SUMMARY NOTES
MEND WORKSHOP
"Managing Mine Wastes in Permafrost Zones"

University of Alberta
Edmonton, Alberta
May 5, 1997

This workshop was presented and sponsored by
Falconbridge Limited
University of Alberta
and
MEND Secretariat

May 8, 1997

May 8, 1997

Participant;

The MEND Prediction and Monitoring Committee would like to take this opportunity to express our appreciation for your participation in the recent MEND workshop held in Edmonton May 5, 1997. The workshop, *"Managing Mine Wastes in Permafrost Zones"*, was a success primarily due to the high degree of interest and involvement by the participants. The comments on specific gaps in technology will be used by the MEND Secretariat to assist for formulating the requirements for post-MEND research in northern climates.

We also appreciate your suggestions for additional topics, and for ways of making these technology transfer sessions more effective.

A summary of the panel discussion is provided in Section 2. Copies of the presentations and in some cases additional technical materials are included in Section 2.

If you have any questions or require further information, please do not hesitate to contact me.

Sincerely,

Carl Weatherell

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2. SUMMARY OF OPEN DISCUSSION

An open discussion on current practice and priorities for future research on the issue of permafrost to manage mine wastes was held at the end of the workshop. Grant Feasby initiated the discussion by summarizing the information presented during the day and indicating the areas where substantial uncertainty remains. These comments are detailed in section 3.11 and capture the essence of the discussion.

In summary, although engineered structures incorporating permafrost have been used successfully for mine waste control, there is a lack of fundamental knowledge pertaining to the geochemical aspects of the behaviour of mine wastes in northern environments. A number of competing factors need to be studied to fully understand the fundamentals of mine waste oxidation at low temperatures. Technical issues yet to be resolved include:

1. Oxidation kinetics at low temperatures;
2. Unfrozen water in tailings;
3. Freezing point depression by process chemicals;
4. Thermal effects of oxidation at low temperatures; and
5. Effective covers in permafrost zones.

Future areas of research should focus on addressing the issues above.

3. PRESENTATION OVERHEADS

3.1. INTRODUCTION TO WORKSHOP

Carl Weatherell
MEND Secretariat

MANAGEMENT OF MINE WASTES IN PERMAFROST ZONES

A MEND Workshop

May 5, 1997

Objectives

- ☐ To present and discuss currently available knowledge on managing mine wastes in permafrost zones;
  - ■ AMD focus
- ☐ To identify knowledge gaps that need to be filled.

Program

- ☐ Introduction
- ☐ Operator Experience
- ☐ Research Results
- ☐ Discussion - Practice, Requirements, Priorities

Coming Attractions

- ☐ Fourth International Conference on Acid Rock Drainage

  "Application of Technology"

  May 31-June 6, 1997

- ☐ Visit MEND on Internet

  www.nrcan.gc.ca/mets/mend

3.2. OVERVIEW OF MEND

Grant Feasby
MEND Secretariat

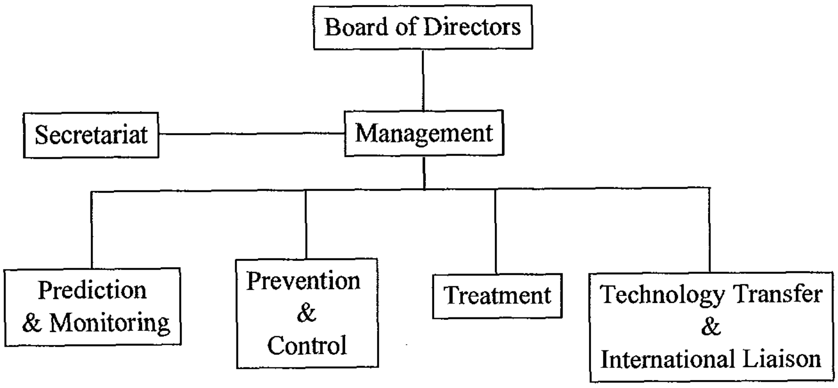
Mine Environment Neutral Drainage (MEND)

- A 9-year cooperative research program, financed and managed by three partners
- 1997 is 9th and final year
  - New initiative under discussion
  - Better prediction tools
  - Cold weather environments

MEND is composed of..

- 20 companies, 5 provinces, Canada
- $18 million, tripartite funding
- Volunteers
- Defined program for technology development

MEND Organization



Funding

- Initial commitment
  - 1/3 Industry, 1/3 Canada, 1/3 (5) Provinces
- Annual plan and budget
- Project-by-project basis buy-in
- To date approximately $16 million spent

What was Needed

- ☐ **Reduction in liability associated with acidic drainage**

What was Needed

- ☐ More accurate prediction techniques
- ☐ Cheaper closure methods for tailings and rock and mine sites
- ☐ More site-specific options
  - ■ new mines without acid
- ☐ Cheaper, widely applicable monitoring tools

MEND Results

- No magic bullets
- Prevention best strategy
- Existing sites:
  - reduce, treat, monitor
- New mines
  - underwater disposal
  - “walkaway” possible

Some of MEND successes

- Buy-in by stakeholders
  - commitment to technology only
  - mining industry shares results
  - full disclosure
- Volunteer participation

Other MEND Successes

- Governments working **with** industry
  - *decision-makers at the table*
- Expertise widely available
- New mines opening without AMD
- Major reduction in liability

Unfinished Business and Challenges

- Better science for acid generating waste rock
  - Predictive methods - acid/no acid, rate, onset
  - Delay of onset of acid
- **Walkaway** technology for old tailings areas
- Control of AMD in mine openings
- Reduce the mountain of information

Post MEND

- ☐ Retain network and expand to include international expertise
- ☐ Monitoring & Reporting Results
- ☐ Non-acid Issues

MEND

A Successful Canadian Enterprise

3.3. SUMMARY OF MEND STUDY - STATE-OF-THE-ART

Richard Dawson
Norwest Mine Services

NORWEST

AN OVERVIEW OF PERMAFROST FOR ARD CONTROL

RICHARD DAWSON
NORWEST MINE SERVICES

OUTLINE

-BACKGROUND

- ISSUES

- CONTROL STRATEGIES

- RESEARCH REQUIREMENTS

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Figure 1.1 Canada's Northern Permafrost Regions

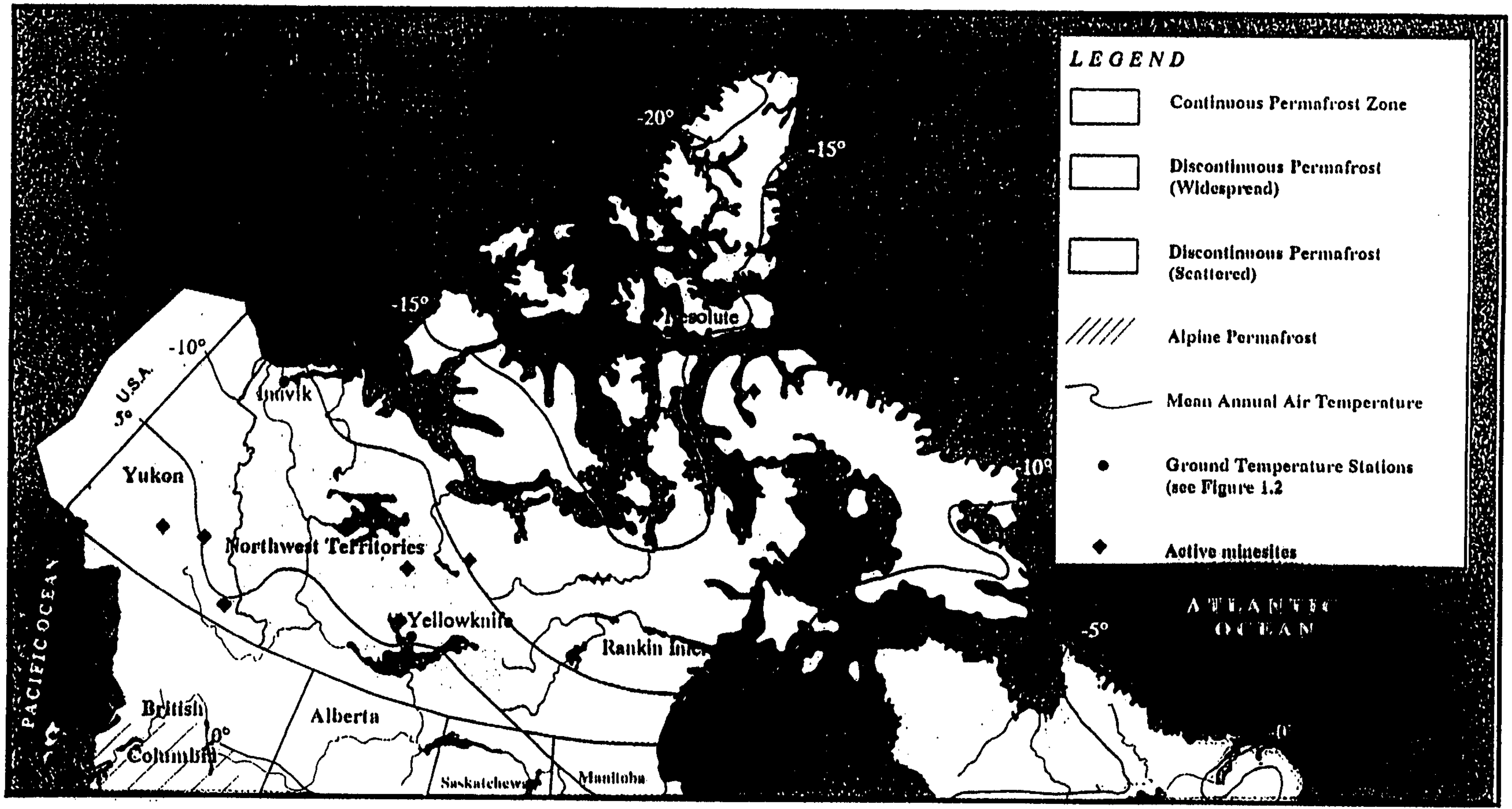
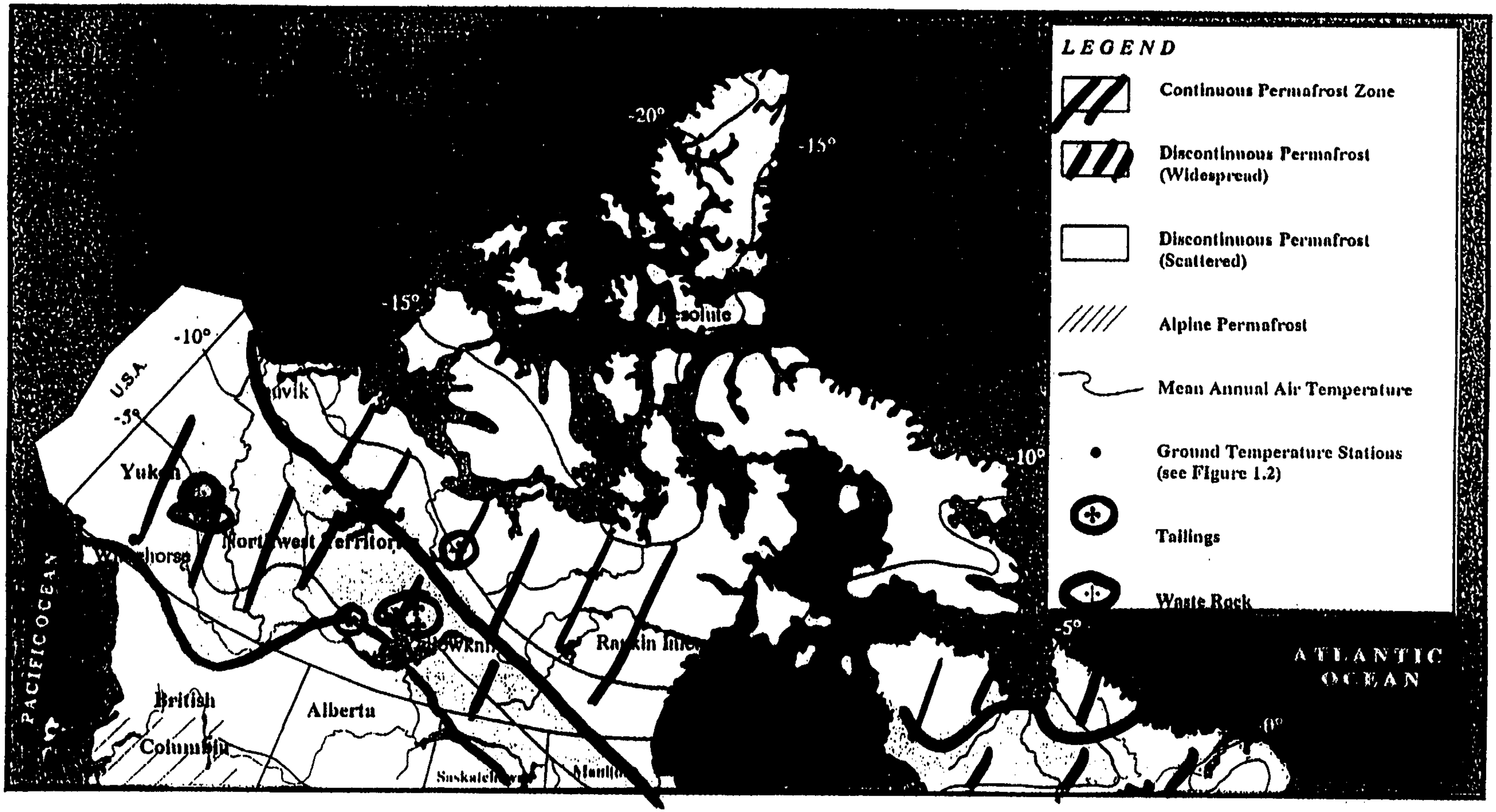


Figure 2.1 NWT and Yukon Minesites Exhibiting Acid Mine Drainage



NORWEST

COLD TEMPERATURE ARD ISSUES

- FREEZE AND THAW RATES
- OXIDATION RATES
- UNFROZEN WATER
- FREEZING POINT DEPRESSION

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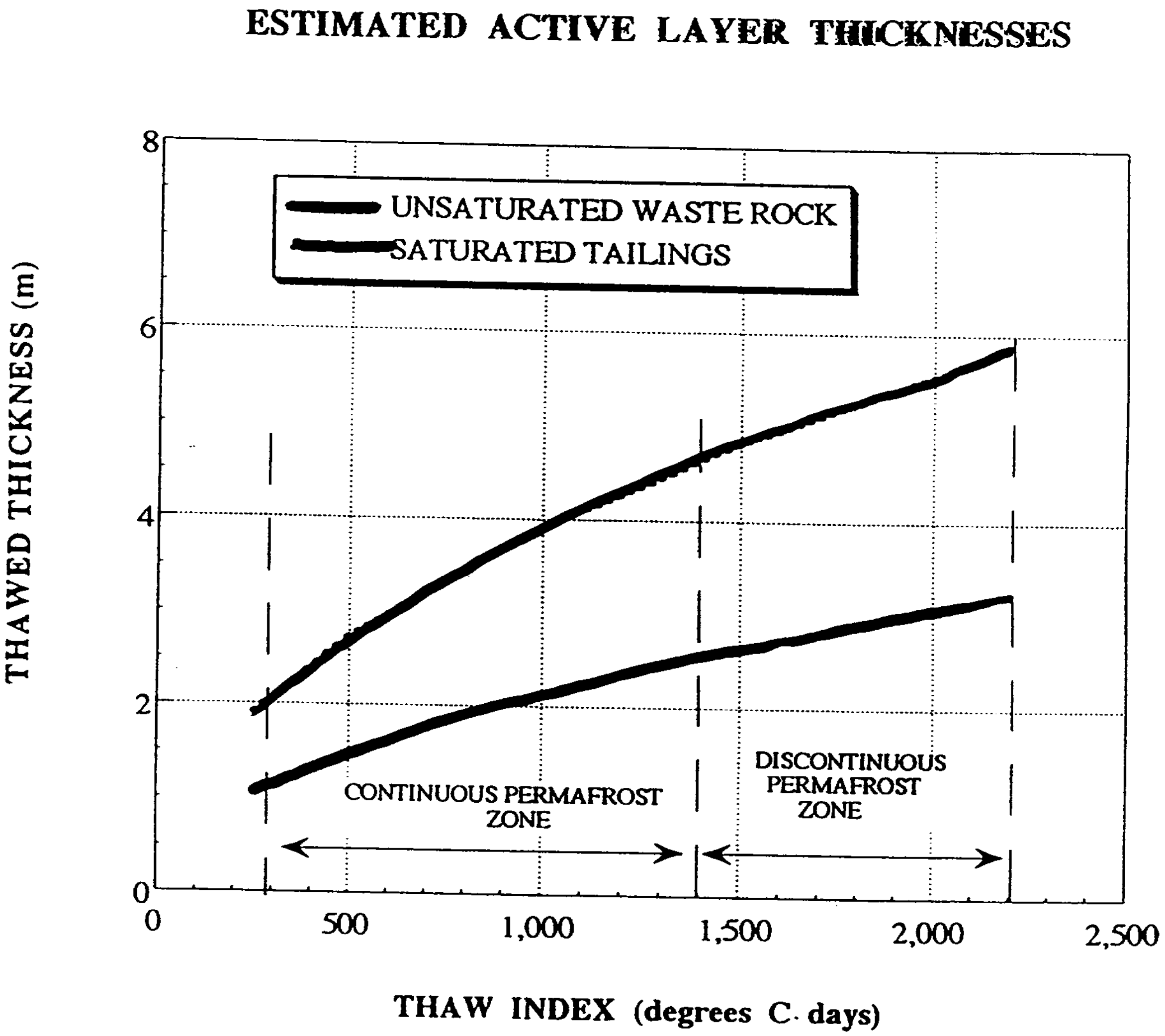

Figure 4.1: Seasonal Thawing Thickness for Mine Waste in Permafrost Regions

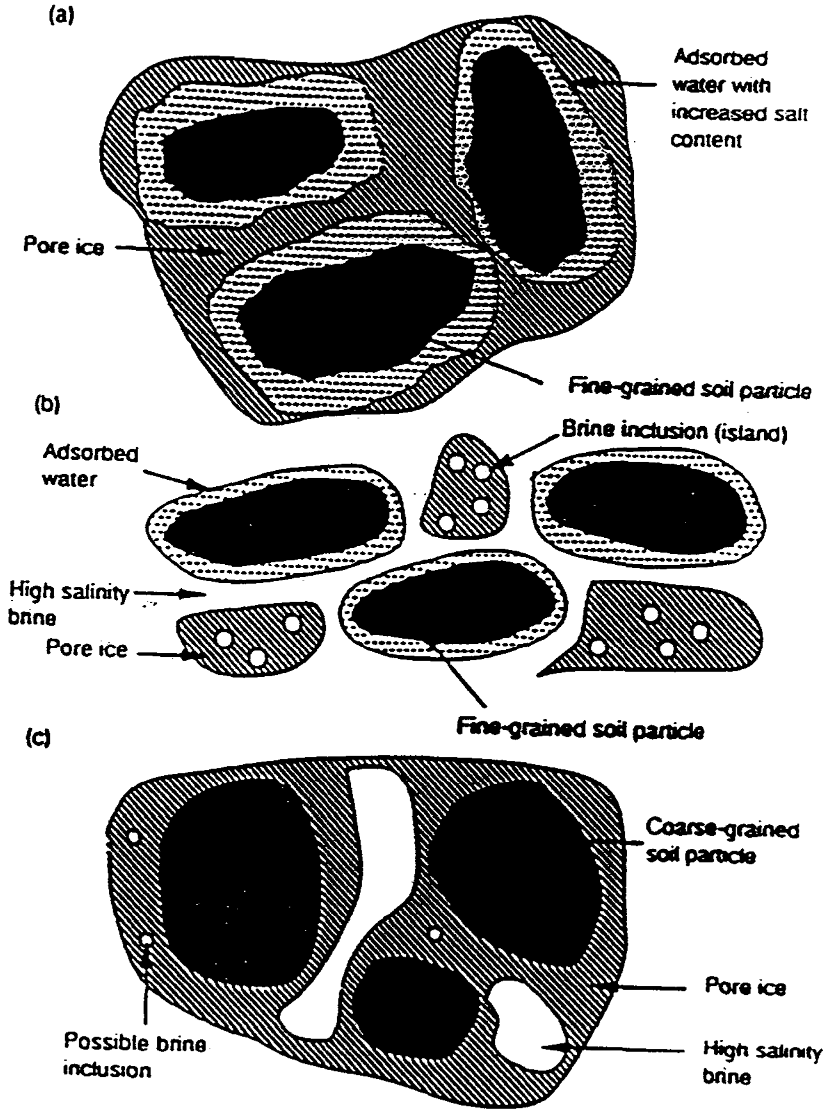

Figure 3.5 Distribution of Unfrozen water in frozen soils.
(a) Low salt concentration pore fluid in fine - grained soil.
(b) High salt concentration pore fluid in fined - grained soil.
(a and b) following Sheeran and Yong (1975).
(c) High salt concentration pore fluid in coarse - grained soil.

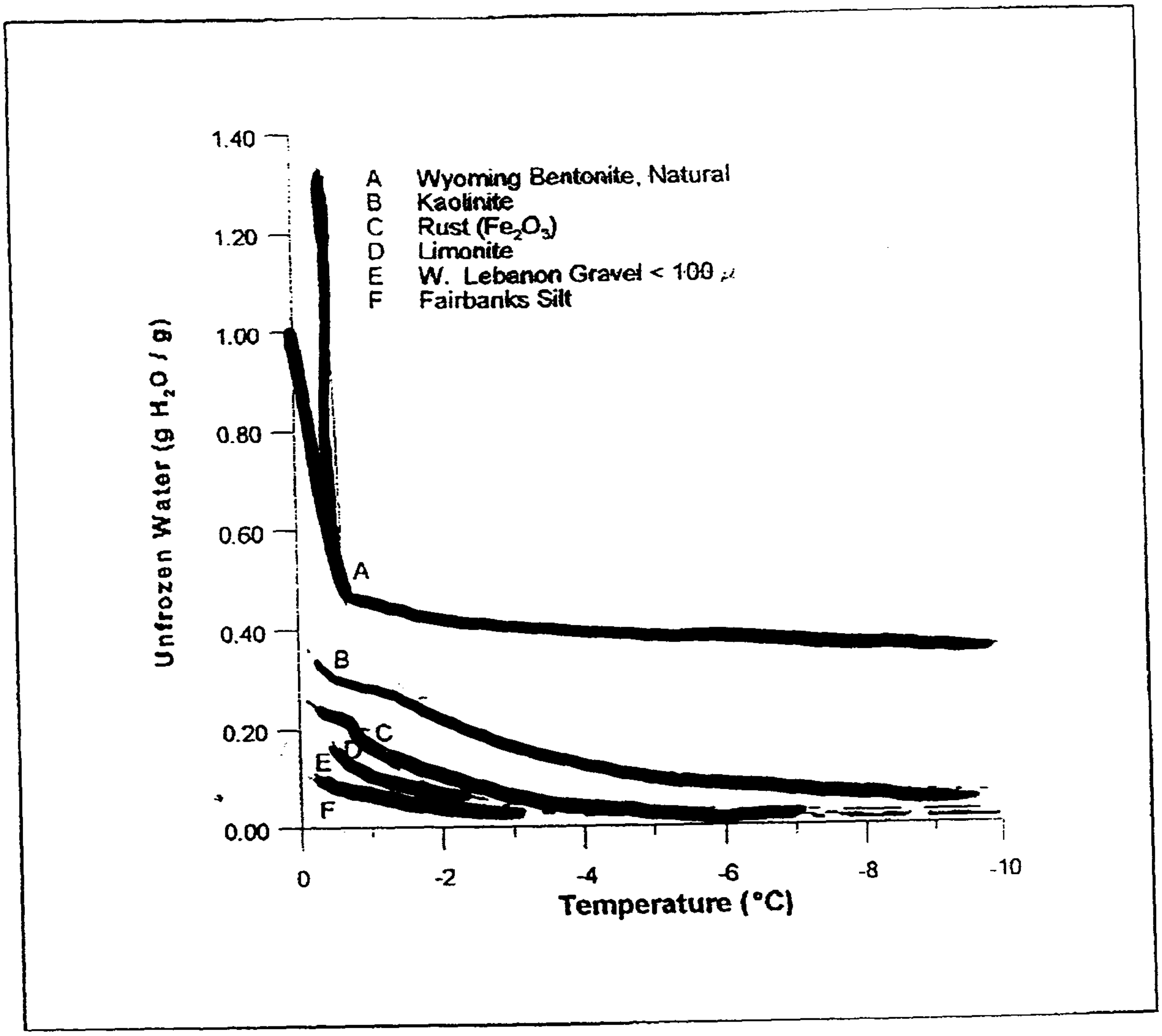

FIGURE 3-4. Unfrozen Water Content vs. Temperature (from Anderson and Morgenstern, 1973).

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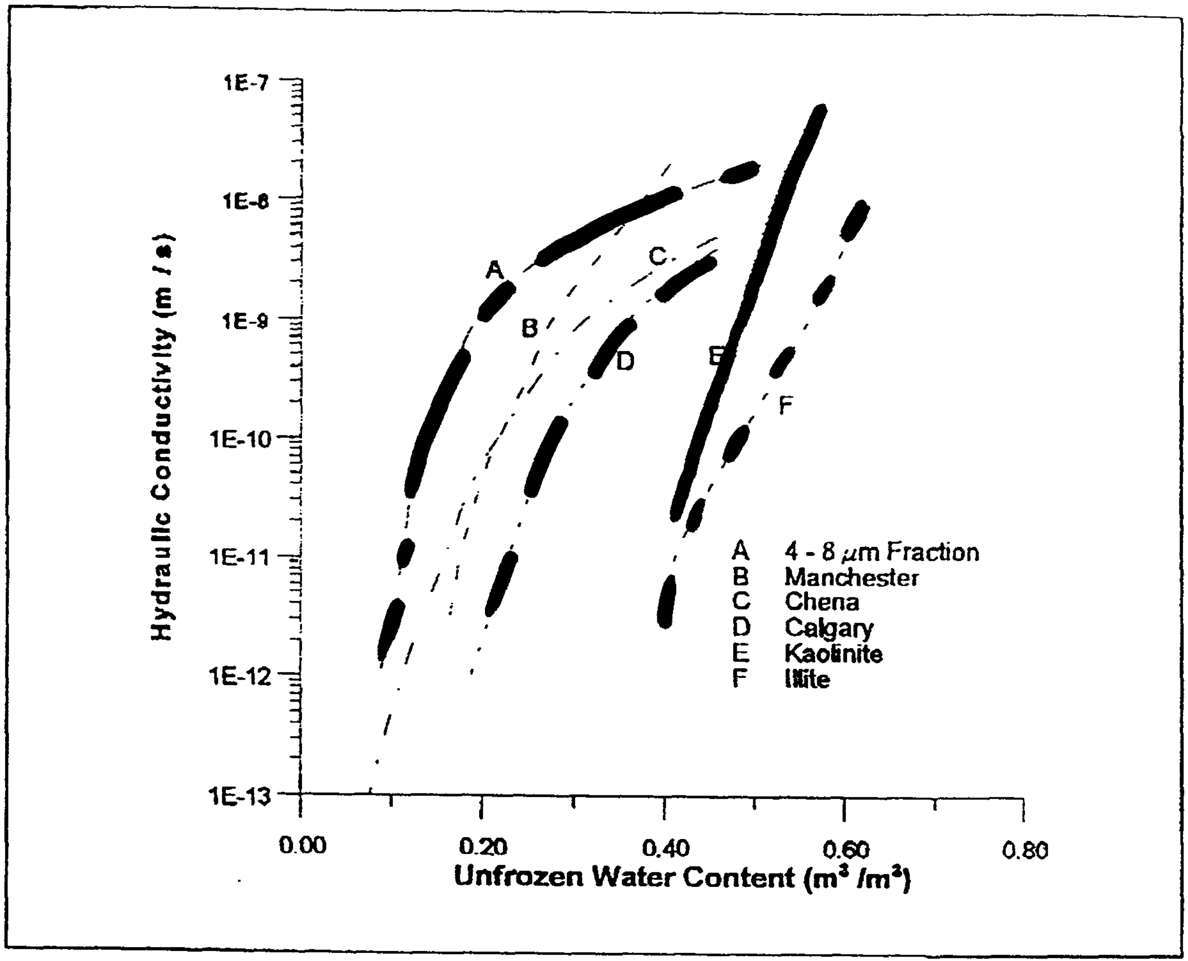


FIGURE 3-6 Frozen Hydraulic Conductivity vs. Unfrozen Water Content (after Horiguichi and Miller, 1983).

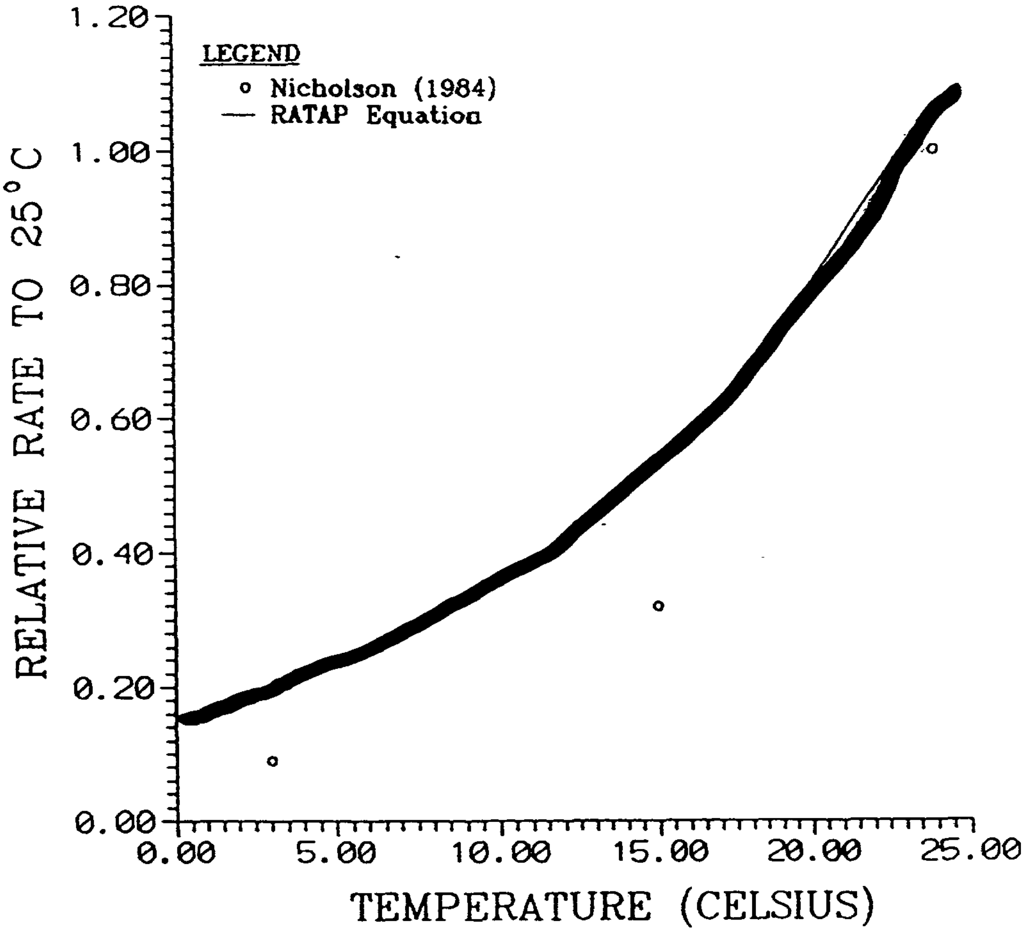


Figure 3.2: Relative Rate of Chemical Oxidation versus Temperature (adapted from Senes, 1991)

NORWEST

CONTROL STRATEGIES FOR TAILINGS

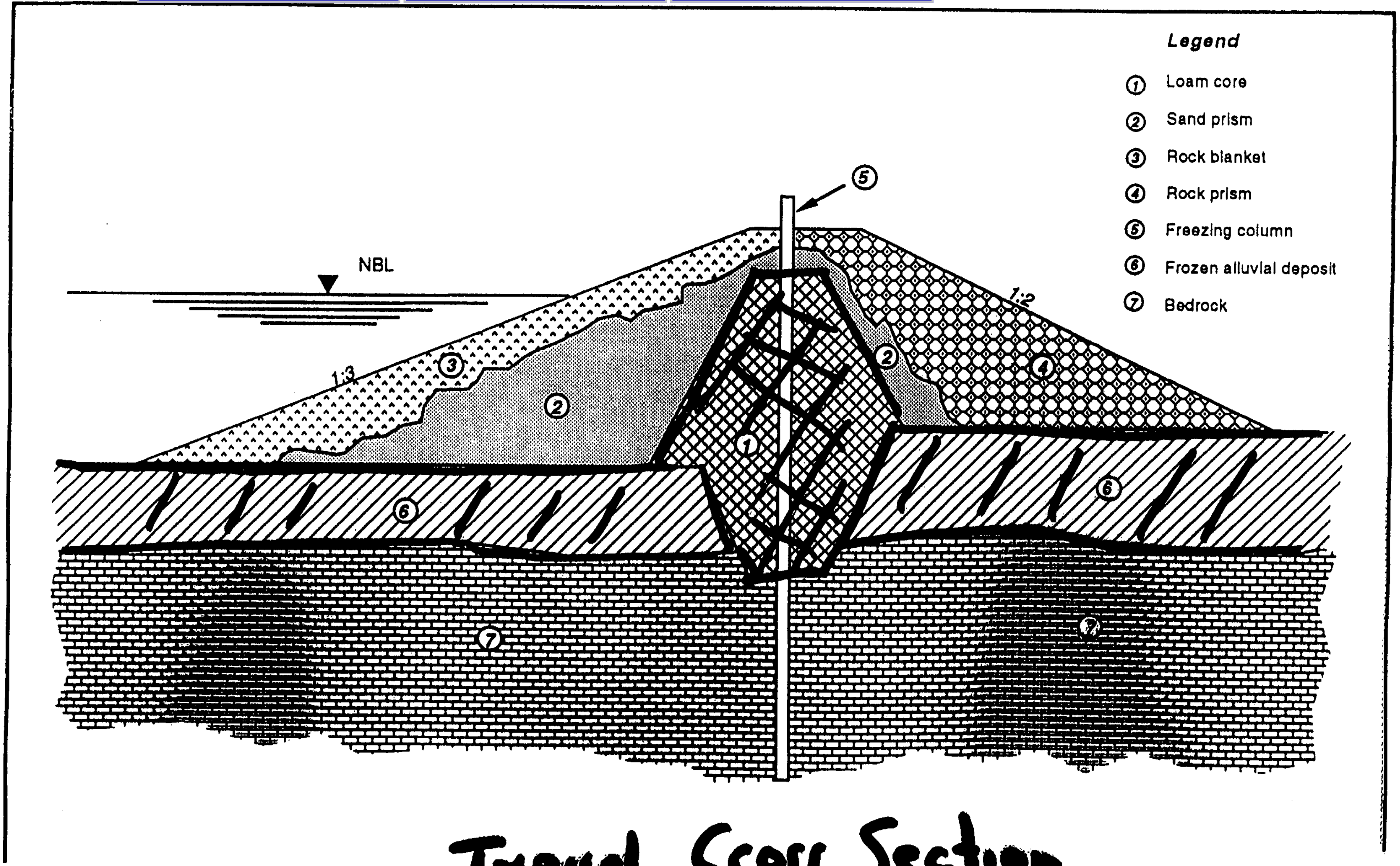
*1. FREEZE CONTROLLED**

- *PERIMETER FREEZING*
- *TOTAL FREEZING*

*2. FREEZE-THAW DEWATERING**

3. ENGINEERED COVERS
4. SUBAQUEOUS DISPOSAL
5. COLLECTION AND TREATMENT
6. SEGREGATION AND BLENDING

**UNIQUE TO COLD CLIMATES*



Typical Cross Section of Frozen Core Dam

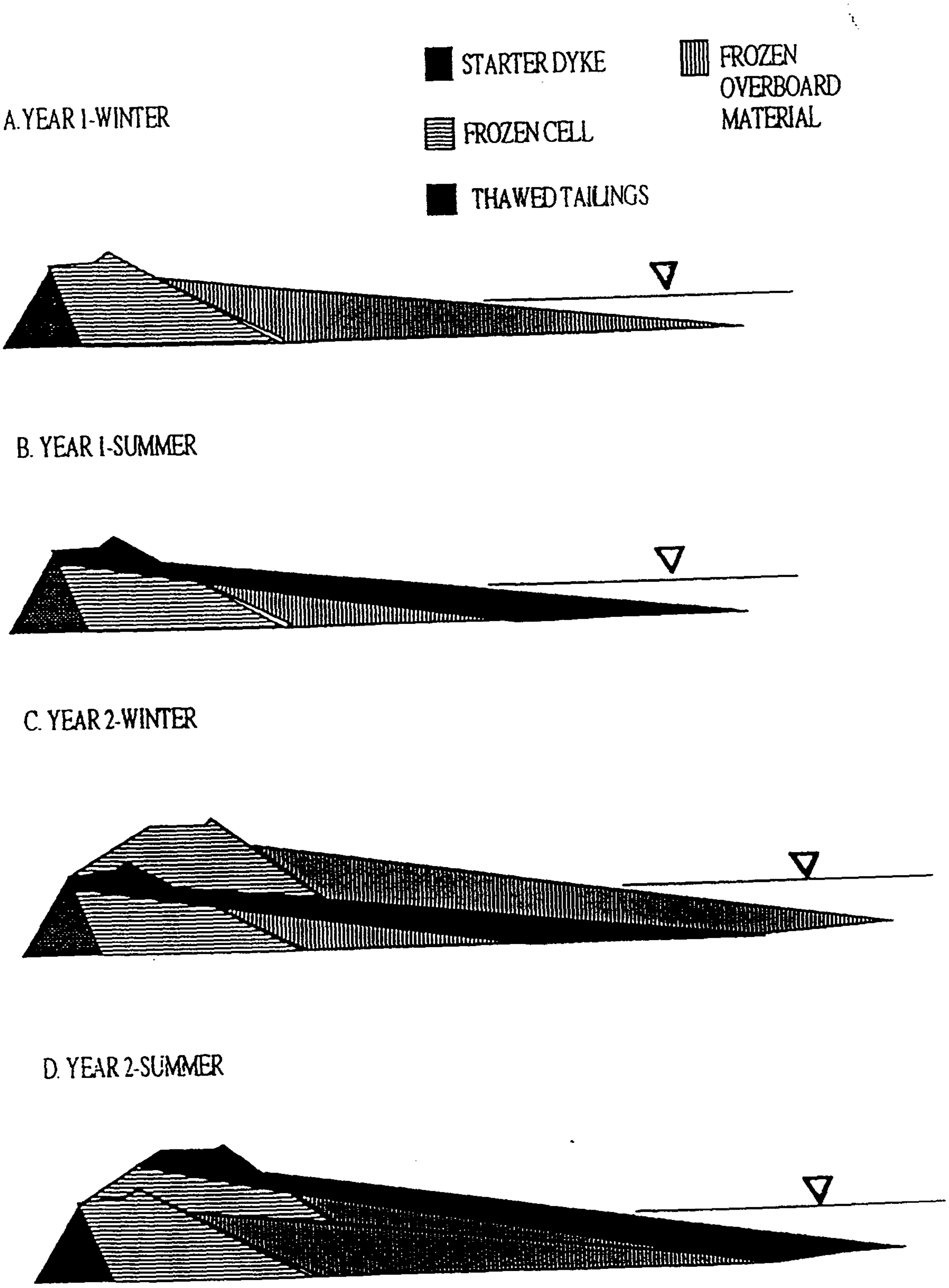


Figure 4.4: Tailings Thin Layered Freezing Design Concept

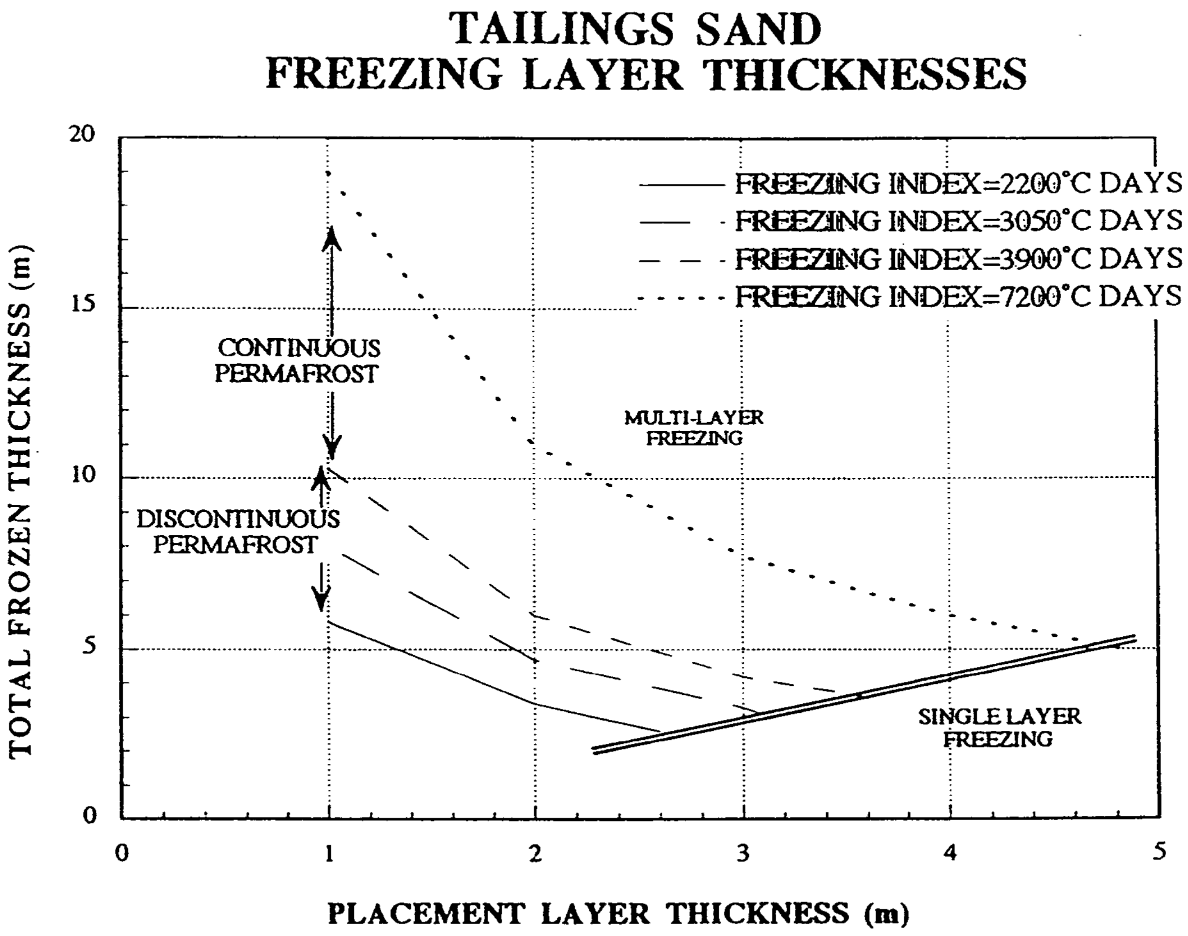


Figure 4.3: Tailings Sand Freezing Layer Thicknesses

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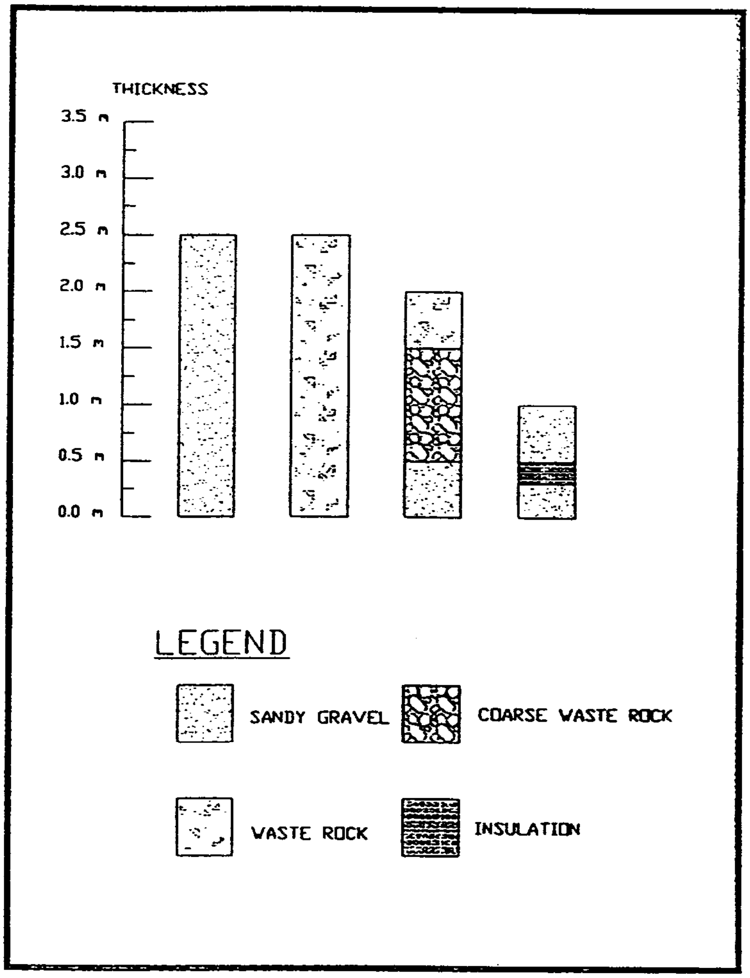

Figure 4.2: Insulating Cover options for Total Freezing in Continuous Permafrost Regions (after MEND 6.1, 1993)

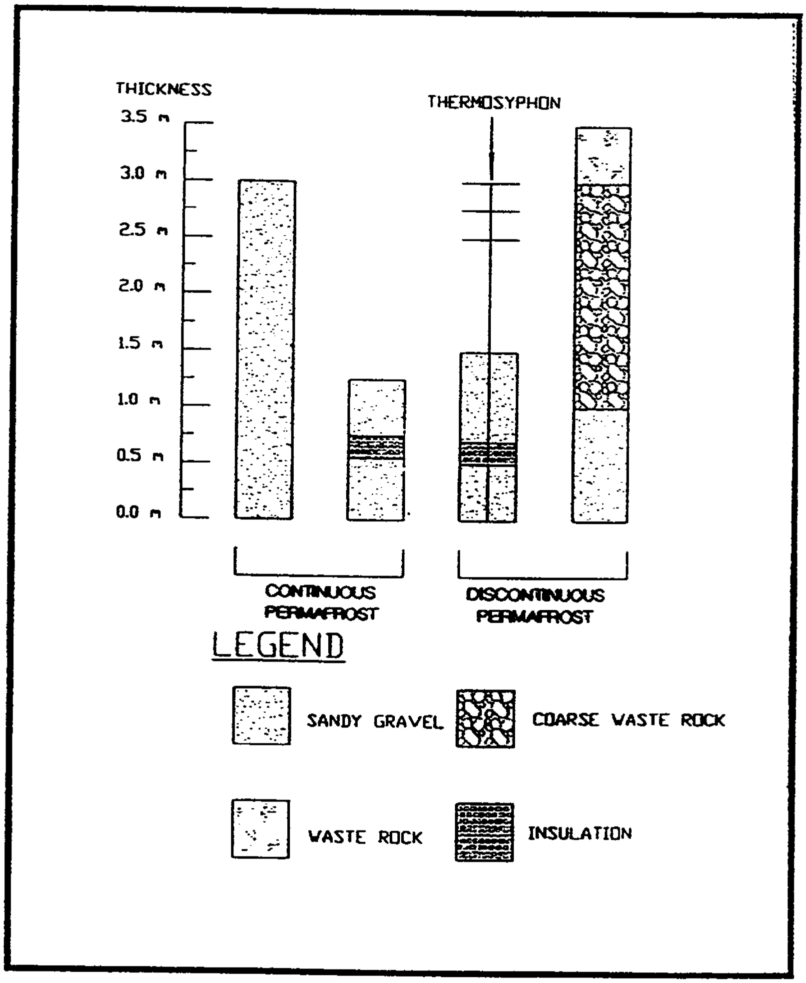

Figure 4.5: Insulating Cover Options for Perimeter Freezing (after MEND 6.1, 1993)

NORWEST

CONTROL STRATEGIES FOR WASTE ROCK

*1. FREEZE CONTROL *- layered freezing*

2. CLIMATE CONTROL- segregation and zoning*

3. ENGINEERED COVER

4. COLLECTION AND TREATMENT

5. SEGREGATION AND BLENDING

**COLD WEATHER STRATEGIES*

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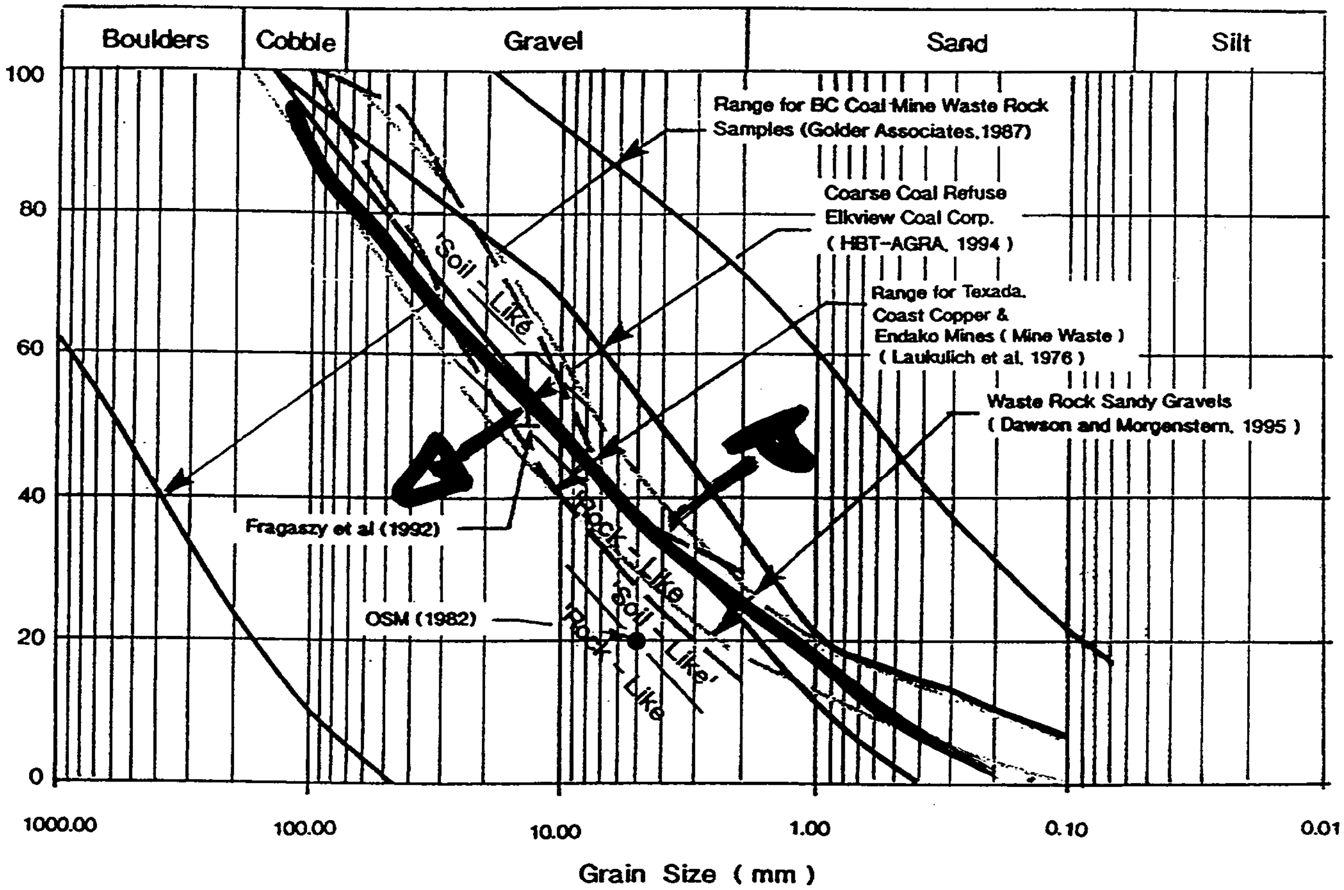


Figure 4.6: Typical Grain Size Distributions of Waste Rock Materials

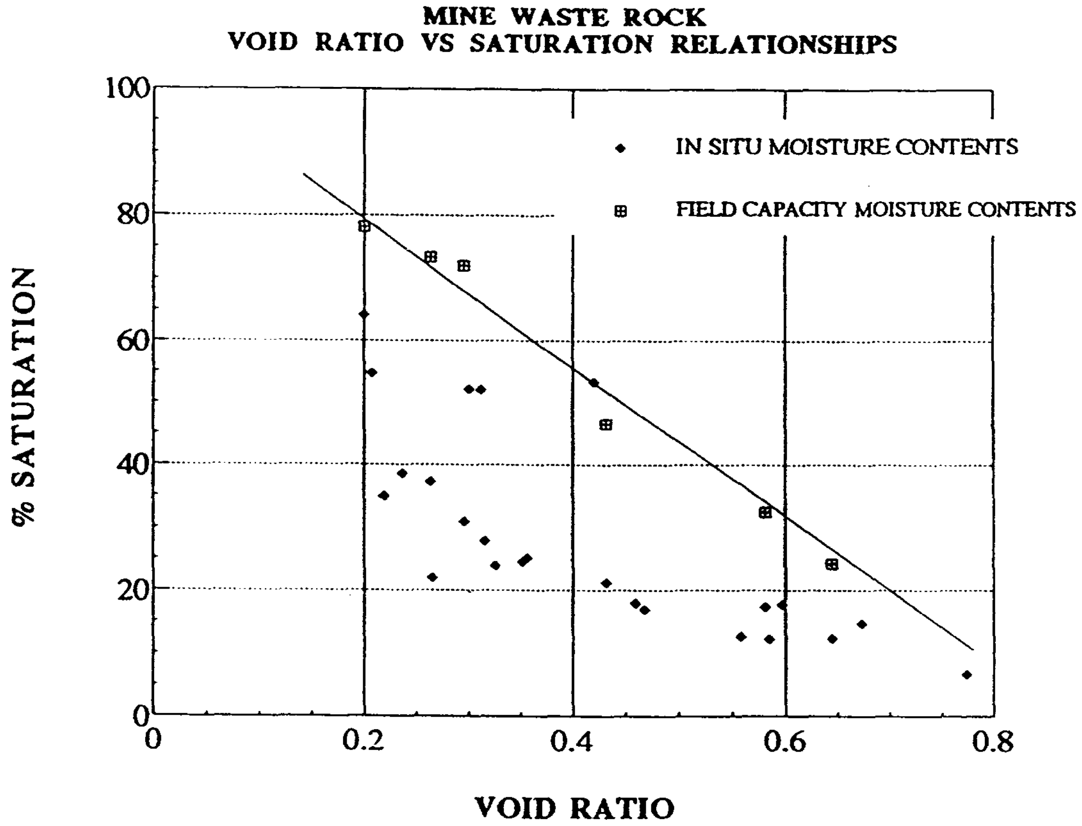
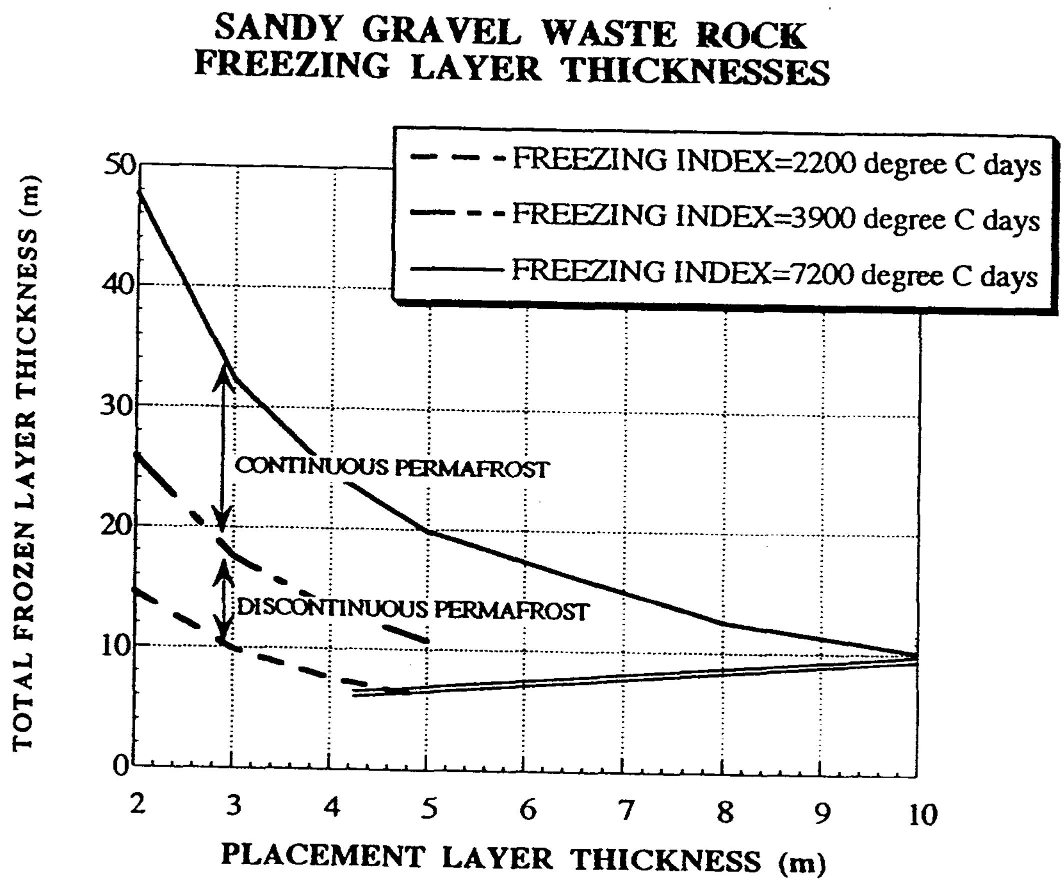


Figure 4.7: Saturation Relationships for Sandy Gravel Mine Waste Rock Materials



SANDY GRAVEL WASTE ROCK
FREEZING LAYER THICKNESSES

Figure 4.8: Sandy Gravel Waste Rock Freezing Layer Thicknesses

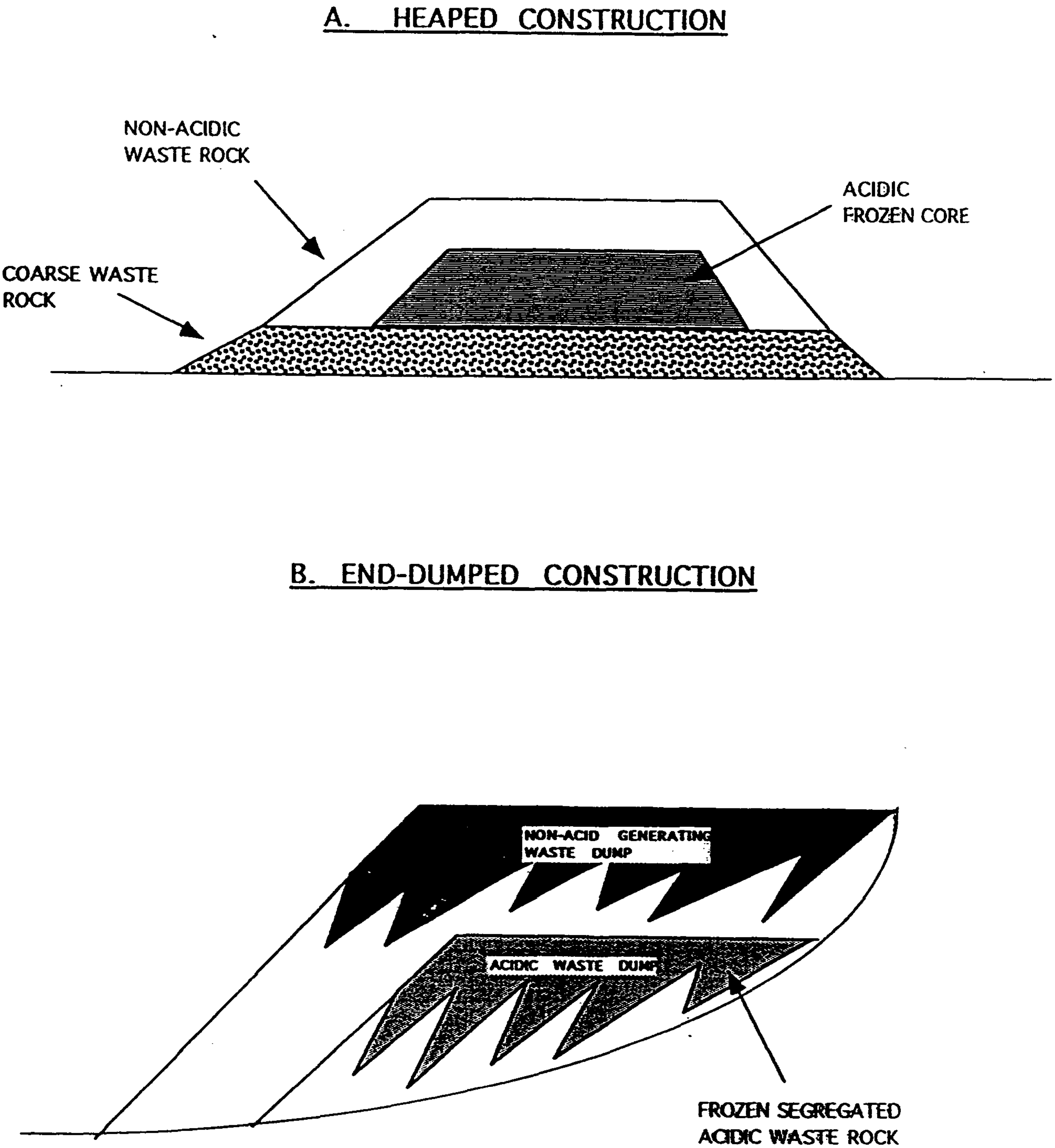


Figure 4.9: Freeze Controlled ARD Control Strategies for Waste Rock

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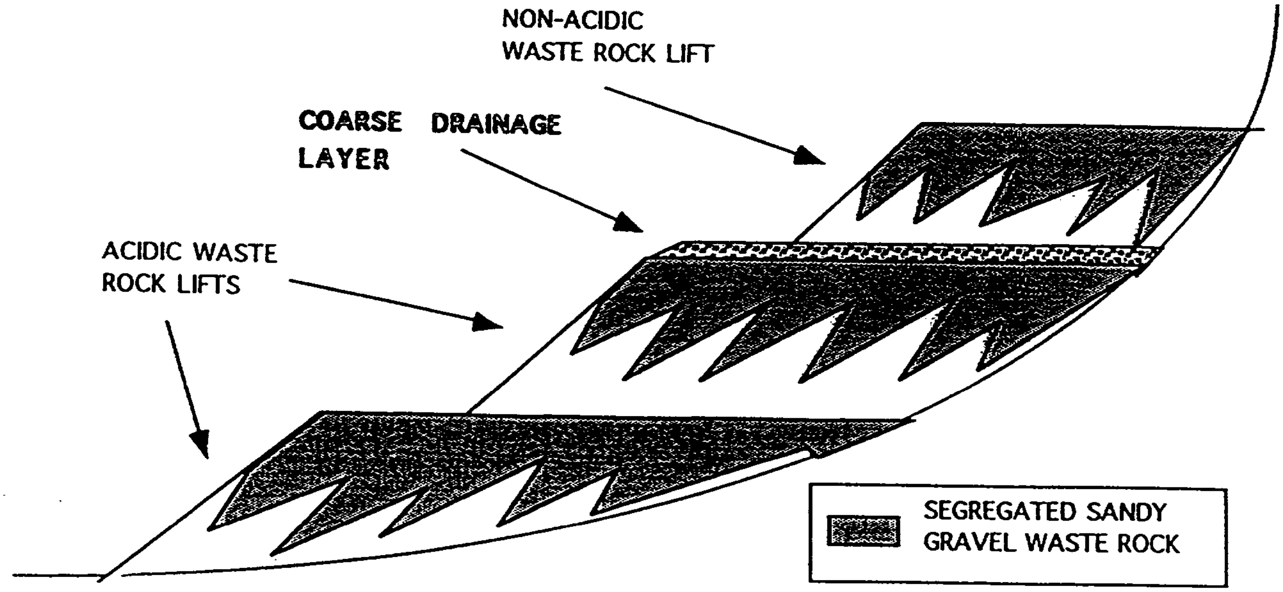
A. CONSTRUCTION CONFIGURATION



B. RE-SLOPED CONFIGURATION

NOTE: RE-SLOPING OF FINER SANDY GRAVEL WASTE SERVES TO REDUCE AIR FLOW THRU BASE OF PILE. COARSE DRAINAGE LAYER BENEATH NON-ACIDIC UPPER LIFT LIMITS INFILTRATION INTO ACIDIC WASTE

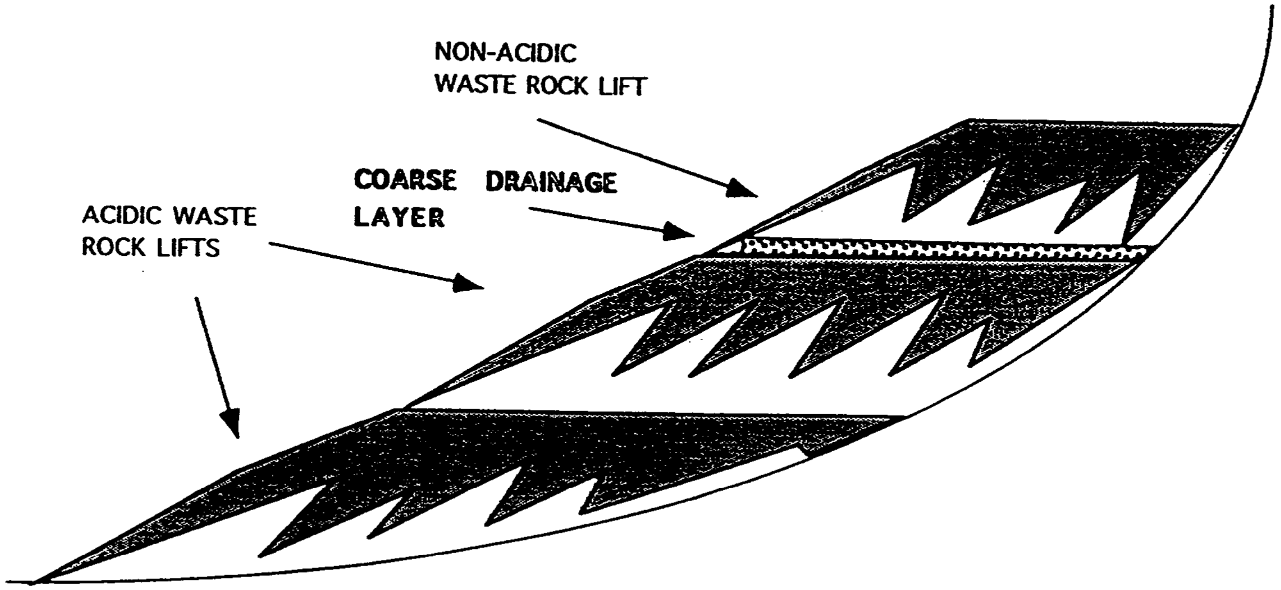


Figure 4.10: Climate Controlled ARD Strategy for Terraced End-Dumped Construction

NORWEST

RESEARCH AND DEMONSTRATION REQUIREMENTS

- FREEZING POINT DEPRESSION DUE TO PROCESS CHEMEICALS

- ECONOMIC INSULATING COVER DESIGNS

- WATER AND HEAT TRANSFER IN WASTE ROCK DUMPS

3.4. ECHO BAY - LUPIN MINE

Rick Nutbrown
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Introduction

The Lupin Operation is an underground gold mine on the west shore of Contwoyto Lake, about 400 km northeast of Yellowknife and 80 km south of the Arctic Circle. The deposit was discovered in 1960 by the Canadian Nickel Company, a subsidiary of INCO Ltd. Between '61 and '64, Canadian Nickel conducted exploration at the site including geological mapping, geophysical surveying, trenching, stripping and channel sampling. The site was purchased by Echo Bay Mines from INCO in the late 70s, and initiated an underground exploration program in 1979. The information gained from this program indicated enough ore reserves to provide six years of production at a mill processing rate of 950 tons per day. In August of 1980 the decision was made to proceed with development and construction of the mine. Commercial production began in 1982.

The mineralogy of the ore at Lupin consists mainly of amphibole, quartz, garnet, pyrrhotite, arsenopyrite, minor pyrite and trace chalcopyrite. The gold is fine grained, generally less 100 microns in diameter and is associated mainly with pyrrhotite and arsenopyrite. Although not common, visible gold has been reported, usually in close proximity to quartz veining.

The ore at Lupin has been shown through various studies to be capable of generating acid upon oxidation. The waste rock produced in the mining process contains very little sulphur (about 0.5%) and is considered to have very little potential of acid production.

In regards to site facilities, other than the transportation requirement for materials and supplies necessary to sustain the workforce and industrial operation, the Lupin site is completely self contained. The two main complexes on the site are the kitchen/residential/accommodation buildings and the industrial complex which includes the mill and various maintenance areas, the headframe, powerhouse, and warehouse areas and office facilities. Associated with the two complexes mentioned are support areas consisting of shops and various yards, cold storage buildings, explosives magazines, tank farms, the sewage facilities, the landing strip and aircraft control office, the mill tailings line and the tailings containment area.

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Mining

As I mentioned, Lupin is an underground mine. Presently, the bottom of the mine is at about 1300 metres. Equipment employed includes diesel scoop trams and haul trucks and electric/hydraulic drilling equipment. Production is accomplished through a process of drilling, blasting and mucking. Broken ore is hauled to ore passes where it is put through a rock breaker to reduce the amount of oversize material, and routed to the skips for transport to the surface for milling.

Milling

The ore brought from underground is stored in a 600 ton coarse ore bin. From the coarse ore bin, the ore is fed through cone crushers to two 1000 ton capacity fine ore bins. The fine ore is then fed into the grinding circuit, first through a rod mill then two ball mills in a parallel configuration. The discharge from the ball mills is classified using hydrocyclones. The underflow from the cyclones, +200 mesh or coarse material, is fed back to the ball mills, while the overflow from the cyclones, -200 mesh or fine material, is pumped to the pre-aeration circuit.

The -200 mesh material enters pre-aeration thickener for settling of the solid fraction. The overflow solution from this thickener is returned to a recycle water tank while the underflow slurry is pumped to the first of three pre-aeration tanks. These pre-aeration tanks provide air to oxidize the sulphide minerals which would otherwise consume large amounts of cyanide later in the milling process as well as increasing the risk of the formation of acid rock drainage in the tailings containment area. The pre-aeration circuit operates under alkaline conditions and has a lead nitrate reagent added and is diluted with recycle water.

Slurry from the pre-aeration circuit is pumped to a series of six agitated and aerated tanks where the gold is leached with cyanide. The gold particles are dissolved by a reaction between the cyanide, oxygen and water. Lime is used to maintain the system pH at about 10. After approximately 30 hours of retention, the slurry is transferred to the cyanidation thickener for separation of the solid and liquid fractions. The liquid fraction is known as the pregnant or gold bearing solution and is routed to the pregnant solution tank. The underflow slurry, which also contains some gold is pumped to the filtration circuit.

A two stage filtration system separates the dissolved gold from the solids by washing with barren or non-gold bearing solution. Each of the two stages consists of four vacuum drum filters. The slurry is retained on the outside of the filter unit while the solution is drawn through, taking the dissolved gold with it. The filter cake from the filtration circuit is either repulped and pumped out to the tailings containment area or transferred to the paste backfill system for placement underground.

The pregnant solution is processed through three pressure clarifiers to remove fine suspended solids. Oxygen is then removed in a de-aeration or Crowne tower prior to precipitation. Zinc dust is added to precipitate the gold which is collected in the precipitation presses. Once the press becomes loaded with precipitate, it is transferred to the refinery. The precipitate is smelted in the bullion furnace to produce dore bullion and slag. The slag is returned to the mill to be reprocessed. The bullion contains approximately 85% gold and 12% silver, the remaining impurities being base metals.

Paste Backfill

The first method of mine waste management that I will briefly talk about is paste backfill. As I mentioned earlier, the solids collected on the vacuum filters are either repulped and pumped to the tailings containment area or used as backfill underground. In general, the paste formed is a high density mixture of water and the fine filter solids. Cement is added to the mixture and it is pumped underground through a pipeline to inactive mine voids or to active stopes. In 1997, we expect to dispose of 50-60% of the tailings solids produced through the paste backfill operation.

Tailings Containment Area

The use of the tailings containment area is the second method of mine waste management used at Lupin. Any tailings solids not disposed of underground and all excess waters from the milling process are handled at the tailings containment area. The slurry is pumped from the mill to the TCA through an insulated 8" steel pipeline. The TCA is about 6 km south of the minesite and covers 361 hectares within a 750 hectare lease. There are three main components to the TCA, the solids retention cells, Pond 1 and Pond 2.

The tailings slurry pumped from the mill is first dumped into one of the solids retention cells where separation of the liquid and solid fractions occurs. These pictures show the slurry being dumped into an almost full area of the TCA.

At times, the tailings lines are strung out into the cells to fill in low areas of the cells and to avoid creating tailings beaches that are too close to the surface of the internal dams that divide the TCA.

The water is collected in Pond 1 and stored for up to 11 months before it is transferred to Pond 2. Pond 2 also retains the water for up to 11 months before it is discharged to the environment. This long retention period allows natural degradation to reduce the contaminants in the water. Typically, the cyanide concentration is reduced by up to 90% by the time the water is collected in Pond 1. Metals such as Zinc, Nickel and Copper are reduced by 70 to 80% in the first phase of the retention.

Arsenic, on the other hand, is only reduced by about 25%. For this reason, during the transferred from Pond 1 to Pond 2, an iron salt (ferric sulphate) is added to the water to form a stable iron/arsenic precipitate which settles in Pond 2. Lime is also added for pH adjustment.

The TCA is impounded through natural terrain relief and a series of engineered retaining structures. Due to the selection of natural lakes as polishing ponds and the low relief of the surrounding land, the perimeter dams generally vary up to about8 metres in height.

This schematic shows a general cross-section of the dams. The upstream side employs a synthetic liner covered with sand andriprap. The synthetic liner is for initial control of seepage while the frozen core of the dam develops.

Various studies have been initiated over the life of the mine to evaluate the extent of the development of the frozen dam cores as well as the thickness of the active thaw zones in reclaimed sections of the tailings containment area. These reclaimed areas are sedimentation cells that have been filled to capacity with tailings and covered with a layer of esker gravels. The intent of covering the tailings is to form a barrier to prevent the oxygen transfer responsible for the eventual formation of acid rock drainage. As well, the depth of esker cover will be adjusted to place the long-term active thaw zone above the tailings, thereby keeping the tailings in a permanently frozen condition, further reducing the risk of ARD production. The following series of overheads shows the results of some of the ground temperature work undertaken over the past couple of years.

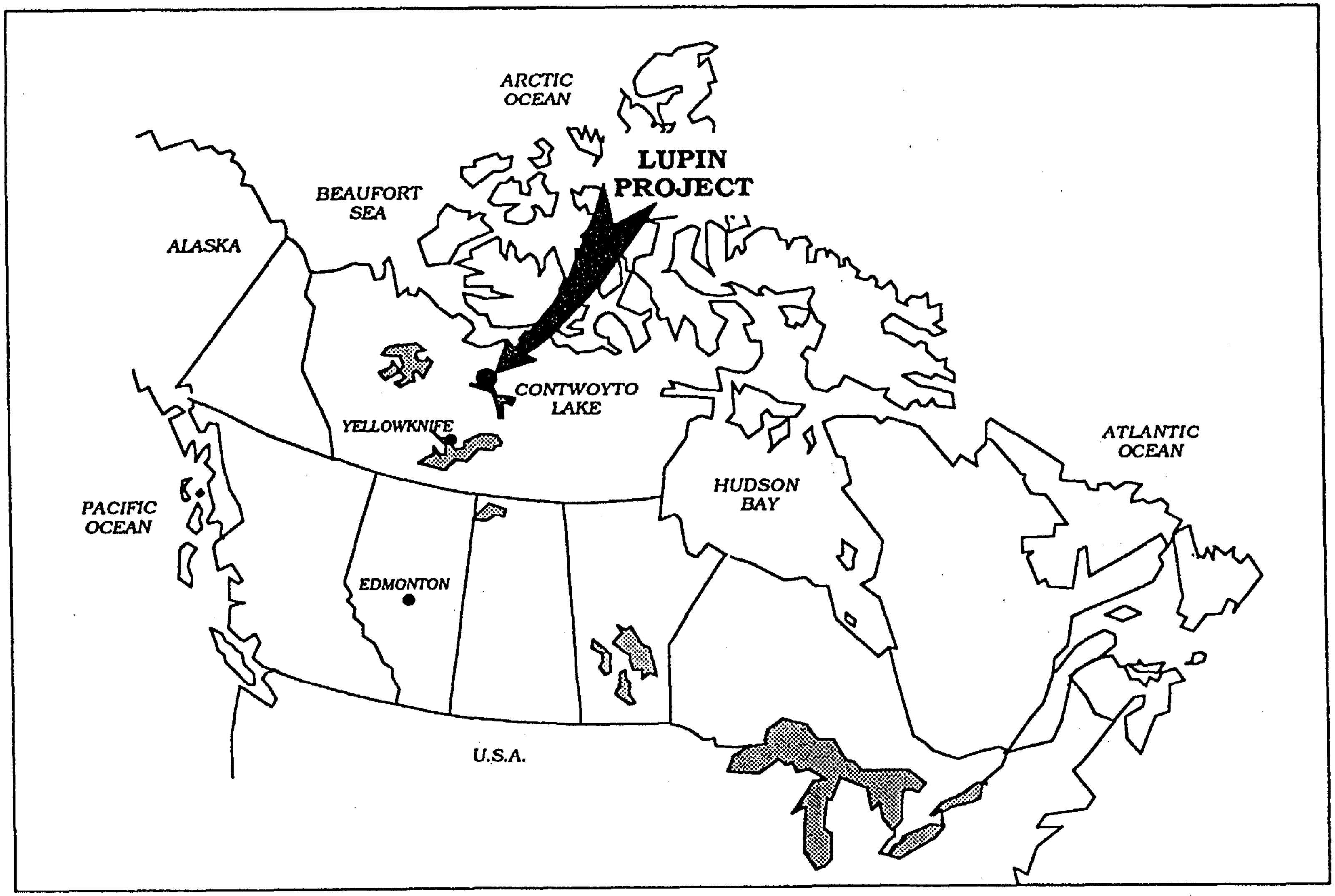
ARCTIC OCEAN
LUPIN PROJECT
BEAUFORT SEA
ALASKA
CONTWOYTO LAKE
YELLOWKNIFE
ATLANTIC OCEAN
HUDSON BAY
PACIFIC OCEAN
EDMONTON
U.S.A.

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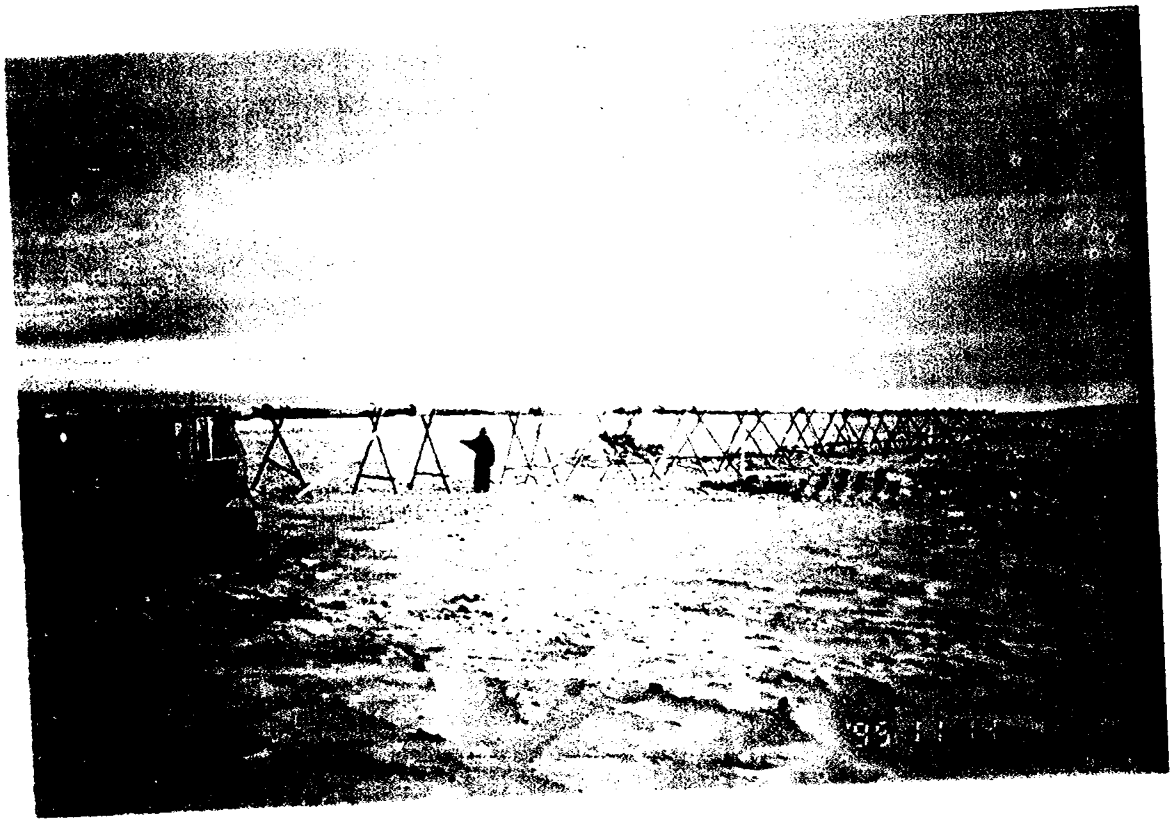
Photo 1 Aerial view of Lupin minesite on 29 June 1993 Note extent of ice cover on waterbodies

Photo 2 Aerial view of Norma Lake (left) and Norma Pond (right) with tailings pond in the background. Photo on 29 June 1993.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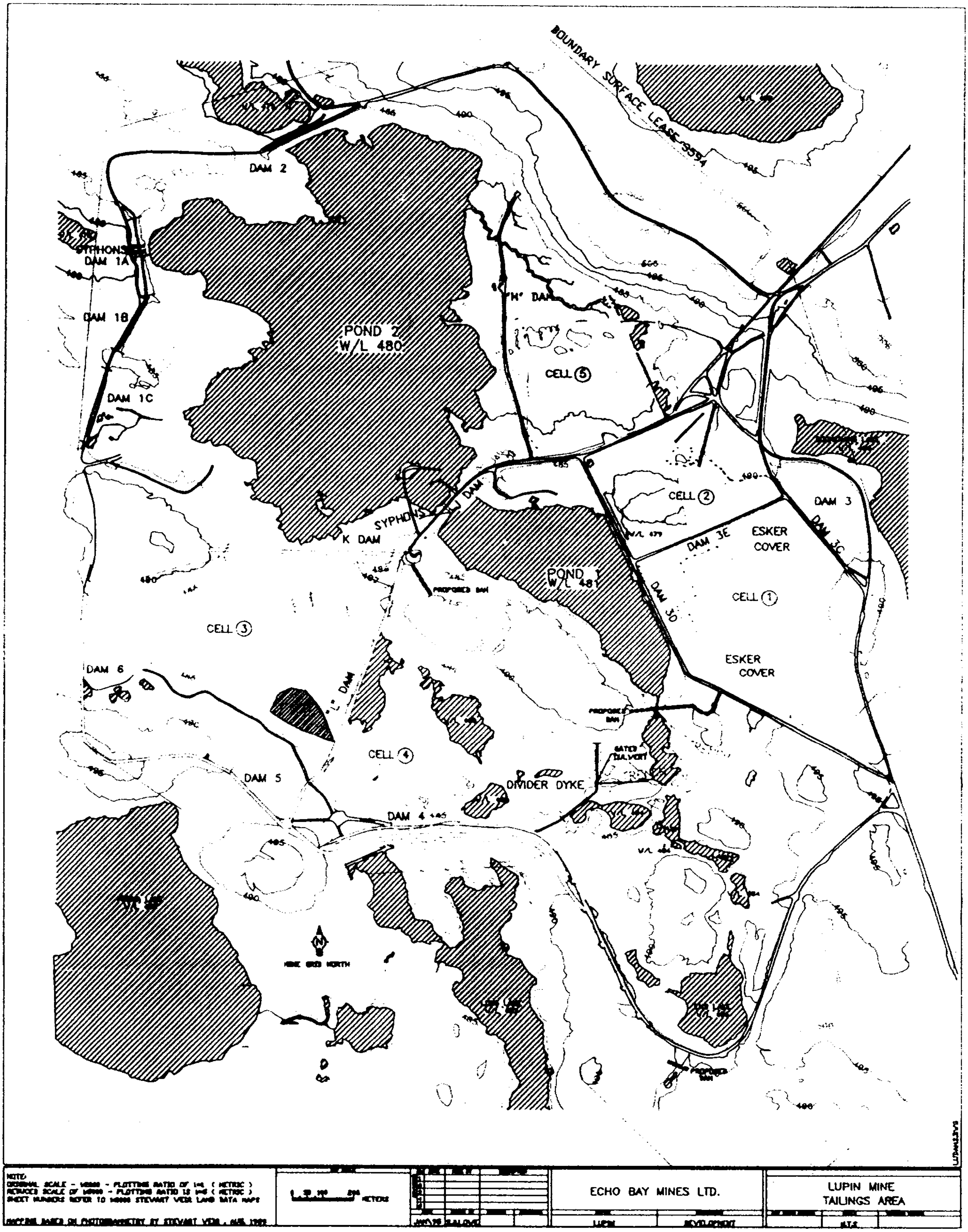

Figure 3; Lupin Mine Tailings Area - 1995

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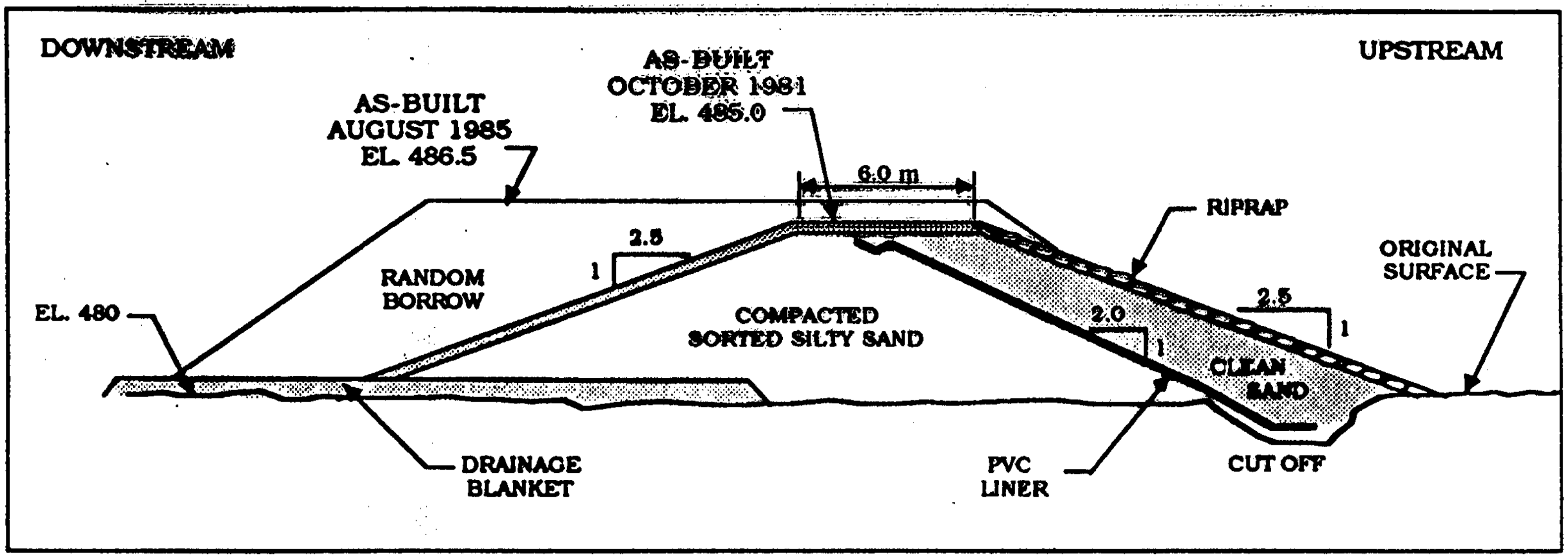

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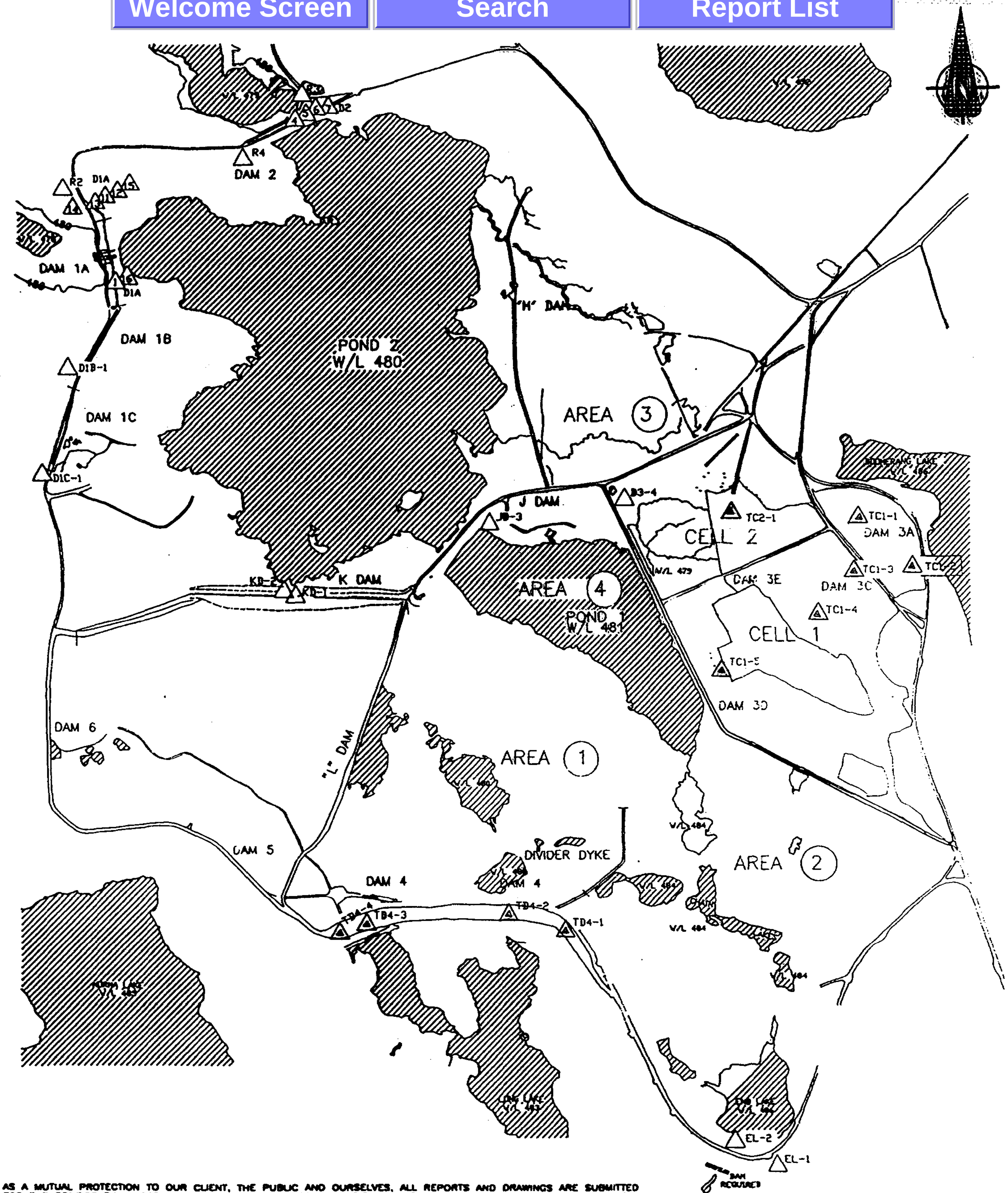

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SCALE

KLOHN-CRIPPEN

PROJECT
1996 ANNUAL THERMISTOR REPORT

TITLE
LUPIN MINE
THERMISTOR LOCATION MAP

CLIENT
ECHO BAY MINES LTD.

DATE OF ISSUE	PROJECT No.	DWG. No.	REV.
JAN. 13/97	PM 7592	A-7592-01-02	
APPROVED			

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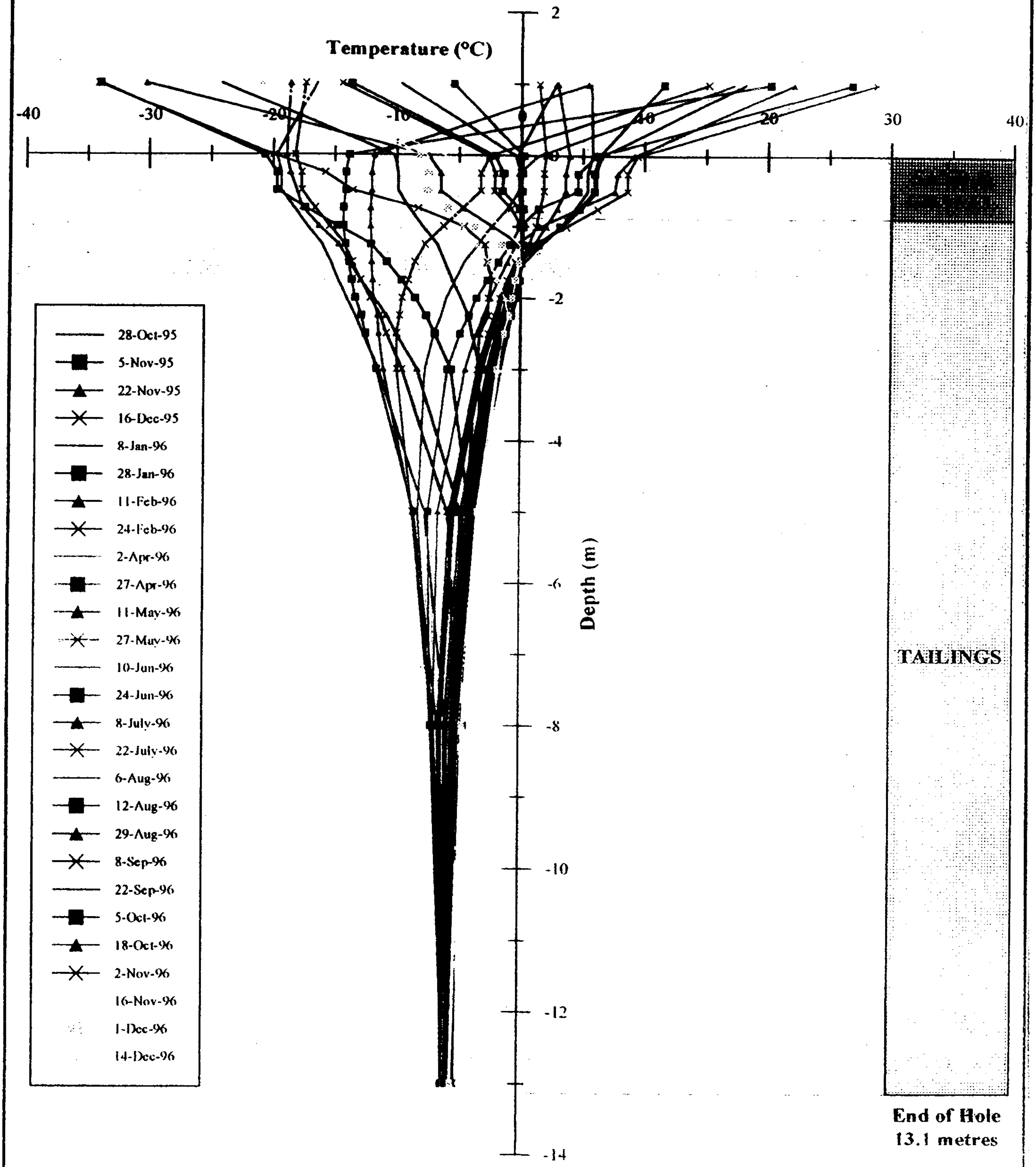
GRAPH OF TEMPERATURE VERSUS DEPTH FOR THERMISTOR TC1-1



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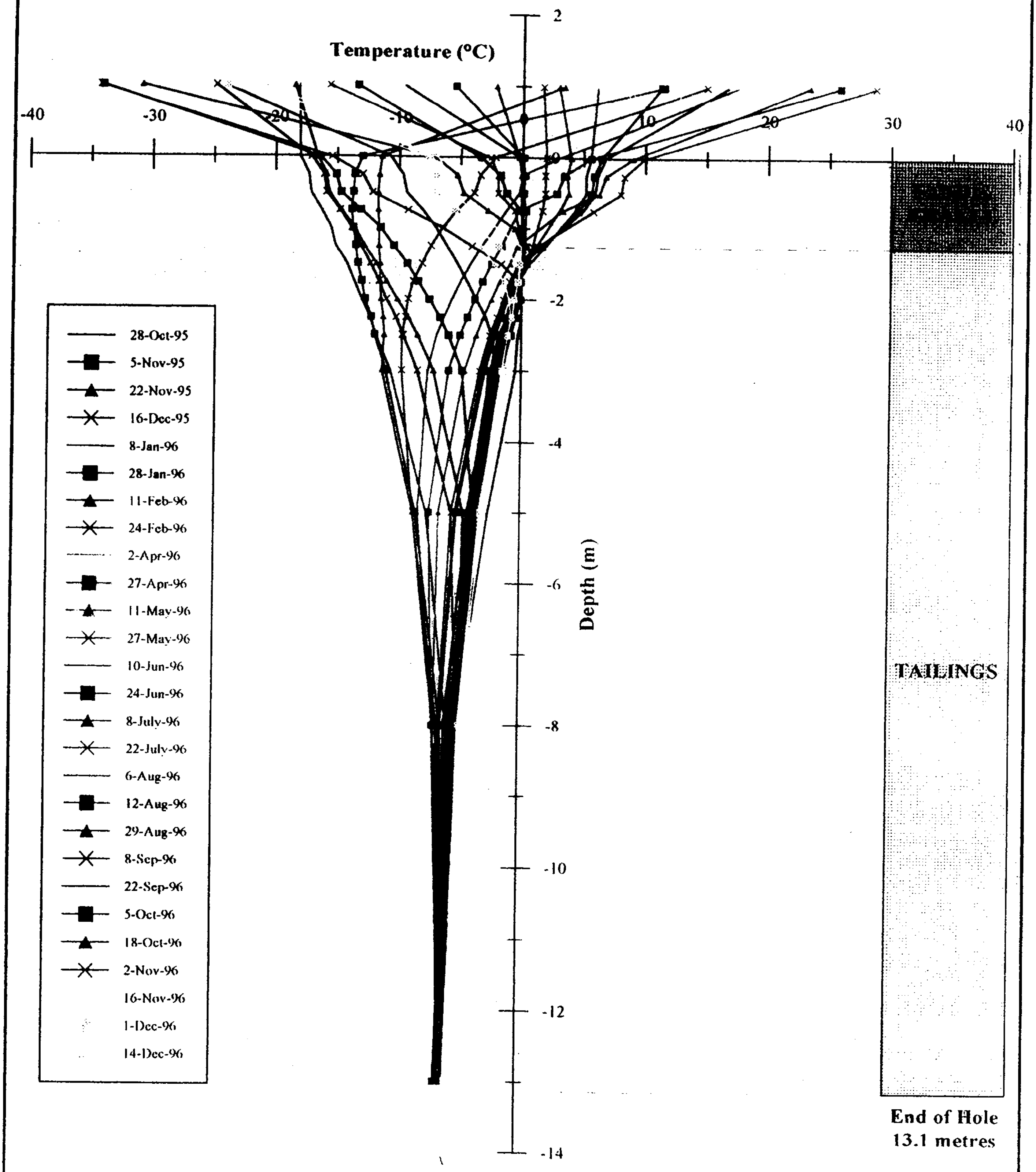

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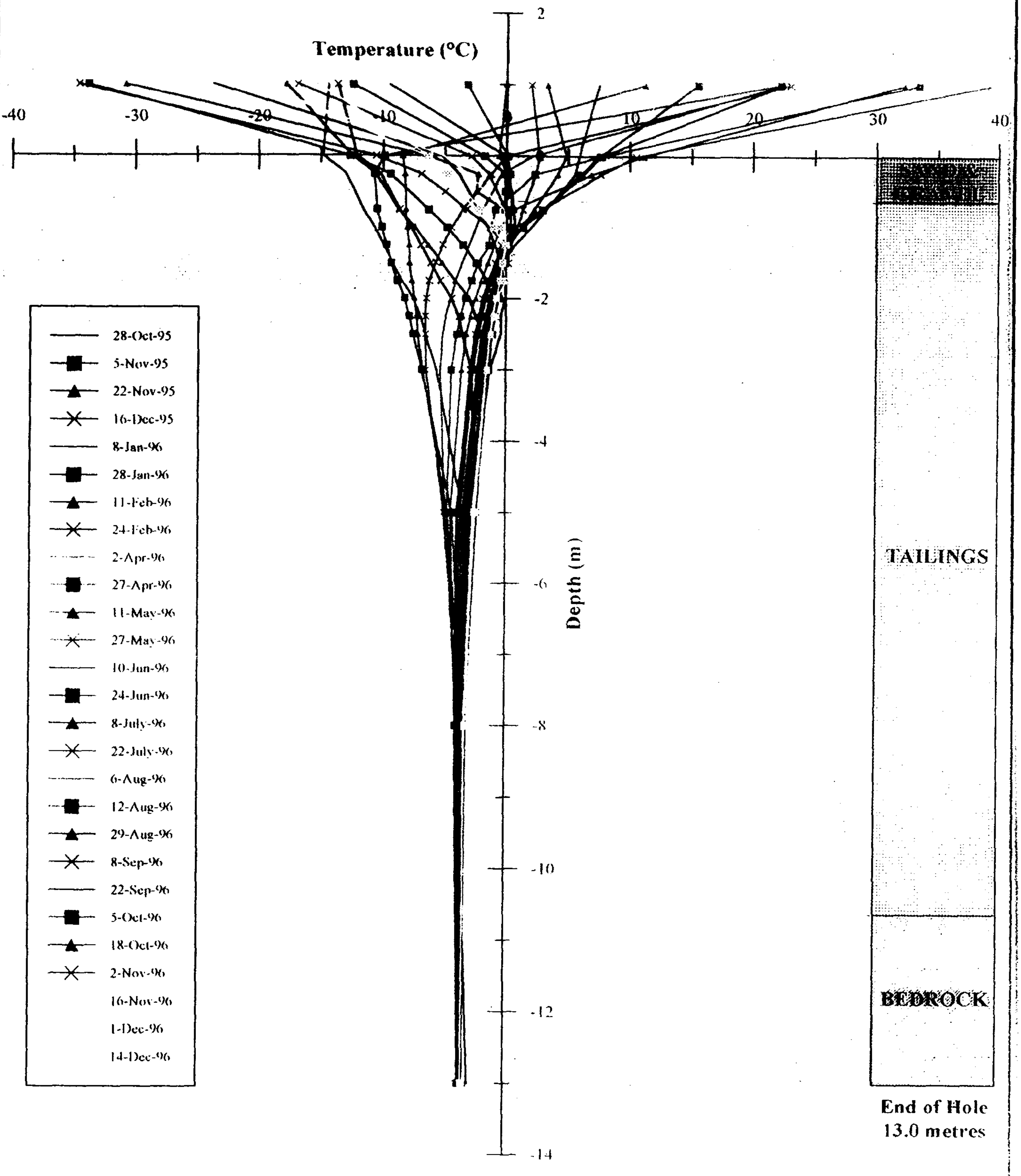
FOR THERMISTOR TC1-4



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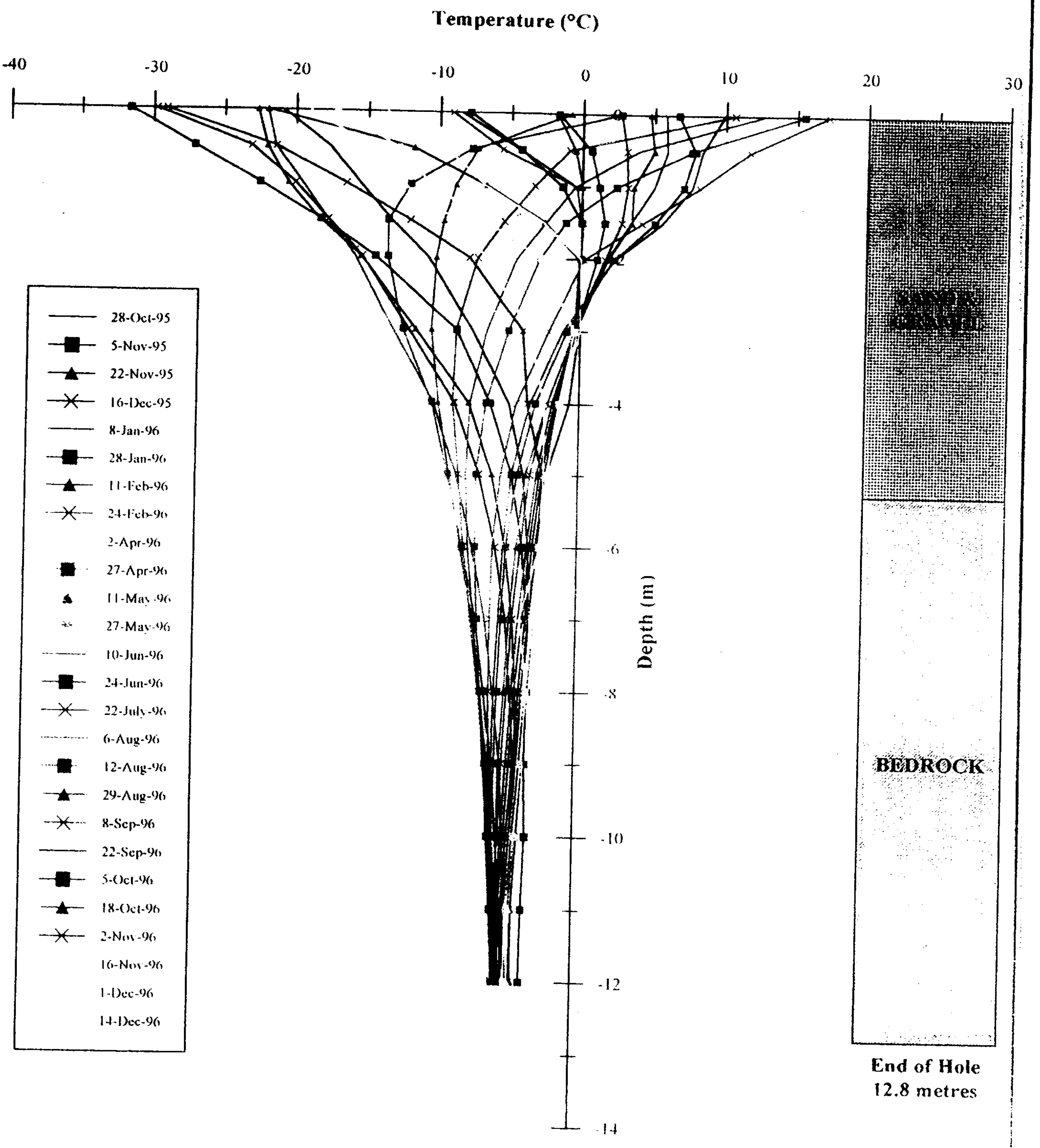
GRAPH OF TEMPERATURE VERSUS DEPTH FOR THERMISTOR D4-1



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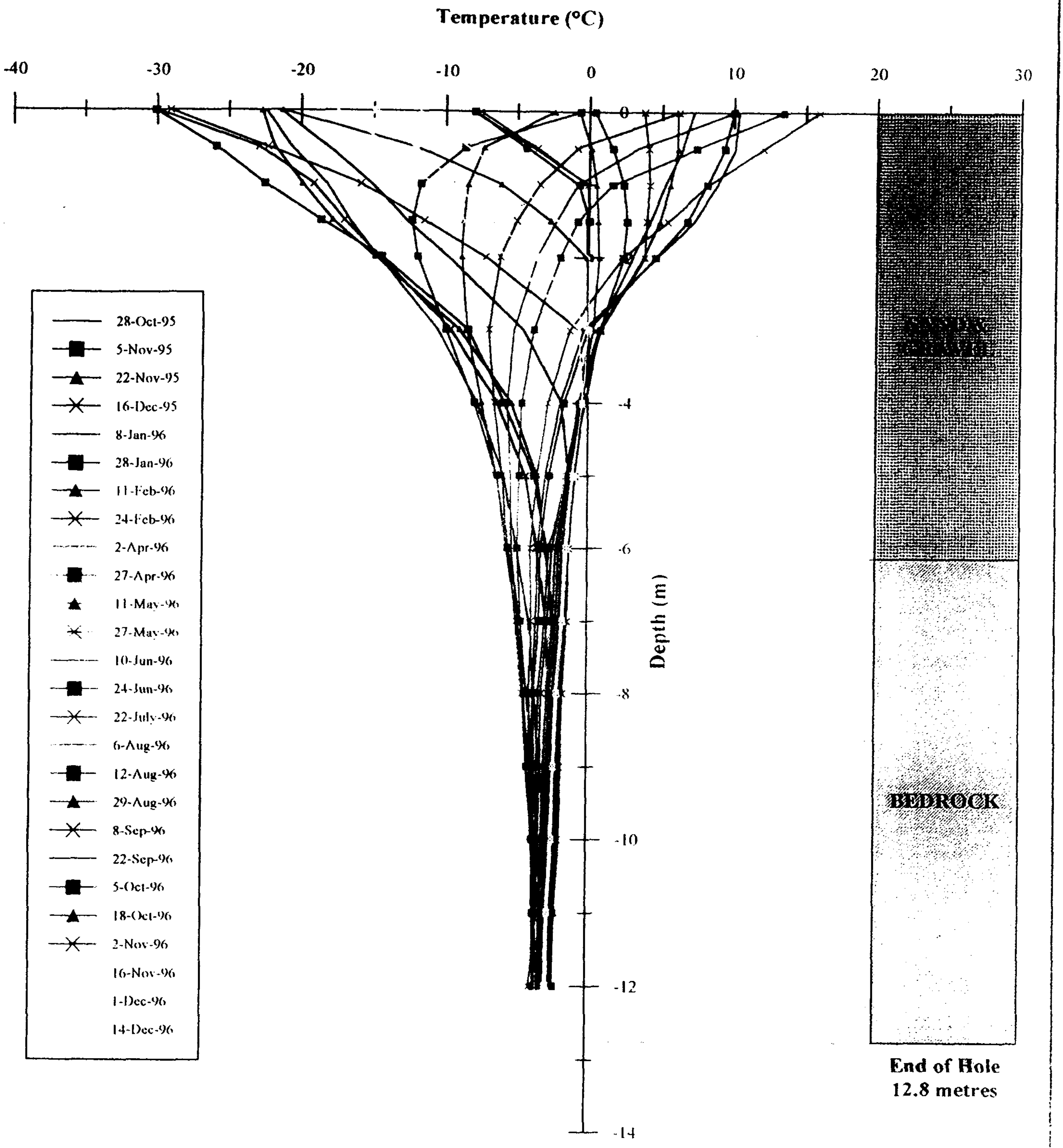
GRAPH OF TEMPERATURE VERSUS DEPTH FOR THERMISTOR D4-2



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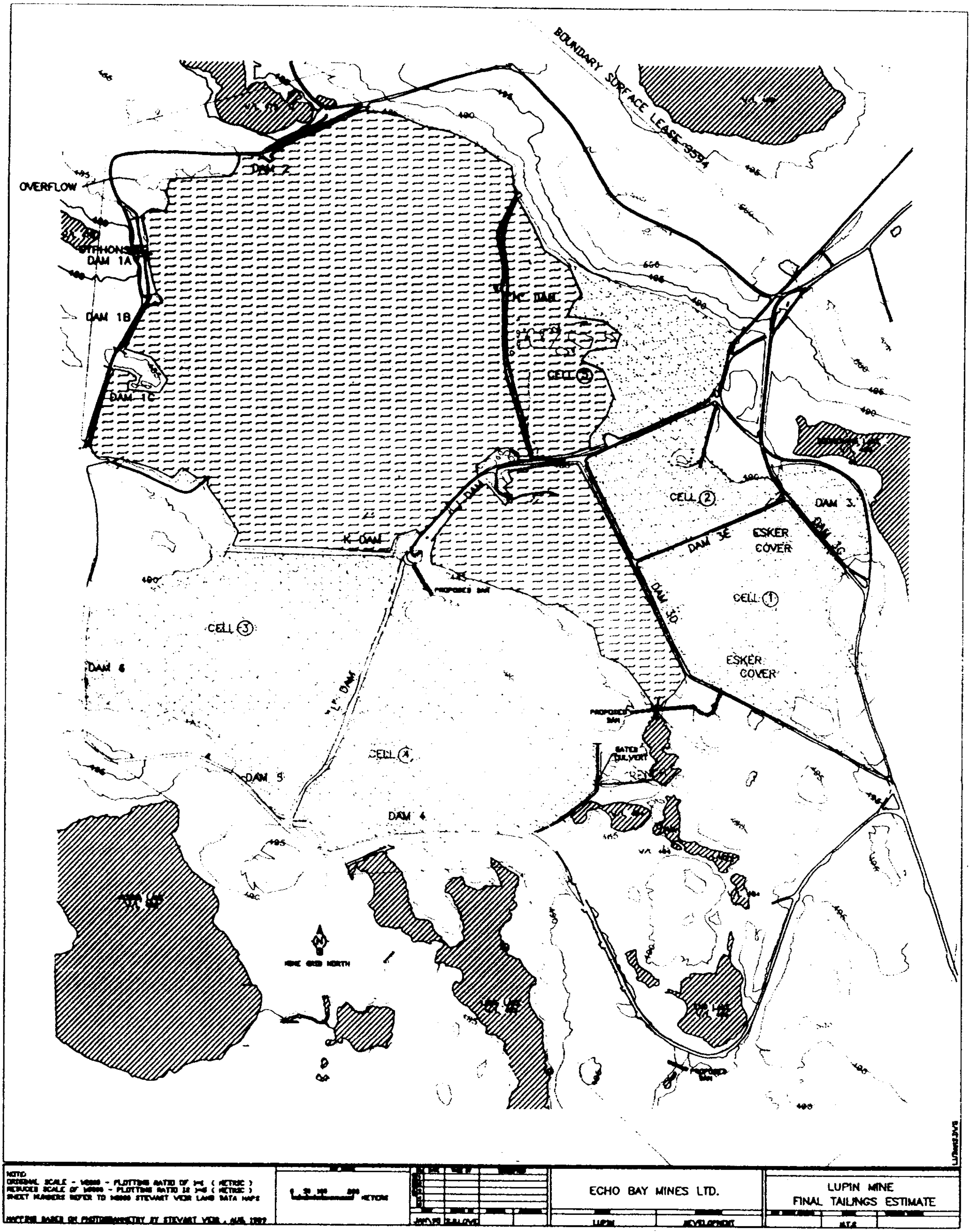
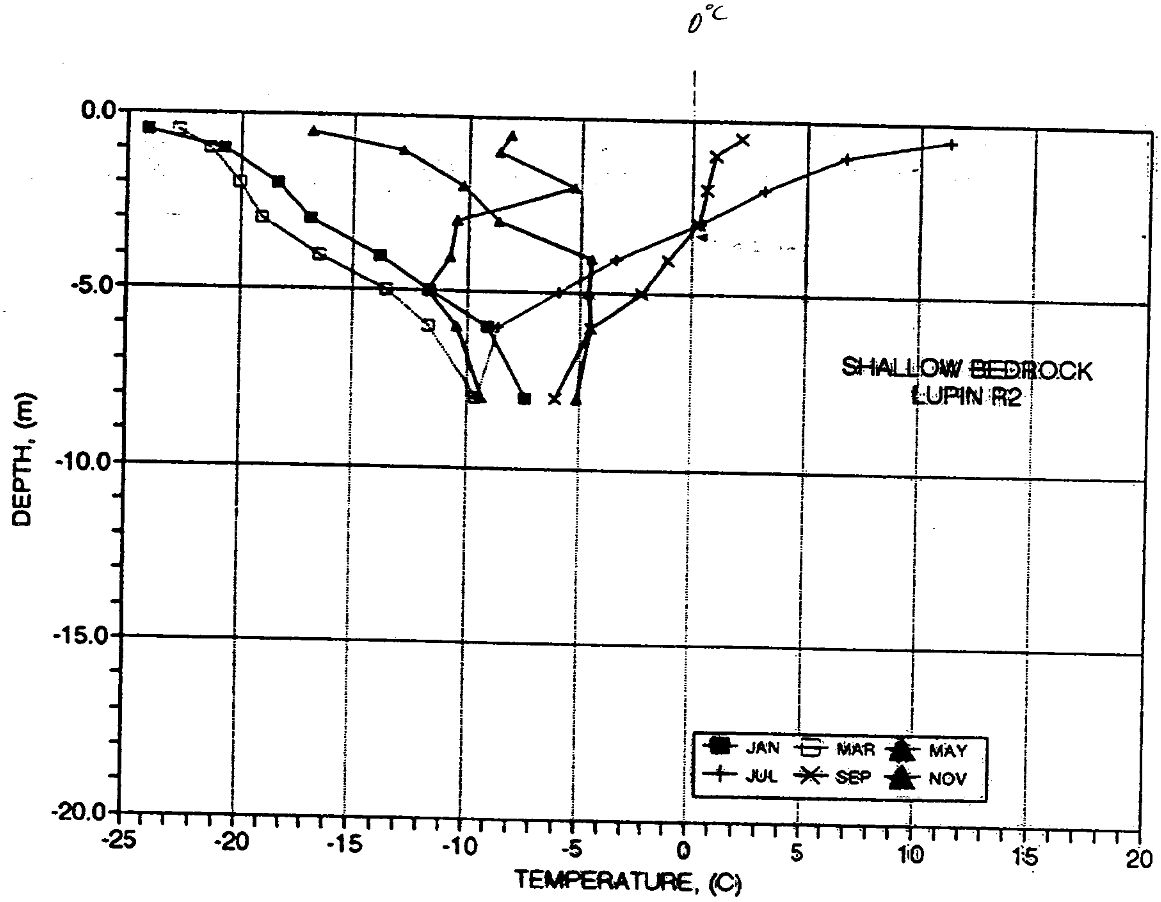


Figure 4; Lupin Mine Final Tailings Estimate


0°C
SHALLOW BEDROCK
LUPIN R2
DEPTH, (m)
0.0
-5.0
-10.0
-15.0
-20.0
-25
-20
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-10
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20
TEMPERATURE, (C)
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NOV

3.5. FREEZE BACK OF RECLAIMED TAILINGS AT NORTH RANKIN NICKEL MINE

Larry Dyke
Geological Survey of Canada

Preliminary Report on Investigation of Reclaimed Tailings at Rankin Inlet, N.W.T.

L.D. Dyke, M. Douma, and C. Hyde
Geological Survey of Canada, 601 Booth St., Ottawa, Ontario K1A 0E8

Background

Between 1992 and 1994, tailings, originally produced by nickel ore concentration at Rankin Inlet, were excavated, re-deposited in the drained open pit portion of the mine workings, and covered with gravel. This operation was part of a program to render inert this potentially hazardous material. Sulphide minerals in the tailings consist mainly of pyrrhotite with lesser amounts of pentlandite and chalcopyrite. Ponds in the tailings impoundment area (Fig. 1) exhibited near-neutral pH but acidic conditions were recorded in ephemeral streams draining into the area. Dust from the tailings surface was a continuing nuisance and potential health hazard, while the land occupied by the tailings was desired for town expansion.

The reclamation program was funded by the federal Department of Indian and Northern Affairs and carried out by consultants and contractors under the direction of the territorial Department of Public Works. Tailings reclamation involved treatment and drainage of water filling the abandoned mine depression, backfilling of the depression with oxidized tailings, and placement of a gravel cover over this and the remaining undisturbed tailings. An additional dike was constructed to supplement existing protection from wave erosion along the Hudson Bay shore. The expectation is that the reclaimed tailings will become permanently frozen and protected from erosion by the gravel cap and dikes. In late March, 1997, the Geological Survey of Canada (Larry Dyke, Martin Douma, and Christoff Hyde) and Queen's University (Heather Jamieson and Joanna Meldrum) assisted DPW (Paul Erickson) in assessing both the progress of permafrost aggradation into the reclaimed tailings and chemical changes which may be taking place in the remaining unfrozen pore fluids as freezing advances.

Site Activities

The primary means of assessment was by air-rotary drilling. The objective of this drilling was to:

1. Allow installation of thermistor cables
2. Obtain cuttings samples of frozen and thawed tailings
3. Manually determine the depth of freeze-back
4. Obtain boreholes for electrical conductivity logging
5. Obtain boreholes to different depths in frozen tailings for subsequent core sampling.

The air-rotary drilling was carried out in two stages over two days. Twenty five holes, 6.5 inches in diameter and ranging in depth from 1.5 to 3.5 m, were completed across the reclaimed tailings area. These holes were intended for subsequent collection of cores. Because rocks or metallic debris within the tailings would halt coring, these holes were drilled in clusters to several depths to increase the likelihood of avoiding such obstructions. A further 7 boreholes were attempted to the bottom of the reclaimed tailings (Fig.2, Boreholes 1-7). Although drilling could not continue into unfrozen tailings, casing was pushed and vibrated below the top of the unfrozen zone, meeting refusal due to the rock bottom or debris at depths between 6 and 12 m. These boreholes and one 18 m borehole through remaining undisturbed tailings, till, and bedrock (Fig. 2, Borehole 8) were logged for electrical conductivity. Thermistor cables were installed in the borehole penetrating bedrock (to 16 m) and in the two deepest boreholes in the reclaimed tailings (to 8 and 11 m).

Electrical conductivity (EM) surveys were also carried out over the surface of the reclaimed tailings and over part of the remaining undisturbed tailings. The two instruments used allowed apparent conductivities to be recorded over a range of depths between about 2 and 30 m across the 200 x 300 m grid area. The primary objective of this survey is to provide a means of extending borehole data on the thickness of the frozen and unfrozen parts of the reclaimed tailings.

Due partly to a delay in the arrival of equipment and to poor weather, coring was carried out in only one of the shallow boreholes. However, the cuttings samples from all levels in the frozen part of the reclaimed tailings, as well as limited sampling from within the unfrozen tailings, and core from the top of the frozen tailings, will permit a preliminary analysis of pore water chemical evolution accompanying freeze-back. The site will be revisited in late-May to collect at least one complete core through frozen tailings. All samples were shipped to Queen's University in the condition collected and will be analyzed there and at GSC for mineralogy and pore fluid composition.

Results

Cuttings samples were collected from the series of shallow holes. Several samples of thawed tailings and associated pore water were collected from the series of deeper holes. The water is highly saline with an electrical conductivity of about 50,000 umhos/cm and a pH ranging between about 5.5 and 7. One piezometer was installed, showing a static fluid level of 2.5 m below the ground surface. This level was also reached by fluid leaking into the casing of two of the deeper boreholes. These water levels are lower than would be expected if consolidation were actively taking place. Given that they appear to be at an elevation approximately equal to sea level, the remaining unfrozen part of the tailings may be hydraulically connected with the ocean.

Drilling and ground temperature measurements indicate that the tailings were ice-bonded to a depth of about 4 m, as of March 31, 1997. To this depth the temperature warmed steadily to about -4°C and continued to warm gradually to about -1.5°C at a depth of 11 m (Fig. 3). Thus the tailings are partially frozen between about 4 and 6 m, or between temperatures of about -4 and -2°C, and completely unfrozen below a depth of 6 m or above a temperature of -2°C. Even below -4°C there may be a considerable fraction of unfrozen fluid. These observations are confirmed by electrical conductivity logging of the deep borehole series, whereby conductivity in general increases between depths of about 4 and 6 m, reflecting the contribution to conductivity of increasing unfrozen water content (Fig. 4). Although no determination of pore water salinity has yet been made, the apparent freezing point depression in the reclaimed tailings suggests a pore water salinity roughly that of sea water, i.e. about 30 parts per thousand.

Ultimately, the reclaimed tailings should fall to a temperature of about -7°C. This is suggested by the temperature profile for the borehole placed outside the reclaimed tailings area (Borehole 8 in Fig. 2) where ground temperatures are probably in equilibrium with the climate. The time taken for the reclaimed tailings to completely freeze will be included in the final report for this project. It is dependent on the thermal conductivity of frozen tailings and on any increase in unfrozen pore water salinity which may accompany continued freeze-back. Increases in pore water salinity to date should be revealed by pore water chemistry analyses which are to be carried out on samples presently in hand.

Surface EM surveys outlined a high conductivity area coincident with the reclaimed tailings area. Presumably the high conductivities are associated with the unfrozen part of the tailings. An interpretation of the survey data will allow the thickness of this unfrozen part to be determined over the entire reclaimed tailings area. The part of the survey extended over adjacent undisturbed tailings showed a circular zone of negative readings surrounded by a zone of very high positive readings. This also awaits interpretation but the circular pattern may reflect the original depositional pattern of this part of the tailings and segregation of conductive sulphide minerals down the sides of a tailings spoil pile.

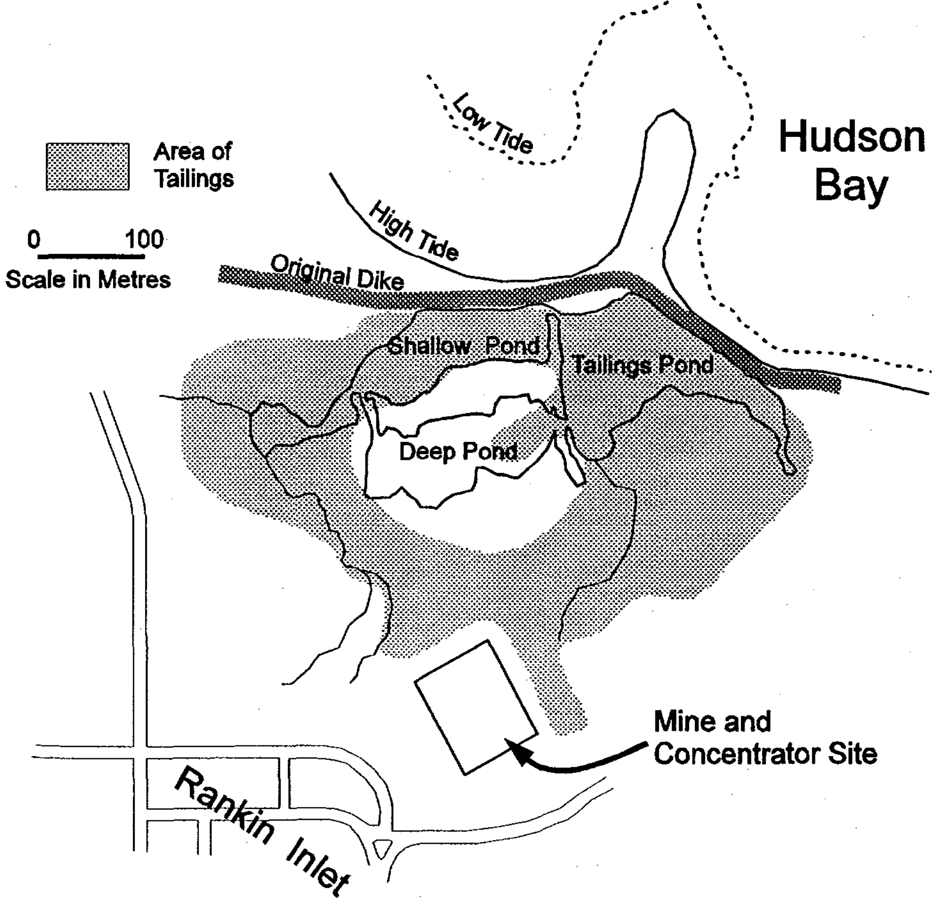

Fig. 1. Distribution of tailings prior to reclamation. Thickest tailings are immediately inland from Tailings Pond with thicknesses up to about 4 m. Beyond that area, tailings rapidly decrease in thickness to less than 0.5 m. Tailings Pond and Shallow Pond were both 0.5 m or less deep. Deep Pond was up to 10 m deep.

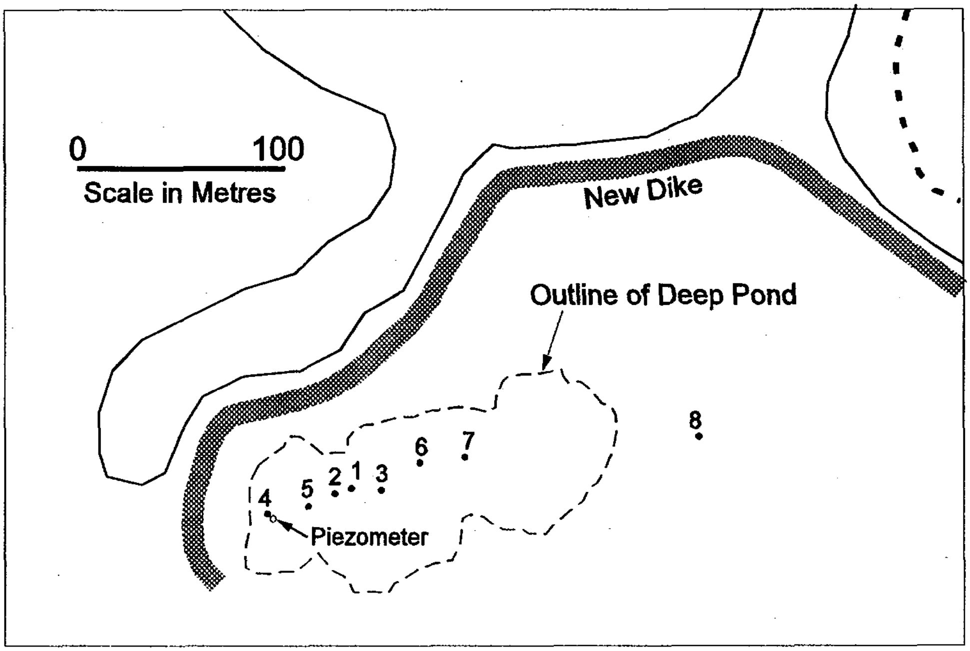

Fig. 2. Enlargement of area receiving reclaimed tailings showing new dike and inundation of Shallow Pond by the ocean. Black dots show location of cased boreholes. Boreholes 1-7 are located in the former site of Deep Pond in which the reclaimed tailings are held. Borehole 8 is located in unrecovered tailings.

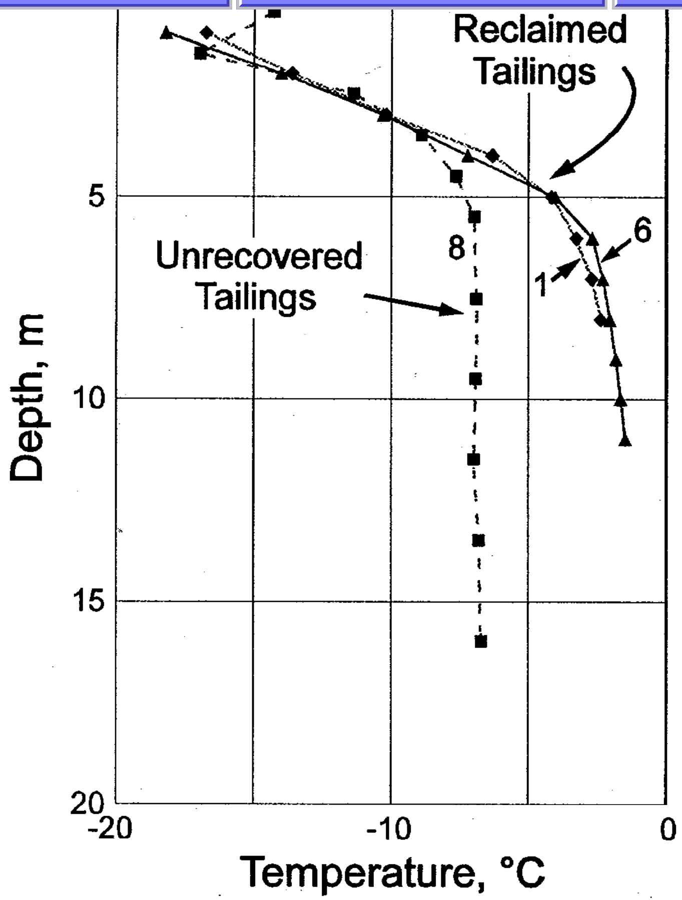

Fig. 3. Subsurface temperatures on March 29, 1997 in reclaimed tailings (Boreholes 1 and 6) and in area where undisturbed tailings remain (Borehole 8).

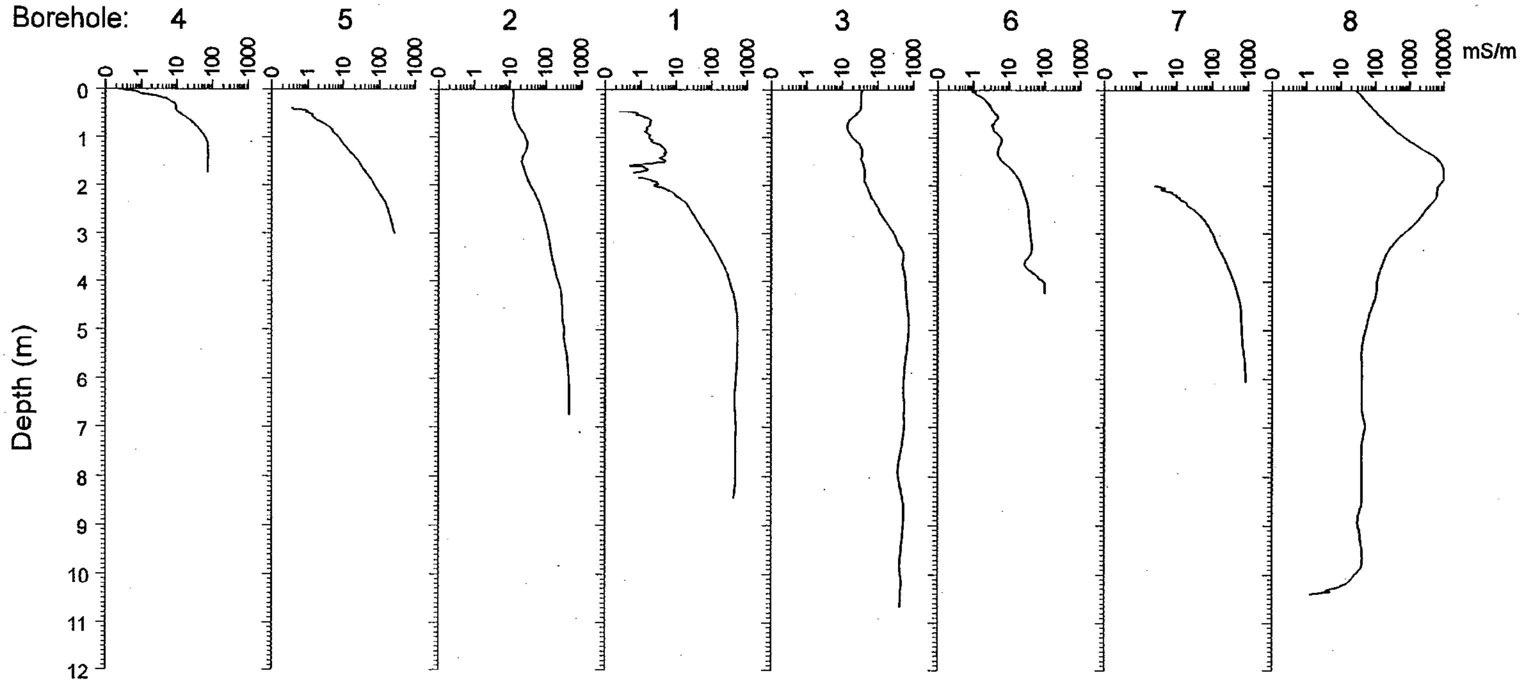

Fig. 4. Electrical conductivity logging of boreholes 1-8 as shown in Fig. 2. Note logarithmic scale for conductivity (mS/m). Increase in conductivity in the upper 4 m for boreholes 1-7 is probably caused by the increasing content of saline pore water in the tailings. Conductivity peak in borehole 8 is probably due to unrecovered tailings.

3.6. LEACHING CHARACTERISTICS OF CULLATON LAKE TAILINGS

Nand Davé
Natural Resources Canada - CANMET

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Leaching Characteristics of Cullaton Lake Tailings

Nand Davé and
F. V. Clulow

Work Sponsored by
Homestake Canada Ltd., and
The Mine Environmental Drainage Program (MEND)

Objectives:

- To evaluate oxidation and leaching characteristics of Cullaton Lake B and S- Zone tailings at:

⇒ 25 °C
2 °C and
10 °C

⇒ Acid Rock Drainage is an issue as the orebodies contained pyrite, pyrrhotite and other sulphide and metal bearing minerals

⇒ Preparation of final decommissioning plan etc.

Site Location:

- District of Nunavut and Keewatin sub-district, Northwest Territories
- Located 416 Km northwest of Churchill, Manitoba
- Site is at tree line and in the zone of continuous to wide spread discontinuous permafrost
- Cullaton Lake Gold Mines Ltd. (Company) operated 300 tonnes gold mill from October 1981 to August 1985.
- Ore from two distinct orebodies, B - and Shear (S) - Zones
- Total of 373,000 tonnes milled, 150,00 from B - zone and the balance 223,000 tonnes from S - zone

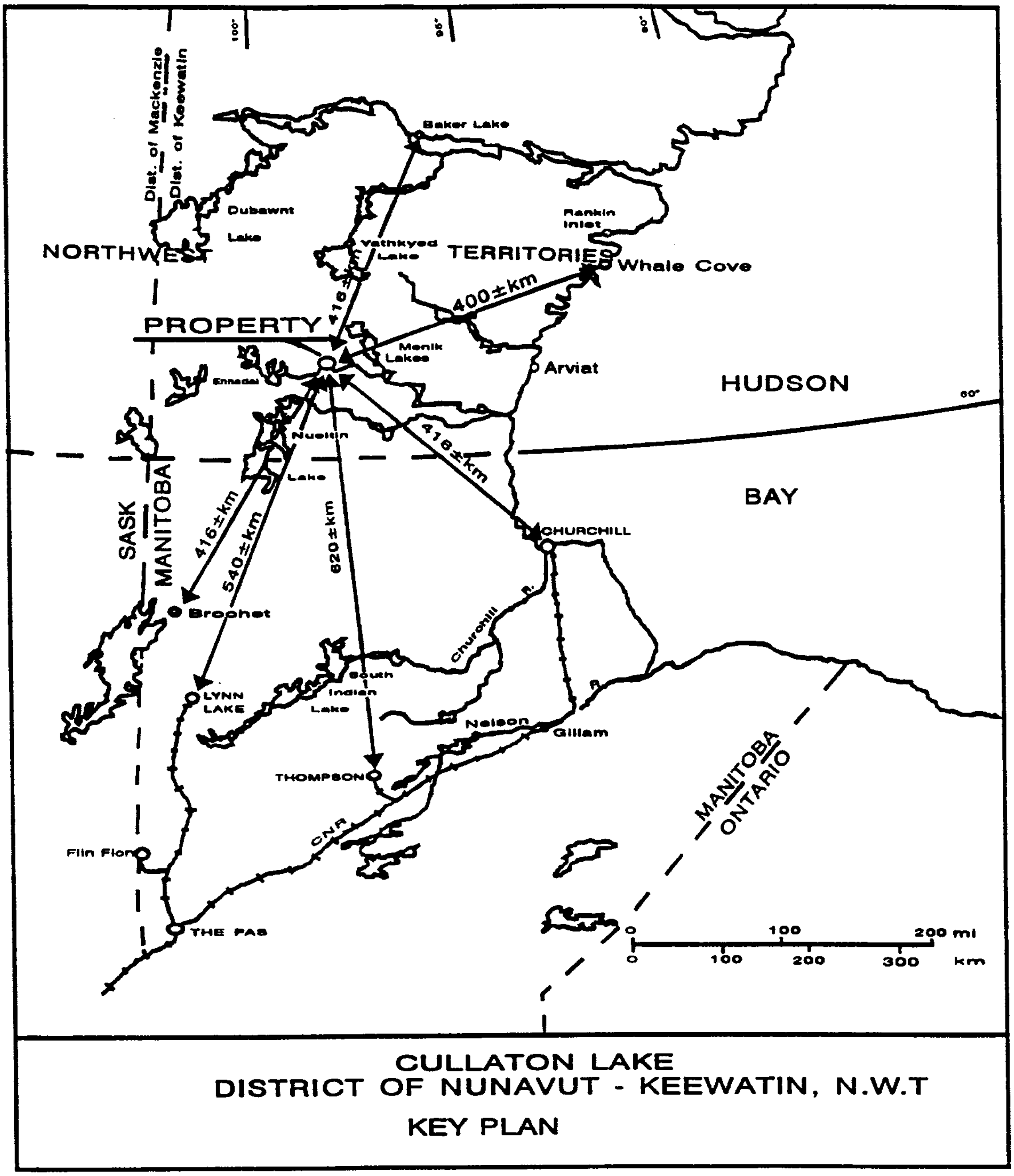

Fig. 1 Location of Cullaton Lake mine, Northwest Territories.

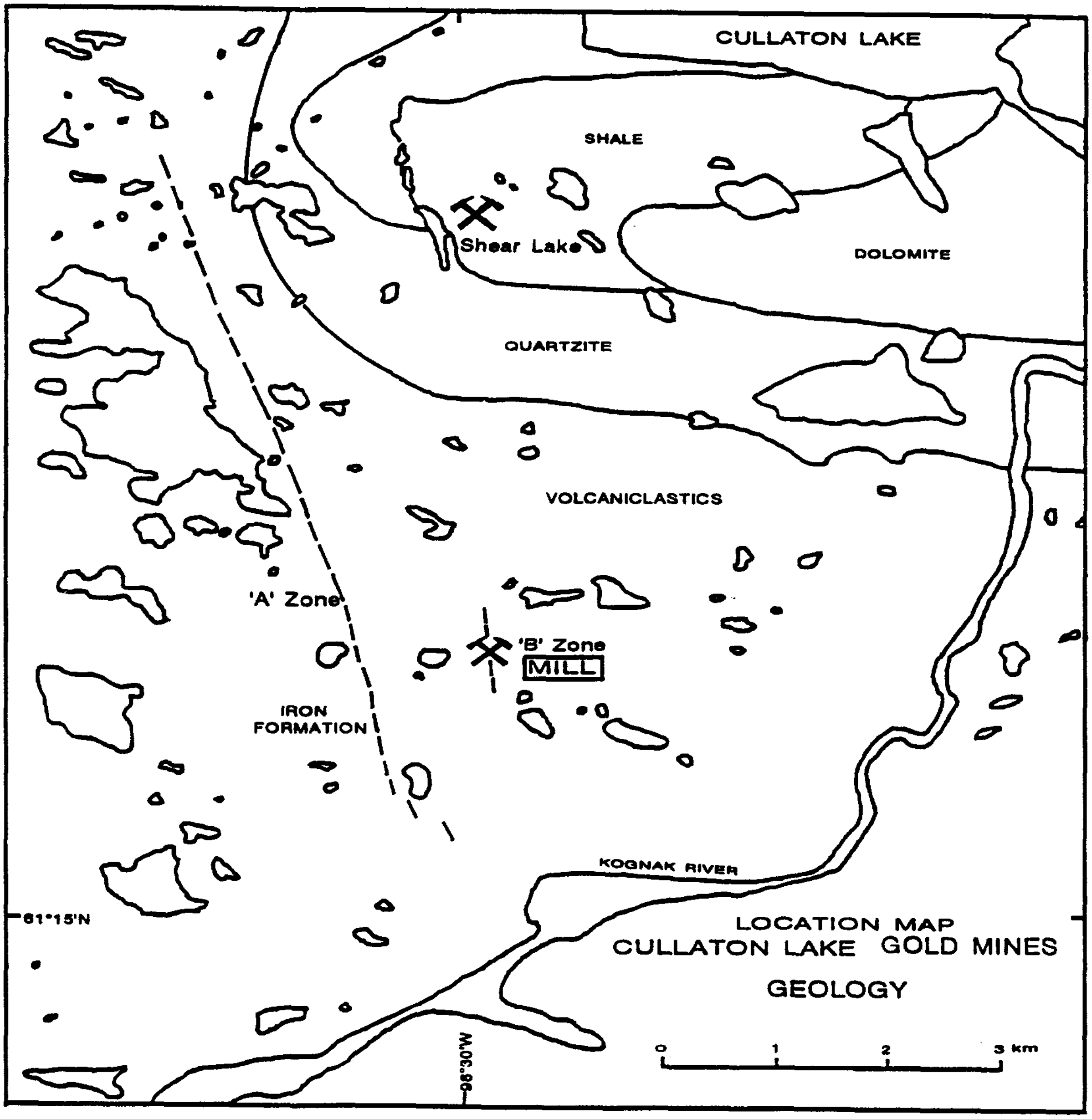

Fig. 2 Location of B- and Shear-Zones at the Cullaton Lake mine property.

B - Zone:

- Gold bearing iron formation in a turbiditic sedimentary basin which formed part of the Rankin Inlet - Ennadi Archean greenstone belt in the Keewatin district of Nunavut (NWT).

Shear (S) - Zone

- Gold occurred in fractured and sheared orthoquartzite . Mineralization in altered shears, breccia zones, pyritic shears, and pyritic impure quartzite.

Table 1. Physical characteristics of B and Shear (S) - Zones tailings.

Parameter	**B - Zone**	**Shear (S) Zone**
Colour	Greenish grey	Brownish orange
Texture	sandy silt	sandy silt
Particle size	70% less than 100 µm	50% less than 100 µm
D_{50}	65 µm	100 µm
D_{10}	35 µm	45 µm
Moisture content (% wt)	9.3	9.5
Wet bulk density (tonne / m^3)	1.80	1.58
Grain density (tonne / m^3)	3.00	2.50
Porosity (%)	40	36.8
Wet mass of tailings in Column (kg)	9.7	9.7
Total bulk volume dry tailings (l)	4.89	5.56
Total pore volume dry tailings (l)	1.95	2.05
% pore volume moisture saturation	46	45

Table 2. Chemical characteristics of B and Shear (S) - Zones tailings. All concentration values are given in percentiles, except where noted.

Parameter / Element	**B - Zone**	**Shear (S) Zone**
Al (%)	1.62 ± 0.008	0.47 ± 0.003
Ba (μg/g)	83.6 ± 0.6	101.5 ± 0.8
Ca (%)	2.37 ± 0.032	0.09 ± 0.002
Cd (μg/g)	<10	<10
Co (μg/g)	<10	16.1 ± 0.52
Cr (μg/g)	36.4 ± 0.2	24.4 ± 0.2
Cu (μg/g)	45.4 ± 0.3	15.5 ± 0.3
Fe (%)	20.07 ± 0.085	2.96 ± 0.01
K (%)	0.305 ± 0.07	0.15 ± 0.025
Mg (%)	0.88 ± 0.006	0.057 ± 0.003
Mn (%)	0.09 ± 0.0003	0.01 ± 0.0001
Na (%)	0.14 ± 0.001	0.06 ± 0.002
Ni (μg/g)	60.6 ± 10.8	48.6 ± 1.1
Total phosphorus (% P)	0.06 ± 0.014	0.009 ± 0.006
Pb (μg/g)	65.8 ± 1.9	48.4 ± 0.9
Total sulphur (% S)	2.63 ± 0.32	0.49 ± 0.1
Soluble sulphur (as % S)	0.32 ± 0.01	0.09 ± 0.01
Total sulphide sulphur (as % S)	2.31 ± 0.33	0.4 ± 0.11
Ti (%)	0.069 ± 0.0008	0.012 ± 0.0002
V (μg/g)	58.6 ± 2.0	15.4 ± 0.4
Zn (μg/g)	45.7 ± 0.4	12.1 ± 0.1
Zr (μg/g)	53.1 ± 3.0	44.4 ± 1.2
Total acid generation potential, kg $CaCO_3$/tonne	72.2	12.5
Total alkalinity, kg $CaCO_3$/tonne	45.36	2.0
Net neutralization potential, kg $CaCO_3$/tonne	-26.84	-10.5

Leaching Procedure:

- Leaching in cylindrical columns
- Inoculation of tailings with T-ferrooxidans culture in the columns
- Batch leaching using natural lake water (pH ~6.8, acidity 3-5 mg/l, SO_4 ~ 6-8 mg/l, etc.)
- Sampling at intervals of 1 to 2 weeks
- Effluent analyzed for pH, Eh, total potential acidity, total alkalinity, total sulphate, major metals and cyanide
- Cold temperature: placement in a walk in freezer maintained at the desired temperature(s)

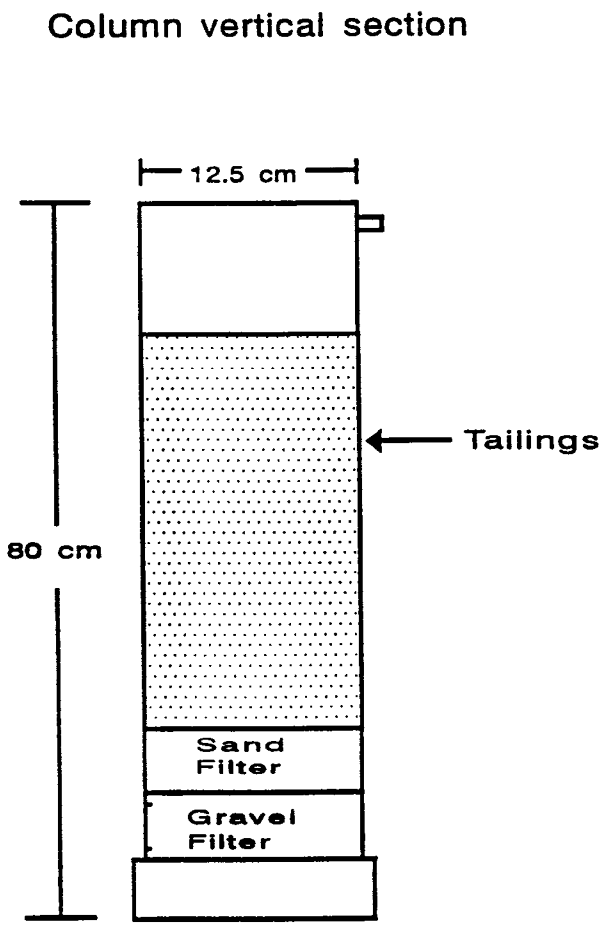

Fig. 3 Vertical section of a leaching column.

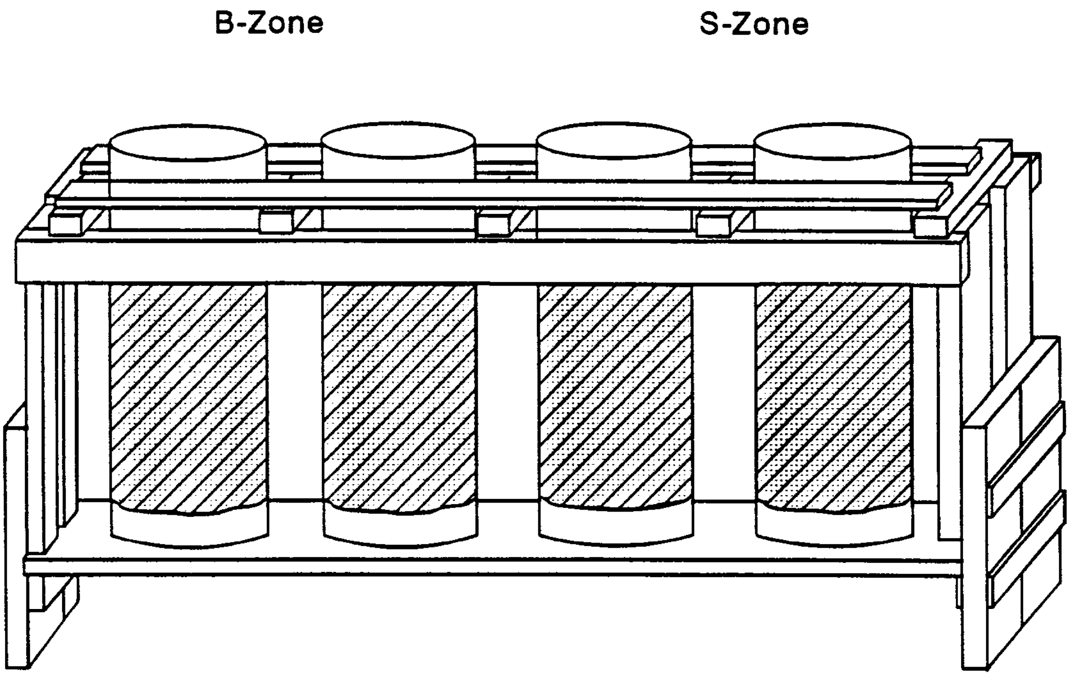

Fig. 4 Experimental arrangement of leaching columns.

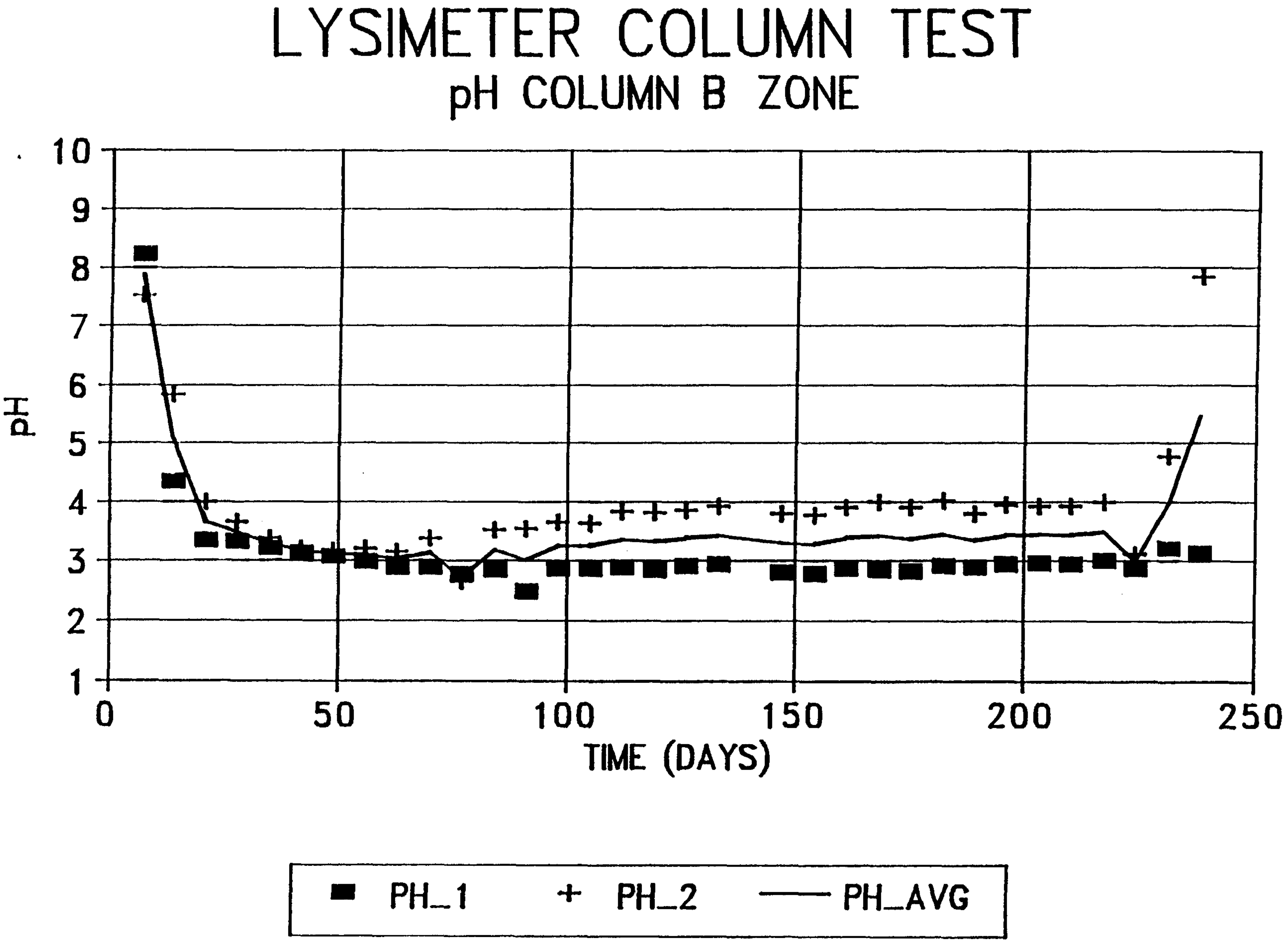

Fig. 8 - Effluent pH for B Zone columns.

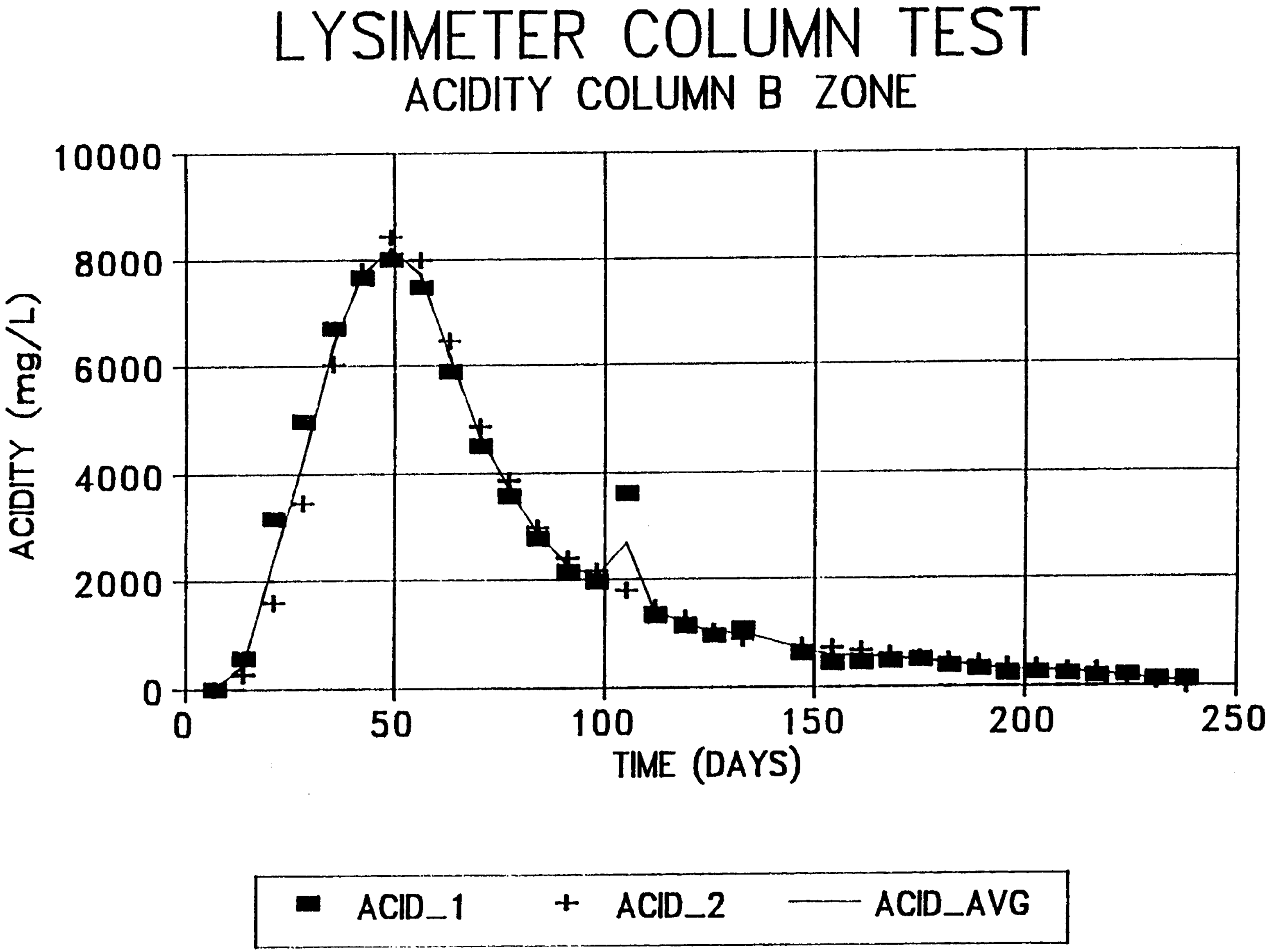

Fig. 11 - Effluent acidity for B Zone columns.

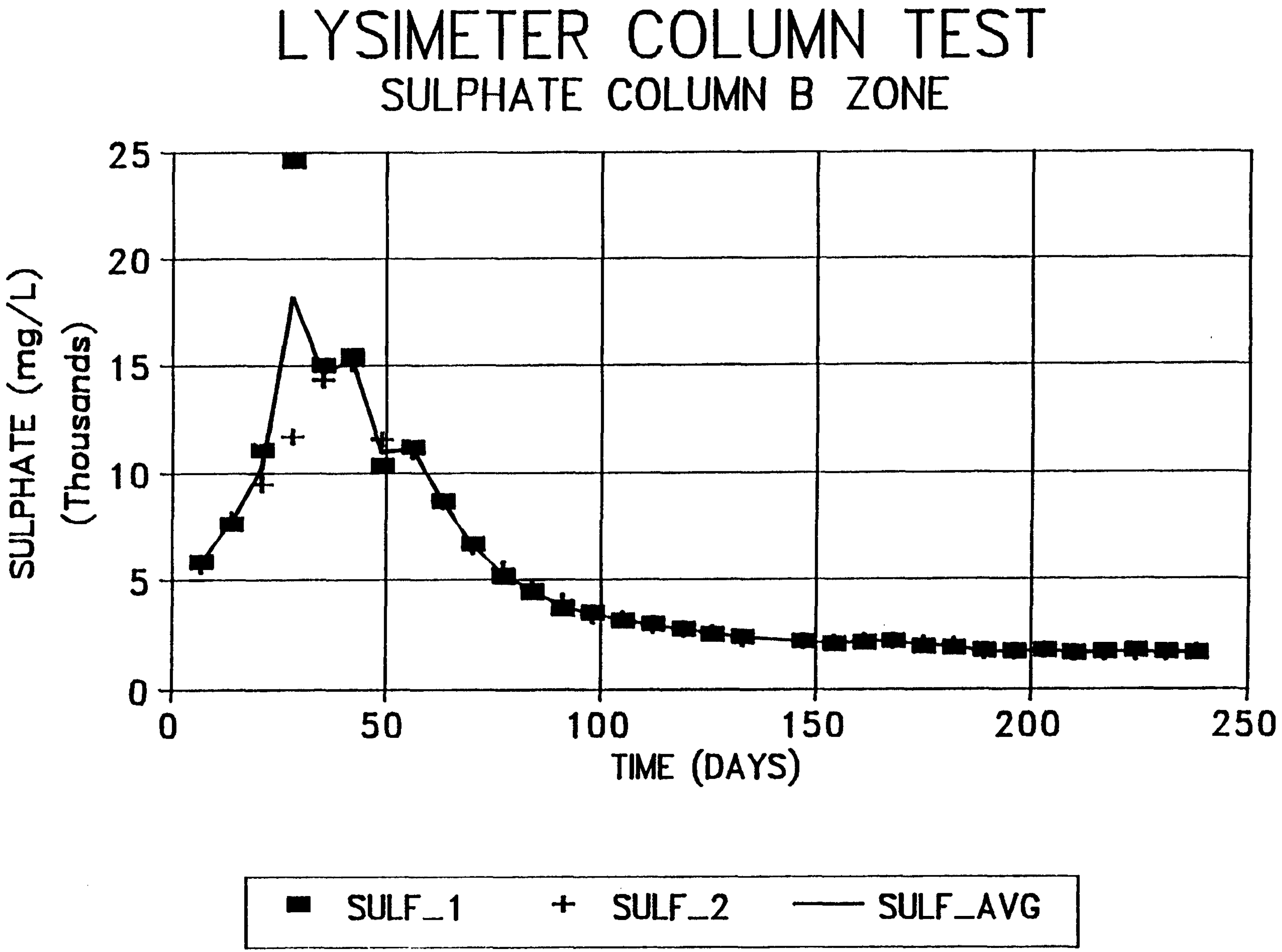

Fig. 13 - Effluent total sulphate (SO_4^{-2}) concentration for B Zone columns.

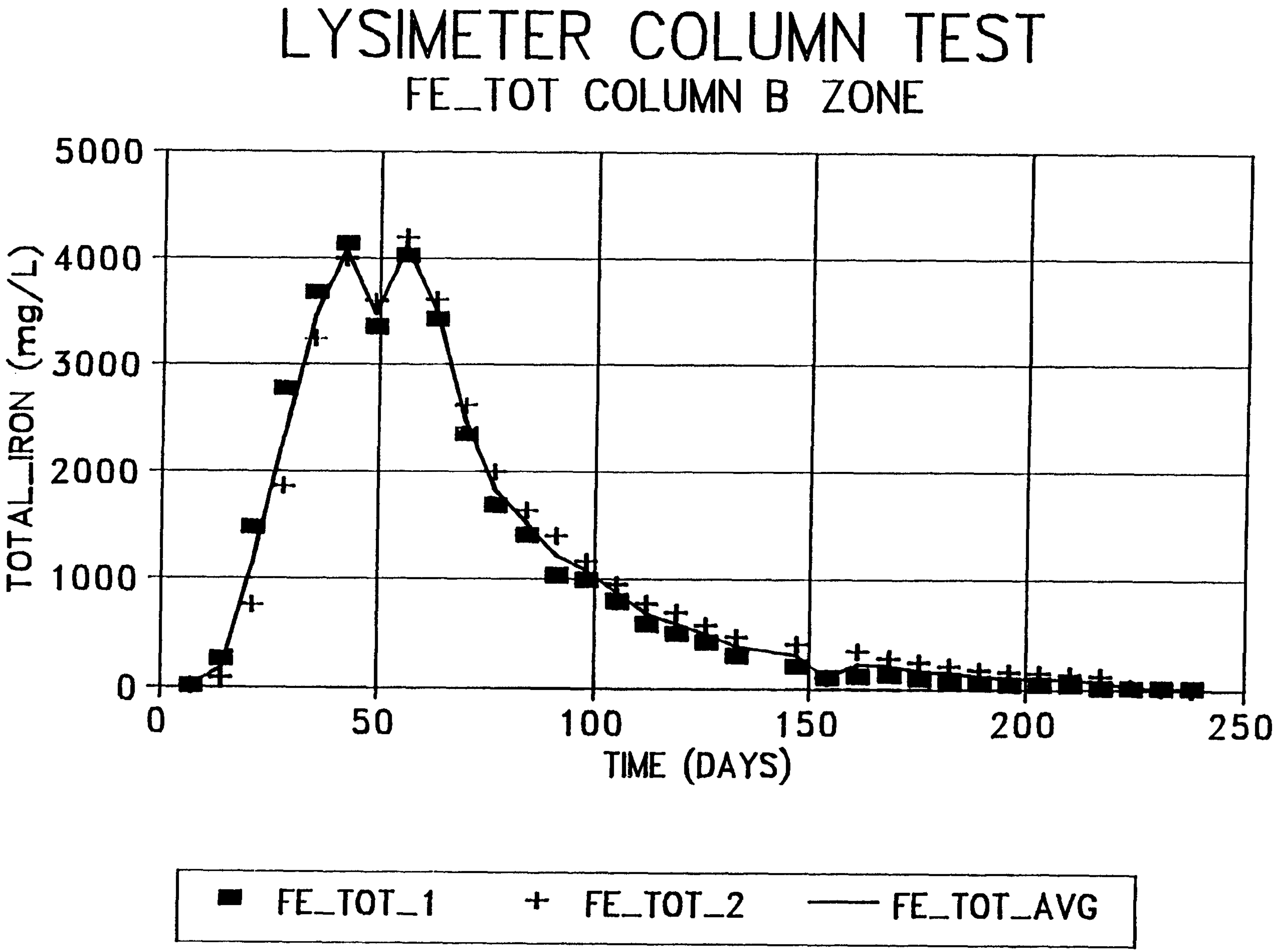

Fig. 14 - Effluent total iron (Fe) concentration for B Zone columns.

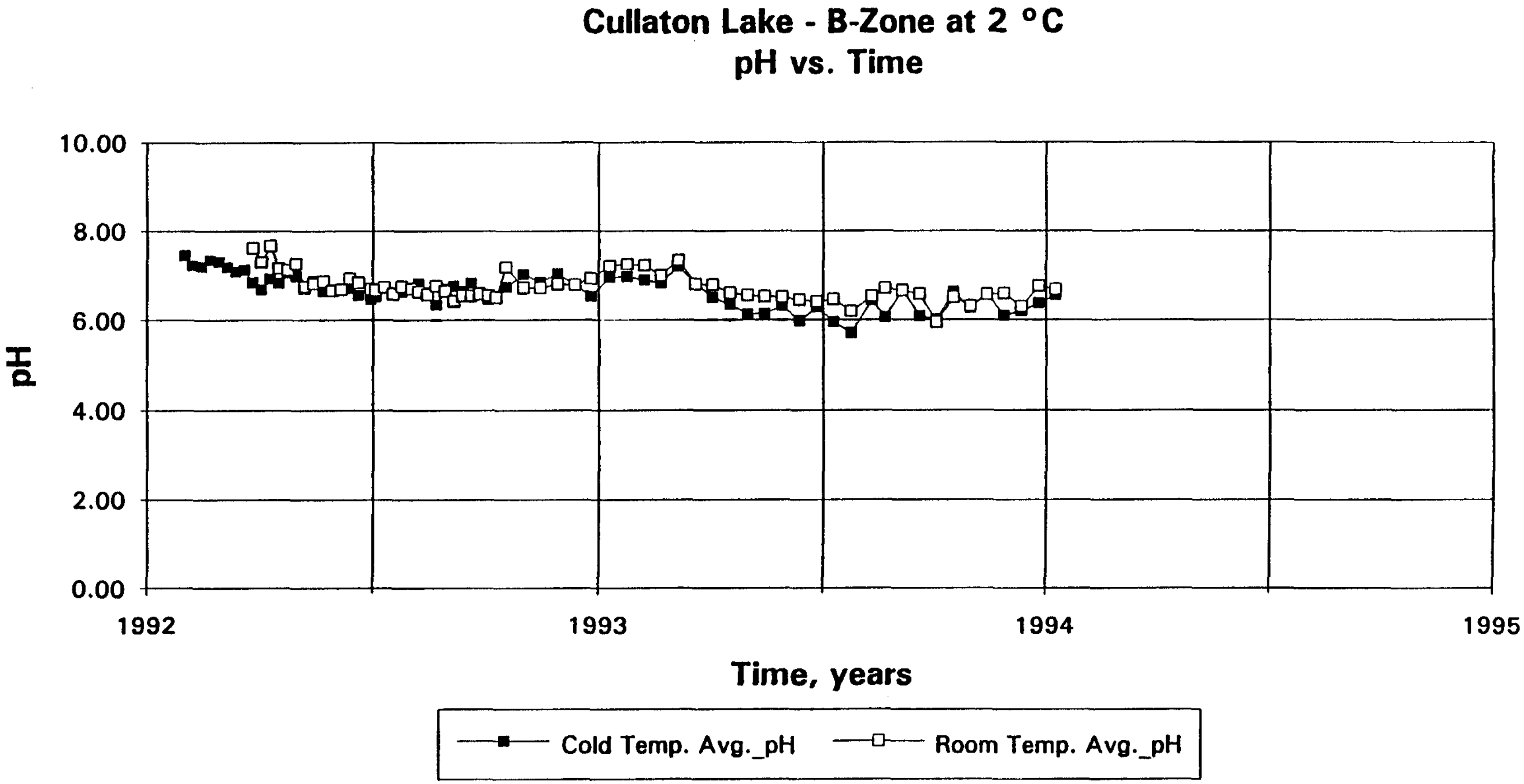

Fig. 6a B - Zone: effluent pH's at 2 °C and room temperature.

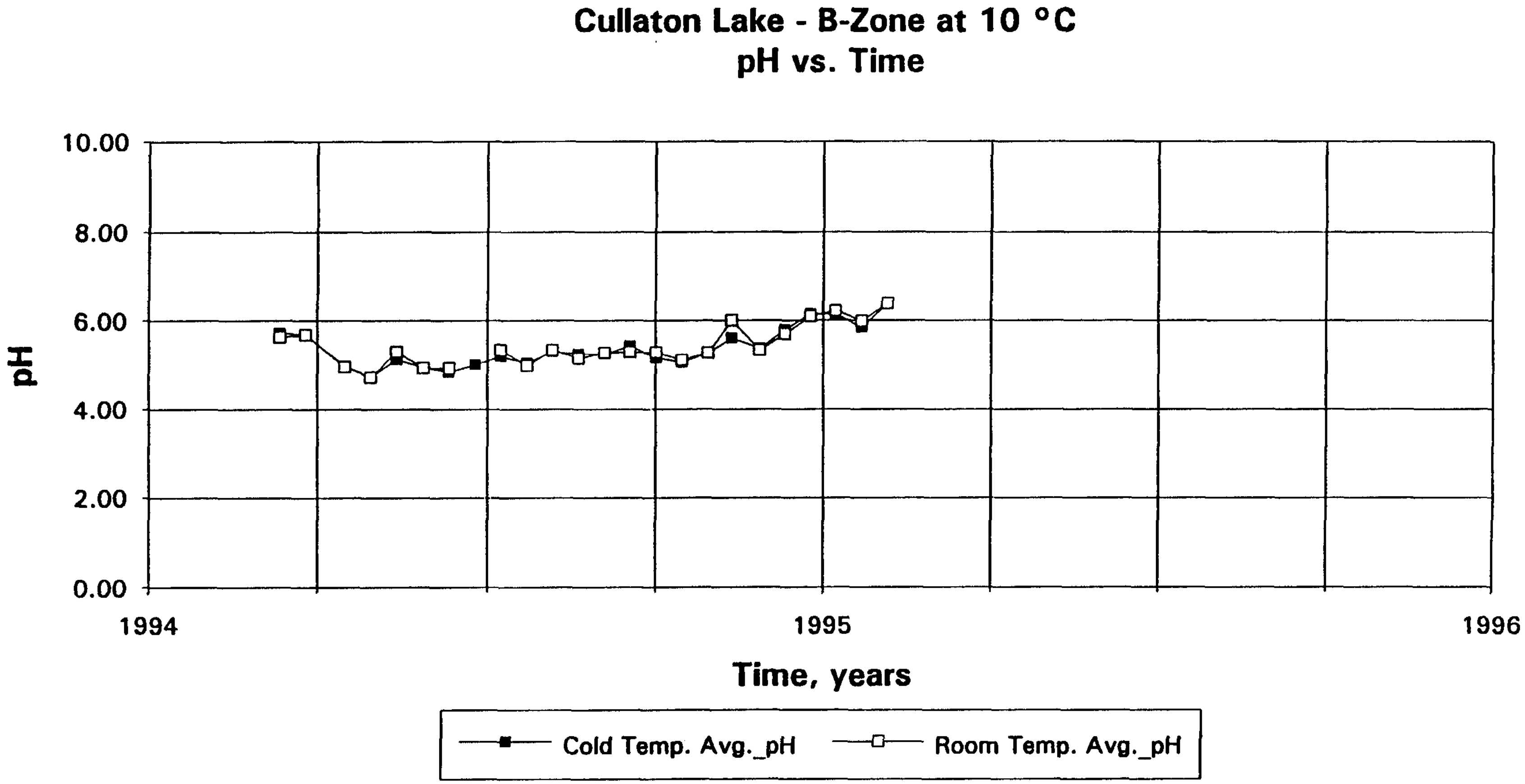

Fig. 6b B - Zone: effluent pH's at 10 °C and room temperature.

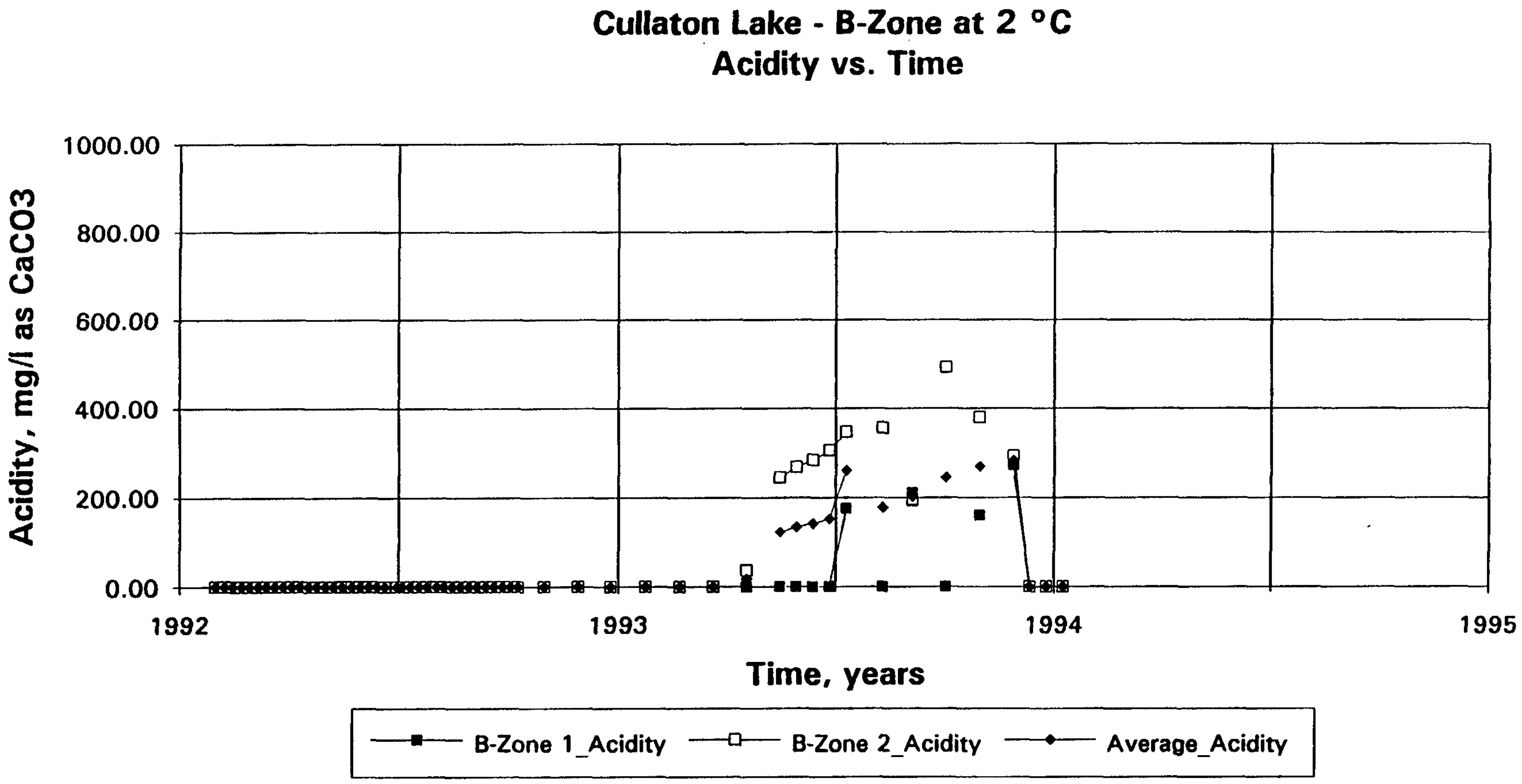

Fig. 9a B - Zone: effluent total acidity at 2 °C.

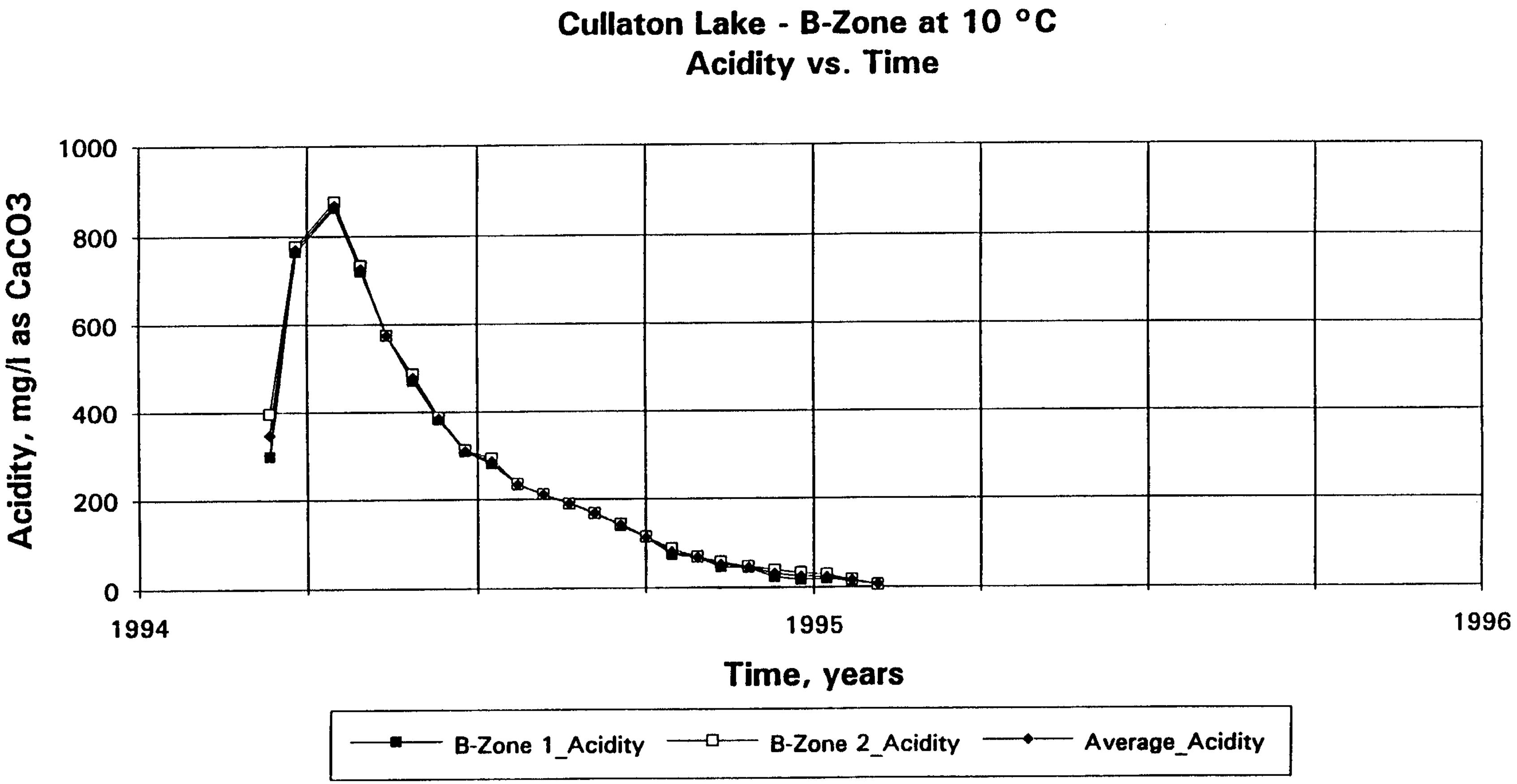

Fig. 9b B - Zone: effluent total acidity at 10 °C.

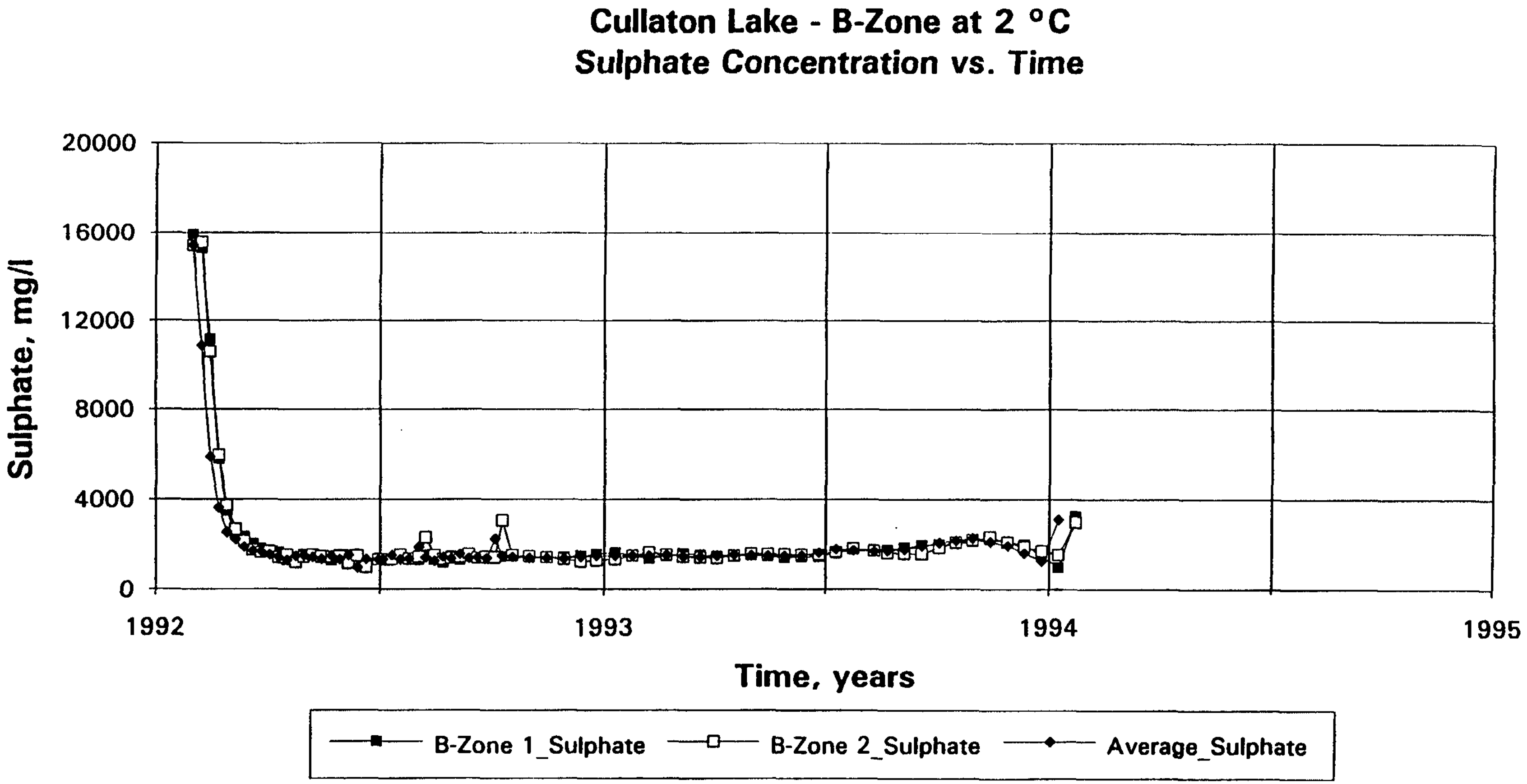

Fig. 11a B - Zone: effluent dissolved sulphate concentration at 2 °C.

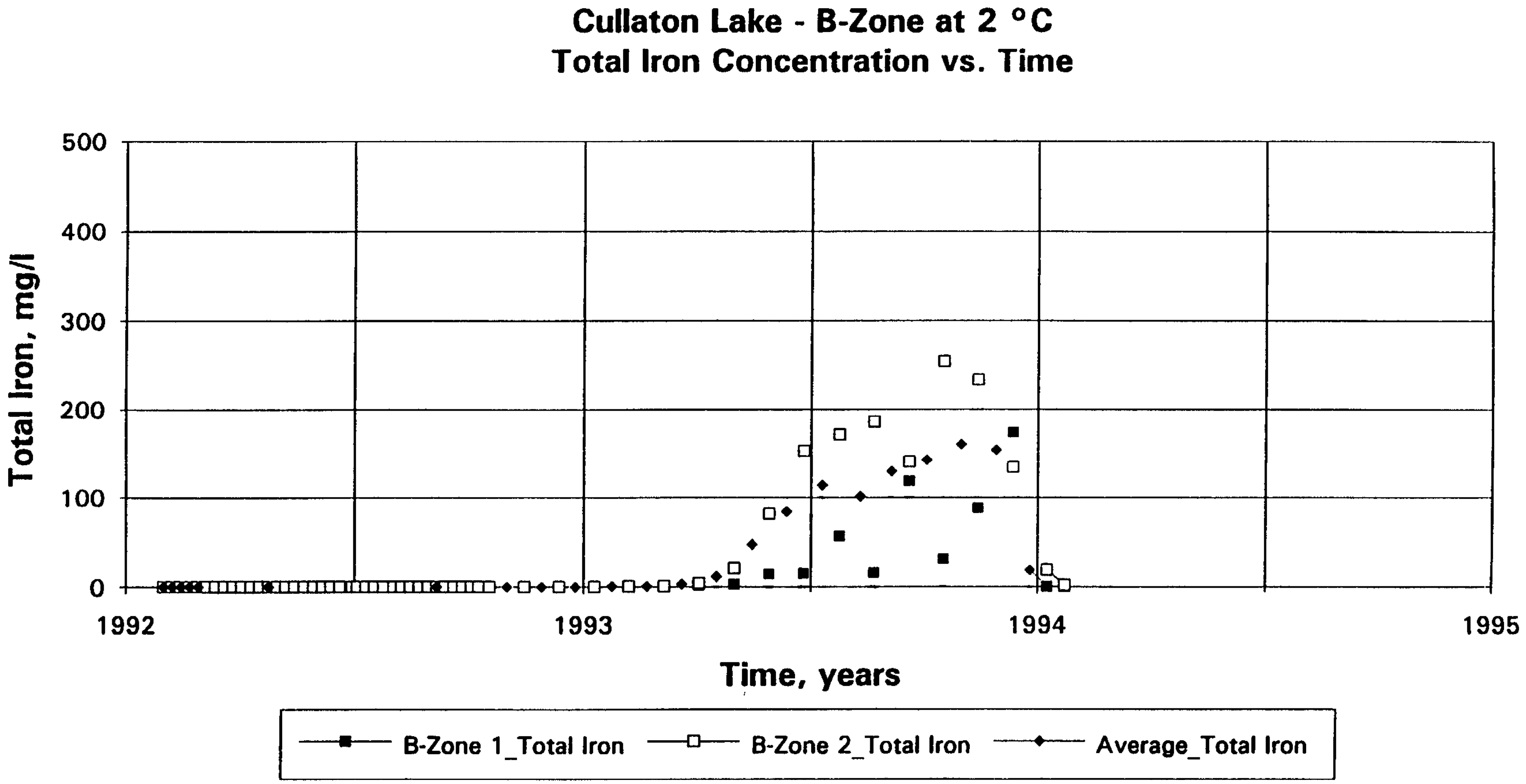

Fig. 14a B - Zone: effluent dissolved total iron concentration at 2 °C.

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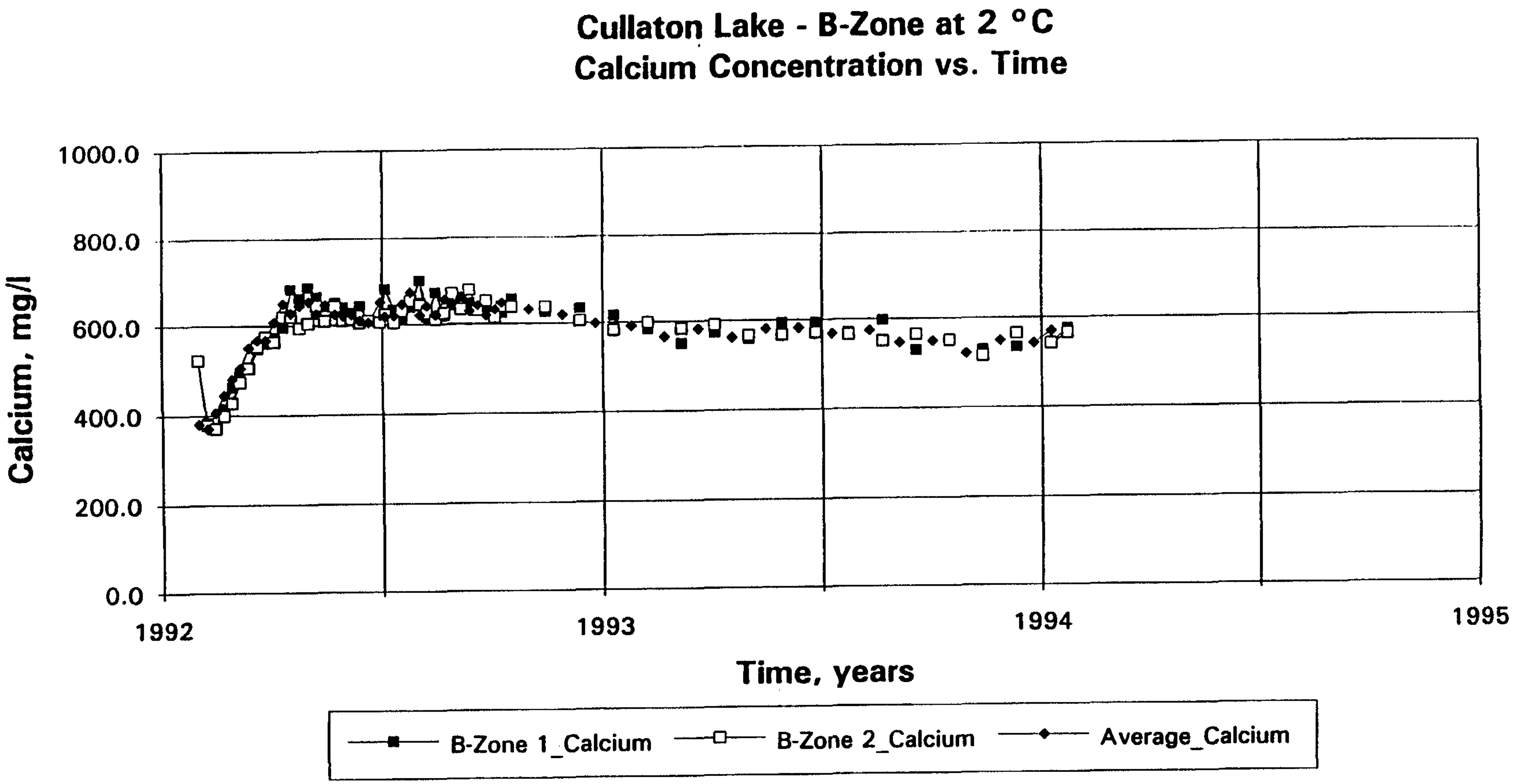

Fig. 15a B - Zone: effluent dissolved calcium concentration at 2 °C.

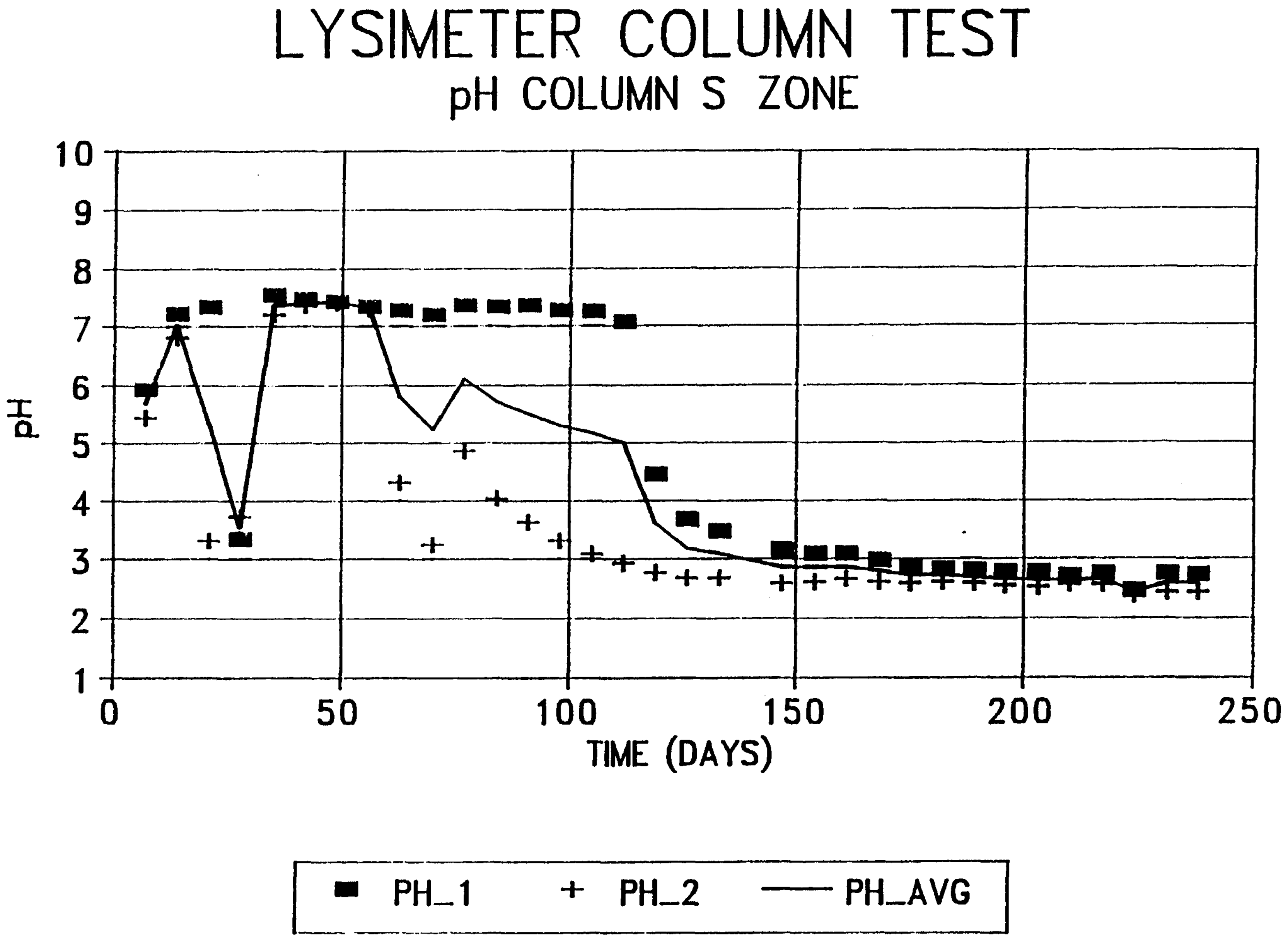

Fig. 26 - Effluent pH for S Zone columns.

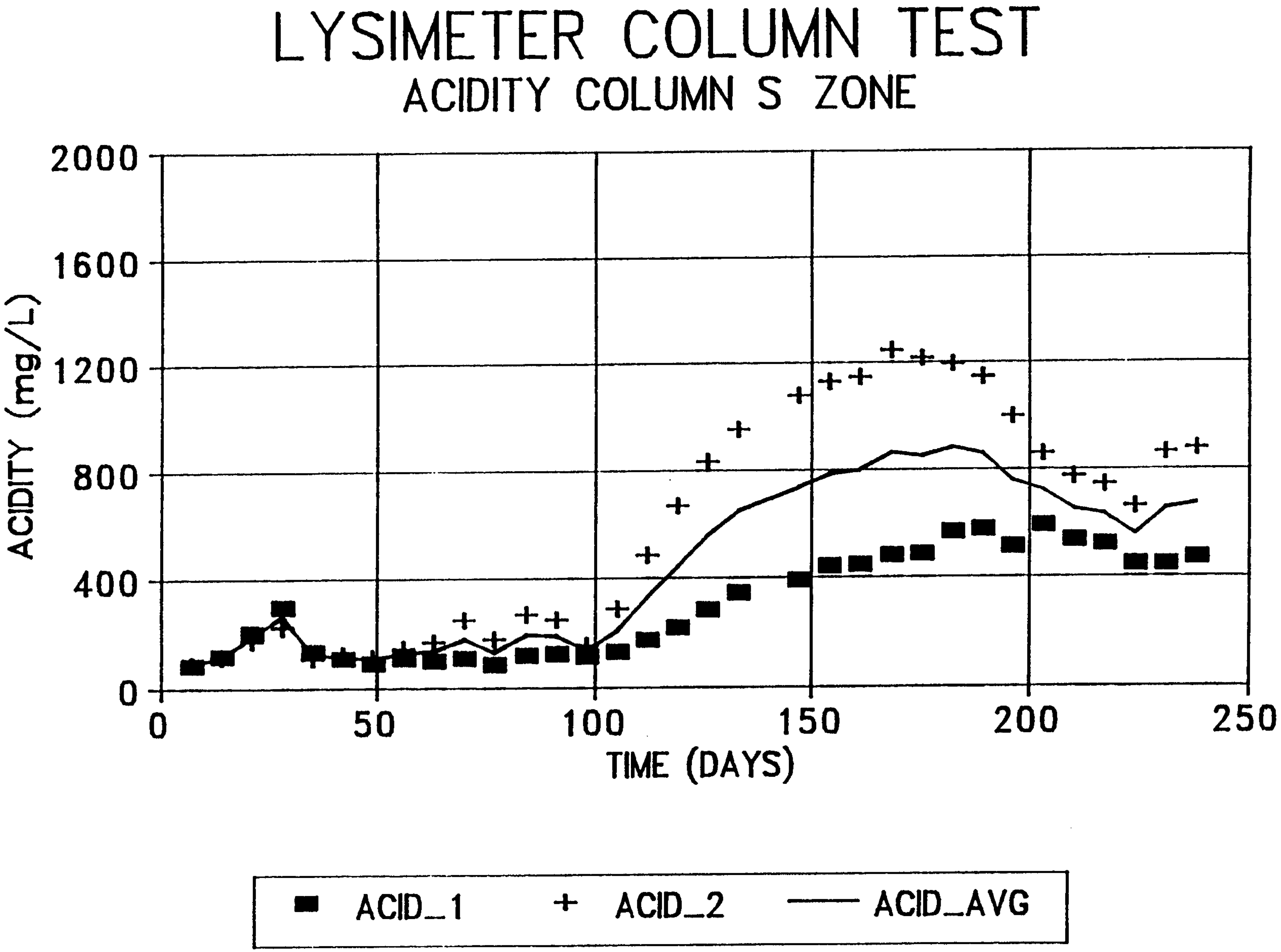

Fig. 29 - Effluent acidity for S Zone columns.

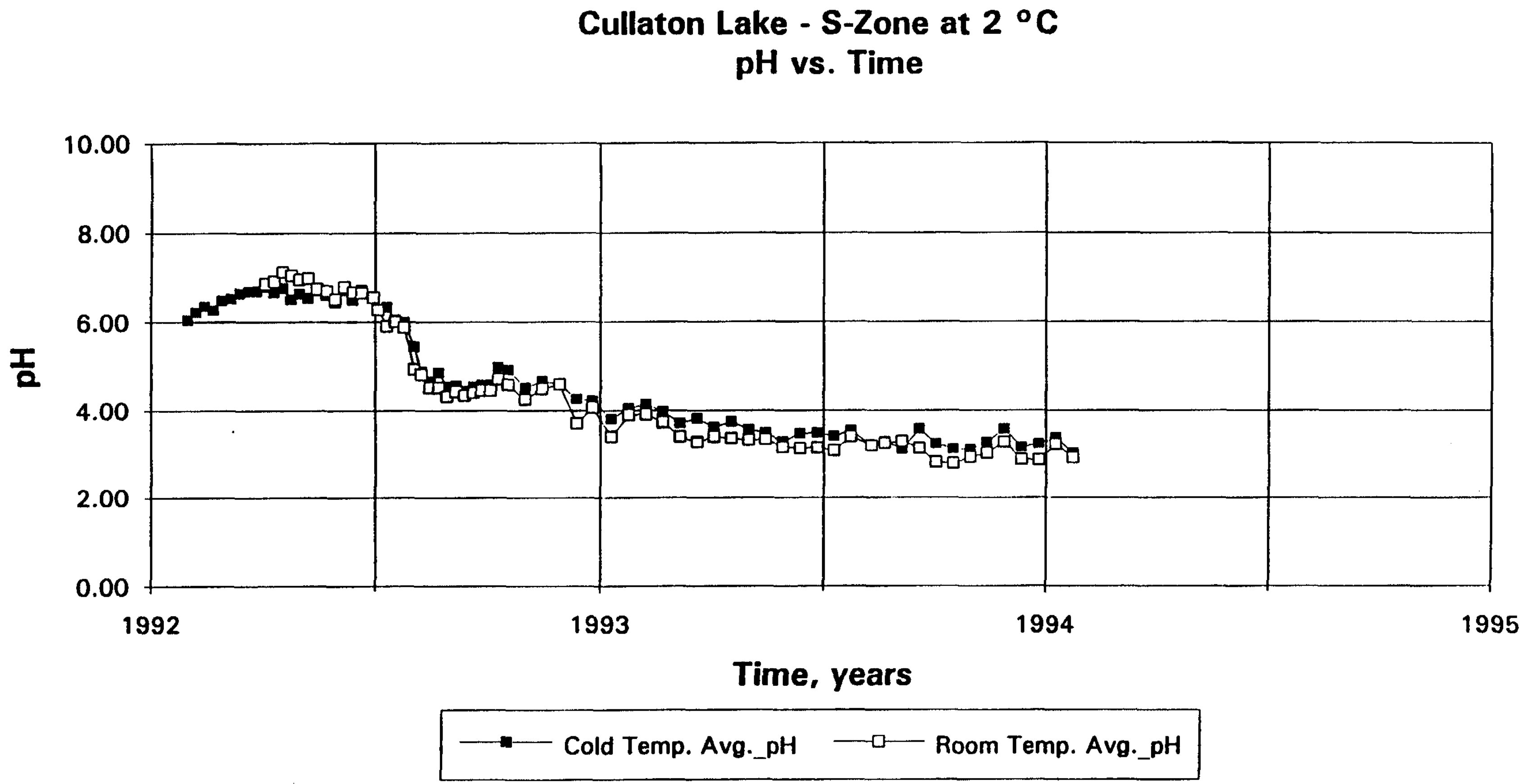

Fig. 30a S - Zone: effluent pH's at 2 °C and room temperature.

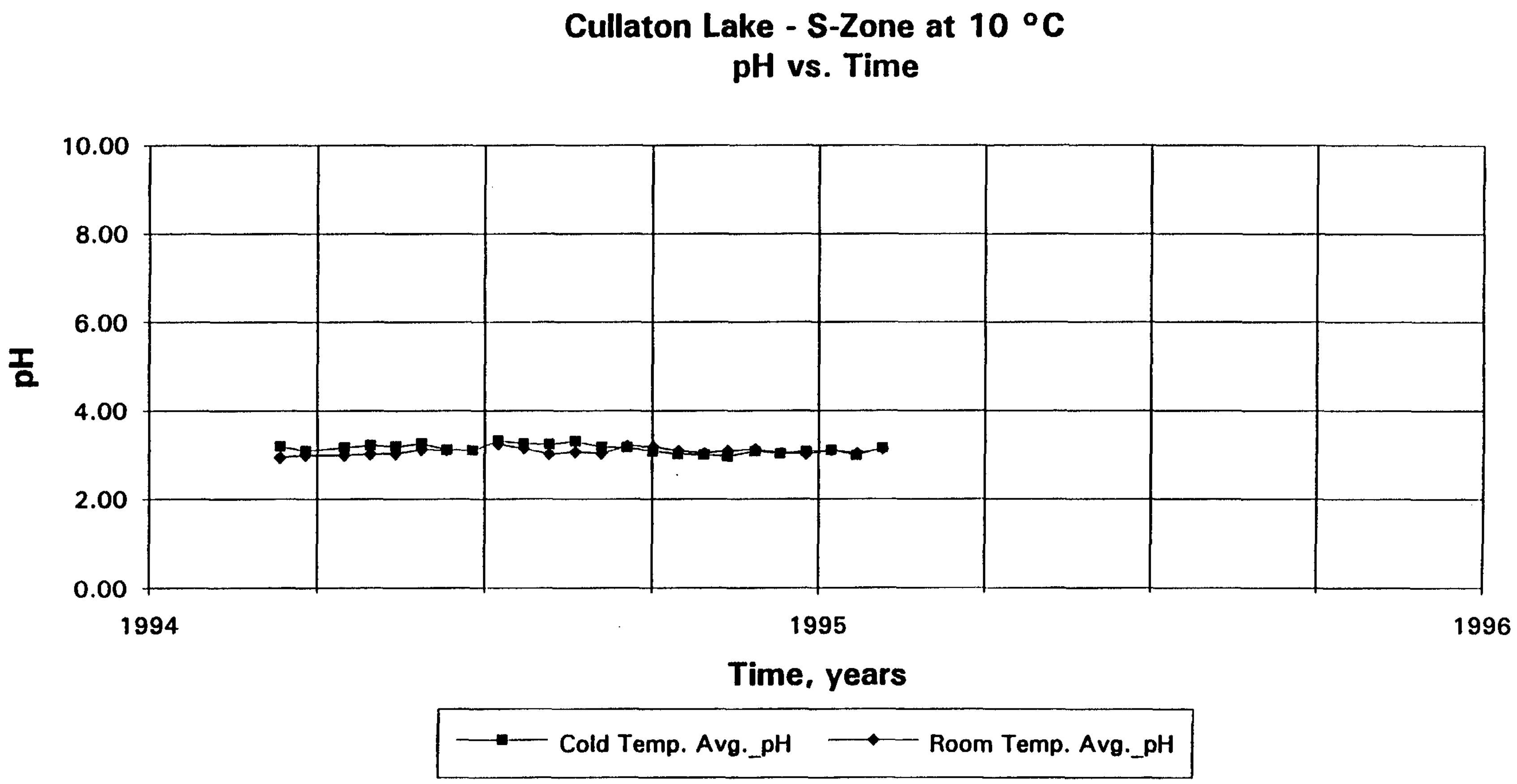

Fig. 30b S - Zone: effluent pH's at 10 °C and room temperature.

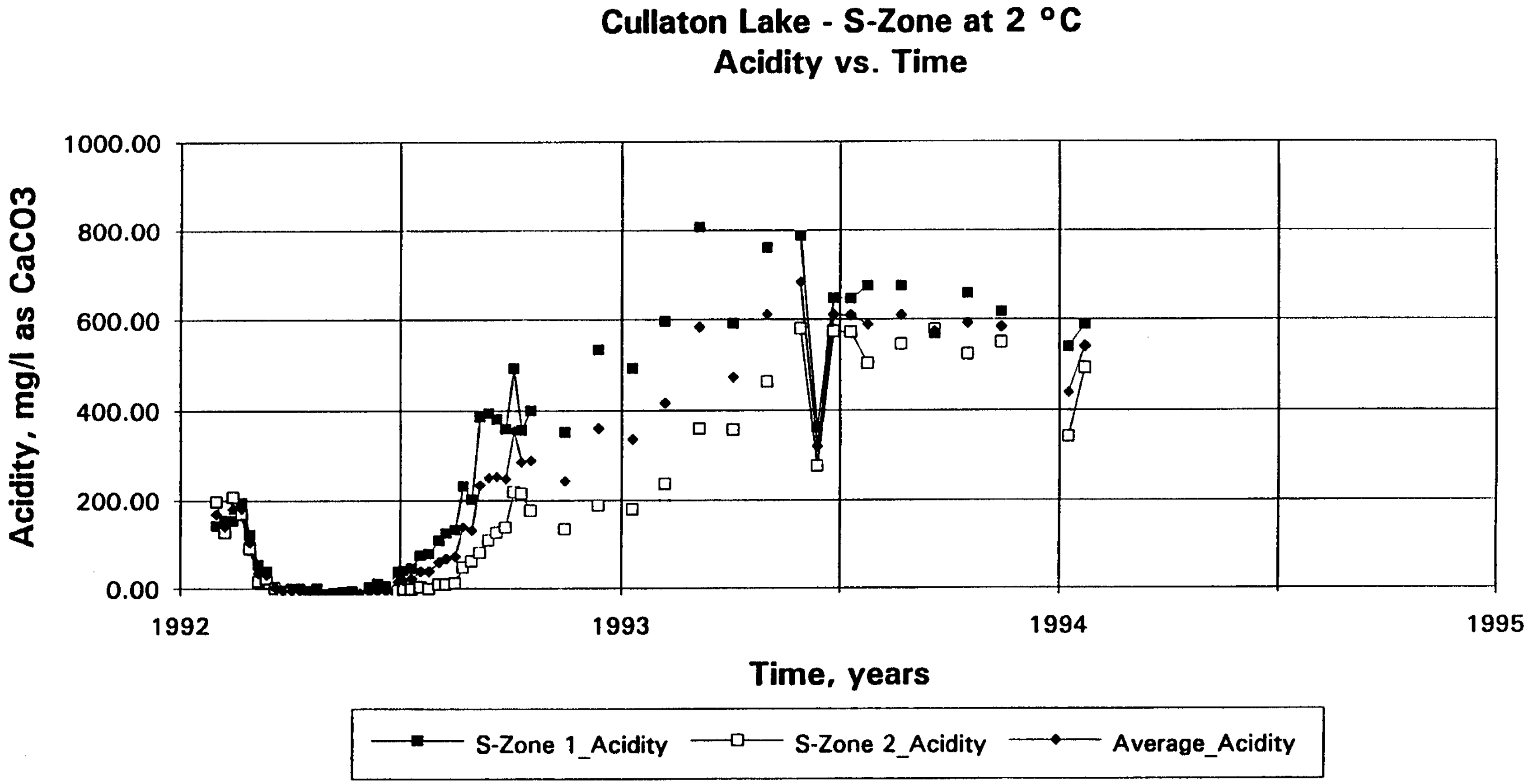

Fig. 33a S - Zone: effluent total acidity at 2 °C.

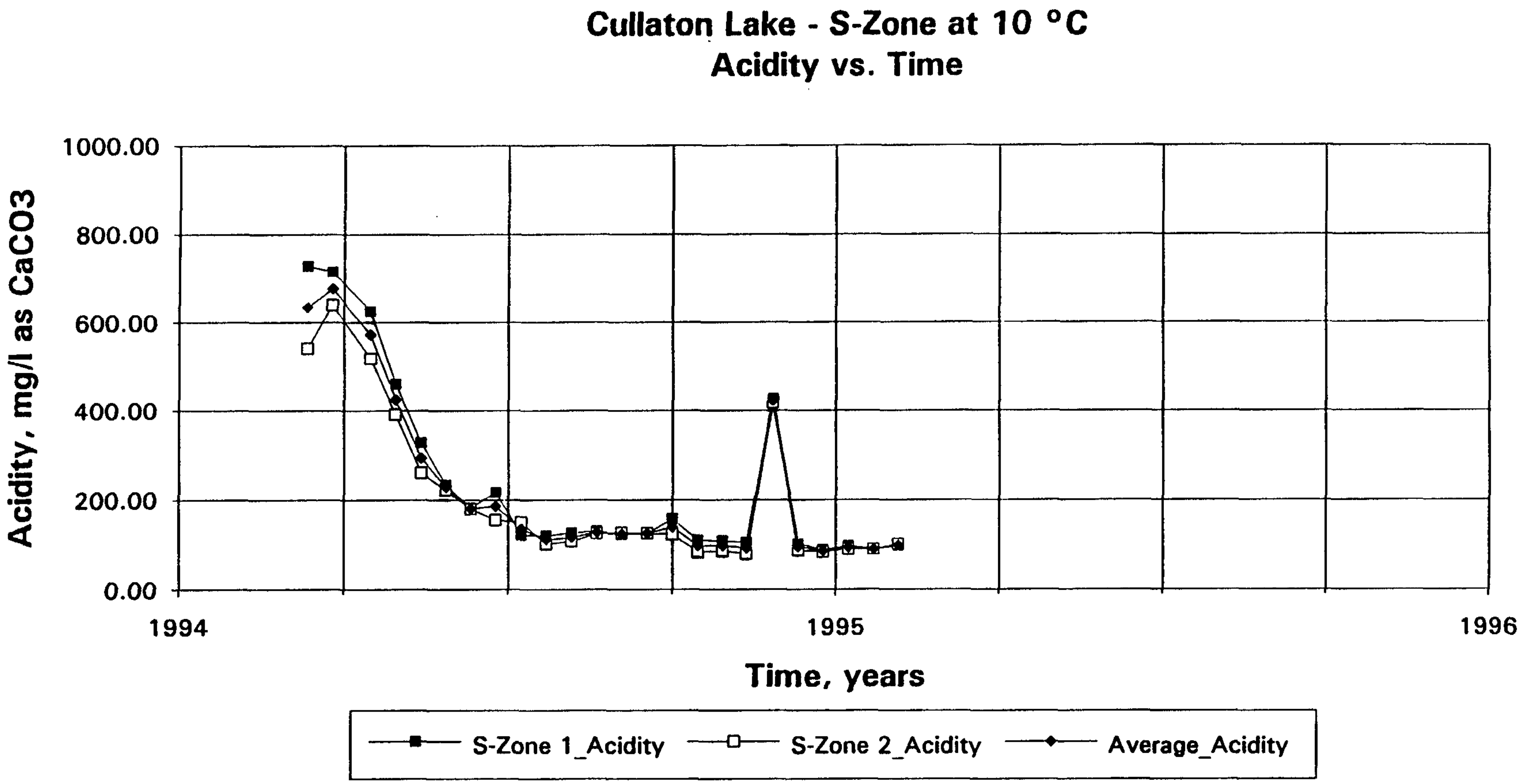

Fig. 33b S - Zone: effluent total acidity at 10 °C.

Results:

- Both B and S - Zones tailings have low sulphide contents (2.4 and 0.5 % S, respectively)
- Negative NNP (-31.6 and -14.3 Kg $CaCO_3$/tonne) and hence acid generating
- ARD more pronounced for B - zone then S - zone at 25 °C
- At 2 °C the acid generation rate is low providing a longer neutralization period and delayed ARD for B- zone than S-zone
- Upon freeze thaw continuity of ARD ceases
- At 10 °C some initial ARD occurs, but in all cases the high moisture retention characteristics of the tailings controls the duration of ARD

Results:

- Calculated rate of acid generation at 2 °C for B - Zone tailings is approximately 10% of that at 25 °C, which is comparable to reported value of ~ 16%
- Lowering of tailings temperature would delay occurrence of ARD but would not prevent it unless porewater is permanently frozen

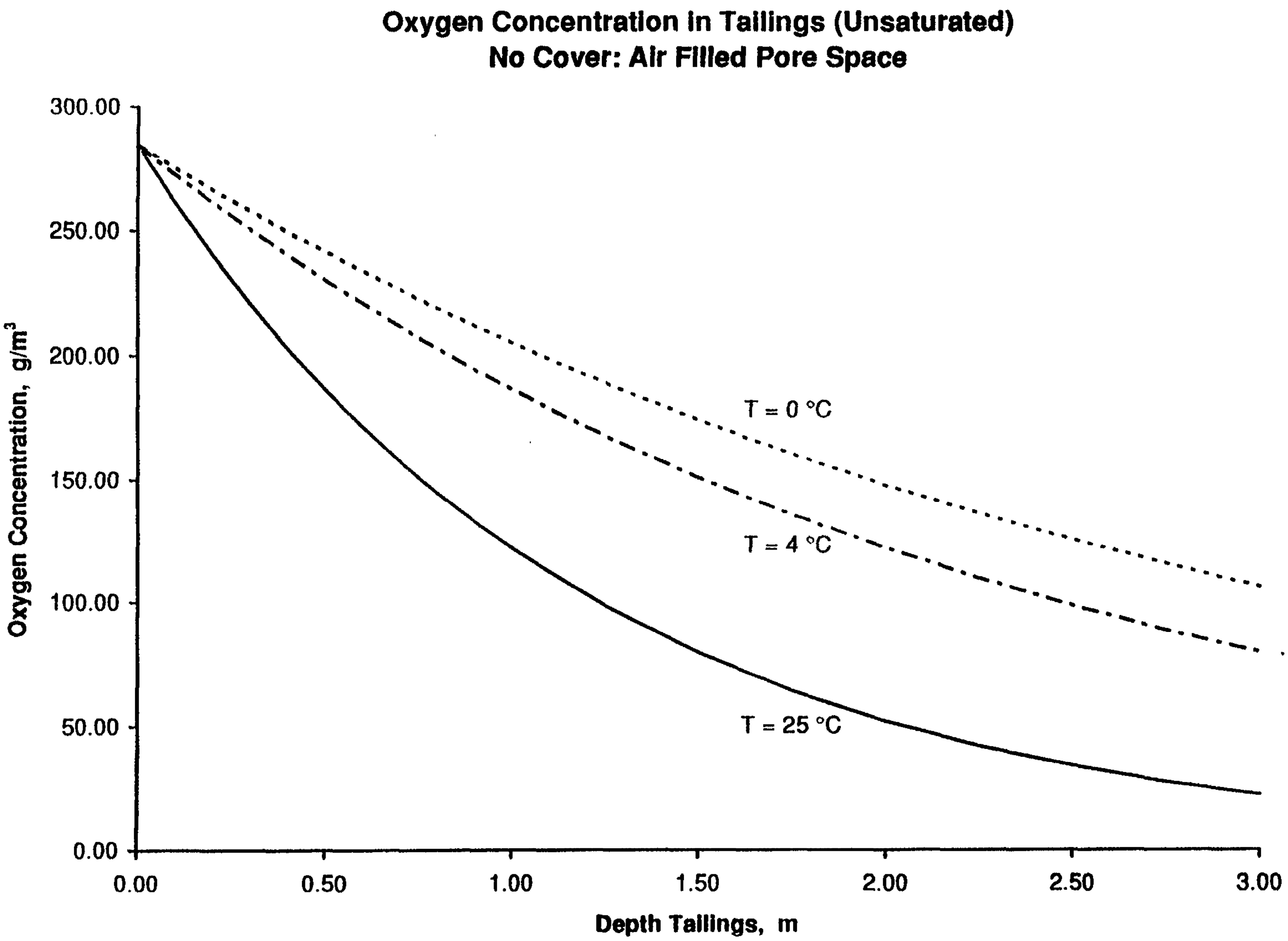

Figure 4.1 Oxygen concentration profiles as a function of depth at 25°, 4°, and 0°C in unsaturated tailings (air filled pore spaces) without cover. The air/tailings interface is at 0 m.

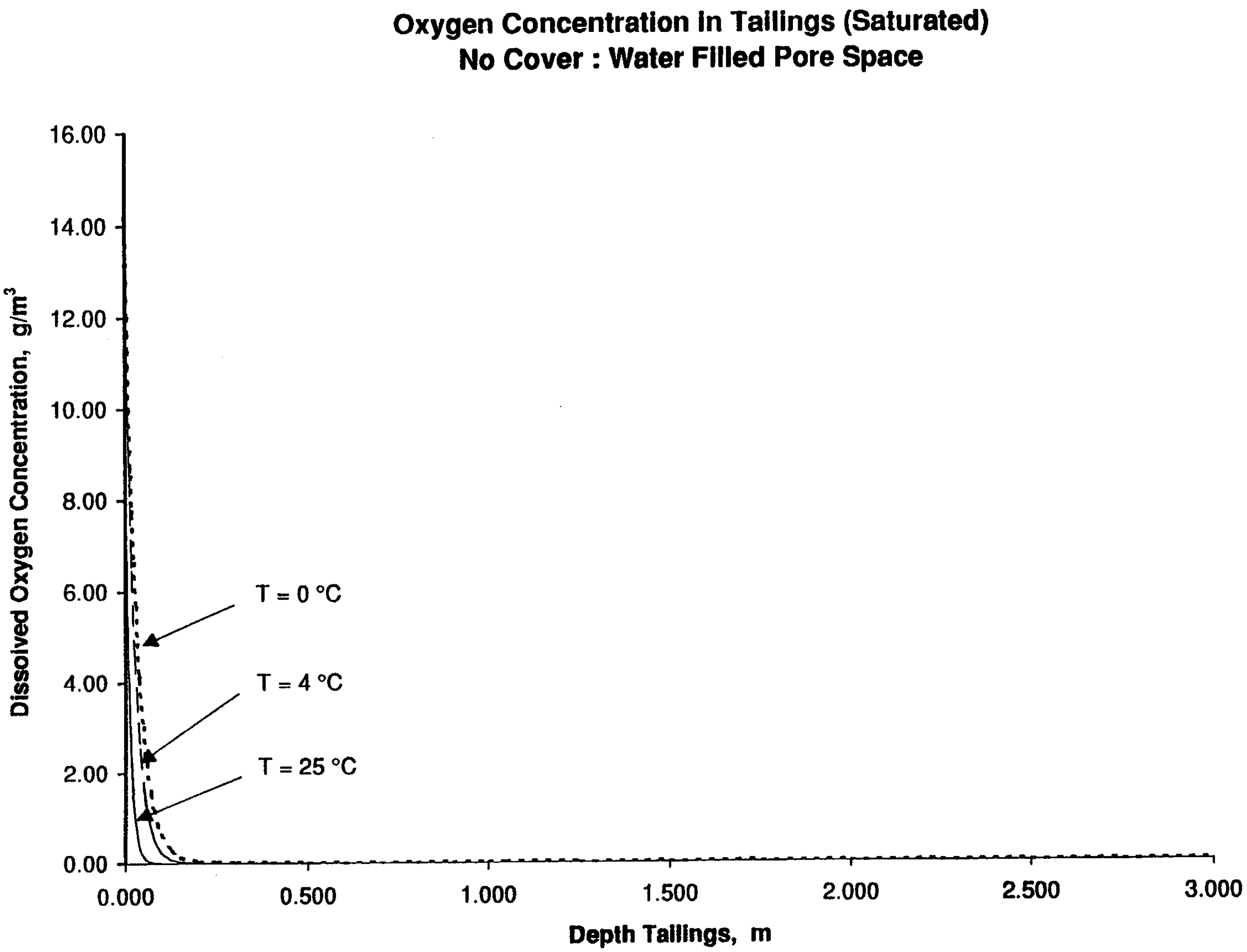

Figure 4.2 Dissolved oxygen concentration profiles as a function of depth at 25°, 4°, and 0°C in saturated tailings (water filled pore spaces) with no additional cover. The air/tailings interface is at 0 m.

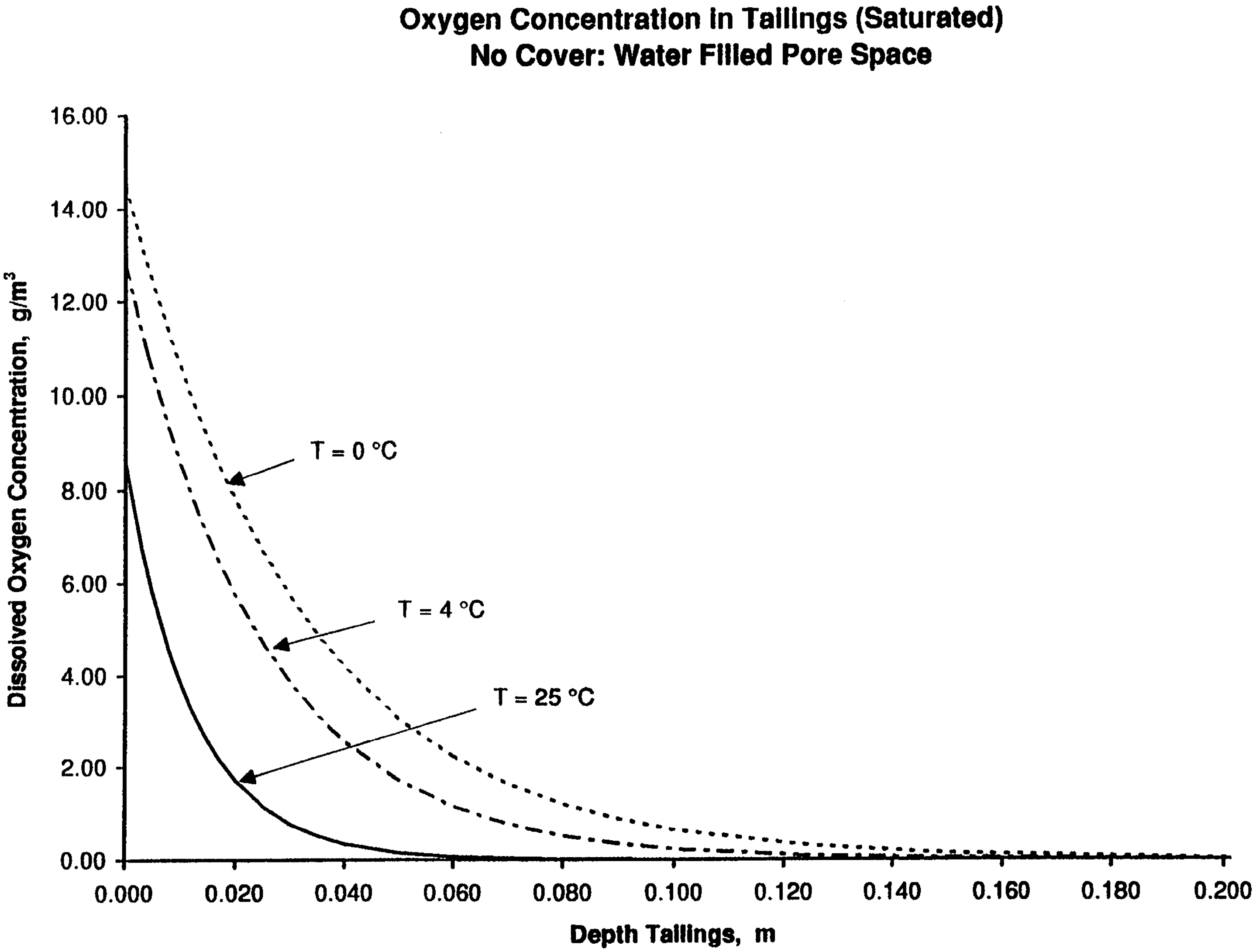

Figure 4.3 Dissolved oxygen concentration profiles (expanded scale) as a function of depth at 25°, 4°, and 0°C in saturated tailings (water filled pore spaces) with no additional cover. The air/tailings interface is at 0 m.

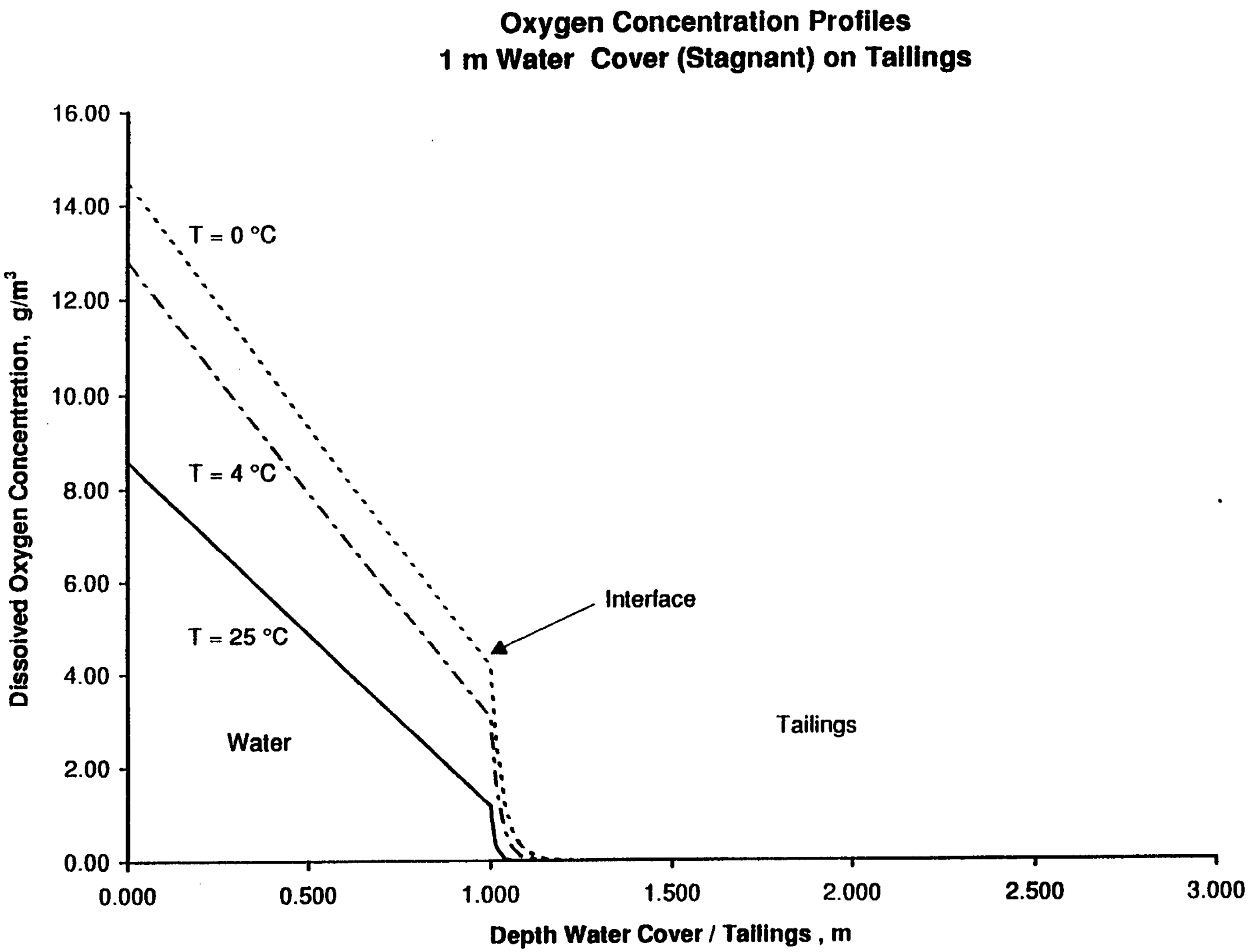

Figure 4.4 Dissolved oxygen concentration profiles as a function of depth at 25°, 4°, and 0°C in unmixed water cover of depth 1 m and underwater deposited tailings. The tailings-water interface is at depth 1.0 m from the surface of the water cover.

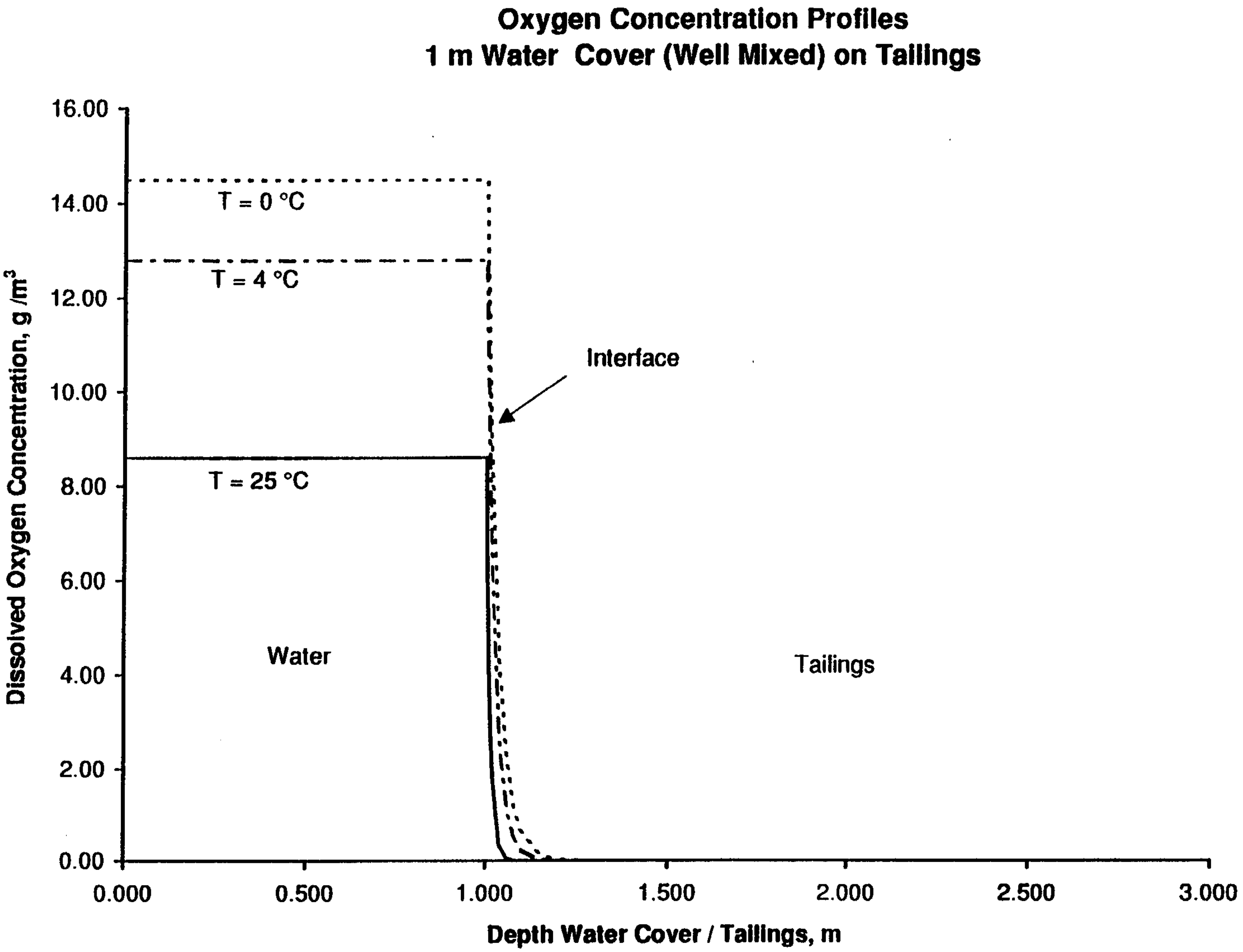

Figure 4.6 Dissolved oxygen concentration profiles as a function of depth at 25°, 4°, and 0°C in a well mixed water cover of depth 1 m and underwater deposited tailings. The tailings-water interface is at depth 1.0 m from the surface of the water cover.

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Table 4.2: Steady state oxygen diffusion flux J(0) in the waste at the interface boundary (g m^{-2} y^{-1}) and the total time (y) in years to completely oxidize a tailings pile, 100 ha in area containing 10 million tonnes of tailings at 20% pyrite.

Scenario		Flux J(0), g m^{-2} y^{-1}	Time (y) Years
Case 1:	No cover: air exposed and unsaturated	10,926 (25°C) 5,463 (4°C) 4,234 (0°C)	181.2 (25°C) 362.4 (4°C) 467.6 (0°C)
Case 2:	Water saturated waste: zero depth of water cover above the interface	3.49 (25°C) 2.60 (4°C) 2.28 (0°C)	5.67×10^5 (25°C) 7.61×10^5 (4°C) 8.68×10^5 (0°C)
Case 3:	Water covered waste: depth of water 1 m above the interface without mixing (stagnant)	0.47 (25°C) 0.62 (4°C) 0.65 (0°C)	4.21×10^6 (25°C) 3.19×10^6 (4°C) 3.05×10^6 (0°C)
Case 4:	Water covered waste: depth of water 2 m above the interface without mixing (stagnant)	0.25 (25°C) 0.35 (4°C) 0.38 (0°C)	7.92×10^6 (25°C) 5.66×10^6 (4°C) 5.21×10^6 (0°C)
Case 5:	Water covered waste: depth of water 1 m above the interface and well mixed	3.49 (25°C) 2.60 (4°C) 2.28 (0°C)	5.67×10^5 (25°C) 7.61×10^5 (4°C) 8.68×10^5 (0°C)

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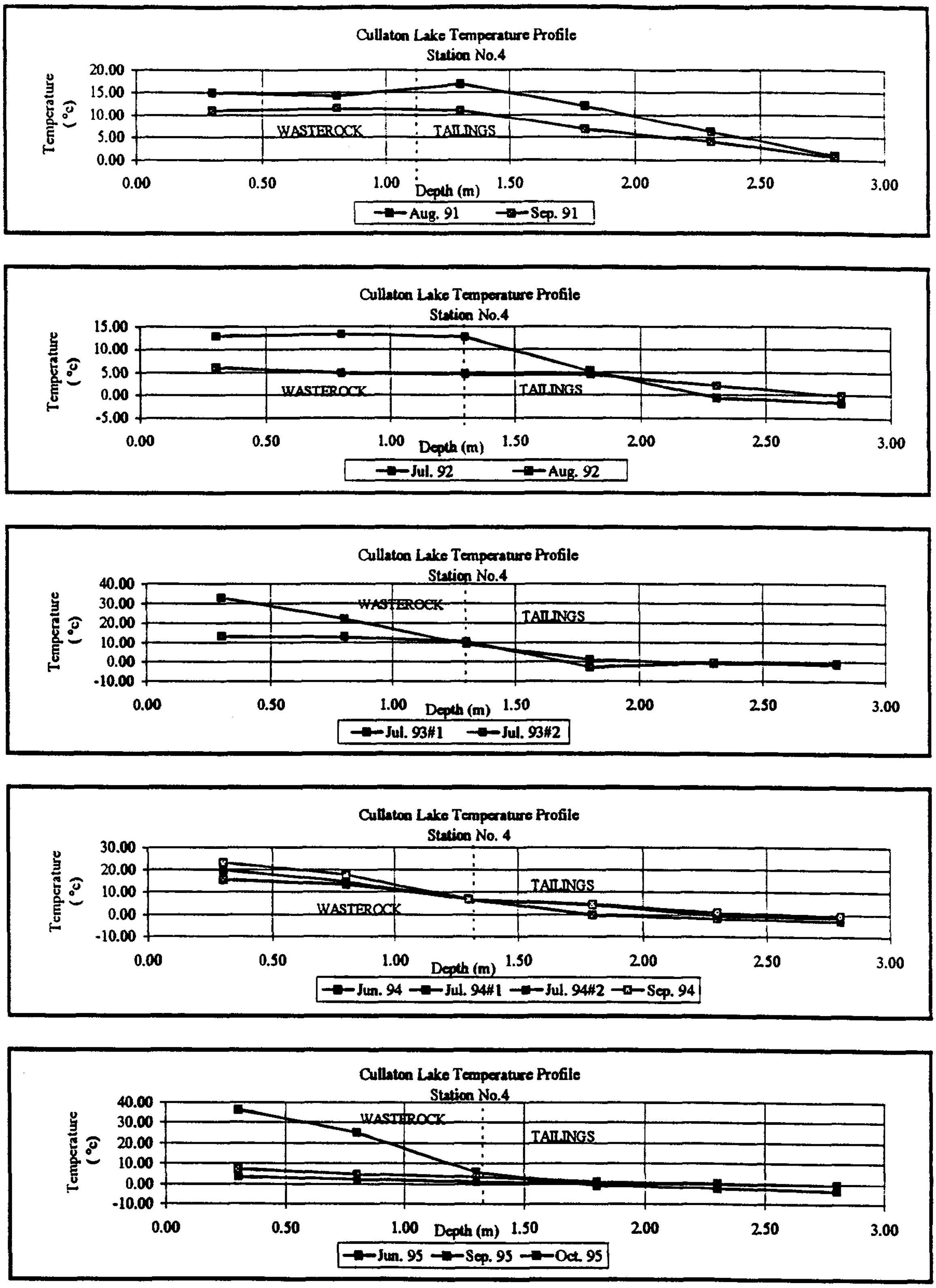

Fig. 56 Temperature profiles in wasterock and tailings at the Cullaton Lake site, Station 4.

3.7. SUMMARY OF CURRENT RESEARCH WORK ON TAILINGS

Dave Sego
University of Alberta

Measurement of Thermal Properties of Saturated Tailings (ARD Control in Permafrost Regions)

by

Dave Sego and Richard Dawson*

Geotechnical and Geoenvironmental Group
University of Alberta
***Norwest Mine Services Ltd**

Outline of presentation:

- Objective of research study
- Laboratory test program
- Test equipment and preliminary results
    - Physical and chemical properties
    - Consolidation and hydraulic conductivity
    - Unfrozen water content versus temperature
    - Thermal conductivity versus temperature
    - Frost heave

Objective of research carried out:

To measure the effects of pore water chemistry and sulfides on the unfrozen water content of saturated tailings.

Need for research to be carried out:

The thermal and hydraulic flow properties of freezing and frozen tailings are strongly influenced by amount of unfrozen water in tailings at temperatures below freezing point.

Proposed test program:

The following test to be carried out on each tailings and with different fluids supplied.

- *Physical characterization* (grain size distribution, specific gravity, atterberg limits, mineralogy)
- *Chemical characterization* (pH, conductivity, acid base accounting, pore water sulfates)
- *Saturated flow and deformation characteristics of unfrozen and frozen samples* (consolidation and hydraulic conductivity)
- *Unfrozen water content versus temperature*
- *Thermal conductivity versus temperature*
- *Frost heave test*

Physical and chemical properties

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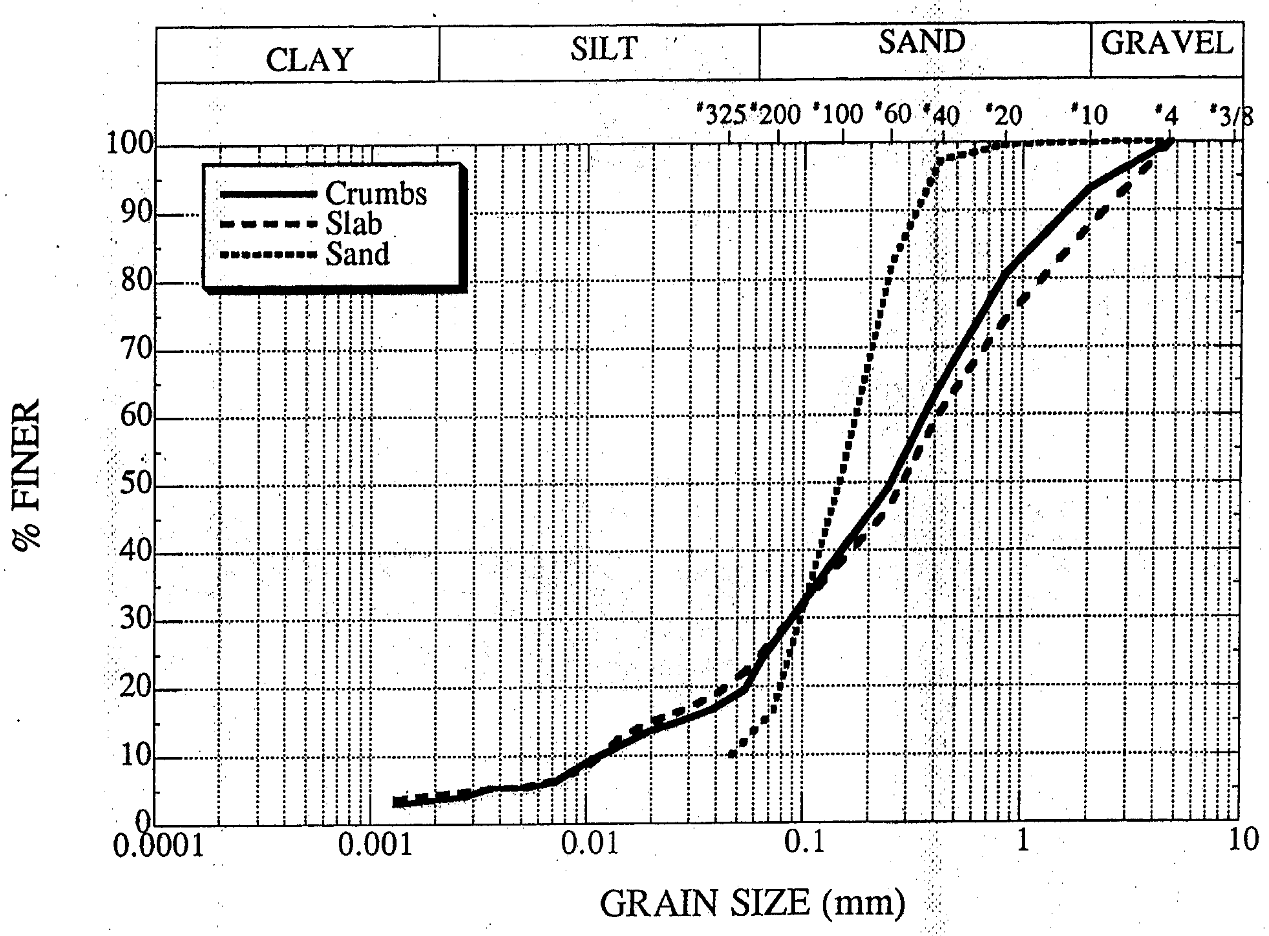
Oxidized Wellgreen Tailings
Grain Size Distribution



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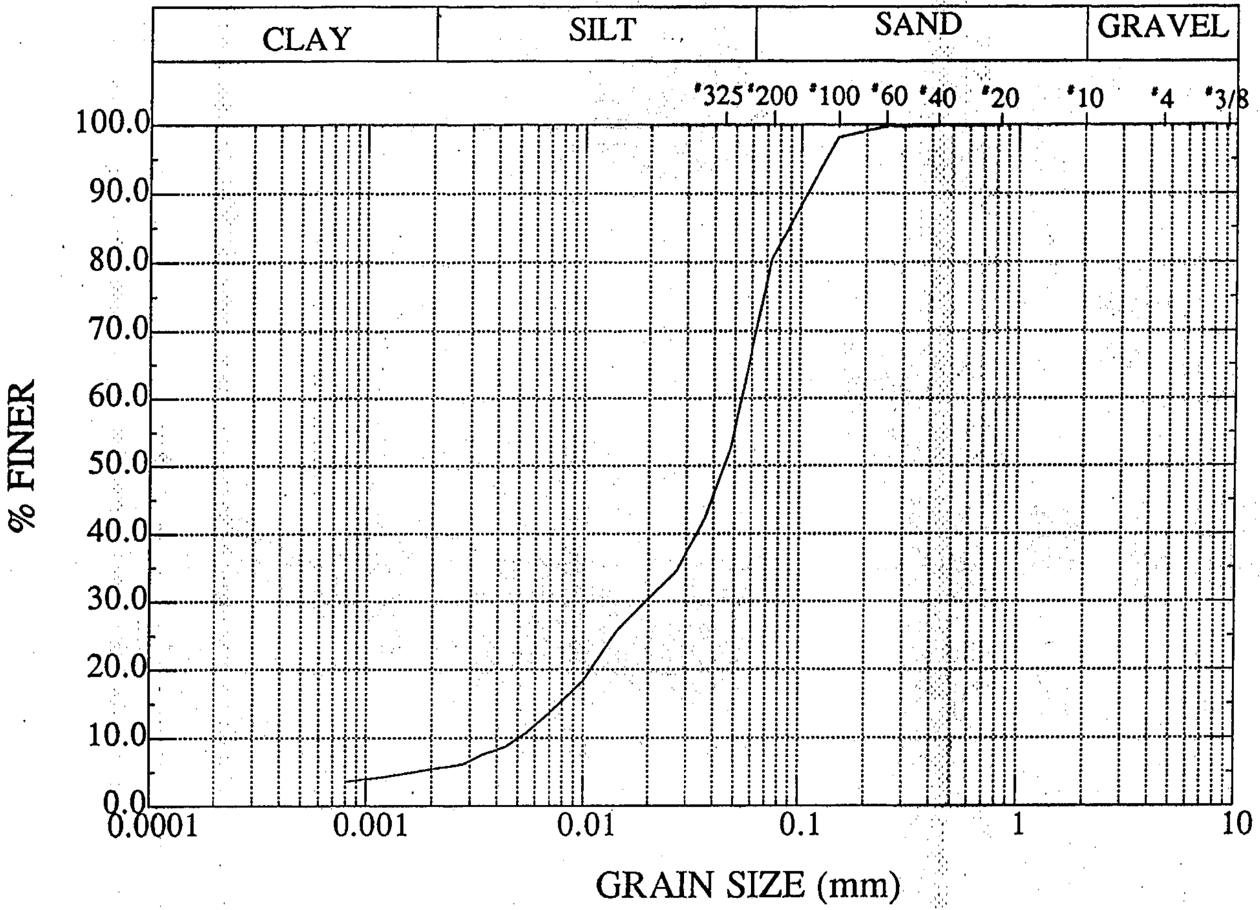
Lupin Tailings
Grain Size Distribution



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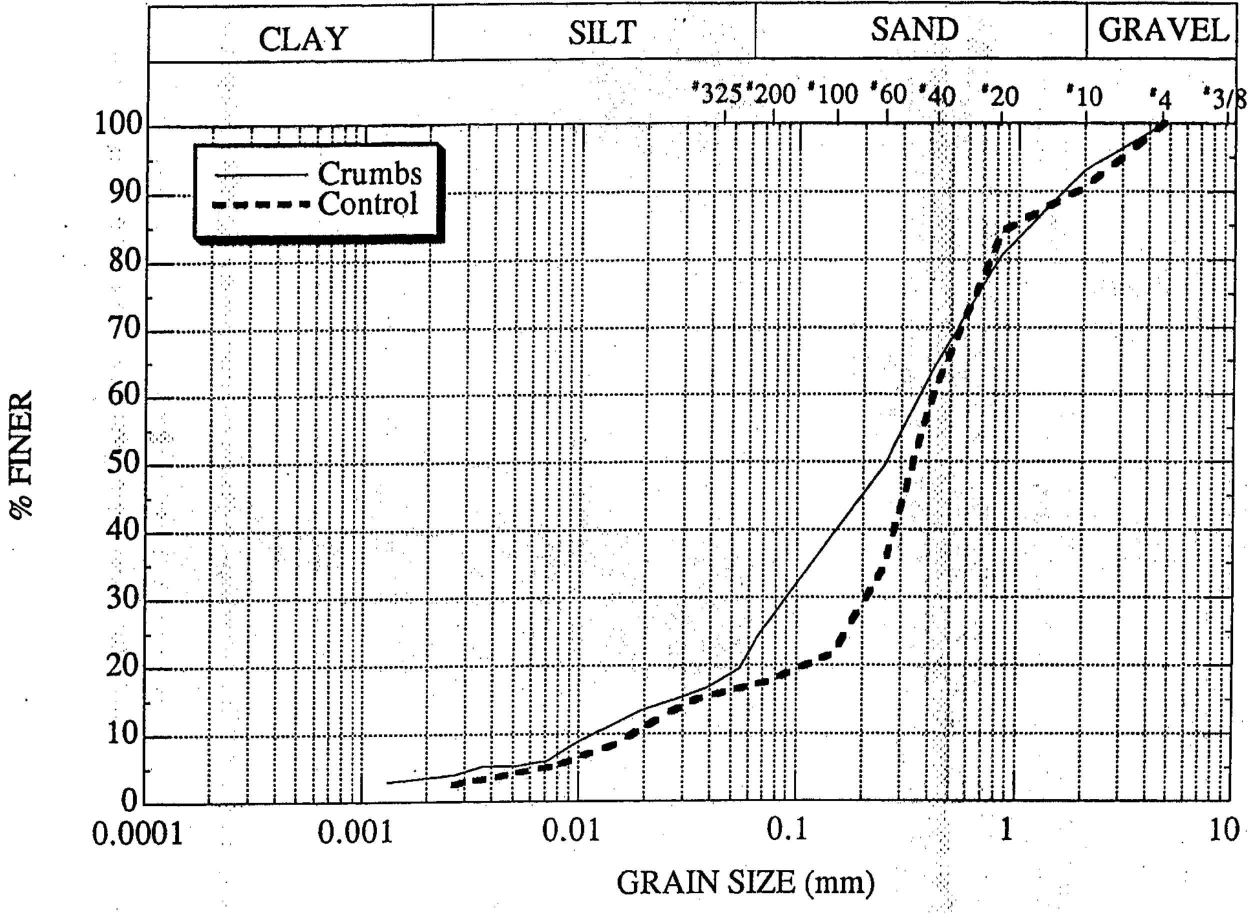
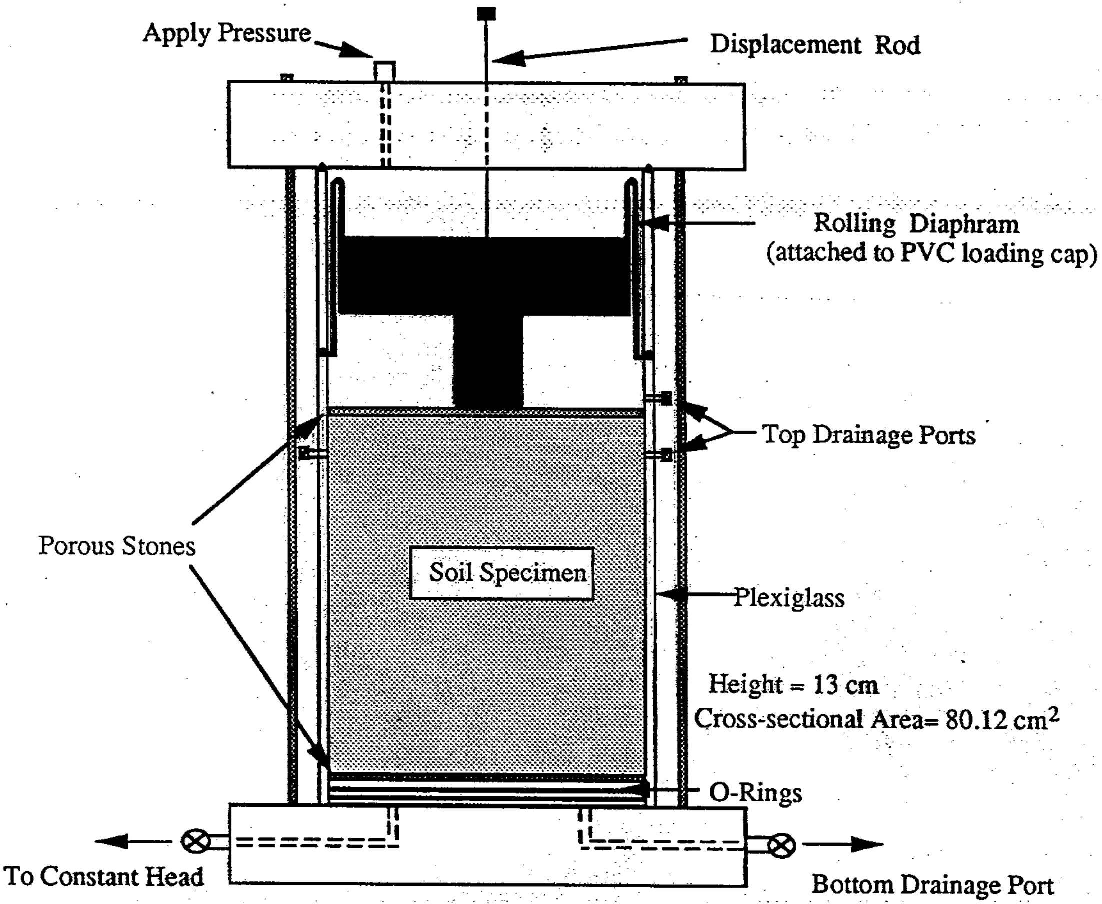
Oxidized Wellgreen Tailings
Grain Size Distribution

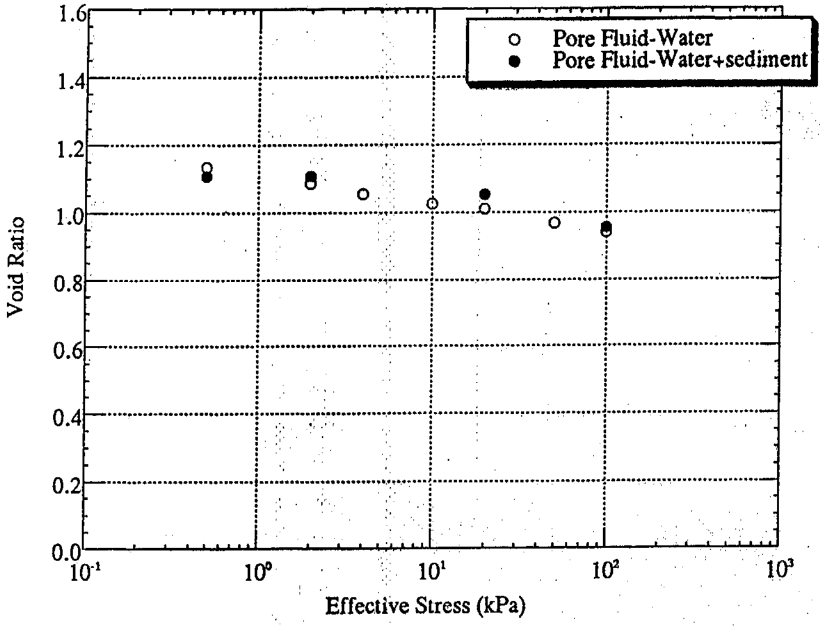


Consolidation and hydraulic conductivity

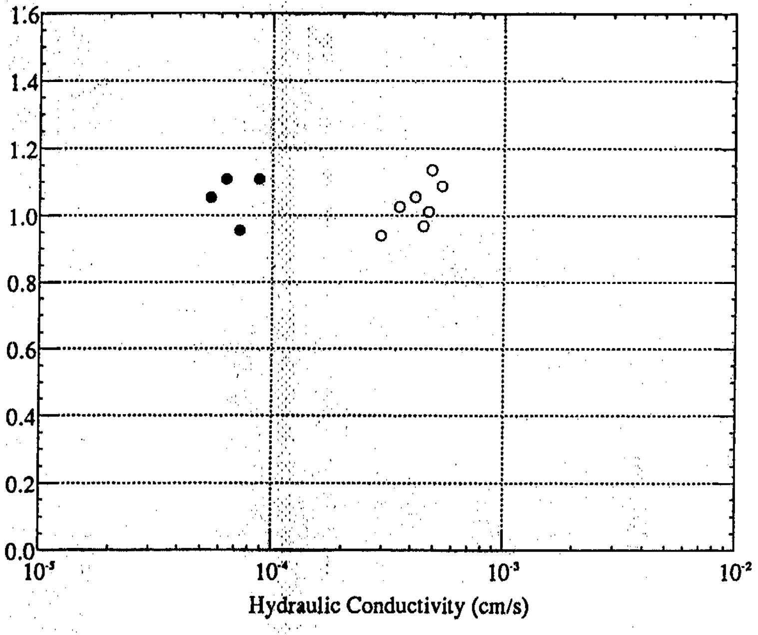
CONSOLIDATION CELL



COMPRESSIBILITY OF CRUMBS



HYDRAULIC CONDUCTIVITY OF CRUMBS



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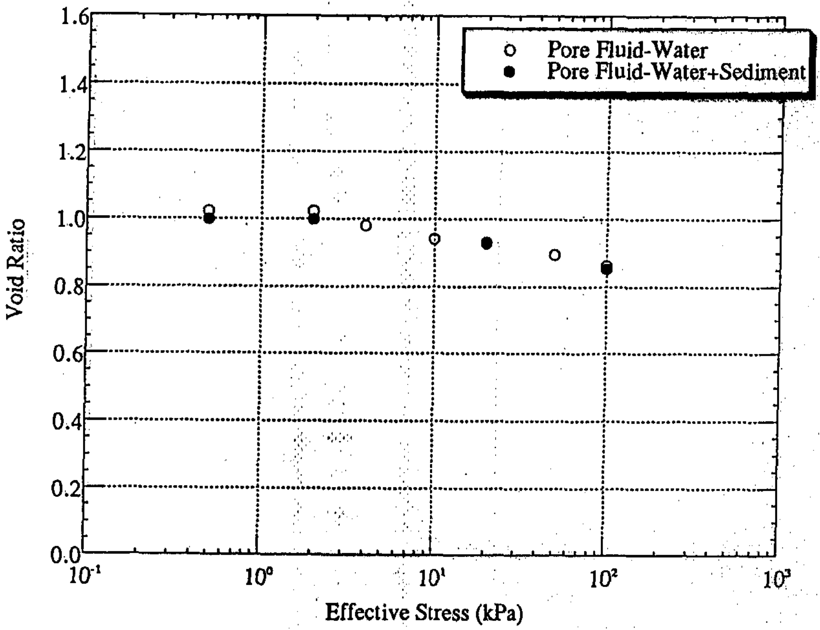
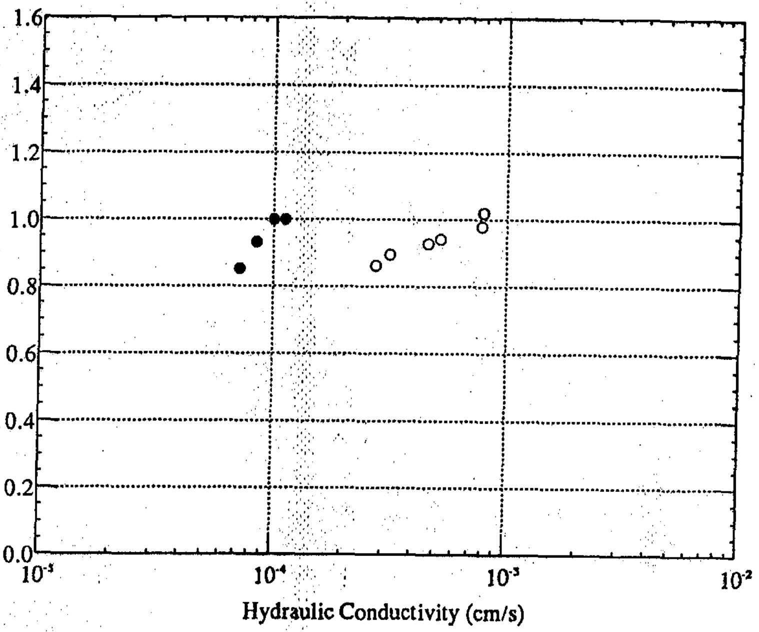
COMPRESSIBILITY OF SLAB



HYDRAULIC CONDUCTIVITY OF SLAB



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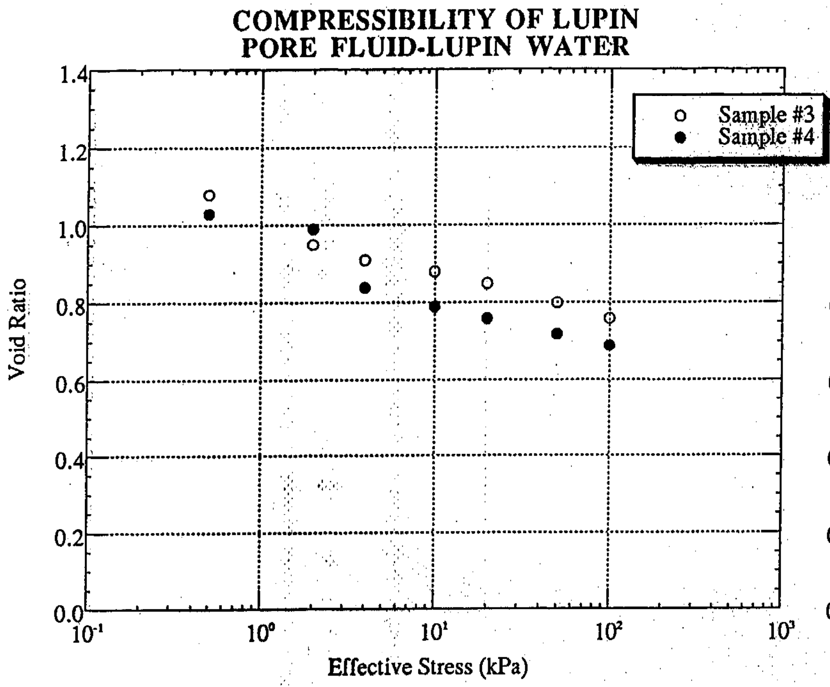
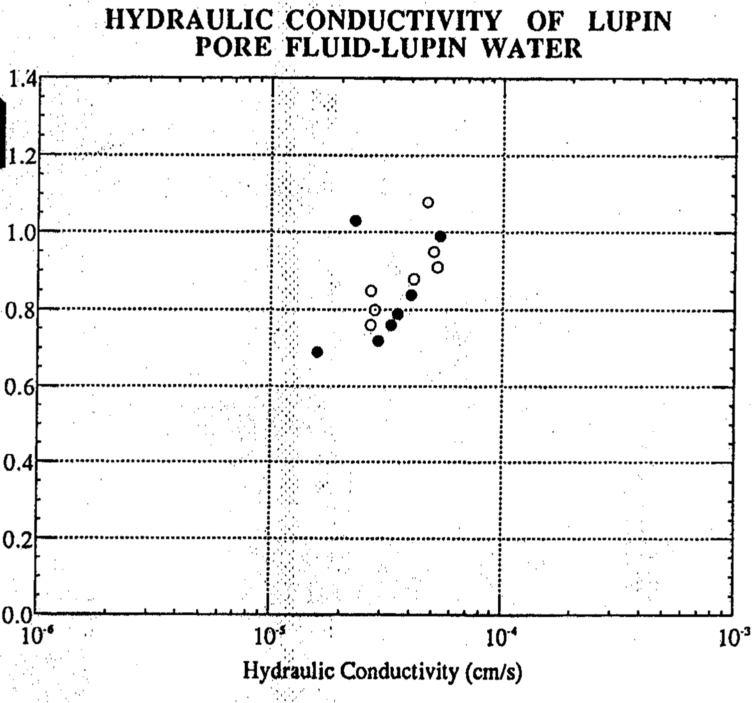


COMPRESSIBILITY OF LUPIN
PORE FLUID-LUPIN WATER



HYDRAULIC CONDUCTIVITY OF LUPIN
PORE FLUID-LUPIN WATER

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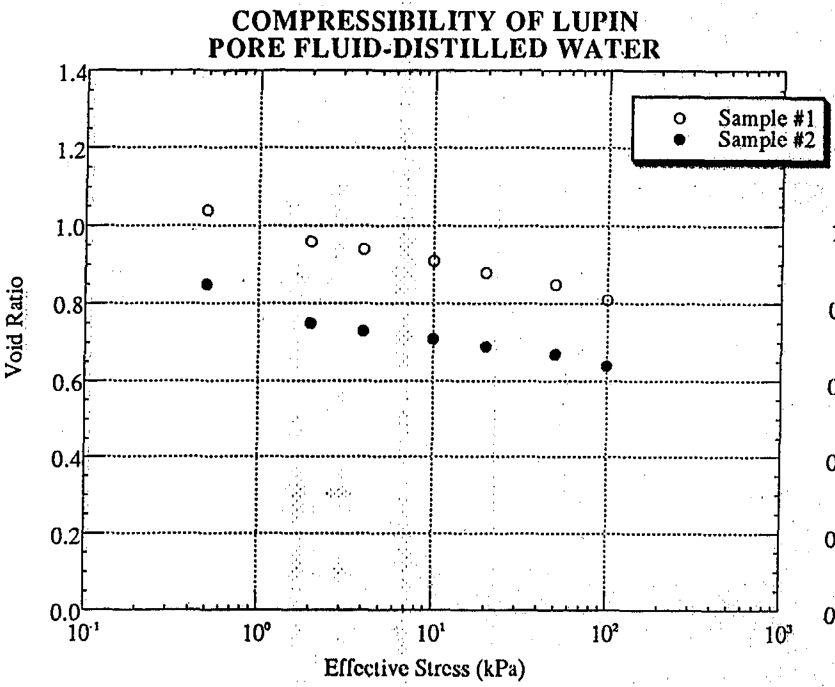
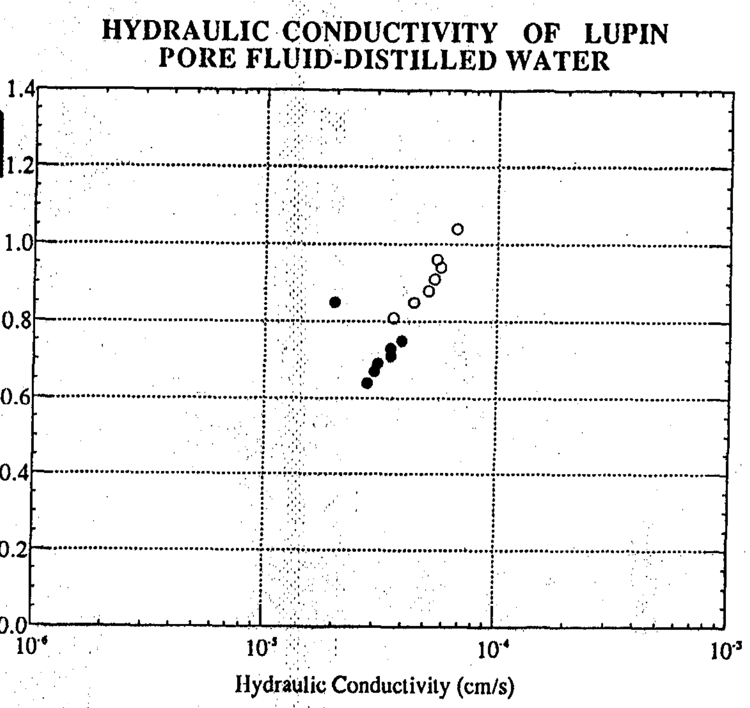

COMPRESSIBILITY OF LUPIN
PORE FLUID-DISTILLED WATER


HYDRAULIC CONDUCTIVITY OF LUPIN
PORE FLUID-DISTILLED WATER

Unfrozen water content versus temperature

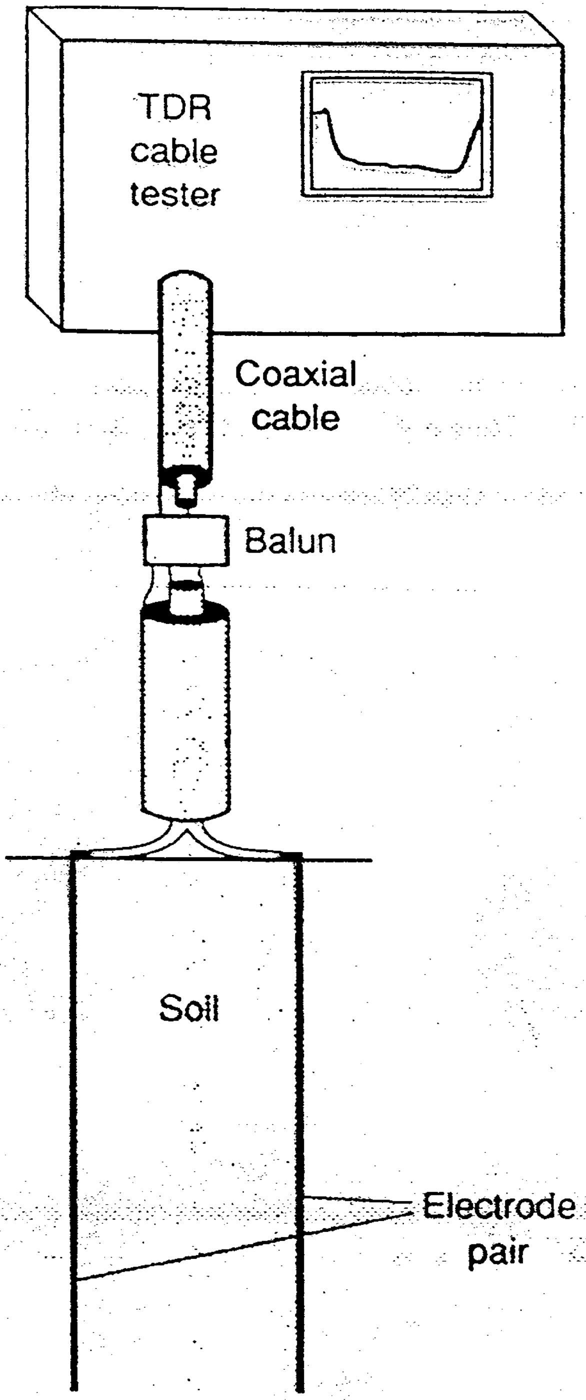


Figure 2.17 TDR circuit (modified from Herkelrath et al., 1991).

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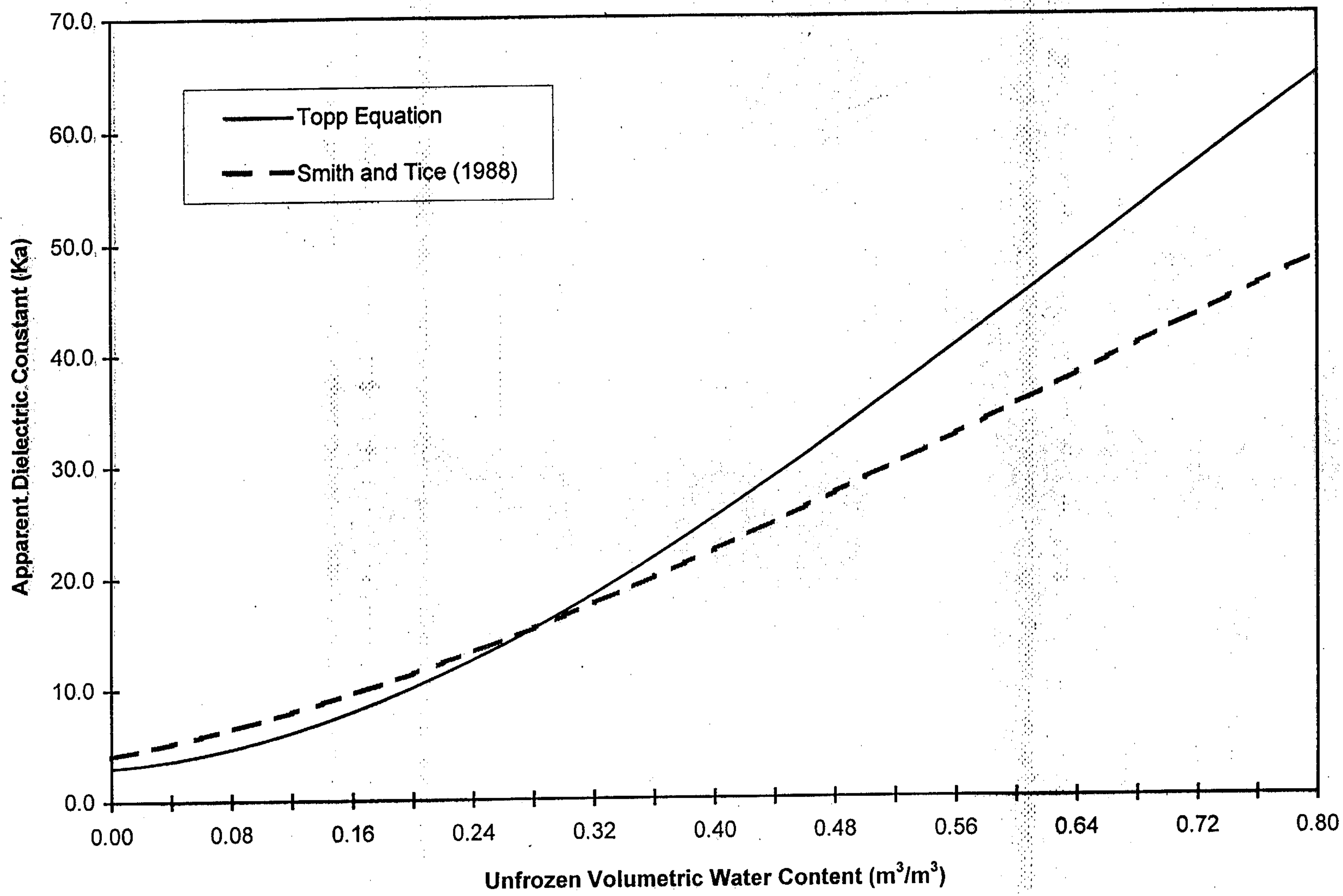
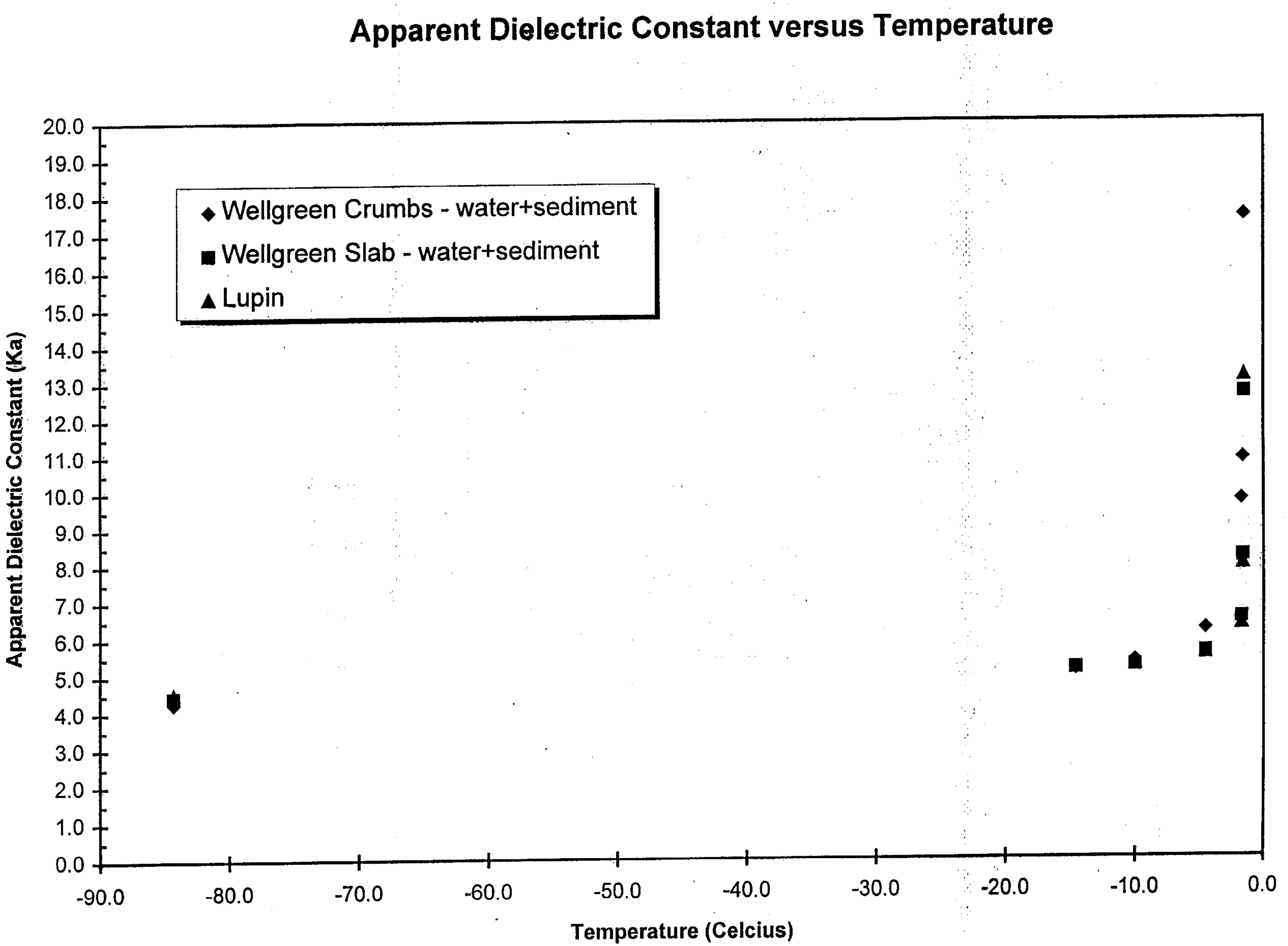
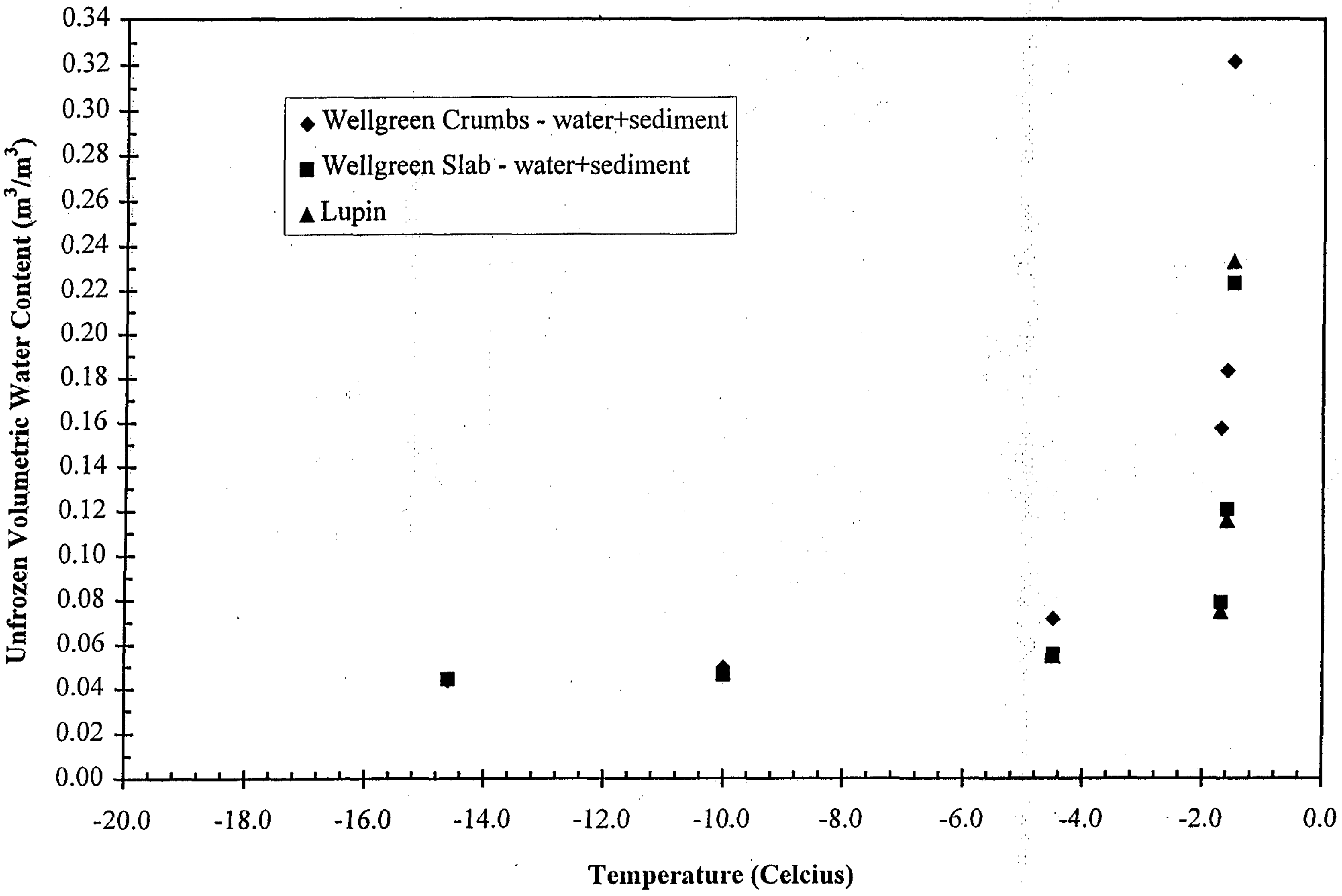
Apparent Dielectric Constant versus Unfrozen Water Content



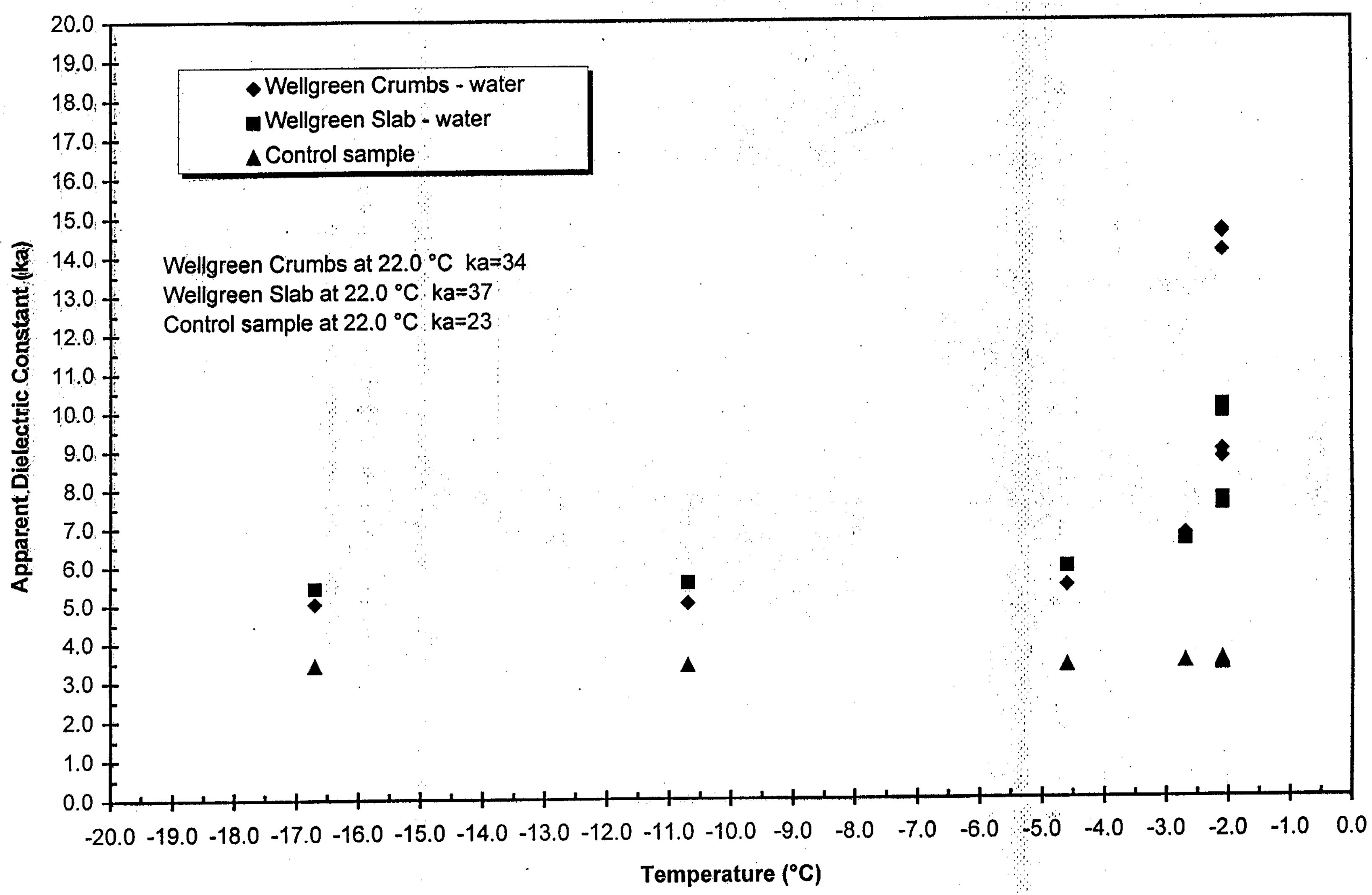

Apparent Dielectric Constant versus Temperature
◆ Wellgreen Crumbs - water+sediment
■ Wellgreen Slab - water+sediment
▲ Lupin
Apparent Dielectric Constant (Ka)
20.0
19.0
18.0
17.0
16.0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-90.0
-80.0
-70.0
-60.0
-50.0
-40.0
-30.0
-20.0
-10.0
0.0
Temperature (Celcius)



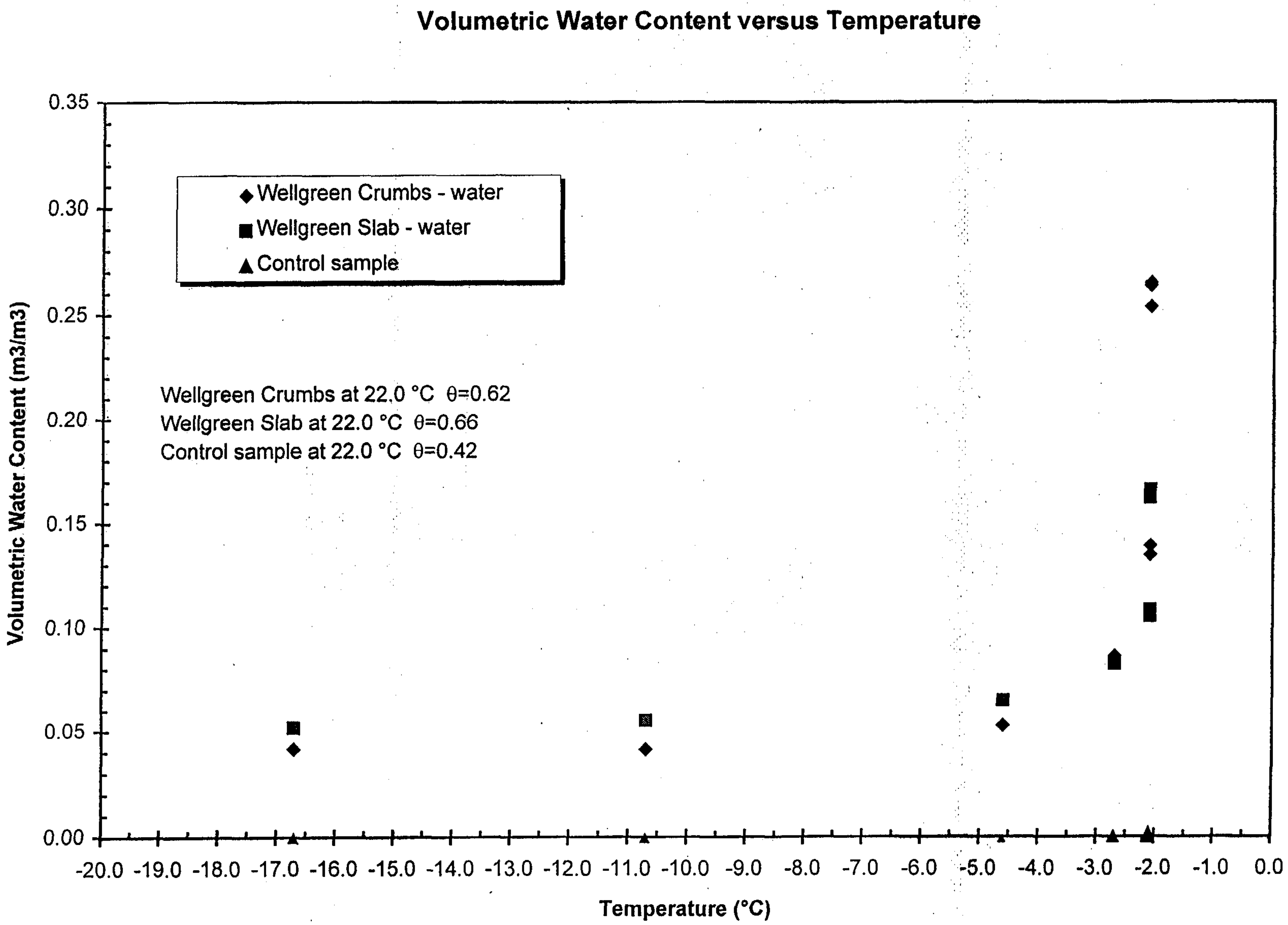
Unfrozen Volumetric Water Content versus Temperature

(Smith and Tice, 1988)

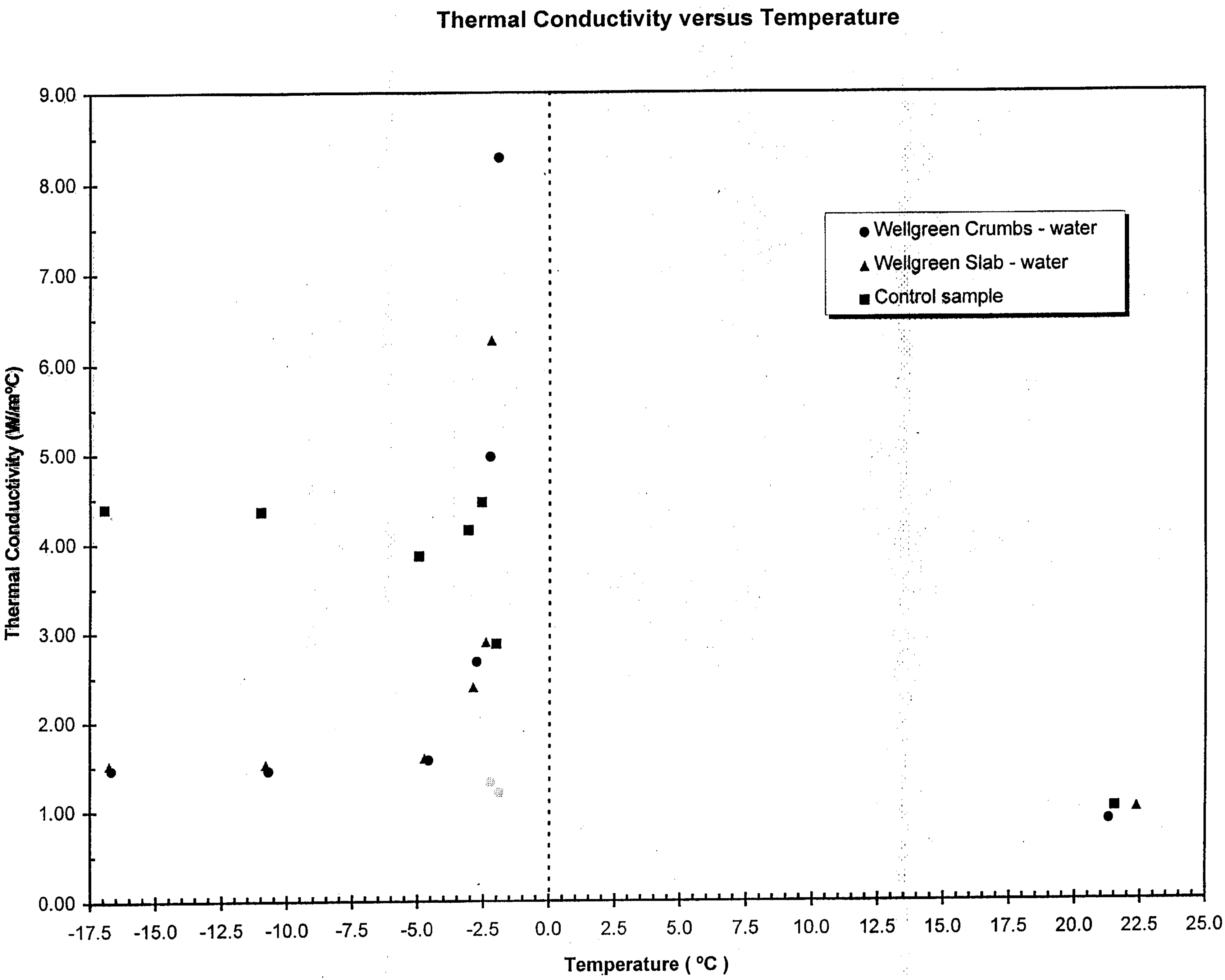
Apparent Dielectric Constant versus Temperature



Wellgreen Crumbs at 22.0 °C ka=34
Wellgreen Slab at 22.0 °C ka=37
Control sample at 22.0 °C ka=23

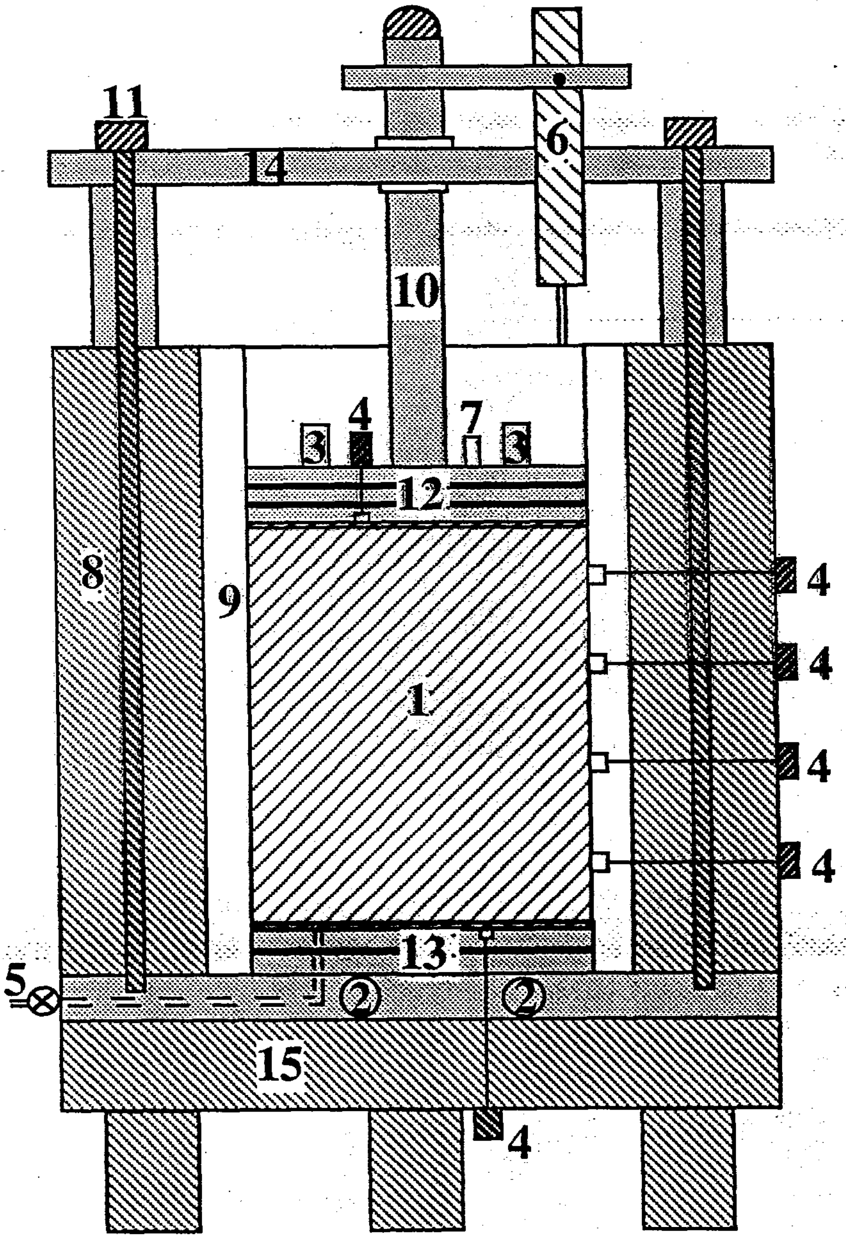

Volumetric Water Content versus Temperature
◆ Wellgreen Crumbs - water
■ Wellgreen Slab - water
▲ Control sample
Wellgreen Crumbs at 22.0 °C θ=0.62
Wellgreen Slab at 22.0 °C θ=0.66
Control sample at 22.0 °C θ=0.42
Volumetric Water Content (m3/m3)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-20.0
-19.0
-18.0
-17.0
-16.0
-15.0
-14.0
-13.0
-12.0
-11.0
-10.0
-9.0
-8.0
-7.0
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
Temperature (°C)

Thermal conductivity versus temperature

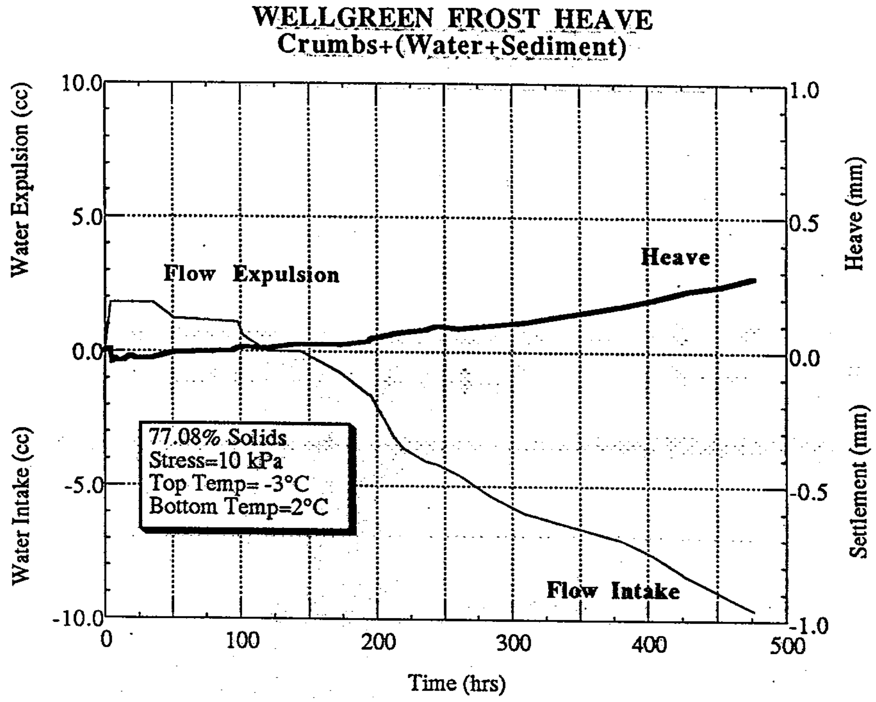

Thermal Conductivity versus Temperature
Thermal Conductivity (W/m°C)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
-17.5
-15.0
-12.5
-10.0
-7.5
-5.0
-2.5
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
25.0
Temperature (°C)
● Wellgreen Crumbs - water
▲ Wellgreen Slab - water
■ Control sample

Frost heave

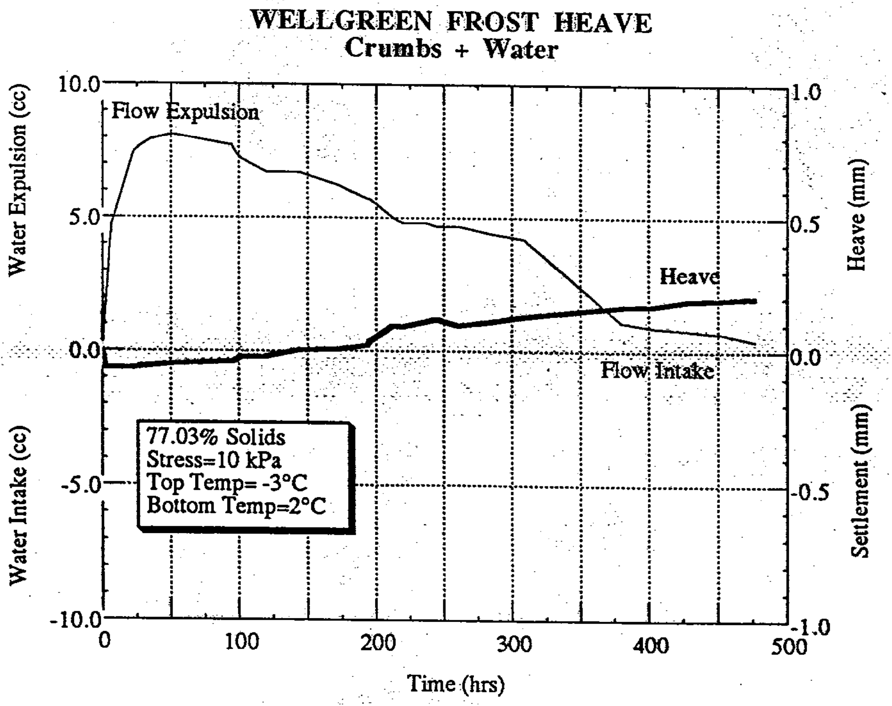
FROST HEAVE CELL



1 Soil Specimen
2 Bottom Coolant Ports
3 Top Coolant Ports
4 RTD Outlets
5 Bottom Drainage
6 LVDT
7 Atmospheric Port
8 PVC Jacket
9 Teflon Liner
10 Load Piston
11 All Thread Clamps
12 Aluminium Top Cap
13 Aluminium Bottom Pedestal
14 Load Guide Bar
15 PVC Base



WELLGREEN FROST HEAVE
Crumbs+(Water+Sediment)



WELLGREEN FROST HEAVE
Crumbs + Water

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Summary of Test Results:

- Hydraulic conductivity are consistent with granular materials
- Deformation behavior is also consistent
- Unfrozen water content exists below zero C and must be accounted for in all thermal calculations
- Thermal conductivity measurements confirm unfrozen water content measurements.
- Samples frost heave ie attract water to freezing front

Conclusions

- Potential exists for water movement in frozen tailings due to thermal potential, electrical potential and chemical potential gradients.

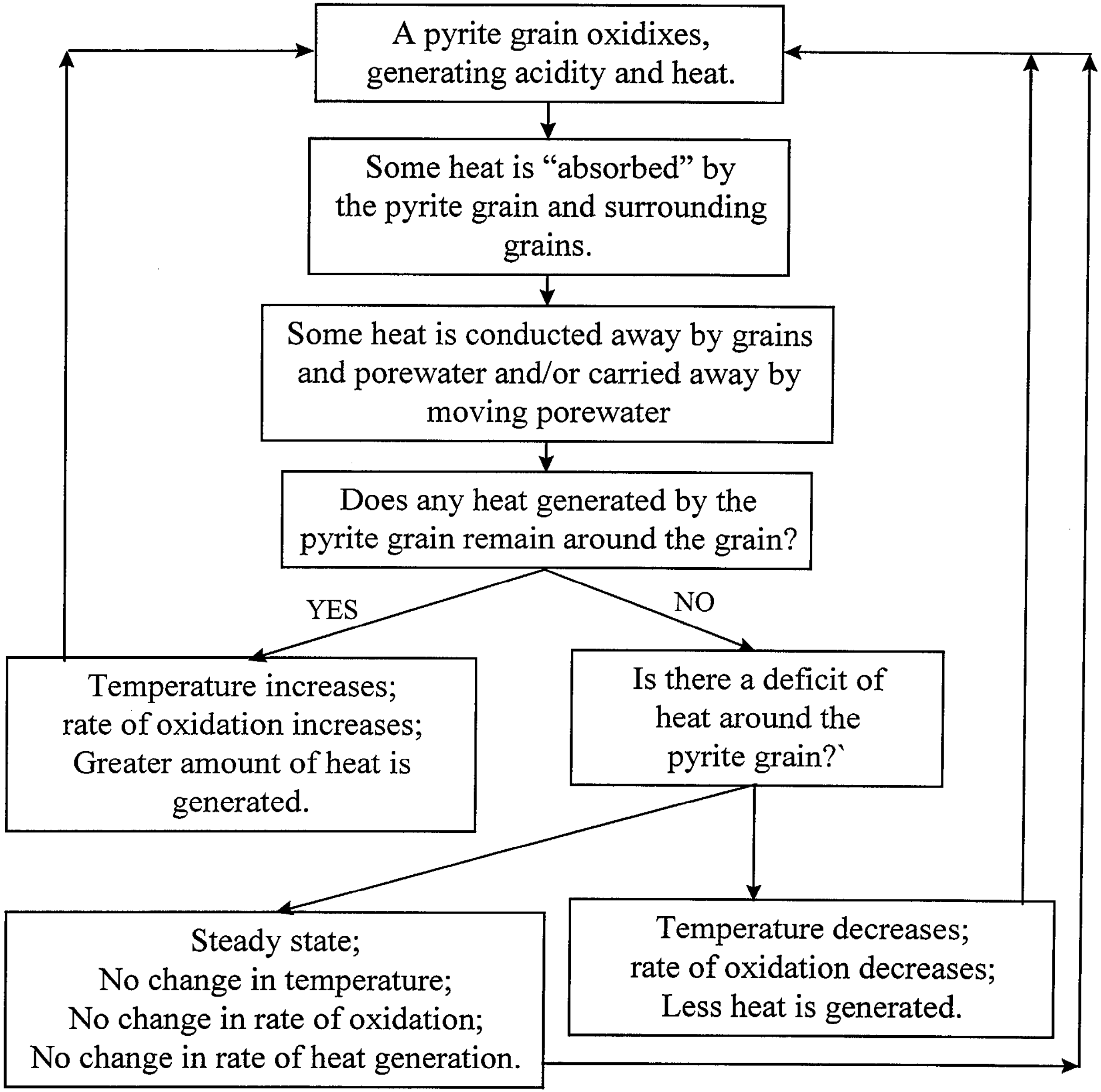
3.8. PERMAFROST: IMPLICATIONS FOR MINESITE-DRAINAGE CHEMISTRY

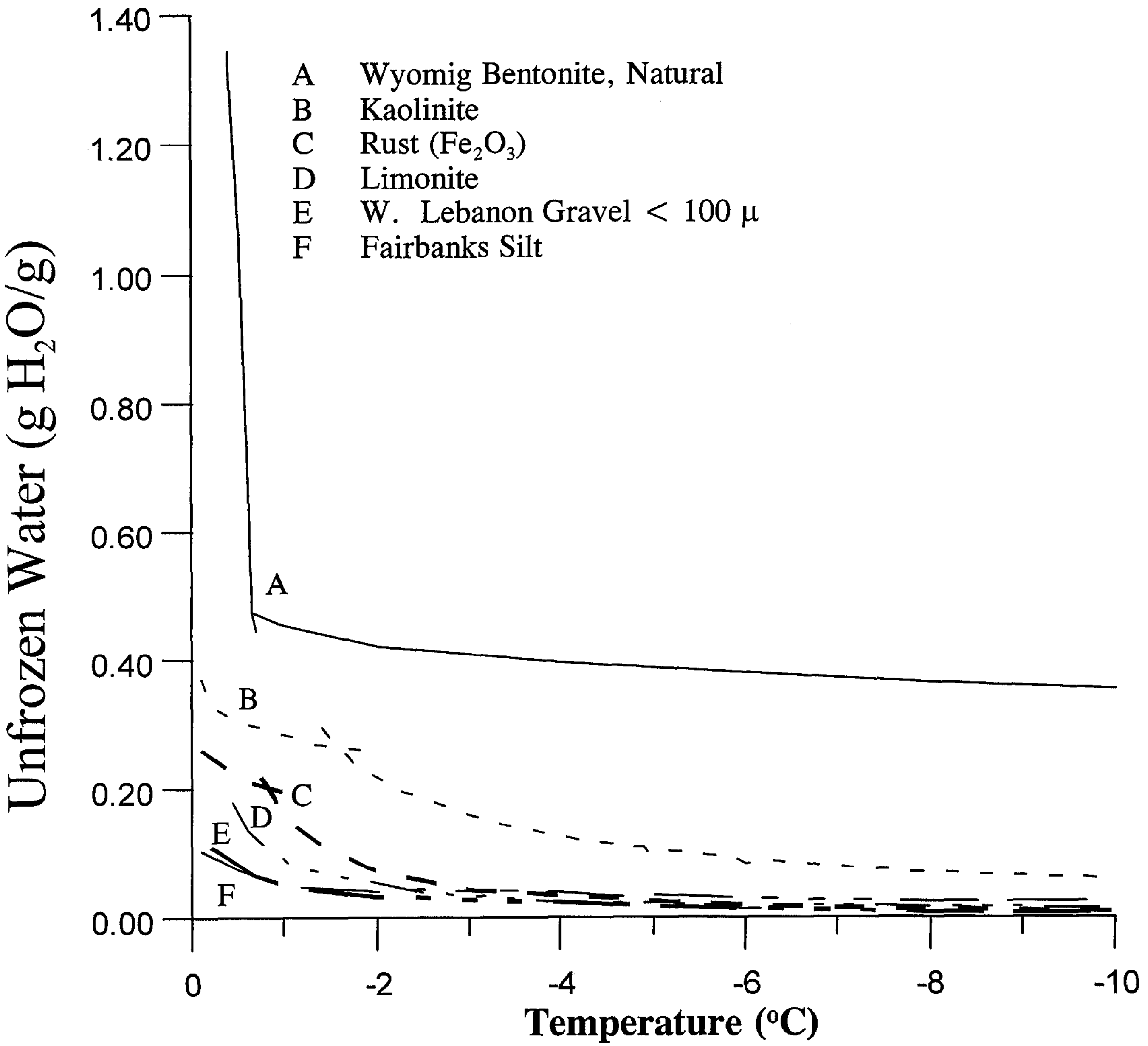
Kevin Morin
Morwijck Enterprises

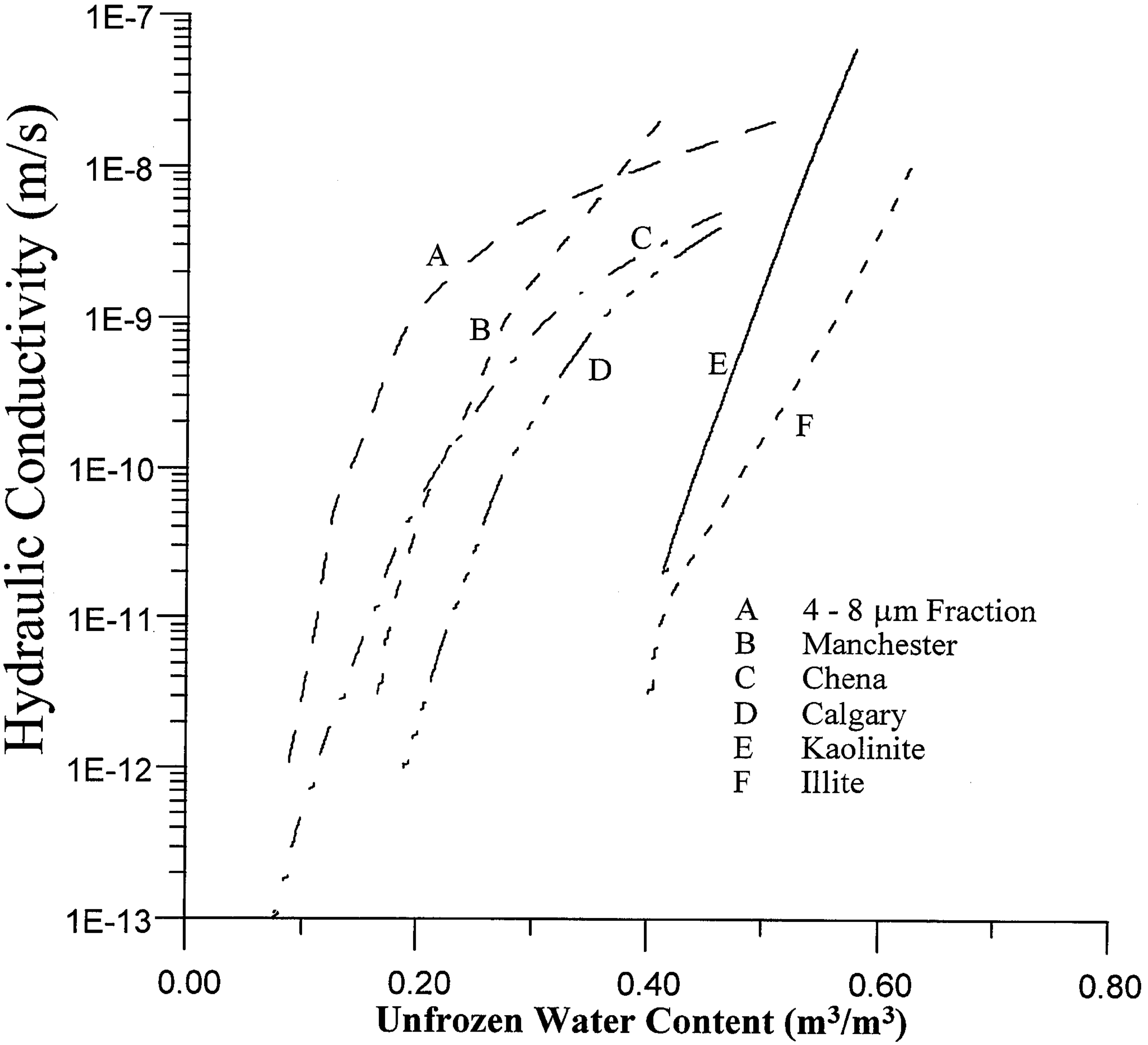
Permafrost:

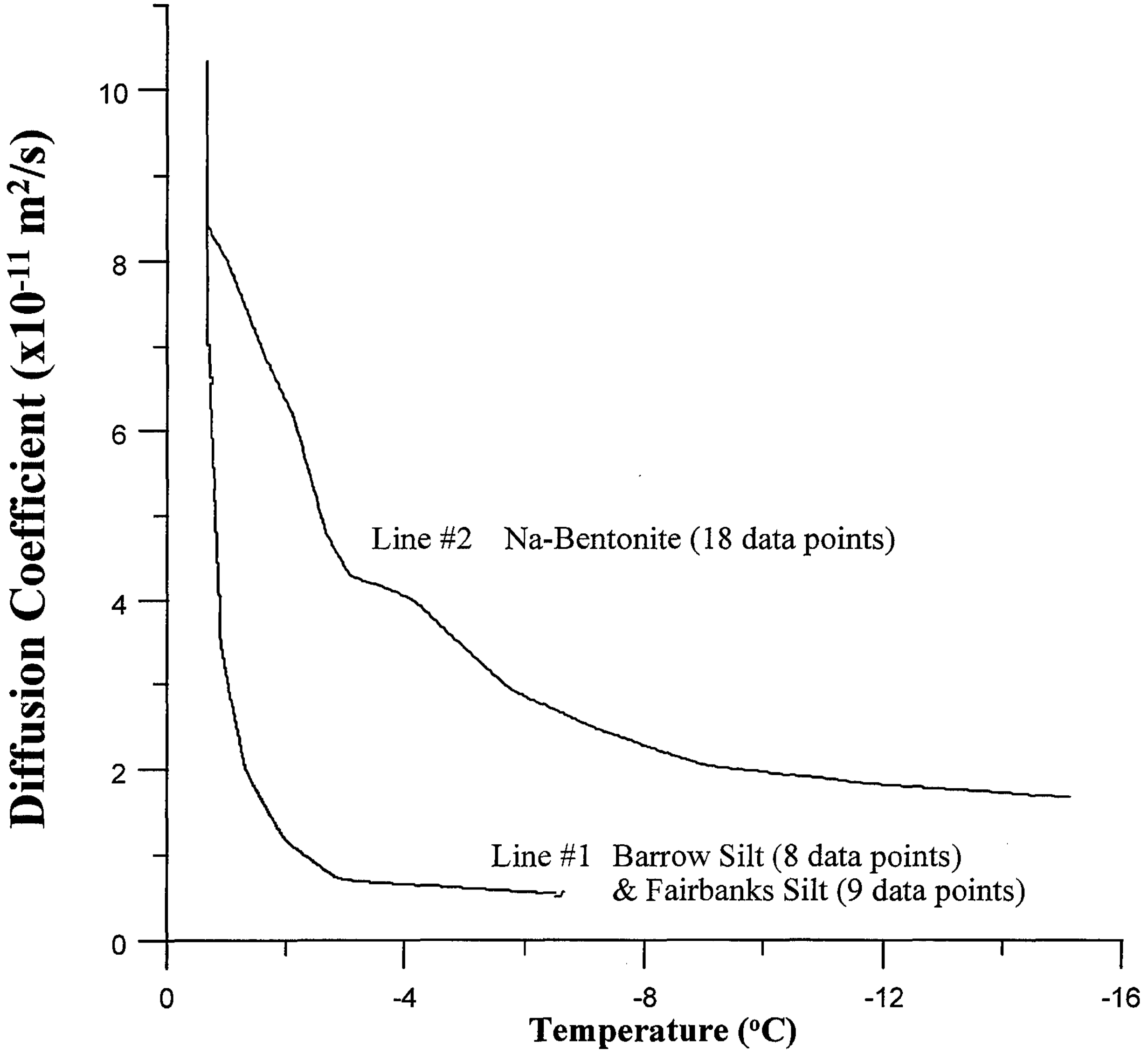
Implications for Minesite-Drainage Chemistry

Minesite Drainage Assessment Group


A pyrite grain oxidixes, generating acidity and heat.
Some heat is “absorbed” by the pyrite grain and surrounding grains.
Some heat is conducted away by grains and porewater and/or carried away by moving porewater
Does any heat generated by the pyrite grain remain around the grain?`
YES
NO
Temperature increases; rate of oxidation increases; Greater amount of heat is generated.
Is there a deficit of heat around the pyrite grain?`
Steady state; No change in temperature; No change in rate of oxidation; No change in rate of heat generation.
Temperature decreases; rate of oxidation decreases; Less heat is generated.


A Wyomig Bentonite, Natural
B Kaolinite
C Rust (Fe_2O_3)
D Limonite
E W. Lebanon Gravel < 100 µ
F Fairbanks Silt
A
B
C
D
E
F
Unfrozen Water (g H_2O/g)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
-2
-4
-6
-8
-10
Temperature (°C)


1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
1E-13
Hydraulic Conductivity (m/s)
0.00
0.20
0.40
0.60
0.80
Unfrozen Water Content (m³/m³)
A
B
C
D
E
F
A 4 - 8 µm Fraction
B Manchester
C Chena
D Calgary
E Kaolinite
F Illite


Diffusion Coefficient (x10^-11 m^2/s)
10
8
6
4
2
0
Line #2 Na-Bentonite (18 data points)
Line #1 Barrow Silt (8 data points)
& Fairbanks Silt (9 data points)
0
-4
-8
-12
-16
Temperature (°C)

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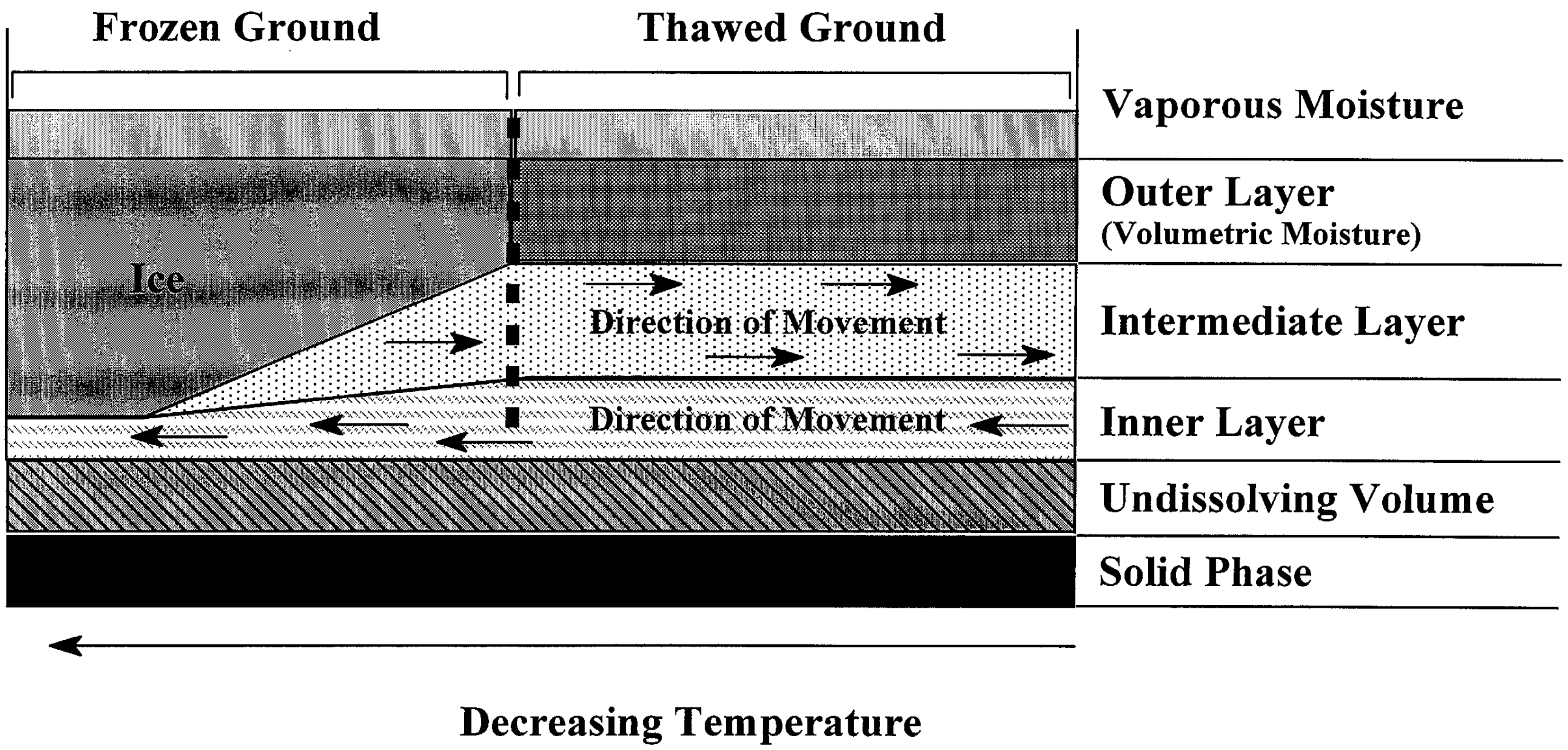

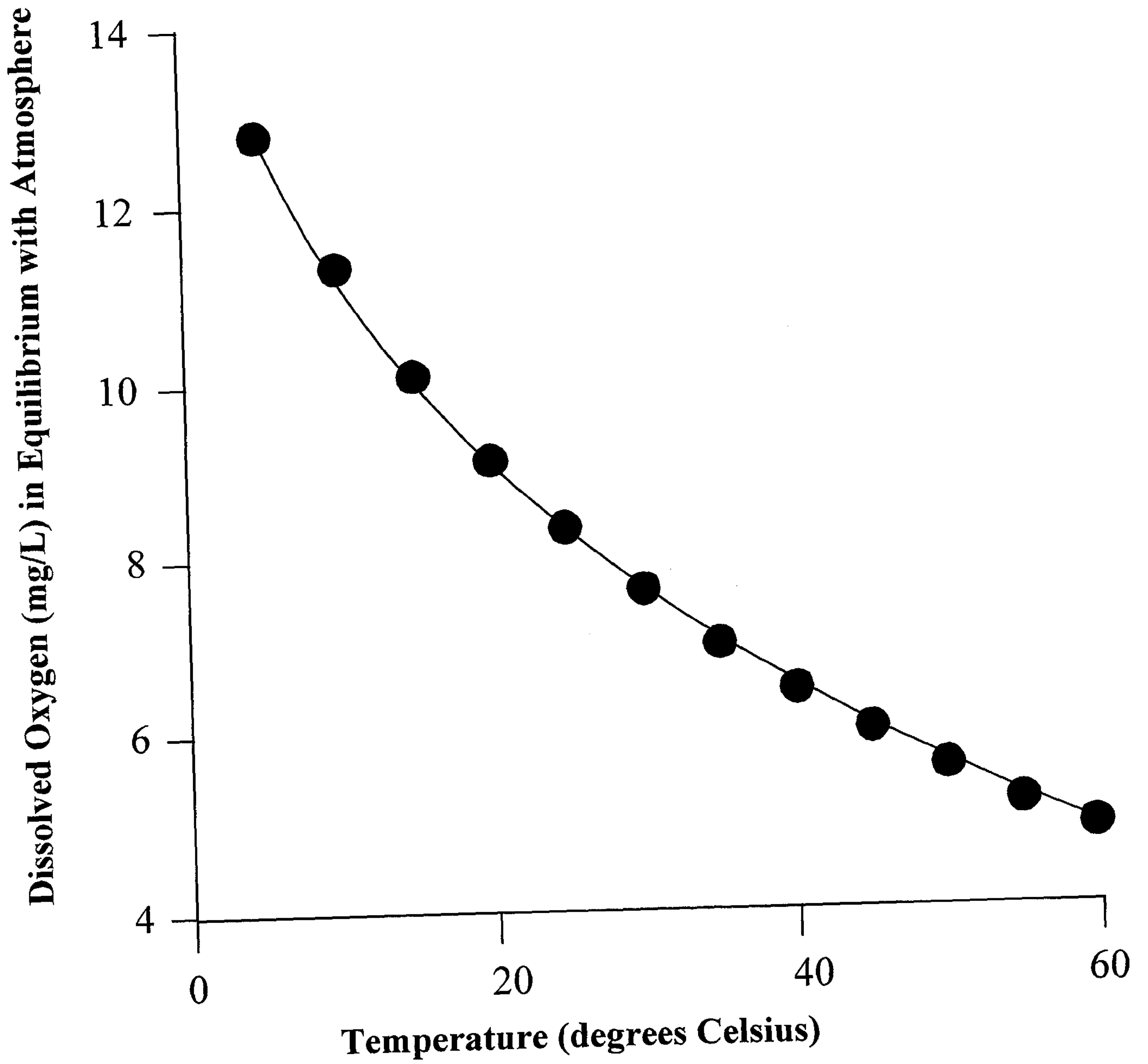
Dissolved Oxygen (mg/L) in Equilibrium with Atmosphere
14
12
10
8
6
4
0
20
40
60
Temperature (degrees Celsius)

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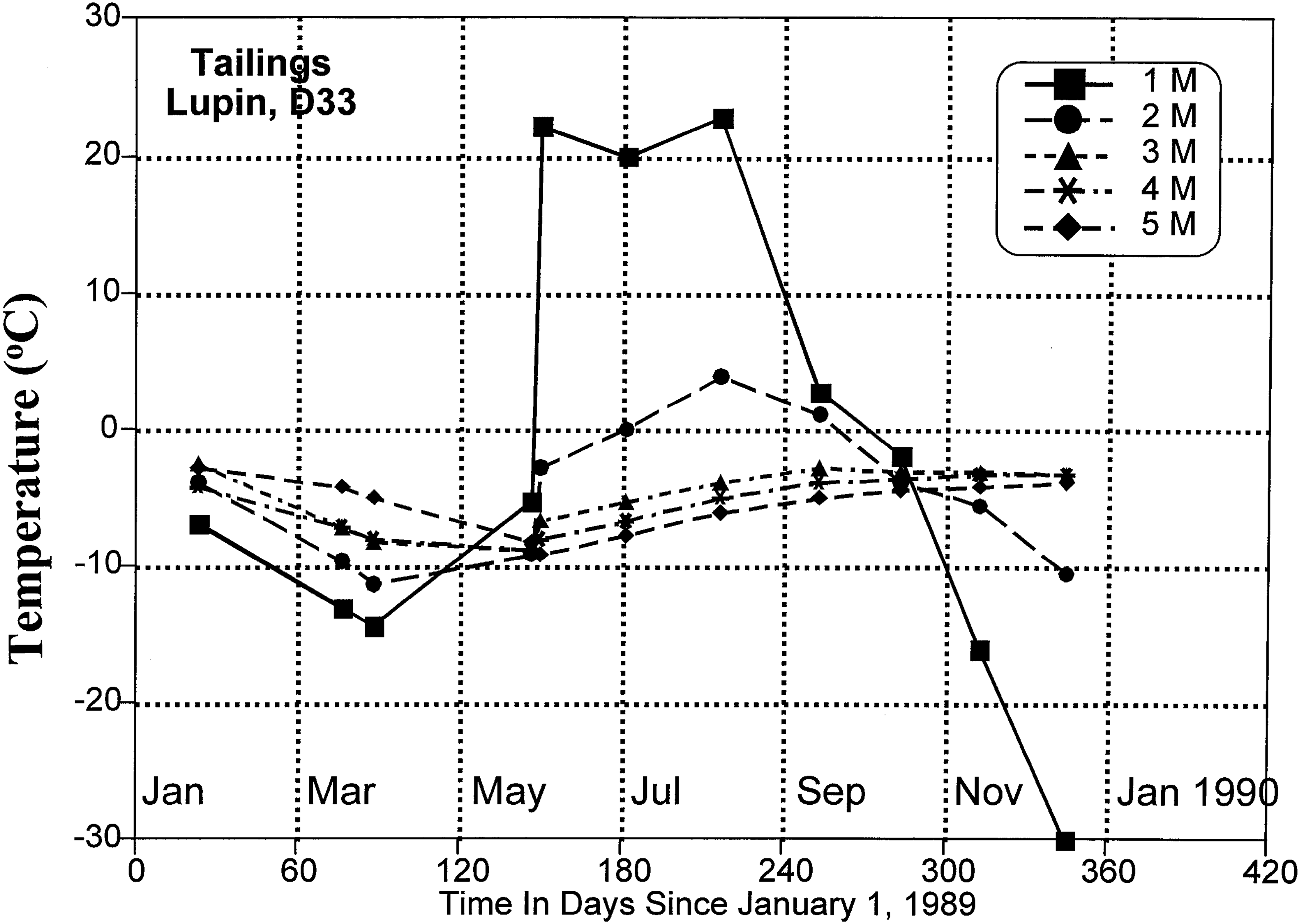
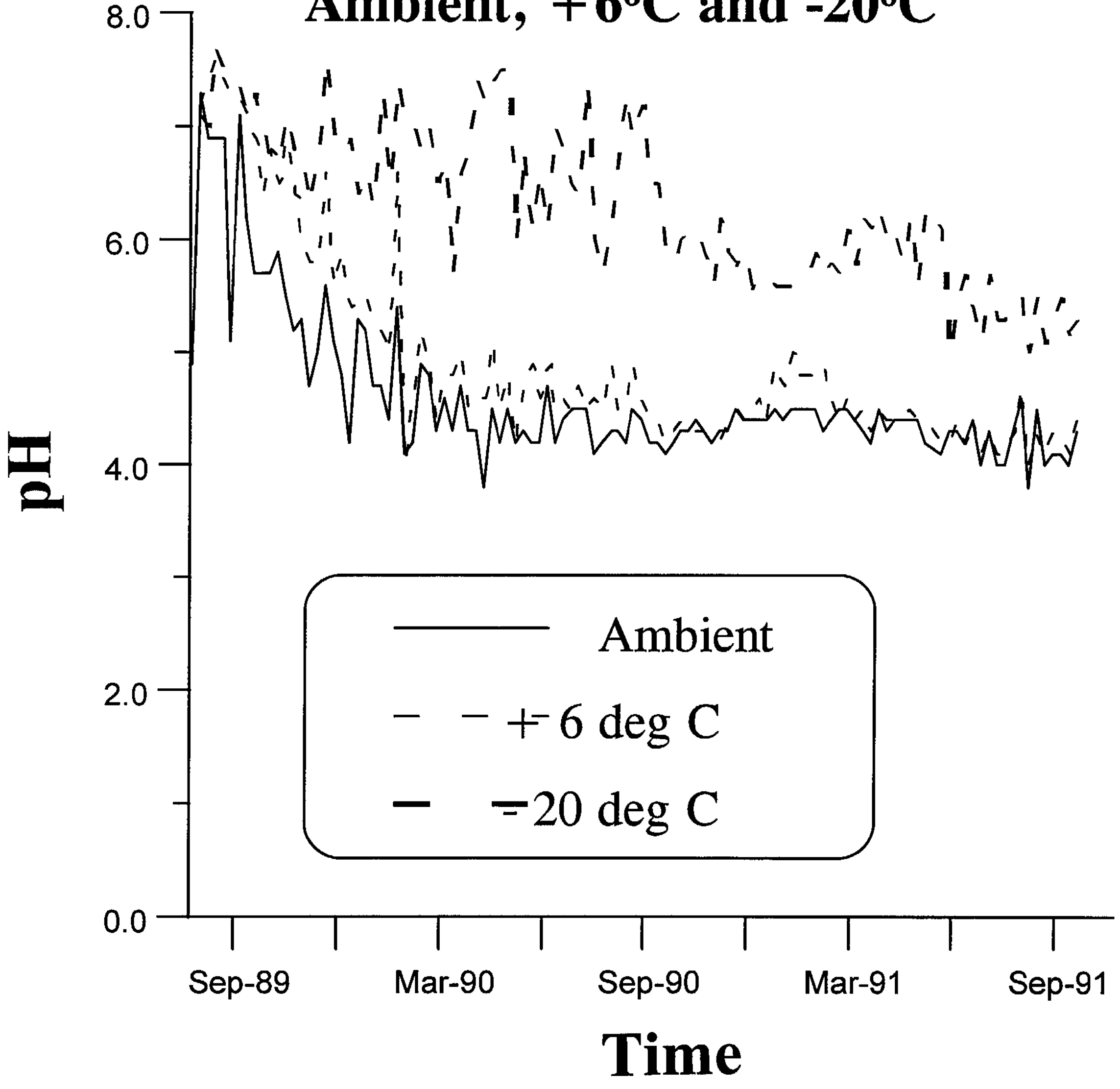
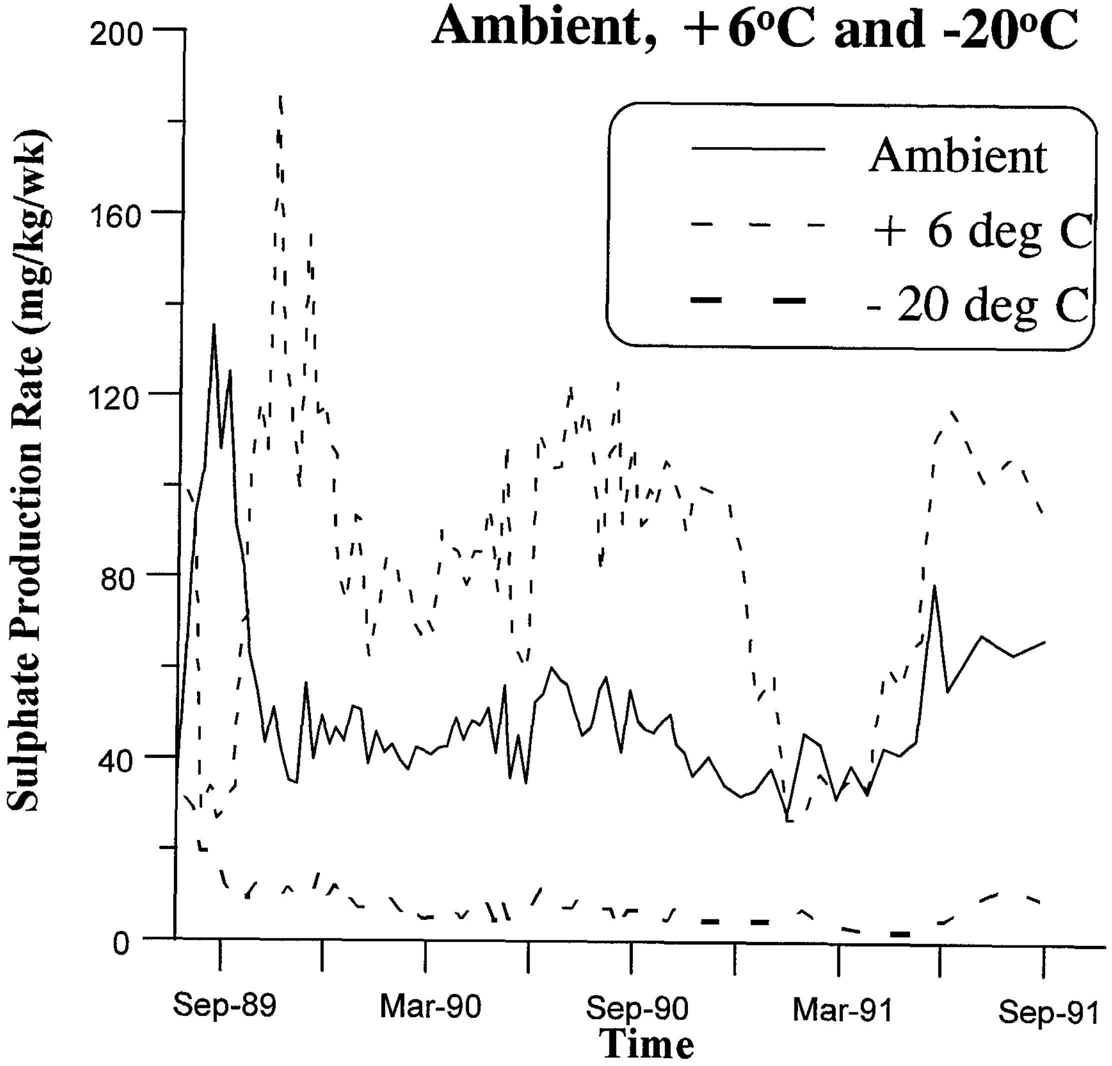
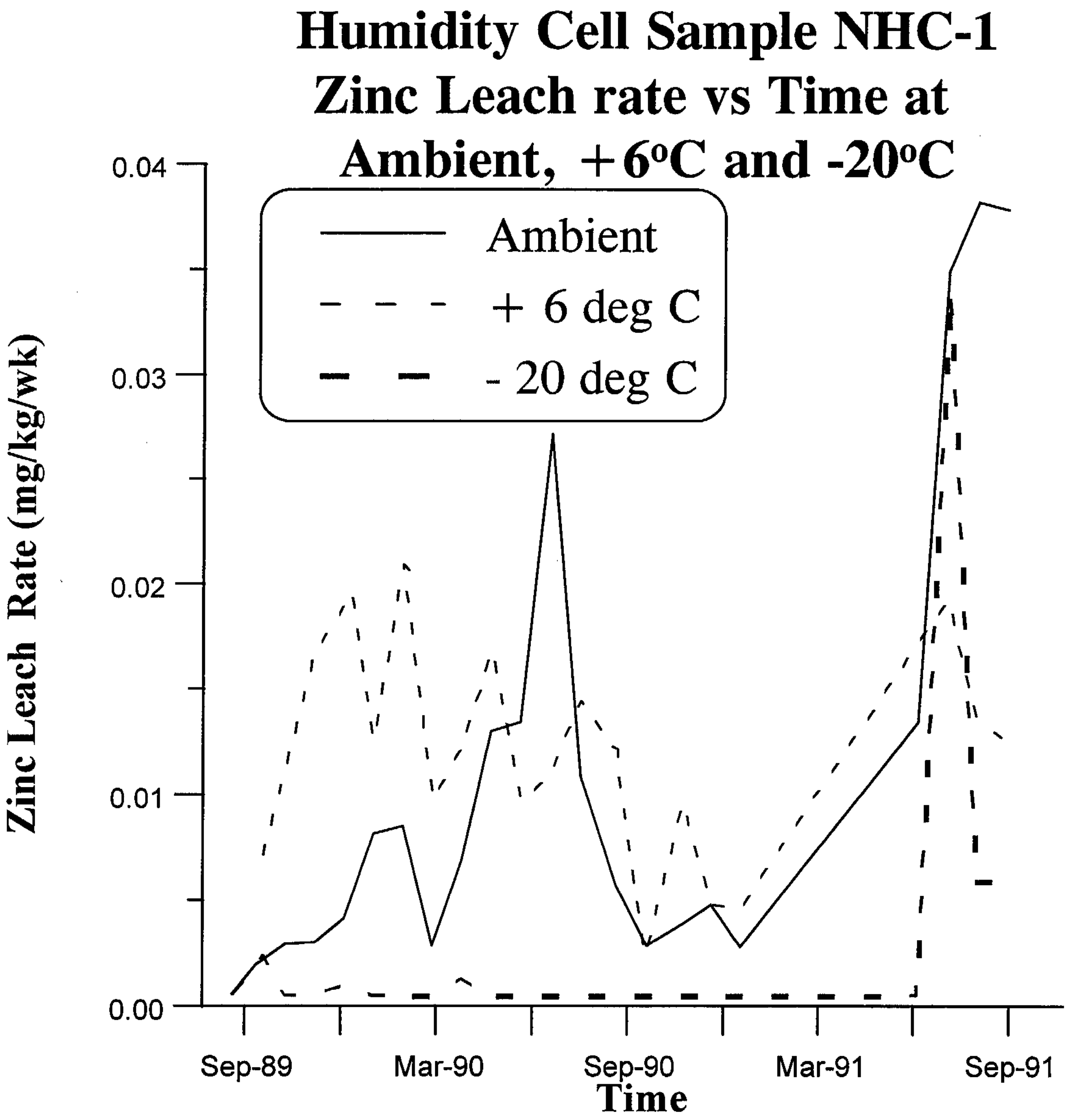


Humidity Cell Sample NHC-1
pH vs Time at
Ambient, +6°C and -20°C

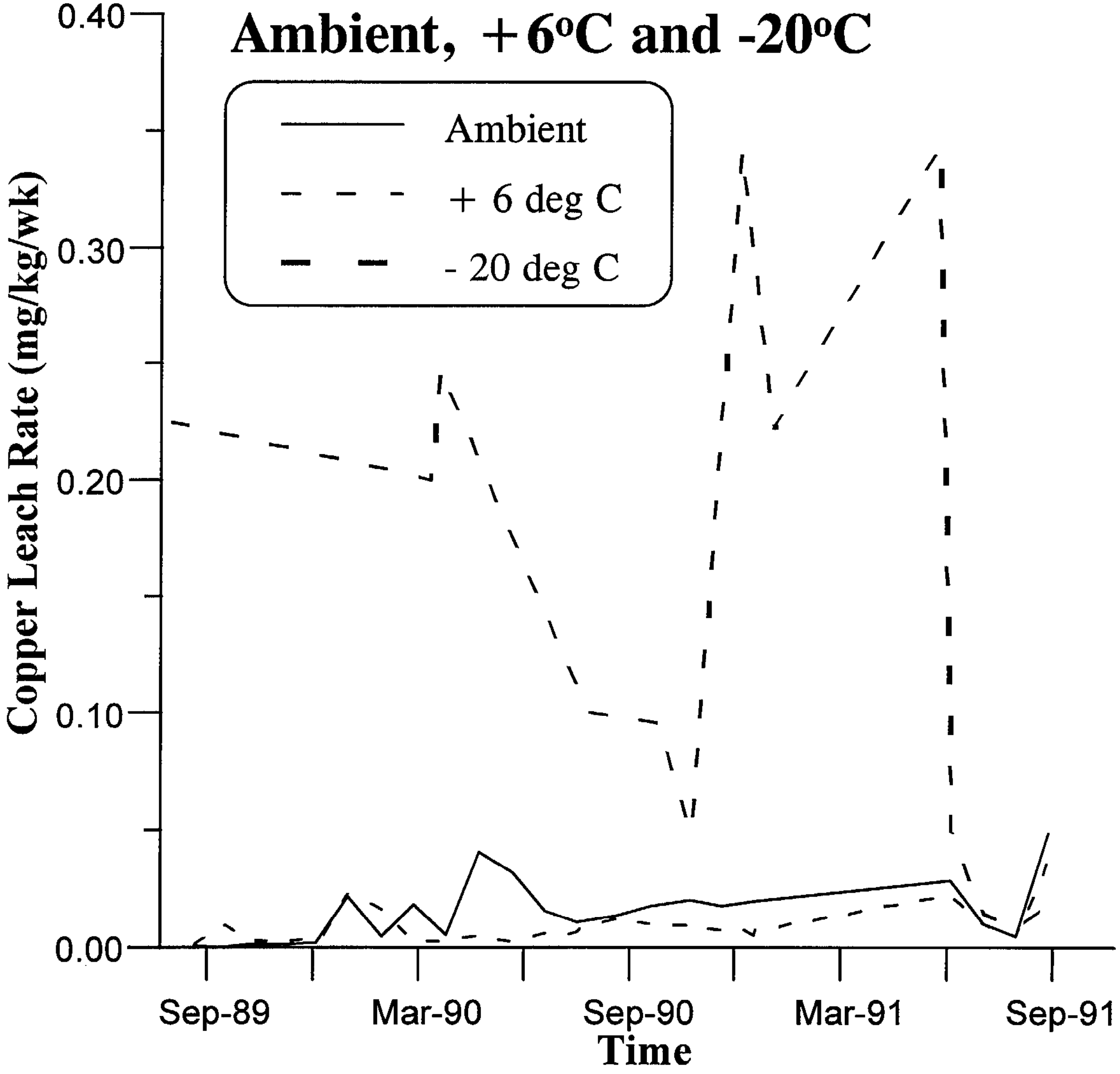


Humidity Cell Sample NHC-1 Sulphate Production Rate vs Time at Ambient, +6°C and -20°C

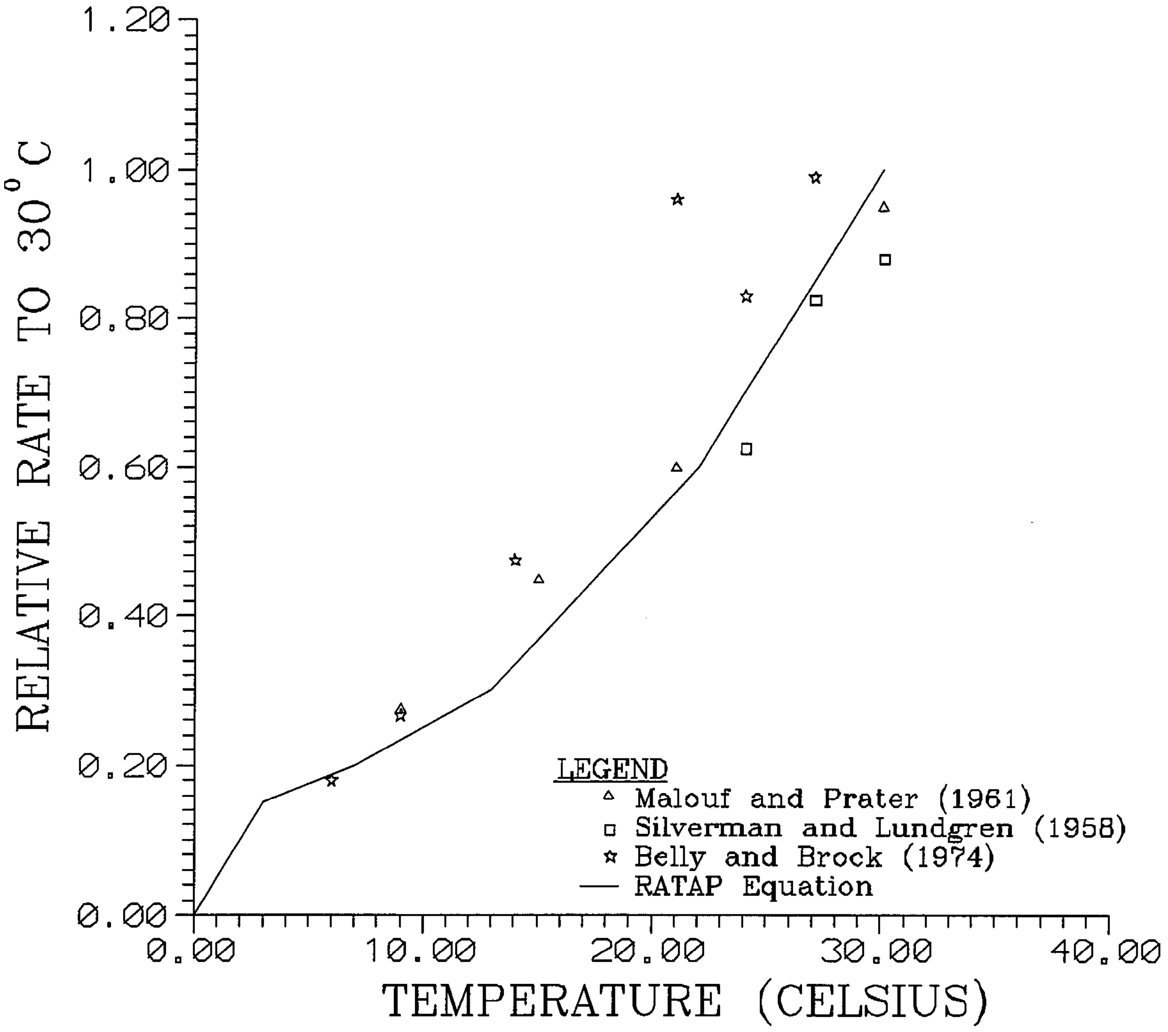



Humidity Cell Sample NHC-1
Zinc Leach rate vs Time at
Ambient, +6°C and -20°C
Ambient
+ 6 deg C
- 20 deg C
Zinc Leach Rate (mg/kg/wk)
0.04
0.03
0.02
0.01
0.00
Sep-89
Mar-90
Sep-90
Mar-91
Sep-91
Time

Humidity Cell Sample NHC-1 Copper Leach rate vs Time at Ambient, +6°C and -20°C



RELATIVE RATE OF BIOLOGICAL OXIDATION VERSUS TEMPERATURE



THIOBACILLUS

Kalin (1987) reported on slow-growing *Thiobacillus* at the Nanisivik Mine that had apparently acclimatized to cold temperatures and would generally not reproduce at a warmer temperature of 12°C It is possible that *T. ferrooxidans* could adapt to unusual conditions, perhaps even to sub-zero temperatures when sufficient oxygen and unfrozen water are present.

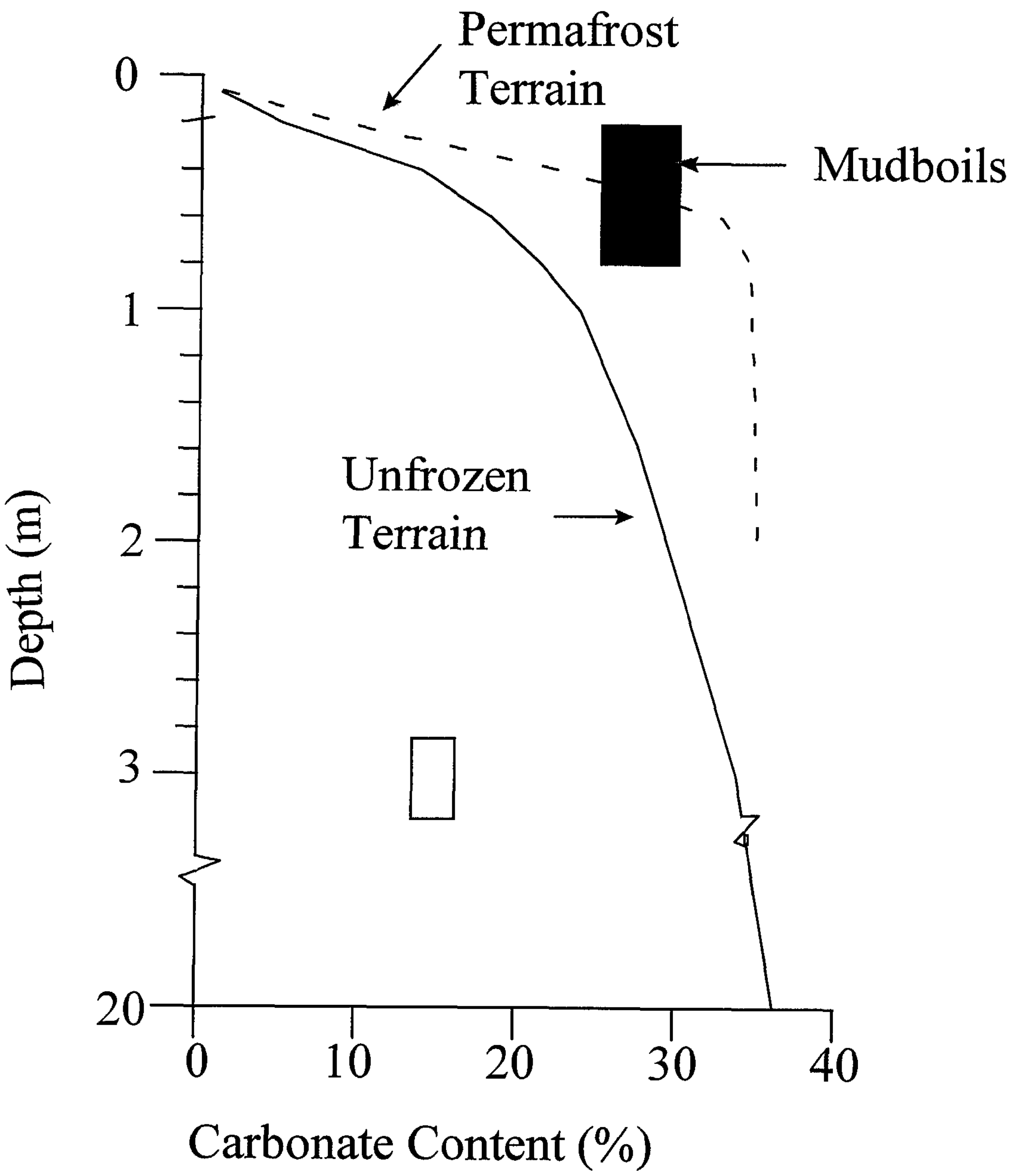
NWT MASSIVE-SULPHIDE DEPOSITS

Agricola Lake~480 km northeast of Yellowknife (Cameron, 1977); continuous permafrost; “intensive” sulphide oxidation near surface and at depth; natural acidic drainage and metal leaching with pH as low as 2.4; jarosite minerals.

Melville Peninsula: continuous permafrost (Cameron, 1979); pH as low as 3.1; active layer roughly 1 m thick, but oxidation believed occurring to tens of meters; attributed to graphite and/or sulphide minerals acting as inert conductors of electrons, which passed from the deep sulphide minerals to atmospheric oxygen.

CAMERON (1977):

"Permafrost is no deterrent to active oxidation of sulphide bodies. In fact O_2 is more soluble in cold water and the exothermic nature of many oxidation processes provides a continuing energy source. In frozen ground, thin, intergranular water films allow chemical processes to be active, even in winter.... The presence of springs and sink holes in the vicinity of the mineralization show that taliks (thawed channels) exist in the permafrost."


Permafrost
Terrain
Mudboils
Unfrozen
Terrain
Depth (m)
0
1
2
3
20
0
10
20
30
40
Carbonate Content (%)

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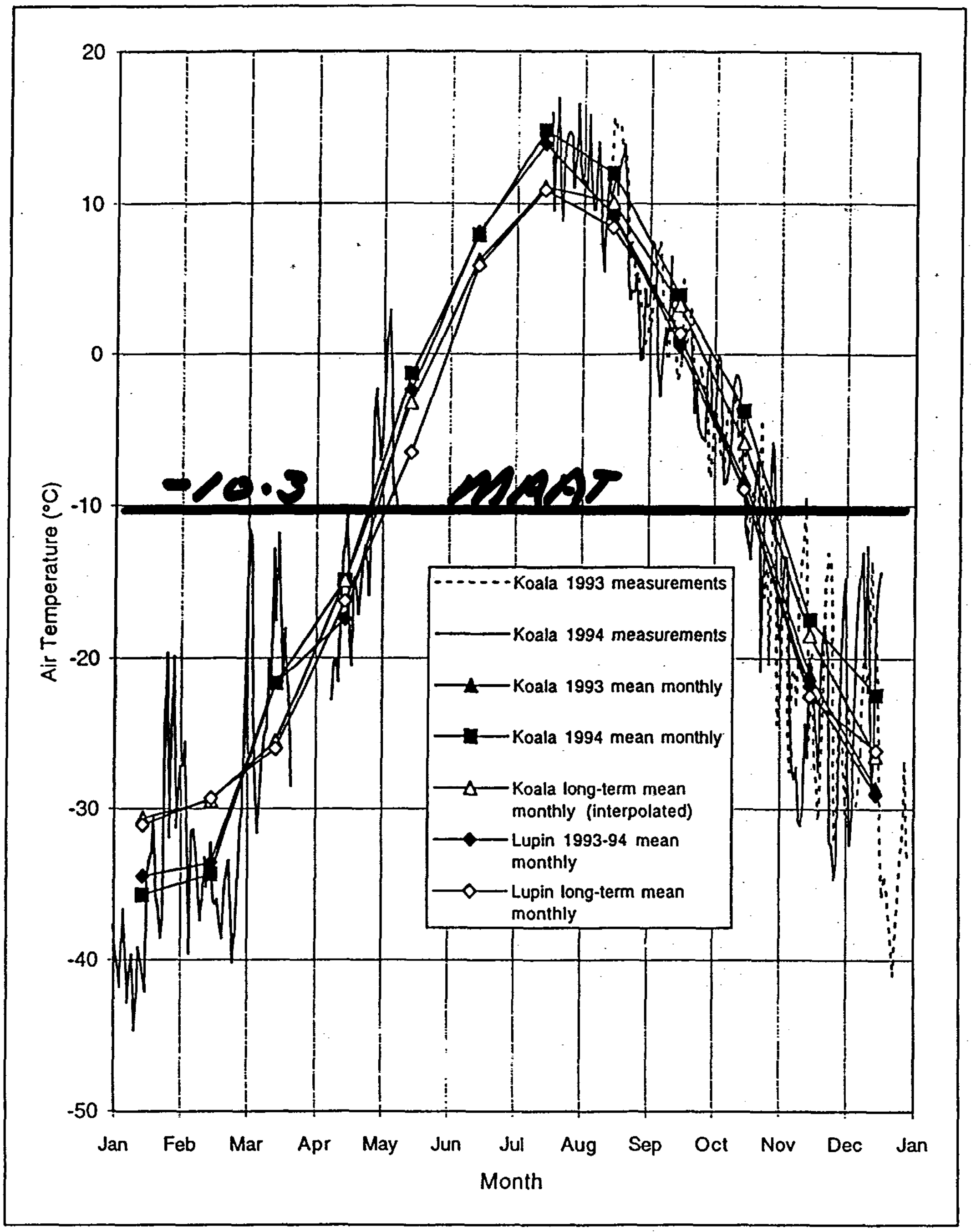
3.9. A MODEL FOR PERMAFROST FORMATION IN WASTE ROCK PILES AT THE BHP DIAMONDS PROJECT

Don Hayley
EBA Engineering Ltd.

A Model For Permafrost Formation In Waste Rock Dumps
BHP, NWT Diamonds Project

by:
Don Hayley
Wim Van Gassen
Edward Gu

eba



Climate at Lac de Gras

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Dump Characteristics

- Granite
  - sand to 2 m boulders
  - 2 mg/m^3 dry density
  - 1 % water content
- Foundation
  - Rock or Till
  - Permafrost @ -5°C

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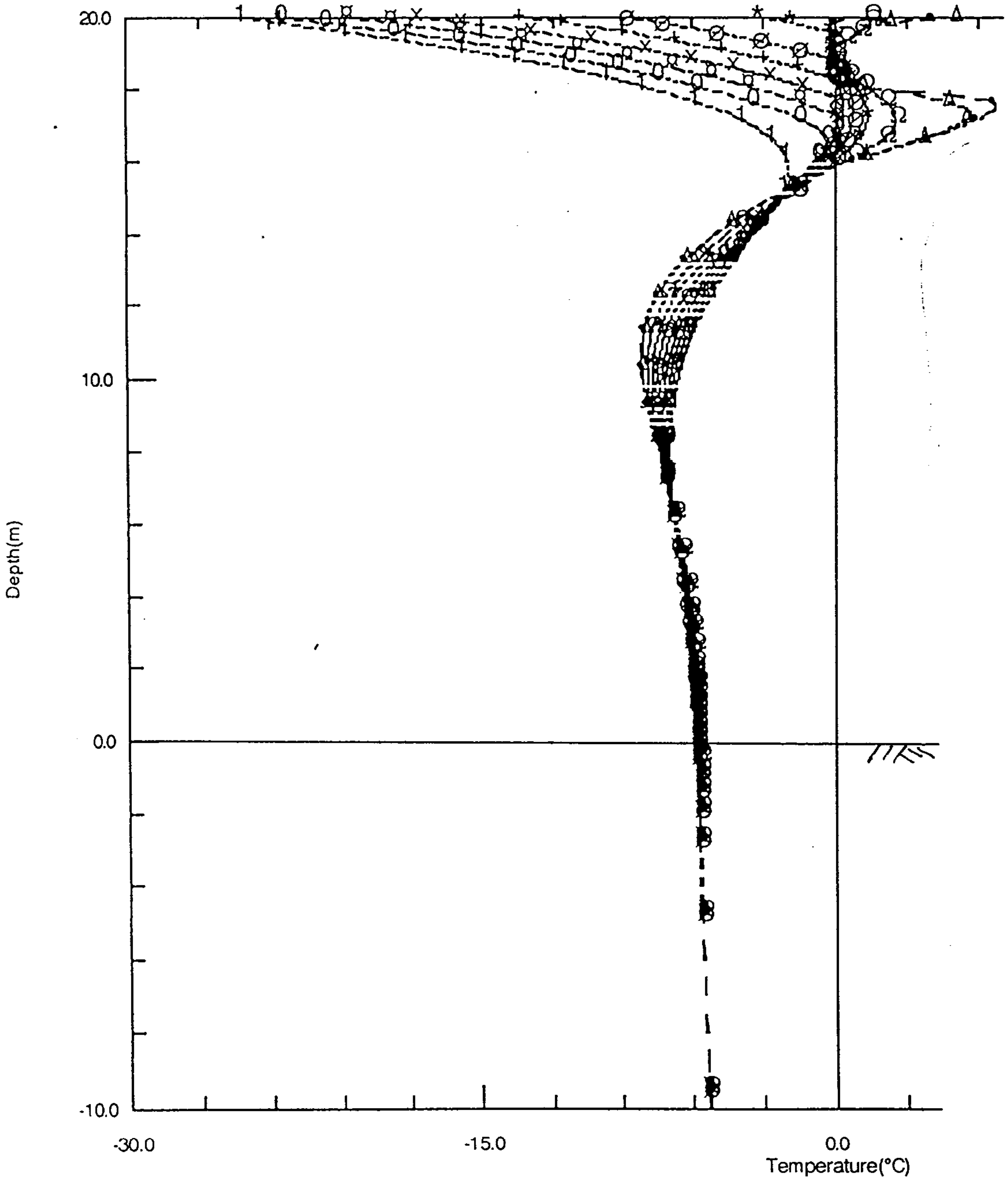
TABLE 1
MATERIAL PROPERTIES IN THERMAL ANALYSIS FOR BHP WASTE DUMPS

MATERIAL	WASTE ROCK	SATURATED WASTE ROCK	FOUNDATION TILL
Water Content (%)	1.0	12.0	8.0
Frozen Dry Density (kg/m^3)	2,000	2,000	2,100
Unfrozen Dry Density (kg/m^3)	2,000	2,000	2,100
Clay Fraction (%)	0.0	0.0	0.0
Frozen Thermal conductivity (W/mC°)	0.94	2.89	2.03
Unfrozen Thermal conductivity (W/mC°)	0.60	2.10	1.70
Bulk Density (kg/m^3)	2,020	2,240	2,270
Frozen Specific Heat (KJ/kg C°)	0.75	0.88	0.83
Unfrozen Specific Heat (KJ/kg C°)	0.77	1.10	0.99
Latent Heat (MJ/m^3)	-7.0	-80.0	-56.0

Material Properties

Construction Sequence

- 2 m thick lifts
- 20 m total height in 3 years
- Rock at bottom placed @ -5°C
- Rock at top placed @ -0.5°C
- Construction sequence modeled in 10 temperature steps
- Dump temperature at end of construction -5°C except at top



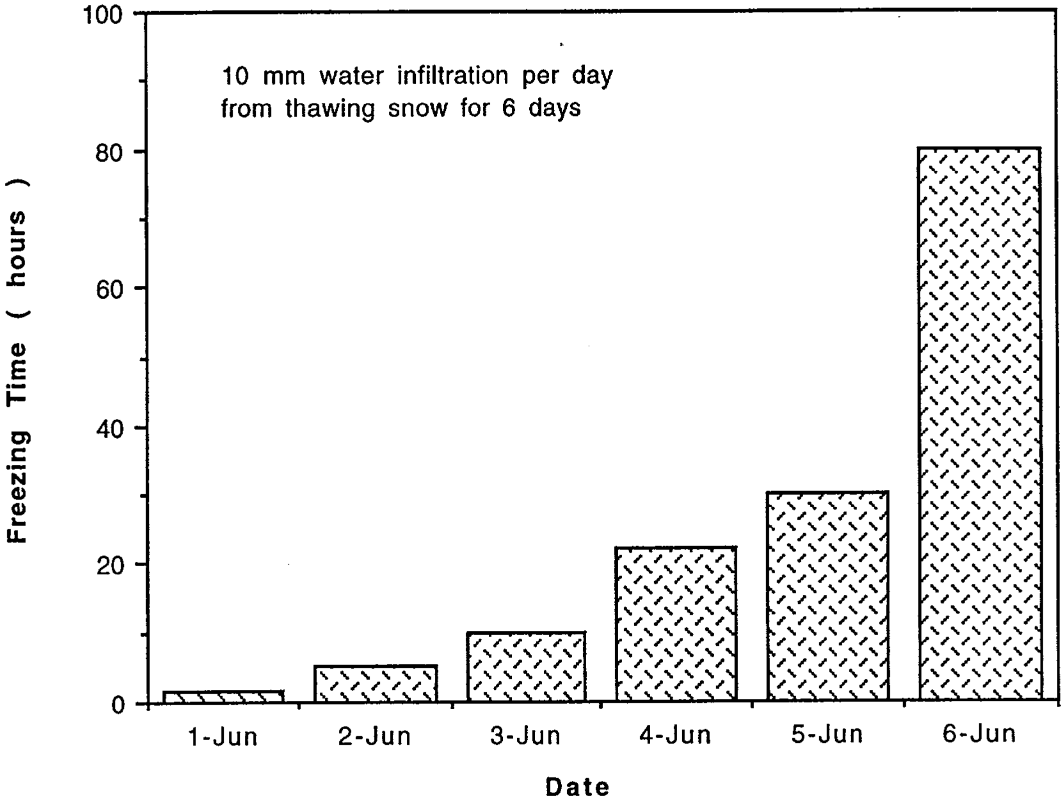
Dump Temperature, End Of Construction

Water Impacts

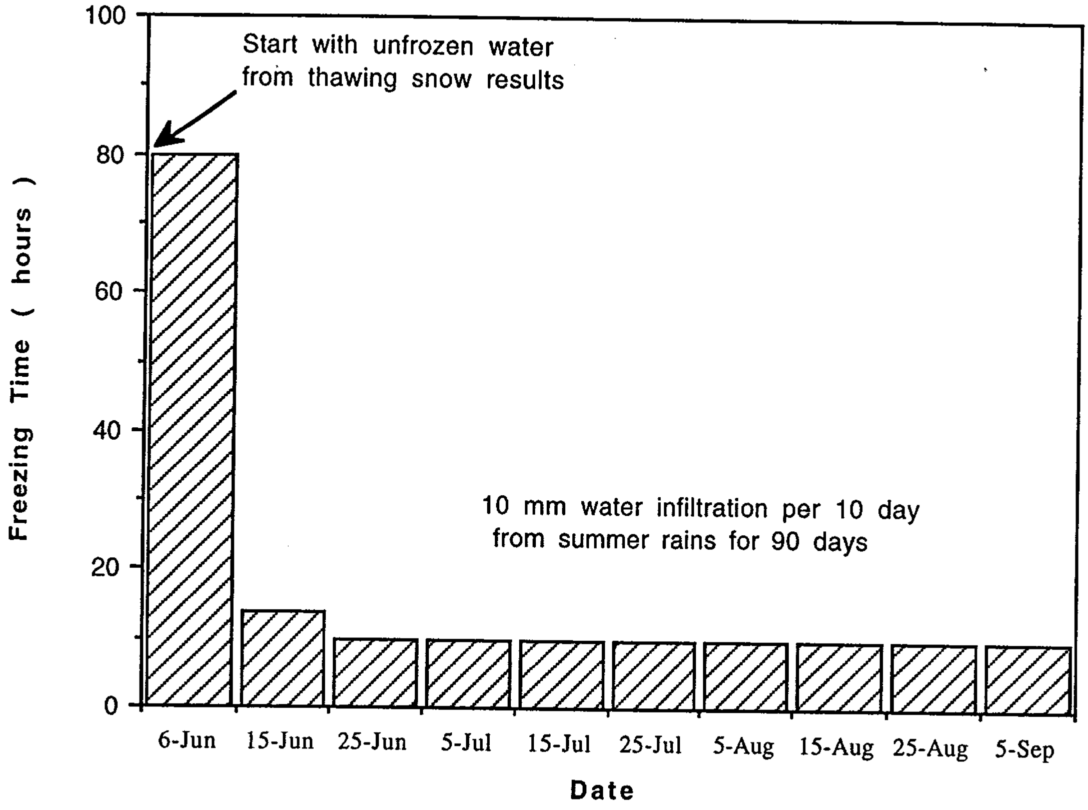
- 300 mm annual precipitation, 50 % falls as snow
- Assume about half will infiltrate the dump
  - 40 % of the snow
  - 60 % of the rain
  - 150 mm total
- Snowmelt infiltrates in 6-10 mm daily episodes (60 mm)
- Rainfall infiltrates as 9- 10 mm episodes over 10 days (90 mm)
- Drops to the bottom saturating a 40 mm high portion of the rockfill (porosity of 25%)
- Water percolates slowly toward dump perimeter
- How far will it travel before it freezes?

Retention Time

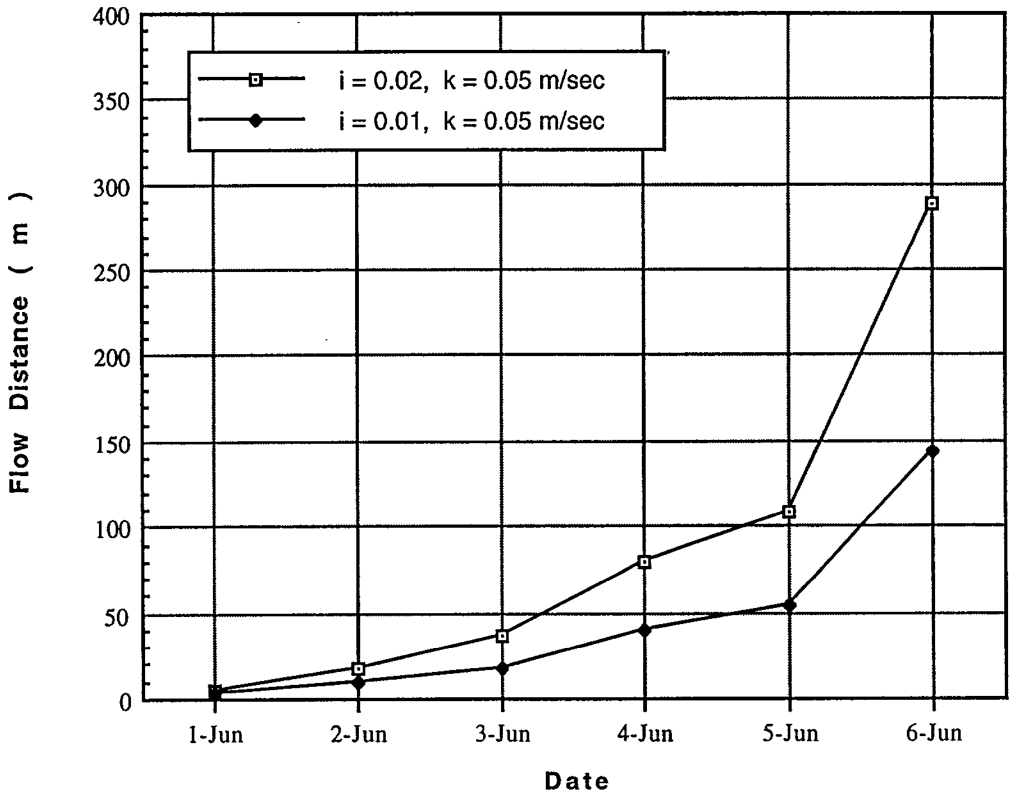
- Initial hydraulic gradient 2%
- Hydraulic conductivity 5 x 10^{-2} m/sec
- Seepage velocity from Darcy's Law - 3.6 m/hr
- Water is typically retained for several days



Freezing Time For Snowmelt



Freezing Time For Rain



FLOW DISTANCE BEFORE FREEZING DURING SNOW THAWING

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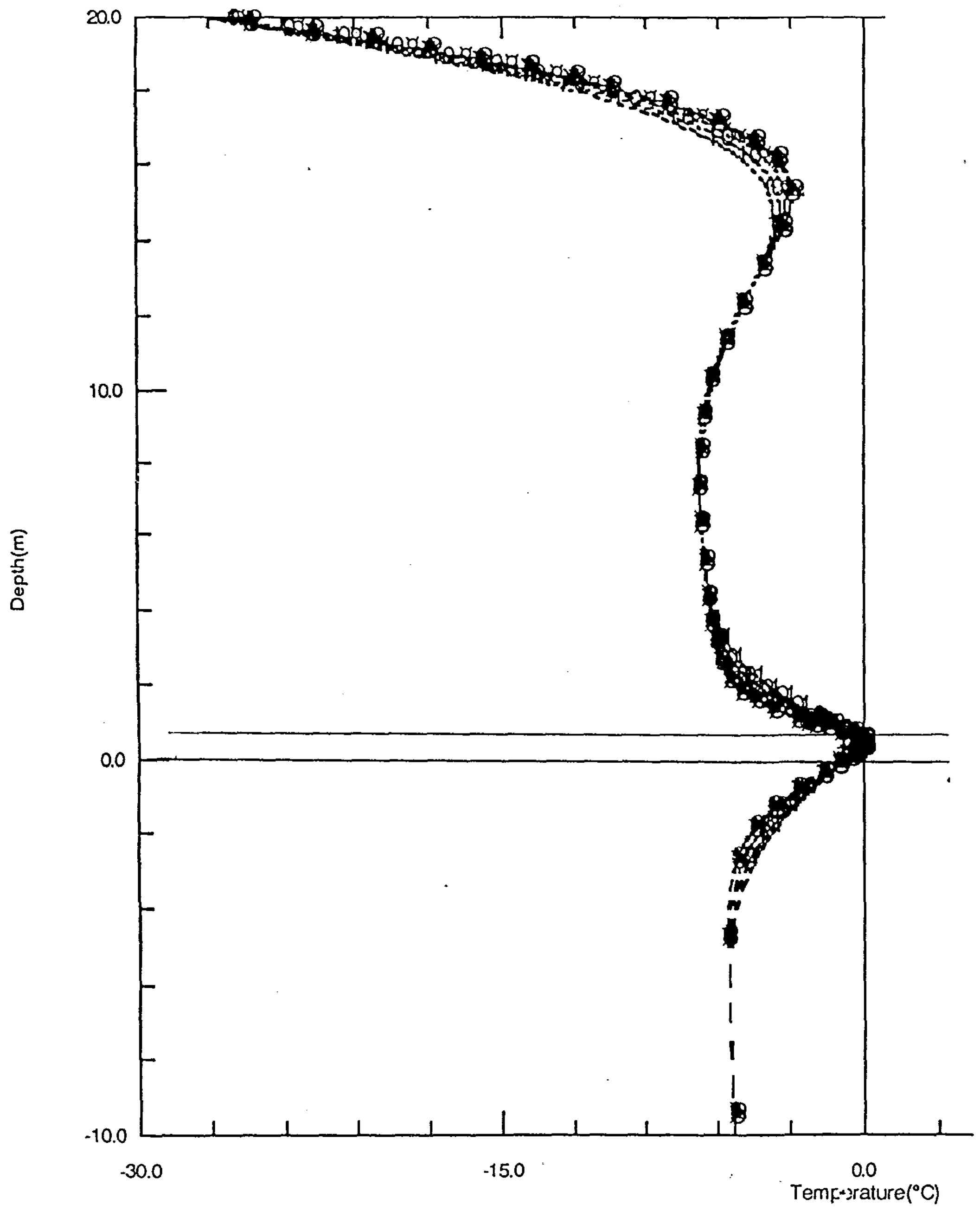
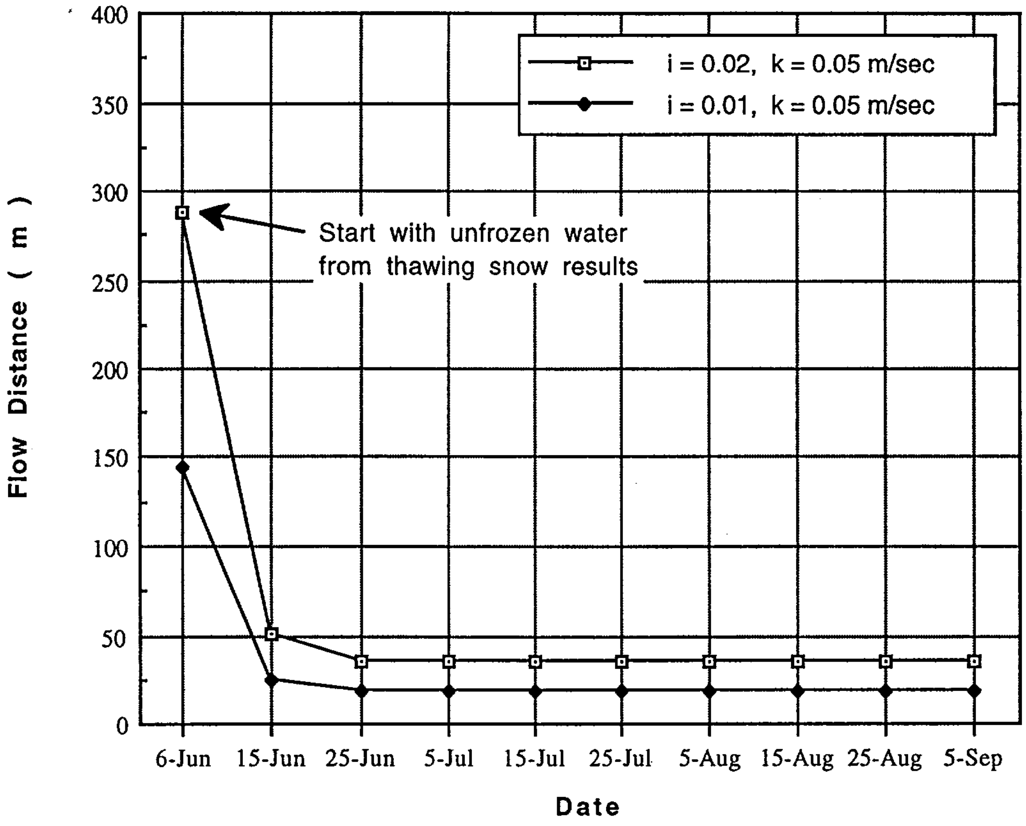


Freezing Rate Predictions

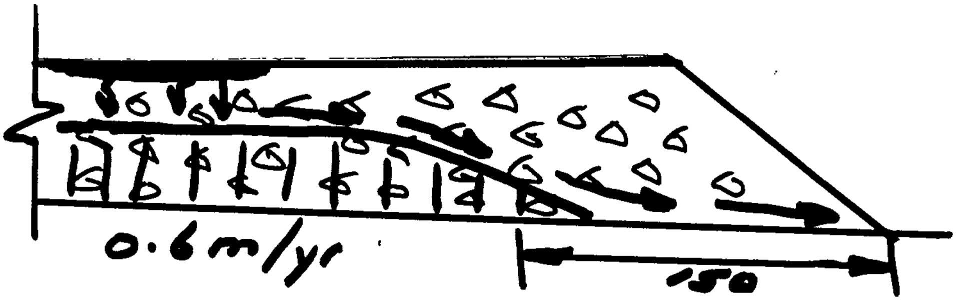
eba



FLOW DISTANCE BEFORE FREEZING DURING SUMMER RAINS

Results

- Exfiltration fringe about 150 m wide
- An ice saturated core will form at the rate of 600 mm/yr
- The core will gradually increase the gradient and seepage velocity
- Eventually all the infiltration (150 mm/ m^2) will exfiltrate through the fringe.
- The core will remain frozen and ice saturated.



Optimization Options

- A berm of finer grained rock around perimeter
  - Increased retention time
  - decrease fringe width
- Selectively place ARD potential rock in the core zone
- Increase surface slope and decrease lift thickness.
- Enhance saturation rate by adding water

eba

Research Priorities

- Temperature profile within dumps
    - Fox dump @ Koala
- Confirmation of ice saturation
    - Insitu permeability
    - Geophysics (GPR)
- Careful site observations

3.10. RESEARCH PRIORITIES FOR NORTHERN ARD

Stephen Day
Norecol Dames & Moore

RESEARCH DESIGN FOR NORTHERN ARD

Indian and Northern Affairs Canada

Stephen Day

Norecol, Dames & Moore,

Vancouver, BC

CONLUSIONS OF 1993 VANCOUVER WORKSHOP

- Opportunities and limitations for management of ARD/Metal leaching in the north
- quantitative knowledge of mechanisms and technologies

OBJECTIVES OF DIAND'S RESEARCH EFFORT

- Quantify main factors dictating management of ARD in northern regions
- Develop practical solutions to ARD management (in the context of other initiatives)

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APPROACH TO DEVELOPMENT OF THE RESEARCH PLAN

- Subdivide the North into bedrock geological and environmental sub-regions
- Classify sub-regions by significance for mining and ARD/metal leaching potential
- Determine research themes for high priority sub-regions
- Group themes and identify research projects.

TYPES OF REGIONS

- Geological & mineral deposits
- Surficial deposits
- Permafrost
- Precipitation
- Net precipitation
- Proximity to water bodies
- Major parks and protected areas

HIGH PRIORITY SUB-REGIONS

- Most of Yukon Territory (3 sub-regions)
- Slave structural province
- Arctic Platform
- Innuitian Orogen

Potential options for ARD/Metal Leaching control were identified in each of the sub-regions.

OPTIONS FOR ARD CONTROL IN SUB-REGIONS

SUB-REGION	ENVIRONMENTAL SUB-REGION DESCRIPTION	PASSIVE - LOW TEMPREATURE	PASSIVE - SNOW MELT	DRY COVERS - NATURAL	SUB-AERIAL ICE ENCAPSULATION	ENCAPSUALTION IN PERMAFROST	EVAPORATIVE COOLING	UNDERWATER (natural)	UNDERWATER (artificial)	WASTE ROCK MIXING	ACTIVE WATER TREATMENT	PASSIVE WATER TREATMENT
G1. West of Tintina Fault	Excess precipitation, high precip. due to Pacific influence, surficial deposits in valleys, permafrost absent to discontinuous, mountainous			X	X				X	X	X	X

OPTIONS FOR ARD CONTROL IN SUB-REGIONS

SUB-REGION	ENVIRONMENTAL SUB-REGION DESCRIPTION	PASSIVE - LOW TEMPREATURE	PASSIVE - SNOW MELT	DRY COVERS - NATURAL	SUB-AERIAL ICE ENCAPSULATION	ENCAPSUALTION IN PERMAFROST	EVAPORATIVE COOLING	UNDERWATER (natural)	UNDERWATER (artificial)	WASTE ROCK MIXING	ACTIVE WATER TREATMENT	PASSIVE WATER TREATMENT
G6. Slave Structural Province	Excess evaporation, dry continental climate, very thin surficial deposits, continuous to widespread permafrost. Shield	X	X			X		X	X		X	

THEORY AND PREDICTION RESEARCH PLAN

Develop Predictive Models for Acid Generation/Metal Leaching Processes in Cold Climates

Acid-base Balance for Cold Wastes **(All regions)**	Temperature Controls on Reaction Rates in Sub-Aerial and Buried Wastes **(All Regions)**	Interaction Between Cold Waters and Fresh Mine Wastes **(Slave, Eastern Arctic, Innuitian)**	Interaction Between Cold Waters and Oxidized Rock **(East of Tintina Fault)**

PREVENTION AND CONTROL RESEARCH PLAN

Develop Design Criteria for Safe Disposal of Potentially Acid-Generating Mine Wastes

Dry Covers and Freezing of Tailings and Waste Rock	Evaluation of Materials for Dry Covers	Underwater Disposal of Wastes	Blending of Waste Rock
(All regions except part of east of Tintina Fault)	**(Slave & part of east of Tintina Fault**	**(Slave, Eastern Arctic, Innuitian)**	**(Slave & part of east of Tintina Fault**

TREATMENT RESEARCH PLAN

Develop Design Criteria for Treatment of ARD and Metal Containing Drainage Waters

Passive and Active Treatment Technologies

(All regions)

Lime Treatment Plant Operation

(Slave & part of east of Tintina Fault

CONCLUSIONS

- Research plan developed to account for extreme environmental variability in Canada's North
- Four high priority regions recognised based on mining importance, risk of ARD and specific environmental constraints
- Research themes grouped into Prediction, Prevention & Control, and Treatment action plans.

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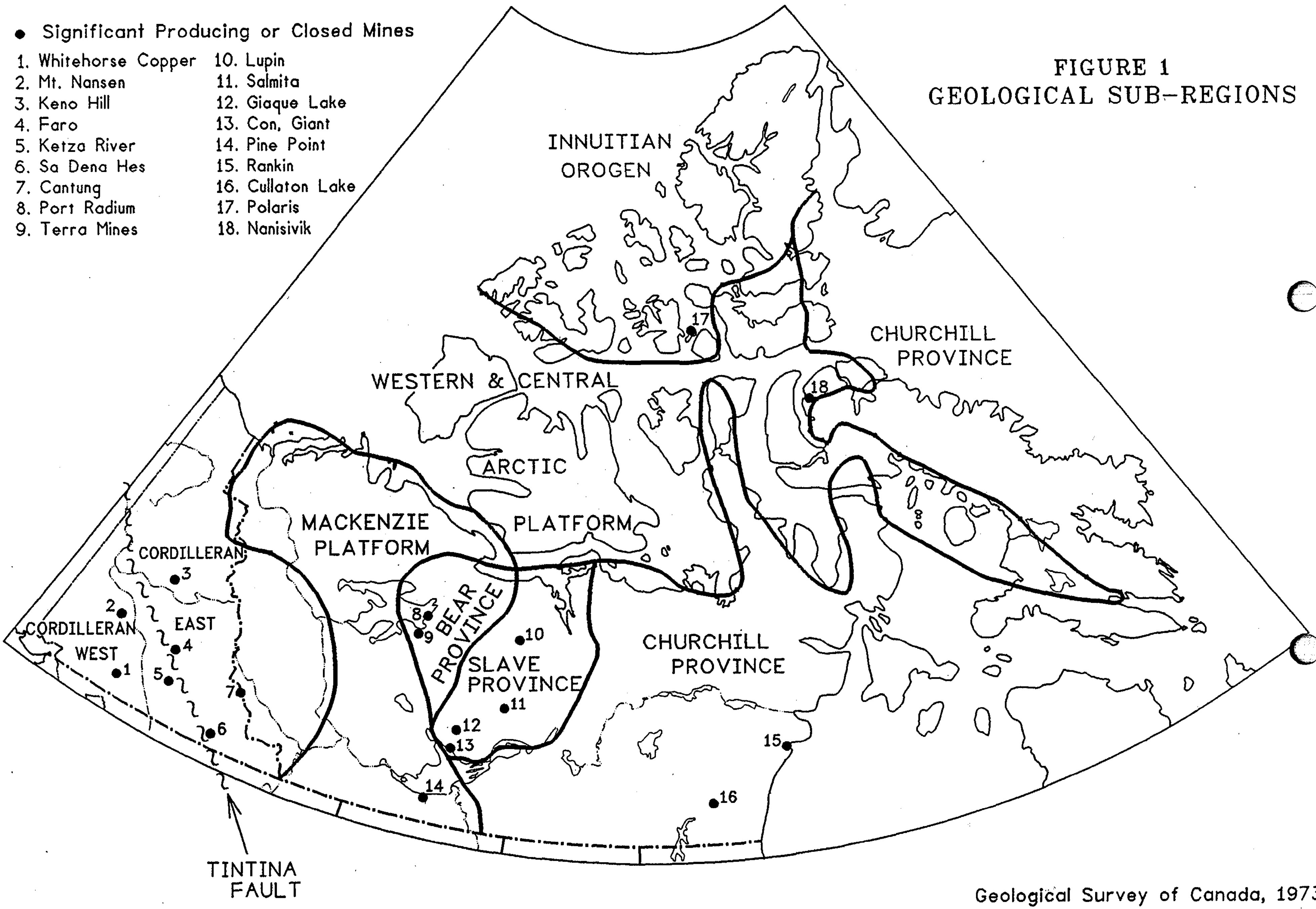
FIGURE 1
GEOLOGICAL SUB-REGIONS



Geological Survey of Canada, 1973

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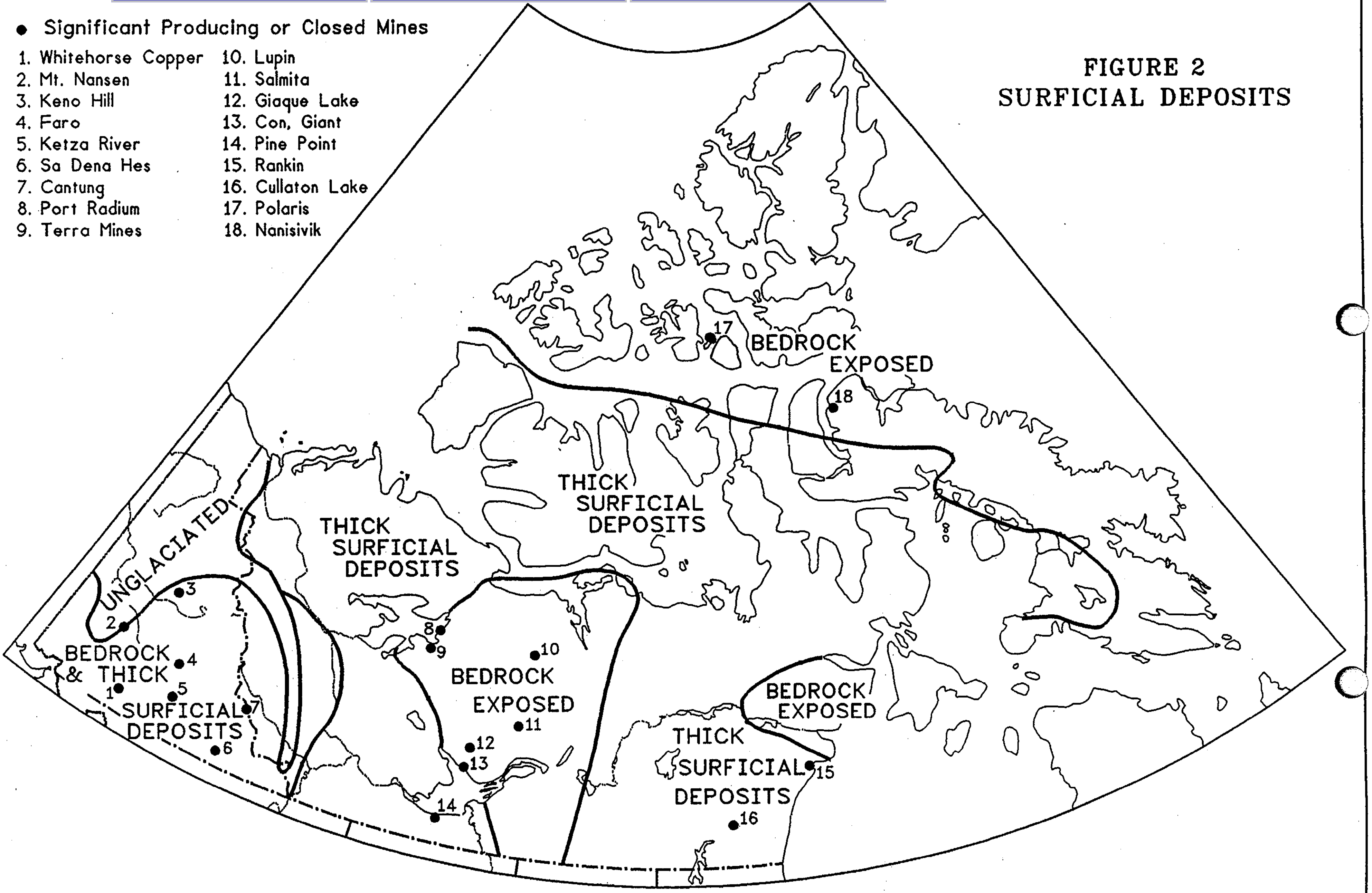
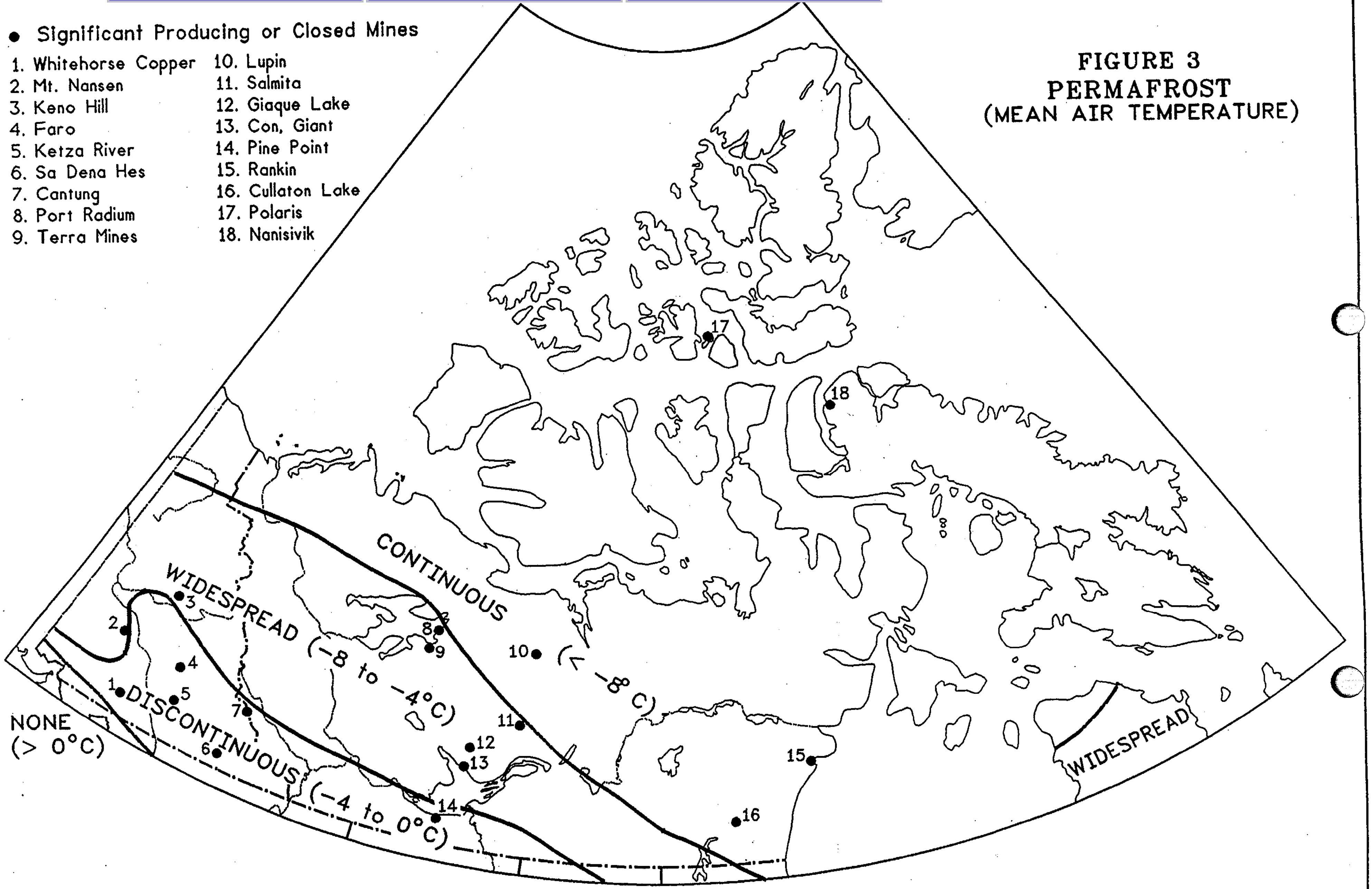
FIGURE 2
SURFICIAL DEPOSITS



National Atlas of Canada (1974)

FIGURE 3
PERMAFROST
(MEAN AIR TEMPERATURE)



Geological Survey of Canada (1967)

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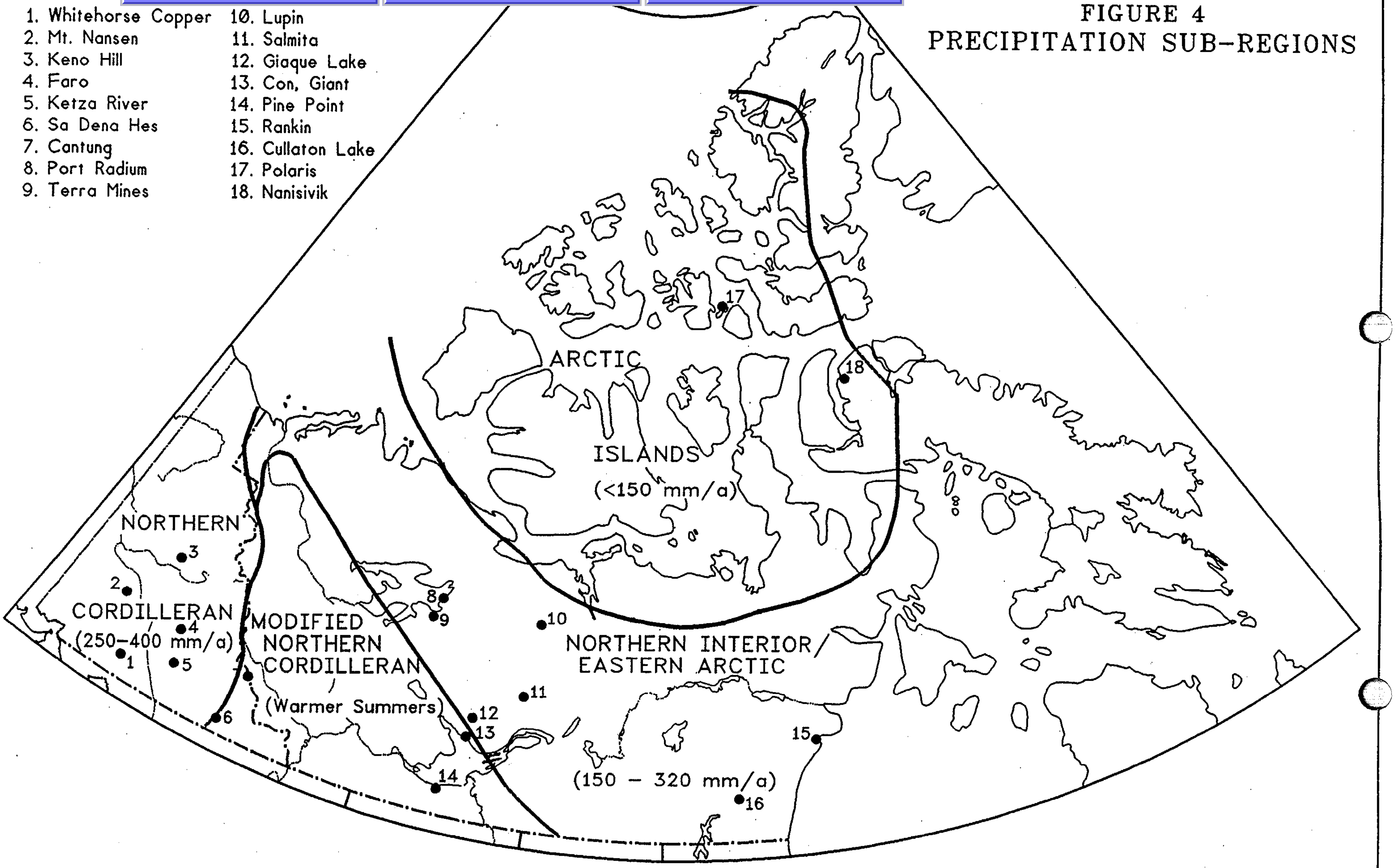
FIGURE 4
PRECIPITATION SUB-REGIONS

● Signifi

1. Whitehorse Copper
2. Mt. Nansen
3. Keno Hill
4. Faro
5. Ketza River
6. Sa Dena Hes
7. Cantung
8. Port Radium
9. Terra Mines
10. Lupin
11. Salmita
12. Giaque Lake
13. Con, Giant
14. Pine Point
15. Rankin
16. Cullaton Lake
17. Polaris
18. Nanisivik

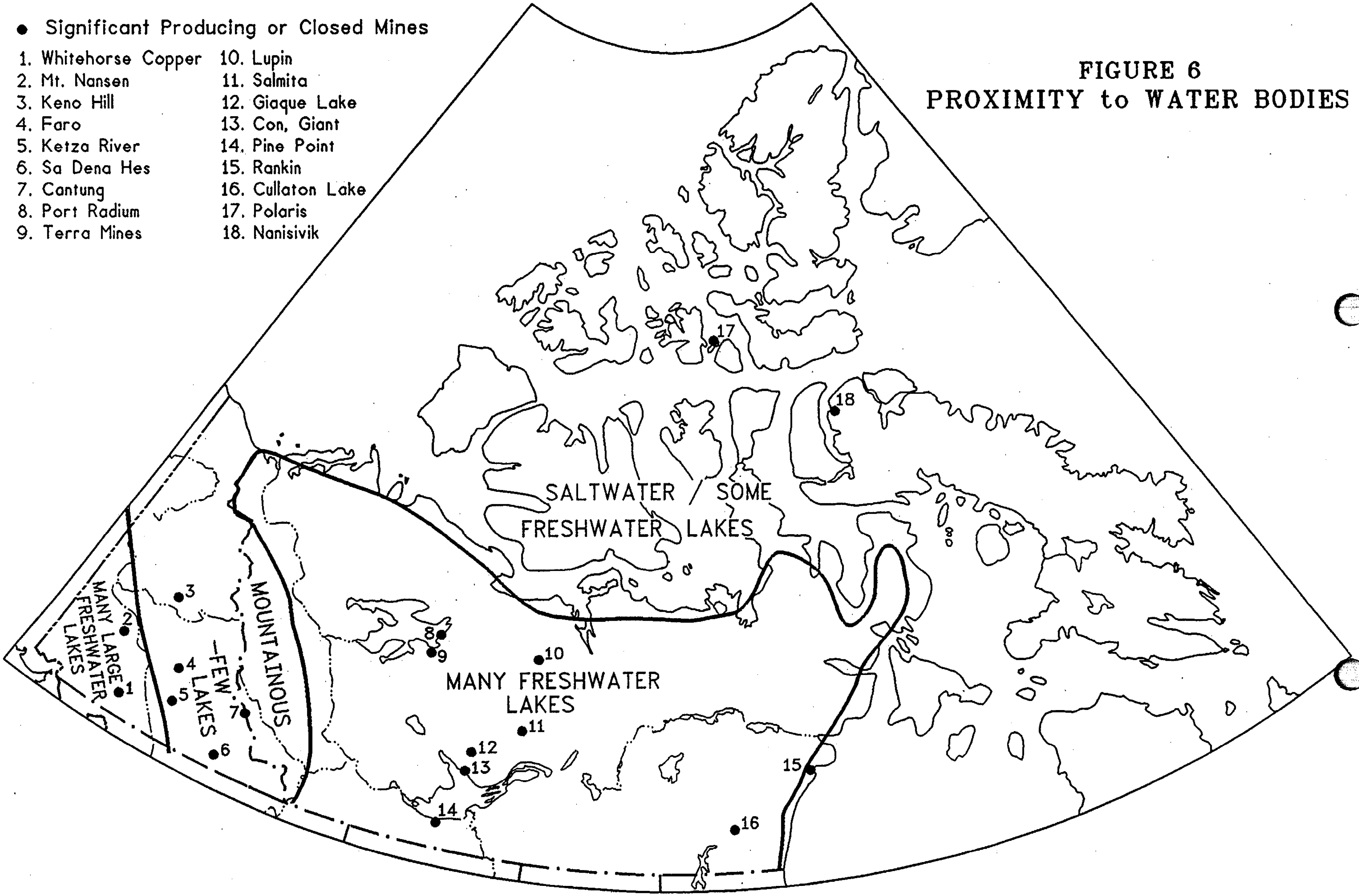


National Atlas of Canada (1974)

● Significant Producing or Closed Mines

1. Whitehorse Copper
2. Mt. Nansen
3. Keno Hill
4. Faro
5. Ketza River
6. Sa Dena Hes
7. Cantung
8. Port Radium
9. Terra Mines
10. Lupin
11. Salmita
12. Giaque Lake
13. Con, Giant
14. Pine Point
15. Rankin
16. Cullaton Lake
17. Polaris
18. Nanisivik

FIGURE 6
PROXIMITY to WATER BODIES



National Atlas of Canada (1974)

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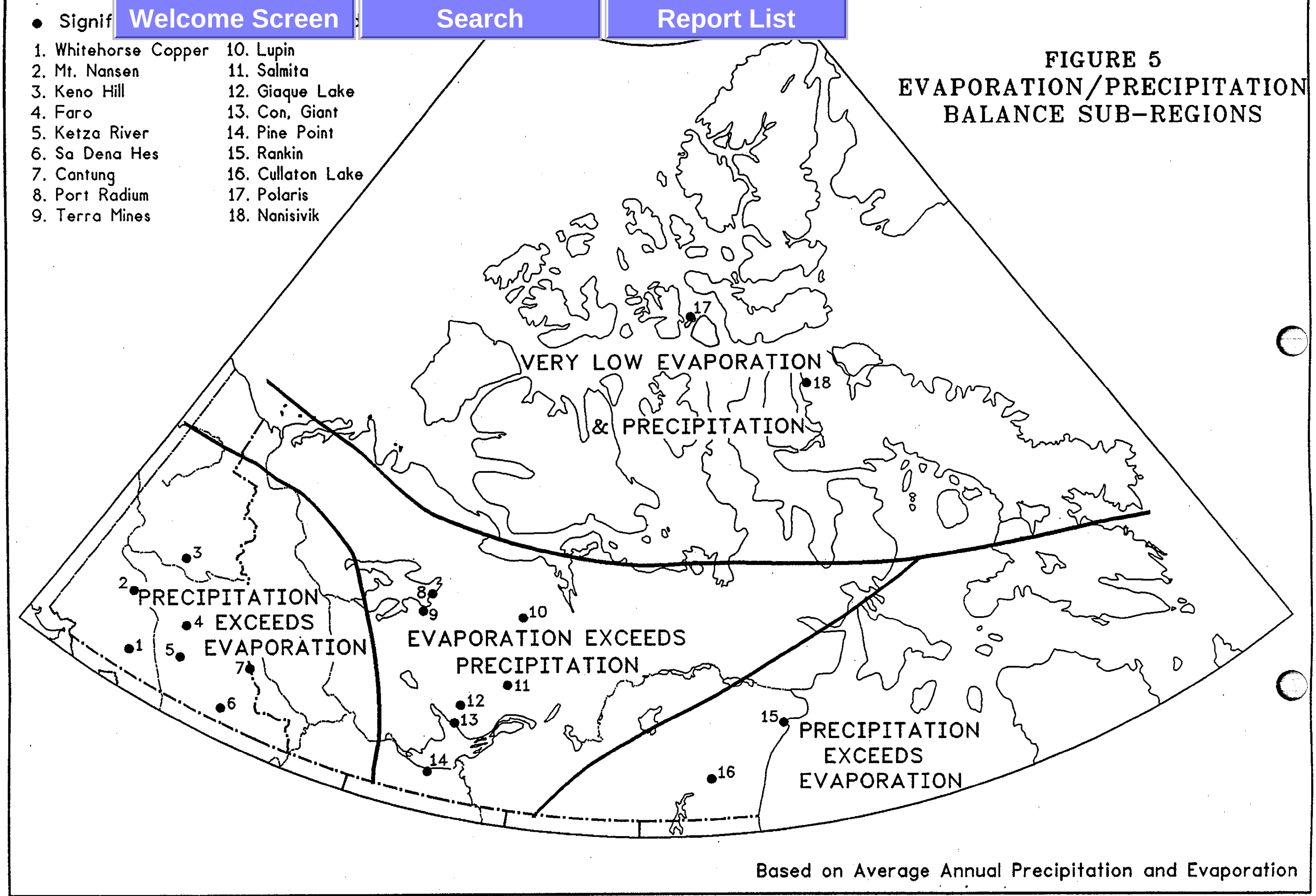
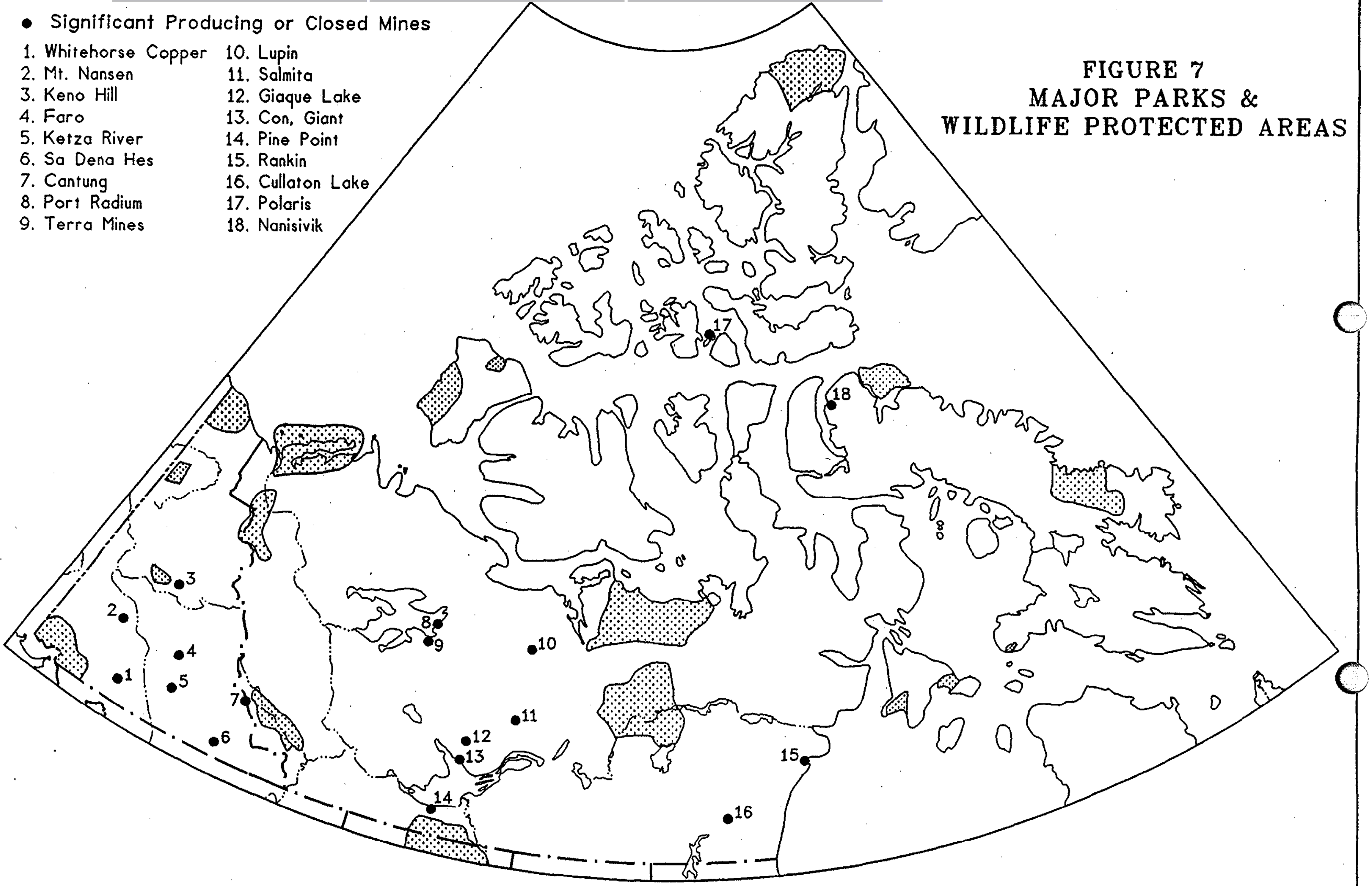
FIGURE 5
EVAPORATION/PRECIPITATION BALANCE SUB-REGIONS



Based on Average Annual Precipitation and Evaporation

FIGURE 7
MAJOR PARKS & WILDLIFE PROTECTED AREAS



Environment Canada (1982)

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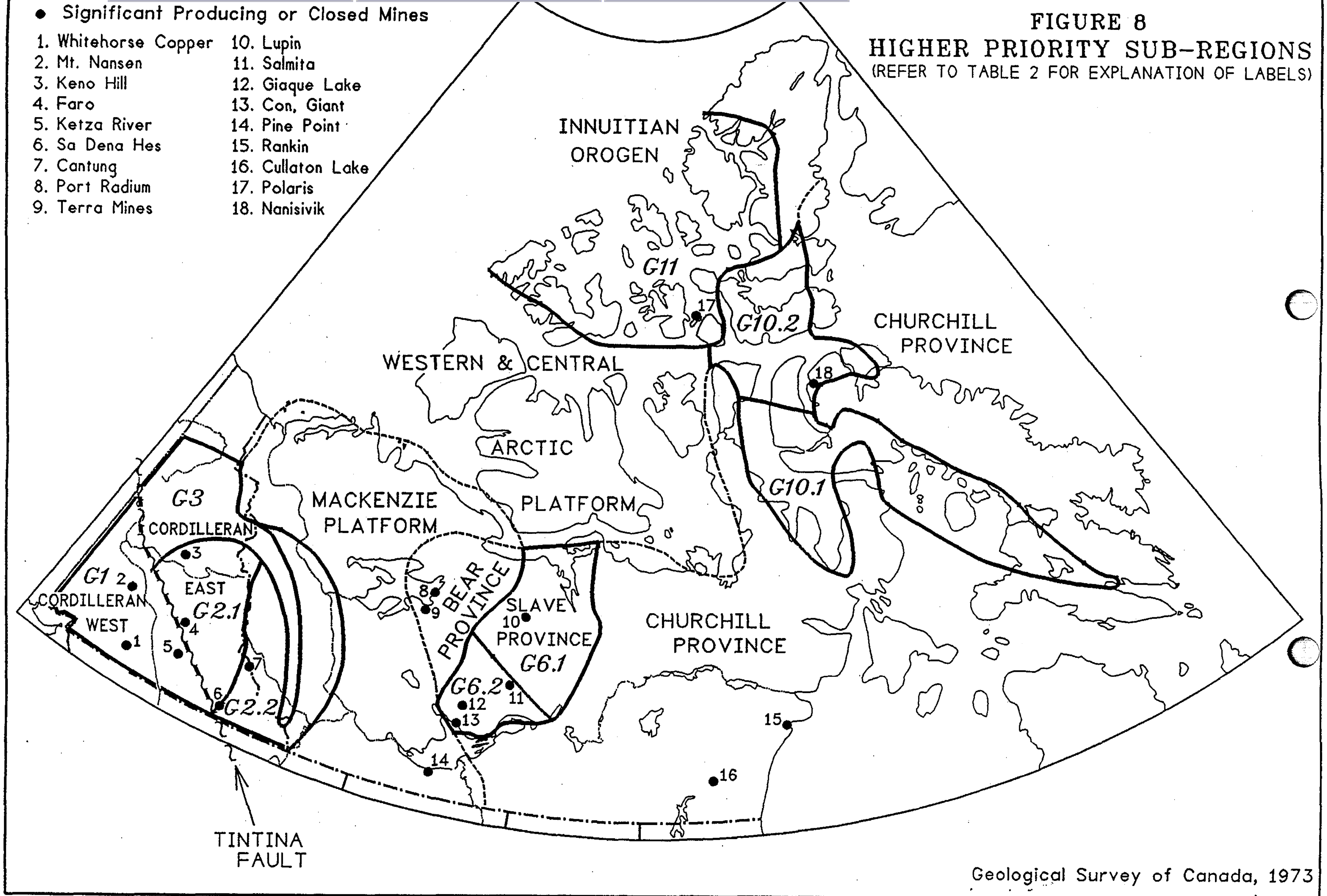
FIGURE 8
HIGHER PRIORITY SUB-REGIONS

(REFER TO TABLE 2 FOR EXPLANATION OF LABELS)



Geological Survey of Canada, 1973

3.11. SUMMARY OF GAPS IN CURRENT KNOWLEDGE

Grant Feasby
MEND Secretariat

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SUMMARY OF GAPS IN CURRENT KNOWLEDGE

1. Oxidation rates of S^{2-}
  1.1. Relatively undefined at low temperature (6 °C → < -2 °C)

2. Competing Factors in Cold Climates – for example:
  2.1. Heat generation during sulphide oxidation vs freezing
  2.2. Increased oxygen solubility vs decreased reaction rates at low temperatures
  2.3. Observed reaction rates higher at low temperatures than ambient temperature (e.g. Cu in Windy Craggy test cells)
  2.4. Biotic oxidation – bacteria adapting at low temperature vs biotic oxidation rate at low temperature
  2.5. Electrochemical oxidation

3. Natural Analogues – What are they telling us?

4. Test Methods
  4.1. Are chemical prediction tests performed at ambient temperature (25 °C) relevant for northern climates?
  4.2. Are chemical models using oxidation rates ‘calibrated’ to ambient temperature applicable to northern climates?

5. Waste Rock Dumps

- 5.1. Hydrogeology of waste rock dumps still a large unknown
- 5.2. Thermal effects in waste rock dumps at low temperatures not well defined
  - 5.2.1. Freezing mechanisms

6. Field Experience

- 6.1. Tailings and waste rock in northern climates limited compared to more ‘southern’ areas (i.e. non-permafrost zones)

7. ARD, Alkaline drainage, Metal Fluxes

- 7.1. Data, field experience for northern climates needed

8. Treatment for remote, cold sites – lime treatment the only option?

9. Freezing Point Depression due to Process Chemicals

- 9.1. Is this a significant effect?

10. Economic Insulating Cover Designs

- 10.1. With lack of cover materials in north and no ‘proven’ designs, can a protocol for covers in the north be designed with the above in mind?