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THE GEOCHEMISTRY OF WESTMIN RESOURCES LTD.

MYRA CREEK MINE TAILINGS

By

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ABSTRACT

Westmin Resources Ltd. operate a 3000 tpd copper-lead-zinc mine 93 km by highway south-southwest of Campbell River in Strathcona Provincial Park. The mine began operations in 1966. Tailings were initially discharged directly to the bottom of Buttle Lake; a practice which continued until an on-land tailings disposal facility was commissioned in June 1984.

Testwork has indicated significant acid production potential in the sulphide tailings. Tailings are now deposited by the "subaerial" method; a procedure designed to produce an unsaturated, high density tailings mass with low horizontal and very low vertical permeability. This is a relatively new technique in Western Canada and the Myra Falls facility provided an ideal opportunity to evaluate the effectiveness of subaerial deposition to limit acid generation and contaminant migration.

A number of surveys have been conducted by Environment Canada and Knight and Piesold Ltd. to evaluate the geochemical and geotechnical characteristics of the tailings mass over the deposition history. This report describes a detailed study conducted by Environment Canada and L.M. Broughton in 1989, with reference to the previous study (Broughton and Ferguson, 1989) to evaluate changes over time.

The field sampling component of this study included surface solids sampling of fresh and older tailings, deposited over a seven month time period. Surface water samples were collected. Depth profiles through the newer and old tailings layers in the tailings impoundment and an emergency storage pond were established of the geotechnical and geochemical characteristics through solid sampling over depth, pore water sampling, and laboratory testing including paste analyses, shake flask extraction tests.

Sulphide oxidation was occurring at the surface and over depth in the tailings. Contaminant fronts over the vertical profile of the tailings mass were identified, and the rate of infiltration estimated. Elevated zinc, acidity, sulphate and conductivity levels were detected at depth in the impoundment. The infiltration of alkaline tailings water from freshly placed tailings neutralized low pH fronts and precipitated metals constrained by pH (Cu and Fe) near the interface of fresh and older tailings.

Oxygen and carbon dioxide profiles were developed to determine oxidation rates, oxygen consumption and the ingress of oxygen to the depth in the tailings. Geotechnical characteristics of the tailings mass within the layers sampled were similar to measurements at a conventional saturated tailings impoundment. The placement of a fresh tailings layer did not appear to significantly change the rate of oxidation or contaminant migration through the tailings. Layers of fine silt with high moisture content limited the vertical diffusion of oxygen into the tailings, and the rate of oxidation. Due to operational constraints, there were long periods between tailings deposition which allowed drying and cracking of the subaerial tailings mass, and development of surface oxidation and low pH fronts which have penetrated to depth in the tailings. Vertical cracking of the tailings allowed the ingress of the oxygen to more permeable underlying sand layers promoting oxidation at depth in the tailings.

Relatively simple field and laboratory techniques were developed and applied to evaluate the characteristics and performance of the subaerial tailings mass. Such evaluations should be conducted to determine the nature of the tailings during operation, and for design of alternative closure schemes, but must be carefully designed to recover the essential data within a reasonable time frame and scope of laboratory and field work. The results of investigations of the geochemical nature of the Myra Falls tailings impoundment indicate that acid generation, metal leaching, and contaminant migration are established in the subaerial tailings mass. Closure and reclamation strategies must address limiting the rate and extent of acid generation, and address containment of the contaminated drainage water within the impoundment. All acidic drainage from the Westmin site is collected and treated in a lime neutralization circuit and series of settling ponds, and is sampled and analyzed prior to discharge.

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1.0 INTRODUCTION

1.1 Background

The Westmin Resources Ltd. - Myra Creek Mine is a 3000 tpd copper-lead-zinc mine 93 km by highway south-southwest of Campbell River in Strathcona Provincial Park, as shown in Figure 1. The mine began operations in 1966. Initially tailings were discharged directly to the bottom of Buttle Lake. This continued until an on-land tailings disposal facility was commissioned in the Myra Creek Valley in June 1984. Tailings are now deposited by the "subaerial" method in one of two areas behind a berm constructed parallel to Myra Creek, as shown on the site plan, Figure 2. Raw tailings are cycloned to separate the sand fraction which is stockpiled prior to re-use as mine backfill. The finer slime fraction is thickened and deposited subaerially in the tailings disposal facility.

The subaerial method of tailings disposal is designed to produce an unsaturated, consolidated tailings mass with low horizontal and very low vertical permeability. The unsaturated nature of the impoundment, with high negative pore pressures provides control of water movement and provides "...strict control of seepage during operation, and, since the tailings are fully drained and consolidated at all times, allows for relatively simple decommissioning and the elimination of long term environmental concerns." (Knight and Haile, 1983). The constant removal of process water from the tailings during deposition results in a considerable reduction in the volume of tailings to be stored, and corresponding economies in impoundment size and embankment construction requirements.

Conventional tailings disposal systems are essentially "subaqueous" or beneath water as opposed to "subaerial" which implies beneath air. With such systems, the key concern is seepage through the embankments, and thus control of the phreatic surface. The tailings are generally saturated and therefore less dense than with a drained system. There are concerns about the geotechnical stability of a saturated tailings mass. A detailed discussion of the geotechnical nature of conventional and subaerial tailings impoundments is however beyond the scope of this report. Details of geotechnical aspects of the design and construction of the Key Lake subaerial tailings facility are discussed by Knight and Haile (1984). A geotechnical investigation of a large tailings impoundment is presented by Singh et al. (1984).

FIGURE 1 LOCATION OF WESTMIN RESOURCES LTD. MINING OPERATION

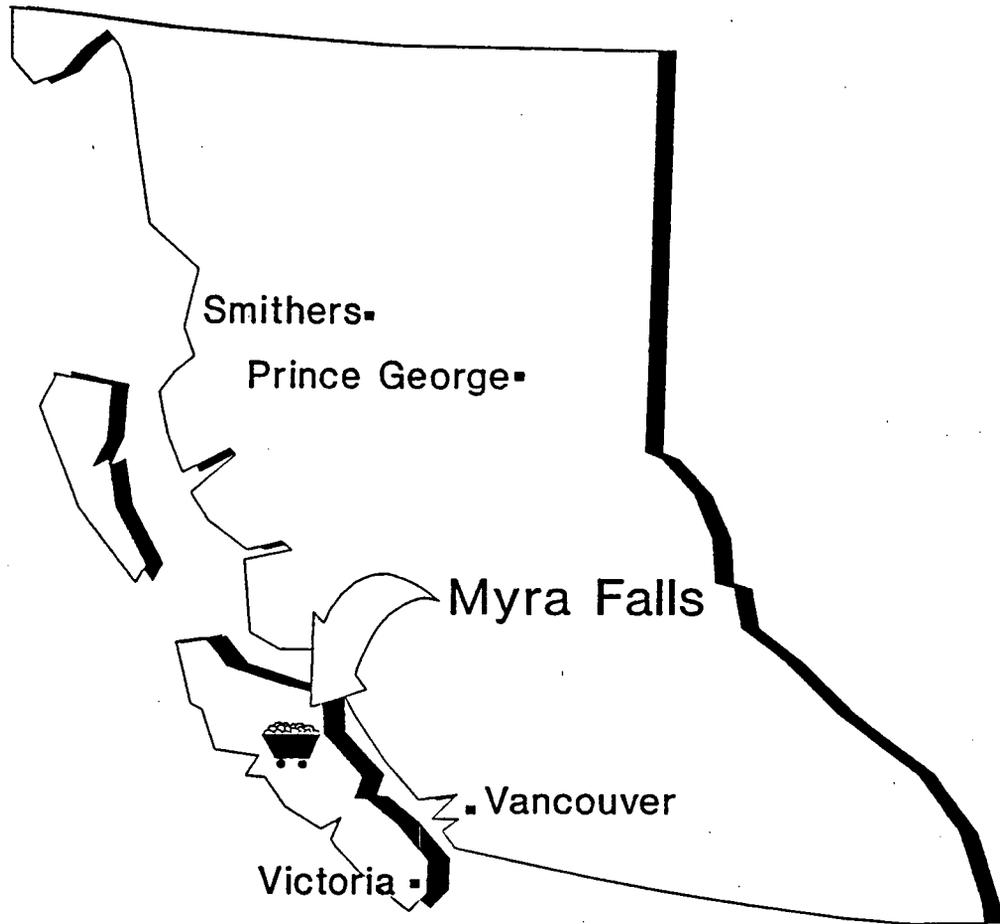
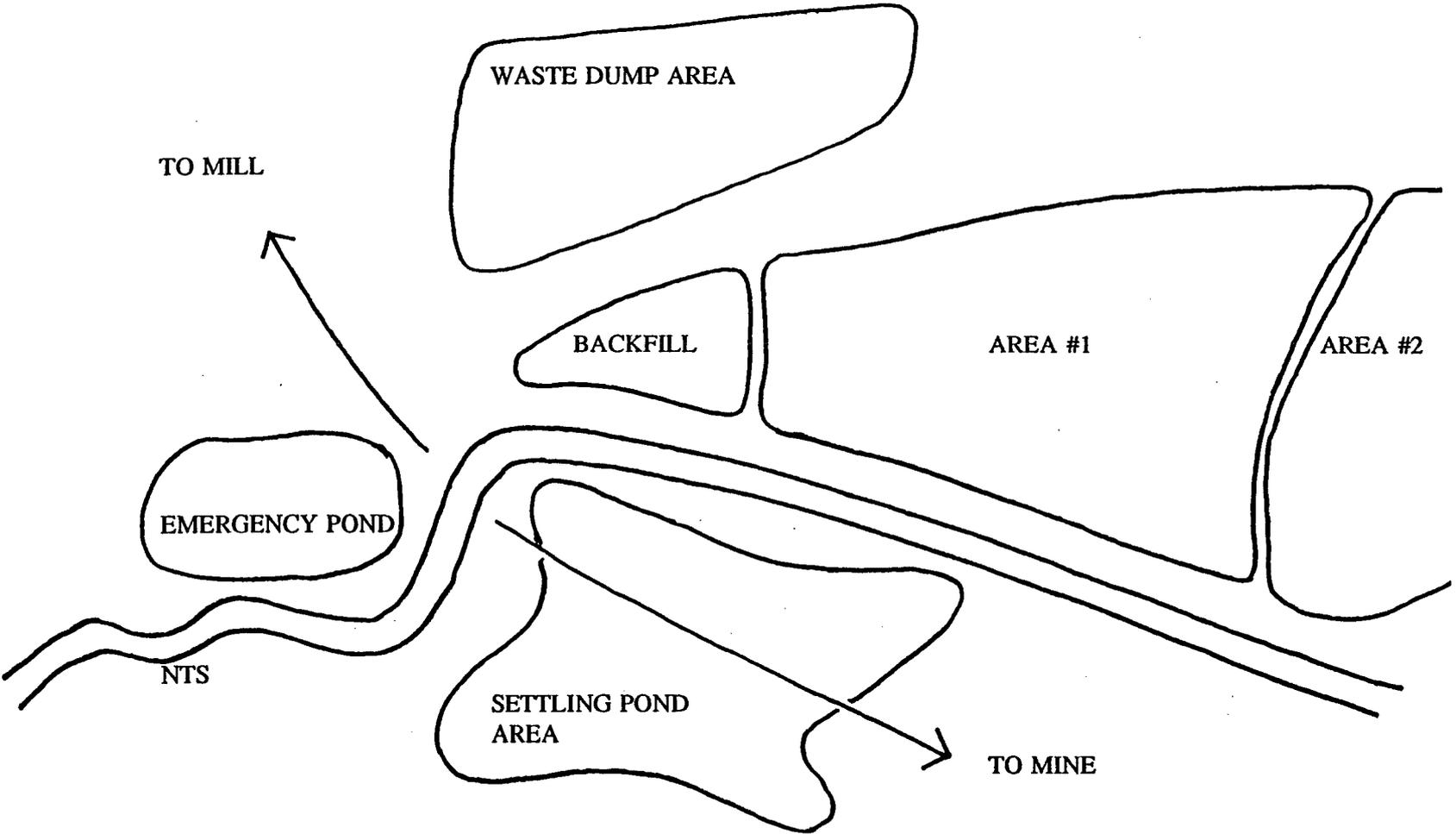


FIGURE 2 SITE PLAN



The concept of interior drains for tailings impoundments to control hydraulic conditions, however, is not a new concept. It "...involves the adaptation of well developed principles and practices from the fields of groundwater, geotechnical and agricultural engineering." (Charlie et al., 1983). The technique has been developed over a number of years in Central and South Africa, Britain and Australia, and more recently been applied in Canada and the U.S., primarily for uranium facilities.

Tailings are deposited in the impoundment in thin layers on a flat slope from a series of spray bars. Each layer is allowed to settle, drain, and partially air dry prior to the placement of another layer (Knight and Haile, 1983). Tailings solids settle on the beach as the water drains from the mass and accumulates in a small pond downslope. The particle segregation that occurs horizontally over the impoundment during deposition and vertically within each layer during settling is an important characteristic of the subaerial technique. The vertical layering provides anisotropy in which the vertical coefficient of permeability can be up to two orders of magnitude less than the horizontal (Knight and Haile, 1983). The horizontal segregation with coarser particles deposited near the spray bar should result in higher densities near the discharge point. This may however also correspond to higher sulphide content and higher porosities in this area and increased potential for oxidation.

The impoundments are designed with a drainage system underneath the tailings, which generally consists of an underdrain filter blanket and piping network, to promote the dewatering of the tailings and increase the settled density, and prevent the buildup of excessive pore pressures. Air drying of each layer of solids would preconsolidate the tailings, and further increase the settled density. There is also a surface runoff component of drainage which collects downslope and is decanted from the impoundment or the removed through a backdrain system. The movement of moisture through the tailings to the filter blanket, however, becomes very low once the depth of tailings exceeds about 1.5 m (Haile and East, 1986). The underdrain layer can then act as a long term monitoring system for the impoundment. The drainage system does ensure that all contaminated water is collected from the impoundment and, if necessary, can be piped to the water treatment facility which treats all contaminated drainage from the rest of the site. There is no uncontrolled discharge of acidic drainage from the Myra Falls site.

At closure, the subaerial impoundment, as it is proposed, should be a consolidated, fully drained

tailings mass with no potential for long term seepage or drainage. The short term performance of a properly operated system should require a minimum of maintenance but a high amount of operation attention. However the pH and dissolved solids in the tailings, and potential migration of fine tailings into the underdrain system could reduce the efficiency of the system. The long term changes in the physical and chemical nature of the tailings impoundment are more difficult to predict. Chemical reactions within the tailings, particularly oxidation of the sulphide minerals, can result in changes to the engineering properties of the tailings (Charlie et al., 1983). The extent of the consolidation during operation is critical to the long term reclamation of the facility. Differential settling between the coarse (sands) and fine (slimes layers) can affect the integrity and performance of a cover. Miller et al. (1990) discussed the impact of consolidation on reclamation of tailings impoundments.

Testwork prior to the commissioning of the Westmin tailings disposal system, on Myra-Lynx ore, indicated that the tailings would exhibit a potential to generate acid drainage. In 1985, mining began in a large sulphide rich orebody and the new "HW" mine and mill were commissioned in August 1985. Testwork identified this material as exhibiting substantial acid generating potential.

The production of acid drainage from conventional disposal of high sulphide tailings is a recognized phenomenon at mines throughout Canada. At these sites, acid drainage is typically generated in the upper layers of the deposited tailings where air, water, and acidophilic bacteria can interact to oxidize sulphide minerals to sulphuric acid and release associated metals into solution. Acidic solutions generated in the upper zones of the tailings mass infiltrate through the tailings, consuming neutralizing minerals, eventually appearing at the toe of the impoundments as acidic seeps. In some cases the tailings pond supernatant might also become acidified. Detailed discussions and comprehensive reviews of acid rock drainage are available in the published literature (British Columbia Acid Mine Drainage Task Force, 1989).

Current approaches to deal with acid generation potential involve predictive, preventative and remedial programs. Prediction of acid generation potential is important for all mine rock, including waste rock, mill tailings and construction materials. The technical and design options available to control and prevent acid drainage are much greater at proposed mines than existing mines. If the

problem is anticipated before mining, control options for both limiting acid generation and controlling contaminated drainage can be implemented. The subaerial method of tailings deposition has been recently been proposed for several sites in British Columbia as a method to reduce or eliminate the acid drainage from a potentially acid generating tailings mass. The Westmin Resources Ltd. Myra Creek Mine subaerial tailings impoundment has provided an ideal site for study of the effectiveness of subaerial disposal in preventing acid generation.

The tailings disposal facility at the Westmin site consists of two areas, designated as Areas #1 and #2 as shown in Figure 2. Tailings from the Myra-Lynx mine were deposited in Area #1 from July 1984 through to March 1985 when the HW mine was commissioned. Tailings from the HW mine were deposited in Area #1 through to October 1985, at which time deposition into Area #2 was initiated. Construction work to move and raise the berm defining these two areas began in 1988. In December of 1988, approximately 1.5 metres of tailings was deposited in Area #1 before returning to deposition in Area #2. As of July/August 1989, tailings were deposited in Area #1.

Area #1 primarily consists of tailings deposited by subaerial methods. Some conventional spigotting of bulk tailings was required because of occasional thickener downtime. This was confined to one area at the west side of the impoundment, adjacent to the back drain. These tailings consisted of coarser material with a higher sand content than the subaerial tailings. Use of spigotting has been more frequent in Area #2 because of difficulties with thickener operation.

1.2 Previous Studies

Studies of the Westmin tailings facility, to date, relevant to the potential for acid mine drainage formation, have been conducted by both Environment Canada, Environmental Protection (EP) and Knight and Piesold Ltd. The overall objectives of the continuing studies of the Westmin tailings facility are three-fold:

- i) to determine if the subaerial method of tailings deposition results in a tailings mass exhibiting a low potential for acid production, and;
- ii) to determine if the subaerial method of tailings deposition limits contaminant transport

through the tailings mass and into the surrounding environment.

- iii) to determine if reasonably simple techniques used in these studies can be successfully applied to assessment of the generation of acid drainage in a tailings mass.

The results of previous studies were summarized in Broughton and Ferguson (1988) and are briefly summarized below. Details of each study are available in the referenced reports.

The initial study was conducted by EP in 1985 (Ferguson, 1986) to evaluate the potential for acid generation from the tailings material after deposition. Approximately 3 m of tailings had been deposited in Area #1, primarily by subaerial methods. The study found evidence of significant acid generating potential. Segregation of the dense sulphide minerals occurred with deposition, resulting in higher concentrations of acid generating material near the spray bars, with acid neutralizing carbonate materials concentrated near the back drain. Sulphur content was estimated from solid sample metals assays and it was found that calcium assays could be used to estimate neutralization potential. The neutralization potential of a sample refers to the acid consuming or alkaline minerals, generally carbonates. Thus the calcium content should reflect the calcium carbonate content, or neutralization potential, of a sample if CaCO_3 is the main neutralizing mineral.

In August 1986 Knight and Piesold Ltd., consulting engineers, conducted a sampling and laboratory test programme of the Area #1 facility to evaluate in-situ geotechnical parameters and assess the structural integrity of the facility. By design, subaerial deposition limits the formation and migration of acid drainage by forming a high density, low permeability tailings mass and thus many of these physical characteristics determined by the Knight and Piesold testwork are relevant to the study of acid drainage potential. The results of this study can be summarized (Broughton and Ferguson, 1988):

- i) moisture content ranged from 8.1 % to 45.3 %
- ii) specific gravity ranged from 3.01 to 3.94, generally lower at depth in test pits A and C corresponding to Lynx tailings, and higher values corresponding to higher sulphide HW tailings
- iii) degree of saturation ranged from 27.3 % to 81.8 %
- iv) tailings material consisted of partially saturated, non-plastic, fine sandy silt with less

than 10 % clay, with lenses of moderately to fully saturated, wet silt of low plasticity
v) coefficient of permeability ranged from 5×10^{-8} to 7×10^{-10} m/s, decreasing with decreasing
void ratio.

Chemical analyses of solids samples again indicated that the tailings material was potentially acid generating. However paste pH analyses did not indicate acidic conditions with the exception of one sample near the decant outlet.

After eighteen months exposure of the tailings in Area #1, a study was conducted by EP (Ferguson, 1987) to determine if there was any indication of acid generation. Surface and core samples collected April, 1987 were tested for both geochemical and geotechnical parameters. Results of metal analyses from an earlier sampling programme (July, 1986) were also reported. The significant acid generation potential of the Westmin tailings was again demonstrated, and low surface paste pH and neutralization potentials indicated that oxidation was occurring at the surface of the tailings mass. A front of low pH was identified within the upper six centimetres of the tailings. The tailings samples were fine grained, with moderate porosity and relatively low permeability. Most areas were unsaturated although some near surface samples were close to saturation.

The degree of oxidation (as indicated by paste pH) was found to correlate well with the calculated oxygen diffusion coefficient which in turn was largely related to the moisture content. The relatively high moisture content of some of the tailings inhibited oxygen diffusion and thus hindered oxidation, although a high moisture content is contrary to the concept of subaerial deposition.

An extensive study was conducted in May, 1988 (Broughton and Ferguson, 1989) to determine the extent and progression of acid generation and drainage in Area #1 after 30 months of exposure, (ie. 30 months since the last tailings deposition). A detailed sampling programme was conducted in Area #1 with some samples of fresher tailings from Area #2 for reference. The field and laboratory programme evaluated both geochemical and geotechnical parameters and included surface sediment sampling, surface water samples, and test pits to develop profiles over the depth of the tailings mass. The interpretations and specific conclusions of this investigation are provided in detail in the referenced report. The general conclusions were, briefly:

1. After 30 months exposure, acid generation was well established in the surface and to varying depths throughout the impoundment depending on the geotechnical characteristics of the layers and the degree of cracking. Cracking of surface layers allowed the transport of oxygen and water to depth, promoting oxidation. Saturated silt layers appeared to hinder oxidation however the presence of saturated layers is contrary to the concept of subaerial deposition. Possibly conventional flooded impoundments could be more effective in inhibiting acid generation.
2. The layered heterogeneity of the subaerial tailings mass appeared to affect the acid generation characteristics of the tailings mass and affect the migration of contaminants.
3. The rate of migration of contaminants from a facility determines whether acid production is of concern. The migration rate of contaminants appeared much slower than predicted by saturated hydraulic conductivities, suggesting that the unsaturated conditions in a subaerial impoundment might slow the rate of contaminant migration compared to conventional saturated tailings ponds.
4. The simple techniques used to date were useful in identifying factors that control acid generation and contaminant transport in a heterogeneous tailings mass. More detailed analyses of contaminant concentrations, transport mechanisms and gas diffusion controls are necessary to confirm the results of this study, although these would require slightly more sophisticated field and laboratory techniques.

1.3 Objectives

Based on the results of the previous studies and continued deposition in the subaerial tailings impoundment, it was determined that a detailed laboratory and field study would be conducted in 1989. The primary objective of this study was to determine the status of acid generation in Area #1, approximately 44 months after deposition. The tailings were covered with approximately 1 metre of tailings after 37 months of exposure. This surface was then left exposed for approximately 7 months prior to this investigation. Some specific objectives of this sampling programme included:

- i) investigate effects of cover of fresh tailings on acid generation in old tailings layer;
- ii) investigate acid generation and progression in fresh tailings layer;

- iii) monitor progress of acid generation and contaminant migration in both layers using shake flask test procedures and compare to actual pore water concentrations;
- iv) conduct a detailed evaluation of the geochemistry at a few sites to maximum depth;
- v) develop and test simple field techniques for pore water analysis and gas measurement.

The extent of change in acid generation and contaminant migration in the tailings impoundment will be evaluated by comparison with the results of the 1988 study, as discussed by Broughton and Ferguson (1989).

1.4 Elements of the Study

An extensive sampling programme was conducted in Area #1 with some sampling of "fresh" tailings from Area #2 for reference. Based on the results of the 1988 study, three sites in Area #1 representing a range of oxidation and contaminant migration profiles were selected for detailed sampling. Surface and geotechnical samples were collected in the backfill sands storage area. Surface and test pit samples were collected from the Emergency Pond.

The Emergency Pond shown in Figure 1 was used intermittently from 1968 to 1984 and contained primarily raw tailings (not cycloned). Recent excavation work by mine personnel in and around the Emergency Pond revealed visible oxidation at various depths. Hence this area was included in the sampling programme. Table 1 summarizes the samples collected and the analyses conducted.

TABLE 1

ELEMENTS OF THE 1989 STUDY

<u>SAMPLE TYPE</u>	<u>LOCATION</u>	<u>ANALYSES</u>
<u>Surface Solids</u>	Areas 1 and 2, Emergency Pond, and Backfill Sands	<ul style="list-style-type: none"> • Paste pH • Total metals on selected samples
	Areas 1 and 2	<ul style="list-style-type: none"> • Total and dissolved metals • pH, Acidity, Alkalinity, • Sulphate, Conductivity
<u>Test Pits</u>	Area 1	<ul style="list-style-type: none"> • Paste pH
	Emergency Pond	<ul style="list-style-type: none"> • Shake Flask Extractions: • pH, Eh, Acidity • Conductivity, Sulphate • ICP for metals • Acid/Base Accounting • Total metals on selected samples
<u>Pore Waters</u>	Area 2	<ul style="list-style-type: none"> • pH, Eh, Acidity
	Emergency Pond	<ul style="list-style-type: none"> • Conductivity, Sulphate • ICP for metals
<u>Geotechnical</u>	Area 1	<ul style="list-style-type: none"> • Specific Gravity, Bulk Density
	Emergency Pond	<ul style="list-style-type: none"> • Moisture Content, Porosity
	Backfill Sands	<ul style="list-style-type: none"> • Void Ratio, Degree of Saturation
<u>O₂/CO₂ Gas Measurements</u>	Area 1	<ul style="list-style-type: none"> • Measurements with depth
	Emergency Pond	

2.0 SAMPLING METHODS AND ANALYTICAL PROCEDURES

2.1 Surface Sediment Samples

The surface sampling pattern of Area #1 and the backfill sands is shown in Figure 3. A grid was established of 5 lines approximately 50 or 100 m apart extending from the back drain towards the subaerial spray bar beach. A total of 39 samples were collected along these lines, sampling at 10, 30, 60, 80, 100, 120, 140, 160, and 170 m. Line L-L was located approximately where line E-E of the 1988 study was located (Broughton and Ferguson, 1989). Line E-E was most extensively studied in 1988.

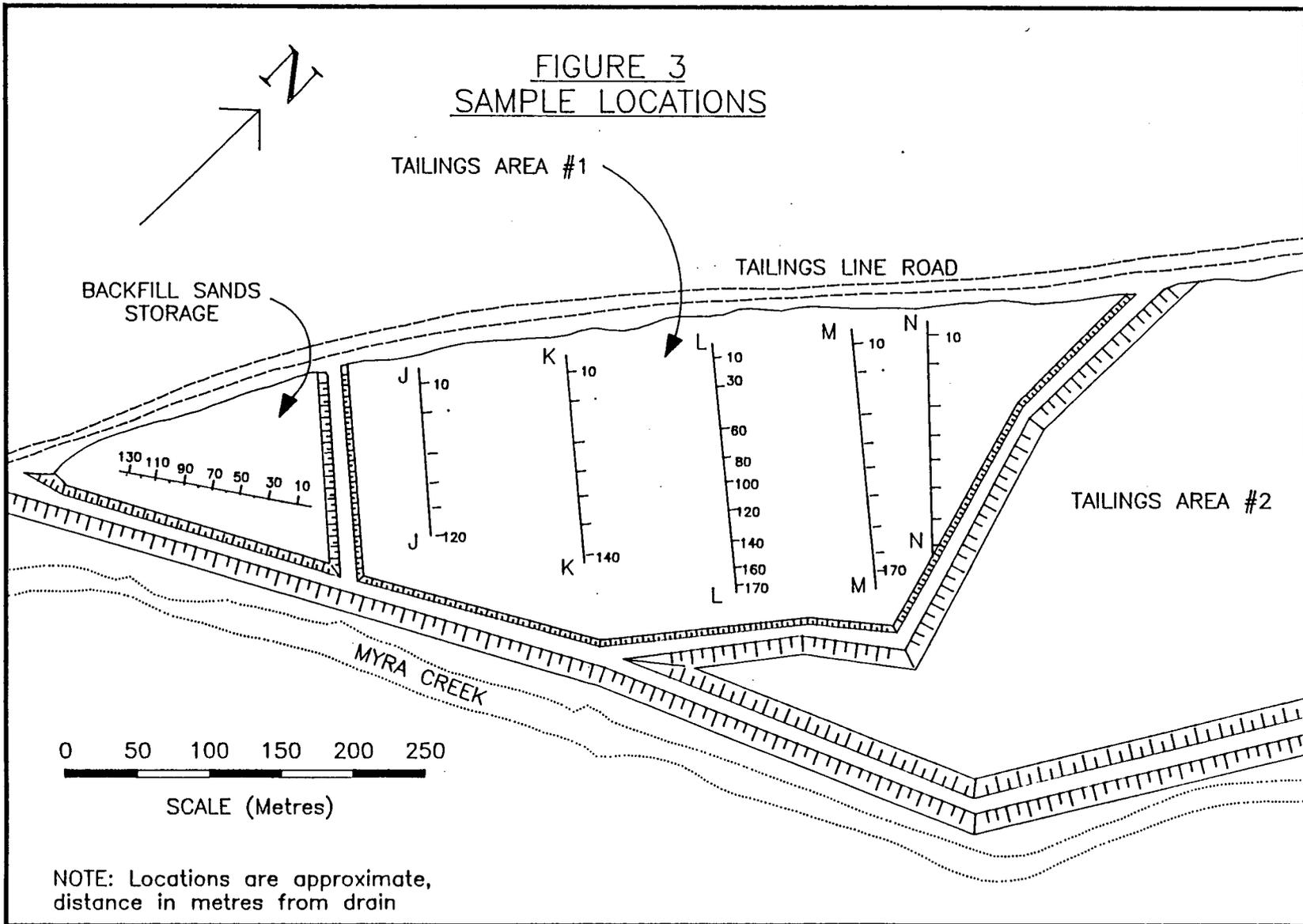
Two types of samples were collected from Area #2; duplicate samples of "fresh" tailings from the northern corner near the tailings discharge point, and duplicate samples of "old" tailings (one month) from the beach adjacent to the southern berm between Areas #1 and #2. Surface samples were collected from the backfill sands storage area along a line approximately northeast-southwest, at intervals of 10, 30, 50, 70, 90, 110, and 130 m. This line was selected by observation of the sands to cover a variety of types, ages and moisture content of material.

The Emergency Pond was sampled using two intersecting lines of surface sampling. Line "A" ran approximately northwest by southeast for 130 metres, stopping at the test area. Line "B" ran at right angles to "A" for 80 meters and intersected A at EPA 30. Ten sediment samples were collected.

Surface samples were collected by recovering approximately the top 2 cm of tailings and placing them in whirl pak bags. Samples for total metals analysis were stored in paper assay bags immediately upon recovery. Samples were stored in a cool environment and transported to the Environment Canada Laboratories in West and North Vancouver for analysis.

At the EP North Vancouver laboratory, analyses for paste pH were conducted according to procedures outlined in Sobek *et al.* (1978); representative 10 g subsamples were mixed with approximately 20 g of water and measured with a hand held probe. Selected samples were analyzed for total metal content by ICP at the West Vancouver Chemistry Lab. Observations of sample particle size (ie. sand, silt, clay), colour, and moisture content were also made to compare with field observations.

FIGURE 3
SAMPLE LOCATIONS



Shake flask extraction tests were conducted to determine the water soluble fraction of the tailings, using the same procedure as previous years. This procedure was a modification of procedures described by B.C. Research in Report 60601 (Steffen, Robertson and Kirsten, 1987a). A tailings subsample was oven dried overnight at 110°C and 25 g of tailings diluted with 500 mL of distilled water. The mixture was placed on a shaker table for 22-24 hours and decanted through a GFC filter to remove solids. The solution was sampled for pH, sulphate, alkalinity and acidity analyses. Solution pH and ORP was measured immediately. The remaining solution was filtered through a 0.45 micron Sartorius membrane, acidified and submitted for ICP dissolved metal analysis (at the EP West Vancouver lab). These tests were conducted on the surface samples from Area #2.

2.2 Surface Water Samples

Surface water samples relevant to this study were collected of impoundment supernatant in Area #2, and from samples of fresh tailings which were allowed to settle. These samples were collected in duplicate, preserved appropriately for the various analyses and transported to the West Vancouver laboratory for analysis. Analyses included total and dissolved metals by ICP, pH, alkalinity, acidity, sulphate, and conductivity.

Pore water samples were also recovered from the two tailings solid samples using a pore water squeezing technique developed by Dr. Ken Reimer of Royal Roads Military College, and described in more detail in Section 2.5.

2.3 Geotechnical Samples

The seven samples collected for geotechnical analyses from Area #1, backfill sands, and Emergency Pond were recovered using pre-weighed stainless steel cans. The cans were punctured at the end to allow air to escape and pushed into the tailings. After maximum penetration, the surrounding tailings were excavated and the edge of the tailings at the can edge cut with a taut string. The samples extended to different depths due to the variable sizes of the sampling cans.

These geotechnical samples were collected from the surface layers of each pit along the L-L line,

both of the pits in the Emergency Pond, and two samples from the backfill sands surface at stations BS30 and BS70. Each can was weighed on-site with and without the tailings sample using a triple beam balance. Samples were carefully bagged and transferred to the EP warehouse. The samples were then dried and reweighed, and the volume of each can determined. Classification of the materials as sand/silt/clay was made by observation of the samples; the previous year's study (Broughton and Ferguson, 1989) having indicated that observed descriptions in the field and measured size classifications corresponded well.

2.4 Depth Profiles

Depth profiles of the tailings were obtained from test pits in Area #1 and the Emergency Pond located as shown in Figures 2 and 3. A total of 5 test pits were excavated by hand to a depth of about 1 m. A hand held auger was then used to continue sampling to a total depth of approximately 4.5 metres in Area #1, and 3 metres in the Emergency Pond, varying with the material encountered in the test pit. The primary concern in Area #1 was to excavate below the most recent application of tailings, and to excavate as far as possible into the "old" or previously sampled tailings.

In Area #1, these pits were excavated along the L-L line, near the centre of Area #1 extending from the backdrain to subaerial spray bar beach. Two test pits were excavated in similar fashion in the Emergency Pond.

Immediately after excavating each test pit, the layers were logged and sampled by scooping tailings material into whirl pak bags. Discrete layers were visually identified in each pit according to grain size (sand or silt), colour (orange, yellow, etc.), and/or water content (dry, moist, wet).

All samples were transported to the Environment Canada labs for analysis. Paste pH measurements were made on all samples, and total metals analyses were conducted on selected samples using the procedures outlined above. Five samples from the Emergency Pond were selected and sent to Chemex Labs in North Vancouver for acid-base accounting work (neutralization potential, sulphur species, maximum potential acidity, and paste pH). Shake flask tests to determine the water soluble fraction were conducted on all samples using the procedures described above.

2.5 Pore Water Recovery

The recovery of pore waters was conducted using a procedure recently developed and tested by Dr. Ken Reimer of Royal Roads Military College. The objective was to characterize the actual drainage water in the tailings mass. Pore water samples were extracted from solid samples from Area #1, 2 and the Emergency Pond.

In previous studies, the relative concentration of dissolved metals in the tailings solids was estimated using shake flask extraction tests. These solid samples were diluted in this procedure and it was difficult to estimate in-situ concentrations. Also, the effect of sample preparation and dilution on solution chemistry could not be quantified. The recovery of undiluted pore waters from tailings samples was therefore important to determine the extent of metal leaching and the actual in-situ contaminant concentrations. There was concern over potential changes in solution chemistry between the time of field sampling and lab testing. Therefore a procedure that could recover pore water on site and preserve the samples for analysis was required. This technique was selected for recovery of pore water samples on site, to eliminate potential changes in pore water chemistry during transportation to a laboratory with appropriate equipment, such as a centrifuge.

Dr. Reimer developed a technique and field equipment for lake and marine sediment sampling and he accompanied the sampling team on-site to test the procedure on the Westmin samples. The technique was a "squeeze" extraction procedure in which a sample of tailings solids was placed in a plastic "donut" and covered with a rubber diaphragm prior to sealing with a plastic cover. Nitrogen gas was then forced under pressure onto the surface of the diaphragm which effectively "squeezed" the sample, forcing much of the contained pore water out of the sample. The entire procedure, including loading the cell, was conducted under a nitrogen atmosphere to prevent changes in speciation.

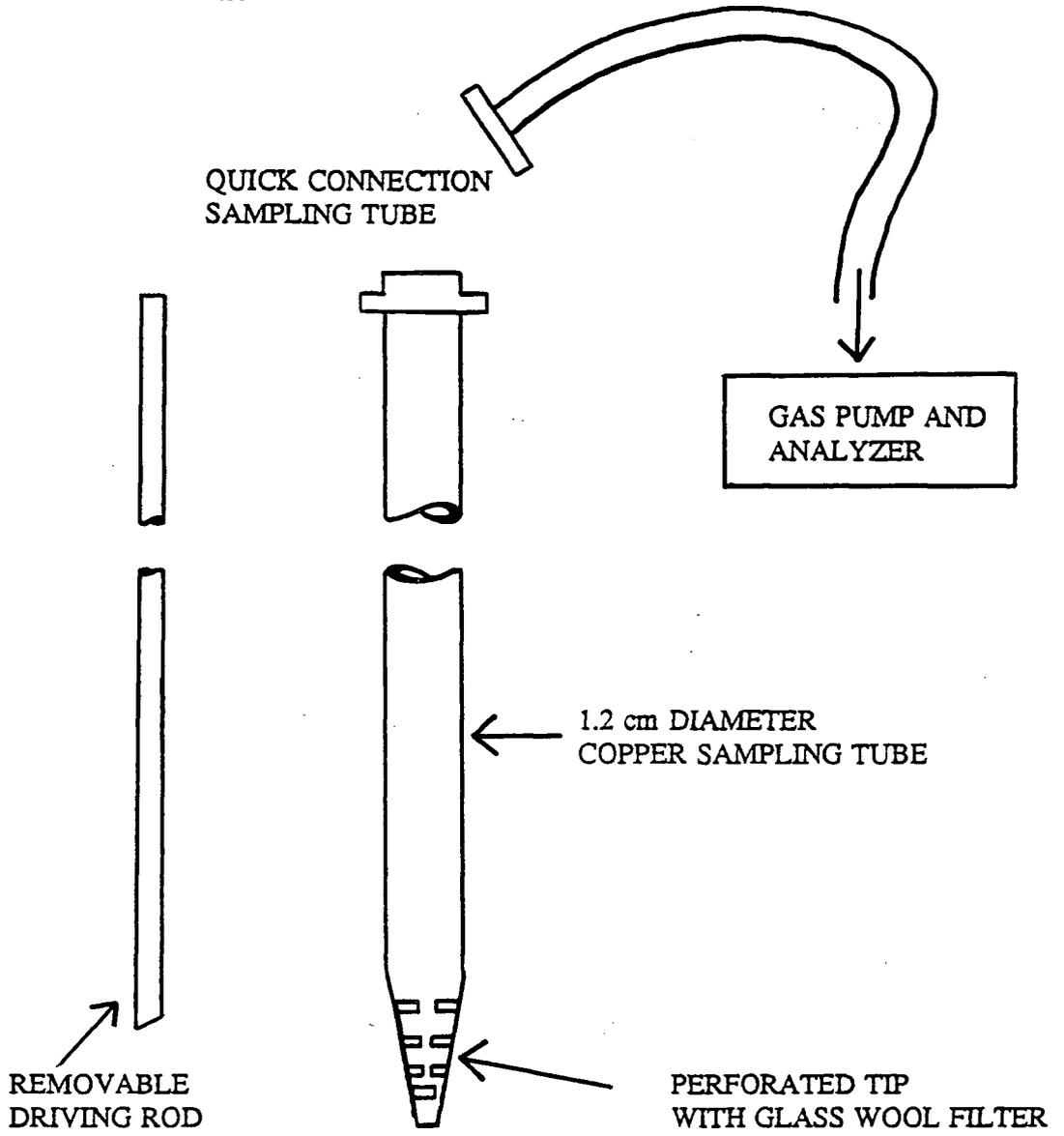
Pore water samples were collected in a series of nitrogen purged bottles and then immediately frozen with dry ice for preservation until analysis by Dr. Ken Reimer at his laboratory at Royal Roads Military College. Subsamples of each were also transported to the West Vancouver laboratory for analysis, consisting of total metals by ICP and pH, conductivity, sulphate, and acidity, depending upon the amount of sample available.

Recovery of pore water from tailings solids, particularly coarse materials even if saturated, is complicated by the relatively small solution volume and the degree of residual saturation. These tailings samples were typically drier and coarser than the marine sediments for which the equipment was originally developed and pore water recovery was most successful for wet silty materials.

2.6 Oxygen and Carbon Dioxide Gas Measurements

Measurements of oxygen and carbon dioxide concentrations were made in Area #1 and the Emergency Pond to determine the extent of oxygen diffusion and consumption over depth in the tailings. The instruments used for sampling in the tailings were made in the Environment Canada lab as shown in the diagram of Figure 4. A 1.5 cm diameter copper probe with a slotted tip was inserted into the tailings in 10 cm increments for sampling, as marked on the outside of the probe to a maximum depth of 1 m. A solid rod was inserted into the probe for insertion into the tailings, and removed to allow air flow during sampling. Tubing was attached to the exposed end of the probe with an easily connected fitting, and attached to the gas analyzer for sampling. A Nova O₂/CO₂ portable analyzer was used to measure gas concentrations at depths down to 1 metre in the tailings.

FIGURE 4 GAS SAMPLER



3.0 RESULTS AND DISCUSSION

Section 3.1 discusses the results of the surface sediment sampling conducted in Areas #1 and #2, the backfill sands storage area, and the Emergency Pond. Sediment samples were collected for paste pH with selected lines of samples also analyzed for total metals. Neutralization potential and paste pH values are calculated for samples on which total metals were measured.

Section 3.2 summarises the results of surface solution sampling in Area #2. Analysis of these water samples included pH, acidity, alkalinity, sulphate, conductivity, and total and dissolved metal contents. Both surface water and pore water samples are discussed.

In Section 3.3 the results of the geotechnical sampling in Area #1, the backfill sands storage and the Emergency Pond are presented. Section 3.4 discusses the results of the geochemical testing and test pit sampling in Area #1 and the Emergency Pond, including test pit logs, paste analyses, laboratory testing with shake flask extraction tests, pore water sampling, and pore gas sampling. The results of these analyses are compared with corresponding results of the previous year's survey to evaluate the changes that occurred over the intervening 14 months.

The geochemical and geotechnical results presented in this section are further discussed in Section 5, to develop an overall evaluation of the progress, and controlling factors, of acid generation and contaminant migration in the tailings impoundment.

3.1 Surface Sediment Samples

3.1.1 Tailings Impoundment General Appearance

The tailings surface in Area #2, in which tailings were being deposited at the time of this study, was dark grey with a shallow pond covering over half the surface. Most of the tailings in Area #2 were deposited subaerially through spray bars located along the southeast side of the impoundment (along the main access road as shown in Figure 2). Raw (not cycloned) tailings were also deposited by steady addition through the rear spigot when the backfill plant was down. The tailings in Area #2 drain to the northeast corner of the area, covered by the pond water at the time of sampling. The tailings surface was generally dark grey in colour and very wet.

Samples of tailings from Area #2 were taken at the tailings discharge point (fresh tailings), and at the southeast corner of the area, near the end of the berm dividing Areas #1 and 2. This tailings material was thought to be approximately one month old and deposited primarily by spigotting. Samples were taken very close to the berm as the tailings were too wet (unstable) to walk out on. Large cracks, from 5 to 15 cm in width were evident in this eastern corner, and some surface drainage channelling. There was some limited orange coloration indicating oxidation at the surface along cracks or transport of oxidation products down cracks in this area.

The surface of Area #1 showed more distinctions in colour and a varied pattern of surface cracking. Variations in colour related to both surface oxidation and variable moisture content. The darker, grey areas near the centre of Area #1 were wetter, silty material with some surface water ponding near the back drain. Extensive surface cracking was evident in this area with cracks ranging from 2 to 10 cm in width and at least 5 cm in depth. It was difficult to measure the depths of these cracks as the material was soft and relatively plastic, deforming easily. The browner and lighter grey areas of the impoundment generally corresponded to drier and sandier material. The surface of the tailings became sandier with much finer cracking towards the backdrain and the northeastern side of the impoundment.

3.1.2 Paste Analyses

Area #2

The results of paste analyses of the duplicate samples taken of fresh and one month old tailings samples are summarized in Table 3. The samples were all very wet, dark grey silts with some sand and visible sulphide (pyrite). These coarse tailings with visible pyrite differed from tailings deposited subaerially due to the lack of sand/slime separation usually accomplished in the cyclone stage. After drying, the samples appeared to be silty sands although fractional analyses were not conducted.

The paste pH values of both the fresh and one month old samples were slightly alkaline. The results did not indicate a significant change in pH over the one month period, although one of the older samples had a slightly higher pH of 8.3. This may be related to changes in the milling circuit (particularly pH modification) or tailings processing (cycloning). In the 1988 study, no significant change in pH was noted for tailings ranging in age from fresh to six months. In general, the paste pH

of the tailings was slightly higher in 1989 than in the previous year; again this may be related to changes in the ore, milling circuit or tailings processing.

TABLE 2
SURFACE SEDIMENT PASTE pH - FRESH TAILINGS

SAMPLE	AGE	PASTE pH
	(weeks)	(pH units)
<hr/>		
1989 SURVEY		
FRESH 1	< 1	7.6
FRESH 2	< 1	7.7
OLD 1	4	7.8
OLD 2	4	8.3
1988 SURVEY		
SUB 1-3	< 1	6.9
SUB 4-6	12	6.6
SUB 7-9	24	6.8

Area #1

The results of the paste pH analyses of surface samples from Area #1 are summarized in Figure 5 where lines of approximately equal pH are drawn. Tabulated results of paste analyses are provided in Appendix 1. Although the sampling intervals were relatively large, the results indicated a pattern of pH depression similar to that noted in the 1988 study. The degree and areal extent of the impoundment surface exhibiting low pH values, however, was much less than in the previous study, a function of the shorter period of exposure. These tailings were deposited relatively recently over top of the surface

sampled in 1988 and had been exposed for approximately six months at the time of the study. The 1988 study sampled surface material that had been exposed for approximately 30 months.

The surface of the tailings ranged from neutral to acidic values (7.1 to 2.6). Generally the lowest pH values were in the northeast corner of the impoundment near the decant tower and along the backdrain from line L-L to N-N. These low pH areas also showed significant orange/yellow coloration indicating oxidation of the tailings surface. Descriptions of the samples along line N-N (near the decant area) indicated that the surface material in this area was drier and sandier than the most of Area #1, being composed of very dry loose sands varying from grey/white coarse sand to brown/yellow sand with visible sulphide minerals.

There was also evidence of previously ponded water in this northeast corner of the impoundment. A surface drainage channel, which was dry at the time of sampling, was noted about 10 m in from the backdrain and again orange/yellow coloration was evident.

Areas of higher pH, ranging from 5.0 to 7.1 along the J-J and K-K lines, corresponded to the wetter, siltier areas of the impoundment. Samples along the J-J line were all described as wet, grey silts except J60, a silty sand. A pocket of low pH (less than pH 4) was located near L60 to L90 and across to M80 to M100. These samples were generally observed to be moist to dry yellow/brown sands, in contrast to the more silty, wet, grey samples with more alkaline pH values surrounding this pocket.

The physical descriptions and patterns of surface oxidation and pH depression are similar to the results of the study by Ferguson (1987) of the previous tailings surface after six months exposure. The results seem to indicate that oxidation was inhibited when the tailings were wet, but that relatively rapid pH depression occurred on the surface when the tailings solids dried out. The variation of paste pH with the type of material and moisture content was postulated in earlier reports (Broughton and Ferguson, 1989; Ferguson, 1987) and supported by this surface sediment sampling. These data from the surface sediment sampling indicated qualitatively that paste pH varied directly with increasing silt content and moisture content for most samples (particularly L-L).

Backfill Sands

The paste pH values for the backfill sands area ranged from a low of 3.0 to near neutral 6.0 as summarized in Table 4 and appeared to be related to moisture content and age of the sample (i.e. exposure). All samples were brown sands, with occasional orange blebs. Exact ages of samples were not available. Samples BS10 through 50 appeared to have been deposited for some time (several weeks to months) with apparent oxidation correlated with visible orange coloration at BS30. Samples BS30 and BS50 were located on a slight rise of sands, appeared relatively undisturbed and were acidic, with pH values of 3.0 and 3.8. Sample BS10, however, was in a low lying wet area and exhibited a pH of 5.7.

Sample BS70 was located in a freshly exposed area (as shown in Figure 3) and had a paste pH similar to samples BS90 and BS110 (pH 5.1 to 6.0) which were located in water channels leading to the pool at the edge of the sands storage area. The material previously overlying this sample had recently been moved and possibly limited the access of air to these solids, thereby reducing the rate of acid generation. Within the water channels, it is possible that the water cover limited oxidation and acid production. A slightly acidic pH (4.5) was evident in the last sample along the line at BS 130, beside the water pool.

The results of these paste analyses showed that oxidation and acid generation were indeed occurring in the backfill sands as predicted in initial testwork (Ferguson, 1986). Samples of these backfill sands in 1988, however, did not indicate any acid generation, although one sample was thought to be at least three years old. It is not clear why oxidation was not detected in the previous sampling program, although the degree of exposure of the sands and moisture content may have limited oxidation previously.

Emergency Pond

The Emergency Pond contained tailings deposited at various times up to 1984. Most of the tailings were deposited prior to the development of the HW ore zone with a significantly lower sulphide content.

The surface of the Emergency Pond was generally uniform in appearance; predominantly dry

to slightly moist grey/white sands. The appearance of these tailings was much different than tailings from the subaerial impoundment, with no visible sulphide mineralization. The drainage and decant area in the centre of the pond was dry at the time of the sampling and exhibited marked orange/white coloration as evidence of oxidation and evaporation. Paste pH values were generally near neutral ranging from 5.7 to 6.9 with the exception of one sample, at 2.5. This sample, EP 70, was located within the oxidized area of the drainage ditch. There were no visible sulphides in these samples.

3.1.3 Total Metals Analyses

Area #1 and Area #2

Results of the total metals analyses of samples collected along the L-L line are detailed in Appendix 1, summarized in Table 3, and presented graphically in Figure 6. Total metals analyses were

TABLE 3
SUMMARY OF SURFACE TOTAL METALS ANALYSES ALONG L-L

SAMPLE	pH	Ca	TOTAL METALS (mg/g)		
	paste	ug/g	Cu	Fe	Zn
L10	2.6	670	1.17	405	1.84
L30	5.5	1990	1.44	251	5.86
L60	3.5	1800	1.311	382	2.44
L80	2.8	1300	0.898	266	1.97
L100	5.3	3820	1.41	338	4.12
L120	5.1	5680	1.73	275	8.56
L140	6.1	8220	1.79	249	8.87
L160	5.4	6230	1.85	245	9.07
L170	6.3	8070	1.95	242	9.49

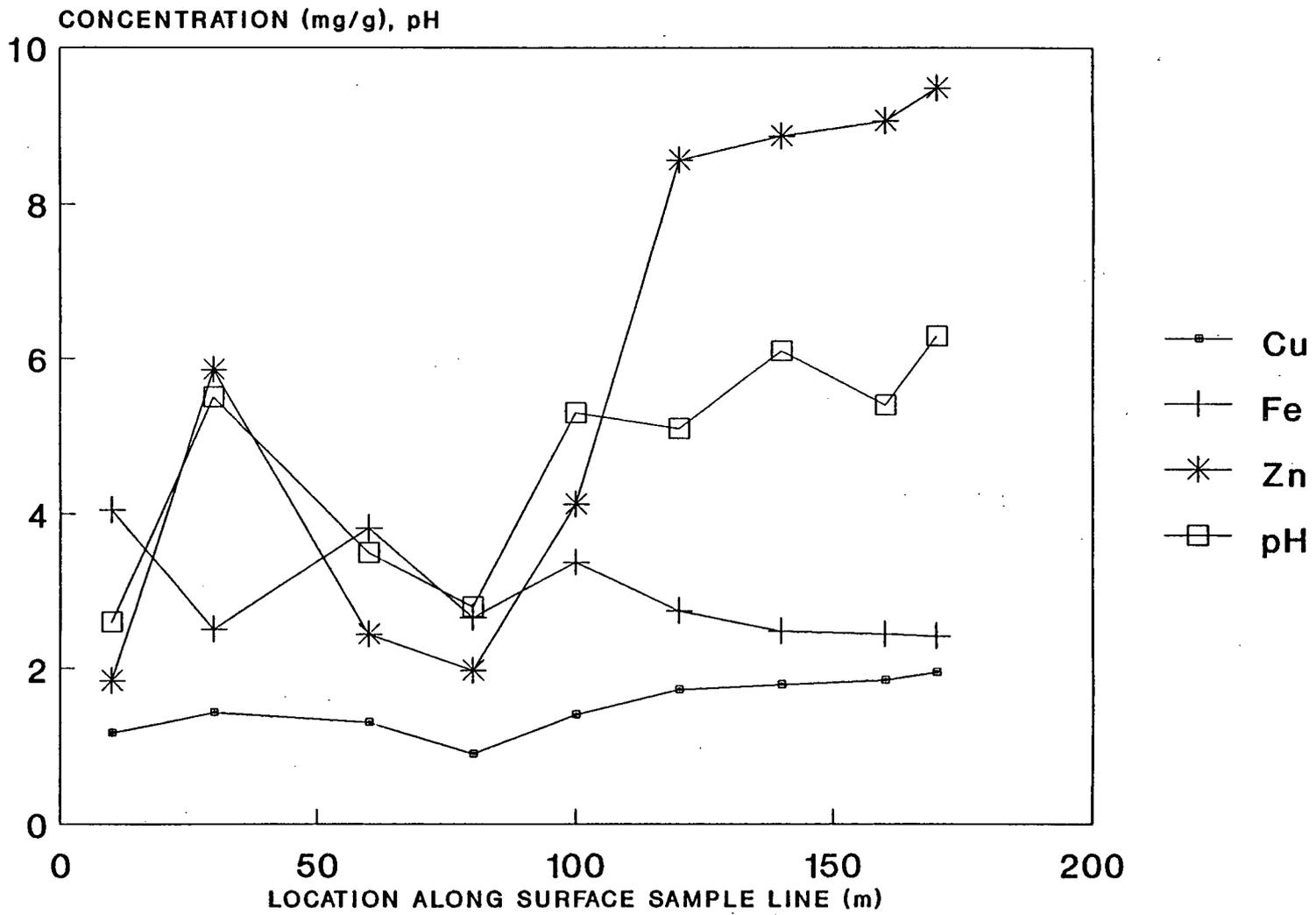


FIGURE 6 TOTAL METALS AND pH - AREA #1

not conducted in this survey on samples of fresh tailings. However, an earlier total metals analysis of tailings from the HW ore was available for comparison (Knight and Piesold, Dec. 1986; Ferguson, 1987).

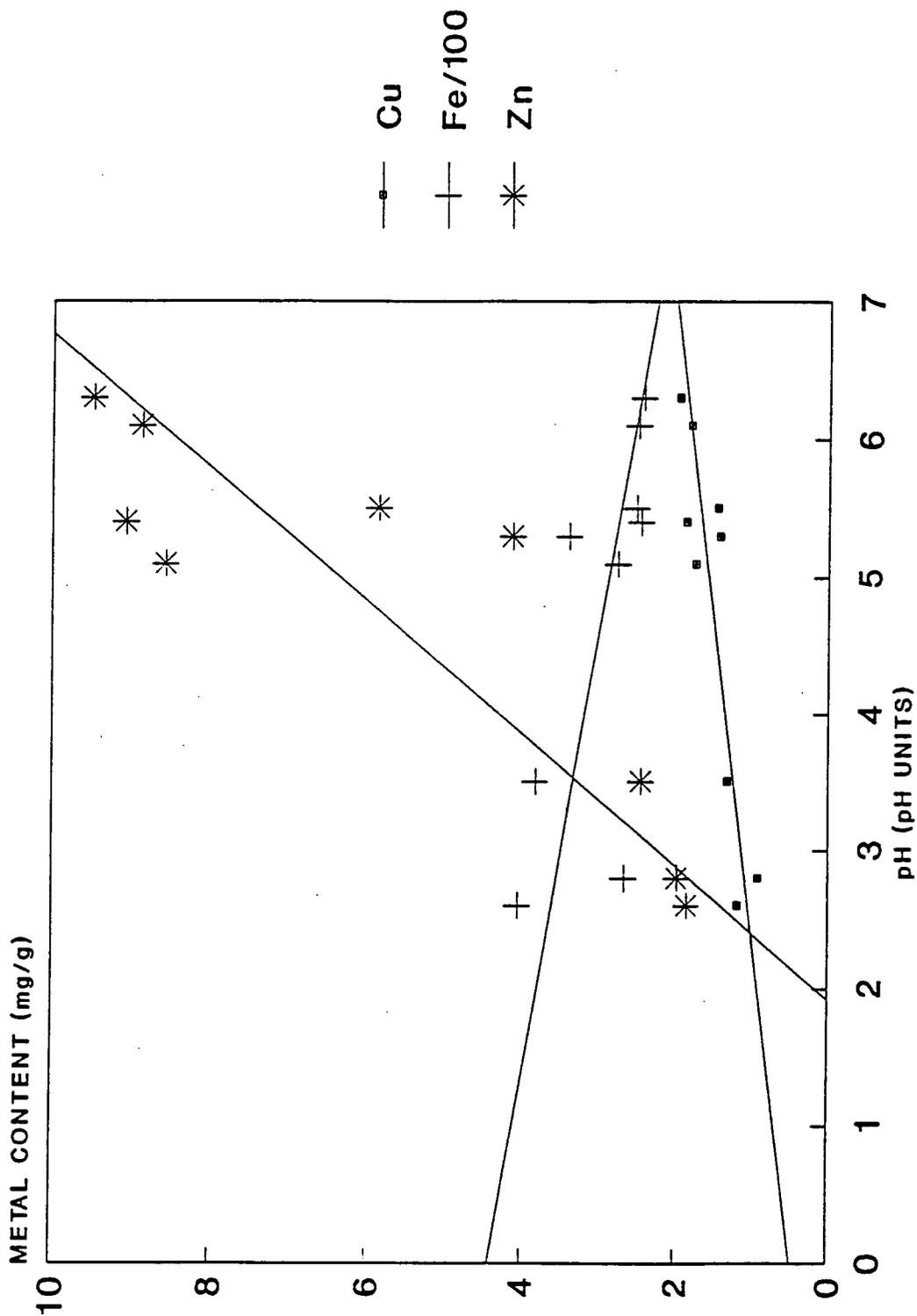
These metal analyses can be useful indicators of the extent of metal leaching that has occurred in the tailings impoundment. At least three mechanisms could be active in controlling the metal concentrations in the surface solids:

- i) solution of soluble sulphides as pH drops below mill effluent pH of approximately 11,
- ii) acid generation from oxidation of sulphides and leaching of metals,
- iii) surface runoff of acidic drainage containing elevated metal levels followed by evaporation and precipitation of metal salts.

Total copper and zinc concentrations were highest at sites closest to the spray bar beach: sites L120 to L170. Iron values at these sites were typical or slightly lower than the H.W. tailings, ranging from 24.2 to 27.5 %. The concentration of copper in the solids ranged from 1.73 to 1.95 mg/g, and zinc concentrations ranged from 8.56 to 9.49 mg/g. These sites also had higher paste pH values, ranging from 5.1 to 6.3, probably due to the higher moisture content. Field and laboratory descriptions of these samples and L30 were generally wet, silty material, which in previous testwork also tended to exhibit higher pH and less oxidation. Previous reports have also indicated that segregation of dense sulphide minerals due to gravity concentration can occur on the fluvial plane, tending to concentrate high iron and sulphide minerals near the spray bars.

Total metals concentrations were lowest at site L80, with a paste pH value of 2.8; Cu of 0.9 mg/g, Fe of 26.6 % and Zn of 1.97 mg/g. Metal concentrations were also low at site L10, with the lowest paste pH, 2.6. The concentration of iron was elevated at this location at 40.5 %, probably due to deposition of iron salts from acidic runoff. Significant iron and salt staining was evident in the orange (iron oxides and hydroxides) and white (aluminum hydroxides and sulphates) precipitates at site L10 which was located at the apparent edge of a former drainage channel. This site was closest to the backdrain in Area #1.

FIGURE 7 METALS AS A FUNCTION OF pH - SURFACE TAILINGS AREA #1



The effect of pH on the total metals concentration was considered in Figure 7. A correlation between pH and Zn and Cu concentrations was apparent. As sample paste pH decreased, the total metal content also decreased. Linear regression analyses showed that the relationship between pH and copper (Equation 1) and zinc (Equation 2) concentrations could be approximated by the equations:

$$[\text{Cu}] = 0.22 \text{ pH} + .47 \quad \text{where } r^2 = 0.87 \quad (1)$$

$$[\text{Zn}] = 2.07 \text{ pH} - 3.97 \quad \text{where } r^2 = 0.88 \quad (2)$$

These relationships suggest that zinc was removed from the tailings solids much more rapidly with pH reduction than copper, and was mobilized at more alkaline pH values reflecting the relative solubility of zinc and copper. Based on the data from this sampling, the total copper content was reduced from 1.95 mg/g at pH 6.3 to 0.9 mg/g at pH 2.8, a decrease of 54 %. Total zinc content was reduced by almost 80 % over the same interval. Zinc is mobilized (leached) at higher pH than copper; becoming increasingly soluble below pH 10 (in the interstitial water), whereas copper is least soluble at pH 8, and increasingly soluble below pH 6.0. As can be seen in Figure 7, zinc concentrations varied much more significantly above pH 6 than did copper. Iron values did not vary as directly with pH as did copper and zinc, possibly due to iron participation in the oxidation reactions, rather than simply direct leaching as copper and zinc.

While some variability in total metal content could be expected from sampling bulk sulphide tailings, the above relationships indicate that oxidation of the sulphide minerals and mobilization of copper and zinc have occurred at the surface of the tailings, reducing the copper and zinc contents as a function of oxidation and decreased pH. These sites (L10, 60, and 80) for which changes in metal content were noted were all described as sands, varying from yellow/orange to brown. Well drained sands tended to exhibit more rapid oxidation, and thus metal leaching, and more rapid flushing than in silty materials (Broughton and Ferguson, 1989).

Backfill Sands

The backfill sands consisted of the coarse fraction of cycloned tailings material stored for use as mine backfill. This material differed from tailings material deposited in Area #1 in both size distribution and mineralogy, due to the processing. The cyclone stage concentrated the coarser and

higher density particles, particularly sulphides, into the backfill sands and removed the finer particles and less dense carbonate minerals to the tailings. The deposition and removal of material in the sands storage area is also a batch process, resulting in zones of different types of material and different degrees of exposure of the sands than in the layered tailings impoundment.

Changes over time in the total metal distribution in each sample would be affected by similar mechanisms as the tailings. The original material, however, would be slightly different. Variations in mill feed over the deposition time period would also affect the type of material in Area #1 versus the backfill sands. The coarser particle size distribution of the backfill sands as compared to the tailings slimes might also affect sulphide reactivity. Coarser particle size would mean less total surface area per unit mass and typically decreased oxidation rate. These factors must be kept in mind when comparing samples within the backfill sands storage area and with Area #1 tailings samples.

Generally the backfill sands had more consistent metal distributions than the tailings in Area #1, possibly due to more uniform size distribution and deposition patterns. The backfill sands typically

TABLE 4
SUMMARY OF SURFACE TOTAL METALS ANALYSES - BACKFILL SANDS

SAMPLE	pH	Ca (ug/g)	TOTAL METALS (mg/g)		
			Cu	Fe	Zn
BS10	5.7	5350	2.14	273	7.51
BS30	3.0	690	1.90	342	6.02
BS50	3.8	850	1.39	270	5.03
BS70	5.1	570	1.80	393	7.22
BS90	5.1	5050	2.40	324	4.85
BS110	6.0	3660	3.13	352	8.18
BS130	4.6	2890	1.65	350	3.34

FIGURE 8 TOTAL METALS AND pH - BACKFILL SANDS

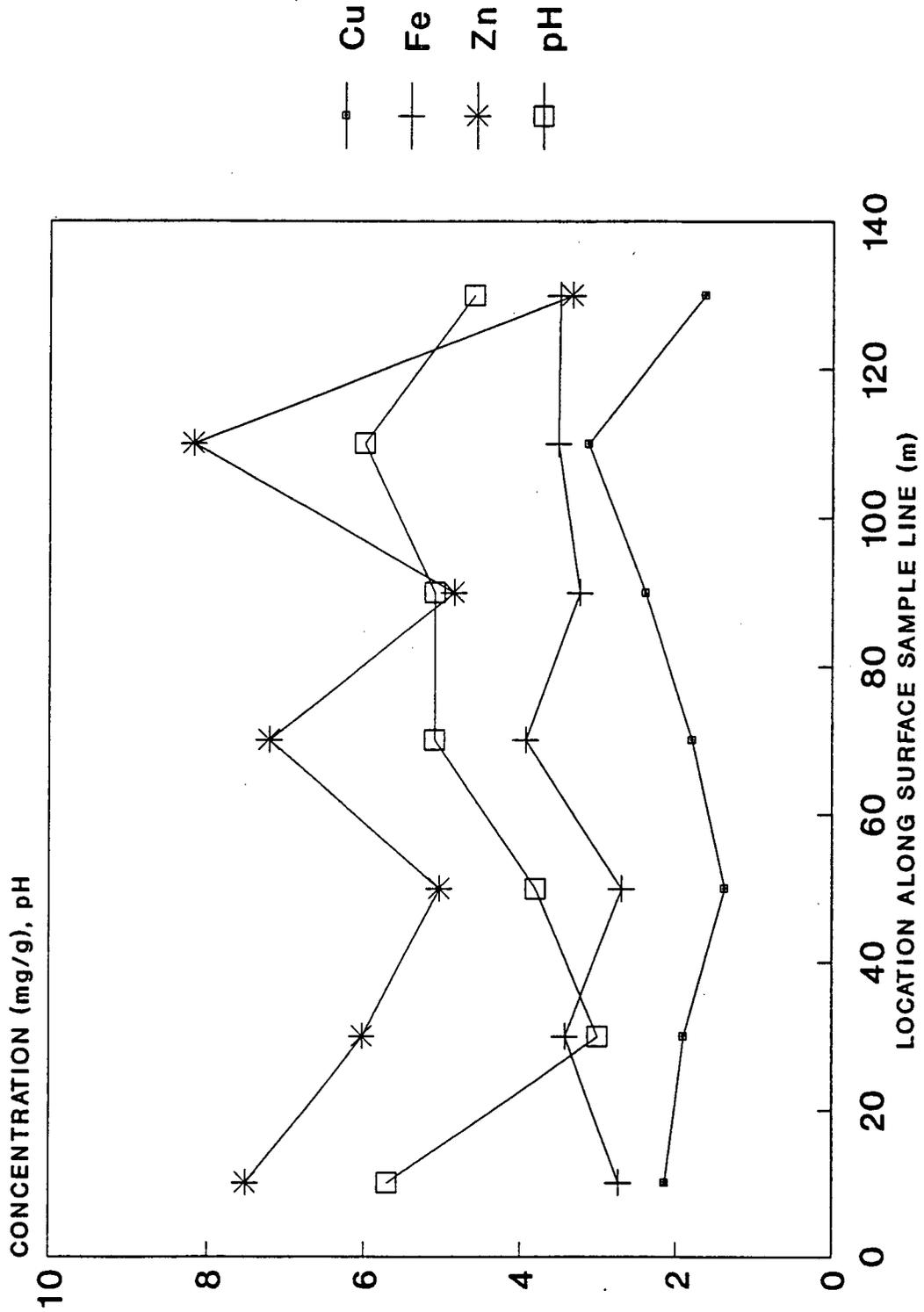
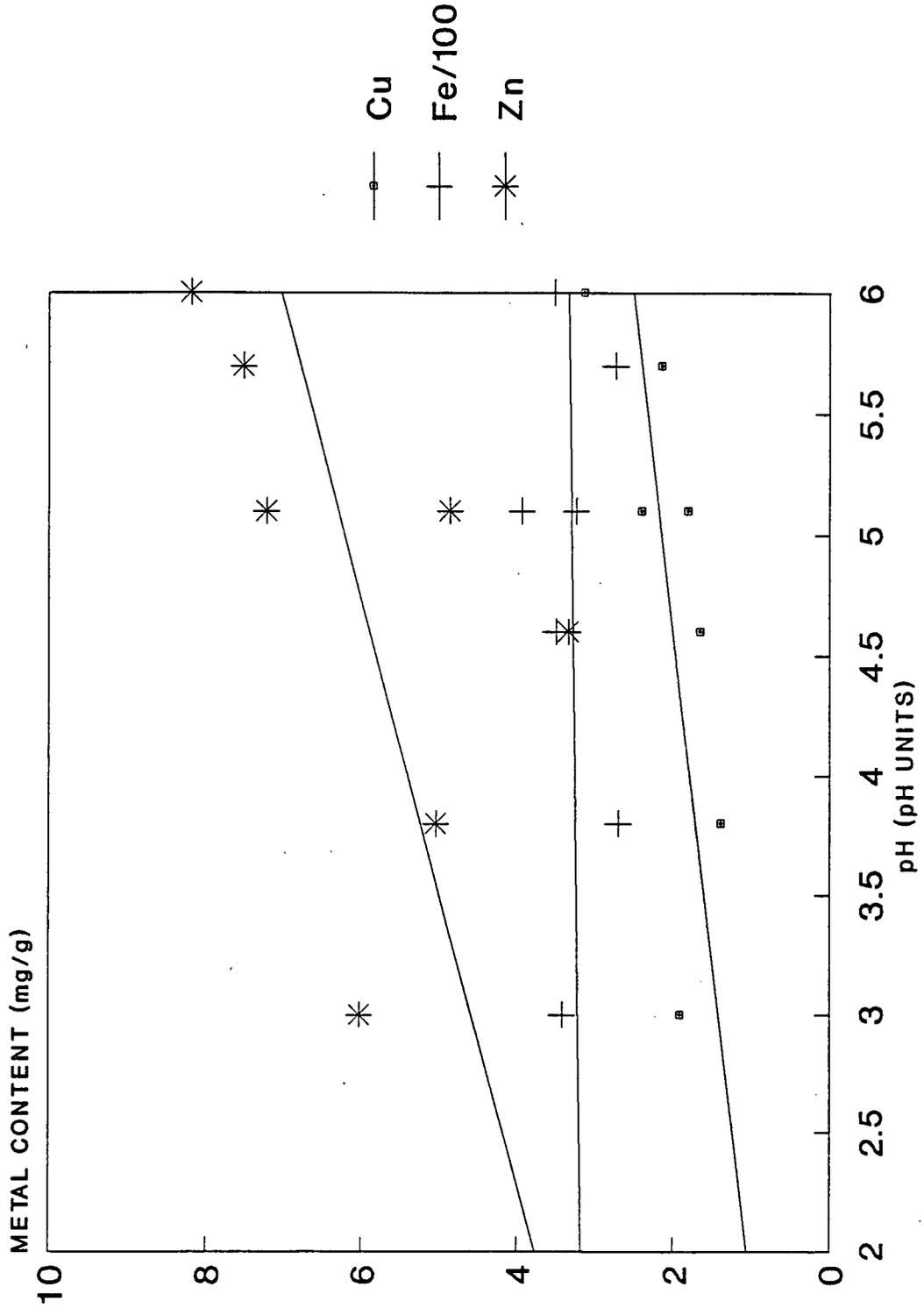


FIGURE 9 METALS AS A FUNCTION OF pH - BACKFILL SANDS



showed lower metal concentrations than the tailings particularly Al, Ca, K, Mg, Mn, Pb, Si and Zn. Total copper and iron concentrations were slightly higher in the backfill sands. The detailed results of the backfill sands total metal analyses are provided in Appendix 1 and summarized in Table 4.

The correlation between low pH and low metal concentrations was not as obvious in the backfill sands as in the tailings, as shown in Figures 8 and 9. Copper, zinc and iron values were low at sites such as BS30 and BS50 with pH values less than 4. Copper values, however, were also low at BS70 with pH 5.1, and copper and zinc at BS130 with pH 4.6. Copper, zinc and iron were relatively high at site BS 110 with a pH of 6.0. Linear regression analyses for pH with each of the metals did not result in correlation coefficients greater than 0.66 for pH/Cu, and 0.5 for pH/Zn.

Generally the iron values in the backfill sands samples were similar or slightly higher than in the surface tailings solids in Area #1, indicating that the (iron) sulphide content of the backfill sands was similar to the tailings slimes in Area #1. As shown in Tables 3 and 4, the tailings samples averaged 29.5 % Fe and the backfill sands 33 % Fe. Total copper and zinc values were also slightly higher in the coarse sands than in the tailings.

3.1.4 Calculation of Neutralization Potential and Paste pH

The neutralization potential of a sample typically reflects the carbonate mineral content. Previous testwork at this site has shown that the total calcium measured in a sample can be used to estimate neutralization potential (Ferguson, 1987, 1986) using relationships developed from these studies, as shown in Equations 3 and 4. The slope of the line in Equation 3 was similar to the stoichiometric ratio of calcium to calcite, 0.00249, indicating calcite was the main carbonate mineral present.

$$\text{Neutralization Potential} = 0.00254 \text{ Ca} + 6.8 \quad (r^2=0.92) \quad (3)$$

$$\text{Neutralization Potential} = 0.00578 \text{ Ca} - 5.4 \quad (r^2=0.99) \quad (4)$$

In the 1987 report, paste pH values were also predicted from calcium content:

$$\text{paste pH} = 2.45 \ln \text{ Ca} - 14.1 \quad (5)$$

Similar calculations were conducted for the 1989 test program for surface samples for which total metals analyses were conducted; backfill sands and line L-L in Area #1. To predict neutralization potential, which was not determined in the test program, the relationships between the calcium content

and the neutralization potential described by Equations 3 and 4 were applied to these data. Paste pH values were also predicted using Equation 5. This predicted geochemistry is summarized in Table 5, with the measured values of paste pH for comparison.

TABLE 5
PREDICTED GEOCHEMISTRY OF SURFACE SEDIMENTS

AREA #1

PARAMETER	L10	L30	L60	L80	L100	L120	L140	L160	L170
Ca ug/g	670	1990	1800	1300	3820	5680	8220	6230	8070
Calculated Neutralization Potential (kg CaCO ₃ /t)									
Equation 3	9	12	11	10	17	21	28	23	27
Equation 4	-2	6	5	2	17	27	42	31	41
Calc. Paste pH	1.8	4.5	4.3	3.5	6.1	7.1	8.0	7.3	7.9
Meas. Paste pH	2.6	5.5	3.5	2.8	5.3	5.1	6.1	5.4	6.3

BACKFILL SANDS

PARAMETER	BS10	BS30	BS50	BS70	BS90	BS110	BS130
Ca ug/g	5350	690	850	570	5050	3660	2890
Calculated Neutralization Potential (kg CaCO ₃ /t)							
Equation 3	20	9	9	8	20	16	14
Equation 4	26	-1	0	-2	24	16	11
Calc. Paste pH	6.9	1.9	2.4	1.4	6.8	6.0	5.4
Meas. Paste pH	5.7	3.0	3.8	5.1	5.1	6.0	4.0

The predicted values of neutralization potential and near neutral pH values of many samples indicate that oxidation and acid generation were not established or not expected in all samples. As acid is produced from sulphide oxidation reactions, the available carbonate minerals are consumed in neutralization reactions removing acidity from the zone of acid production. Thus initially pH will vary little although carbonate, and calcium, content can decrease significantly in the solid sample. At sites BS70 and BS90, the measured paste pH values were the same but the calcium content at BS70 was 10 % of the content at BS90. This could be due both to lower initial N.P. values, or higher acid production and thus consumption of the neutralization potential at BS70. At the relatively low Ca content of sample BS70, a lower pH would have been expected.

Paste pH values predicted by Equation 5 did not correspond to measured paste pH values; possibly reflecting the shorter period of exposure and different stages of oxidation and depletion of neutralization potential for these samples, as compared to those for which the equations were developed. Analysis of these data provided a linear best fit relationship of paste pH to calcium content for the 1989 data as expressed in (6):

$$\text{paste pH} = 0.0004 \text{ Ca} + 3.05 \quad \text{where } r^2 = 0.84 \quad (6)$$

3.2 Surface Water and Surface Solids Pore Water

3.2.1 Solution pH

Solution samples were collected from Area #2 to characterize the solution chemistry within a short period of time after discharge. The solution samples collected from Area #2 of the tailings impoundment facility consisted of:

- surface water - impoundment supernatant near discharge
 - settled fresh tailings solution from discharge
- pore water recovered from surface solids - fresh tailings
 - one month old tailings

Two samples were collected at each sampling location. The pore water extractions were conducted on the duplicate samples and each extraction was subsampled and preserved identically for

analysis at both the Environment Canada, West Vancouver lab, and the Royal Roads laboratory. The results of the pH analyses on these solution samples are summarized in Table 6.

TABLE 6
AREA #2 SOLUTION SAMPLE pH MEASUREMENTS

SAMPLE TYPE	SOLUTION/PORE WATER pH	
	Environment Canada	Royal Roads
Settled fresh tailings sol'n (1)	11.1	not analyzed
Settled fresh tailings sol'n (2)	<u>10.8</u>	not analyzed
Average	11.0	
Area #2 supernatant (1)	10.2	not analyzed
Area #2 supernatant (2)	<u>9.9</u>	not analyzed
Average	10.1	
Pore water - fresh tailings (1)	8.3	8.09
Pore water - fresh tailings (2)	<u>8.0</u>	<u>7.95</u>
Average	8.2	8.02
Pore water - 1 month old tailings (1)	6.8	6.61
Pore water - 1 month old tailings (2)	<u>7.8</u>	<u>7.59</u>
Average	7.3	7.10

The pH values decreased significantly over the range of these four samples; from the settled fresh tailings solution at an average pH of 11.0 to the 1 month old pore water at pH 7.3. The final pH of the tailings discharge from the Westmin mill is typically in the range of pH 10 to pH 11, which was reflected in the pH of the settled fresh tailings solution. This sample was collected immediately below

the tailings discharge point and thus was most representative of the final mill effluent.

The supernatant collected from Area #2 was slightly lower in pH at approximately pH 10, probably due to dilution with low pH rainwater and/or absorption of atmospheric carbon dioxide (recarbonation).

The tailings samples collected for pore water extraction and shake flask testing were gathered from the surface layer of the tailings impoundment. The fresh tailings sample was collected below the discharge point and may have been deposited a couple of hours prior to sampling. The pore water pH of this fresh tailings sample was significantly lower than the previous two samples, averaging approximately 8.1. The pore water pH of the samples approximately 1 month had further decreased to pH 7.3. This last change in pH, over one month, was much faster than pH changes reflected by paste pH in previous surveys.

The relatively rapid decrease in pH particularly evident in the three fresh samples in Table 6 suggests the tailings samples are poorly buffered, exhibiting a rapid drop in pH over the period of at most several hours. The tailings rapidly decreased in pH to the calcite equilibrium pH value (approximately pH 8.3 in an open system with P_{CO_2} at atmospheric concentration of $10^{-3.5}$ bars). Under these conditions, Ca^{2+} solubility from calcite is 25.2 mg/L. It is difficult to calculate buffering capacity from ICP data, as these are kinetic reactions, and such equilibrium chemistry calculations are not appropriate. The two potential mechanisms by which this acidification might have occurred include; adsorption of atmospheric carbon dioxide and/or rapid oxidation of the tailings sample. Over the next month, the pH of the tailings pore water then decreased to 7.3. This is below calcite solubility, suggesting either that insufficient calcite is present to neutralize acidity, or that the neutralization reaction is too slow to achieve equilibrium conditions. These data do seem to confirm that the tailings are poorly buffered.

3.2.2 Total and Dissolved Metals

The settled tailings and supernatant samples were analyzed for total and dissolved metals. The pore water samples, which had been filtered at 0.45 microns as part of the recovery process, were therefore analyzed for dissolved metals. Two samples of each were collected and analyzed for comparison. The detailed results of these analyses are provided in Appendix 2 and summarized in Table 7.

The duplicate analyses of each of the four sample types showed considerable variation in the elements of particular interest; Cu, Fe, Pb, Zn and Ca. This variability was particularly evident for dissolved metals in the pore water samples, and for total metals in the settled tailings samples. Total metals might have been affected by residual concentrate froth from the milling process. The variability also reflects the difficulty of obtaining representative samples from a tailings impoundment, and the variation in concentrations within even a small area.

The water quality of the settled fresh tailings was quite typical of mill effluent; high pH and alkalinity and low dissolved metals values (copper <0.005, iron <.2, and zinc <1 mg/L). The sulphate and conductivity levels were slightly elevated, probably due to contaminants released during the milling process. Total metal concentrations were also the typical of mill effluent, reflecting residual concentrate flotation froth or slow settling of colloidal metal complexes.

The supernatant from Area #2 was lower in pH than the settled tailings solution and similarly lower in dissolved calcium, carbonate hardness and total hardness. Dissolved and total metal levels were also lower in the supernatant than the settled tailings solution, with the exception of zinc. Total zinc concentrations increased from 2.4 mg/L in the effluent sample to 7 mg/L in the supernatant, although dissolved values were lower in the supernatant.

Assuming Na, K and sulphate to be nonreactive constituents at these alkaline pH values, it was estimated that the tailings solution was diluted approximately 24 % by fresh water. The difference in concentrations between the settled fresh tailings solution and the supernatant shown in Table 7 was greater than this factor, indicating that the surface water dilution was not the factor affecting contaminant concentrations in solution.

TABLE 7

SUMMARY OF WATER QUALITY DATA
SOLUTION AND PORE WATER SAMPLES FROM AREA #2

PARAMETER	SETTLED SUPERNATANT				PORE WATER			
	FRESH		ONE MONTH		FRESH		ONE MONTH	
	#1	#2	#1	#2	#1	#2	#1	#2
pH	11.4	10.8	10.2	9.9	8.3	8.0	7.8	6.8
Acidity	<1	<1	<1	<1	-	-	-	-
Alkalinity	192	-	221	148	-	-	-	-
Sulphate	400	360	290	290	-	-	-	-
Conductivity	1380	1380	980	1030	1250	1280	2900	1600
DISSOLVED METALS								
Ca	339	330	232	230	318	318	799	373
Cu	<.005	<.005	<.005	<.05	.006	<.005	.071	.029
Fe	.104	.128	.023	.009	.03	.018	.178	.027
Zn	0.72	.582	.116	.112	.373	.053	.014	.108
TOTAL METALS								
Ca	322	326	258	257	-	-	-	-
Cu	.374	.611	.313	.33	-	-	-	-
Fe	10.9	15.3	3.68	3.81	-	-	-	-
Zn	2.40	3.68	7.03	6.93	-	-	-	-

NOTE: All units mg/L except pH (pH units), conductivity (umhos/cm), and alkalinity and acidity (mg/L CaCO₃ equivalent).

Considerable variation was evident in the pore water sample assays, between both the duplicate samples and over the one month time interval, as shown in Table 7. Generally, the one month old samples averaged lower pH, higher conductivity, and higher dissolved Cu and Fe than the fresh samples. The first sample of the one month old tailings pore water, however, was quite different than the other three samples. Analysis showed conductivity and hardness values twice that of the other samples, elevated concentrations of Ca, Cu, Fe, and Mg, and the lowest pH and zinc concentration. This sample might have been recovered from low zinc tailings, or the zinc was rapidly leached and flushed from this sampling area.

In summary, this relatively small sampling program indicated the difficulty of obtaining representative samples from a heterogeneous tailings mass, and that small changes in solution chemistry did occur over a relatively short period of time in the fresh tailings; notably in sulphate, conductivity and dissolved zinc. Solution pH and pore water pH decreased over time, affected by possibly three mechanisms; dilution with low pH rainwater, acidification from absorption of atmospheric carbon dioxide, and possibly the rapid onset of sulphide oxidation and acid generation. Solution pH and acidity, however, did not indicate significant oxidation and acid production.

Oxidation products, including dissolved metals accumulated in the surrounding pore water would be flushed by precipitation and infiltration. The metal analyses of the mill effluent indicated that the tailings solution contained zinc and iron in the total metals at much higher levels than in the dissolved metals suggesting they occurred as particulates or solids. As the solution pH decreased, even over the neutral pH range, zinc and iron could be released into the pore water solution.

3.3 Geotechnical Samples

The results of the geotechnical analyses are summarized in Table 8. Estimation of particle size was based on comparison with the test pit logs and fractional analyses reported in the 1988 study (Broughton and Ferguson, 1989).

The results of the geotechnical analyses were similar to previous tests of the tailings impoundment and corresponded to the field observations of the surface of the tailings. Sample L30

represented three near surface horizons which are discussed in more detail in Section 3.4 (Layer A, B and part of Layer C). Sample L100 was collected from the two near surface horizons (Layer A and down into Layer B). Sample L160 went down through horizons A, B, and half of C.

TABLE 8
SUMMARY OF GEOTECHNICAL DATA

PARAMETER	SAMPLE						
	L30	L100	L160	EP1	EP2	BS1	BS2
Interval (cm depth)	16.5	19.5	19.5	10	11.2	16.5	16.5
Volume of Sample (L)	1.18	1.42	1.42	0.32	0.44	1.18	1.18
Wet Soil Mass (kg)	2.75	3.26	3.11	0.62	0.70	2.60	2.33
Wet Density (kg/L, t/m ³)	2.33	2.30	2.19	1.94	1.59	2.21	1.98
Dry Soil Mass (kg)	2.21	2.86	2.49	0.47	0.58	2.45	2.19
Dry Density (t/m ³)	1.88	2.01	1.75	1.46	1.31	2.08	1.86
Specific Gravity	3.64	3.80	3.63	2.95	3.01	3.71	3.55
Water Content	0.24	0.14	0.25	0.33	0.21	0.06	0.06
Void Ratio	0.94	0.89	1.07	1.02	1.30	0.79	0.90
Porosity	0.48	0.47	0.52	0.50	0.57	0.44	0.47
Degree of Saturation	0.94	0.60	0.83	0.95	0.49	0.29	0.24
Particle Size (est.)							
% Sand	10	72	23	8	72	80	80
% Silt	82	23	71	85	24	19	19
% Clay	8	5	6	7	4	1	1

The surface and near surface material at L30 and L160 was primarily silty, with a sandy area around L100. The silt samples were poorly drained reporting 94 % saturation with 82 % silt content and 8 % clay. The sand sample had a much lower water content at 60 % saturation. Sample specific gravity measured 3.64 for silty samples; comparable to the measured value of 3.61 for tailings material in 1986 (Ferguson, 1987). Higher sand content corresponded to higher specific gravity (3.80) and dry density (2.01 t/m^3) and therefore higher sulphide content.

Ferguson (1987) summarized the published data for geotechnical parameters for conventional deposition of tailings. At Equity Silver, with a similar particle size distribution as Westmin Myra Falls tailings and specific gravity of 2.88, the dry density was 1.49, void ratio 0.92, porosity 0.48, and degree of saturation 0.65. The calculated hydraulic conductivity in previous surveys was 10^{-7} to 10^{-9} cm/s. Thus, the samples from the Westmin subaerial tailings exhibited similar geotechnical characteristics to conventional tailings deposition.

The geotechnical samples collected from the backfill sands area corresponded to surface sampling sites BS30 and BS70 respectively. Samples from the backfill sands area were somewhat similar to sands samples from the 1988 study, although with a significantly lower degree of saturation (24 % compared to 70 %), higher dry density (2.08, 1.86 compared to 1.78 t/m^3). Sample BS1 had a higher specific gravity than BS2, and higher wet and dry density, and degree of saturation, and a lower void ratio.

The samples from the Emergency Pond were collected as close as possible to the two test pit sites. Sample EP1, representing Layer A and half of Layer B from the test pit logs corresponded to a wet silt (95 % saturation) with low S.G. (2.95) and dry density (1.46 t/m^3). Sample EP2, taken from the top layer of the test pit, was a moist to dry sand at 50 % saturation, and very low dry density, 1.31 t/m^3 . The lower specific gravity of the Emergency Pond material compared to the tailings samples (from the HW ore) reflected the lower sulphide content of the Lynx ore from which these tailings were primarily produced.

The potential effect of placing the new layer of tailings on the density and solution flow of the old tailings layer was considered. Varying with the thickness of the new tailings layer and geotechnical

characteristics, the increase in total stress on the tailings surface ranged from approximately 37,000 N/m² at L30, 46,000 N/m² at L100, and 51,000 N/m² at L160. These figures were based on the geotechnical data presented in Table 8. Without more detailed geotechnical information and survey data it is impossible to determine the extent of compaction that has occurred in the tailings mass. The test pit logs were compared to logs from the previous study at approximately the same location and showed that little or no compaction had occurred within the upper 1 m of the old tailings layer that was logged in both surveys.

3.4 Test Pits

3.4.1 Paste pH and Sample Logs

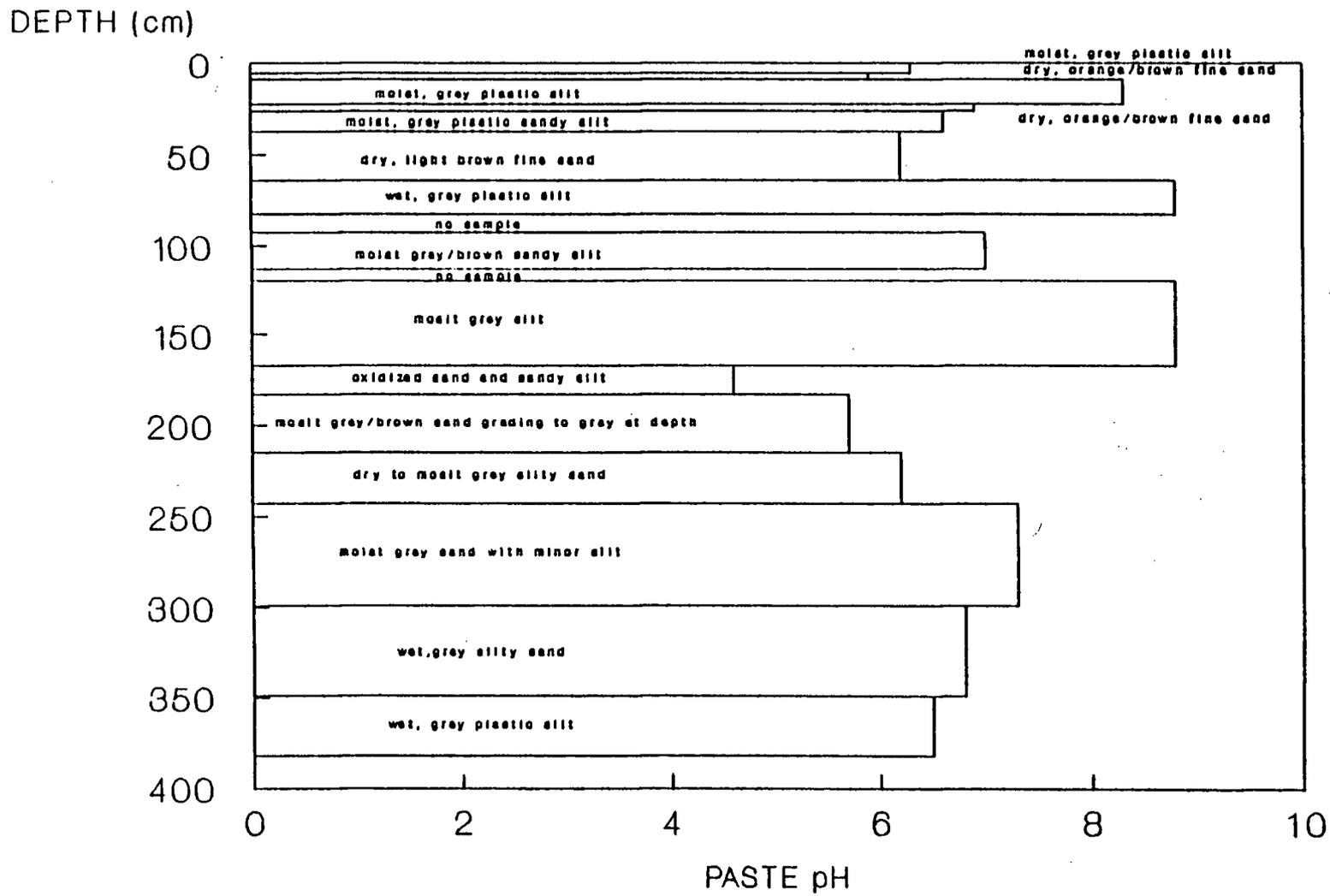
Each test pit was logged and sampled over the depth. The layers were distinguished by observation based on change in appearance. In thick lenses of material, over 50 cm, the sample was split into two or more layers to ensure that sampling intervals were reasonably consistent. Each layer was tested for paste pH. A fence diagram was constructed for Area #1 from the test pit logs showing an approximate profile of the layering in the impoundment to develop an understanding of controls on oxidation and possible drainage patterns. It is recognized that the test pit intervals were large, and that significant variations can exist between the sampling locations. This diagram is presented and discussed with the results of the shake flask analyses in Section 3.4.2.

Area #1

The descriptions of each layer are presented graphically with the results of the paste pH analyses of each layer in Figures 10 through 12. The layered nature of the tailings is apparent in these figures. This layered settling pattern is a design feature of the subaerial deposition method; the theory being that as the layer of tailings is spread over the surface of the impoundment, different particles will settle at different rates resulting in layers of coarse, denser material and layers of finer, silty material. This contributes to the low vertical permeability of the tailings mass.

In test pit L30, Figure 10, the material ranged from wet, grey plastic silt to dry orange/brown sand. The paste pH values ranged from 4.6 to 8.8 over the total 3.8 metre depth of the pit. Generally

FIGURE 10 PASTE pH AND SOIL TYPE PROFILE - TEST PIT L30



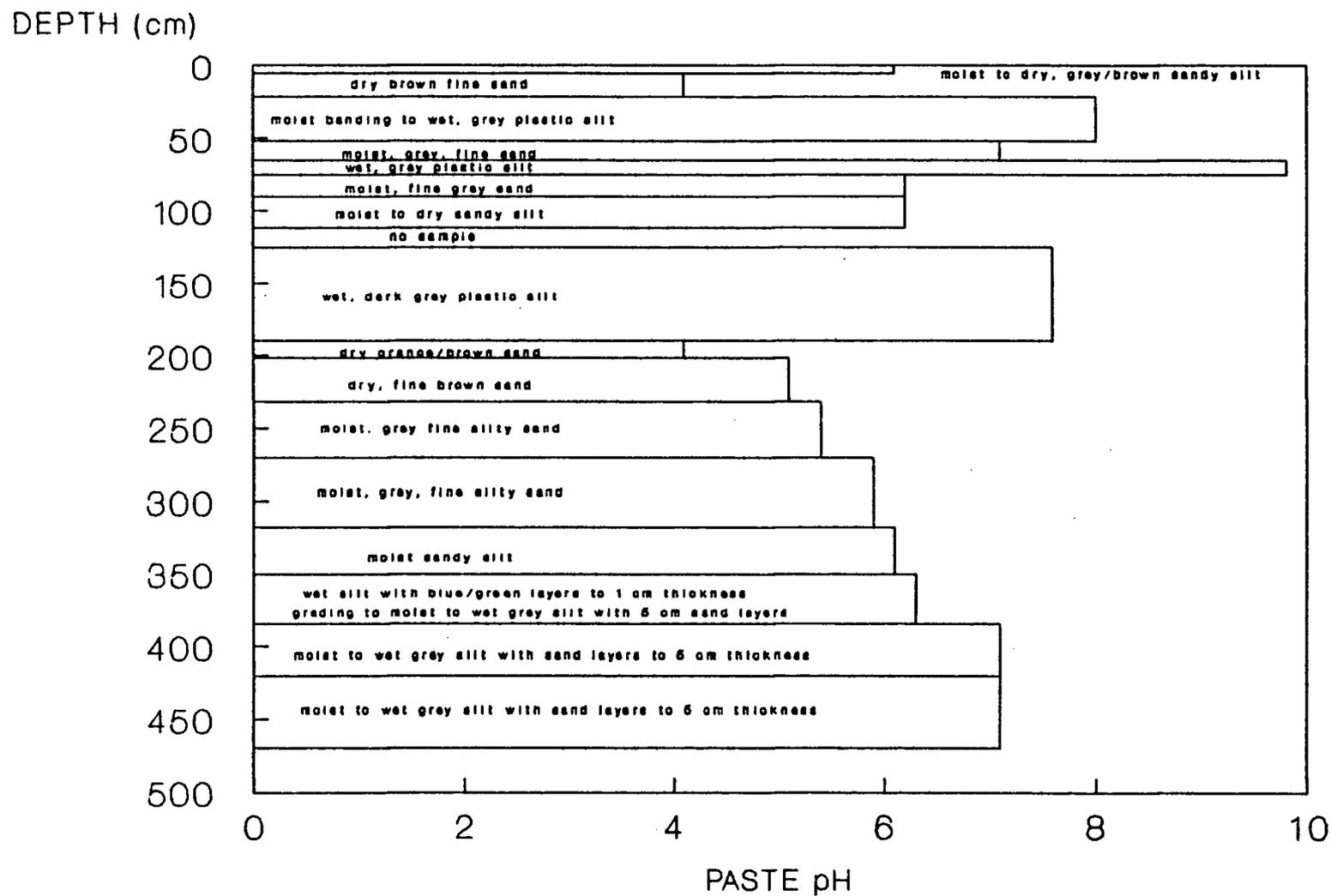
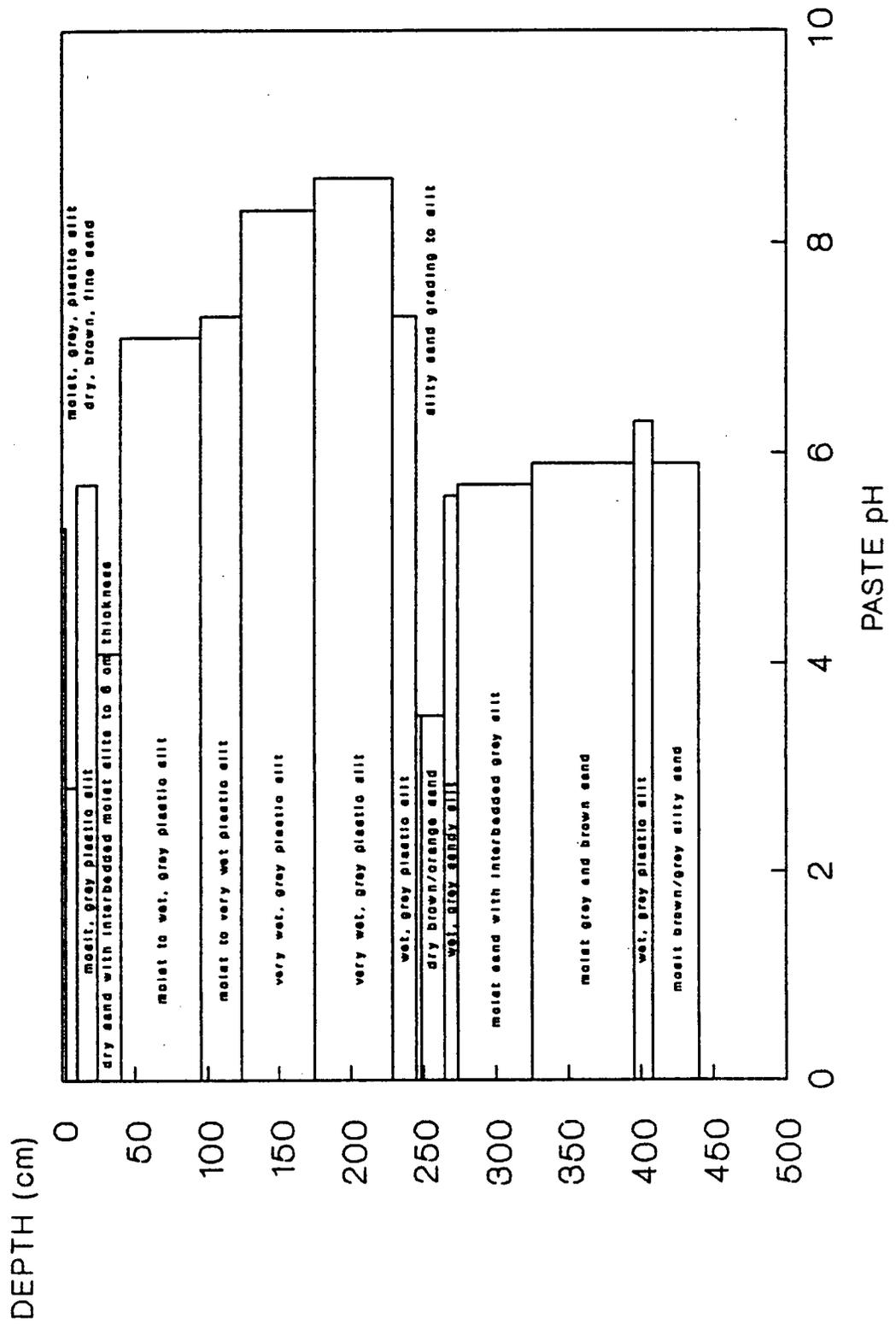


FIGURE 12 PASTE PH AND SOIL TYPE PROFILE - TEST PIT L160



the highest pH values were found in the moist silt layers (eg. layer H from 93 - 113 cm at pH 8.8) and the lowest values were located in dry oxidized sand and sandy silt layers (eg. layer J from 167-183 cm at pH 4.6). In the upper 1.5 m of the tailings the pattern of pH varied markedly with each layer, that is, there was not a gradual increase and then a decrease in pH as was evident in the lower depths of the test pit.

Test pit L100, Figure 11, showed a similar distribution of material size and paste pH, with pH varying from 4.1 (layer B) to 9.8 (layer E). Again, the lower pH values were associated with drier, sandier material than the near neutral wet silts. Alternate layers of low and near neutral pH were evident in the upper 2 m of this test pit. Paste pH values increased gradually with depth below layer J at pH 4.1, to layer R at 4.7 m depth and pH 7.1. The older layer of tailings in this test pit generally showed lower pH than the old layer in test pit L30. Unique to this test pit, there was a thin layer of wet silt, at about 3.5 m depth that contained distinct blue-green bands of about 1 cm thickness. The appearance of the blue green material within the silt was similar to oxidized copper (malachite) or copper sulphate.

In test pit L160, Figure 12, there was a significant proportion of wet silty material near neutral pH, with bands of sand and silty sand from pH 5.9 to 2.8. The near surface sand layer from 2 to 10 cm at pH 2.8 corresponded to a similar low pH layer at L100, 5 - 21 cm, at a pH of 4.1. A sand layer from 5 to 9 cm in L30 also exhibited the lowest pH of the newly placed tailings of 5.9. The test pit was excavated to total depth of 4.4 m, terminating in a silty sand layer.

The test pit logs were also used to estimate the location of the "old" tailings layer. The surface of Area #1 that was exposed for the 1988 survey and covered by additional subaerial tailings was thought to be one to two and a half meters below the new surface. The test pits in this survey were roughly over the E-E line of the 1988 survey and thus sites L30, L100 and L160 should have corresponded roughly to sites E30, E100 and E160 from the 1988 survey. The approximate location of the tailings surface in the previous survey was estimated from comparing the 1988 test pit logs (Broughton and Ferguson, 1989) for the sites prefixed with "E", with the 1989 survey sites prefixed "L":

- at test pit E30, the upper 30 cm consisted of alternating grey silt and orange sand, which corresponded to layers J and K in L30. This placed the old tailings surface about 1.7 m below

the new tailings surface.

- at test pit E100, the surface layer consisted of 12 cm of dry, brown sand underlain by 14 cm of interbedded white/grey sand and silt. These appeared to correspond to layers J and K of L160, placing the old tailings surface 1.9 m below the new surface.
- at site E160, the surface layer consisted of approximately 17 cm of moist silt underlain by a 10 cm thick layer of dry, orange yellow, fine sand. This could correspond to layers H, I, and J in L160 at 2.29, 2.45 and 2.49 m depth respectively. Above 2.29 m, the logs described moist to wet silt of almost 2 m thickness, with no sand layers. The old tailings surface thus appeared to be approximately 2.3 m below the new surface.

Emergency Pond

The two test pits excavated in the Emergency Pond were also logged and sampled for paste pH. The results are presented in Figures 13 and 14. This material was not deposited subaerially. The layers that were evident were probably due to deposition of bulk tailings at different times.

Test pit EP1 was composed primarily of wet, grey silts with two thin sand layers near the surface. The silt layers showed some evidence of earlier cracking which allowed oxidation as sharply contrasting orange/brown streaks were found in the wet grey silt. There were no open cracks in the tailings evident during the test pit excavation. The paste pH values varied over a small range; from pH 6.4 to 7.1.

Test pit EP2 again was primarily silt in the lower 1.5 m, but had layers of brown sand in the upper 2 m, with loose white sand on surface. The paste pH values, however, varied over only a small range; from 6.5 to 6.9. Vertical and horizontal cracks were again evident by the orange streaking in the grey silt of layer F, from 84 to 132 cm.

Total metals analyses were conducted on samples from the upper layers of test pit EP1, that is, from the layers excavated by hand. These results are included in Appendix 1. Copper levels ranged from 0.9 to 2.2 mg/g. Iron content was high, ranging from 53.3 to 99.8 mg/g. Zinc ranged from 6.1 to 14.7 mg/g.

FIGURE 13 PASTE pH AND SOIL TYPE PROFILE - TEST PIT EP1

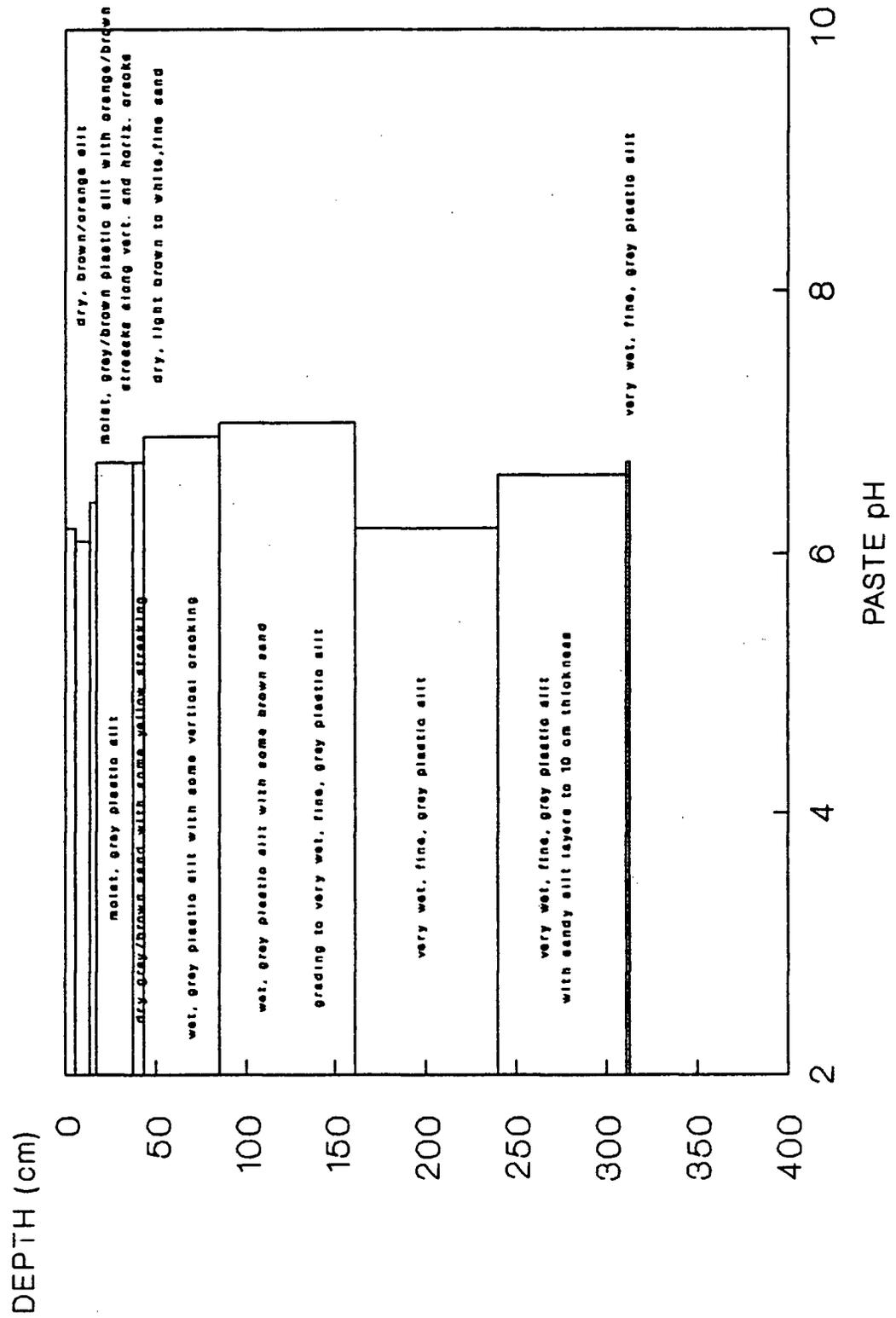
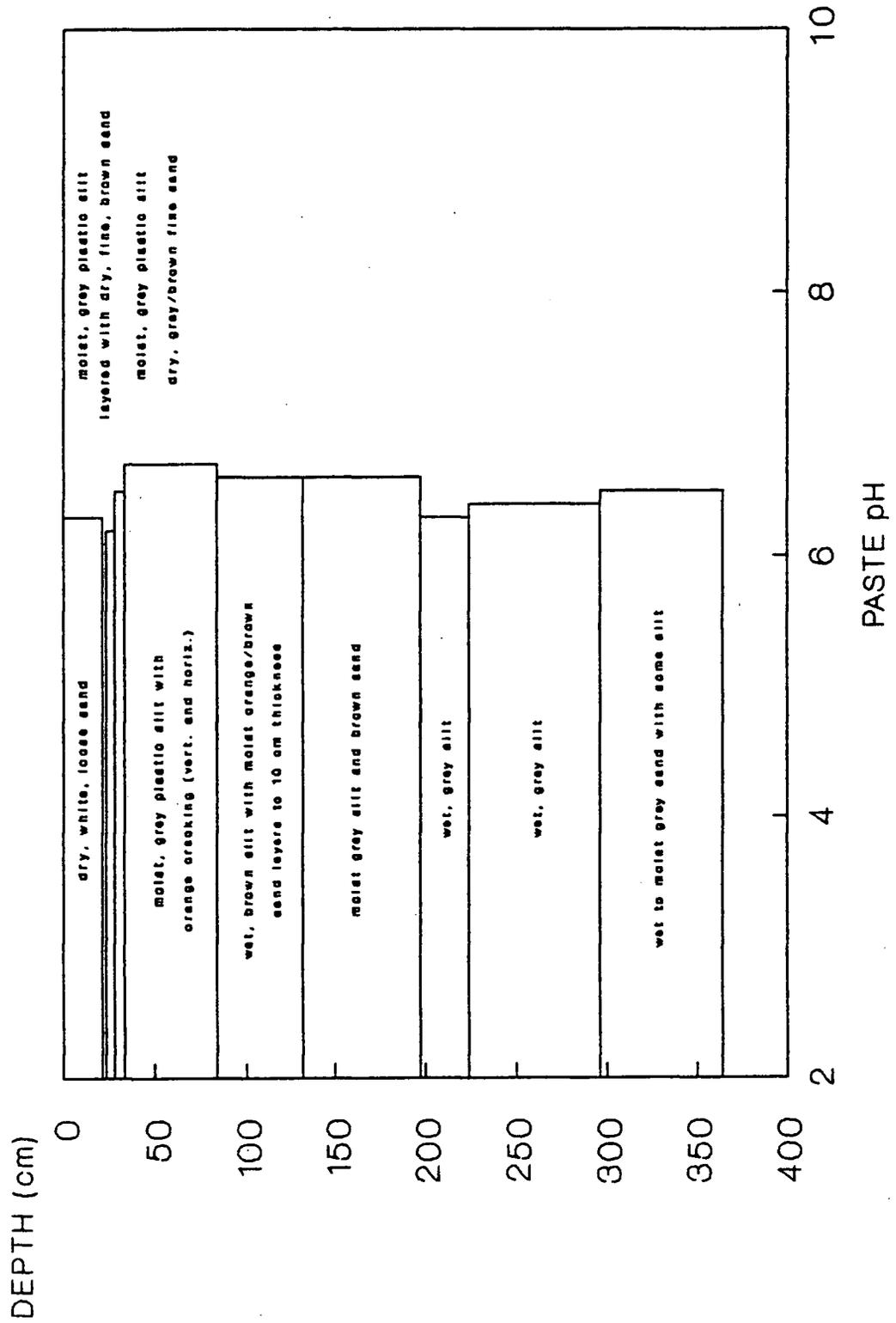


FIGURE 14 PASTE pH AND SOIL TYPE PROFILE - TEST PIT EP2



The total metal analyses were also used to estimate the acid generation potential of the tailings in the Emergency Pond, as shown in Table 9. Equations developed from the 1985 data (Ferguson, 1986, 1987) for Area #1 tailings were used to calculate total sulphur content and neutralization potential. Total sulphur content was predicted using Equation (7), developed from multiple linear regression analyses relating sulphur to metal content.

$$\% S = -2.01 + 0.00014Fe - 0.00379Cu - 0.00015Zn \quad (7)$$

Based on the metals content and stoichiometric ratios, sulphur was shown to be present primarily in iron sulphide minerals, copper as a copper/iron sulphide, zinc as sphalerite and iron as pyrite or pyrrhotite. Neutralization potential values were calculated using Equation (3) as discussed in Section 3.1.4.

TABLE 9
PREDICTED GEOCHEMISTRY OF EMERGENCY POND TAILINGS

SAMPLE	PASTE pH	PREDICTED GEOCHEMISTRY		
		% S	NP	NNP
		(t CaCO ₃ /1000 t)		
EP1 A	6.2	3.1	52	- 45
EP1 B	6.1	0.0	53	+ 53
EP1 C	6.4	0.0	58	+ 58
EP1 D	6.7	0.8	57	+ 32
EP1 E	6.7	7.2	58	-167
EP1 F	6.9	0.0	50	+ 50

These equations were developed from analyses of tailings from Area #1 (primarily from the HW ore zone) and thus provide only an estimate of tailings geochemistry from the Emergency Pond. The

Emergency Pond tailings were placed prior to milling the high sulphide HW material and thus have a lower sulphide content. The type of mineralization should be similar; that is, pyrite, pyrrhotite, chalcopyrite, and sphalerite although the proportions might vary.

The results indicate much lower sulphide content in the Emergency Pond and generally marginally acid consuming nature in the upper metre of test pit EP1. Two layers within the test pit EP1 did show negative net neutralization potentials indicating potentially acid generating material, EP1 A and EP1 E. These were both layers with visual evidence of sulphide oxidation; orange or yellow coloration.

3.4.2 Shake Flask Extractions

The detailed results of the shake flask tests to determine the characteristics of the water soluble fraction of the tailings samples were analyzed to determine the changes in the tailings chemistry and locations of contaminant fronts, and results are included in Appendix 3. Shake flask tests were conducted on surface samples of relatively fresh tailings from Area #2, and test pit samples from Area #1 and the Emergency Pond. The results of the shake flask tests were evaluated for three aspects of contaminant release and transport within the tailings impoundment:

- i) the trends in acid and metal release and drainage over the depth of each test pit (Section 3.4.2.1);
- ii) the magnitude of the soluble fraction and the change over time, by comparison with shake flask tests on fresh samples (Section 3.4.2.2);
- iii) the rate of transport and mobility of contaminants through the tailings mass by identifying elevated concentrations or "contaminant fronts" (Section 3.4.2.3).

The results of the tests discussed in the following sections are presented by area: fresh tailings, Area #1 and the Emergency Pond.

3.4.2.1 Acid Generation and Metal Release

The data are presented graphically in Appendix 4, summarizing the shake flask test results as a function of depth in the test pit for key parameters:

- a) paste and solution pH measurements
- b) shake flask solution pH and ORP
- c) acidity
- d) pH, acidity, and dissolved calcium
- e) sulphate and conductivity
- f) dissolved copper and iron
- g) zinc and acidity.

AREA #2

The shake flask tests on the Area #2 samples were conducted primarily to determine baseline or background concentrations of the water soluble fraction of fresh tailings material. These concentrations could then be compared to the older tailings sample from Area #1.

Two samples of fresh tailings and two samples of tailings that had been deposited in the impoundment for approximately one month were tested. The duplicate test results were comparable and average values used for all further calculations (Appendix 3). Key parameters are summarized in Table 10.

Solution pH values were alkaline and acidity measurements very low for both the fresh and one month old samples in this survey. Sulphate and conductivity levels were low in the fresh tailings samples but higher in the one month samples; even higher than after three months of exposure in the previous survey. Dissolved metal concentrations were low in the fresh samples and slightly elevated in the older samples. Cu and Fe concentrations in the one month sample approached values found in samples that had been exposed for three months from the 1988 survey.

A marked increase was evident in zinc concentrations over one month, from 1.3 to 8.2 mg/L, although pH and acidity were near neutral. At these pH values most metal oxide and hydroxide complexes are relatively insoluble and elevated dissolved metal concentrations would not be expected.

Zinc, however, becomes increasingly soluble below pH 9.5. The results indicate that zinc is released into solution or is readily water soluble soon after deposition. The previous study showed a similar trend in shake flask tests with zinc concentrations increasing from 0.82 mg/L to 11.8 mg/L over three months. The dissolution of zinc at early times and throughout the deposition period of the tailings material is further discussed in the following section with reference to the Area #1 shake flask tests.

TABLE 10
SUMMARY OF SHAKE FLASK TEST RESULTS - AREA #2

PARAMETER	SAMPLE TYPE			
	1989*		1988**	
	FRESH	1 MONTH	FRESH	3 MONTHS
pH	8.2	8.2	8.0	8.0
Acidity	1.2	1.8	1.3	6.7
Sulphate	90	475	140	27
Conductivity	215	830	430	666
Dissolved Cu	.039	.046	.026	.026
Dissolved Fe	.011	<.005	.006	.005
Dissolved Zn	1.34	8.20	.82	11.8

All units mg/L except pH (pH units), conductivity (umhos/cm), acidity (mg/L CaCO₃ equivalent).

* results are average of two tests on each sample type

** results are average of three tests on each sample type

In summary, comparison between the fresh and older sample indicated changes in some key parameters over a relatively short period of time, notably sulphate, conductivity and dissolved zinc. Solution pH and acidity did not indicate widespread oxidation and acid production.

AREA #1

Three pH measurements were conducted for each of the shake flask tests; paste pH of the solids, shake flask solution pH immediately after filtration, and shake flask solution pH at the West Vancouver laboratory after storage of the samples for 2 to 5 months. This was not a planned storage period but a function of laboratory turn around time. As shown in the (a) series of graphs, Appendix 4, there is considerable variation in the paste pH measurements over depth in the test pit compared to the shake flask solutions. Paste pH measurements were generally lower than the shake flask values. These observations are probably both due to the dilution of acidic pore water with the distilled water required in the shake flask tests.

It was also evident from these figures that the solution pH values were consistently lower for the immediate measurements than for the samples which had been stored for some time, with the exception of three samples between pH 4 and 6. The contrast between pH values could be due either to differences in the equipment or standardization between the laboratories, or to changes in solution chemistry over time. The stored solutions were, however, tightly capped and maintained in a cold room to minimize changes in solution chemistry. Solution ORP values were generally inversely related to solution pH as shown in the series of graphs (b); near neutral pH corresponded to an ORP of approximately 200 mV, and an acidic pH of 4.5 corresponded to an ORP around 280 mV.

The acidity of the shake flask samples ranged from < 1 mg/L to 258 mg/L. As seen in the series of graphs (c), concentrations ranged over the depth of the hole, and were considerably higher and more varied over the depth of L160 than in L100 or L30.

Comparing acidity values with dissolved calcium concentrations and shake flask solution pH (graph series (d)) did not indicate a direct relationship between acidity and dissolved calcium. At some points with elevated acidity, calcium concentrations were low, eg. L30 from 22-26 cm and 243-299 cm. Sulphate and conductivity concentrations in the shake flask solutions varied similarly for all three test pits in Area #1 as shown in graphs (e). Sulphate is probably the dominant anion contributing to conductivity. Sulphate concentrations ranged from 120 mg/L (L160) to 820 mg/L (L160). Conductivity values ranged from 350 umhos/cm (L100) to 1330 umhos/cm (L160).

Dissolved metal concentrations were graphed for copper and iron in the series of graphs (f) and for zinc and acidity in (g), Appendix 4. The greatest variations in Cu and Fe were evident over the depth of L160, ranging from <0.005 mg/L to 23.7 mg/L Cu and 60.4 mg/L Fe. Zinc and acidity concentrations behaved similarly for all three test pits. The greatest range of values was again evident in test pit L160, ranging from <1 mg/L to 258 mg/L acidity and from 1 to 72 mg/L Zn.

The results of these shake flask analyses were compared with the data from the previous survey to examine changes in solution chemistry that had occurred over the intervening 14 months. This comparison is particularly important in the "old" layer of tailings, to determine the effect on the oxidation and contaminant generation processes since the tailings were covered with up to 2.3 m of fresh tailings. Decommissioning of subaerial impoundments typically includes covering the tailings to limit the ingress of water and oxygen. The recently deposited tailings layer would act to some degree as a cover and the changes in chemistry of the underlying tailings layer might be indicative of the long term behaviour of covered tailings, although this is a relatively wet cover. An installed cover would be designed for lower hydraulic conductivity. The rates of oxidation and contaminant release are critical to evaluating the potential environmental impact and alternative decommissioning measures for the tailings impoundment.

The tailings layers discussed for the "L" sites are below the surface of the recently deposited tailings, i.e. within the "old" tailings layer and approximately the same material tested in the 1988 survey. The sites from the 1988 survey were prefixed by "E", and the 1989 survey by "L".

To determine if the changes in concentration discussed above reflected changes in actual production and accumulation rates, or simply changes in distribution, weighted average concentrations were calculated for this and the previous survey for acidity, sulphate, conductivity, copper and iron. Zinc is discussed in more detail in subsequent sections.

The test pits in the previous survey were much shallower averaging less than 1 m depth whereas test pits in this survey extended at least a metre deeper from the old surface layer. Weighted average values were calculated for the 1988 survey. Average concentrations were also calculated over the greater depth of the 1989 survey test pits.

To provide a common basis for comparison between the 1988 and 1989 data an estimate was made of the potential range of concentrations in the extended depth of the test pit, in which measurements were not made in 1988. Two concentrations were used for these depths:

- the concentration of the deepest measured layer was used for all layers to the bottom of the extended depth (which were not measured in 1988) as essentially the "worst case" comparison and noted as (A), and,
- background concentrations i.e. from samples which had not undergone oxidation or contaminant migration from the shake flask tests, were applied to this extended layer to estimate the lowest probable concentration, noted as (B).

Predicted concentrations in 1989 were then calculated for each of 1988 test pits (E30, E100 and E160) from the results of the 1988 survey based on the average concentration for the previous year. These are compared with the calculated weighted average concentration in approximately similar test pits (L30, L100 and L160) from the 1989 survey. Comparison of the weighted average concentrations in each survey, and the predicted concentration, with the actual value should indicate whether changes in contaminant production rates have occurred or if there has simply been a change in distribution. These calculations are summarized in Table 11.

In contrast to the previous survey, solution pH values were approximately neutral throughout the tailings mass, ranging from pH 6.4 to 8.2. The acidic pH values which marked the low pH fronts in near surface layers in the previous survey (pH 2.8 to 3.9) were not evident in this year's sampling. Below the depth of the contaminant fronts from the previous survey, however, solution pH values were slightly more acidic at sites L30 and L100 than in the previous study. The highest value at E30 (1988 site) was 8.0 whereas L30 (1989 site) was at 6.9, E100 showed pH values of 7.6 and 7.7 whereas L100 reached 6.8 at similar depths and only 7.3 at greater depth than the previous year's survey. Site E160 and L160 were similar at pH values around 8. The solution pH values were more consistent over depth than in the previous survey, possibly due to larger sampling intervals or to diffusion and dispersion.

TABLE 11

CALCULATED WEIGHTED AVERAGE CONCENTRATIONS OVER DEPTH

Test Pit	Acidity	Sulphate	Conduct.	Cu	Fe
	mg/L	mg/L	umhos/cm	mg/L	mg/L
E30 (A)	39	202	450	.42	3.58
E30 (B)	12	202	525	.42	3.57
L30	1.6	262	598	.01	0.005
Predicted L30 (A)	58	296	659	.61	5.24
Predicted L30 (B)	17	296	770	.62	5.24
E100 (A)	21	367	692	.58	.28
E100 (B)	6	247	579	.58	.27
L100	14.5	338	671	.01	.005
Predicted L100 (A)	31	538	1015	.85	.41
Predicted L100 (B)	9	362	850	.85	.41
E160 (A)	20	267	590	.56	1.61
E160 (B)	7	234	577	.56	1.61
L160	25.6	300	614	.82	2.35
Predicted L160 (A)	29	391	865	.82	2.35
Predicted L160 (B)	11	343	846	.82	2.36

NOTE: (A) Concentration in deepest layer used for all layers not sampled.

(B) Background concentration used for all layers not sampled.

Acidity levels were much lower at L30 and L100 than in the previous survey (E30 and E100). Calculated over the depth of the 1988 test pits, the weighted average acidity was 39 mg/L at E30 and 2 mg/L at L30, 21 mg/L at E100 and 15 mg/L at L100. At site L160, however, the calculated average acidity was higher than in the previous survey at 26 mg/L as compared to 20 mg/L. The overall increased accumulation of acidity, however, was lower than predicted based on the average concentrations from the previous year. As with pH, acidity levels showed less variation over depth in this testwork than in 1988.

Sulphate and conductivity levels were elevated at each of the three sites, although the peak values were not as high as in the previous survey. The calculated weighted average sulphate concentration in this survey was higher than in the previous survey at sites L30 and L160, but not as concentrated as predicted from the 1988 figures. The results at sites L100 were conflicting (depending on the value used for the extended layer) but suggest that there has been a decrease in sulphate accumulation over the depth of the test pit. The average conductivity value over the depth of each "L" test pit was elevated for each test pit but not as high as predicted from the "E" test pit data.

Copper and iron concentrations were much lower than in the previous survey with few layers of peak concentrations which identified the 1988 contaminant fronts. The average concentrations over the depth of the test pit were similar to background levels in L30 and L100, and slightly elevated in L160. The change in contaminant distribution evident for pH, acidity, sulphate, and conductivity with smoothing of peak values and slightly elevated concentrations spread over depth was not evident in metal distributions. Rather metal concentrations were considerably reduced within the area of the old fronts and essentially the same at depth. At all sites, copper concentrations were lower at the location of the previous front, and essentially the same at depth at <0.02 mg/L. Iron levels were very low, close to the detection limit of 0.005 mg/L with the exception of one layer in test pit L160. At this depth, from 20 to 36 cm below the old surface, iron concentrations were about 0.4 mg/L. This corresponds to the previous study, in which elevated iron concentrations (31 mg/L) were only detected at E160 in the layer from 17 to 28 cm below surface. The solubility of copper and iron are limited by pH, particularly above pH 5.5 to 6. Thus the more alkaline conditions in the upper layers of the old tailings might have

resulted in precipitation of copper and iron, and the absence of elevated concentrations within the near surface layers of the old tailings.

The distribution of zinc was different than other metals in that the concentrations of zinc varied significantly from L30 to L160. Concentrations of zinc at L30 in this survey were much lower than in the previous study at E30. Concentrations were similar at L100 to E100 with the exception of a much lower value in the surface layer at 3 mg/L compared to 42.8 mg/L at E100. Concentrations at L160, however, were much higher than at E160 with the exception of the surface layer at 2 mg/L compared to 22.8 mg/L. Zinc is much more soluble than either copper or iron over these pH ranges.

In summary, comparison of the shake flask test results in this survey with the previous year's results indicates a "smoothing" or dampening effect on concentrations of many contaminants over the depth of the test pit and total concentrations similar or slightly lower than expected based on the production/accumulation measured in 1988. Low pH and high acidity peaks in the near surface layers of the 1988 study were not evident in 1989, due to either or both larger sampling intervals and infiltration of highly alkaline tailings water from the fresh tailings layer. Elevated metal concentrations which are limited by solution pH, particularly copper and iron, also evident in 1988, were not evident in this survey in the more alkaline layers. Site L160 was the most acidic at an average concentration of 26 mg/L and had the highest average metal concentrations. Sulphate and conductivity average values were highest at L100.

Emergency Pond

Shake flask tests were also conducted on the samples collected from the two test pits in the Emergency Pond. Graphs of the data are included in Appendix 4, series (a) through (g). There has not been deposition into the Emergency Pond since 1984 and thus a sample of fresh material was not available for reference and background levels. As discussed in Section 3.4.1, the sulphide content of the material tested in the near surface layers of the Emergency Pond was relatively low, and the material marginally acid consuming, with the exception of two higher sulphide layers.

The pH values shown in series (a) for the Emergency Pond generally indicated the lowest pH values were paste pH readings on the solids, ranging from pH 6 to pH 7. Shake flask solution pH

values measured immediately after filtration were similar to the paste values, whereas values measured later in the EP lab were 1.5 to 2 pH units higher. Solution ORP values varied slightly with pH as shown in graph (b), however, not significantly as the precision range of the hand held instrument was 20 mV.

Acidity values were low in the Emergency Pond (c), with the maximum value of 5.2 in EP1. Dissolved calcium values varied in the shake flask tests (d), with the lower concentrations corresponding to the sandy layers of the test pit logs. Possibly the entrained process solutions in the silt layers contained a higher calcium content as a residual of the milling process.

Sulphate and conductivity levels varied correspondingly in the Emergency Pond shake flask tests as shown in graph (e), similar to the results for Area #1. Levels of both the sulphate and conductivity were elevated in several layers of both the test pits with sulphate concentrations as high as 260 mg/L and conductivity as high as 630 umhos/cm in layer EP1B.

Dissolved copper and iron values were not elevated in either of the test pits and concentrations varied little as shown in graph series (f). Zinc concentrations were slightly elevated in several layers, particularly in EP1 reaching a high of 8.58 mg/L.

3.4.2.2 Comparison of Fresh and Subaerial Tailings

The results of the shake flask tests conducted on the "fresh" tailings samples were then compared to the subaerial tailings samples to evaluate the extent of changes that had occurred over the deposition period; 7 months for the top layer, and 44 months for the lower layer. The ratio of each parameter with respect to the fresh samples from Area #2 was calculated and the data are provided in Appendix 3. The change in pH over time was more clearly represented by calculating the difference between the tailings sample and the fresh samples. These calculations were not conducted for the Emergency Pond as fresh tailings samples were not available for comparison.

The 1989 results for fresh tailings were used for all comparisons in the following discussion to eliminate differences due to test methodology and analytical determinations between the 1988 and 1989 test programs. The 1989 and 1988 fresh tailings samples showed similar results in the shake flask tests with the exception of conductivity and sulphate values. Acidity was slightly lower and sulphate and conductivity much lower than in 1988. Dissolved metal levels were slightly higher in the 1989 survey.

These differences were not considered significant given the variability of tailings material that has been placed in the impoundment; the overall conclusions of the analyses are not changed by the fresh data set used. Using the 1988 fresh samples in the old tailings layer (of which the 1988 material is most representative) the changes in pH, acidity, sulphate, and conductivity are slightly lower and the changes in dissolved metals slightly greater than with the 1989 samples. Calculations based on fresh samples from the 1988 test data are provided in Appendix 3 for comparison.

The change in pH over the 44 months of deposition is summarized in Figure 15. Figure 16 (Broughton and Ferguson, 1989) is presented for comparison and was developed from similar calculations in the 1988 survey. The general form of the two graphs is the same, with greater changes in pH were evident in the near surface samples than at depth. In this survey, however, changes of greater than 3 pH units were evident within only the top 50 cm of tailings. This was probably due to the relatively short period of exposure of this upper layer of tailings.

It was estimated that the "old" tailings surface was located between 1.7 to 2.3 m below the new surface. At these depths this survey indicated decreases in pH of less than 2 pH units, compared to 5 in the previous study. Some pH modification has occurred making the samples less acidic, possibly due to drainage of more alkaline fresh tailings solution through the older layers. The amount of change in each of the other parameters, as estimated by the ratio to the fresh tailings sample, is summarized in Table 12.

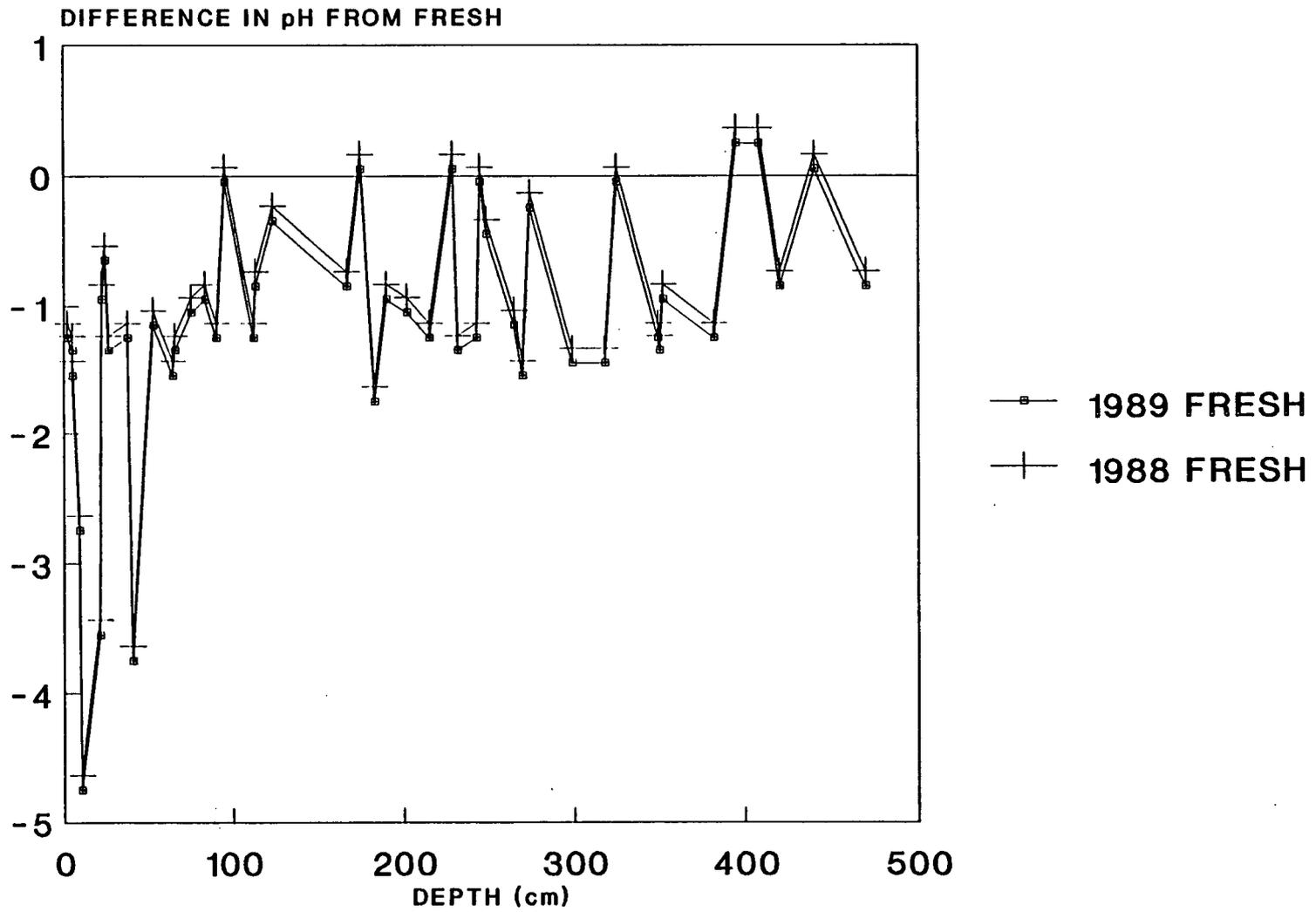


FIGURE 15 DIFFERENCE IN pH OVER DEPTH BY COMPARISON WITH FRESH TAILINGS

FIGURE 16 FRESH vs 30 MONTH SUBAERIAL TAILINGS

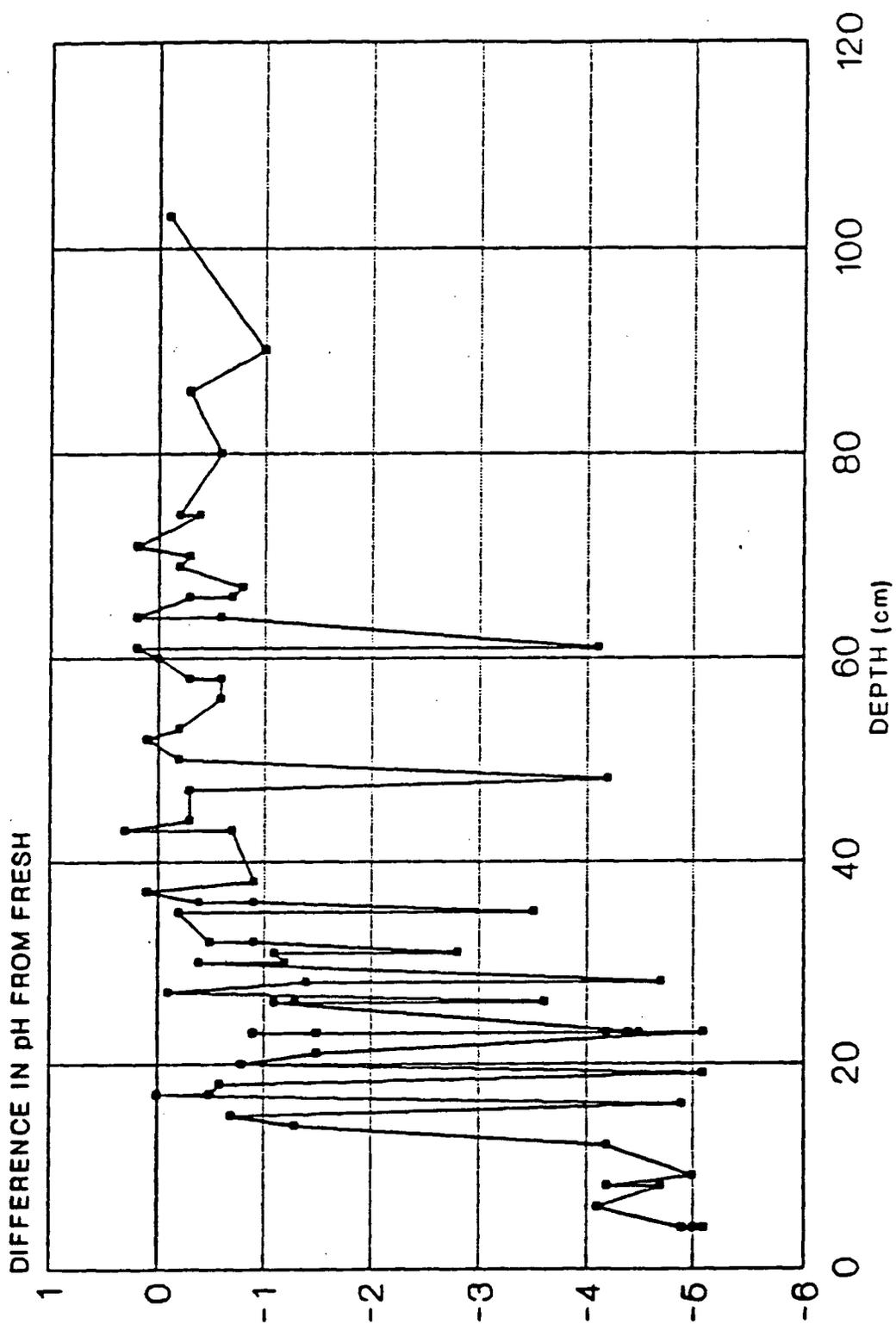


TABLE 12

CHANGES IN SHAKE FLASK PARAMETERS FROM FRESH SAMPLES

PARAMETER	FRESH	CHANGE FROM FRESH VALUE		
	(ave.)	NEW LAYER	OLD LAYER	PREVIOUS STUDY
pH	8.15	0 to 4.75	0 to 1.75	5.2 pH units
Acidity	1.15	0 to 224.3	0 to 72	298 times fresh
Sulphate	90	1.7 to 9.1	1.3 to 6.3	9.3 times fresh
Conductivity	215	1.6 to 6.2	1.7 to 4.6	5 times fresh
Copper	0.04	0 to 616	0 to 96	2396 times fresh
Iron	0.01	0 to 5,752	0 to 35.1	66632 times fresh
Zinc	1.33	0 to 54	0 to 42	248 times fresh

NOTE: All units mg/L except pH (pH units) and conductivity (umhos/cm).

The data show that changes have occurred in each parameter over the deposition period in the impoundment, reflecting changes in solid and solution chemistry. The changes in pH, acidity, sulphate and conductivity in the upper tailings layer were similar to the changes measured in the previous study. While metal concentrations also showed variation, the degree of change was much less than in the 1988 study in both the newer and old tailings layers. Within the old tailings layer, the changes in concentration were lower than previously measured, about half the value. This dampening of concentration peaks in the old layer was noted previously (Section 3.4.2.2).

The largest increases in acidity, sulphate, and conductivity, and difference in pH were evident in the upper layers of the fresh tailings, notably at L160, and decreased with depth towards the estimated interface of the old and new layers of tailings. Below this interface and thus within the previously oxidized old tailings layer, the degree of change increased, although not as high as in the near surface

fresh tailings, and decreased again with depth. Thus, the greatest degree of change was evident at the new tailings surface and decreased with depth in the new layer of tailings. This pattern was repeated in the old tailings layer although the degree of change was not as great as in the newer layer, or in the previous survey.

The degree of change in pH, acidity, sulphate, and conductivity within the newer tailings layer after 7 months was very similar to the ratios found in the previous study after 30 months exposure of the tailings. The proportion of samples exhibiting large increases in concentrations, however, was much smaller in this survey. Thus it would appear that the rate at which contaminants are generated and accumulate in the tailings solids can be established within the first six to eight months of placement, but in isolated pockets. As the exposure time lengthens the extent of tailings material undergoing oxidation becomes more widespread, neutralization potential is depleted allowing low pH/high acidity zones to develop, and contaminants are transported through the tailings mass. Over time this results in a greater proportion of samples exhibiting large changes in concentration from the fresh tailings placed. Dissolved metal concentrations would increase, particularly those dependent on low pH environments for mobility.

Metal concentrations in this study showed much less variation than in the previous study where copper values were as high as 2396 times the fresh concentration, iron 66,632 times fresh and zinc 248 times fresh. Even the range shown in the above table is somewhat deceptive for the dissolved metals as only a few of the samples showed a significant change from the fresh values, eg. 16 % of Cu assays indicated increase in Cu concentrations, 12 % of Fe assays, and 65 % of Zn. Zinc concentrations were elevated and showed the most variation over depth, particularly in L160. Elevated copper and iron levels were evident only in the near surface layers and at the estimated interface between new and old tailings.

The influence of both the infiltration of alkaline tailings waste, and migration of contaminants on the distribution of elevated concentrations over depth in the tailings is evident from this discussion. Changes in solution pH over time affected the metal concentrations in solution. Generally, copper oxides and hydroxides begin to precipitate around pH 5, whereas zinc can remain in solution up to pH 9.5. This would also explain the greater range over which elevated zinc concentrations were detected.

3.4.2.3 Identification and Location of Contaminant Fronts

In order to determine the progression of acid generation and the flow patterns of the acid drainage and its characteristic contaminants, the shake flask data were also used to locate "contaminant fronts". This analysis was first conducted in the 1988 survey, and repeated for this survey at selected locations to identify changes which had occurred in the intervening fourteen months. The three test pit sites were selected at locations across the impoundment which showed very different profiles in the previous year. In 1988, site E30 (roughly corresponding to L30) had distinctly layered sand and silt strata and contaminant fronts located from 30 cm depth through to the bottom of the hole. Site E100 had a mixture of sands and silts with fronts located over a range of depths. Site E160 showed a range of sands and silts with relatively shallow fronts.

The location of a contaminant front was determined using shake flask test results for fresh tailings samples and test pit samples. The fresh tailings samples from Area #2 were used as background values and subtracted from the older tailings result for each parameter. The difference between the background value, and the reading after 7 (fresh layer) or 44 (old layer) months deposition was calculated for each depth interval to determine where elevated levels of the parameter existed.

The definition of an "elevated level" as used in the previous study was primarily an empirical decision based on examination of the shake flask test data. Although the changes in shake flask solution concentrations were not as large for dissolved metals in this study as in last year's, the same criteria were applied to the data for comparison. The criteria are described below:

- For pH, a difference of greater than or equal to 2 pH units,
- For acidity a difference of greater than or equal to 10 mg/L,
- For sulphate a difference of greater than or equal to 300 mg/L,
- For conductivity a difference of greater than or equal to 600 umhos/cm,
- For copper a difference of greater than or equal to 1 mg/L,
- For iron a difference of greater than or equal to 1 mg/L,
- For zinc a difference of greater than or equal to 3 mg/L.

A difference larger than the values listed was considered to indicate that a significant change has occurred at that sample location due to acid generation at that location, and/or the transport of acid drainage (by advection, diffusion, and dispersion) to that position.

The depth of the front in each test pit (as summarized in Table 13) was plotted for each contaminant in Figures 17, 18, and 19. Test pits in which elevated levels appeared at different depths, but not continuously, were noted on the graphs ("v" for variable pattern). The position of the contaminant fronts were also plotted on a fence diagram, Figure 20. This diagram was constructed from the test pit logs to indicate the layered nature of the tailings, and the type of material in which the contaminants were concentrated.

The concentration and distribution of each contaminant is dependent on a number of factors:

- i) source configuration, i.e. depth and area over which the acid is being generated,
- ii) groundwater flow rate, and vertical and horizontal components of flow and the associated flushing and dilution of contaminants from the zone of oxidation
- iii) order and rate of generation of each front
- iv) retardation reactions (particularly affected by pH)
- v) diffusion and dispersion effects in each layer

Thus the positions of the fronts indicate both the order of generation and mobility of each front under the given conditions. Insufficient information was available from this program to differentiate the two effects. The layered heterogeneity of the tailings has been noted previously and was again apparent in the distribution of elevated contaminant concentrations.

The positions of the contaminant fronts varied for each contaminant, and within each test pit. The fronts were very shallow, or not evident in test pit L30, and deeper in L100 and L160. Copper, iron and pH fronts appeared to be the least mobile, or the last generated as they appeared at the shallowest depths. An elevated copper concentration was evident at L160, 2.49 m depth, close to the former exposed surface of the tailings. Copper and iron require low pH environments for mobility and thus it is reasonable that these fronts are coincident with pH. Oxide and hydroxide formation and precipitation reactions inhibit metal mobility in alkaline conditions.

TABLE 13

LOCATION OF CONTAMINANT FRONTS

EXTENT OF CONTAMINANT FRONT (depth in cm)			
TEST PIT	L30	L100	L160
pH	5-9	5-21	2-10
			24-40
Acidity	0-5	5-21	0-40
		90-112	245-274
		190-270	
Sulphate	9-22	0-52	0-40
		190-270	95-265
Conductivity	0-5	0-5	0-40
		21-52	249-265
		90-112	
		202-232	
Copper	-	5-21	2-10
			24-40
			249-265
Iron	-	-	2-10
			24-40
Zinc	0-9	0-21	0-40
		90-112	95-123
		202-231	245-325

FIGURE 17 DEPTH OF pH, Cu AND Fe FRONTS

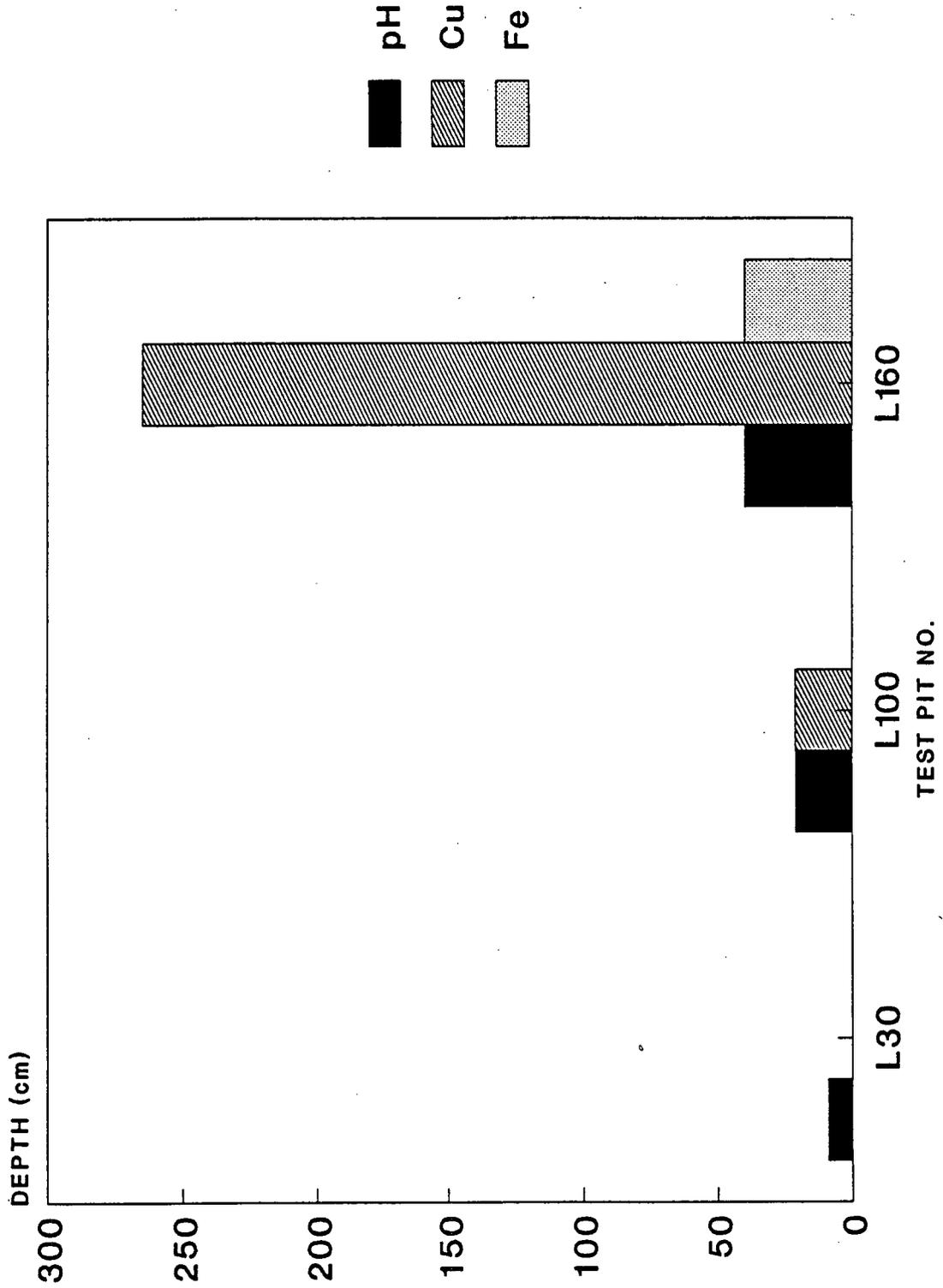
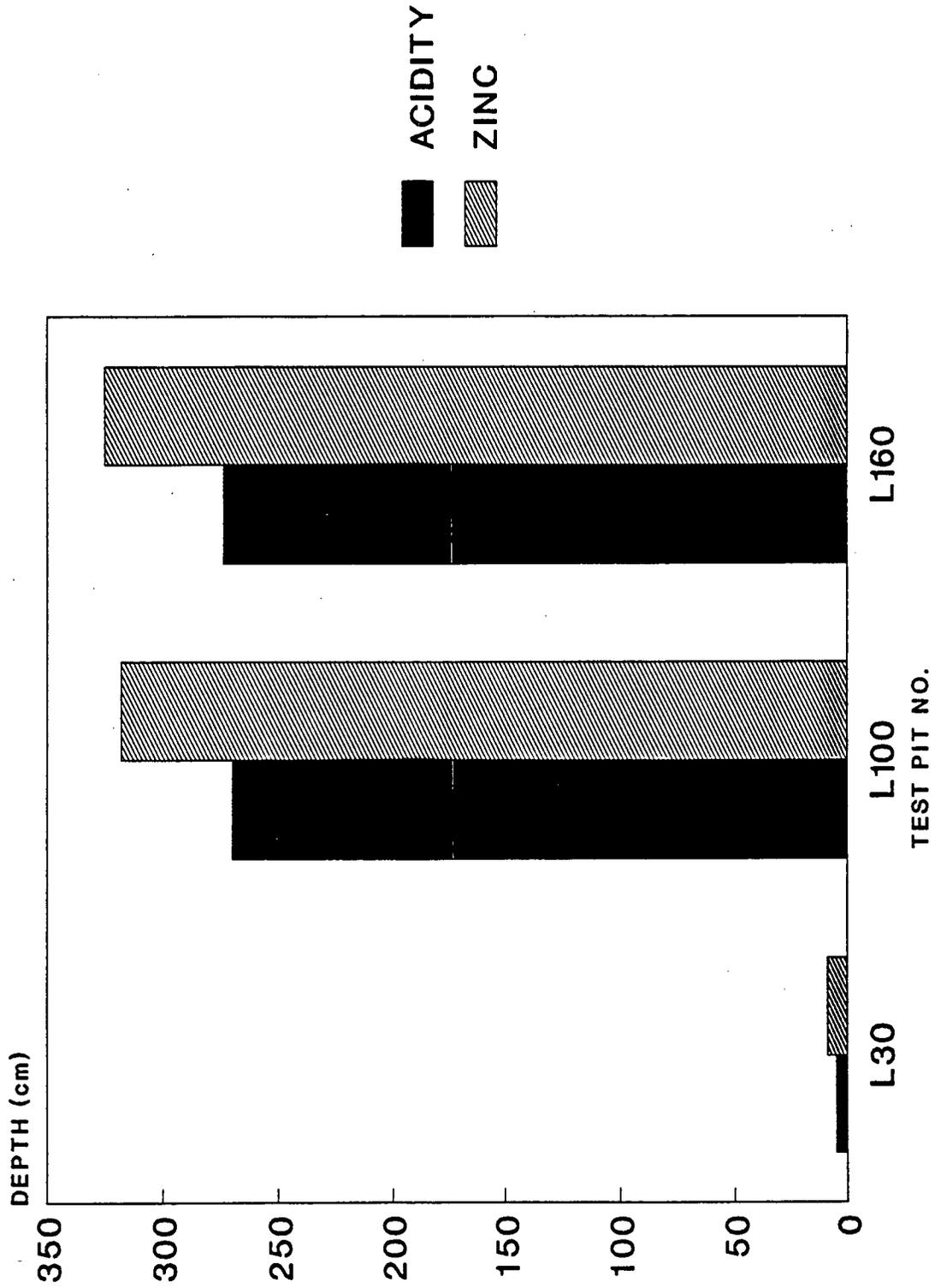


FIGURE 18 DEPTH OF ZINC AND ACIDITY FRONTS



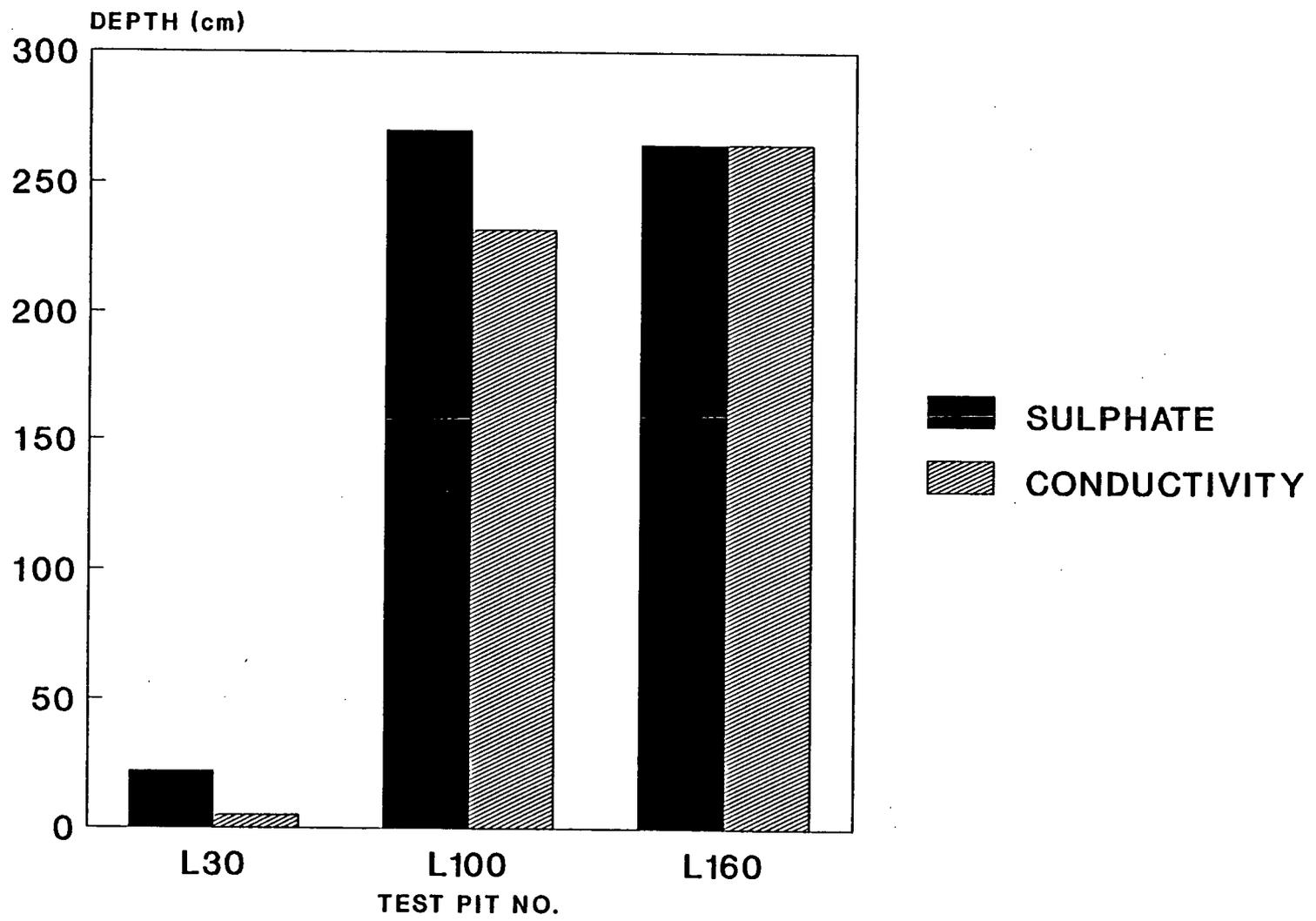
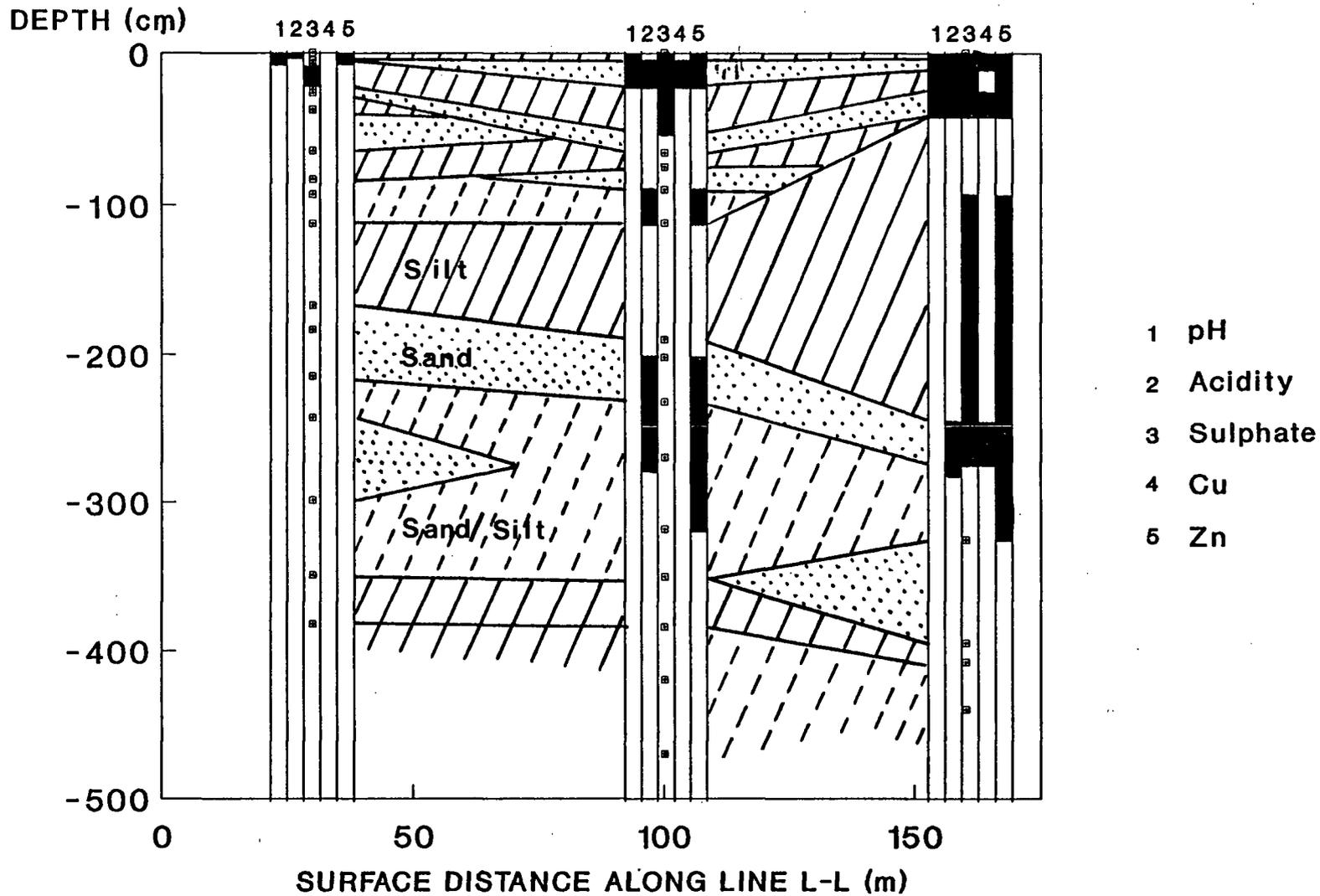


FIGURE 19 DEPTH OF SULPHATE AND CONDUCTIVITY FRONTS

FIGURE 20 FENCE DIAGRAM



The zinc, acidity, sulphate and conductivity fronts were more mobile, appearing over 3.25 m of depth in the tailings. Elevated zinc concentrations were evident at 3.2 m in L100 and 3.25 m in L160. Elevated acidity values were noted as deep as 2.7 m in the tailings in a variety of layers over a total of 2.2 m of depth.

Sulphate and conductivity fronts appeared at a maximum depth of 2.65 m. The coincidence of these two fronts is reasonable; sulphate ions are probably the dominant anions and would therefore contribute significantly to conductivity. The total depth over which elevated levels were noted, however, was 3.6 m for sulphate and only 1.5 m for conductivity. This is in part due to the somewhat arbitrary definition of single value criteria for an "elevated" level, as high sulphate levels corresponded to high conductivity, which is not apparent when considering only a front.

The fence diagram (Figure 20) clearly shows the extent to which the fronts have penetrated for each test pit. It is difficult to extrapolate the results across the impoundment given the limited number of test pits, and variability of tailings layers. Each test pit is evaluated individually as drainage patterns and relationships throughout a given layer cannot be determined.

The distribution of fronts suggests that the nature of the tailings material (particle size and saturation) might affect the generation and movement of contaminants. At L30, oxidation has been established within the top 9 cm of the tailings (based on low pH) and elevated acidity, conductivity and zinc are evident. This upper 9 cm consisted of a moist silt surface layer and dry sand underneath. Elevated sulphate concentrations appeared down to 22 cm depth within a layer of moist silt. No fronts were evident below this silt layer. Fronts appeared to be limited at sites with a silty surface layer.

The contaminant fronts in test pit L100 were located in groupings at three levels in the test pit. Low pH and elevated acidity indicated that oxidation was established in the upper 21 cm of sandy silt and a layer of dry, fine brown sand. The conductivity and sulphate fronts from surface extended deeper into a thick layer of moist to wet silt similar to L30. Elevated levels of acidity, conductivity, and zinc were also located within the sandy silt layer between 90 and 112 cm depth. The third grouping of fronts was located at the estimated old surface of the tailings at approximately 1.8 m depth. Conductivity was elevated in the dark, orange brown sand at 2 m. Sulphate, zinc and acidity fronts were noted to much

greater depth in the old tailings layer, extending through sand and silty sand material. Sulphate levels were elevated from 1.9 m to 2.7 m depth. The tailings in this area were described as fine sands and silty sands, grading from dry to moist over depth and with increasing silt content. The acidity front extended from near the old tailings surface down to 2.7 m depth. Elevated zinc levels were found from 2 m to 3.2 m depth, through sands and silty sands.

Contaminant fronts were located at two intervals in test pit L160. The upper 50 cm of the tailings showed elevated dissolved metals, conductivity, sulphate, acidity and low pH. This upper strata consisted of five layers of alternating moist silt and dry sand with the lower limit primarily moist silt. Dissolved metal fronts were not evident, however, in the middle silt layer. Elevated zinc and acidity levels were noted again from 0.95 m depth to 3.25 m. The upper 1.5 m of this interval consisted of wet silty material. Below this silt, the tailings changed to sand and silty sand, and pH, acidity, and conductivity fronts appeared within the old tailings layer.

Emergency Pond

As described earlier, fresh tailings samples were not available from the Emergency Pond. Thus comparisons were made to the Area #2 fresh tailings to estimate positions of contaminant fronts. Based on this criterion, the only contaminant fronts in evidence were zinc fronts, in test pit EP1. These occurred in the near surface silt layer with evidence of cracking, and the lower silt and sandy silt layers.

3.4.3 Pore Water

The actual concentration of metals and acidity in the pore water and drainage water within the tailings can be difficult to determine, and yet is key to evaluating the progression of acid generation, and the short and long term drainage quality from the tailings impoundment. Collection of pore water samples can be difficult from unsaturated soils, and requires relatively sophisticated equipment. Shake flask tests are often used instead, to determine the water soluble fraction of the tailings. Such tests, however, may not be indicative of the actual concentrations in the drainage through the tailings.

Pore water samples were therefore collected in this survey to determine the actual concentrations of contaminants in the interstitial fluids of the tailings mass. The samples were analyzed and the results are summarized in Table 14. Comparison with the results of shake flask tests on the same samples

TABLE 14

**ANALYTICAL DATA FOR PORE WATER AND CORRESPONDING
SHAKE FLASK SAMPLES**

SAMPLE	pH	ACIDITY	Ca	SO ₄ ²⁻	CONDUCT.	DISSOLVED METALS			
						Cu	Fe	Pb	Zn
Pore Water Samples									
L100 C	7.0	-	275	-	-	0.03	<.005	<0.05	7.12
L160 C	5.4	-	386	-	-	4.78	0.02	0.3	112
L160 E	6.7	-	295	-	3000	0.09	0.01	<0.05	0.05
EP1 D	6.6	-	630	-	2050	0.01	0.01	<0.05	16.9
EP1 F	6.0	-	584	-	1950	0.01	0.01	<0.05	44.3
EP2 B	6.5	-	684	-	-	0.14	<.005	<0.05	51.4
EP2 C	6.8	-	618	-	-	0.10	0.01	<0.05	50.6
EP2 E	7.0	-	631	-	2800	0.02	<.005	0.05	33.2
Shake Flask Samples									
L100 C	7.0	3.2	203	403	850	0.01	<.005	<0.05	1.21
L160 C	7.5	32.2	199	470	930	0.01	0.02	<0.05	26.3
L160 E	8.1	2	136	250	580	0.01	0.01	<0.05	1.11
EP1 D	8.4	< 1	74.5	100	340	0.01	0.01	<0.05	0.21
EP1 F	8.4	< 1	64.2	100	305	0.01	0.01	<0.05	3.2
EP2 B	8.5	< 1	86.3	100	350	<.005	<.005	0.11	6.5
EP2 C	8.4	< 1	135	200	480	0.01	0.01	0.06	0.57
EP2 E	8.4	< 1	61	100	280	<.005	<.005	<0.05	0.08

Note: All units mg/L except pH, pH units, conductivity (umhos/cm), acidity (mg/L CaCO₃ equivalent).

should indicate if shake flask tests are representative of the tailings drainage water. In Table 15, the ratio of pore water to shake flask concentration has been calculated for each sample.

TABLE 15
RATIO OF PORE WATER TO SHAKE FLASK CONCENTRATION

SAMPLE	pH*	ACIDITY	Ca	SO ₄ ²⁻	CONDUCT.	DISSOLVED METALS			
						Cu	Fe	Pb	Zn
L100 C	0	-	1.4	-	-	2.0	4.4	1.0	5.9
L160 C	2.1	-	1.9	-	-	531	243	6.0	4.3
L160 E	1.4	-	2.2	-	5.2	7.2	2.1	1.0	0
EP1 D	1.8	-	8.5	-	6.0	1.3	2650	1.0	79.0
EP1 F	2.4	-	9.1	-	6.4	0.5	32.1	1.0	13.8
EP2 B	2.0	-	7.9	-	-	8.1	122	0.5	7.9
EP2 C	1.6	-	4.6	-	-	3.9	27.0	0.8	88.8
EP2 E	1.4	-	10.3	-	10.0	1.1	680	1.0	400

* Note: pH expressed as absolute difference (shake flask - pore water)

The analyses of the Area #2 samples (relatively fresh tailings) were presented in Section 3.2.1 and 3.2.2. The ICP analyses of duplicate samples of pore water from the fresh tailings sample were very close. Marked differences were evident, however, between the two pore water samples from the one month old tailings samples, indicating potential difficulties in obtaining and identifying representative tailings pore water samples.

The results of the shake flask tests on the Area #2 tailings solids described in Section 3.4.2 were also compared to the pore water sampling from the fresh and one month tailings samples discussed in

Section 3.2.2. In the pore water samples conductivity, dissolved copper and dissolved iron values increased over the 1 month deposition period. Zinc concentrations in the pore water were variable and did not show the same increase as shake flask solutions.

Shake flask extraction tests were conducted using approximately 500 mL of distilled water with 25 g of sample, considerably more dilute than the pore water samples. The soluble fraction of the tailings plus any contaminants that remained on the solids after drying would report to the shake flask solution. The pore water solution would contain contaminants already in solution in situ. Due to the dilution, pore water samples would therefore be expected to have significantly higher concentration than the shake flask samples, however, this was not evident in the data.

The slight decrease in pore water pH in the Area #2 samples would not be apparent in the more dilute shake flask solutions. Calcium and conductivity values in pore water were only six to seven times the shake flask value. Copper concentrations were similar, and iron and zinc values lower in the pore water than in the shake flask sample. Recovery of pore water is difficult from unsaturated materials, particularly coarse sandy tailings, and small volumes of solution were recovered limiting the extent of analysis. The comparison, however, between the elevated concentrations in the shake flasks and the relatively low concentrations in the pore water suggested there was a significant water soluble fraction in the tailings solids after a short deposition period.

Pore water samples were also collected where possible from the older Area #1 tailings from the test pits. Generally this was only possible from silt samples which contained a higher residual moisture content, approaching saturation. There was insufficient pore water in the sandier samples to collect a sample for analysis.

As discussed above, if there were no dissolution during the shake flask procedure, the concentration in the pore water should be at least 500 times the shake flask, if in equilibrium. It is evident from the data in Table 14 that the ratio of concentrations varied. The ratio of pore water concentrations to shake flask concentrations varied from 0 (for less than detection values in both cases) to 2,650 (Fe in EP1 D). The ratios varied from sample to sample and were not similar for any one constituent.

The pore water analyses revealed higher metal concentrations and lower pH values than the corresponding shake flask tests with the exception of copper in one Emergency Pond sample, and zinc in L160 E. Metal solubility, however, is related to pH and shake flask solutions were quite consistently near neutral. Differences in pH between the pore water and shake flask samples were as high as 2.4 pH units (EP1 F). The pore water samples also exhibited a larger range of concentrations than did the shake flask tests. Copper values were very low, and generally less than ten times the shake flask concentrations at pH values ranging from 6.0 to 7.0. The exception, however, was L160 C, at 4.8 mg/L, at 531 times the shake flask value. This pore water sample had the lowest pH at pH 5.4, 2.1 pH units less than the shake flask value. The highest lead and zinc concentrations, and elevated iron content were also evident in this sample reflecting pH limits on solubility. Metal solubility tends to increase appreciably as pH decreases below a critical pH; below approximately pH 10 for zinc, and pH 6 for copper.

Iron and zinc values were considerably higher in the pore water sampling than in the shake flask solutions. Pore waters ranged from 0.02 to 15.9 mg/L Fe, and 0.05 to 112 mg/L Zn. Shake flask concentrations ranged from less than detection to 0.02 mg/L Fe, and 1.1 to 26.3 mg/L Zn. Dissolved iron and zinc concentrations in the pore waters varied inversely with pH. Based on the ratio of concentration for iron, as shown in Table 15, the total metal in solution was greater in the shake flask than the pore water samples in most cases. Two Emergency Pond samples, however, EP1D and EP2E, showed higher concentrations in the pore water samples than in the shake flasks. In all cases, the shake flask tests extracted considerably more zinc on a mass basis than was present in the pore water samples.

These results may be due to a store of readily soluble oxidation products in the tailings solids that can be released when flushed with fresh water. The apparently lower concentrations in the pore water samples might also be a result of the extraction process, which does not recover all of the residual moisture in a sample. The water held most closely within the pore spaces of a solid sample, not recovered in the pore water sample, may contain a higher dissolved load than the more readily extracted (and flushed) pore water.

Based on the results of this test program, it would appear that in many cases the shake flask tests

do result in extraction of the water soluble fraction within a solid sample, resulting in apparently higher solution concentrations than might be present in the pore water. These shake flask values, however, would be indicative of the stored soluble oxidation products, and thus the extent of oxidation, and also of the potential drainage quality in terms of total mass of soluble metal, not concentration, from flushing the tailings solids. There are insufficient samples, however, in this program to identify trends, or develop a correlation between pore water and shake flask samples. Sampling was also limited to very wet, silt samples and might not be truly representative of the comparison between pore water and shake flask sampling. Low pH samples are needed to complete such an analysis.

3.4.4 Oxygen/Carbon Dioxide Measurements

The availability of oxygen is an important parameter in controlling the onset and initial rate of sulphide oxidation. To evaluate oxygen diffusion through the tailings and consumption by oxidation reactions, measurements were made of gaseous oxygen and carbon dioxide concentrations near each of the test pits. The results of the tests at each site are provided in Table 16, and graphed in Figures 21 through 27. These gas profiles were then compared with the test pit profiles in Figures 10 through 14 showing the type of soil and thickness of each horizon to determine the type of material in which the readings were taken.

Generally the results of the sampling showed variations in oxygen concentration from atmospheric (20.8 %) to as low as 4.8 %. Carbon dioxide concentrations varied correspondingly from 0 % to as high as 4.3 %. A marked decrease in oxygen concentration and increase in carbon dioxide content was evident in each test pit in Area #1, and EP1, coinciding with a layer of dry, fine brown sand in each case. The carbon dioxide maximum in each hole frequently occurred slightly shallower than the oxygen minimum, possibly due to the production of carbon dioxide by acid dissolution of carbonates at the leading edge of the oxidation zone, and the upward migration of CO₂.

TABLE 16

NEAR SURFACE OXYGEN/CARBON DIOXIDE MEASUREMENTS - AREA #1

TEST PIT L30	TEST NO. 1			TEST NO. 2		
	DEPTH	O₂	CO₂	DEPTH	O₂	CO₂
	(cm)	(%)	(%)	(cm)	(%)	(%)
	0	20.8	0.0	0	20.8	0.0
	8	17.5	0.0	8	13.6	3.4
	-			15	16.6	1.5
	20	20.0	0.0	20	18.2	0.9
22-26 cm sand	-			25	14.1	2.3
	30	10.6	3.4	30	9.4	2.8
37-64 cm sand	40	5.2	3.4	40	3.0	4.0
	50	4.8	3.3	50	5.2	3.3
	60	15.0	0.9	60	13.2	1.4
	70	12.4	0.6	70	10.1	0.9
	80	14.2	0.5	80	11.6	1.4
	-			90	11.0	1.1

TABLE 16 (cont'd)

NEAR SURFACE OXYGEN/CARBON DIOXIDE MEASUREMENTS - AREA #1

TEST PIT L100	TEST NO. 1			TEST NO. 2		
	DEPTH	O ₂	CO ₂	DEPTH	O ₂	CO ₂
	(cm)	(%)	(%)	(cm)	(%)	(%)
	0	20.8	0.0	0	20.8	0.0
5-21 cm sand	5	20.8	0.0	8	20.6	0.0
	10	20.4	0.2	-		
	15	16.3	1.7	15	13.5	2.7
	20	16.3	1.7	-		
	25	19.1	0.5	-		
	30	19.2	0.4	31	no flow	
	35	19.0	0.4	-		
	40-50	no flow				

TABLE 16 (cont'd)

NEAR SURFACE OXYGEN/CARBON DIOXIDE MEASUREMENTS - AREA #1

TEST PIT L160

	DEPTH O ₂	CO ₂	DEPTH O ₂	CO ₂
	(cm)	(%)	(cm)	(%)
	0	20.8	0.0	
2-10 cm sand	5	20.2	0.2	
	10	19.7	0.4	
	15	18.9	1.1	
	20	19.6	0.5	
24-40 cm sand	25	19.6	0.5	
	30	11.7	4.3	
	35	14.5	2.8	
	40	17.3	1.4	
	45-65	no flow		

TABLE 16 (cont'd)

NEAR SURFACE OXYGEN/CARBON DIOXIDE MEASUREMENTS - AREA #1

	DEPTH	O ₂	CO ₂
	(cm)	(%)	(%)
TEST PIT EP1	0	20.8	0.0
	8	17.5	0.0
22-26 cm sand	20	20.0	0.0
	30	10.6	3.4
37-64 cm sand	40	5.2	3.4
	50	4.8	3.3
	60	15.0	0.9
	70	12.4	0.6
	80	14.2	0.5

TEST PIT EP2	0	20.8	0.0
5-21 cm sand	5	20.8	0.0
	10	20.4	0.2
	15	16.3	1.7
	20	16.3	1.7
	25	19.1	0.5
	30	19.2	0.4
	35	19.0	0.4
	40	no flow	

FIGURE 21 GAS PROFILE AREA #1 - TEST PIT L30 TEST 1

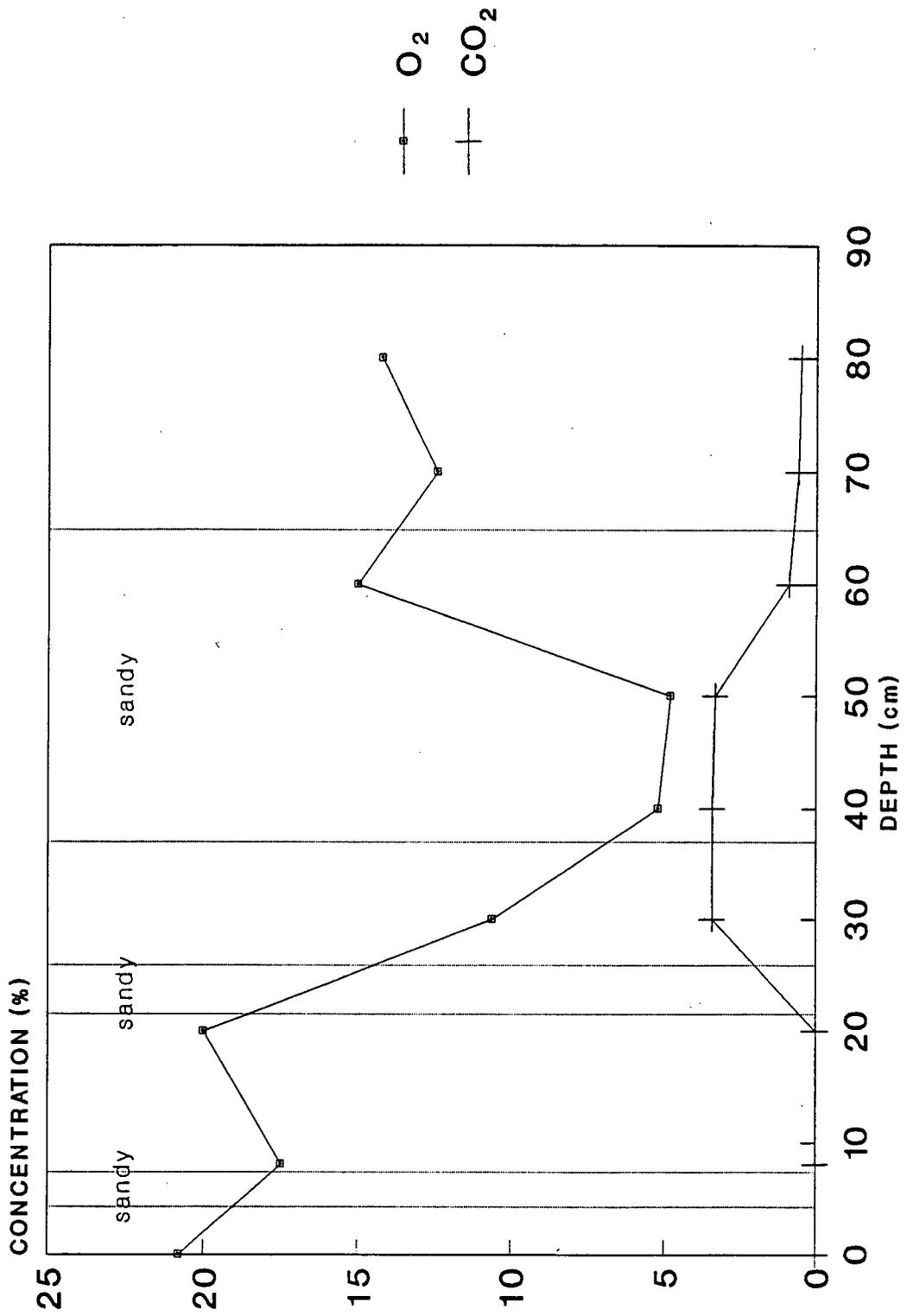


FIGURE 22 GAS PROFILE AREA #1 - TEST PIT L30 TEST 2

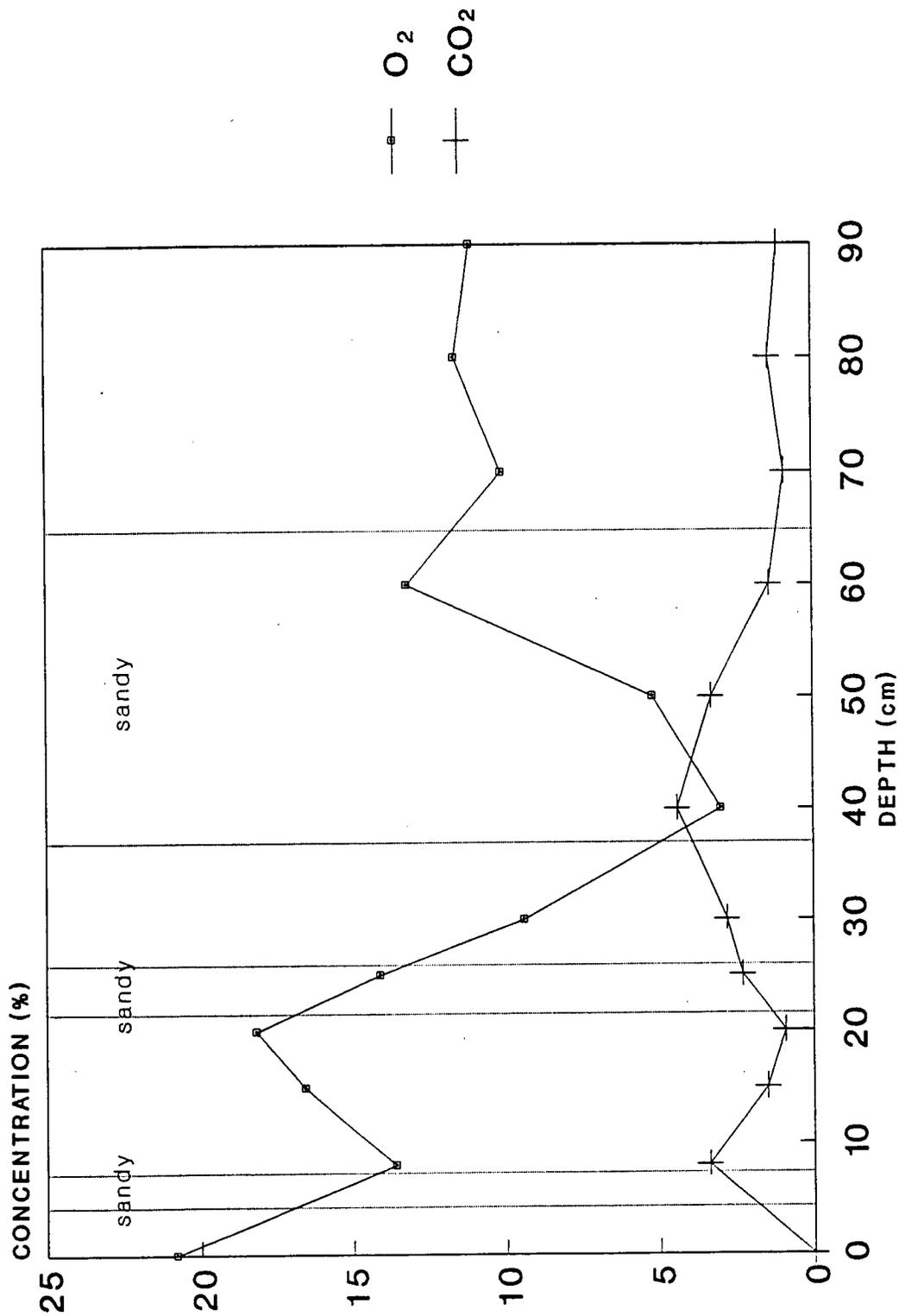


FIGURE 23 GAS PROFILE AREA #1 - TEST PIT L100 TEST 1

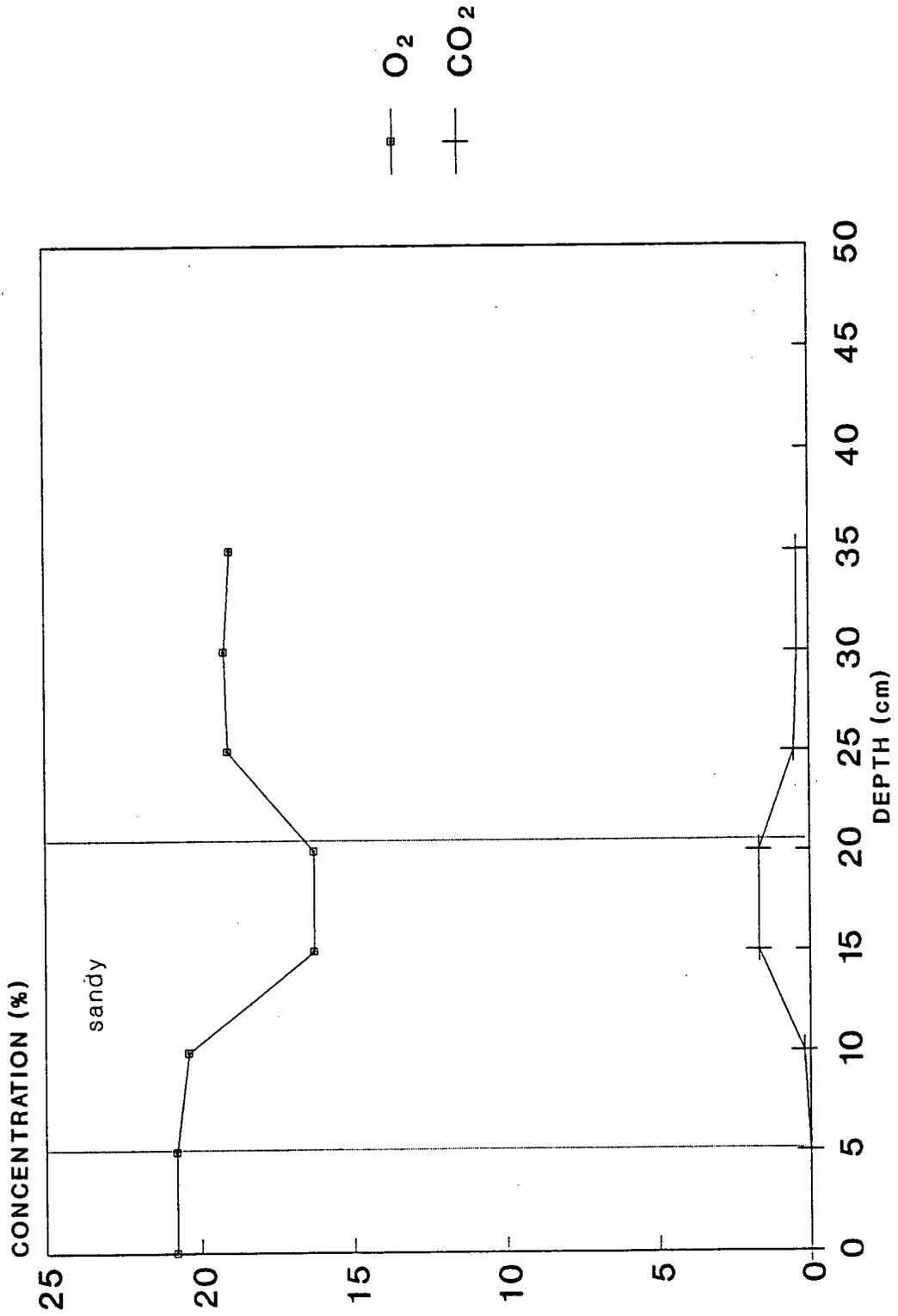


FIGURE 24 GAS PROFILE AREA #1 - TEST PIT L100 TEST 2

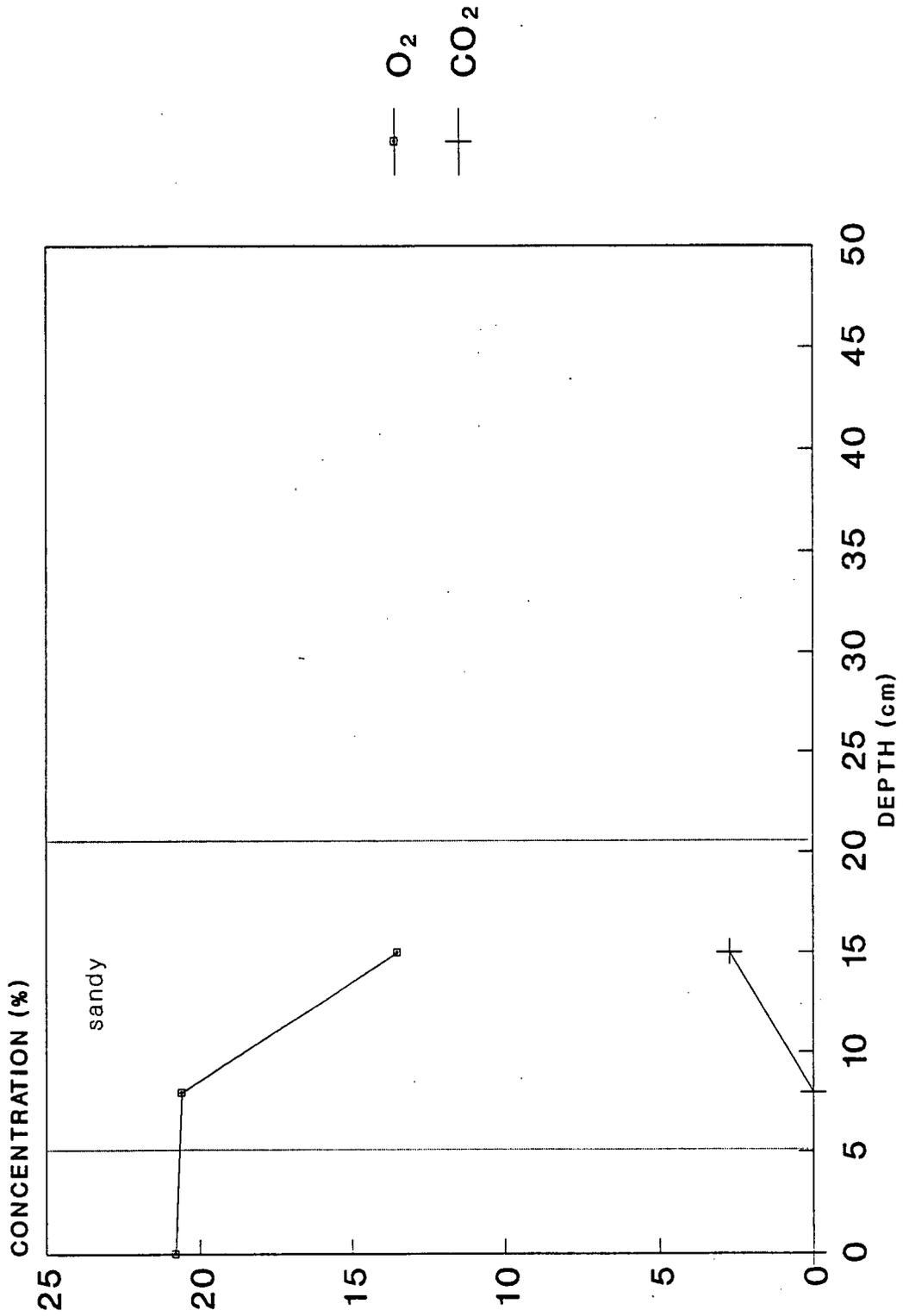


FIGURE 25 GAS PROFILE AREA #1 - TEST PIT L160 TEST 1

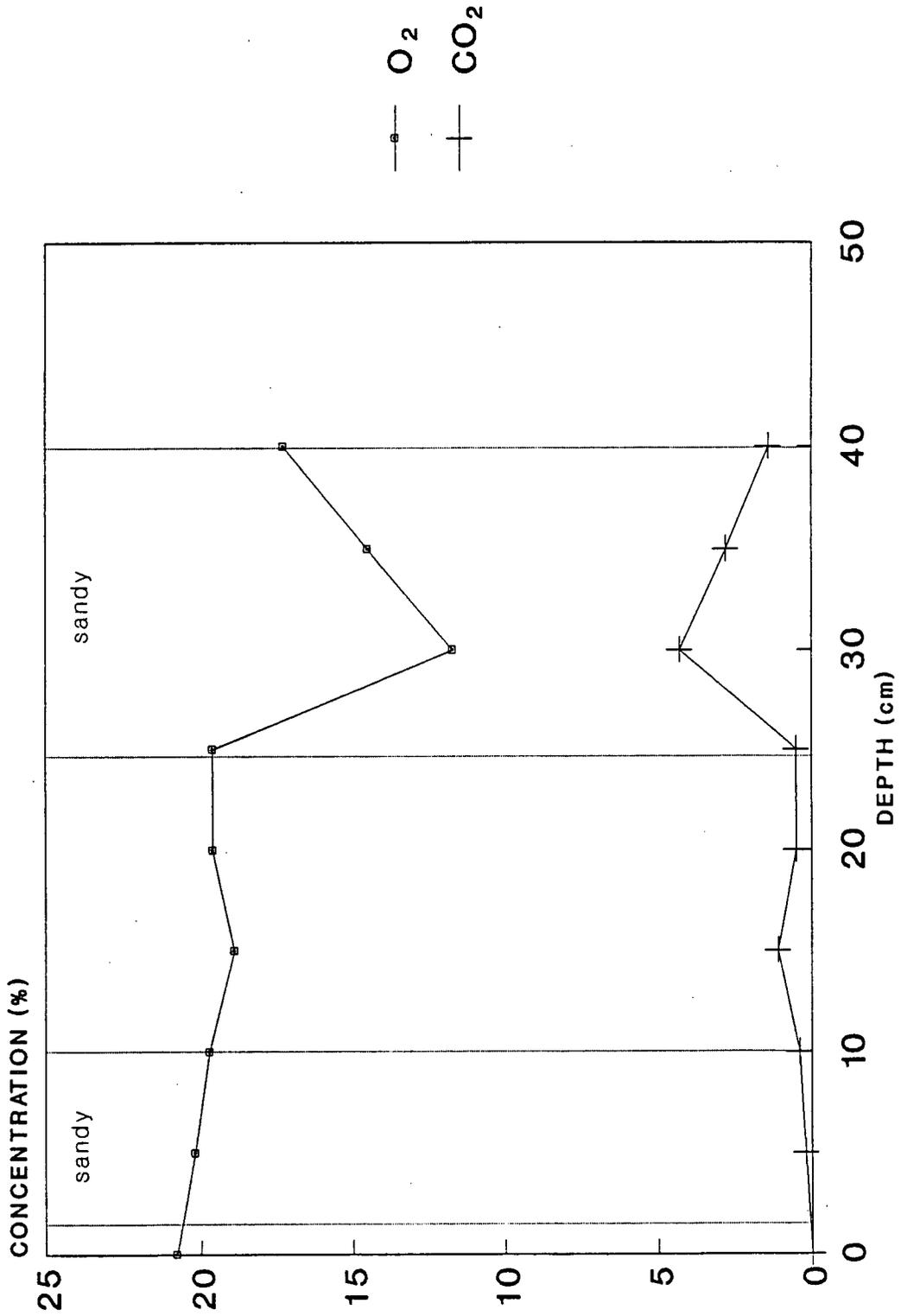


FIGURE 26 GAS PROFILE AREA #1 - TEST PIT EP1

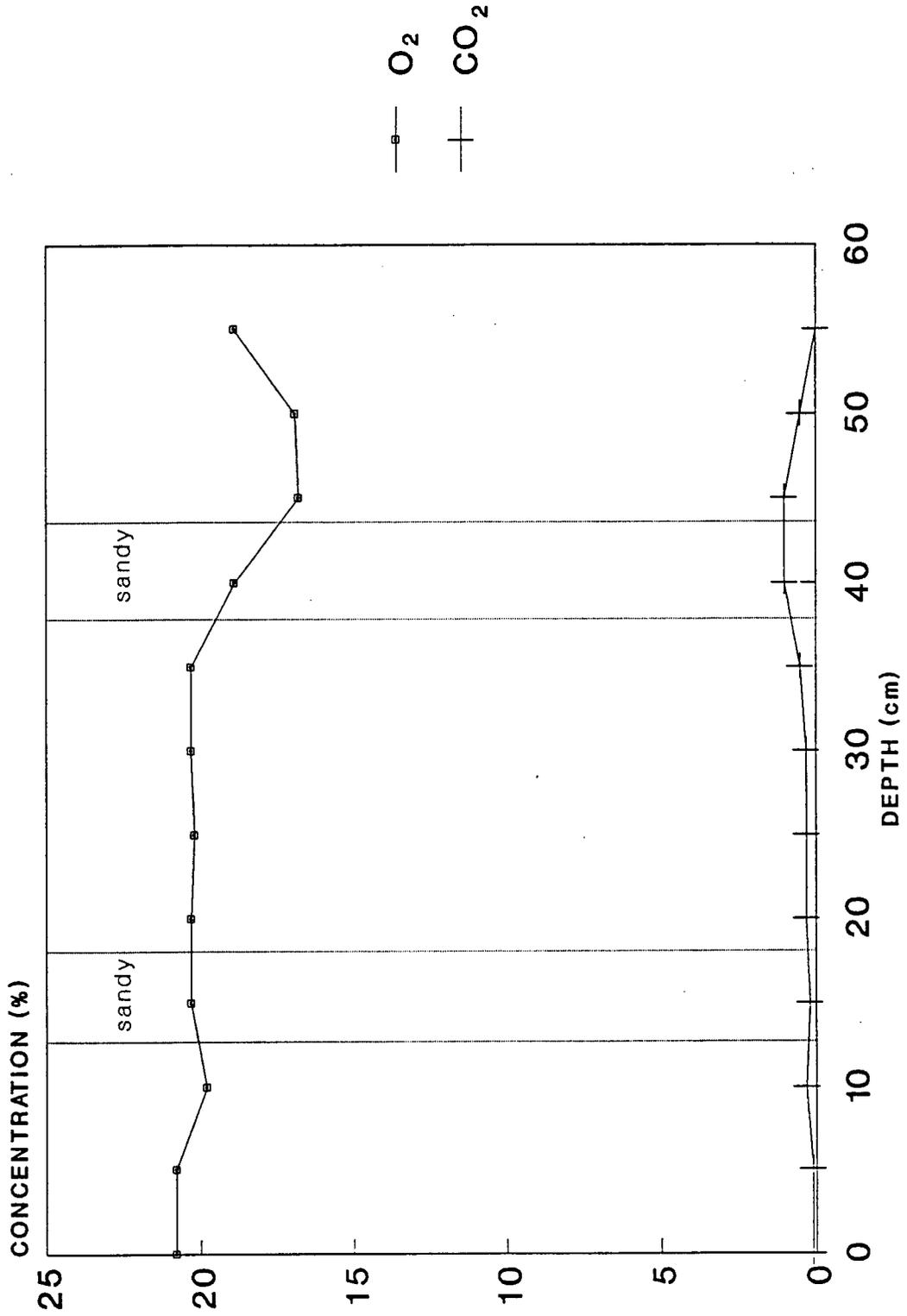
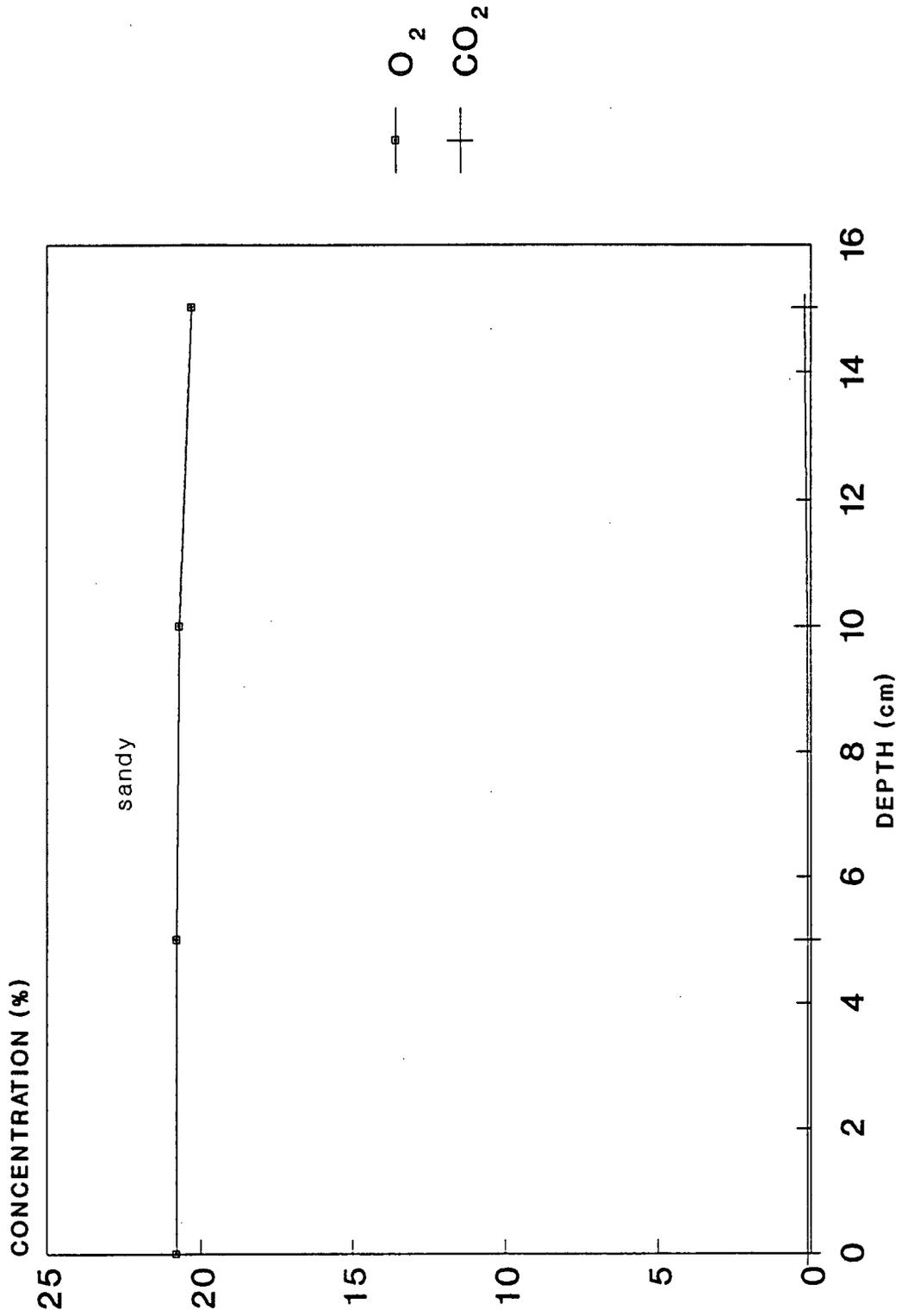


FIGURE 27 GAS PROFILE AREA #1 - TEST PIT EP2



The two profiles obtained near test pit L30 were reasonably consistent as shown in Figures 21 and 22. Concentrations were near atmospheric at surface, decreased slightly in the sand layer B and then increased again near the interface with the underlying silt layer at about 20 cm depth. The lowest oxygen and highest CO₂ readings (3.0 % O₂ and 4.0 % CO₂) were taken between 40 and 50 cm depth in both tests. This was a layer of dry, light brown fine sand. Oxygen content increased and carbon dioxide decreased above and below this layer; at 20 cm, and at 60 cm depth which was near the boundary with the underlying silt layer. The carbon dioxide maximum appeared at 30 cm, while the oxygen minimum appeared between 40 and 50 cm depth.

The tests conducted around test pit L100 showed similar results as shown in Figures 23 and 24. Test 2, Figure 25, however, encountered wet silt at approximately 30 cm which plugged the flow of air through the sampler. A decrease in O₂ and an increase in CO₂ were noted at 15 cm, within a layer of dry, brown sand. A sharp decrease in oxygen content and elevated CO₂ were evident in Test 1 between 15 and 20 cm, near the bottom of layer B, a layer of dry brown fine sand. Gas concentrations approached atmospheric levels again within the upper 4 cm of the underlying moist silt layer.

The logs of test pit L160 indicated significantly higher silt content than the other sites and flow through the gas sampler was plugged at 45 cm depth (Figure 25), within a layer of moist to wet, grey plastic silt. The O₂ content decreased slightly from atmospheric to 18.9 % over 15 cm, through thin layers of silt and sand and increased slightly to 19.6 in a layer of moist silt. The sharp decrease in oxygen content to 11.4 % and 4.3 % CO₂ was evident at 30 cm depth, within a layer of dry sand with interbedded moist silts. Moving deeper, the oxygen content increased again at the interface of the sand with the underlying silt layer.

Much less variation in oxygen content was evident in the Emergency Pond sampling as shown in Figures 26 and 27. Similarly, the test pit profiles indicated little variation, with primarily wet silts in the Emergency Pond. Sampling near test pit EP1 did, however, indicate a decrease in oxygen content to 19.8 % at 10 cm and to 16.8 % at 45 to 50 cm depth. Increases in CO₂ content to 0.3% were evident at 10 cm depth, and to 1 % from 40 to 45 cm depth. The shallow peak corresponded to layers of moist silt with orange/brown streaks along cracks and dry, light brown to white, fine sands (layers B and C).

The deeper oxygen minimum and CO₂ maximum corresponded to layer E and the upper portion of F; dry, grey/brown sand with yellow streaking and a wet grey silt with some vertical cracking.

A slight decrease in oxygen content was evident in the dry, white sand of the upper 15 cm of sampling near test pit EP2. The sampler was plugged and flow blocked at 20 cm depth, the upper limit of a layer of moist, grey, plastic silt.

From this limited oxygen and carbon dioxide sampling program, it was evident that gas concentrations varied over depth in the tailings. There are two primary mechanisms which might affect gas concentrations;

- i) diffusion of air through the tailings both vertically from surface and horizontally through more diffusive (gas permeable) dry sand layers, and,
- ii) consumption of oxygen and production of carbon dioxide by sulphide oxidation and neutralization reactions.

In each sampling profile the overall concentration of oxygen decreased with depth from atmospheric to approximately 18 % within the silt layers. The marked decrease in oxygen and increase in CO₂ of the dry, sand layers indicates consumption of oxygen within these strata at a similar rate (assuming the system is at steady state) to which oxygen is replaced from the atmosphere. The diffusion coefficient of dry sand material is much greater than wet silt (Broughton and Ferguson, 1989), suggesting that a significant flow of air does not occur either vertically from the atmosphere through the overlying silt layer, or horizontally along the sand layer in the areas sampled. It also must be considered that these "layers" might be isolated pockets of material, rather than continuous layers allowing flow of air; the lack of continuity in the layers was also suggested by the 1989 study. It would thus appear that diffusion of air into the tailings mass is limited by the diffusivity of the overlying surface layer.

4.0 GEOCHEMICAL AND GEOTECHNICAL

The geotechnical characteristics of the layered, subaerial tailings impoundment are designed to limit both the factors contributing to the geochemical processes of sulphide oxidation and metal leaching and to control drainage mechanisms and contaminant transport within the impoundment. The following sections discuss the geochemical nature of the impoundment, and changes that have occurred since the previous survey, in light of the geotechnical characteristics of the tailings.

4.1 Changes in Contaminant Fronts Since 1988

The location and movement of the contaminant fronts in this and the previous study are key to evaluating the generation and the transport of contaminants through the tailings mass. The primary concern with acid generating tailings is the potential long term drainage quality from the impoundment. The following discussion was developed to estimate the rate of vertical movement of the contaminant fronts. Emphasis is placed on the old tailings layer for which there are data for comparison from the 1988 study.

A key design principle of a subaerial tailings mass is the layered heterogeneity resulting in low horizontal and very low vertical permeability. To provide a common baseline for comparison of the two surveys, the estimated depth of the old tailings surface was added to the depth of the contaminant fronts from the 1988 survey. The results are presented in Table 17. This was suggested by the patterns of contaminant fronts in the previous survey. In a layered mass the vertical flow rate is limited by low conductivity layers, thus the overall vertical hydraulic conductivity is a weighted geometric average of the conductivity of each layer. The horizontal conductivity, however, would equal that of the most permeable layer of material, along which solution would tend to flow. The vertical rate of advance does not completely describe solution flow in the impoundment as there is thought to be a horizontal component of flow in the tailings mass, along the more permeable sand layers. It is impossible to predict the horizontal component of flow, however, without more knowledge of hydraulic gradients and separate values in the horizontal direction within the tailings mass.

TABLE 17

LOCATION OF CONTAMINANT FRONTS 1988, 1989

DEEPEST EXTENT OF CONTAMINANT FRONT (cm)				
	1988	1989	1988	1989
TEST PIT	E100	L100	E160	L160
pH	202	21	258	40
Acidity	226	270	265	274
Sulphate	248	270	258	265
Conductivity	216	232	258	265
Copper	202	21	258	265
Iron	202	0	258	40
Zinc	248	318	265	325

The above data indicate that in many cases where the contaminant fronts were found within the old tailings mass, these fronts were located deeper than in the previous year's survey. The estimated depth of the contaminant fronts might have been influenced by the estimation of the old tailings surface location, although the degree of difference is not consistent at each site. The fronts located in this study within the old tailings mass included acidity, sulphate, conductivity, and zinc. Low pH fronts were not detected within the old tailings layer, nor were iron fronts. A copper front was detected only at L160.

There were no fronts detected within the "old" tailings at site L30. The fronts at site L100 were more mobile over the intervening year than at site L160. Generally zinc fronts seemed most mobile, appearing 60 to 70 cm deeper in the 1989 survey. Acidity fronts were also mobile, appearing 9 to 44 cm deeper. Sulphate and conductivity were less mobile. Copper, iron, and pH fronts were no longer evident within the old tailings layers, except copper at L160. This is probably due to the infiltration of

alkaline water from the new tailings resulting in pH modification and precipitation of copper and iron from solution in the upper layers of the old tailings. This pattern of metal mobility, with acidity, sulphate, conductivity and zinc most mobile and pH, copper and iron less mobile, was similar to that identified in previous studies (Broughton and Ferguson, 1989) and discussed in Section 3.

It was also considered that acid generation had slowed and less leaching of metals was occurring within the old tailings layer, sufficiently that residual neutralization potential reduced acidity and precipitated copper and iron from solution and therefore fronts were no longer evident. Previous studies, however, showed little or no residual neutralization potential in oxidized layers. At E30, there was no neutralization potential in the top 30 cm, however, the pH and metal fronts found in the previous survey were not found in 1989. Therefore the infiltration of alkaline water is the most probable explanation.

As shown in Table 18, calculations were made of the infiltration rate of the contaminant fronts based on the depth of the front, both for these data and the 1988 study data. Sulphate and zinc are typically considered conservative components (non-reactive chemically) in groundwater investigations and thus should indicate the most rapid rate of advance of the drainage solution. Zinc fronts appeared most mobile and thus were probably indicative of the rate of drainage through the impoundment, least affected by retardation reactions. It should be noted that infiltration rates were calculated for "fresh" and "old" tailings layers, that is, within the tailings placed in the past 14 months, and in the tailings that were placed 44 months ago. The time period for the fresh tailings layer was 7 months, i.e. from end of deposition and for the old tailings layer an incremental increase of 14 months since the last study.

These calculations are approximations of the vertical rate of advance of each front and did not include any horizontal component of flow. The results are useful for estimating the rate of advance of each front and predicting the potential for eventual contaminant release from the tailings impoundment through the underdrain below the tailings. Infiltration rates also reflect the rate of generation of each contaminant. Comparison of these infiltration rates with previous studies provided some indication of changes that occurred over time and with the addition of the fresh tailings layer. The new layer of

TABLE 18
CALCULATED INFILTRATION RATES OF CONTAMINANT FRONTS
Results of 1989 and 1988 Surveys

FRONT	VERTICAL INFILTRATION RATE (cm/s)				
	L30		L100		L160
	FRESH	FRESH	OLD	FRESH	OLD
pH	5.0×10^{-7}	1.2×10^{-6}	-	2.2×10^{-6}	-
Acidity	2.8×10^{-7}	6.2×10^{-6}	1.2×10^{-6}	2.2×10^{-6}	2.5×10^{-7}
Sulphate	1.2×10^{-6}	2.9×10^{-6}	6.1×10^{-7}	2.2×10^{-6}	1.9×10^{-7}
Conductivity	2.8×10^{-7}	6.2×10^{-6}	4.4×10^{-7}	2.2×10^{-6}	1.9×10^{-7}
Copper	-	1.2×10^{-6}	-	2.2×10^{-6}	1.9×10^{-7}
Iron	-	-	-	2.2×10^{-6}	-
Zinc	5.0×10^{-7}	6.2×10^{-6}	1.9×10^{-6}	6.8×10^{-6}	1.7×10^{-6}

FRONT	E30	E100	E160
	pH	4.0×10^{-7}	1.5×10^{-7}
Acidity	5.7×10^{-7}	4.6×10^{-7}	4.5×10^{-7}
Sulphate	4.0×10^{-7}	7.5×10^{-7}	3.6×10^{-7}
Conductivity	4.0×10^{-7}	3.3×10^{-7}	3.6×10^{-7}
Copper	4.0×10^{-7}	1.5×10^{-7}	3.6×10^{-7}
Iron	1.2×10^{-7}	1.5×10^{-7}	3.6×10^{-7}
Zinc	7.7×10^{-7}	7.5×10^{-7}	4.5×10^{-7}

tailings could potentially limit the ingress of oxygen and surface water, and affect the hydraulic gradient, and cause compaction of the old tailings layer.

The calculated vertical infiltration rates were higher in the fresh layer of tailings than in the upper layer of the previous year's study. Infiltration rates in the fresh layer ranged from 2.8×10^{-7} to 6.8×10^{-6} cm/s in this study but were generally in the range of 10^{-6} cm/s, relatively low permeability. Infiltration of fronts was slowest at site L30 at 10^{-7} cm/s with the exception of the sulphate front at 1.2×10^{-6} cm/s. Infiltration rates at the latter two sites (L100 and L160) were in the range of 10^{-6} cm/s. The infiltration rates were varied at site L100 with zinc, acidity and conductivity most mobile. Movement of fronts in the fresh tailings layer at site L160 was most uniform, although zinc appeared to infiltrate much more rapidly than the other fronts. Using the highest calculated vertical infiltration rate in the old tailings layer of 6.8×10^{-6} cm/s, and an assumed depth of 3 m, the breakthrough of the zinc front might occur in about five years. This estimate must be viewed with caution as it was based on a number of assumptions: a constant hydraulic conductivity over depth represented by the calculated values in Table 18, and only vertical flow. The potential horizontal component of flow was not included.

In the previous study, the rates of infiltration of the contaminant fronts in this layer of the tailings were lower at 10^{-7} cm/s. These tailings, however, had been in place for 30 months, much longer than the fresh tailings layer, and settling of the tailings over time and lower saturation might have reduced the hydraulic conductivity of the older tailings layer. Flushing can also be affected by seasonal variations in the amount of precipitation. The fresh tailings were deposited over the winter months and were exposed for only seven months at the time of the study.

Within the old tailings layer, the infiltration rates over the 14 months since the previous study ranged from 1.9×10^{-7} to 1.9×10^{-6} cm/s (Table 18). These were slightly faster at L100 and slightly lower at L160 than rates measured in this layer in the previous survey. The rate of infiltration of zinc, however, was higher in this survey at both sites L100 and L160, at about 1.8×10^{-6} cm/s, compared to 4.5×10^{-7} (E160) and 7.5×10^{-7} cm/s (E100) previously. The acidity and conductivity fronts at L100 were also more mobile in the past 14 months than at E100. The increased infiltration rates in the "old" layer

may be due to increased moisture content due to draining of the new layer of tailings.

The addition of the new tailings layer does not appear to have increased the hydraulic gradient from the new tailings layer by causing increased infiltration rates. The disappearance of copper and iron fronts in the old tailings layer would suggest the infiltration of alkaline tailings water as previously suggested. The infiltration of alkaline tailings water does appear to extend over the full depth of tailings, since, below the depth of the previous (1988) pH, Cu and Fe fronts depressed pH and higher acidity are found. Thus the infiltration rate of the fresh tailings solution is comparable to the previously estimated drainage rate within the tailings, as indicated by the rate of zinc advance. Using the vertical infiltration rate for zinc from the 1988 survey for each site, fresh tailings solution could have travelled down to 193, 218 and 247 cm depth at sites L30, L100 and L160 respectively. For the first two, this depth is at or beyond the limit of the former contaminant fronts. At site L160, however, the apparent advance of the fresh tailings solution is above the fronts, and a copper front was still present from 249 to 265 cm depth. It is not clear whether this is due to a lower conductivity because of compaction, or to a lack of resaturation of these tailings. Apparently the alkaline tailings water has not flushed the tailings at this depth and thus solution flow rates through the tailings do not appear to be accelerated due to the change in hydraulic head from the new tailings layer.

The movement of contaminant fronts is controlled by both the geotechnical nature of the tailings and thus the physical control on solution infiltration rates, and the geochemical controls on contaminant release and solubility. Contaminant fronts are defined arbitrarily as elevated concentrations for this evaluation, however, lower concentrations may still be environmentally significant. Thus the absence of contaminant fronts in this survey does not indicate the extent of acidification and metal release in the tailings is no longer of concern. A long term flux of acidity or dissolved metals at a concentration lower than the "front" can be equally of concern as a high concentration "slug". Area #1 still contains elevated contaminant levels, although there are fewer fronts evident using the same definition as in previous studies.

4.2 Rate of Zinc Release

The rate of metal release and metal mobility within a tailings mass undergoing oxidation is a key factor in determining the long term drainage quality from the tailings impoundment. Zinc is of particular concern in this study. It has been shown to be mobile in tailings and movement is typically not limited by solution pH; zinc can be present in solution as high as pH 9.5. Zinc fronts appeared deep in the tailings both in the fresh and old tailings layers. The depth to which each front appears is a function both of metal mobility, depth of oxidation and time of release.

Zinc production rates were calculated for this and the previous study, based on total zinc production over a column of tailings of unit surface area, averaged over the time of exposure/deposition of the tailings; 7 months for the fresh tailings layer, 44 months for the old tailings layer in this study, and 30 months for the old tailings layer in the 1988 survey. These results are summarized in Table 19.

**TABLE 19
CALCULATED RATE OF ZINC PRODUCTION**

TEST PIT	ZINC PRODUCTION RATE g/month/m ²		
	1988	1989	
	30 months	7 months	44 months
E30	9.1	-	-
E100	13	-	-
E160	6	-	-
L30	-	8.3	1.5
L100	-	39	10
L160	-	95	16
Total (g/m ²)	282	329	9.2

The rate of zinc release was considerably faster over the first 7 months of exposure of the fresh tailings layer at 47 g/month/m² than in the old tailings layer, at 30 and 44 months after the initial period of exposure. The average rate of release in the old tailings layer after 30 and 44 months was essentially the same averaged over the three test pits at 9 g/month/m². The total production confirms that most of the zinc is released soon after deposition with little further production. This decrease in the rate of zinc production since the first seven months would suggest that there are other mechanisms by which zinc is mobilized than the oxidation of zinc sulphide minerals in the tailings, as it has been shown that the extent of oxidation in the near surface layers increased with time.

This observation of high dissolved zinc values in slightly acidic drainage and rapid release of zinc into solution has been noted at other sites undergoing acid generation (Steffen Robertson and Kirsten et al., 1989; Ferguson, personal communication, 1989). Three mechanisms have been postulated as contributing to the release of zinc at near neutral pH values:

- i) microscopic low pH environments causing zinc release from sulphide mineralization;
- ii) zinc dissolution from oxidation without neutralization and precipitation - the oxidation rate is low enough that drainage solution is rapidly neutralized before migrating away, however, zinc remains in solution and is not significantly precipitated (below pH 9.5);
- iii) release of zinc from other complexes - oxide, hydroxide, sulphate.

Sulphide particles remaining in the tailings and residual flotation froth might also contribute to the early zinc release by providing pockets in which local (microscopic) low pH environments could develop around concentrated sulphide mineralization. The flotation process produces a concentrated zinc sulphide froth which, if not skimmed off in the milling process, can report with the tailings. Once the frothing agent breaks down, pockets of high sulphide material with little or no neutralization potential are deposited. Particulate zinc material was detected in both the settled tailings solution and pond supernatant. Total zinc concentrations in the supernatant and fresh tailings solution samples averaged 4.3 mg/L whereas dissolved values averaged 0.4 mg/L.

It is possible that zinc is also present in the final mill tailings in the sulphate, oxide, or hydroxide form which is solubilized with flushing and small changes in pH, i.e. from pH >10 to pH <8.

The Area #2 samples seemed to support this theory; shake flask tests to extract the soluble component from fresh and 1 month old tailings samples resulted in higher soluble zinc component extraction from 1 month old samples of 8.2 mg/L (average) compared to only 1.3 mg/L from the fresh samples. Sample pH did not seem to be a rate controlling factor in the release of the zinc in this pH range as there was little variation in pH between the fresh and older samples; in fact the one month old sample had a slightly higher pH than the fresh sample (8.1 versus 7.7).

It is recognized that there are many factors that affect the calculation of the rate of zinc release. The data and calculations do, however, indicate an early rapid release of zinc into solution prior to the establishment of oxidation and low pH throughout the tailings mass. Zinc continued to be released into solution and accumulated in the tailings after 44 months at close to the same rate as at 30 months (assuming the rate of flushing has remained similar). It is difficult to distinguish changes in the rate of zinc production and accumulation due to the progression of oxidation reactions, and changes due to the covering layer of tailings placed between the two sampling intervals.

4.3 Oxidation Rates

Oxidation rates within the tailings mass were estimated at each test pit based on sulphate concentration values from the shake flask analyses and the tailings density values from the geotechnical data. Several assumptions were made:

- the bulk density of layers which were not sampled for geotechnical analyses was estimated from the log descriptions for similar material in this and the previous study;
- that the depth of the oxidation zone from which the sulphate was produced could be defined by paste pH values less than pH 4.5, or by a low pH front;
- that all of the sulphate produced from oxidation reactions within a column of unit surface area was still contained in the column, that is, there is no horizontal movement;
- that gypsum formation/dissolution was not a factor at these sulphate concentrations;
- that the oxidizing tailings material was 34 % sulphur (Ferguson, 1986).

The calculated rate of oxidation is expressed in terms of the rate of sulphate production from

a column of tailings material at each test pit. In the first calculation the total amount of sulphate produced over the column was calculated from the shake flask data and expressed per square meter of tailings surface. This total sulphate production was then averaged over the 7 months for which these tailings were exposed to calculate an oxidation rate expressed in terms of moles of sulphate produced per month over each square meter of tailings surface area. The oxidation rate was also calculated in terms of sulphate produced each month per unit mass of tailings, and per unit mass of sulphur. The results are summarized in Table 20.

TABLE 20
CALCULATED OXIDATION RATES

TEST PIT	$\frac{\text{mmoles SO}_4^{2-}}{\text{m}^2 \cdot \text{month}}$	$\frac{\text{mmoles SO}_4^{2-}}{\text{g} \cdot \text{month}}$	$\frac{\text{mmoles SO}_4^{2-}}{\text{g S} \cdot \text{month}}$	DEPTH OF OXIDATION
"New" tailings layer				
L30	1.3×10^4	1.7×10^{-1}	5.0×10^{-1}	5-9 cm
L100	2.1×10^4	6.5×10^{-2}	1.9×10^{-1}	5-21 cm
L160	2.8×10^4	6.4×10^{-2}	1.9×10^{-1}	2-10, 24-40 cm
"Old" tailings layer				
L30	3.1×10^3	Low pH fronts not detected within the		
L100	5.6×10^3	old tailings layer.		
L160	3.7×10^3			

These data were compared to data presented by Halbert et al. (1983) in which laboratory sulphide generation rates were calculated for lead-zinc mine tailings. The tailings consisted of 15.9 % sulphur, 20.0 % Fe, 1.84 % Zn and 0.06 % Cu. In laboratory tests conducted on these tailings using media containing Thiobacillus ferrooxidans, sulphate generation rates were 1.1×10^{-1} mmole/g tailings per month at 6°C, and 1.1 mmole/g tailings per month at 21°C. These oxidation rates were slightly higher than the calculated field values for the Westmin tailings during the 1988 and 1989 field studies. This would be expected as the laboratory tests were conducted in agitated flasks with pH control and prepared media providing optimum oxidation conditions, particularly oxygen transfer. The reaction rate does appear to be valid however, as oxidation in the tailings mass did not appear to be oxygen limited, and therefore the oxidation reactions are kinetically controlled.

As low pH fronts were not detected in the old layer of the tailings in this study, the extent of tailings undergoing oxidation could not be estimated. Comparison though of the sulphate production per unit surface area at each of the three test pits indicated similar or slightly higher oxidation rates calculated over 44 months (as shown in Table 20) than in the previous survey; 1.5×10^3 to 3.5×10^3 moles/m²/month over 30 months. These oxidation rates, however, are at best estimates. The results indicate primarily that oxidation was still occurring within the old tailings layer and at a similar rate to the previous survey. This was reflected in the calculated weighted average concentrations, Section 3.4.2. There may, however, be leaching of the zinc minerals by acidic drainage water, without associated oxidation given that a water cover has essentially been established over the tailings, which would be expected to limit oxygen flux and oxidation once the residual oxygen was consumed.

4.4 Oxygen Diffusion

Previous reports (Ferguson, 1987; Broughton and Ferguson, 1989) concluded that the degree of oxidation correlated with the calculated diffusion coefficient for the surface layer, and in turn with the degree of saturation of that layer. Diffusion coefficients were calculated for the 1989 survey data and as shown in Table 21. Two methods of calculating diffusion coefficients were used;

Senes and Beak (1986); $D_e = \frac{.203 [\ln(1-S_r) - 0.05]^{1.7}}{0.95}$ (8)

Silker and Kalkwarf (1983); $D_e = 0.070e^A$; where $A = (-4 (S_r^{-5}n^2 + S_r^5))$ (9)

Where S_r = degree of saturation

n = porosity

The first equation is applicable to a wide range of porosity and saturation values but indicates a diffusion coefficient of zero for samples near saturation (Senes and Beak, 1986). The second equation, originally developed for radon gas diffusion through soil covers, is more applicable to near saturation samples (Silker and Kalkwarf, 1983).

TABLE 21
CALCULATED DIFFUSION COEFFICIENTS

TEST PIT	LAYER	DEPTH (cm)	n	S_r	D_e *	D_e **	% SILT (est)
L30	A,B,C	16.5	0.48	0.94	-	0.0002	82
L100	A,B	19.5	0.47	0.60	0.0076	0.0079	23
L160	A,B,C	19.5	0.52	0.83	0.0009	0.0013	71
EP1	A,B	10.0	0.50	0.95	-	0.0002	85
EP2	A	11.2	0.57	0.49	0.0197	0.0166	24
BS1	-	16.5	0.44	0.29	0.0228	0.0272	19
BS2	-	16.5	0.47	0.24	0.0298	0.0330	19

* Calculated from equation 8.

** Calculated from equation 9.

As shown in the above equations 8 and 9, the calculation of a diffusion coefficient is based on the residual moisture content and porosity of a sample. The residual moisture content (saturation, S_r) of a porous material in unsaturated conditions is related to grain size distribution (capillarity) of the material. Finer grained materials tend to retain more moisture than coarser, sandy materials (Freeze and Cherry, 1979).

The relationship of the estimated tailings particle size to the degree of saturation in this survey is shown in Figure 28. Two groupings of points were evident; in tailings layers with less than 30 % estimated silt content, the degree of saturation was less than 60 % while samples with greater than 70 % silt exhibited greater than 80 % saturation.

The diffusion coefficient of a sample is a function of the moisture content, which has been shown to be a function of the particle size distribution of the tailings. As shown in Figure 29 with the diffusion coefficient plotted on a log scale, the diffusion coefficient varied with silt content. Two groups of points were again evident in Figure 29. Samples with an estimated silt content less than 30 % had diffusion coefficients greater than $0.006 \text{ cm}^2/\text{s}$ whereas samples with much higher silt contents, greater than 70 % had much lower diffusion coefficients, less than $0.001 \text{ cm}^2/\text{s}$.

The effective diffusivity of a soil controls the rate of oxygen transport through the layer and thus to a degree the oxidation rate of the underlying layer. In Area #1 the lowest diffusion coefficient was noted at L30. Paste pH values were considerably higher (5.9 to 8.3) in the near surface layers, and the penetration of contaminant fronts much shallower at this site than L100 or L160. Site L100 had a relatively high diffusion coefficient in the sandy near surface layers and paste pH values reflected this, ranging from 4.1 to 6.1. Contaminant fronts occurred variably over a 1 m depth in the newer tailings. The diffusion coefficient at site L160 was low, similar to L30, and yet the pH contaminant front was located deeper in this test pit than in the other two. The contaminant fronts extended almost uniformly about 0.5 m into the newer layer of tailings. These results suggest that there are other mechanisms active in controlling the rate and extent of oxidation in the tailings. These could include the effects of surface cracking which allow oxygen and water transport directly into deeper layers and variations in the acid generation and neutralization potential of the tailings.

FIGURE 28 PARTICLE SIZE AND DEGREE OF SATURATION

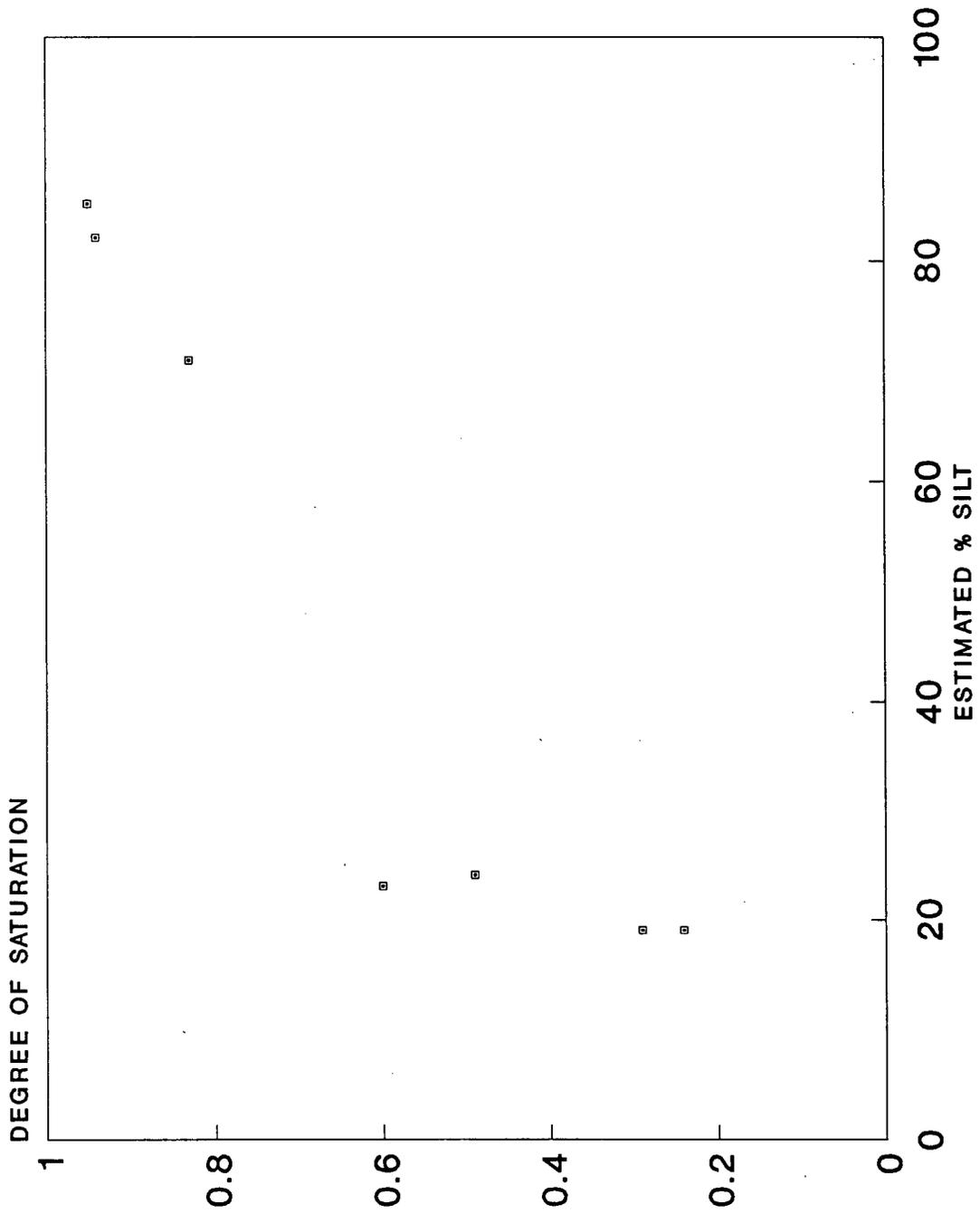
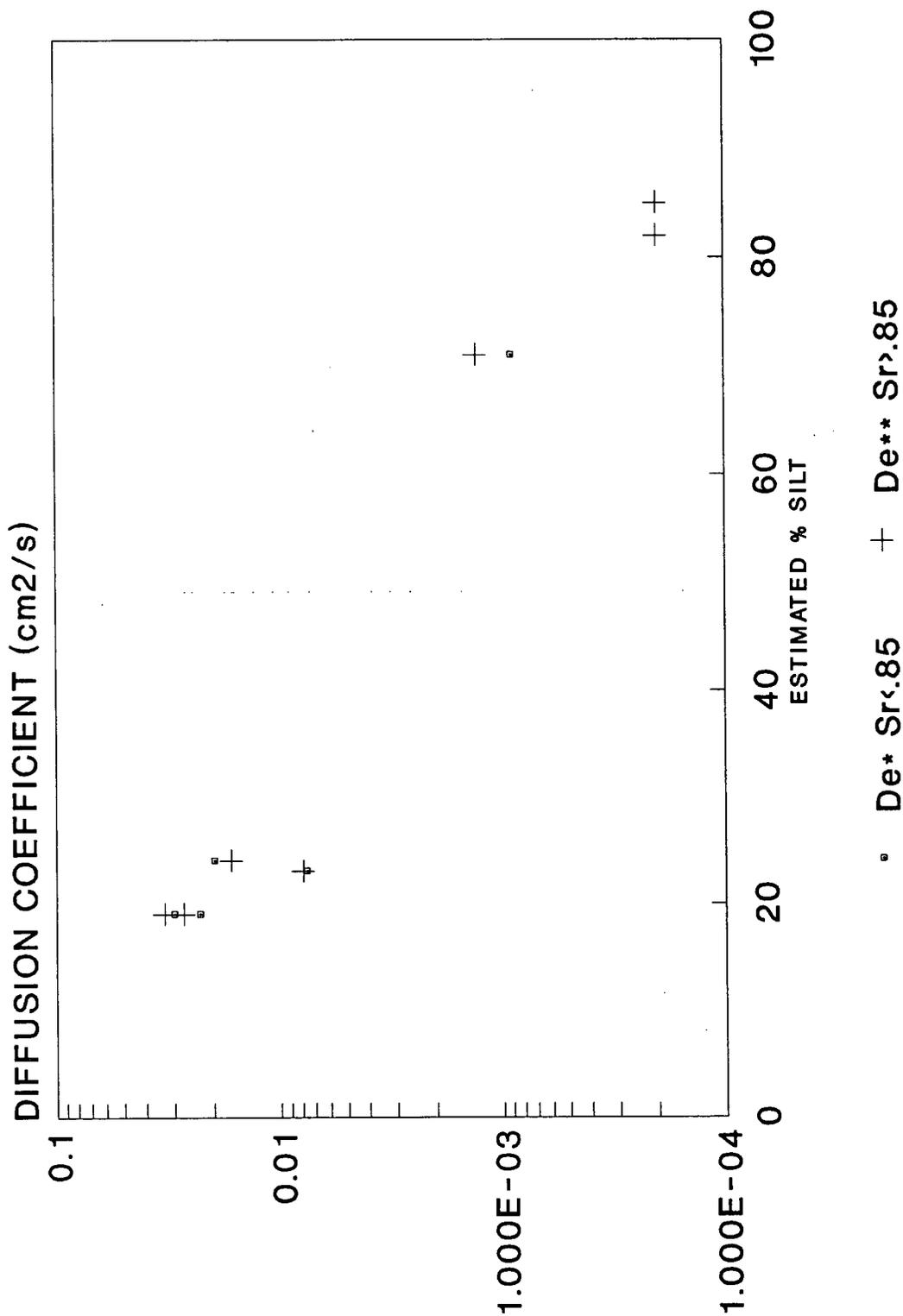


FIGURE 29 PARTICLE SIZE AND DIFFUSION COEFFICIENT



Comparison was made of the calculated diffusion coefficients with the oxygen and carbon dioxide profiles discussed in Section 3.4.4. The oxygen and carbon dioxide content at any point in the tailings is a function of both the rate of consumption and the rate at which air is replenished, it was assumed that the rate of oxidation (oxygen consumption) in the sand layer throughout the near surface of the tailings was the same. At site L30, with a low diffusivity surface layer, the oxygen minimum and CO₂ maximum were more severe than at site L100 which had a more gas permeable surface layer. Although the sand layer in L30 was located deeper than at L100, once the diffusion process began (ie. once oxidation started depleting available oxygen in that layer and the concentration gradient was established), the rate of air flow into the tailings should be reasonably constant or proportional with the rate of oxidation. Site L160 had a low diffusivity surface layer and a greater depth of oxidation yet a less severe oxygen minimum. This suggests that oxygen was replenished in this layer from other sources than diffusion through the surface, possibly through vertical cracking and ingress of air through more permeable, deeper layers.

4.5 Oxidation Rate and Oxygen Consumption

In an attempt to correlate oxygen consumption with oxidation rates and then quantify the horizontal and vertical components of oxygen flux, oxygen concentration gradients and the resultant diffusive flux of oxygen were calculated for test pits in Area #1. The results are provided in Table 22. Oxygen diffusion in tailings is generally considered a vertical (one dimensional) flux (Senes, 1988; Collin, 1987). The diffusion coefficient or effective diffusivity of the surface layer would limit the vertical influx of oxygen into the underlying tailings, as shown in the previous study. Thus the diffusion coefficients calculated in Table 21 were used in estimating the flux of oxygen from the atmosphere into the tailings as a function of diffusivity and concentration gradient. Oxygen can also be introduced into saturated tailings by diffusion through water or as dissolved oxygen in infiltrating pore water. In these mechanisms, the flux of oxygen is limited both by the solubility of oxygen in water and the much lower diffusivity through water, about four orders of magnitude slower than in air (Senes, 1988).

TABLE 22 CALCULATED OXYGEN GRADIENTS AND FLUX

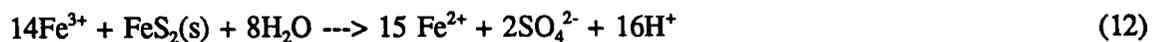
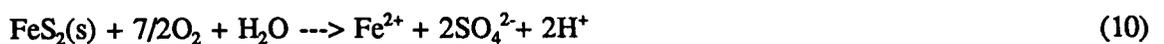
	DEPTH	O ₂	GRADIENT	FLUX
	cm	%	mol/m ³ /mon	mol/m ² /mon
L30	0	20.8	0.0	0.0
	8	13.6	40.2	2.1
	15	16.6	12.5	0.7
	20	18.2	5.8	0.3
	25	14.1	12.0	0.6
	30	9.4	17.9	0.9
	40	3.0	19.9	1.0
	50	5.2	13.9	0.7
	60	13.2	5.7	0.3
	70	10.1	6.8	0.4
	80	11.6	5.1	0.3
90	11.0	4.9	0.3	
L100	0	20.8	0.0	0.0
	5	20.8	0.0	0.0
	10	20.4	1.8	3.5
	15	16.3	13.4	26.4
	20	16.3	10.0	19.8
	25	19.1	3.0	6.0
	30	19.2	2.4	4.7
	35	19.0	2.3	4.5

TABLE 22 (cont'd)

CALCULATED OXYGEN GRADIENTS AND FLUX

	DEPTH	O ₂	GRADIENT	FLUX
	cm	%	mol/m ³ /mon	mol/m ² /mon
L160	0	20.8	0.0	0.0
	5	20.2	5.4	1.3
	10	19.7	4.9	1.1
	15	18.9	5.7	1.3
	20	19.6	2.7	0.6
	25	19.6	2.1	0.5
	30	11.7	13.5	3.2
	35	14.5	8.0	1.9
	40	17.3	3.9	0.9

The oxygen requirements for the rates of sulphate oxidation displayed above were determined using the general pyrite oxidation reactions for chemical and biological oxidation, Stages 1 and 2 in the acid generation process (Ferguson, 1987; Senes, 1988). It is possible that sulphate was also released by other mechanisms than pyrite oxidation alone, such as dissolution of soluble sulphides, although sulphate concentrations were corrected to remove the "background" concentration by subtracting the sulphate extracted in a shake flask leach of fresh tailings.



Thus the ratio of oxygen consumption to sulphate production is 7/2:2 or 1.75 moles O₂ per mole SO₄²⁻ produced. On a monthly basis therefore the required oxygen flux at sites L30, L100, and L160 respectively would be 22.3, 36.7, and 49.5 moles/m². It is evident from Table 22 that this flux is not achieved through vertical diffusion, even at site L100 with the highest diffusion coefficient.

The oxygen depletion at each site was calculated from the oxygen readings; atmospheric oxygen content is 20.8 % or 9.28 mol/m³, the difference between atmospheric and in situ measurement was determined and expressed in terms of moles per unit volume. This calculated depletion was less than 1 mole over the depth of the depleted layer of unit surface area, much less than predicted by the difference between oxygen consumption due to oxidation and replacement by the calculated vertical oxygen flux. The calculations indicate that oxygen was partially replenished by mechanisms other than vertical diffusion; through horizontal flow, and/or oxygen ingress to depth through vertical cracks in the tailings from surface. To determine if sufficient flux through the tailings could be achieved with horizontal flow through more diffusive layers (dry/moist sands as opposed to wet silts), minimum diffusion coefficients were calculated using the highest oxygen concentration gradient in the O₂ depleted layers each test pit. The required diffusion coefficients ranged from 0.002 cm²/s (0.56 m²/month) at L30, through 0.01 cm²/s at L100 and L160 (lower sand layer), to 0.04 cm²/s at L160 near surface. Diffusion coefficients of similar magnitude have been determined for layers in the tailings in this, and the previous survey; generally sandy layers from 60 % to 80 % sand, and ranging from 40 % to 75 % saturation. Thus, horizontal diffusion of oxygen in air through unsaturated, highly diffusive tailings layers is another mechanism by which oxygen consumed in oxidation reactions can be replenished. The profiles indicated, however, that at the time of sampling some layers were depleted in oxygen, suggesting that the flux of air was limited by diffusivity of the sand or surrounding layers, or lack of exposure of sand layers to the atmosphere (ie. confined layers or pockets).

Theoretical expressions for oxidation rate and oxygen flux provide an indication of the relative influence of chemical and biological controls on the oxidation rate and oxygen consumption. The flux of oxygen through the tailings solids would be controlled by diffusion processes, defined by Fick's first law, if pyrite were not present to consume oxygen and create concentration gradients. The controlling

equations are different, however, if oxygen is present. As described by Senes (1988), in the presence of pyrite and "high" oxygen concentrations (> 0.01 atmospheres), oxygen consumption is a zero order reaction and independent of oxygen concentration, i.e. oxidation rate or flux of oxygen is at steady state. Oxygen flux through a layer can be described by the following expressions:

$$F_{UPPER} = \frac{Rdx}{2} + \frac{D_e C_1}{dx} - \frac{D_e C_2}{dx} \quad (10)$$

$$F_{LOWER} = -\frac{Rdx}{2} + \frac{D_e C_1}{dx} - \frac{D_e C_2}{dx} \quad (11)$$

where R = zero order rate constant ($\text{mol}/\text{m}^3 \cdot \text{month}$)

dx = thickness of layer

C_1 = oxygen concentration at upper boundary

C_2 = oxygen concentration at lower boundary

$$R = 3.75(R_1 + R_2) \frac{\alpha_p}{V_g} \quad (12)$$

where R = zero order reaction rate constant ($\text{mol}/\text{m}^3 \cdot \text{month}$)

R_1 = biological reaction rate constant ($\text{mol}/\text{m}^2 \cdot \text{month}$)

R_2 = chemical reaction rate constant ($\text{mol}/\text{m}^2 \cdot \text{month}$)

α_p = pyrite surface area per unit volume tailings (m^2/m^3)

V_g = volume of gas per unit volume of tailings (m^3/m^3)

The limitation on oxidation rate due to oxygen concentration was also described by Senes. The biological oxidation rate described above was independent of oxygen concentration and thus a function of the material. The net biological oxidation rate is equal to this material property constant times a factor for oxygen. To demonstrate the limiting effect of oxygen on the biological reaction rate, the biological oxidation rate is expressed as:

$$R_B = R_1 \frac{P_{O_2}}{L_o + P_{O_2}} \quad (13)$$

where P_{O_2} = partial pressure of oxygen (atm)

L_o = limiting partial pressure (atm)

R_B = oxygen influenced biological specific reaction rate (mol/m²/month)

$$R_1 = R_B \frac{L_o + P_{O_2}}{P_{O_2}} = R_B \times 1 \text{ at high } P_{O_2} \quad (14)$$

$$R_2 = f_p k_c P_{O_2} \quad (15)$$

where k_c = chemical rate constant (mol/m²/month/atm)

R_2 = chemical specific reaction rate (mol/m²/month)

f_2 = pH dependence factor

Therefore by substitution the oxidation rate can be expressed as:

$$\text{Oxid. rate} = 3.75 (R_B + f_p k_c P_{O_2}) \frac{\alpha_p}{V_g} \quad (16)$$

Then assuming no storage within the layer, oxygen consumption (oxidation rate) equals the difference in flux expressed by Equation (10) minus Equation (11):

$$R \frac{dx}{2} + \frac{D_e}{dx} (C_1 - C_2) - \left(-\frac{R dx}{2} + \frac{D_e}{dx} (C_1 - C_2) \right) = R dx \quad (17)$$

From Equations (14) and (17) it can be seen that at high oxygen concentrations the oxidation rate is a function of pH, partial pressure of oxygen, pyrite surface area and volume of gas present. At neutral pH values with chemical oxidation dominating, the chemical reaction rate constant is greater than the biological, and oxidation rate is first order with respect to oxygen (15). Clearly the chemical rate is a function of oxygen and therefore the diffusion coefficient. At acidic pH values the biological reaction rate is greater than the chemical and oxidation rate is therefore independent of the diffusion coefficient.

This analysis would suggest that these tailings are in a transition phase in the first seven month

period between chemical and biological oxidation, with consumption of oxygen in the layers, and yet controls on the oxidation rate by the diffusion coefficient of the overlying layer. It would be expected as oxidation became fully established that the oxygen profile would move to zero over depth and oxygen diffusion would control oxidation rate. At this time it would appear that oxygen is not rate limiting, and kinetic oxidation rates are controlling the rate of oxidation in the tailings.

At the time of deposition, the tailings solids are flooded and no air is present, therefore no oxidation can occur. The surface silt layer maintains a high moisture content in the initial time and therefore a very low diffusion coefficient, limiting oxidation in the partially drained underlying sand layer. If the silt maintains a high moisture content and acts as a cover, then virtually no oxidation would be evident in the tailings. This would correspond to the relation between diffusion coefficient and oxidation rate seen soon after deposition. However, if the overlying silt layer allows some oxygen flux into the sand layer, the oxidation rate within the sands would be controlled by the reaction rate constant (R). Oxygen depletion would be evident only in the sand layer of the tailings profile.

Over time the tailings would drain, with sand layers draining more rapidly and completely than silt layers. Negative pore pressures would be established within the sand layers, with partial filling of the voids with air, and oxidation would be greater than in silts. As the silt layer drains into the sand, high negative pore pressures would develop in the tailings and a gradient would be established allowing a flux of oxygen. A profile such as in Figure 22 would develop with oxygen depletion in the sand and silt layers. With the increased oxidation rate, the gradient would increase to deliver the same flux of oxygen through the constant diffusion coefficient of the cover.

5.0 CONCLUSIONS

This study of the Westmin subaerial tailings impoundment, backfill sands storage area, and emergency pond involved a number of geochemical and geotechnical aspects. Specific conclusions from the various elements of the study are presented in the following discussion. More general conclusions have also been drawn from the overall evaluation of this and previous studies.

The following conclusions were drawn from the data presented herein and the discussion of the results:

1. After six to seven months exposure, sampling of the surface of Area #1 with analysis of paste pH indicated that surface oxidation had occurred. The surface of the tailings varied from wet silts to dry sands. Surface oxidation was evident from orange coloration of the tailings, particularly in areas of former drainage. Paste pH values varied from 2.6 to 7.1. Acidic pH values tended to occur in areas of dry, sandy material rather than wet, silty tailings.
2. Sampling of the surface of the backfill sands storage area indicated that surface oxidation had occurred. Samples from moist areas and in drainage channels were of higher pH than the drier sands. Sampling and observation of the surface of the Emergency Pond also indicated that surface oxidation had occurred.
3. Total metals concentrations in surface solids were generally lower in samples with more acidic paste pH than in the fresh, not oxidized tailings samples. The exceptions to this were samples located in an area in which precipitation of metal salts occurred along former drainage paths.
4. Neutralization potentials of surface samples were estimated from equations developed in a previous survey. Paste pH values calculated from the same series of equations, based on Ca content did not correspond to measured paste pH values. Oxidation was not well established in these samples, thus neutralization potential (reflected by Ca content for carbonate mineralization) was gradually consumed by the acid produced and buffered the pH changes. Ca content would relate more directly to pH in samples in which there was little or no buffering.

5. Tailings pore water pH decreased rapidly from discharge over a one month period, from 11.0 to 7.3. Total metals analyses on the tailings solutions showed considerable variation. The difficulty in obtaining representative samples was demonstrated by the data.
6. Geotechnical samples of surface and near surface material exhibited a range of composition from 80 % sand to 92 % silt and clay. The degree of saturation ranged correspondingly from 24 to 95 % in the samples tested. Samples with a finer particle size exhibited lower specific gravity and wet density, and higher degree of saturation than coarser tailings material.
7. The layered heterogeneous nature of the tailings was demonstrated by the test pit logs and paste pH values for the solid samples. Paste pH over depth in the tailings varied with material type. Lower pH values were generally associated with drier, sandier material often orange/brown in colour.
8. The location of the previous tailings surface was determined based on the test pits logs. These corresponded well to the logs of the previous year's study, despite estimating locations and sampling over large intervals.
9. Total metals analyses were used to predict the geochemistry of the Emergency Pond tailings samples. The upper layers of the tailings generally had a low sulphide content, <1 %, based on other metals, and were potentially acid consuming. Two samples, however, had a sulphur contents of >3 %, and were potentially acid generating, and corresponded to layers of visible oxidation in the test pit sampling.
10. Shake flask extraction tests conducted on relatively fresh tailings samples indicated changes in sulphate, conductivity and dissolved zinc over one month of exposure, at neutral paste and solution pH.
11. Three samples pH values were measured. Paste pH values varied significantly over depth. Solution pH after storage of the sample was more alkaline than immediately after filtration of the shake flask samples.

12. Shake flask extraction tests conducted on fresh tailings samples and test pit samples from Area #1 and the Emergency Pond indicated distinct zones of oxidation and contaminants within the older and fresh layers of tailings. Significant changes in chemical parameters were observed over time. Lower acidity and dissolved metals (Cu, Fe) were evident in the older layer, due to infiltration of alkaline fresh tailings solution. Solution pH, acidity, sulphate and conductivity were less concentrated in distinct layers, although the overall weighted concentrations were slightly higher than in the previous year indicating production has continued since placement of the new tailings layer. Dissolved metal concentrations were lower in the old layer.

13. No direct relation was evident between pore water and shake flask samples. Shake flask concentrations were less dilute with respect to pore water than expected, indicating dissolution of readily soluble products during the leach. The limited scope of the program, and the variability in pore water samples experienced does not allow definition of the relative accuracy of the two techniques. However shake flask sampling may be more representative of the stored contaminant loads within the tailings solids, rather than actual drainage quality on a short term basis.

14. Oxygen and carbon dioxide measurements taken over depth in the tailings corresponded with depth in the tailings, diffusivity of the surface layer, and material type. Oxygen was lowest and carbon dioxide highest in sandy layers. The oxygen minimum frequently occurred deeper than the carbon dioxide maximum, possibly due to release and upward migration of CO₂ from carbonate minerals. Relatively simple techniques worked well to determine gas concentrations which correlated well to the test pit logs, i.e. sand/silt layers, and oxidation profiles.

15. Contaminant fronts were not as evident within the old tailings layer due to infiltration of alkaline tailings water reducing the concentration peaks from contaminant migration, and neutralization and complexing/precipitation of some metals (Cu, Fe) and pH fronts. Calculated vertical infiltration rates in the fresh tailings layer were more rapid than in the previous study, possibly due to settling and seasonal precipitation/flushing rate differences. Within the old tailings layer the rates of advance were similar to or slightly more rapid than previously (Zn, acidity, conductivity).

16. A rapid early release of zinc into solution was evident within the first seven months of deposition, but slowed over time and was similar after 30 and 44 months. This continued release of zinc is of concern.

17. Calculated oxidation rates based on sulphate production were limited by the lack of low pH fronts in the old tailings layer. However they appeared to be established within the first seven months of deposition. Although the depth of the oxidized zone and zinc migration increased, sulphate production has not changed over this time period. This would suggest metal release at depth due to acid leaching, rather than continued oxidation.

18. Oxidation in the underlying tailings mass is limited by wet, silty surface layers with correspondingly low oxygen diffusion coefficients. The horizontal ingress of oxygen along more permeable drier layers, possibly due to vertical cracking, appeared to contribute significantly to oxidation in underlying drier, coarser material based on predicted and measured oxygen consumption.

The following conclusions are more general and were drawn from the overall evaluation of the results of this and the previous study:

1. After 7 months exposure, the surface of the tailings impoundment indicated that surface oxidation was occurring. Near the interface of the old and new layers oxidation and metal leaching were not evident. Within the underlying older tailings mass, sulphide oxidation and contaminant migration continued, despite the covering layer of fresh tailings.

As such, the subaerial method of tailings deposition did not appear to result in a tailings mass with a low potential for acid generation. Oxidation was initiated at the surface layers, similar to conventional impoundments in which potential acid generation is not initiated until tailings deposition ceases and the tailings solids surface is exposed. The prolonged exposure of both layers was not part of the original design but resulted from operational constraints which are possible at any mining and milling facility.

An advantage of the subaerial deposition method is the rapid access to the impoundment for covering at closure, which seems to be essential to prevent surface cracking and the onset of acid generation. Oxygen diffusion is limited by saturated and near saturation silty layers, particularly on

surface. These layers however must be continuous, and not subject to desiccation and cracking to effectively prevent acid generation in the tailings mass. The influence of cracks which allowed access of oxygen and water to depth in the tailings is a drawback of the subaerial deposition system, if exposure of the tailings surface is allowed. Pondered water and saturated surface layers are contrary to the design principles of subaerial tailings deposition. Thus more conventional tailings disposal systems with a flooded impoundment might be more effective in inhibiting acid generation and acidic drainage.

2. Although some of the tailings layers have a higher density than in conventional tailings deposition, the overall vertical infiltration appeared to be similar to the saturated hydraulic conductivity of conventional tailings impoundments. Permeability decreased slightly over time, with depth in the tailings mass. Vertical infiltration of fresh alkaline tailings in the old, covered tailings layer moved at a rate similar to the vertical infiltration of contaminant fronts in the previous survey. The rate of migration of contaminants and thus drainage water quality is the key concern with acid generation. A better understanding of the vertical and horizontal components of flow is required to predict the potential impact of this subaerial tailings facility.

3. The results of this survey cannot be used directly to predict long term behaviour and potential impact of the Westmin tailings facility. However, comparison of the geochemical characteristics before and after the additional layer of tailings indicated that both oxygen and water entry must be strictly limited by the final cover layer. Oxidation has been established in both new and old tailings layers and was not measurably slowed by the addition of the fresh tailings layer. Vertical infiltration rates indicate a breakthrough of elevated zinc levels within five years. The layer of fresh tailings did not appear to significantly slow the rate of acid generation despite low diffusivity silt layers, or contaminant migration. It would appear that the long term reclamation of the tailings impoundment must effectively limit the infiltration of water through the tailings, to limit the flushing of contaminants from the tailings which are undergoing oxidation.

4. The reclamation of the tailings impoundment will also require investigation into the geotechnical nature of the tailings mass; the extent of consolidation and dewatering with respect to the predicted final settled density and moisture content. The tailings must be covered to limit the ingress of oxygen and water, prevent erosion of the tailings surface, and allow reclamation of the facility. The geotechnical characteristics of the mass will affect the long term integrity and efficacy of the cover system.

5. As found in previous survey, the reasonably simple field and laboratory techniques used in this study were useful in developing an understanding of the factors that control acid generation and contaminant transport in a heterogeneous tailings mass. The laboratory and field time requirements were still considerable, however, and programs must be designed carefully to maximize collection of critical data. It is important to conduct studies over an extended time frame to develop an understanding of temporal changes in the impoundment, to evaluate long term behaviour. To identify and evaluate long and short term design options, parameters must be monitored that can be incorporated into a predictive model, particularly for the evaluation of closure options.

6.0 RECOMMENDATIONS FOR FURTHER WORK

Based on the results and discussions presented herein, further investigations should within the scope of work should address the following considerations:

- zinc geochemistry and the rapid early release of zinc into solution. This could include short term leaching tests, and wash tests with various acids, at different pH values;
- pore water quality as compared to shake flask extraction solutions to examine the storage and flushing of oxidation products and soluble species, and also to evaluate the relative merits of the two sampling procedures;
- the effects of pH on metal solubility for drainage from these tailings;
- measurement of drainage flow and vertical and horizontal permeability to more accurately predict the potential for release of contaminated drainage from the impoundment. Initially this drainage could be acidic with elevated zinc concentrations;
- oxygen flow and ingress into the tailings, and the potential to limit vertical cracking and thereby reduce oxygen flux.

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APPENDIX 1

RESULTS OF SURFACE SOLIDS ANALYSES

AREA #1 SURFACE SOLIDS

SURFACE PASTE pH

SAMPLE INTERVAL	PASTE pH				
	LINE J-J	LINE K-K	LINE L-L	LINE M-M	LINE N-N
10	7.1	5.2	2.6	3.5	2.8
30	6.0	6.4	5.5	4.1	3.1
60	5.4	6.0	3.5	4.4	3.5
80	6.7	6.6	2.8	3.0	4.4
100	6.3	6.7	5.3	4.0	5.4
120	5.0	6.8	5.1	5.3	4.4
140		5.6	6.1	5.3	3.6
160			5.4	4.5	5.1
170			6.3	5.2	

SURFACE SOLID SAMPLES - EMERGENCY POND

TOTAL METALS ANALYSES

PARAMETER		EP-1A	EP-1B	EP-1C	EP-1D	EP-1E	EP-1F
ICP (ug/g)	Ag	20	20	33	20	10	20
	Al	17100	17700	10900	17800	10400	14500
	As	64	110	255	52	52	58
	Ba	478	489	303	438	230	439
	Ca	17900	18200	20100	19600	20000	16900
	Cd	19.6	72.7	48.7	31.6	42.1	47.4
	Cr	46.8	54.4	25.9	45.6	23.4	25.3
(mg/g)	Cu	0.9	1.04	2.2	1.12	0.899	1.13
(mg/g)	Fe	67.3	53.3	74.1	59.6	99.8	55.2
	K	2000	2700	600	2500	500	1900
	Mg	15600	14200	12400	15800	11800	12400
	Mn	611	498	570	605	598	584
	Mo	27	33	33	33	34	36
	Na	100	200	70	100	50	100
	Ni	35	36	32	34	39	33
	P	610	480	550	470	500	570
	Pb	1120	835	1480	1100	1140	2340
	Si	1270	1120	902	1200	813	1160
	Sr	83.8	87.5	61	91.4	46.8	90.5
	Ti	206	191	111	84.3	176	76.4
	V	46	44	29	42	29	33
(mg/g)	Zn	6.12	14.7	12.4	8.7	8.88	11.3

SURFACE SOLID SAMPLES - AREA #1

TOTAL METALS ANALYSES

PARAMETER		L10	L30	L60	L80	L100	L120
ICP	(ug/g) Ag	7	7	3	< 2	< 2	3
	Al	1470	7140	2400	4670	4110	5350
	As	509	407	479	317	453	451
	Ba	48.1	104	59	77.9	77.7	84.2
	Ca	670	1990	1800	1300	3820	5680
	Cd	< 0.8	18.4	< 0.8	< 0.8	6.5	31.5
	Cr	8.2	24.3	11	12	17.3	19.5
	(mg/g) Cu	1.17	1.44	1.31	0.898	1.41	1.73
	(mg/g) Fe	405	251	382	266	338	275
	K	< 300	900	< 300	300	400	1000
	Mg	920	5690	1750	4080	3350	3560
	Mn	94.8	283	162	179	244	309
	Mo	84	68	81	60	71	72
	Na	< 20	50	20	30	30	50
	Ni	97	70	93	73	82	75
	P	50	330	100	290	250	190
	Pb	427	927	453	395	621	899
	Si	825	996	889	699	858	905
	Sr	9.4	31	14	13	20.1	26.5
	Ti	29.8	74.8	45.7	90.1	78.9	55.2
	V	38	39	39	31	39	39
	(mg/g) Zn	1.84	5.86	2.44	1.97	4.12	8.56

SURFACE SOLID SAMPLES - AREA #1

TOTAL METALS ANALYSES cont'd

PARAMETER		L140	L160	L170
ICP (ug/g)	Ag	6	5	6
	Al	6020	6340	6710
	As	428	493	466
	Ba	103	91.4	106
	Ca	8220	6230	8070
	Cd	37	39.3	43.6
	Cr	21.8	22.4	24.6
(mg/g)	Cu	1.79	1.85	1.95
(mg/g)	Fe	249	245	242
	K	1000	1000	1000
	Mg	4110	4510	4600
	Mn	363	358	366
	Mo	73	69	73
	Na	70	60	70
	Ni	69	71	67
	P	190	230	200
	Pb	1070	1000	1180
	Si	1060	871	972
	Sr	35.3	31.4	37.2
	Ti	50.4	54.7	52
	V	41	40	43
(mg/g)	Zn	8.87	9.07	9.49

SURFACE SOLID SAMPLES - BACKFILL SANDS

TOTAL METALS ANALYSES

PARAMETER	BS10	BS30	BS50	BS70	BS90	BS110	BS130
ICP (ug/g) Ag	3	3	3	2	3	5	3
Al	3690	2220	3240	1740	3090	2000	2400
As	288	296	242	519	362	375	360
Ba	78.7	67.2	72.9	48.6	68.7	57.6	65
Be	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Ca	5350	690	850	570	5050	3660	2890
Cd	24.5	13	12	16.6	9.8	25.2	< 0.8
Cr	11	9.1	11	9.7	7.3	6	8.2
(mg/g) Cu	2.14	1.9	1.39	1.8	2.4	3.13	1.65
(mg/g) Fe	273	342	270	393	324	352	350
K	< 300	400	400	<300	400	400	< 300
Mg	3500	1750	2730	1300	2630	1610	1900
Mn	137	80.4	92.8	76.9	190	153	138
Mo	54	67	60	71	54	57	58
Na	< 20	20	20	< 20	20	20	< 20
Ni	63	79	65	92	76	78	86
P	190	100	190	30	190	100	100
Pb	576	560	545	585	535	644	458
Si	704	683	601	730	770	658	736
Sn	< 8	< 8	< 8	< 8	< 8	< 8	< 8
Sr	13	4.9	5.8	4.7	18.6	13	15
Ti	79.5	47.2	68.7	33.3	132	87.6	112
V	31	30	28	36	35	31	40
(mg/g) Zn	7.51	6.02	5.03	7.22	4.85	8.18	3.34

APPENDIX 2

RESULTS OF SURFACE SOLUTION SAMPLE ANALYSES

**SOLUTION SAMPLES - AREA #2
TOTAL AND DISSOLVED METALS ANALYSES**

PARAMETER ANALYZED	UNITS	SETTLED TAILINGS		SUPERNATANT	
		SAMPLE 1	SAMPLE 2	SAMPLE 1	SAMPLE 2
ACIDITY	mg/L	< 1	< 1	< 1	< 1
ALKALINITY	mg/L	192	NA	221	148
CONDUCTIVITY	umho/cm	1380	1380	980	1030
pH	Rel. U.	11.4	10.8	10.2	9.9
SULPHATE	mg/L	400	360	290	290
ICP Dissolved Ag	mg/L	< 0.01	< 0.01	< 0.01	< 0.01
Al	mg/L	2.56	2.52	1.95	1.9
As	mg/L	< 0.05	< 0.05	< 0.05	< 0.05
B	mg/L	0.05	0.05	0.04	0.04
Ba	mg/L	0.125	0.131	0.105	0.105
Be	mg/L	< 0.001	< 0.001	< 0.001	< 0.001
Ca	mg/L	339	330	232	230
Cd	mg/L	< 0.005	< 0.005	< 0.005	< 0.005
Co	mg/L	< 0.005	< 0.005	< 0.005	< 0.005
Cr	mg/L	< 0.005	0.005	< 0.005	< 0.005
Cu	mg/L	< 0.005	< 0.005	< 0.005	< 0.005
Fe	mg/L	0.104	0.128	0.023	0.009
K	mg/L	21	21	15	15
Mg	mg/L	< 0.1	< 0.1	< 0.1	< 0.1
Mn	mg/L	0.001	< 0.001	< 0.001	< 0.001
Mo	mg/L	0.07	0.07	0.09	0.09
Na	mg/L	14.1	14	11.4	11.3
Ni	mg/L	< 0.02	< 0.02	< 0.02	< 0.02
P	mg/L	0.6	0.6	0.6	0.6
Pb	mg/L	0.25	0.25	< 0.05	< 0.05
Sb	mg/L	< 0.05	< 0.05	< 0.05	< 0.05
Se	mg/L	0.07	< 0.05	0.06	< 0.05
Si	mg/L	0.23	0.24	0.28	0.27
Sn	mg/L	< 0.05	< 0.05	< 0.05	< 0.05
Sr	mg/L	0.712	0.704	0.621	0.614
Ti	mg/L	< 0.002	< 0.002	< 0.002	< 0.002
V	mg/L	< 0.01	< 0.01	< 0.01	< 0.01
Zn	mg/L	0.72	0.582	0.116	0.112
hardness/Ca+Mg HC	mg/L	847	823	580	574
/total HT	mg/L	863	839	592	586

SOLUTION SAMPLES - AREA #2
TOTAL AND DISSOLVED METALS ANALYSES - cont.

PARAMETER	UNITS	SETTLED TAILINGS		SUPERNATANT		
		SAMPLE 1	SAMPLE 2	SAMPLE 1	SAMPLE 2	
ICP Total	Ag	mg/L	< 0.01	< 0.01	< 0.01	< 0.01
	Al	mg/L	4.45	4.98	2.73	2.83
	As	mg/L	0.06	0.11	< 0.05	0.08
	B	mg/L	0.05	0.05	0.04	0.04
	Ba	mg/L	0.747	0.964	0.41	0.461
	Be	mg/L	<0.001	<0.001	<0.001	<0.001
	Ca	mg/L	322	326	258	257
	Cd	mg/L	<0.005	0.008	0.025	0.026
	Co	mg/L	0.006	0.009	<0.005	<0.005
	Cr	mg/L	0.016	0.014	0.007	0.006
	Cu	mg/L	0.374	0.611	0.313	0.33
	Fe	mg/L	10.9	15.3	3.68	3.81
	K	mg/L	26	25	17	18
	Mg	mg/L	1.2	1.6	0.7	0.7
	Mn	mg/L	0.106	0.143	0.125	0.119
	Mo	mg/L	0.07	0.07	0.06	0.06
	Na	mg/L	14.8	14.9	11.9	12.3
	Ni	mg/L	< 0.02	< 0.02	< 0.02	< 0.02
	P	mg/L	0.6	0.6	0.5	0.6
	Pb	mg/L	0.85	1.08	0.37	0.35
	Sb	mg/L	< 0.05	< 0.05	< 0.05	< 0.05
	Se	mg/L	< 0.05	< 0.05	< 0.05	< 0.05
	Si	mg/L	2.09	2.63	0.94	1
	Sn	mg/L	< 0.05	< 0.05	< 0.05	< 0.05
	Sr	mg/L	0.724	0.735	0.64	0.655
	Ti	mg/L	0.014	0.019	0.002	0.004
	V	mg/L	0.02	0.01	0.01	< 0.01
	Zn	mg/L	2.4	3.68	7.03	6.93

APPENDIX 3

RESULTS OF SHAKE FLASK SOLUTION ANALYSES

**SHAKE FLASK CALCULATIONS
DIFFERENCE AND RATIO FROM 1989 FRESH TAILINGS**

SAMPLE	pH ACIDITY		Ca mg/L	SO ₄ ²⁻ mg/L	CONDUCT. umhos/cm	DISSOLVED METALS (mg/L)			
	mg/L					Cu	Fe	Pb	Zn
FRESH 1	8.2	1	53.4	100	255	0.031	0.005	< 0.05	1.08
FRESH 2	8.1	1.3	36.5	80	175	0.046	0.016	0.13	1.59
average	8.15	1.15	44.95	90	215	0.038	0.010	< 0.09	1.335
MONTH 1	8.1	2.6	215	460	830	0.046	<0.005	< 0.05	8.85
MONTH 2	8.3	< 1	206	490	830	0.046	<0.005	< 0.05	7.54
average	8.2	1.8	210.5	475	830	0.046	<0.005	< 0.05	8.195
L30 A	-1.55	18.8	4.3	4.2	4.1	0.99	< 0.48	< 0.56	13.18
L30 B	-2.75	8.0	3.7	3.6	3.2	1.04	0.86	< 0.56	7.03
L30 C	-0.95	< 0.9	4.5	4.6	3.7	< 0.13	< 0.48	< 0.56	1.02
L30 D	-1.35	2.5	2.9	3.0	2.6	< 0.13	< 0.48	< 0.56	1.39
L30 E	-1.25	2.2	2.5	2.9	2.6	0.26	< 0.48	< 0.56	0.23
L30 F	-1.55	6.1	1.8	3.3	2.9	0.18	< 0.48	< 0.56	2.11
L30 G	-0.95	< 0.9	1.8	2.1	2.0	< 0.13	< 0.48	< 0.56	0.30
L30 H	-0.85	1.1	2.3	2.1	2.2	0.57	< 0.48	< 0.56	0.37
L30 I	-0.85	1.1	2.6	2.2	2.5	0.49	< 0.48	< 0.56	0.35
L30 J	-1.75	1.1	3.2	4.0	3.4	0.94	0.57	< 0.56	0.10
L30 K	-1.25	1.7	3.3	3.9	3.2	0.23	< 0.48	< 0.56	0.82
L30 L	-1.25	1.1	3.6	4.0	3.4	0.23	< 0.48	< 0.56	0.83
L30 M	-1.45	4.4	2.9	2.3	2.6	0.18	< 0.48	< 0.56	2.79
L30 N	-1.25	1.4	2.5	2.2	2.5	0.52	0.57	< 0.56	0.73
L30 O	-1.25	1.1	2.6	2.6	2.5	0.44	0.57	< 0.56	0.45

SHAKE FLASK CALCULATIONS (cont'd)
DIFFERENCE AND RATIO FROM 1989 FRESH TAILINGS

SAMPLE	pH	ACIDITY		Ca mg/L	SO ₄ ²⁻ mg/L	CONDUCT. umhos/cm	DISSOLVED METALS (mg/L)			
		mg/L	mg/L				Cu	Fe	Pb	Zn
L100 A	-1.35	9.1	5.9	7.0	5.0	0.49	< 0.48	< 0.56	6.06	
L100 B	-3.55	43.8	3.3	4.4	3.5	206.2	45.71	16.11	18.05	
L100 C	-1.15	2.8	4.5	4.8	4.0	0.36	< 0.48	< 0.56	0.91	
L100 D	-1.35	3.6	2.3	2.6	2.3	0.21	< 0.48	< 0.56	2.64	
L100 E	-1.05	2.2	3.2	3.2	3.2	0.21	< 0.48	< 0.56	1.45	
L100 F	-1.25	3.3	1.5	1.7	1.6	< 0.13	< 0.48	< 0.56	2.44	
L100 G	-1.25	11.6	4.0	3.9	3.9	0.21	< 0.48	< 0.56	7.44	
L100 I	-0.95	1.1	2.8	3.3	2.9	< 0.13	< 0.48	< 0.56	1.55	
L100 J	-1.05	2.2	3.0	4.7	3.5	0.23	< 0.48	< 0.56	2.18	
L100 K	-1.35	16.5	4.2	5.3	4.2	0.39	< 0.48	< 0.56	11.84	
L100 L	-1.55	12.1	3.5	4.4	3.4	< 0.13	< 0.48	< 0.56	9.14	
L100 M	-1.45	5.0	2.8	3.3	2.8	< 0.13	< 0.48	< 0.56	4.31	
L100 N	-1.35	< 0.9	3.4	4.1	3.4	0.47	< 0.48	< 0.56	1.22	
L100 P	-0.95	< 0.9	3.1	3.6	3.0	0.29	0.57	< 0.56	0.93	
L100 Q	-0.85	< 0.9	2.4	2.6	2.5	< 0.13	< 0.48	< 0.56	0.33	
L100 R	-0.85	< 0.9	2.6	2.9	2.7	< 0.13	< 0.48	< 0.56	0.32	
L160 A	-1.25	101.7	6.3	8.3	5.5	5.17	< 0.48	< 0.56	53.78	
L160 B	-4.75	224.3	5.3	9.1	6.2	615.6	5752	24.56	35.51	
L160 C	-0.65	28.0	4.4	5.2	4.3	0.23	1.81	< 0.56	19.70	
L160 D	-3.75	59.9	4.5	6.3	4.3	158.7	246.7	27.00	25.17	
L160 E	-0.05	1.7	3.0	2.8	2.7	0.34	0.67	< 0.56	0.83	
L160 F	-0.35	7.7	4.3	4.6	3.7	0.39	< 0.48	< 0.56	5.90	
L160 G	0.05	1.1	3.2	4.3	3.5	0.34	0.57	0.67	0.82	
L160 H	-0.05	1.7	3.4	4.9	3.7	< 0.13	< 0.48	0.78	1.18	
L160 I	-0.45	17.6	4.2	4.3	3.6	2.60	< 0.48	< 0.56	13.18	
L160 J	-1.15	72.1	4.8	6.3	4.6	96.10	35.14	27.56	41.72	
L160 K	-0.25	17.6	3.7	4.0	3.2	0.81	< 0.48	1.11	21.42	
L160 Lt	-0.05	6.5	3.6	3.8	3.0	0.23	< 0.48	< 0.56	7.48	
L160 Lb	0.25	< 0.9	2.4	2.0	2.1	< 0.13	< 0.48	< 0.56	1.99	
L160 M	0.25	0.9	1.9	1.3	1.7	0.23	< 0.48	< 0.56	0.70	
L160 N	0.05	< 1.1	4.1	3.8	3.3	0.39	< 0.48	< 0.56	2.98	
L160 Gt	0.05	< 0.9	3.6	3.1	2.9	0.62	< 0.48	< 0.56	3.74	
L160 Gb	0.05	< 0.9	4.1	4.3	3.6	0.88	< 1.24	< 0.56	4.78	

SHAKE FLASK CALCULATIONS (cont'd)
DIFFERENCE AND RATIO FROM 1989 FRESH TAILINGS

SAMPLE	pH	ACIDITY mg/L	Ca mg/L	SO ₄ ²⁻ mg/L	CONDUCT. umho/cmCu	DISSOLVED METALS			
						Fe	Pb	Zn	
EP1 A	0.35	< 0.9	2.4	2.2	2.0	0.29	< 0.48	< 0.56	0.10
EP1 B	-0.05	2.0	3.5	2.9	2.9	0.47	< 0.48	< 0.56	4.88
EP1 C	0.35	< 0.9	0.8	0.7	0.8	0.65	0.67	< 0.56	0.60
EP1 D	0.25	< 0.9	1.7	1.1	1.6	0.18	0.57	< 0.56	0.33
EP1 E	0.45	< 0.9	0.5	0.3	0.5	0.16	< 0.48	< 0.56	0.06
EP1 F	0.25	< 0.9	1.4	1.1	1.4	0.68	0.86	< 0.56	0.14
EP1 G	-0.15	2.5	2.8	2.9	2.7	0.75	0.76	< 0.56	1.76
EP1 H	0.25	< 0.9	2.7	2.9	2.7	0.91	< 0.48	1.00	5.19
EP1 I	-0.15	4.5	1.8	2.2	2.0	0.91	< 0.48	1.11	5.32
EP1 J	-0.05	4.0	2.2	2.2	2.1	0.52	< 0.48	0.89	6.43
EP2 A	0.35	< 0.9	0.4	0.4	0.5	0.26	< 0.48	< 0.56	0.67
EP2 B	0.35	< 0.9	1.9	1.1	1.6	0.47	< 0.48	1.22	0.30
EP2 C	0.25	< 0.9	3.0	2.2	2.2	0.65	0.67	0.67	0.43
EP2 D	0.25	< 0.9	1.9	2.2	1.7	0.49	< 0.48	< 0.56	0.16
EP2 E	0.25	< 0.9	1.4	1.1	1.3	0.36	< 0.48	< 0.56	0.04
EP2 F	-0.25	2.9	1.6	1.1	1.6	1.01	< 0.48	0.56	2.40
EP2 G	0.15	< 0.9	1.8	2.2	1.7	0.83	< 0.48	< 0.56	1.69
EP2 H	0.05	0.9	2.0	2.2	1.9	1.04	< 0.48	0.78	2.01
EP2 I	0.15	< 0.9	1.1	1.1	1.1	1.19	0.95	1.56	1.28
EP2 J	0.15	< 0.9	0.8	0.9	0.9	0.75	< 0.48	0.67	0.81

**SHAKE FLASK CALCULATIONS
TO DETERMINE POSITION OF CONTAMINANT FRONTS
USING 1989 FRESH TAILINGS DATA**

SAMPLE	pH	ACIDITY mg/L	Ca mg/L	SO ₄ ²⁻ mg/L	CONDUCT. umho/cmCu	DISSOLVED METALS		
						Cu	Fe	Zn
L30 A	-1.55	C 20	150	290	C 665	0.00	-0.01	C 16.3
L30 B C	-2.75	8	121	230	465	0.00	0.00	C 8.1
L30 C	-0.95	0	157	C 320	585	-0.03	-0.01	0.0
L30 D	-1.35	2	85	180	335	-0.03	-0.01	0.5
L30 E	-1.25	1	67	170	335	-0.03	-0.01	-1.0
L30 F	-1.55	6	36	210	415	-0.03	-0.01	1.5
L30 G	-0.95	0	37	100	215	-0.03	-0.01	-0.9
L30 H	-0.85	0	58	100	250	-0.02	-0.01	-0.8
L30 I	-0.85	0	73	110	315	-0.02	-0.01	-0.9
L30 J	-1.75	0	101	270	515	0.00	0.00	-1.2
L30 K	-1.25	1	104	260	465	-0.03	-0.01	-0.2
L30 L	-1.25	0	118	270	515	-0.03	-0.01	-0.2
L30 M	-1.45	4	86	120	335	-0.03	-0.01	2.4
L30 N	-1.25	0	68	110	315	-0.02	0.00	-0.4
L30 O	-1.25	0	72	140	315	-0.02	0.00	-0.7
L100 A	-1.35	9	222	C 540	C 865	-0.02	-0.01	C 6.8
L100 B C	-3.55	C 49	102	C 310	535	C 7.90	0.47	C 22.8
L100 C	-1.15	2	158	C 340	C 635	-0.02	-0.01	-0.1
L100 D	-1.35	3	57	140	275	-0.03	-0.01	2.2
L100 E	-1.05	1	100	200	465	-0.03	-0.01	0.6
L100 F	-1.25	3	24	60	135	-0.03	-0.01	1.9
L100 G	-1.25	C 12	136	260	C 615	-0.03	-0.01	C 8.6
L100 I	-0.95	0	80	210	415	-0.03	-0.01	0.7
L100 J	-1.05	1	92	C 330	535	-0.03	-0.01	1.6
L100 K	-1.35	C 18	142	C 390	C 685	-0.02	-0.01	C 14.5
L100 L	-1.55	C 13	111	C 310	515	-0.03	-0.01	C 10.9
L100 M	-1.45	5	83	210	385	-0.03	-0.01	C 4.4
L100 N	-1.35	0	110	280	515	-0.02	-0.01	0.
L100 O/P	-0.95	0	93	230	435	-0.03	0.00	-0.1
L100 Q	-0.85	0	63	140	315	-0.03	-0.01	-0.9
L100 R	-0.85	0	71	170	365	-0.03	-0.01	-0.9

SHAKE FLASK CALCULATIONS (cont'd)
TO DETERMINE POSITION OF CONTAMINANT FRONTS
USING 1989 FRESH TAILINGS DATA

TEST PIT L160

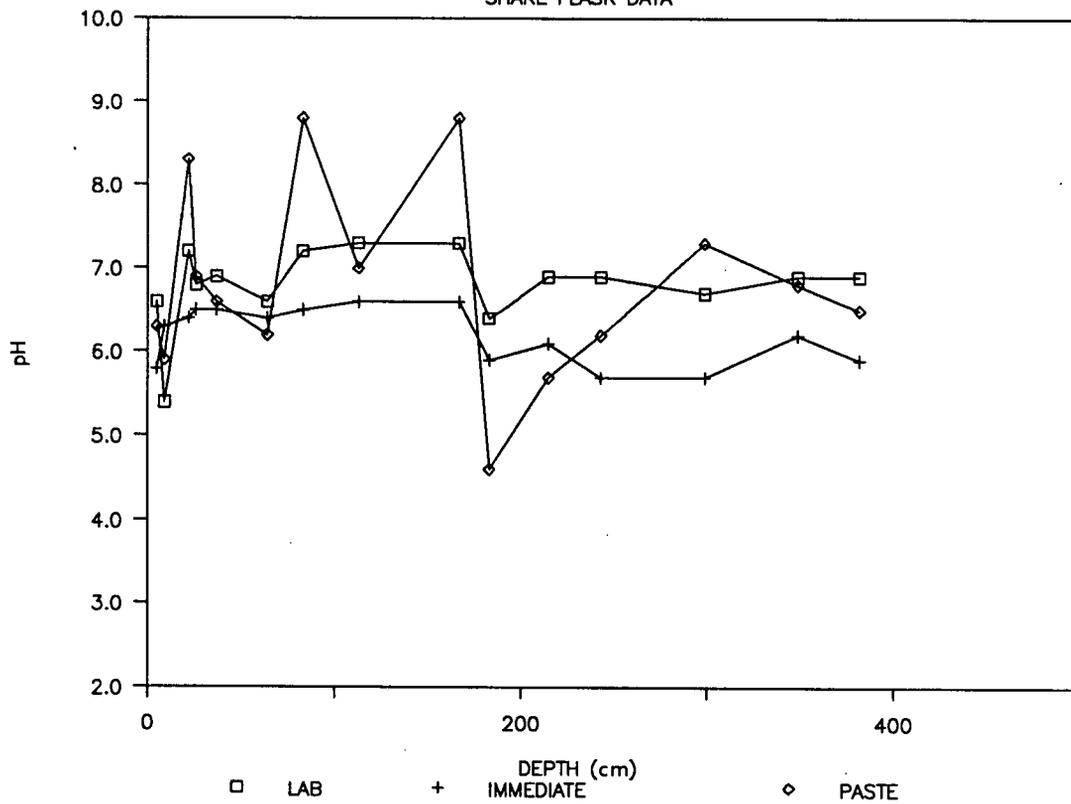
SAMPLE	pH	ACIDITY mg/L	Ca mg/L	SO ₄ ²⁻ mg/L	CONDUCT. umho/cm	DISSOLVED METALS		
						Cu	Fe	Zn
L160 A	-1.25	C116	240	C660	C965	0.16	-0.01	C70.5
L160 B C	-4.75	C257	193	C730	C1115	C23.66	C60.39	C46.1
L160 C	-0.65	C31	154	C380	C715	-0.03	0.01	C25.0
L160 D C	-3.75	C68	159	C480	C715	C6.07	C2.58	C32.3
L160 E	-0.05	1	91	160	365	-0.03	0.00	-0.2
L160 F	-0.35	8	149	C320	585	-0.02	-0.01	C6.5
L160 G	0.05	0	97	300	535	-0.03	0.00	-0.2
L160 H	-0.05	1	108	C350	585	-0.03	-0.01	0.2
L160 I	-0.45	C19	144	300	565	0.06	-0.01	C16.3
L160 J	-1.15	C82	171	C480	C765	C3.66	0.36	C54.4
L160 K	-0.25	C19	121	270	465	-0.01	-0.01	C27.3
L160 Lt	-0.05	6	118	250	435	-0.03	-0.01	C8.6
L160 Lb	0.25	0	62	90	235	-0.03	-0.01	1.3
L160 M	0.25	0	40	30	145	-0.03	-0.01	-0.4
L160 N	0.05	0	139	250	485	-0.02	-0.01	2.6
L160 Gt	0.05	0	118	190	415	-0.01	-0.01	C3.7
L160 Gb	0.05	0	139	300	565	0.00	0.00	C5.0

APPENDIX 4

GRAPHICAL ANALYSES OF SHAKE FLASK SOLUTION DATA

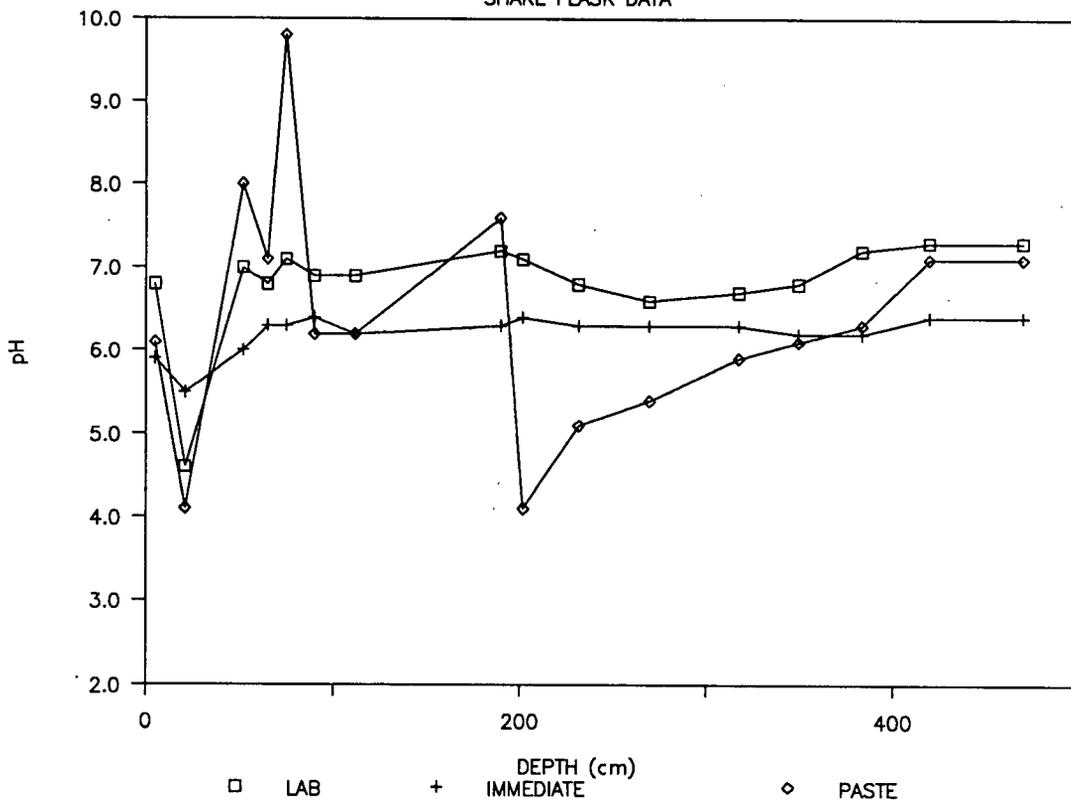
Series a AREA #1 - L30

SHAKE FLASK DATA



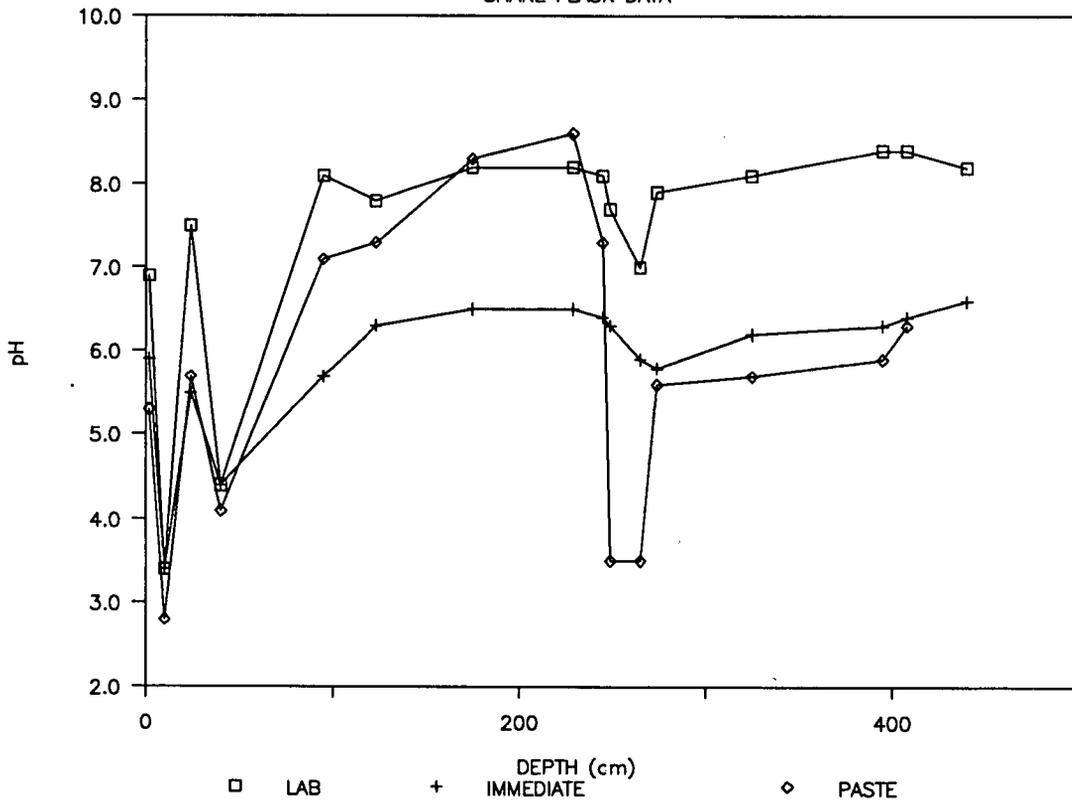
AREA #1 - L100

SHAKE FLASK DATA

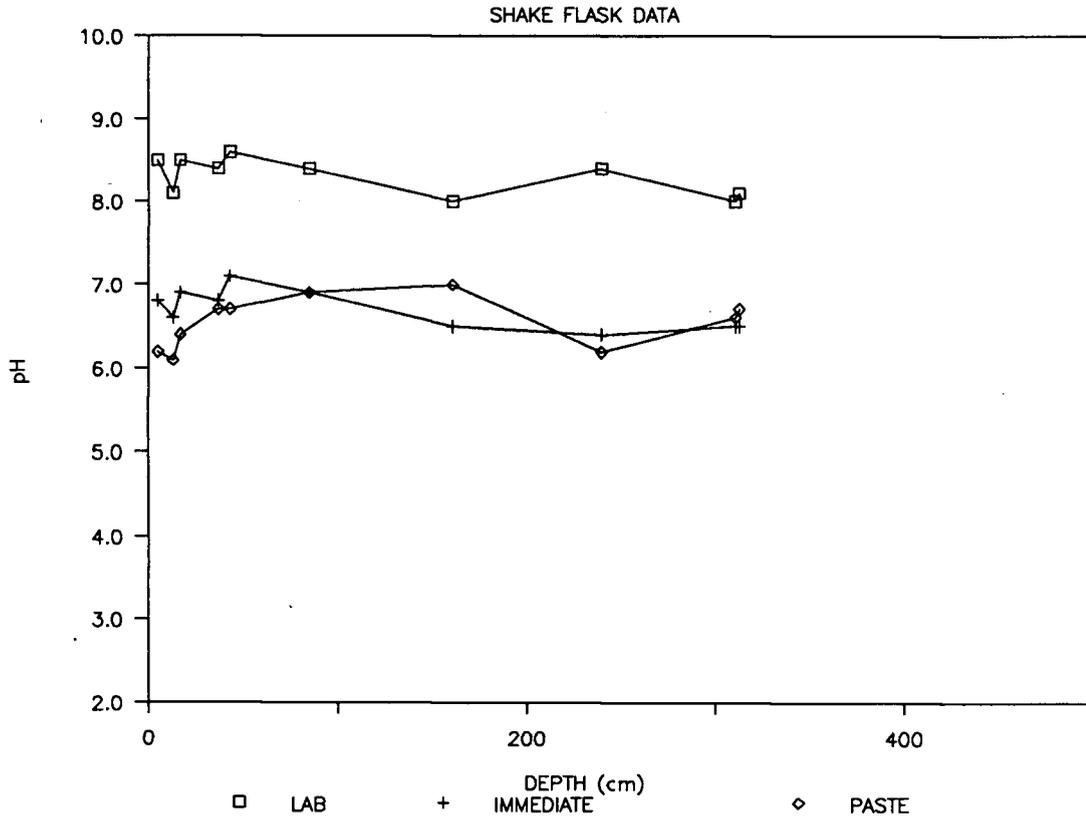


Series a (cont'd) AREA #1 - L160

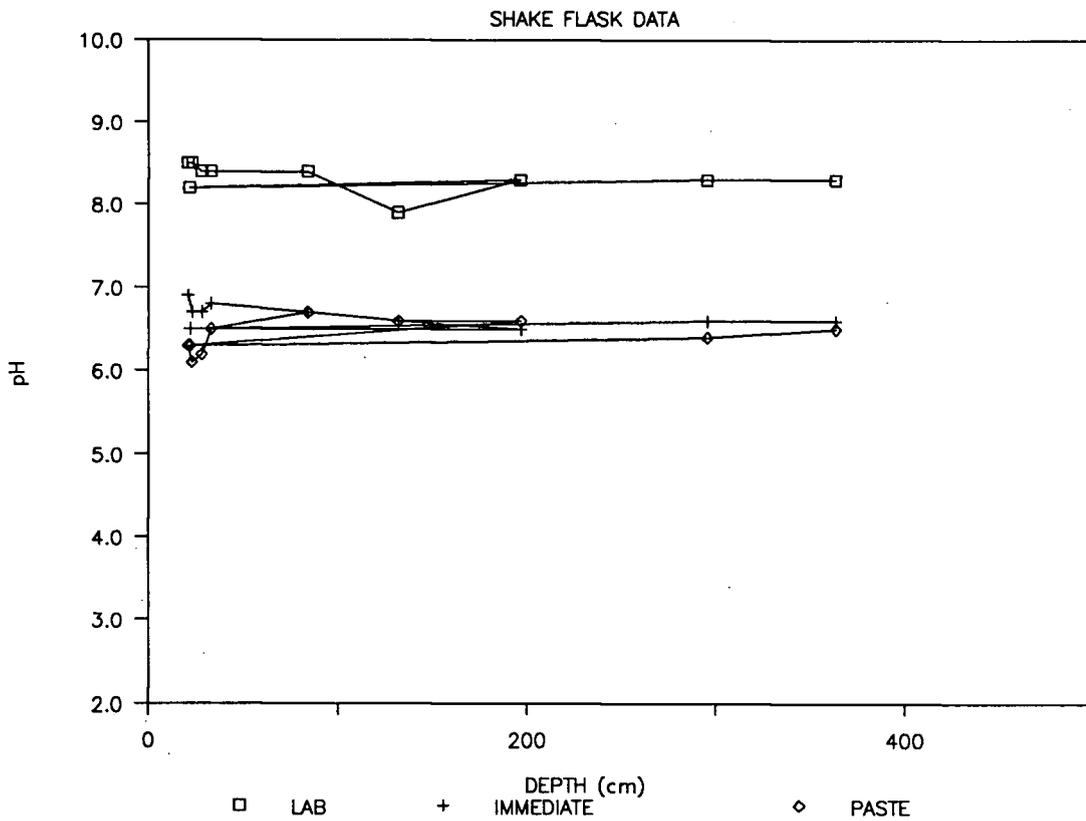
SHAKE FLASK DATA



Series a (cont'd) EMERGENCY POND - EP1

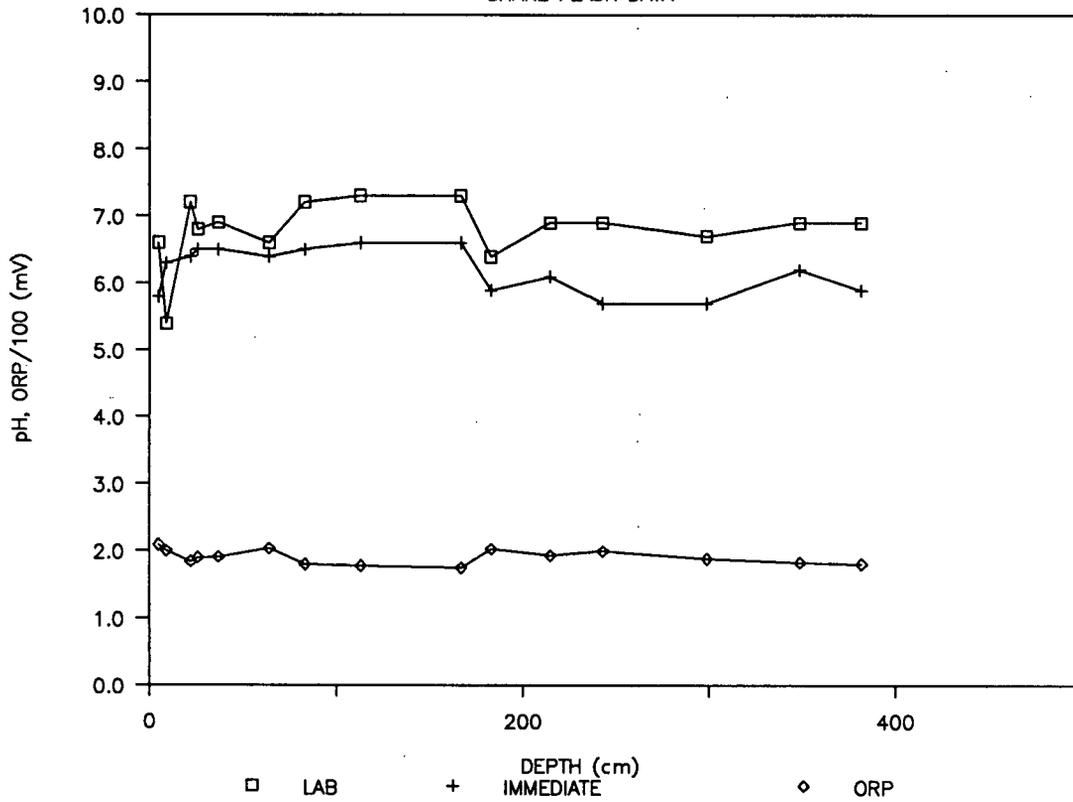


EMERGENCY POND - EP2



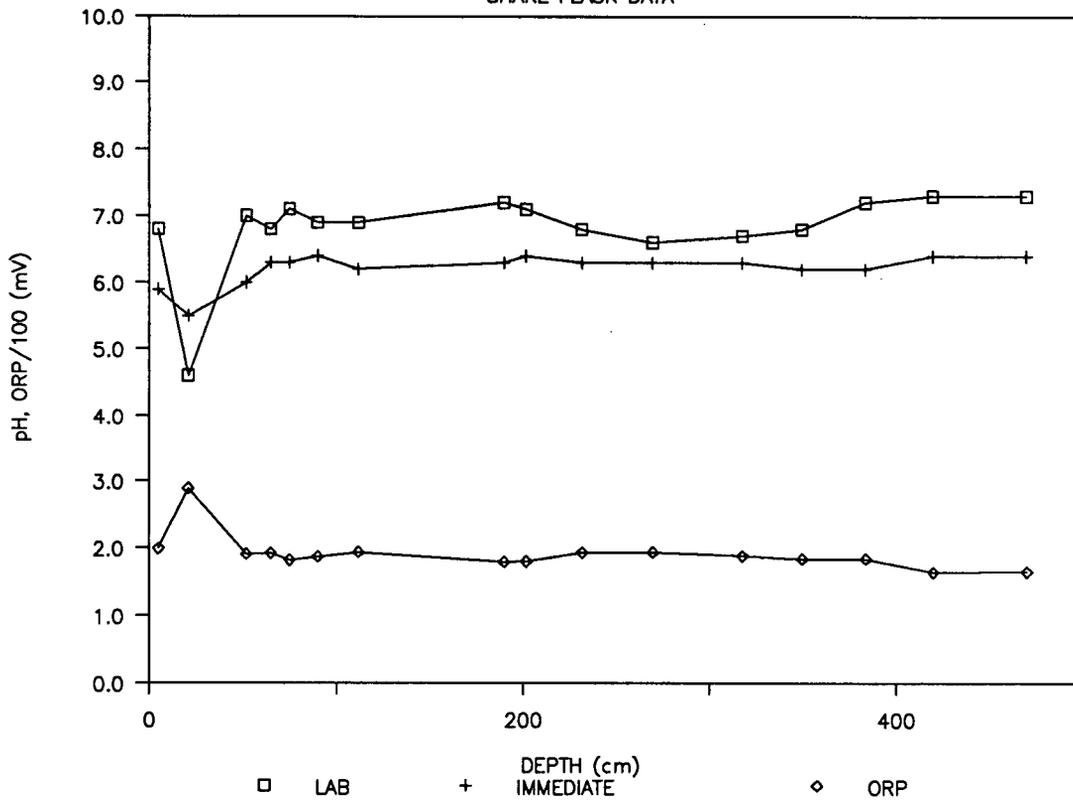
Series b AREA #1 - L30

SHAKE FLASK DATA



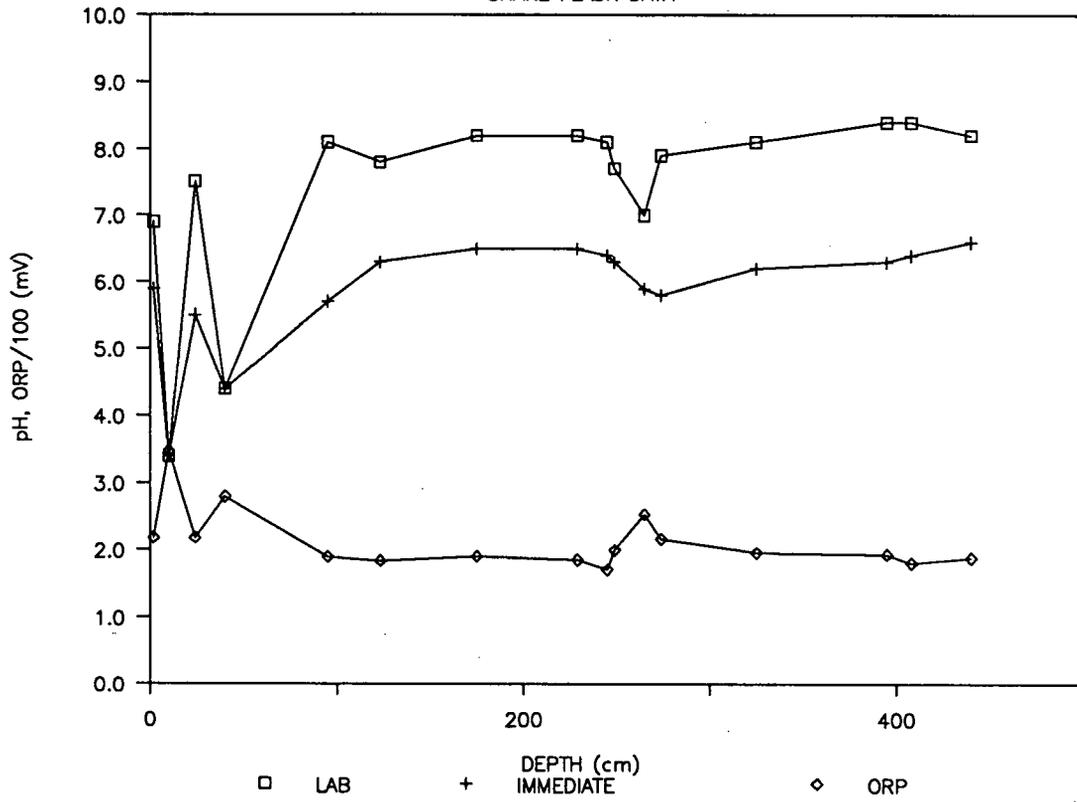
AREA #1 - L100

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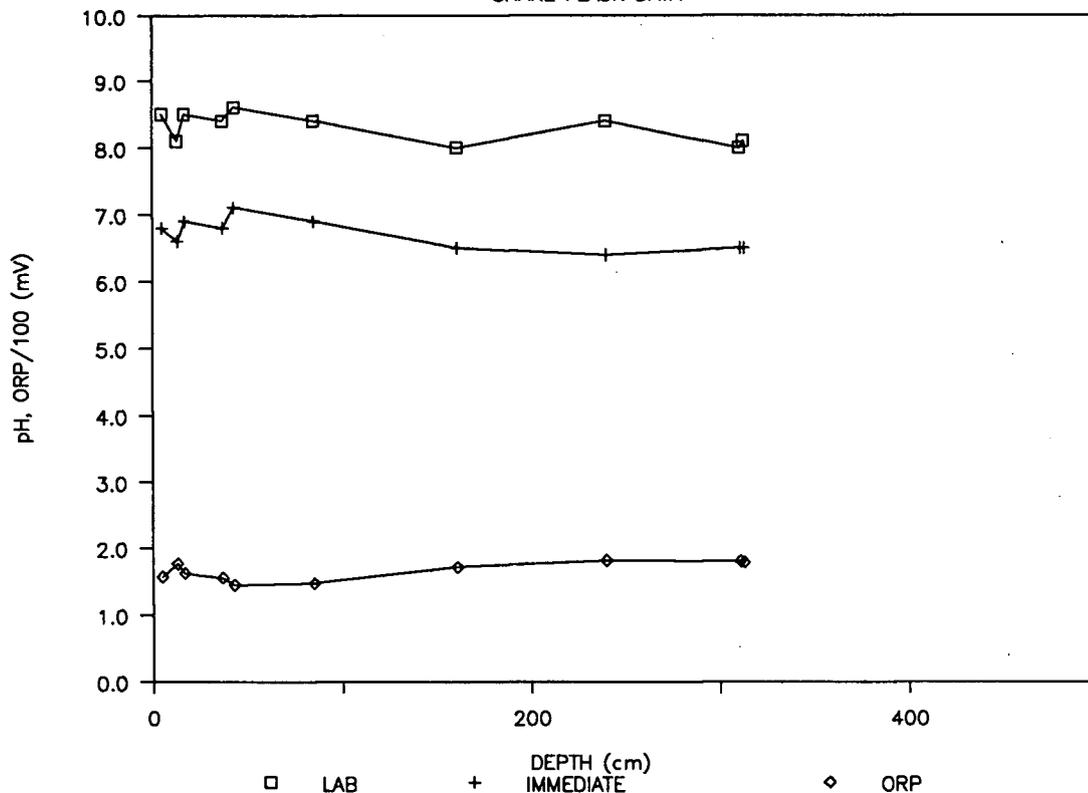
Series b (cont'd)
AREA #1 - L160

SHAKE FLASK DATA



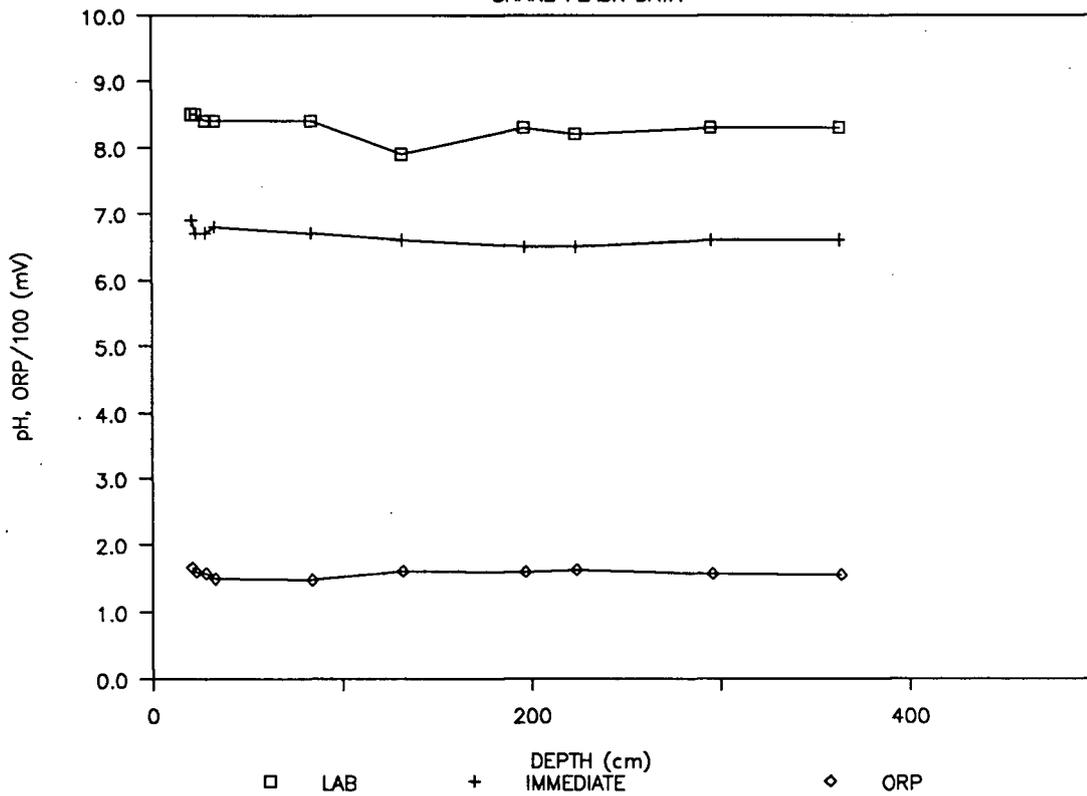
Series b (cont'd) EMERGENCY POND - EP1

SHAKE FLASK DATA

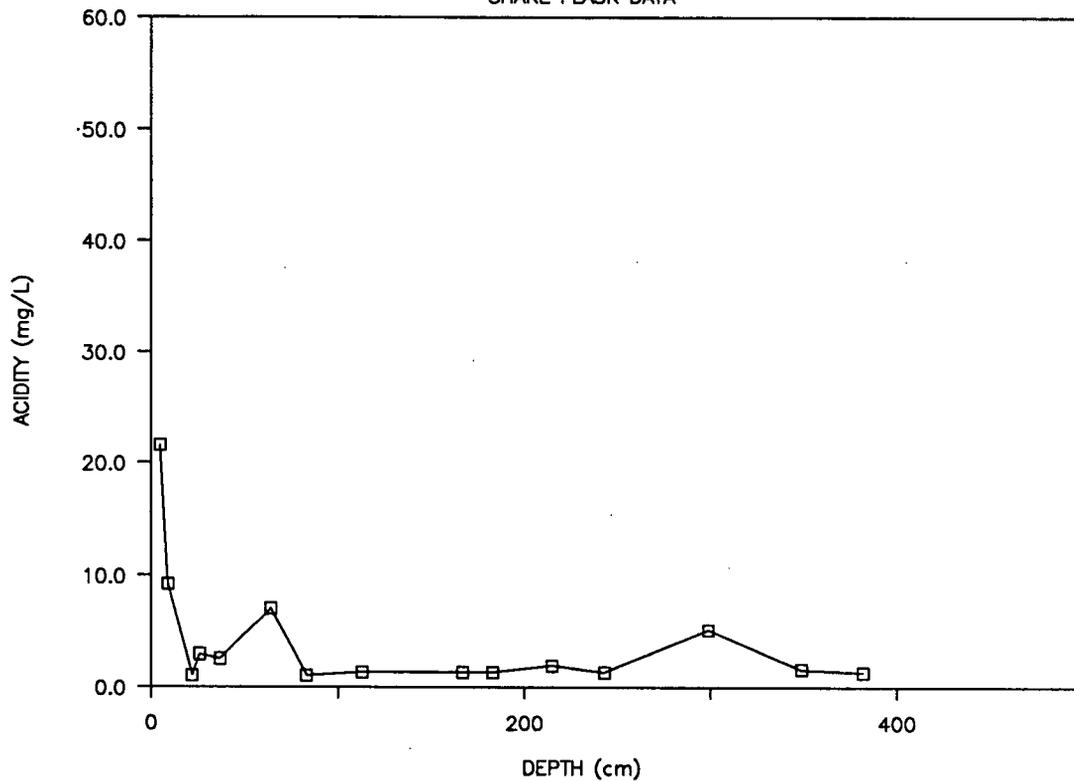


EMERGENCY POND - EP2

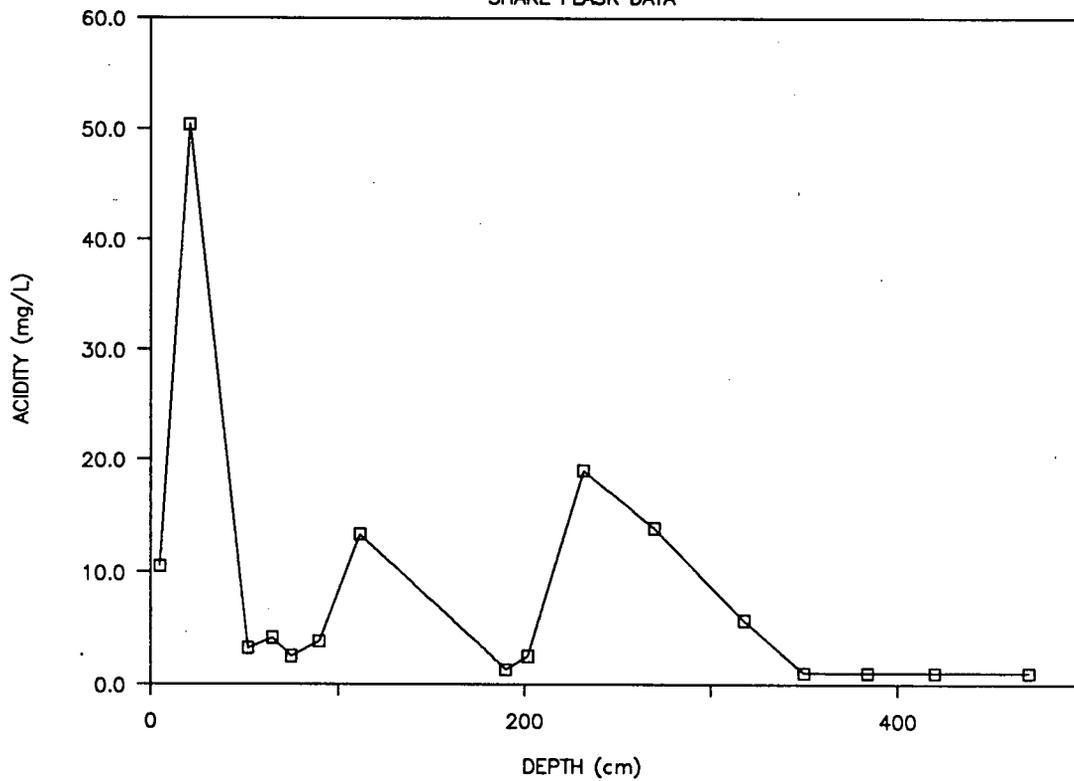
SHAKE FLASK DATA



Series c
AREA #1 - L30
SHAKE FLASK DATA



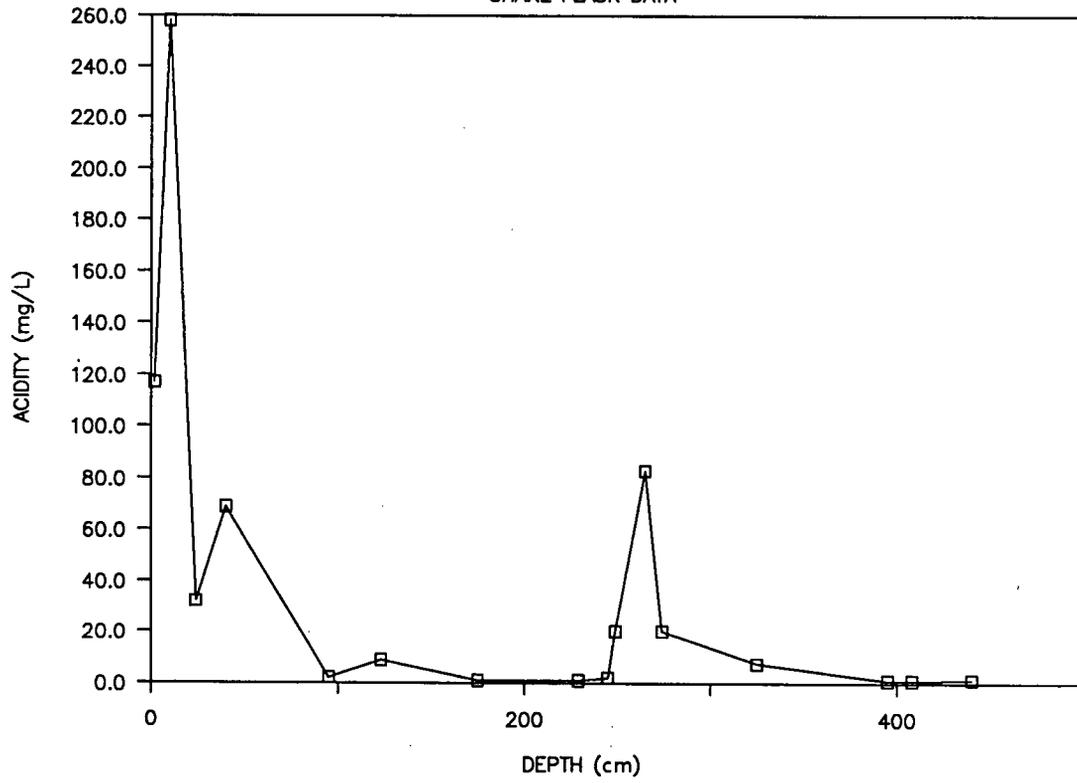
AREA #1 - L100
SHAKE FLASK DATA



Series c (cont'd)

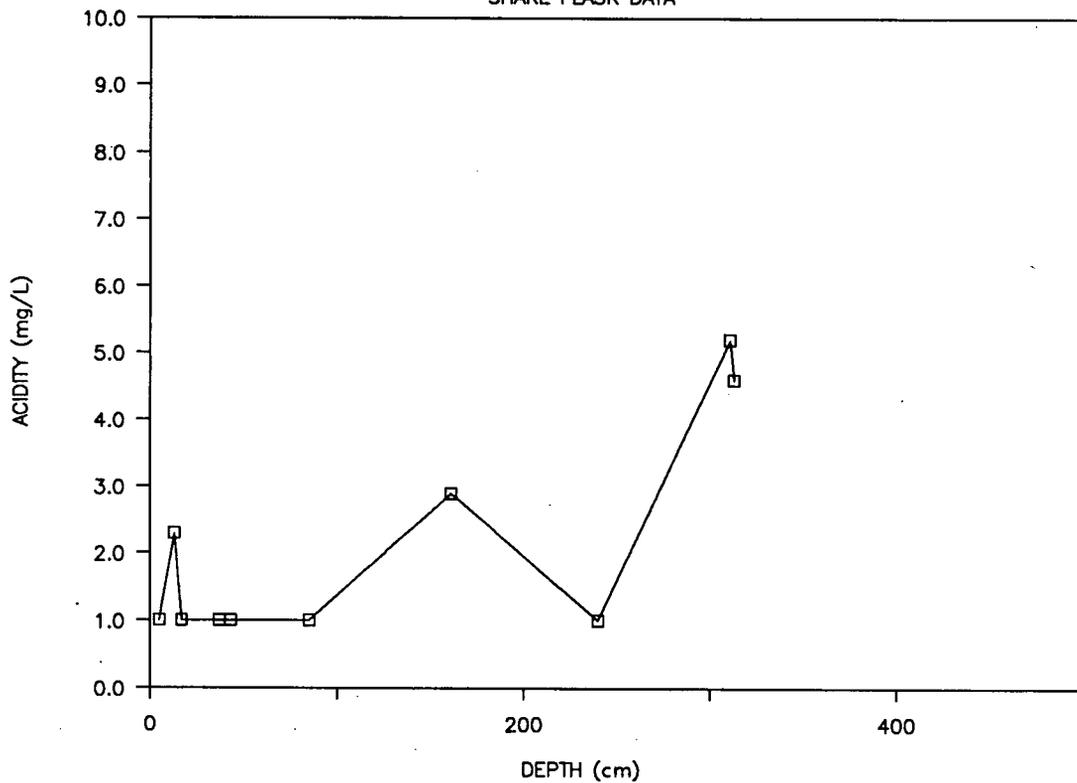
AREA #1 - L160

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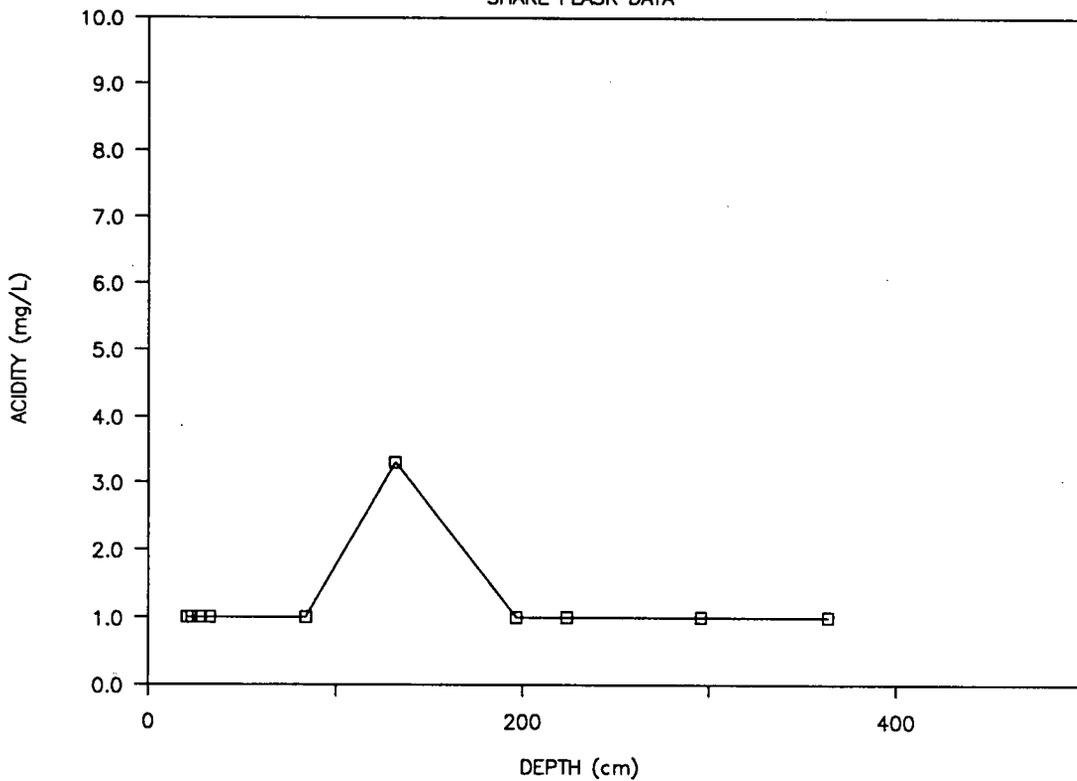
Series c (cont'd) EMERGENCY POND - EP1

SHAKE FLASK DATA



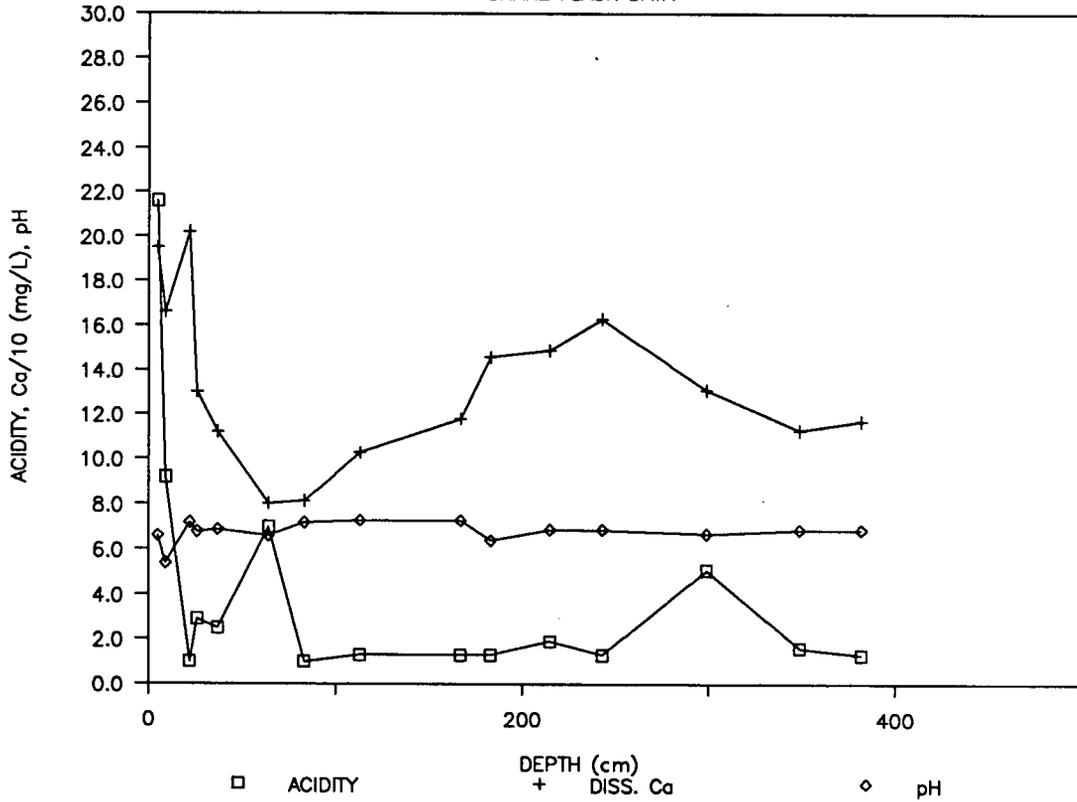
EMERGENCY POND - EP2

SHAKE FLASK DATA



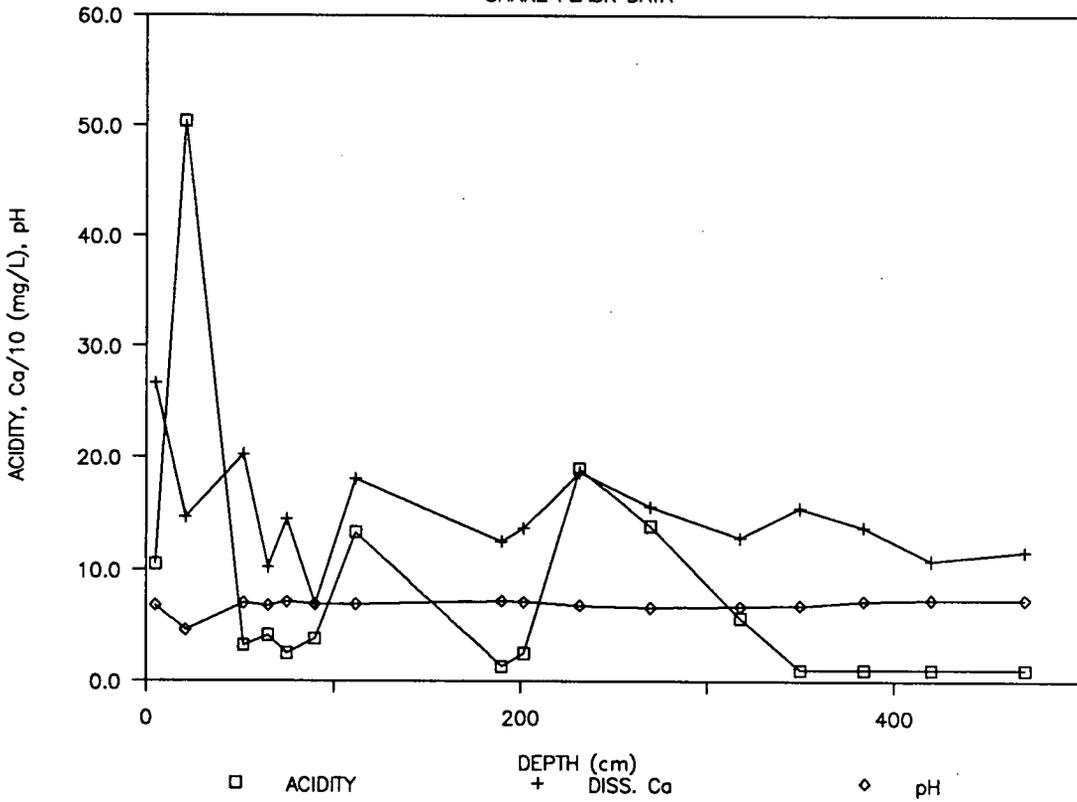
Series d AREA #1 - L30

SHAKE FLASK DATA



AREA #1 - L100

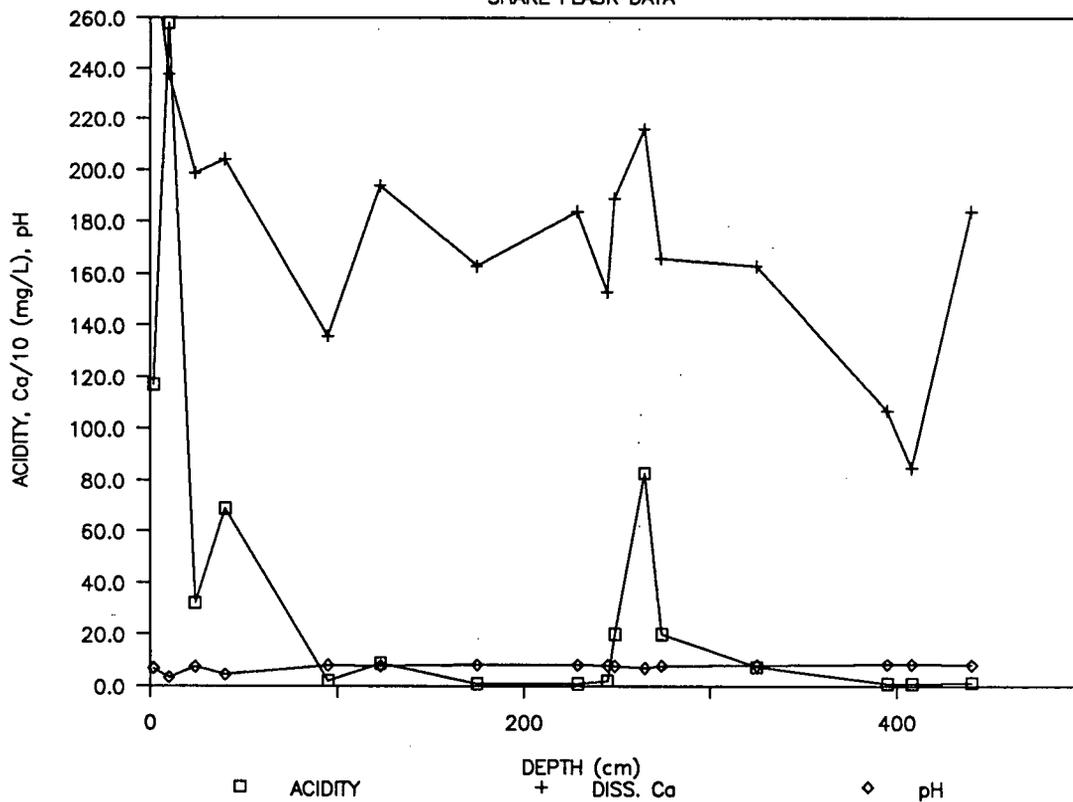
SHAKE FLASK DATA



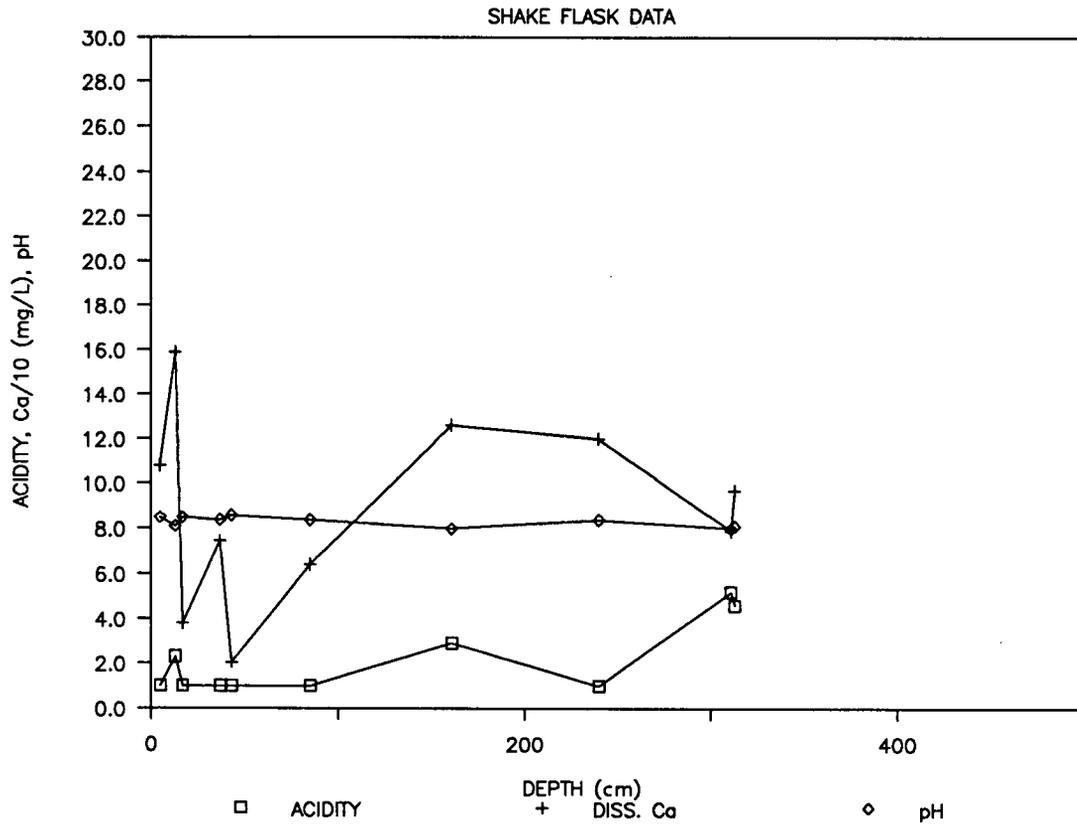
Series d (cont'd)

AREA #1 - L160

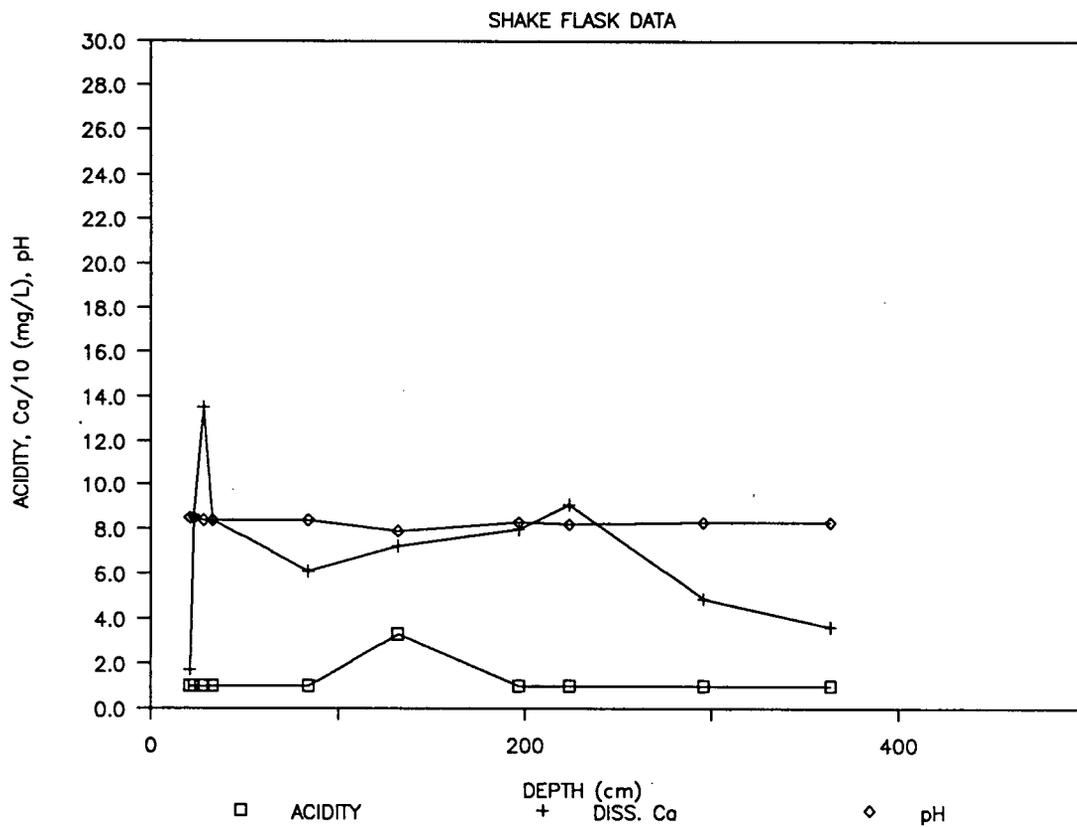
SHAKE FLASK DATA



Series d (cont'd) EMERGENCY POND - EP1

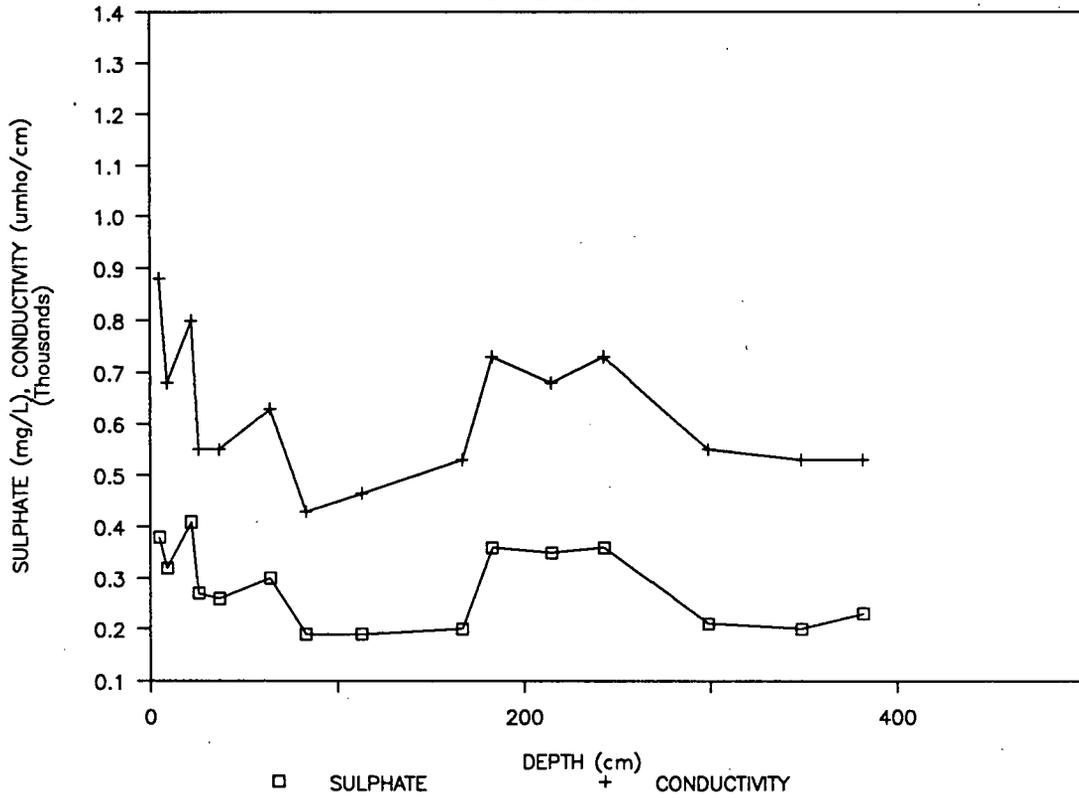


EMERGENCY POND - EP2



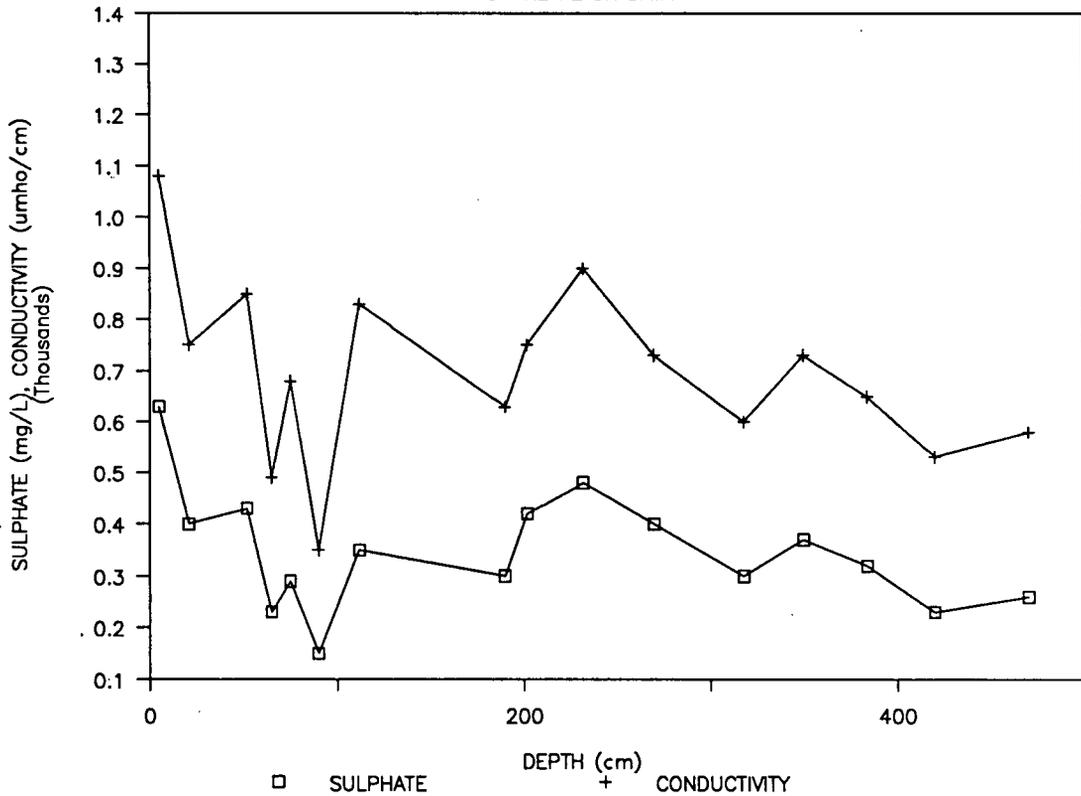
Series e AREA #1 - L30

SHAKE FLASK DATA

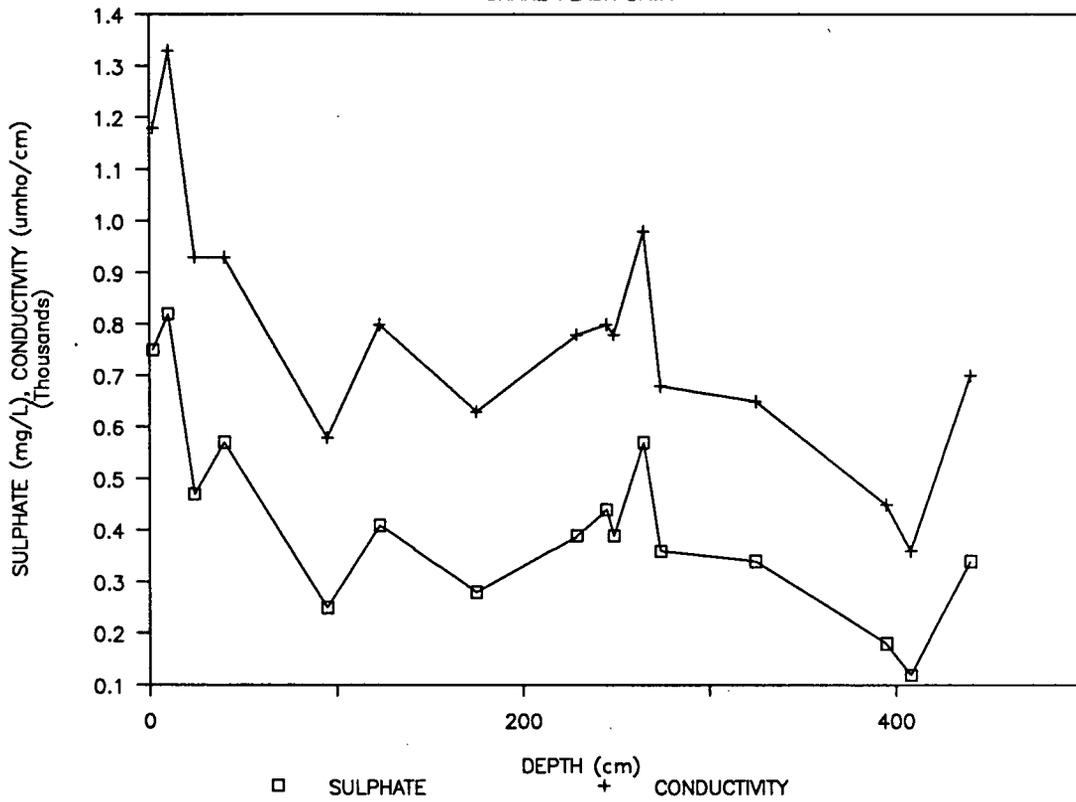


AREA #1 - L100

SHAKE FLASK DATA

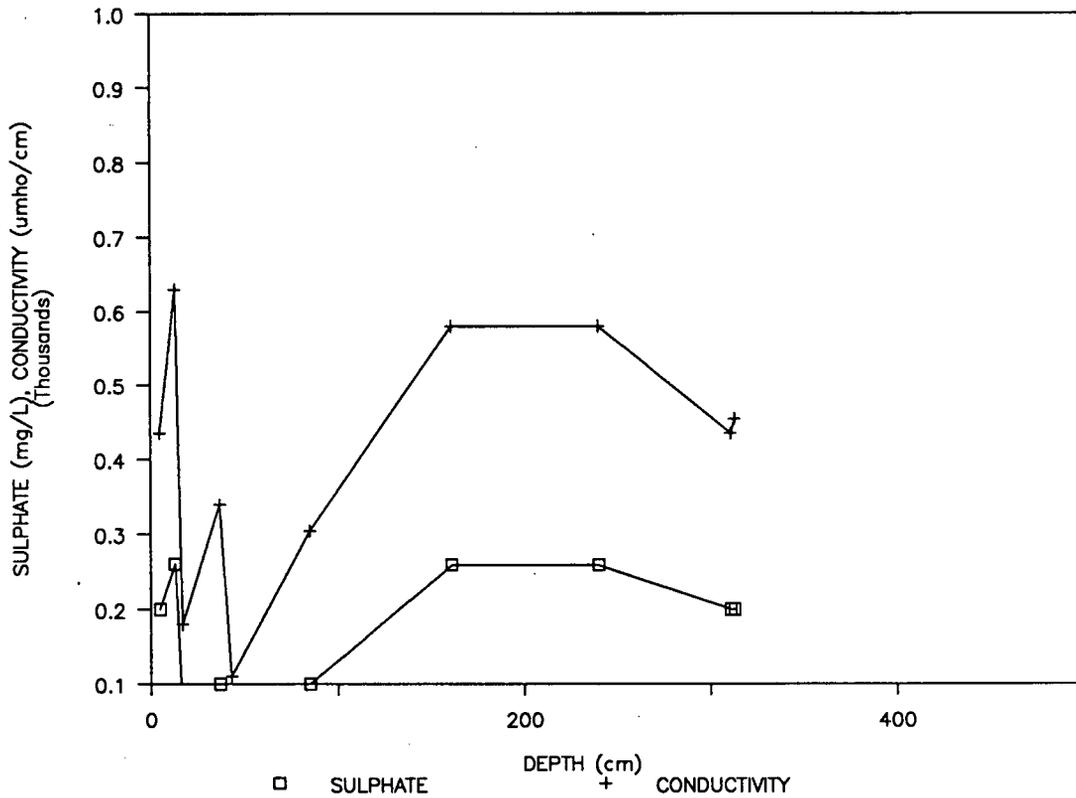


Series e (cont'd)
AREA #1 - L160
SHAKE FLASK DATA



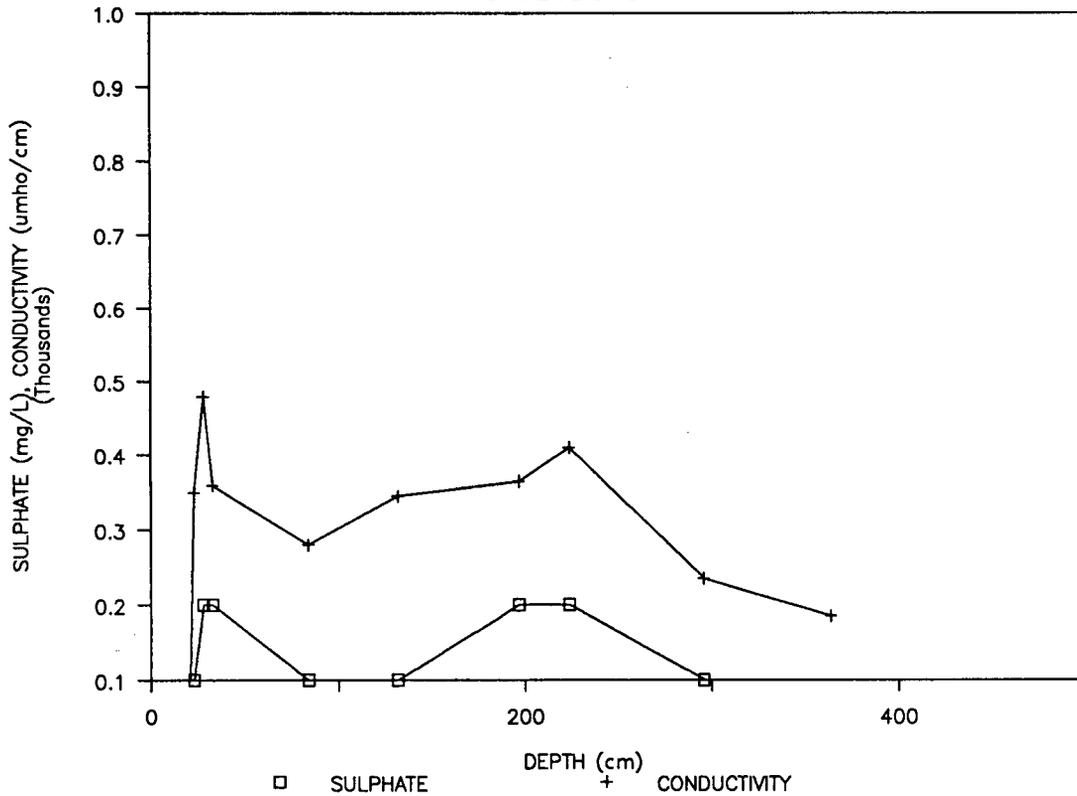
Series e (cont'd) EMERGENCY POND - EP1

SHAKE FLASK DATA



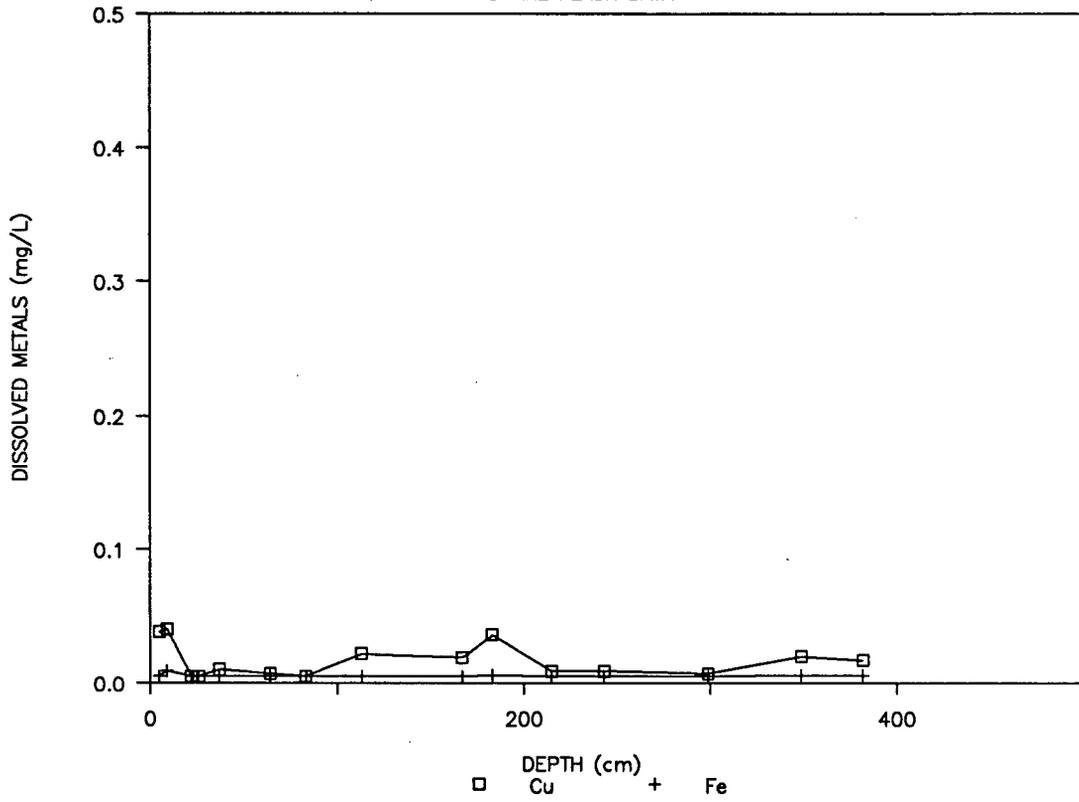
EMERGENCY POND - EP2

SHAKE FLASK DATA



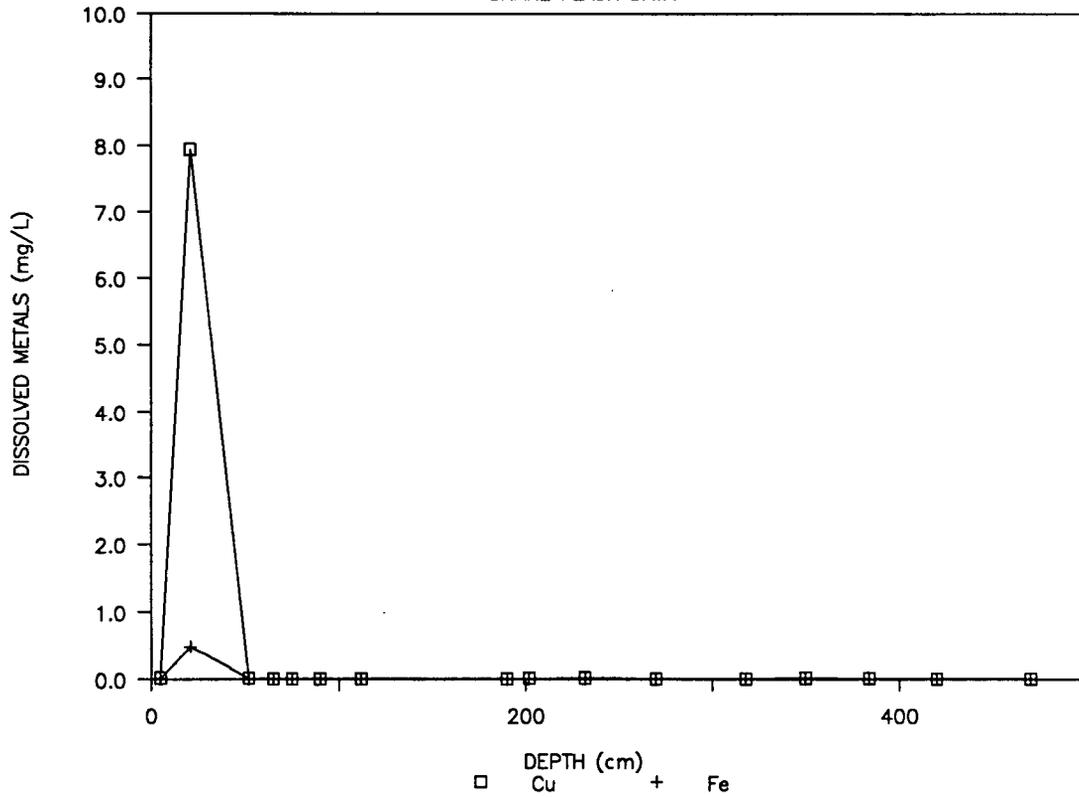
Series f
AREA #1 - L30

SHAKE FLASK DATA



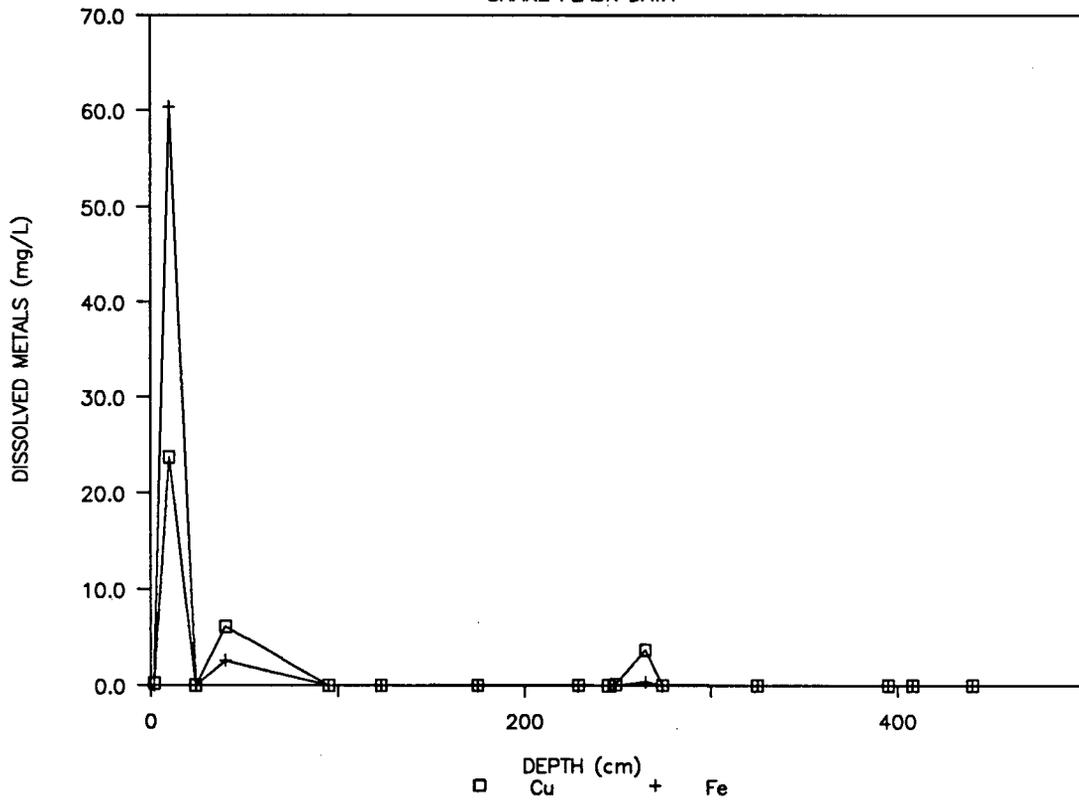
AREA #1 - L100

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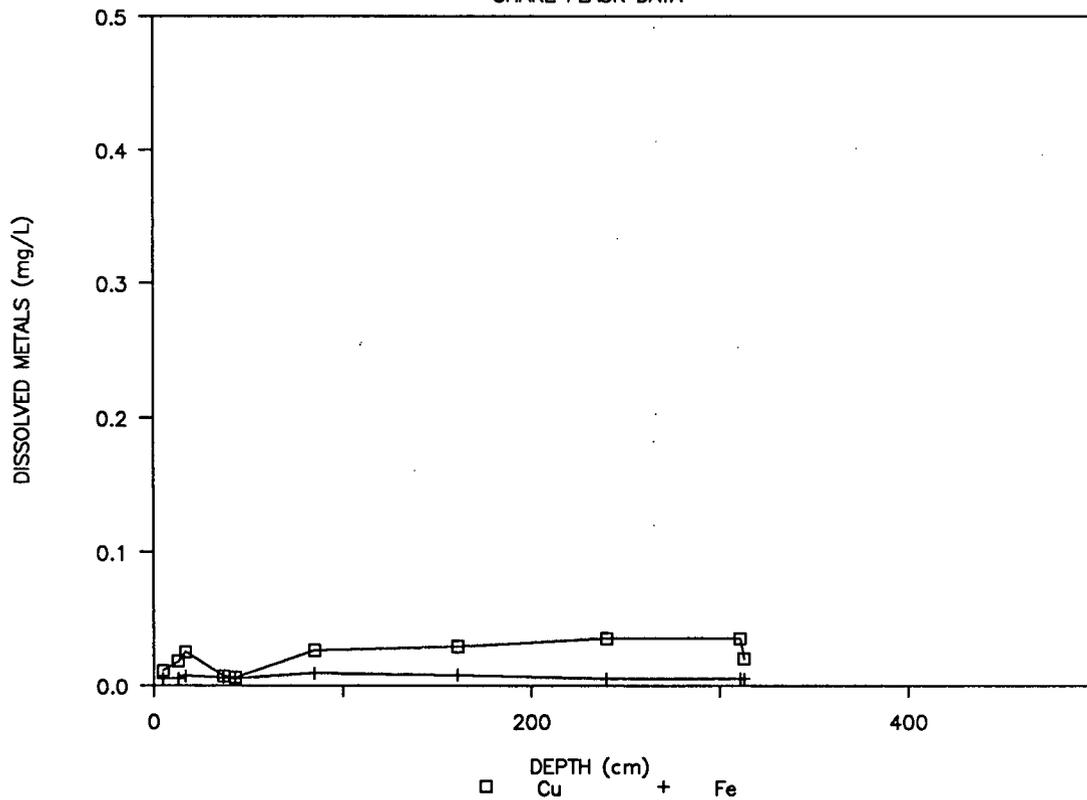
Series f (cont'd)
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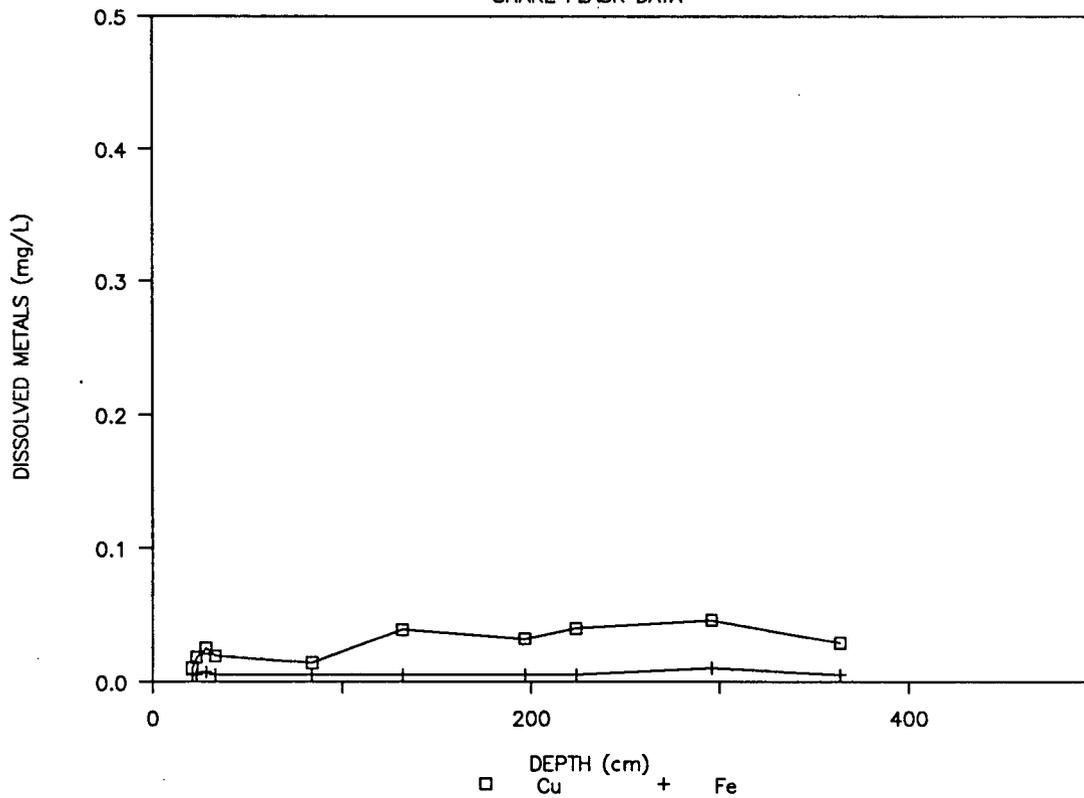
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SHAKE FLASK DATA



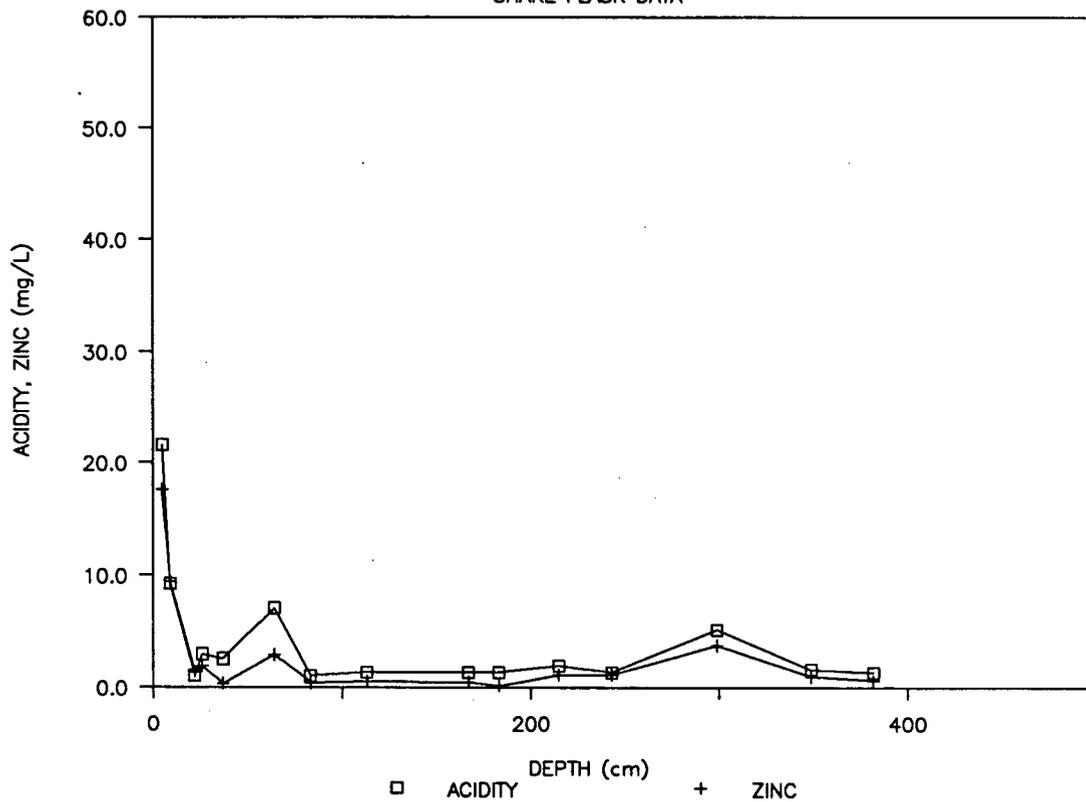
EMERGENCY POND - EP2

SHAKE FLASK DATA



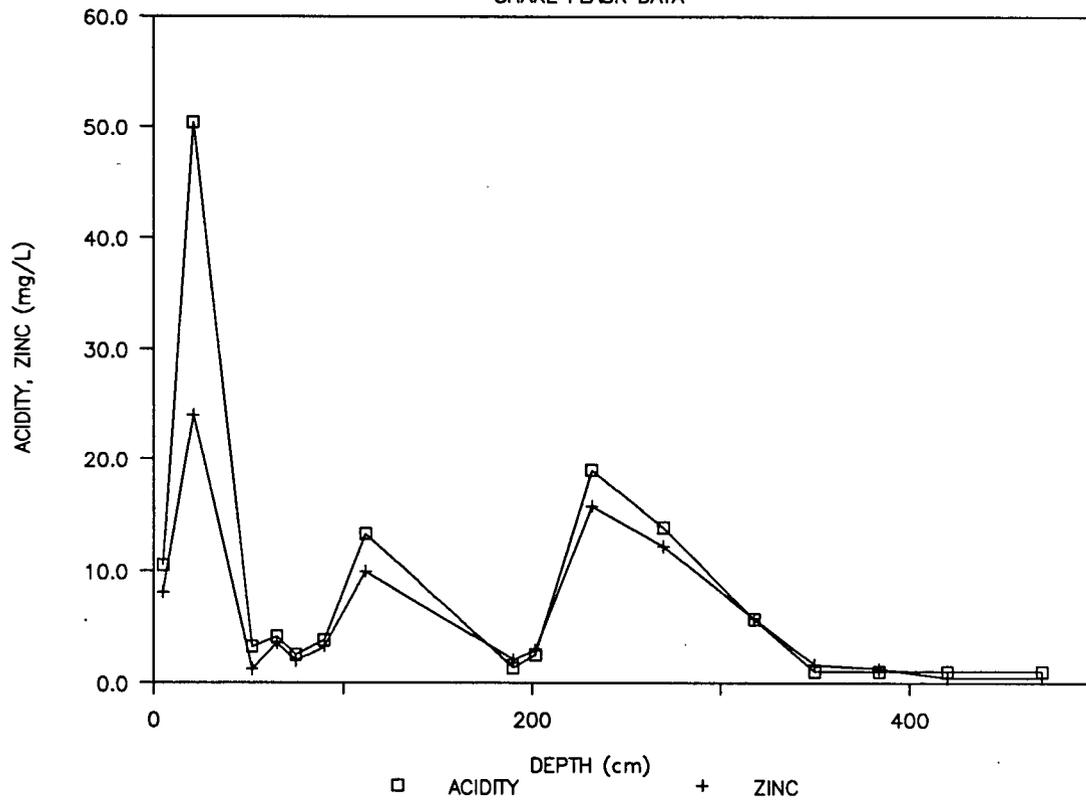
Series g AREA #1 - L30

SHAKE FLASK DATA



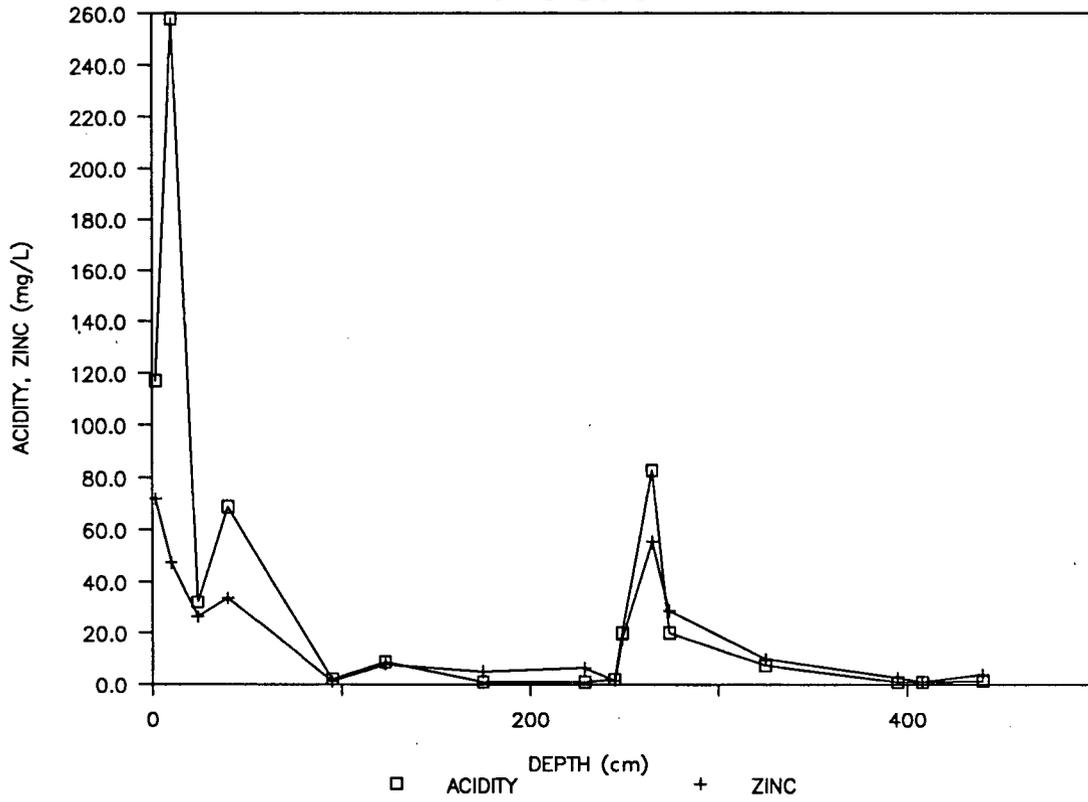
AREA #1 - L100

SHAKE FLASK DATA

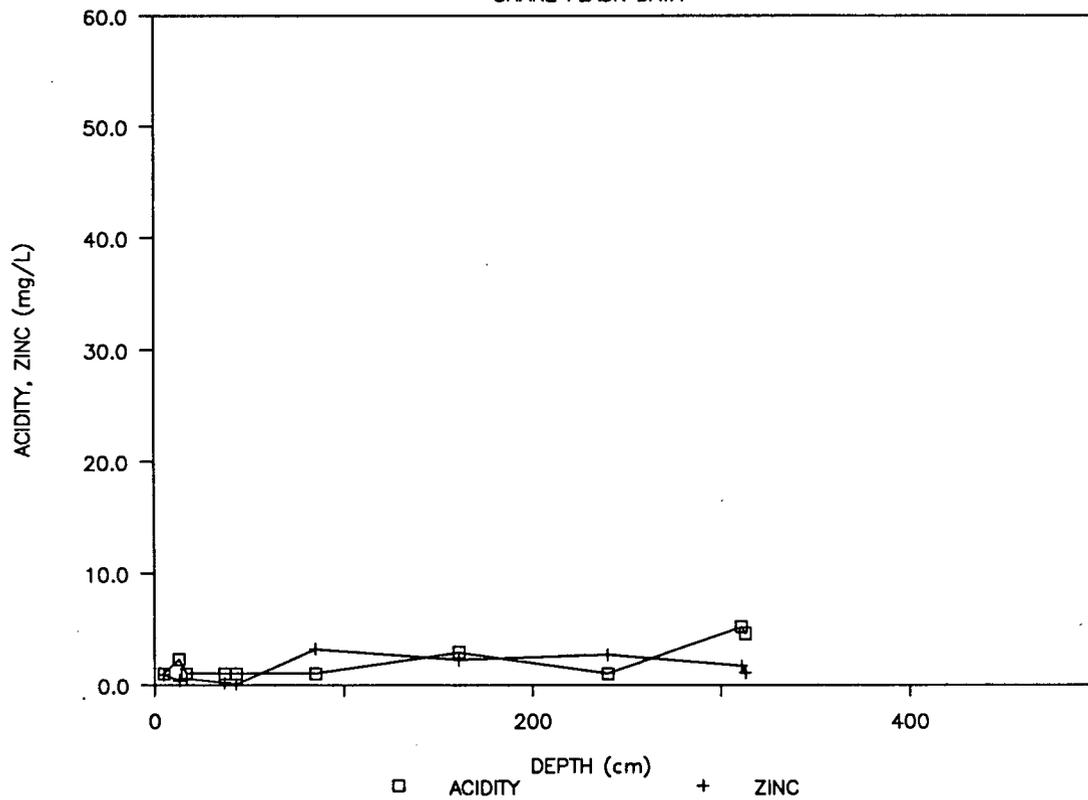


Series g (cont'd)
AREA #1 - L160

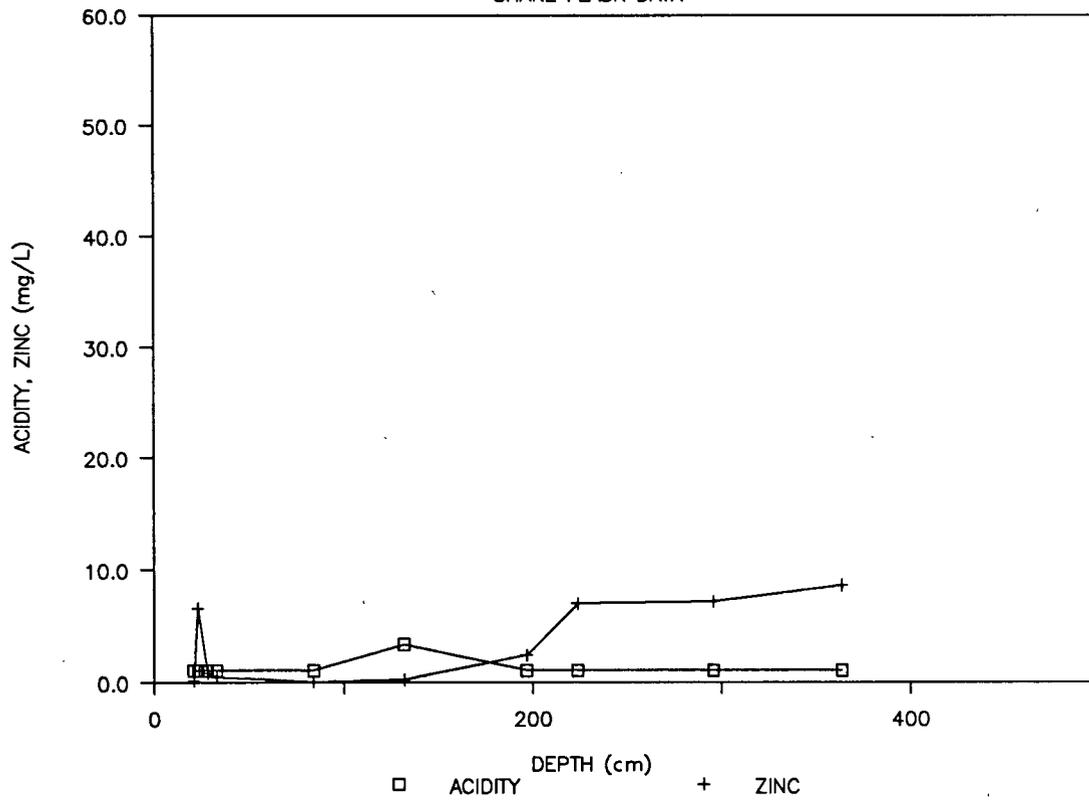
SHAKE FLASK DATA



Series g (cont'd)
EMERGENCY POND - EP1
SHAKE FLASK DATA



EMERGENCY POND - EP2
SHAKE FLASK DATA



**LINDA M. BROUGHTON
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