillar. Following the extraction of the ore, bulkheads were installed underground and the stope was allowed to fill with water. Some waste rock from the mine development was submerged in the pit. Based on recent soundings, the remaining underwater storage capacity in the pit is estimated at 460,000m^3. In 1988, the mining operations at Mattabi Mine ceased and both the underground workings and the open pit were allowed to fill with water (MRP, 1993).

Description of the Crown Pillar Pit

The Crown Pillar pit at the Mattabi Mine site, (Figure 1) is approximately 300 m long and 180 m wide, with a maximum depth of 25 m, and a surface area of 54,000 m^2. The pit is surrounded by bentonite dykes which prevent infiltration of acidic drainage from tailings stored on adjacent land. The sides of the pit have been lined with clean waste rock from within the mine site. This clean waste rock also forms a 2 m high berm around the perimeter of the pit. The pit has been allowed to naturally fill with water, and appears to have developed meromictic conditions.

Sampling and Analytical Methods

Water

In the Crown Pillar pit, water samples for the determination of nutrient, and trace and major element concentrations were collected 1 m below the surface and 1 m above the bottom sediments, at station #3 in the deepest part (i.e., centre) of the pit (Figure 1) using a van Dorn bottle (Rosa et al., 1991). Water samples from adjacent Lyon Creek and Bell River were collected by dipping and filling a one liter polyethelene bottle.

Water samples from 1m below surface (*epilimnion*), and 1 m above the lake bottom (*hypolimnion*) in the pit were collected to quantify the particulate and soluble nutrient concentrations. To determine total suspended matter (TSM), collected water samples were filtered through precombusted (500°C) and pre-weighed Whatman GF/C glass fibre filters of approximate pore size 1 to ~2 μm). Total suspended matter was gravimetrically measured after the samples were dried at 100°C for 3 hrs. The inorganic suspended matter (ISM) was gravimetrically measured by combustion of the samples on the filters at 500°C for 2.5 hrs. The organic suspended matter (OSM), also called 'loss on ignition' (LOI) was calculated as the difference between the TSM and ISM. The water samples collected for the determination of the concentrations of nutrients and major and trace elements were divided into different subsamples which were stabilized with various preservatives such as HNO_3 (conc.) for subsamples for the determination of trace and major elements; and H_2SO_4 for subsamples for the determination of chemical forms of phosphorus. Samples for the determination of particulate organic carbon (POC), particulate nitrogen (PN), chlorophyll *a* corrected and uncorrected for *phaeophytin* (CHLA-C, CHLA-U), were filtered through Whatman GF/C filters with pore size ranges of 1 to 2 µm. Total filtered and unfiltered phosphorus (TFP and TP, respectively), and dissolved organic and inorganic carbon (DOC and DIC, respectively) were determined by the methods described by Environment Canada (1995a). The concentration of total particulate phosphorus (TPP) was calculated as the difference between that of TP and TFP. The concentration of total dissolved carbon (TDC) was calculated by summing that of DOC and DIC.

The concentrations of dissolved major and trace elements in the water samples (Al, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, Pb, Sr, V, and Zn) were determined according to the methods described by Environment Canada (1995b). Prior to the determination of the elements, the water samples were filtered in the field within a few hours of collection using a Millipore glass filter apparatus with 0.45 µm cellulose acetate filters. Filtered samples were acidified with "Ultrex" grade HNO_3 (conc.) to a final concentration of 0.4% and shipped to the laboratory as quickly as possible. The samples were stored at 4°C prior to analysis. In addition to major and trace elements, the concentrations of SO_4^{2-}, SiO_2 and Cl^- were also determined in all collected samples.

At three sites in the pit, continuous surface-to-bottom depth profiles of pH, specific conductance (COND), dissolved oxygen concentration (DO), and temperature were recorded by a HYDROLAB Profiling System, Model DataSonde$_R$ 3.

Also, at the deepest site in the pit, a sediment trap was deployed (Rosa et al., 1991). The sediment trap collects particulate matter as it settles through the water column. Most of the particulate matter concentrates at the bottom of the trap. A portion of the settled particulate matter in the trap will undergo dissolution depending on the exposure time and its organic and inorganic matter composition. Water from the top of the trap (TW), and water from the bottom of the trap (TWC) were analysed for trace and major elements.

Bottom Sediments and Tailings

Sediment samples were taken at station #3 (Figure 1) using a miniponar grab sampler. This sampler encompasses an area of 234 cm^2 and penetrates to an average depth of 5 cm. Retrieved sediment was placed in a glass tray, homogenized with a plastic spoon and subsampled into plastic vials. The samples in the plastic vials were stored at 4°C in the field and freeze-dried after transport to the laboratory. The concentrations of selected major and trace elements in the freeze-dried samples of whole bulk sediments were determined by ICP spectrometry according to the methods described by Bondar-Clegg (1992).

RESULTS and DISCUSSION

Water chemistry

Surface and Bottom Water : Nutrients

In the Crown Pillar pit (CPP) water, the concentrations of all particulate nutrients were generally low relative to unimpacted northern Ontario lakes (Molot and Dillon, 1991), with the exception of organic carbon and phosphorus. The total suspended matter (TSM) concentrations were 1.6 and 2.4 mg/l, at the surface and 1 m above the bottom, respectively. The TSM particles were mainly inorganic as indicated by the low percent loss on ignition in Table 1. The organic suspended matter (OSM) was 44 and 29% of the total suspended matter at the surface and bottom, respectively. The concentrations of soluble nutrients in the surface waters of the Crown Pillar pit were generally lower than those in the bottom waters. The concentrations of carbon and phosphorus in the pit water were not elevated relative to those in the water collected from the Bell River, which was used as a control (Table 1). The concentrations of all other dissolved nutrients were greater in the bottom waters than those at the surface. This was most likely due to the dissolution and mineralization of organic matter. Total and viable chlorophyll as measured by CHLA.U and CHLA.C, respectively, were less than 0.5 ug/l or below the detection limit (ND). This implies that primary production, at least during the sampling period, was extremely low,

TABLE 1.

Nutrient Concentrations in Bell River and in Crown Pillar Pit Water			
Station (depth)	BR1	#3 (1m)	#3 (B-1m)
1) Particulate (mg/l)			
TSM	NS	1.6	2.4
ISM	NS	0.9	1.7
OSM	NS	0.7	0.7
%LOI	NS	44	29
POC	NS	0.248	0.174
TPN	NS	0.0034	0.024
TPP	0.0031	0.0027	0.003
CHLA. U (ug/l)	NS	0.2	0.1
CHLA. C (ug/l)	NS	0.1	ND
2) Dissolved (mg/l)			
Cl	0.48	8.59	16.21
SIO2	1.51	5.22	7.92
SO4	3.6	216.6	341.8
DIC	3.48	17.2	35
DOC	5.51	5.56	5.23
DIC/DOC	0.632	3.094	6.692
TDC	8.99	22.76	40.23
TFP	0.0039	0.0030	0.0021
SRP	0.002	ND	ND
SOP	0.0019	0.0030	0.0021
NO3+NO2	0.115	1.210	1.340
NH3	0.022	0.133	0.845

TABLE 1 cont.

Station (depth)	BR1	#3 (1m)	#3 (B-1m)
3) Total (mg/l)			
TKN	0.255	0.381	1.25
TP	0.0070	0.0057	0.0051

CPP - Crown Pillar Pit

BR1 - Bell River Upstream

NS - No Sample

ND - Below Detection Limit

B-1 m - 1 m above the bottom

relative to nutrient-limited Northern Ontario lakes (Molot and Dillon 1991). The low primary production could not be attributed to low concentrations of nutrients, with the possible exception of soluble reactive phosphorus (SRP) which was below the detection limit (ND, Table 1). The total phosphorus concentration in the surface waters was 0.0057 mg/l, which is typical of concentrations found in nutrient limited central Ontario lakes. According to Molot and Dillon (1991), the chlorophyll/phosphorus relationship for 15 nutrient-limited central Ontario lakes can be expressed as:

$$Chl_{epi} = 0.329TP_{epi} + 0.606$$

Chl_{epi} & TP_{epi}, are the epilimnetic concentrations of total chlorophyll and phosphorus, respectively; and 0.606, is the constant or the y-intercept.

The relationship was established by linear regression using data collected over a 12-year period. Based on this relationship, the total chlorophyll concentration in the water of CPP should be in the range of 2.0 to 3.0 µg/L. Based on lake classification models, and concentrations of carbon and phosphorus the chlorophyll concentrations of CPP (Table 1) are TEN TIMES lower than predicted by the chlorophyll-phosphorus relationship above. This reduced production is not unusual in lakes which have been affected by mining activities, and is usually attributed to toxic effects as a result of high concentrations of soluble trace elements (Mudroch et al., 1994).

Major and Trace Elements

Lyon Creek and Bell River Water

Figure 1 shows the location of only about one-third of Lyon Creek, mainly the section near CPP. The upstream section (not shown) receives its waters from a small lake, and surface and ground water from both Falconbridge and Mattabi Mine sites. With the exception of copper and zinc, the greatest concentrations of trace elements and major ions in the water at the Mattabi Mine site were found in Lyon Creek, at station LC6 (Figure 2, top left), and appeared to originate upstream of CPP. The concentrations of most major and trace elements in the surface water of CPP were three times lower than those at station LC6. Thus it appears that Lyon Creek can be a future source of contamination of water in CPP through ground water flow. Further contaminated water from Lyon Creek could seriously impact the receiving waters of Lyon Lake downstream, through direct input.

Heavy iron oxide staining is visible all along Lyon Creek shoreline from upstream of LC6 to Lyon Lake. This indicates the dispersion of Fe and SO_4 from the beginning of Lyon Creek to Lyon Lake.

The difference in the concentrations of most major and trace elements between the upstream (station BR1), and downstrean (station BR2) are significant (Table 2). The differences were up to 10 times greater at the downstream site, than those in the upstream site, which was the "control" site (Table 3). These differences indicated the input of contaminants into Bell River from the mining activities at the Mattabi Mine site.

Crown Pillar Pit Water

The results of the analysis of surface and bottom water samples for major and trace elements are shown in Table 2. The concentrations of trace elements in the pit were greater than those found at the control site (i.e., BR1, Table 2, Figure 2, top left) with the exception of copper and aluminum.

TABLE 2.

Major and Trace Elements in Water at the Mattabi Mine Site (mg/l)

Station / Time *	No	Al	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	K
CPP B-1 :5/94	#1	2.08	0.708	0.001	178	0.001	0.001	0.024	0.043	0.154	8.89
CPP B-1 :10/93	#2	1.32	0.916	0.001	189	0.008	0.024	0.029	0.043	0.189	9.05
CPP 1m :11/94	#3	0.235	0.541	0.001	116	0.002	0.001	0.013	0.001	0.077	7.44
CPP B-1 :11/94 D1	#4	0.268	0.458	0.001	128	0.004	0.006	0.016	0.001	0.041	7.36
CPP B-1 :11/94 D2	#5	0.279	0.541	0.001	130	0.007	0.011	0.018	0.001	0.076	7.36
LC6 0.1m :11/94	#6	0.361	0.625	0.003	157	0.012	0.031	0.041	0.009	0.251	3.37
BR2 0.1m :11/94	#7	0.106	0.041	0.005	128	0.009	0.026	0.032	0.053	0.076	0.332
TW :11/94	#8	0.279	0.051	0.006	162	0.019	0.041	0.051	0.033	0.866	0.866
TWC :11/94	#9	0.317	1.04	0.008	190	0.018	0.086	0.077	0.065	34.2	6.91
BR1 :05/93	#10	0.111	0.0063	0.001	6.6	ND	ND	0.005	0.009	0.033	0.4
CPP 1m :11/93	#11	0.16	0.0287	0.001	87.2	0.002	0.001	0.01	0.009	0.052	4
CPP B-1 :11/93	#12	0.097	0.354	0.002	144	0.002	0.002	0.013	0.005	0.06	6
ND- Below Detection Limit		Collected in the spring and fall of 1993 and 1994									
B-1 m - 1 m above the bottom											

TABLE 2 continued.

Major and Trace Elements in Water at the Mattabi Mine Site (mg/l)

Station / Time *	No	Mg	Mn	Na	Ni	Pb	Si	Sr	V	Zn	
CPP B-1 :5/94	#1	23.6	2.18	34.4	0.008	0.097	6.19	0.416	0.001	1.04	
CPP B-1 :10/93	#2	25.8	2.46	41.2	60.006	0.032	8.33	0.431	0.014	0.631	
CPP 1m :11/94	#3	16.77	0.731	14.8	60	0.028	3.75	0.281	0.001	1.42	
CPP B-1 :11/94 D1	#4	18.1	0.793	15.2	0.013	0.052	4	0.301	0.002	1.63	
CPP B-1 :11/94 D2	#5	18.2	0.801	15.3	0.015	0.105	4.11	0.297	0.041	1.59	
LC6 0.1m :11/94	#6	26.1	3.05	14.3	0.041	0.208	6.87	0.286	0.068	2.81	
BR2 0.1m :11/94	#7	2.48	0.024	0.635	0.048	0.187	1.39	0.025	0.111	0.091	
TW :11/94	#8	5.99	0.891	14.1	0.061	0.324	4.52	60.323	0.131	1.87	
TWC :11/94	#9	6.91	2.05	16.4	0.079	0.538	8.83	0.377	0.171	7.57	
BR1 :05/93	#10	1.2	0.006	0.8	ND	ND	0.706	0.0186	ND	0.047	
CPP 1m :11/93	#11	13.3	0.709	12.6	ND	0.009	3.61	0.225	ND	1.25	
CPP B-1 :11/93	#12	20.4	1.65	22.7	0.003	ND	4.22	0.388	ND	2.25	

* For a description of the terms in this column, refer to Figure 2.

TABLE 3. Downstream-Upstream Concentration Ratios in Bell River Waters

Sampling Station / Time	No	Al	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	K
BR1 : 05/93	#10	0.111	0.0063	0.001	6.6	ND	ND	0.005	0.009	0.033	0.4
BR2 : 11/94	#7	0.106	0.041	0.005	128	0.009	0.026	0.032	0.053	0.076	0.332
BR2/BR1		1.0	6.5	5.0	19.4	~	~	6.4	5.9	2.3	0.8

Sampling Station / Time	No	Mg	Mn	Na	Ni	Pb	Si	Sr	V	Zn	
BR1 : 05/93	#10	1.2	0.006	0.8	ND	ND	0.706	0.019	ND	0.047	
BR2 : 11/94	#7	2.48	0.024	0.635	0.048	0.187	1.39	0.025	0.111	0.091	
BR2/BR1		2.1	4.0	0.8	~	~	2.0	1.3	~	1.9	

~ - undifined

The concentrations of major and trace elements in the pit water were ten to twenty times greater than those at the control site. However, the concentrations of zinc were much greater, and exeeded the control by a factor of thirty to fifty (Table 3).

The concentrations of major and trace elements in the bottom water were generally two times greater than those in the surface waters. The concentration of barium in the bottom water was fifteen to seventeen times greater than that in the surface waters (Table 3).

Significantly greater concentrations of SO_4^{-2} in the bottom than the surface water most likely reflected the dissolution of particulate matter at the sediment/water interface. The concentrations of SO_4^{-2} in the surface and bottom water were sixty and one hundred times those at the control site, respectively. Also dissolution may occur in the water column if there is a sufficient accumulation (or retention) of particulate matter, as it occurs in sediment traps (Rosa, 1985). Such a release was clearly observed in the sediment trap deployed in the CPP (Figure 2, top right). Correlation analysis to establish relationships among the concentrations of all major and trace elements in collected water samples revealed a statistically significant relationship between only two parameters: silicon and zinc showed a good correlation (r=0.99, Figure 2, bottom left), most likely due to their geochemical association in the study area.

Bottom sediments and tailings

The average concentrations of selected trace elements in the land-disposed tailings near the pit, and in the bottom sediments of CPP, are presented in Table 4. Generally, the concentrations of arsenic, cadmium and cobalt in the tailings are considerably greater than those in the pit sediments. However, they are comparable with tailings at other mining areas (Azcue and Nriagu, 1993; Adriano, 1986). Other studies have attributed the higher arsenic, cadmium and cobalt concentration in the tailings to co-precipitation of these elements with ferric oxyhydroxides (Rescan, 1990). At Mattabi Mines the iron concentrations in the tailings are in the range of 23 to 24% (Brassard and Mudroch, 1995).

All other trace element concentrations were much greater in the sediments than in the tailings, particularly for zinc and manganese.

Zinc is the only trace element that showed elevated concentrations, in both the dissolved fraction (Table 2), and in the total fraction (Table 4), relative to the control site. The concentrations of zinc in CPP sediments were significantly greater than those in the tailings. In the sediments, the concentration of zinc ranged between 157 and 223 µg/g. On the other hand, the concentrations of zinc in the tailings ranged between 38 and 40 µg/g. The increase in the concentrations in the sediments was probably due to zinc held in the different labile phases in the sediments, in addition to zinc in sulphides and silicates in the tailings. This was confirmed by the high dissolved zinc concentrations in the CPP water. Furthermore, dissolved zinc

TABLE 4.

CONCENTRATION OF TOTAL METALS (ug/g), AND LOI (%) IN THE PIT BOTTOM SEDIMENTS (0-5cm) AND LAND-DISPOSED TAILINGS AT THE MATTABI MINES

SAMPLE	As	Cd	Cu	Pb	Zn	Mn	Ni	Co	Cr	Loss on Ignition(%LOI)
TAILINGS										
MT - D1	12.02	1.58	10.13	13.91	37.93	3.421	0.9627	1.119	0.6617	0.9
MT - D2	13.32	1.698	11.61	9.427	40.29	3.587	1.02	1.192	0.6828	1.2
Mean	12.67	1.639	10.87	11.669	39.11	3.504	0.991	1.156	0.672	1.05
BOTTOM SEDIMENTS										
CPP 1	10.41	1.342	29.35	31.64	184	20.6	1.269	0.5481	1.823	1.3
CPP 2	11.91	1.575	34.48	31.82	222.8	23.72	1.011	0.6258	1.399	1.2
CPP 3	7.9	1.106	23.58	14.61	157.4	17.2	0.7316	0.4567	1.019	1.5
Mean	10.07	1.341	29.14	26.023	188.1	20.50667	1.004	0.544	1.414	1.333

ND- Below Detection Limit
CPP- Crown Pillar Pit
MT- Mattabi Tailings

D1, D2 - Duplicates

and silicon concentrations showed a statistically significant correlation in different water samples at the Mattabi Mine site (Figure 2, bottom left). However, the interpretation of these data has to be regarded as tentative owing to the absence of information on subjects such as sediment stratigraphy, the hydrological history of CPP, and concentrations of trace and major elements in the sediment interstitial water.

Water Temperature:

The Crown Pillar pit was thermally stratified during the summer months. The thermal layers were typical of a well stratified northern lake, with epilimnion and thermocline thickness between 2 to 10 m, and 2 to 8 m, respectively, with the remainder of the water column consisting of a cold (4 to 5°C) hypolimnion.

The thermal structure varied considerably between the spring and fall, as shown in Figure 3, and may be considerably different from year to year (Figure 4). This variability is most likely due to different hydrodynamic conditions induced by variable solar radiation and wind forcing at the water surface.

Conductance, pH, and Dissolved Oxygen Concentrations

Conductance in the Crown Pillar pit water increased with the depth. The conductance followed the opposite pattern of dissolved oxygen concentration (Figure 3). In the Crown Pillar pit, minimum conductance was observed in the epilimnion. It increased in the thermocline, and was greatest in the hypolimnion (Figure 3). This increase is probably due to regeneration of major ions from the contaminated bottom sediments and dissolution of suspended matter. The greatest differences observed from the surface to the bottom of pit were in the order of 400 to 500 uS/cm, and usually occured in the spring (Figure 3, top). The pH decreased from approximately 7.85 to 7.0 from the surface to the bottom (Figure 3). The decrease of pH in the hypolimnion coincided with an increase in the DIC concentrations (Table 1), which most likely resulted from the mineralization of organic matter within the pit. Conductance and pH in water at different sites at the Mattabi Mine showed opposite trends, i.e., increasing conductance with decreasing pH (Figures 5 and 6). The concentrations of dissolved oxygen in the epilimnion were all greater than 8.5 mg/l, with a consistant quasi-linear decrease through the thermocline reaching minimum concentrations (i.e., close to 0.0 mg/l) in the hypolimnion. This minimum is typical in stratified meromictic systems (Fry, 1986), and is attributed mainly to the meromixis. However, a small portion of the oxygen depletion could be due to decaying organic matter, since the suspended particulates in the epilimnion contained 45% organic matter (Table 1). Chemical oxygen demand could also be occurring at the bottom sediments in the pit.

Time Series Measurements Using the Hydrolab System.

The Hydrolab Data Logger (HDL) performs on the same principle as the Hydrolab Profiling System (HPS). The HDL was used to continuously measure, every hour, the concentration of the investigated parameters (Figure 6) at 11 to 12 m from the water surface (Figure 7) over the entire year. This depth was chosen to monitor the fluctuations of the chemocline and to confirm the *meromictic* nature of the Crown Pillar pit. It was found that the chemocline fluctuated upwards during the winter and downward in the summer. The hourly data, averaged over two-day periods, is shown in Figure 7. The depth of observation (11 to 12 m) was chosen to correspond with the middle, seasonal average depth of the chemocline. The results showed that the chemocline migrated upwards from the fall to the spring. This was due to the formation of ice-cover over the winter months, decreasing oxygen diffusion in the water column. The lower oxygen diffusion is due to a reduction of turbulent diffusion, by a lower wind forcing at the water surface during the winter months. The diffusion processes were explained by Brassard and Mudroch (1995).

The results obtained in this study confirmed that the pit remains meromictic, i.e., chemically stratified, throughout the year, with the waters below the chemocline free of oxygen all year-round. The volume of water which remains anoxic is greatest in the spring months. At this time, the chemocline can migrate upwards to a depth of 6 to 8 m, as shown by the profiles taken during the month of May (Figure 4). The smallest volume of anoxic water was found to occur in the fall when the chemocline was at a depth of 13 to 14 m, as shown by the profiles taken during the months of October and November (Figure 4). This deep mixing is a result of wind-driven physical mixing processes increasing diffusional fluxes through the chemocline.

CONCLUSIONS

- A study was carried out to obtain baseline data for the development of a model for the estimation of the capacity of a well characterized meromictic water body to contain acid drainage generating mine tailings. The model would also predict the changes that could occur in water chemistry and the tailings after their disposal on the bottom of the water body. This report summarizes and interprets the data collected in the first part of the study of a meromictic pit, and lakes and streams at a base metal mine site in northern Ontario during 1993, 1994 and 1995. Following the survey of abandoned mining pits, the Crown Pillar pit at a base metal mining site near Ignace, Ontario, Canada, was chosen for the study.

- Water samples from 1m below surface (*epilimnion*), and 1 m above the lake bottom (*hypolimnion*) were collected in the Crown Pillar pit to determine the concentration of particulate and soluble nutrient, and major and trace elements (Al, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, Pb, Sr, V, and Zn). Water samples were also collectected in lakes and streams at the mine site, and analysed for the above parameters. One of the sampling sites in Bell River, upstream from the mine site (BR1), was used as a control.

- At three sites in the Crown Pillar pit (CPP), continuous surface-to-bottom depth profiles of pH, specific conductance (COND), dissolved oxygen (DO), and temperature, were recorded in the spring and fall, from 1993 through to 1995. The concentrations of selected trace elements were determined in the land-disposed tailings near the pit, and in the bottom sediments of CPP.

- The results of the study showed that the concentrations of all particulate nutrients were generally low in the Crown Pillar pit water, with the exception of organic carbon and phosphorus. The concentrations of soluble nutrients in the surface waters of the Crown Pillar pit were generally lower than those in the bottom waters. Dissolved organic carbon and dissolved phosphorus concentrations in the pit were not elevated relative to the control station in Bell River. The concentrations of the rest of the determined dissolved nutrients were greater in the bottom than at the surface waters. This was attributed to dissolution and mineralization of particulate material at the bottom of the pit.

- Using lake classification models, and concentrations of carbon and phosphorus, it was found that the chlorophyll concentrations in the pit water were ten times lower than those predicted by previously established chlorophyll-phosphorus relationships. This indicated reduced primary production, most likely due to toxic effects of elevated concentrations of soluble trace elements in the pit water.

- The greatest concentrations of trace elements in water at the Mattabi Mine site were found in Lyon Creek, at station LC6. The input of these trace elements appeared to occur upstream of the Crown Pillar pit. The concentrations of most trace elements were three times lower in the surface waters of the pit than those at station LC6. The results suggest that Lyon Creek can be a future source of contamination for the pit through ground water flow, and a present source of contamination to Lyon Lake through direct inflow of the creek water.

- The concentrations of dissolved sulfate in the surface and bottom waters in the pit were 60 and 100 times greater, respectively, than those at the control site. This was attributed to the dissolution and mineralization of suspended matter in the pit.

- Correlation analysis among all major and trace elements, in collected water samples revealed a statistically significant relationship between only two parameters. The correlation coefficient between the concentrations of dissolved silicon and zinc showed a statistically significant relationship (r=0.99, n=7). This was attributed to the geochemical assosiation of the two elements in the soils and rocks at the study site.

- From all dissolved trace elements determined in the water samples, zinc was the only element that showed elevated concentrations in the pit, relative to the control site. Total concentrations of zinc in pit sediments were significantly greater than those in tailings disposed near the pit. The increased concentrations of zinc in the pit water were attributed to the dissolution and mineralization of zinc in the sediments.

- The water in the Crown Pillar pit was thermally stratified during the summer months, and chemically stratified throughout the year, from 1993 to November 1995. The conductance in the Crown Pillar pit water increased with increasing depth, and followed the opposite pattern to dissolved oxygen concentrations and pH.

- The Hydrolab Data Logger was used to continuously measure the concentration of conductivity, dissolved oxygen, and pH at one depth (i.e., 11 to 12 m from the water surface) over a period of one year from October 1993 to November 1994. The results showed that the chemocline migrated upwards from the fall to the spring, and the chemical gradients of conductivity, dissolved oxygen, and pH remained throughout the year. These results confirmed the *meromictic* nature of the Crown Pillar pit.

- The results obtained confirmed that the pit remains meromictic, i.e., chemically stratified throughout the year, with waters below the chemocline free of oxygen. The volume of water which remained anoxic was greatest in the spring months. At this time, the chemocline can migrate upwards to a depth of 6 to 8 m, as shown by the profiles taken during the month of May. The smallest volume of anoxic water occurred in the fall when the chemocline was found at the depth of 13 to 14 m, as shown by the profiles taken during October and November.

- The results of the study clearly indicated that the Crown Pillar pit has the characteristics of a meromictic water body. Therefore the pit would provide ideal conditions for the testing of the feasibility of subaqueous disposal of acid drainage generating mine tailings and waste rock. It appears that there will be no adverse effect on the surface water quality by materials disposed on the bottom of the pit due to the permanent chemical gradients which isolate the epilimnion from the hypolimnion.

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Figure Captions

Figure 1. Mattabi Mines, Noranda Minerals Inc.

Figure 2. Dissolved trace elements in different water compartments at the Mattabi Mine site

Figure 3. Surface to bottom concentration-depth profiles for Conductance, Temperature, pH and Dissolved Oxygen, for the spring and fall, in the Crown Pillar pit

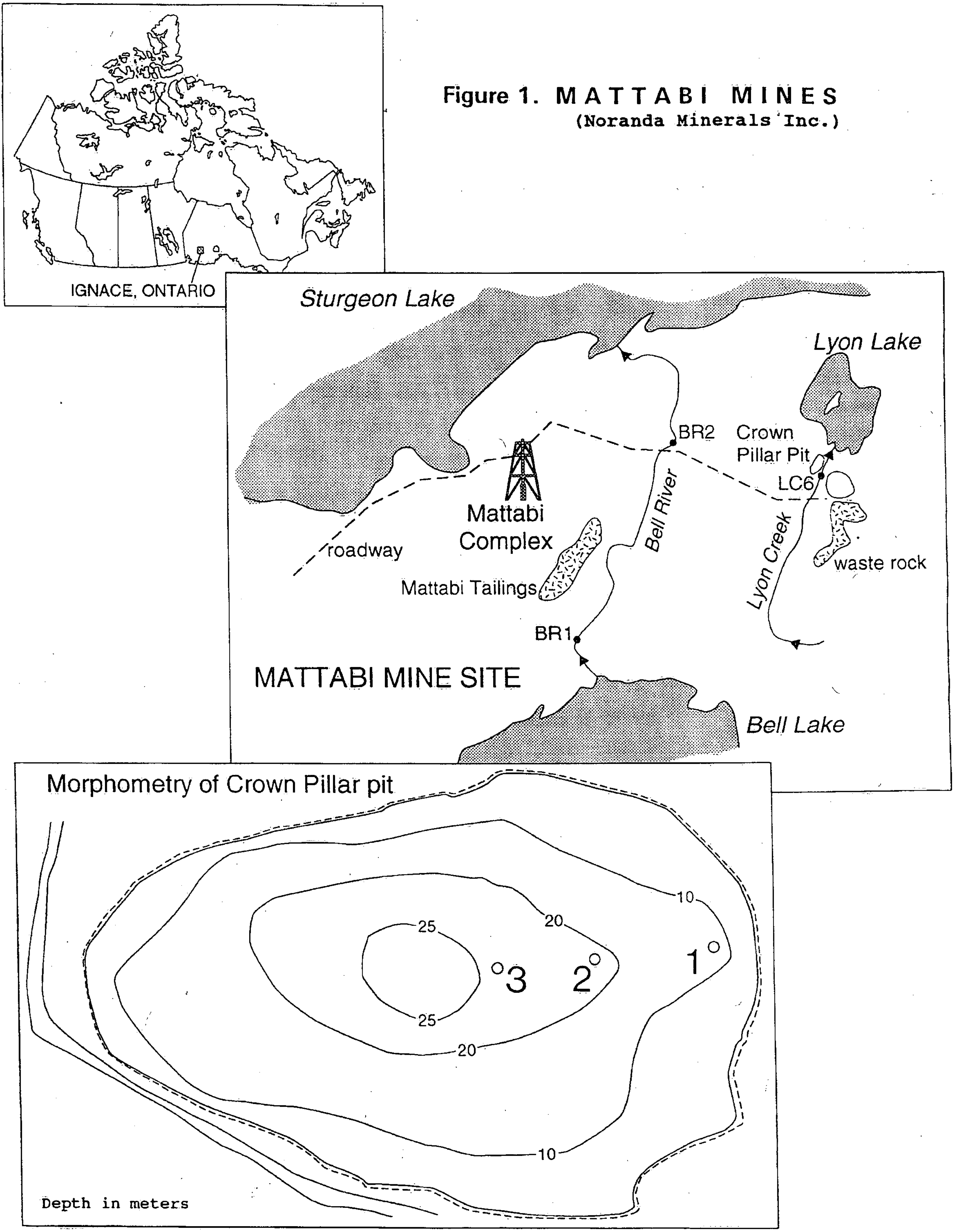
Figure 4. Concentration-depth profiles for Conductance, Temperature, pH and Dissolved Oxygen, for the spring and fall, in the Crown Pillar pit within the transition zone of the water column

Figure 5. Concentration-depth profiles for Conductance and pH, in different areas, at the Mattabi Mine site

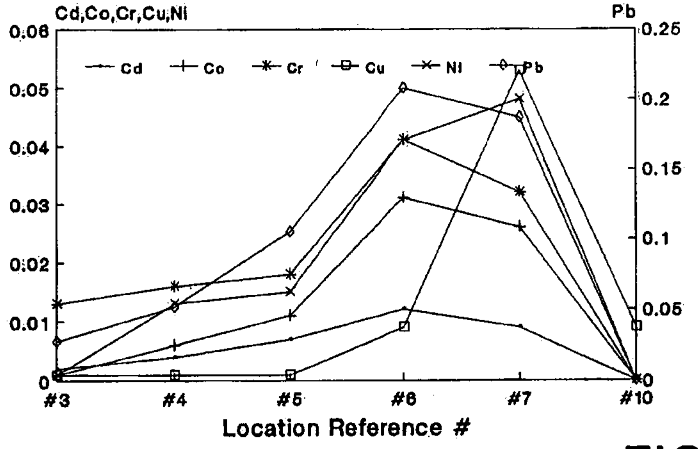
Figure 6. Time-concentration plots of Conductance, Temperature, pH and Dissolved Oxygen, measured at a depth of 12 m in the Crown Pillar pit, from mid-October 1994 to mid-November 1995. (48 hr averages)

Figure 7. Detailed concentration-depth profiles, from 10 to 14 m, for Conductance, Temperature, pH and Dissolved Oxygen, for the fall of 1993, in the Crown Pillar pit

Figure 1. MATTABI MINES
(Noranda Minerals Inc.)



Dissolved Trace Elements (mg/l)
Mattabi Mine Site



Dissolved Trace Elements (mg/l) in three Compartments of Crown Pillar Pit

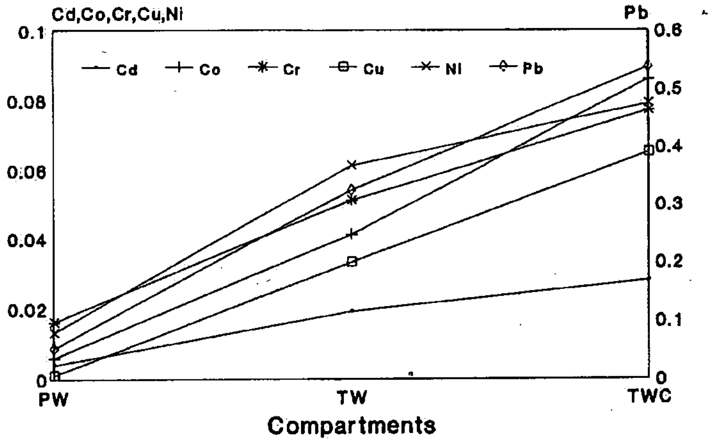
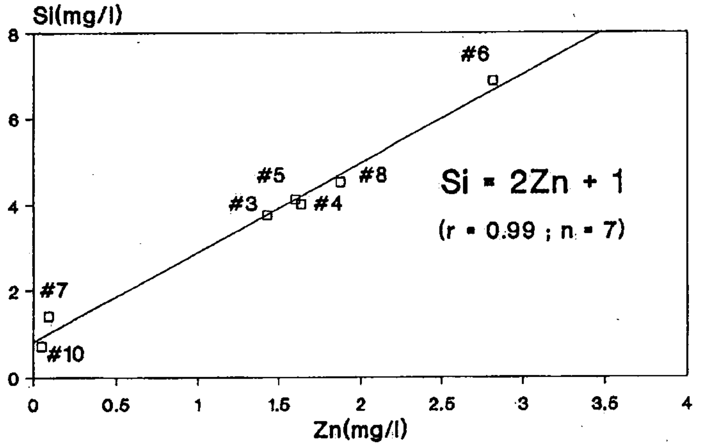


FIGURE 2.

Mattabi Mine Site Water Chemistry
(dissolved zinc & silicon relationship)



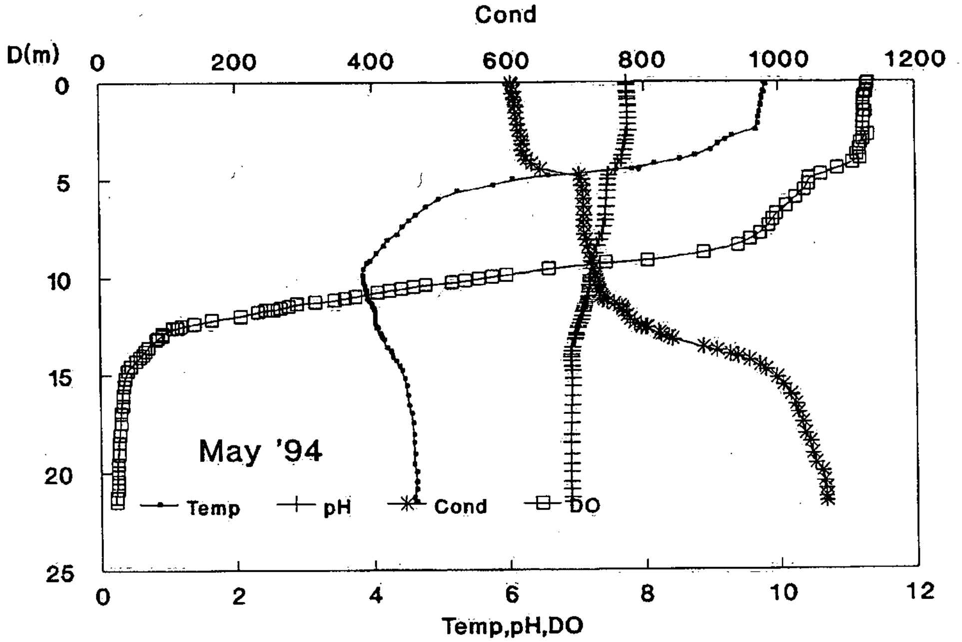
Water Samples Location/Depth/Date

Location		Reference #
CP Pit B-1	5/94	#1
CP Pit B-1	10/93	#2
CP Pit 1m	11/94	#3
CP Pit B-1	11/94 (1)	#4
CP Pit B-1	11/94 (2)	#5
LC 6	11/94	#6
BR2	11/94	#7
TW	11/94	#8
TWC	11/94	#9
BR1	5/93	#10

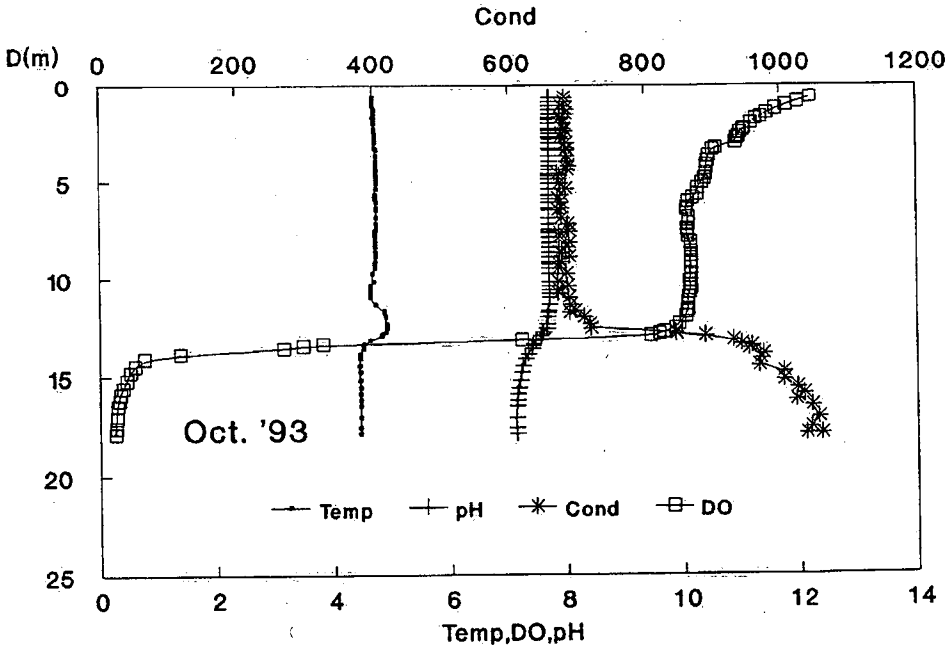
B-1: 1m above bottom
1m: 1m below surface
LC: Lyon Creek
TW(C) trap water (concentrate)

BR1: Bell River "Control"
PW: Pit Water
CP: Crown Pillar

FIGURE 3.



Crown Pillar Pit, Spring and Fall Profiles



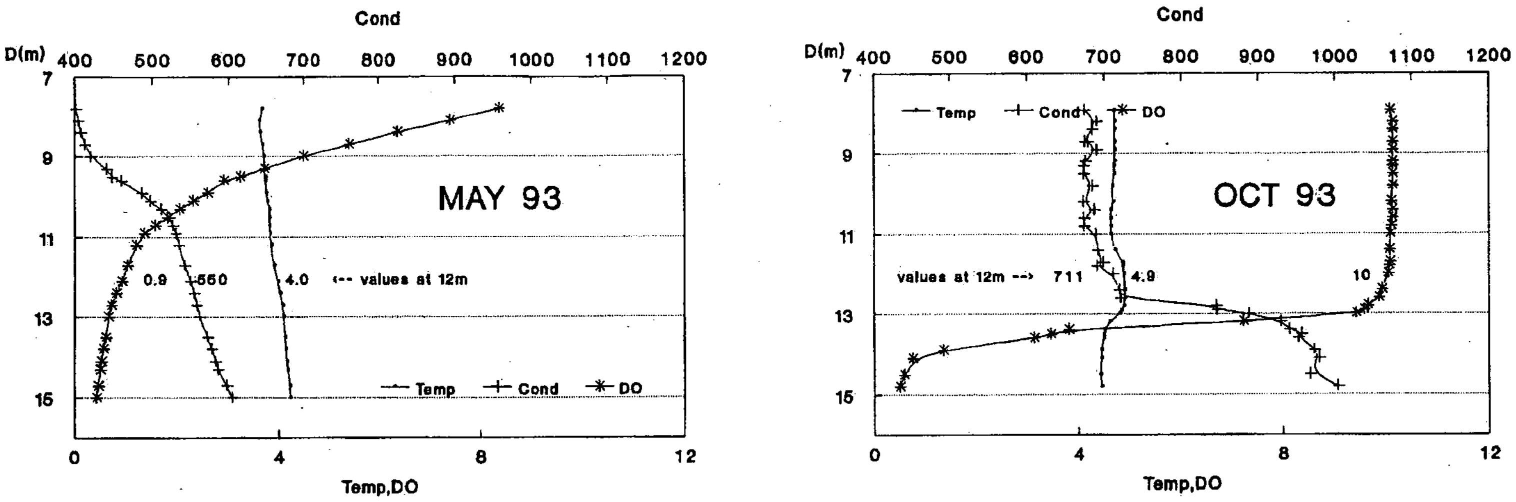


FIGURE 4.

Crown Pillar Pit Seasonal Profiles

(Temp, Deg. C.; DO, mg/l; Cond, uS/cm)

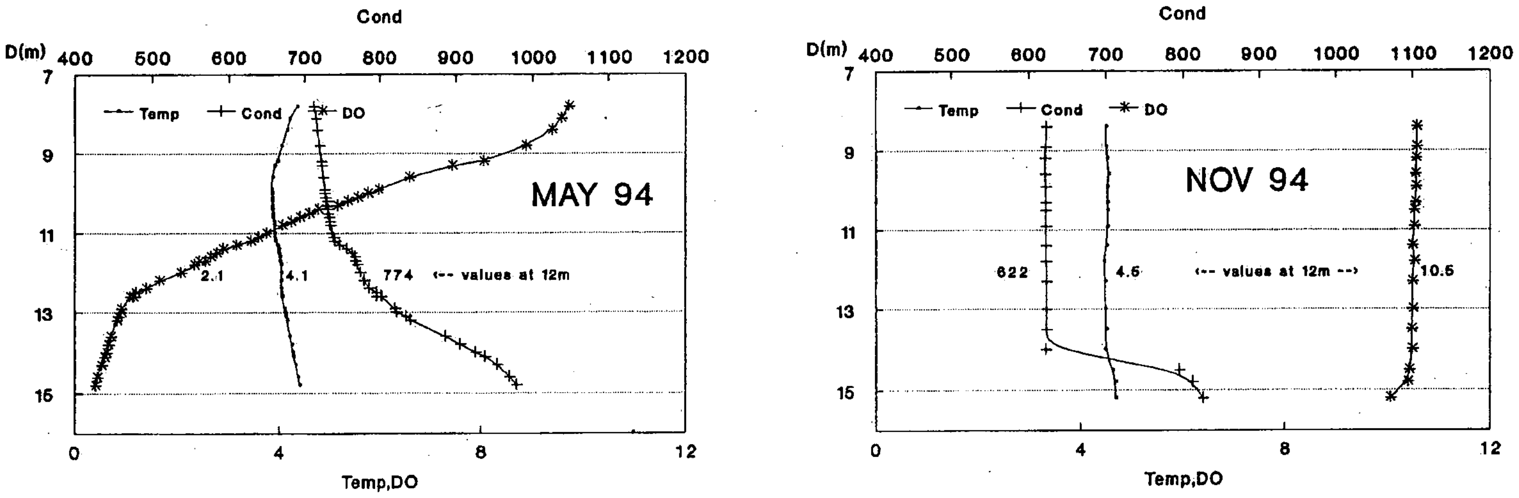
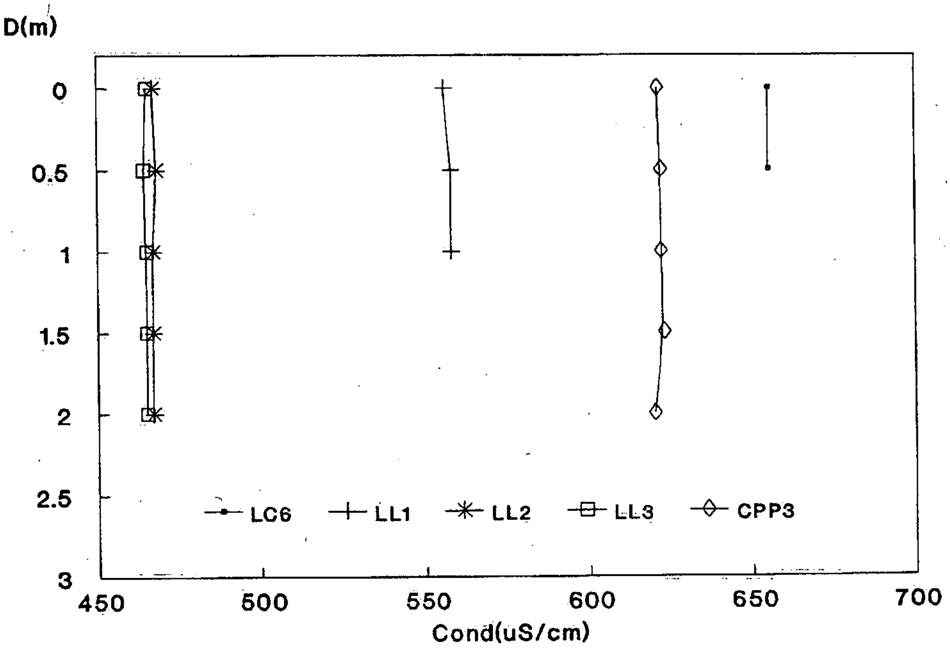


FIGURE 5.



Mattabi Mine Site: Hydrolab Profiles (11/94)

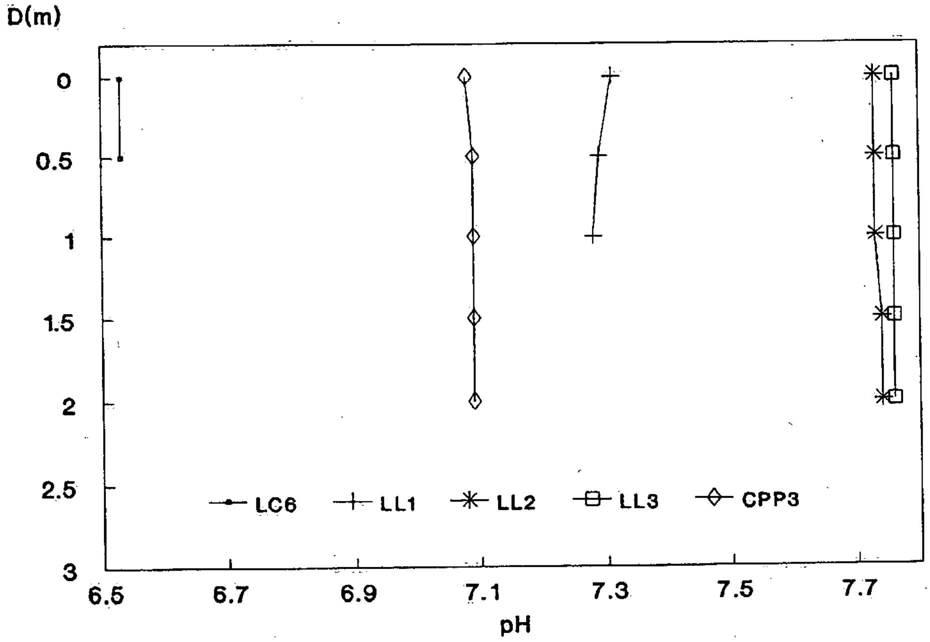
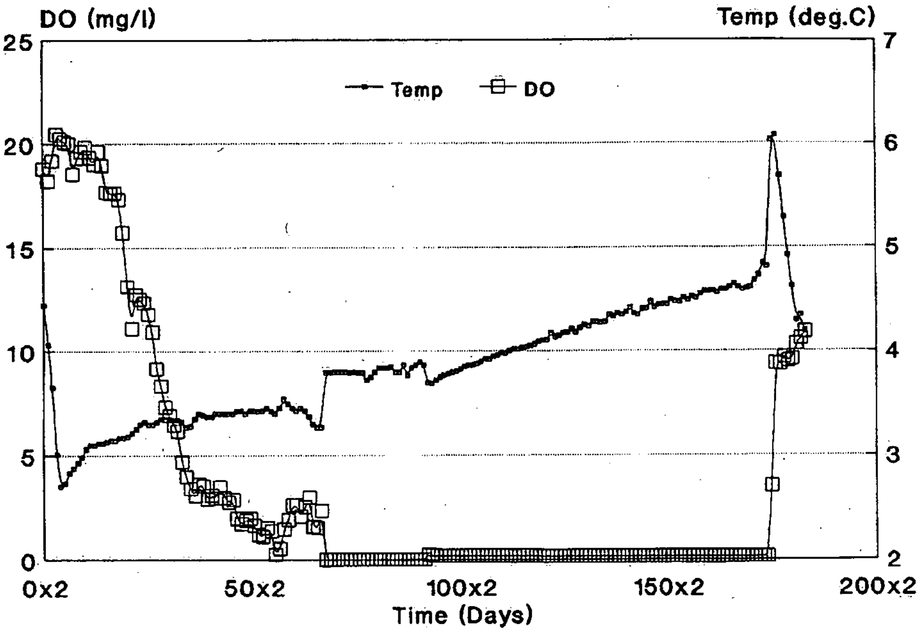


FIGURE 6.



Hydrolab Logger Data

(10/16/94 to 11/15/95, at 12m)

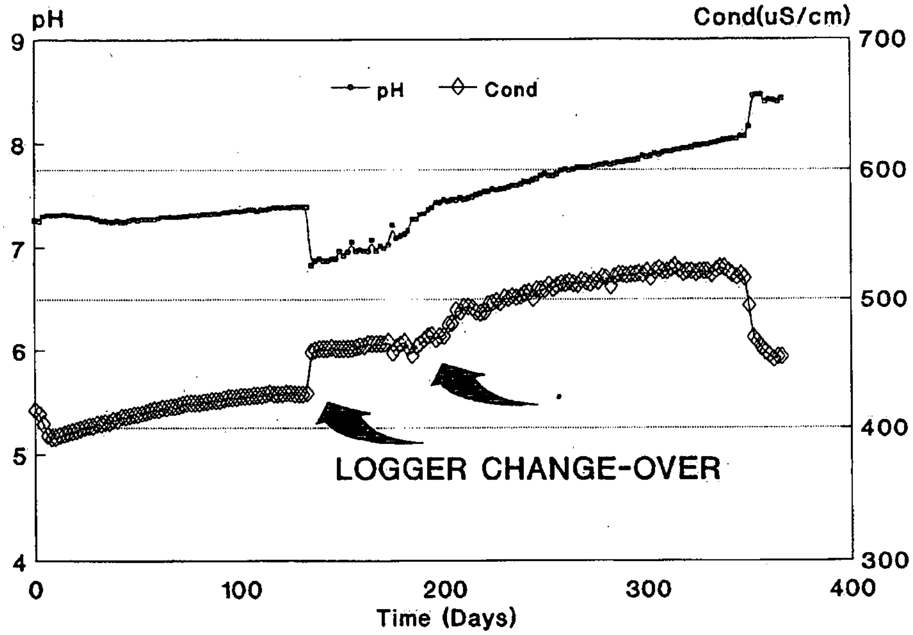
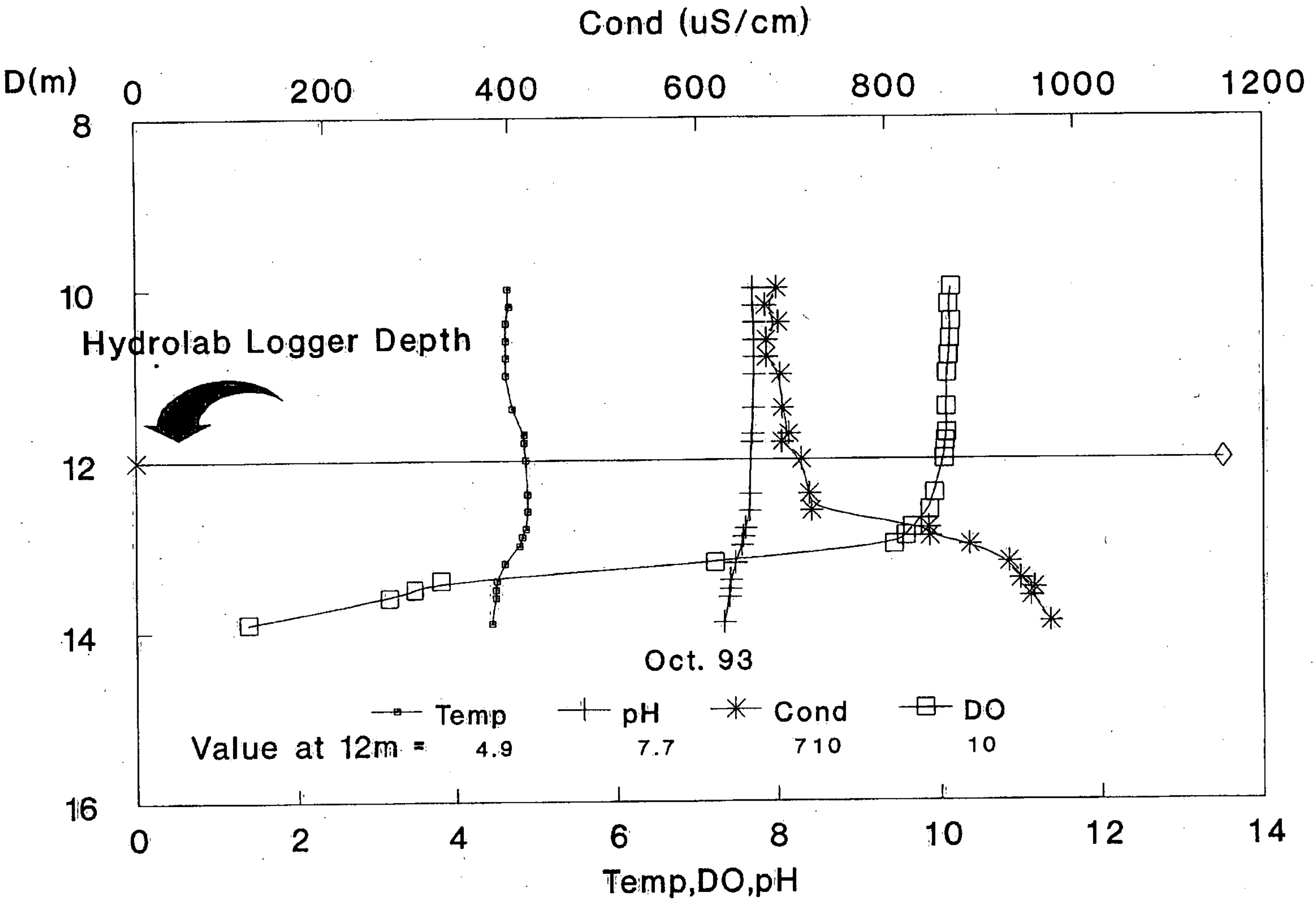


FIGURE 7. Logger Position and Detailed Chemical Structure



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